Groundwaters of New Zealand

Edited for the New Zealand Hydrological Society
by **Michael R Rosen** and **Paul A White**

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Front Cover: artesian well at Dyers Road, Christchurch. John Weeber, Environment Canterbury.
Back Cover: schematic of the geology of a New Zealand coastal plain from the mountains to the sea. Environment Canterbury;
well drilling near Waimarino River, Lake Taupo. Michael Rosen; and
groundwater seepage over a road cut near Waipuna, north of Wanganui. Michael Rosen.

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List of Contributors

Gabor Bekesi is a scientist with horizons.mw (The Manawatu Wanganui Regional Council). He graduated from the University of Miskolc, Hungary, in geophysics, and soon after left Hungary (those days a communist state) for the bright lights of New Zealand. He received a MSc in geophysics in 1989 and a PhD in physical geography in 1999 from Victoria University of Wellington. He specialised in groundwater vulnerability and spatial modelling and published several papers on these subjects. (Postal address: Manawatu-Wanganui Regional Council, Private Bag 11025, Palmerston North).

Len Brown is a hydrogeology consultant who previously worked for New Zealand Geological Survey, DSIR at Christchurch from 1962 to 1979 and Lower Hutt from 1979 to 1992 and the Institute of Geological and Nuclear Sciences from 1992 to 1999. He set up groundwater surveys and databases in the Canterbury and Marlborough regions. North Island groundwater projects included Poverty Bay flats and Heretaunga Plains. He was the New Zealand Geological Survey representative on technical committees advising regional water boards on hydrogeology and groundwater resources. He is the author of 60 published papers, maps and bulletins. (Postal address: 61 Penrose Street, Lower Hutt).

Stewart Cameron is a hydrogeologist for the Institute of Geological and Nuclear Sciences. He has a MSc. in Engineering Geology from University of Canterbury. He previously worked as a hydrogeologist at the Hawke's Bay Regional Council. His present research and consultancy work is focused on river-groundwater interaction, 3D modelling of aquifer structure, aquifer hydraulics, and effect of land use and geology on groundwater chemistry. (Postal address: Institute of Geological and Nuclear Sciences, Private Bag 2000, Taupo).

Bente Clausen is a Senior Lecturer in Hydrology in the Department of Civil Engineering, University of Canterbury. She studied hydrology at Aarhus University in Denmark, where she also lectured until 1996. She did her doctoral research on the interaction between groundwater and streamflow and has since then concentrated on surface water hydrology and its interaction with ecology. (Postal address: University of Canterbury, P O Box 4800, Christchurch).

Murray Close is a Principal Scientist at the Institute of Environmental Science and Research. He started working in groundwater in 1979 in the Water and Soil Division, Ministry of Works. He transferred into DSIR, Geophysics Division and then DSIR Geology and Geophysics. He currently leads ESR's groundwater contamination research group. His current interests include leaching of pesticides and pesticide contamination of groundwaters, modelling the transport and fate of groundwater contaminants, assessment of groundwater quality, and unsaturated zone processes. (Postal address: Environmental Science and Research, P O Box 29181, Christchurch).

Gillian Crowcroft is a water resource scientist at the Auckland Regional Council where she works primarily on groundwater resource projects. She studied Earth Science at the University of Waikato and graduated following hydrogeological modelling of a gravel aquifer in the Hamilton Basin. (Postal address: Auckland Regional Council, Private Bag 92012, Auckland).

Peter Davidson works for Marlborough District Council as a groundwater resources specialist. He studied geology and hydrology at the University of Otago before completing the graduate hydrology course at the University of New South Wales, and more recently, a MSc in Earth Sciences at Victoria University of Wellington. From 1987 he has been involved in aquifer resource management and investigations. (Postal address: Marlborough District Council, P O Box 443, Blenheim).

Helen Davies is a scientist with the Institute of Environmental Science and Research Limited. She obtained her first degree from Leeds University, UK in 1987, followed by a MSc in Environmental Technology from Imperial College, University of London, and was involved in contaminated land and groundwater assessment. Since coming to New Zealand in 1996 she has specialised in chemical contamination of water used for drinking-water supplies (Postal address: Institute of Environmental Science and Research Limited, P O Box 29181, Christchurch).

Andrew D Fenemor holds the position of Manager, Environmental Information with the Tasman District Council, responsible for natural resources investigations and management. Andrew studied agricultural engineering (soil and water management) at Canterbury University and at the Ohio State University, and was previously a groundwater scientist with the Hydrology Centre in Christchurch. He is past president of the NZ Hydrological Society. (Postal address: Manager Environmental Information, Tasman District Council, Private Bag 4, Richmond, Nelson).

Dougall Gordon is an Environmental Scientist with Environment Bay of Plenty. He studied earth sciences at University of Waikato, completing a MSc (Tech) and then worked as Water Resources Officer at Gisborne District Council for three years. In 1998, he moved to Whakatane to work with groundwater, geothermal, and coastal resource investigations and management. (Postal address: Environment Bay of Plenty, P O Box 364, Whakatane).

John Hadfield is a hydrogeologist (scientist) who has worked with Environment Waikato and predecessor the Waikato Valley Authority for 15 years. He has also worked in consultancies in Switzerland and New Zealand. He has responsibilities for groundwater resource investigation in the Waikato Region and has particular interests in groundwater contaminant issues, tracer investigations and resource development. (Postal address: Environment Waikato, P O Box 4010, Hamilton East).

Thomas B Heller is a groundwater hydrologist with the Otago Regional Council. From 1981 he has undertaken environmental monitoring and research of water resources in the Otago region. Some of his current projects include water allocation scenarios in "limited extent" aquifers and the integration of surface water and groundwater management. He is a Registered Engineering Associate and has previously studied civil engineering and natural resource sciences management. He is currently studying for a MSc. in Environmental Science at the University of Otago. (Postal address: Otago Regional Council, Private Bag 1954, Dunedin).

Brydon Hughes is an Environmental Scientist with Environment Southland responsible for developing groundwater monitoring and investigation programs. He studied Engineering Geology at the University of Canterbury and spent five years employed as Groundwater Hydrologist at the Wellington Regional Council. (Postal address: Environment Southland, Private Bag 90116, Invercargill).

Bruce Hunt is a Reader in the Department of Civil Engineering, University of Canterbury. He studied civil engineering at Duke University and fluid mechanics and hydraulic engineering at the University of Iowa. His research has been in the area of groundwater flow and hydraulic engineering. (Postal address: University of Canterbury, P O Box 4800, Christchurch).

Trevor James is Environmental Monitoring Officer at West Coast Regional Council. He studied at University of Canterbury, obtaining a MSc in 1991 in environmental biotechnology (biological waste treatment). After working for an environmental consultancy for several years he moved to his current position with responsibility for managing the following state-of-the-environment monitoring programmes: surface water quality and aquatic ecology, groundwater quality, air quality and contaminated sites. (Postal address: P O Box 66, Greymouth).

Larry D Luba is a director of East Coast Environmental and Associates Limited (ECE), Napier. He graduated from the University of Waterloo, Canada with a M.Sc. in Earth Sciences (contaminant hydrogeology). Prior to establishing ECE he held various positions in government, industry, and consulting. He has been involved in numerous projects related to ground water resource evaluation, liquid and solid waste management, environmental site assessment, ground water contamination and monitoring, open case mine dewatering, and the development of analytical and 3-dimensional numerical computer models. (Postal address: 29 Clyde Road, Napier Hill, Napier).

Matthew Morgan is a Senior Water Resources Engineer with Lincoln Environmental. Until recently he was Section Leader of Resource Investigations with the Wellington Regional Council's Wairarapa Division. He studied civil engineering at the University of Canterbury, followed by 5 years overseas, working as a consultant environmental engineer in the UK and a hydrologist in Nigeria, before returning home to New Zealand. (Postal address: P O Box 133, Lincoln, Canterbury).

Uwe Morgenstern is a Physicist and has a PhD from Technical University, Bergakademie Frieberg, Germany. He is the leader of the Tritium and Water Dating Lab of the Institute of Geological and Nuclear Sciences. His research interests are the development of dating methods using cosmogenic radionuclides, and their application for the study of environmental circulation processes with special emphasis on understanding groundwater resources. Recently he worked on advanced methods for high accuracy tritium dating of groundwater and measurement of the fraction of young waters. (Postal address: Institute of Geological and Nuclear Sciences, P O Box 30368, Lower Hutt).

Susie Osbaldiston is the Groundwater Management Officer for the Northland Regional Council. Susie studied Environmental Science at Lincoln University and carried out additional study in hydrogeology at the Australian Groundwater School. She has previously worked in the field of water quality monitoring for the Canterbury Regional Council, and surface and groundwater resource analysis and reporting for the Hawkes Bay Regional Council. (Postal address: Northland Regional Council, Private Bag 9021, Whangarei).

Calum Revfem is an environmental management analyst engaged in State of the Environment monitoring and reporting for Rotorua District Council. He graduated from Wageningen UR in the Netherlands with a M.Sc in environmental systems analysis, which included research work with Environment Canada's Pacific-Yukon region water quality division. His focus of interest now lies in the development of environmental change indicators. (Postal address: Rotorua District Council, Private Bag 3029, Rotorua).

Christina Robb is a consultant for Lincoln Environmental. She has a background in agricultural engineering and a Masters in Resource Management from Simon Fraser University, British Columbia. She has previously worked for Wellington Regional Council in floodplain modelling. Her current consultancy work is predominantly for central and regional government in the areas of water allocation, groundwater management and irrigation issues. (Postal address: Lincoln Environmental, P O Box 133, Lincoln, Canterbury).

Michael R Rosen is a geochemist who worked on groundwater quality investigations at the Wairakei Research Centre of the Institute of Geological & Nuclear Sciences (GNS) from 1993 to 2001. He was the Groundwater Programme and Groundwater Quality Programme Leader for GNS from 1995 to 2001. Previously he worked at the University of Minnesota, USA, the Division of Water Resources at CSIRO-Australia and Curtin University of Technology, Western Australia, on groundwater and lake water quality issues. He received his degrees in geological sciences from Haverford College (B.Sc.), the University of Rochester (M.Sc.), and the University of Texas at Austin (Ph.D.). Michael now has the position of Nevada Basin and Range Study Unit Chief for the National Water Quality Assessment (NAWQA) programme run by the United States Geological Survey. (Postal address: U.S. Geological Survey, 333 W. Nye Lane, Carson City, NV, 89706-0866, USA).

Wayne J Russell is a senior principal of URS New Zealand Ltd (formerly Woodward-Clyde (NZ) Ltd). Wayne has 28 years experience in hydrogeology and groundwater engineering. His expertise includes regional groundwater resource evaluations; community and industrial water supplies; hydrological evaluation of waste sites; assessment of contaminant movement from waste sites; and dewatering for construction, tunnel and mining excavation. Wayne has undertaken a number of regional resource evaluations including the initial investigations of a number of groundwater basins in New Zealand. Wayne has an interest in training and lectures in hydrogeology at the University of Auckland. (Postal address: URS, P O Box 821, Auckland).

Lester W Sinton studied botany, zoology and mycology at Victoria University, and environmental microbiology at Lincoln University. From 1975 to 1988 he was a scientist in the Hydrology Centre, Water and Soil Division, Ministry of Works and Development, where he studied bacterial contamination of groundwater, groundwater macroinvertebrates, and developed microbial tracing techniques using bacteria and bacteriophages. He then worked for four years in the Groundwater Group, DSIR, investigating new methods for assaying bacteriophages, and establishing rates of transport of phages into and though groundwater systems. He joined ESR in 1992, and now leads a small research team investigating microbial inactivation in surface waters, and also works as part of the ESR groundwater quality research team. (Postal address: Christchurch Science Centre, ESR, P O Box 29-181, Christchurch).

George Skuse was an exploration geologist in the Northern Territory and Queensland. On returning to New Zealand he worked for the East Cape Catchment Board, studying the groundwater of the Poverty Bay flats. From 1986, the Northland Regional Council has employed him as a groundwater hydrologist. (Postal address: Northland Regional Council, Private Bag 9021, Whangarei).

Alastair Smaill is the team leader of Water Resource Investigations at the Auckland Regional Council. He is responsible for surface and groundwater investigation programmes. He graduated from the University of Auckland following research on sedimentology. He has worked in engineering geology and hydrology. (Postal address: Auckland Regional Council, Private Bag 92012, Auckland).

Vivienne R Smith works for Environment Canterbury as the Portfolio Manager: Water, Hazardous Substances & Waste. Leading on from postgraduate studies in engineering geology, she did her doctoral research on the impact of landfill leachate on groundwater quality. Since 1992 she has co-ordinated Canterbury's investigation, monitoring and reporting programmes for groundwater quality, contaminated sites, and waste management with specific interest in the impacts of pesticides, nitrates and hydrocarbons. She has participated in a number of national working parties including that developing the New Zealand Drinking-Water Standards. (Present address: Environment Canterbury, P O Box 345, Christchurch).

Glenn Stevens is a water resource scientist at the Taranaki Regional Council. He has completed a Bachelor of Sciences in geology from the University of Auckland and a Master of Applied Science degree from the Lincoln University in water resources. He has previously worked as a hydrogeologist for Pattle Delamore Partners Ltd, in their Christchurch office prior to moving to the Taranaki Regional Council. (Postal address: Taranaki Regional Council, Private Bag 713, Stratford).

Mike K Stewart is a hydrogeologist at the Institute of Geological and Nuclear Sciences, where he has specialised in the use of isotopes in hydrological studies. He has a MSc from the University of Canterbury and a PhD from the University of Pennsylvania. He has worked in the fields of groundwater and geothermal resources, and headwater catchment processes. His current interests include groundwater dating using CFCs and streamflow source using stable isotopes. (Postal address: Geological and Nuclear Sciences, P O Box 30368, Lower Hutt).

Joseph Thomas is the water resource scientist with the Tasman District Council, Richmond. He obtained his first degree in Applied Science (Engineering Geology) from the National University of Malaysia in 1985. He then completed a Masters Degree in engineering geology at the University of Canterbury in 1989 with a project on groundwater hydrology of the Moutere Catchment in the Nelson Region. He commenced work with the then Nelson Catchment Board as a Research Assistant, moving on to become Groundwater Scientist in the Nelson Marlborough Regional Council. He currently is involved in a wide area of water resource investigations, consents and water policy planning work. (Postal address: Tasman District Council, Private Bag 4, Richmond, Nelson).

Hugh R Thorpe is a Research Fellow in the Civil Engineering Department at the University of Canterbury having originally graduated from that institution in 1959 and subsequently studied at the University of Aberdeen. He has worked in many aspects of water engineering and science, mostly as an employee of the now defunct Ministry of Works and Development. The complexities and pleasures of groundwater science attracted him in 1976 and from 1978 to 1992 he led a multi-disciplinary groundwater research group based in Christchurch. Since 1993 he has been involved happily in a mix of teaching, research and consulting work. (Postal address: 14 Taylors Ave, Christchurch, 8005).

John Weeber is a hydrogeologist at Environment Canterbury and began work as a technical officer at the North Canterbury Catchment Board in 1974. During this time he has been closely involved with groundwater investigations/monitoring including the establishment and ongoing management of a computer information database containing records for over 24,700 wells. In collaboration with Institute of Geological and Nuclear Sciences he is using geological well logs to construct 3-dimensional geological models of Christchurch. Documenting the history of early well drilling and water supply is a particular interest. (Postal address: Environment Canterbury, P O Box 345, Christchurch).

Julian J Weir works with Lincoln Environmental. His environmental research commenced with investigations into stream depletion from groundwater pumping while undertaking his thesis for the Masters of Engineering degree at University of Canterbury. His primary interest is in environmental engineering with an emphasis on groundwater hydrology. (Postal address: Lincoln Environmental, P.O. Box 133, Lincoln, Canterbury).

Paul A White graduated from Victoria University of Wellington in 1980 with a BSc (Hons). He joined the Ministry of Works and Development at the Water and Soil Division's Hydrology Centre in 1980 where he worked on the application of geophysical techniques to groundwater investigations. In 1988 he jointed the Department of Scientific and Industrial Research. He is presently employed by the Institute of Geological and Nuclear Sciences where his roles have included Groundwater Programme Leader and Groundwater Section Manager. Present research interests include the application of groundwater models to understanding surface (rainfall and river) water interaction with groundwater, groundwater flow model validation, computer modelling of aquifer geology, and the application of resource economics to groundwater. He is currently the President of the New Zealand Hydrological Society. (Postal address: Institute of Geological & Nuclear Sciences, Wairakei Research Centre, Private Bag 2000, Taupo).

Preface

Paul White first suggested that the Hydrological Society publish a book on groundwater research in New Zealand in 1997. The idea was that a book specialising on groundwater would complement the previously published more general Hydrological Society books *Waters of New Zealand* (1992) and *Floods and Droughts* (1997). It has taken nearly 3 years to complete the project, but the end result is a book that forms a basis for future groundwater studies in New Zealand and shows the New Zealand "state of the art" for groundwater research. In addition the book has been constructed in such a way that it can be easily updated either electronically or in print. We believe this book is unique in that it attempts to assemble in one place the major references, ideas and developments in groundwater research for the entire country. The book is divided into two parts. After the introduction, the first part provides chapters that summarise New Zealand groundwater history, resources, quality, health, management, processes (recharge and groundwater-surface water interaction) and techniques (isotopic methods). The second part of the book provides up-to-date regional summaries of groundwater resources and quality in every region of the country.

The authors and reviewers of the book chapters represent almost all of the current groundwater researchers in New Zealand. The book has been a collective effort of 34 authors and over 30 reviewers (some of whom did both!). Without the help of both authors and reviewers this book would not have been possible. The enthusiasm and dedication of the authors and reviewers made our job as editors much easier.

In addition, the quality of the book would have suffered without the copy editing of Eileen McSaveney, and the extraordinary amount of word processing and graphical editing provided by the staff at the Institute of Geological & Nuclear Sciences Ltd. (GNS) - many thanks to Tracey Carmody, Diane Tilyard, Michelle Parks, Carolyn Hume and Philip Carthew for their help on this project. We would also like to thank the GNS management for allowing us the time to edit this book, as without this commitment from GNS the book would not have been possible. Our thanks also go to the Hydrological Society for financially supporting production of this book, and special thanks to Lindsay Rowe for encouragement and logistical support during the editing process. Finally, we would like to thank our families for allowing us to use some of our precious free time to write chapters, edit manuscripts, and ferry manuscripts between authors, reviewers, graphical designers and printers. Both of us have young families and without our families' support, the book would have been difficult to complete.

MRR, PAW *June 2001*

1

Introduction

PAUL A. WHITE AND MICHAEL R. ROSEN

Groundwater is an integral part of the hydrological cycle and should be viewed within this wider context. Groundwater is, however, the least-understood component of the hydrological cycle although it is a very important water resource to New Zealand. The authors of this book show how research into groundwater quantity and quality, groundwater and health, and groundwater management in New Zealand contribute to our current understanding of the resource and the interactions of groundwater with other components of the hydrological cycle. The authors of this book also show the importance of New Zealand's groundwater to the country's population and economy and show how New Zealand's regions utilise and manage their groundwater resources.

GROUNDWATER USE IN NEW ZEALAND

Maori used groundwater long before Europeans arrived (Chapter 2), as reflected in the many place names that refer to groundwater: for example *Waikari* (water, dug out) refers to shallow wells, and *Waipuna* to springs. European settlers obtained water from the nearest river, stream or spring, but they soon contaminated the surface water supplies. By 1863—within just a few decades of European settlement—well drilling was established in New Zealand (Chapter 2), and Christchurch, Wellington, Auckland and Dunedin used groundwater as a domestic water supply in their early days. Groundwater was also important to early agriculture and industry.

Present-day use of groundwater resources is considerable—26% of the New Zealand population depend totally on groundwater for drinking water, including residents of the cities of Christchurch, Lower Hutt, Napier, Hastings and Wanganui (Chapter 10). A further 25% of the population drink water that comes from groundwater and surface water sources (Chapter 10). Approximately 30% of the water allocated for consumption in New Zealand is groundwater (Chapter 3), and since 1990 about half of the country's total water allocation has been from groundwater (Chapter 11).

While groundwater is a largely invisible resource, New Zealand can boast of groundwater in its most spectacular form—the steaming geysers and bubbling pools of the geo-thermal areas are national icons. Maori made use of geothermal waters for cooking and recreation. Many geothermal areas were in turn developed by early European entrepreneurs as spas for tourists and Maori often acted as guides to these features. Geothermal areas remain popular as tourist destinations, for example Rotorua receives approximately 1.3 million tourists a year. As well as luring tourist dollars, geothermal areas have an additional economic value, as geothermal steam is used to generate electricity.

AQUIFERS

It is estimated that at any one time 80% of New Zealand's fresh water is underground, (Chapter 3) but this water is not readily available everywhere. The locations of aquifers, and their properties, reflect the complex geological and climatic history of the New Zealand region. New Zealand sits astride the boundary of the colliding Australian and Pacific tectonic plates, giving rise to rapid rates of uplift, subsidence, erosion and deposition; active tectonism is associated with volcanism and geothermal activity (Chapter 3). Aquifers thus exist in a wide range of lithologies in New Zealand,

White P.A. and Rosen M.R. 2001: Introduction. *In* Groundwaters of New Zealand, M.R. Rosen and P.A. White *(eds)*. New Zealand Hydrological Society Inc., Wellington. p1-3.

and yield both cold and hot water. Most of the aquifers are in geologically young sediments and in volcanic deposits, and the stratigraphic relationships between these deposits is often complex. Global climate variations have been a major factor in the deposition of sediments with varied properties, with localised glaciation, changes in sea level, and changes in vegetation affecting erosion rates and causing depositional environments to alter relatively quickly over time.

The physical properties of aquifers (Chapter 12 to 26) are largely determined from well tests. Regional piezometric maps (Chapter 3 and Chapters 12 to 26) are used to determine flow directions within aquifers and their sources of recharge. Flow directions, sources of recharge, and rates of groundwater movement are also assessed using computer models (Chapter 3) and stable isotopes, radioactive isotopes and chemical tracers (Chapter 7).

GROUNDWATER AS PART OF THE HYDROLOGICAL CYCLE

Groundwater cannot be treated in isolation from other components of the hydrological cycle (Chapters 3, 4, 5, 6 and 7). A significant component of groundwater originates as rainfall that seeps through the soil into aquifers. A number of studies have sought to understand and model the mechanisms by which aquifers are recharged from rainfall (Chapter 5). Rivers are also an important source of recharge to groundwater systems (Chapter 6), but in the mobile channels of the gravel-bed rivers that are common in New Zealand it is often particularly difficult to measure recharge. Methods of measuring recharge from rivers include low-flow gaugings, measurements of groundwater levels (Chapter 6), modelling (Chapter 6) and the use of isotopic and chemical tracers (Chapter 7). Groundwater also discharges into rivers, at springs, and at the coast (Chapter 6). Modifications to the groundwater system can cause alterations in surface hydrology and vice-versa, because groundwater and surface water are intimately linked. For example, pumping from a groundwater system may cause a reduction in stream flow or saltwater intrusion into the groundwater (Chapter 6).

GROUNDWATER QUALITY

The hydrochemistry of groundwater in New Zealand is diverse, reflecting the varied lithologies of the aquifers, water flow, and land use in recharge areas. Proximity to the sea is also important, with sodium, chloride, and bromide concentrations in groundwater being derived mainly from sea water through rainfall or sea spray (Chapter 4). Agriculture has an effect on the concentrations of sulphate, potassium, magnesium, nitrate, and possibly calcium and ammonium (Chapter 4). Elevated concentrations of arsenic have been found to be associated with natural sources (e.g. geothermal areas) and with human agricultural activities. The areas of New Zealand most likely to have high nitrate concentrations in groundwater include the Waikato, Manawatu-Wanganui, Taranaki, Wairarapa, Tasman, and North Otago (Chapter 8), which all have relatively intense agricultural land use.

Low levels of pesticides have been detected in some shallow wells in unconfined aquifers, but virtually no pesticides have been found in community drinking water supplies (Chapters 8 and 10). In only a few wells have pesticides been detected in concentrations that are above the New Zealand drinking water guidelines, and these and can be linked with specific sources of contamination (Chapter 8). Long-term changes in the concentrations of nitrate and pesticide in groundwater are difficult to establish however because of a lack of data and, in the case of pesticides, concentrations that vary markedly over time.

The chemical quality of registered community drinking water from groundwater sources is generally good (Chapter 10) and chemical contamination by land-use activities is generally not a health hazard. A few chemicals have been found in community drinking water supplies at concentrations greater than 50% of the New Zealand drinking water guidelines, including arsenic, nitrate, and manganese; nitrate is the only one that is related to land use. Faecal coliform bacteria have been recorded in a small number of groundwater sources supplying small, scattered populations (Chapter 10). Grazing animals are the largest potential source of contamination of New Zealand's aquifers by microbes (Chapter 9), but septic tanks and effluent irrigation systems are also potential sources.

Correct construction of wells and the establishment of well-head protection programmes are important in preventing groundwater pollution from local sources (Chapter 10). Minimising chemical contamination to aquifers is important (Chapters 8 and 10) because contaminants are difficult and expensive to remove once they are in the aquifer.

GROUNDWATER MANAGEMENT

A systems approach to managing groundwater (Chapter 11) is consistent with New Zealand's Resource Management Act (1991), which aims to manage natural resources on a sustainable basis. Management for groundwater quantity commonly overlaps with management for groundwater quality and with land use management.

Many New Zealand rivers are becoming fully allocated and therefore the nation's groundwater reserves are likely to be more in demand in the future (Chapter 11). Investment in resource investigations in the many areas of New Zealand where little is known about the groundwater resource is required to meet the demands of sustainable management. To avoid the environmental and social costs of degradation of groundwater quantity and quality that is occurring in many other countries of the world we must carefully assess the sustainability of the country's groundwater resources, include groundwater in water resource planning, and consider groundwater resources in our land-use planning and policies. It is vital to promote public awareness of the importance of our groundwater resources.

GROUNDWATERS OF NEW ZEALAND

The authors of *Groundwaters of New Zealand*, and New Zealand's groundwater community as a whole, hope that this book represents a significant step—in summarising our current scientific knowledge of groundwater, in providing the recognition of the importance of groundwater to the New Zealand economy, in promoting methods to manage it wisely, and in increasing public awareness of the nation's groundwater resources.

2

A history of groundwater development in New Zealand

JOHN H WEEBER, LEN J BROWN, PAUL A WHITE, WAYNE J RUSSELL, AND HUGH R THORPE

INTRODUCTION

The need to tap into groundwater has increased as agriculture and horticulture have expanded in New Zealand, and towns and industries have grown; with this has come the need to determine the groundwater resources available in different regions.

The history of New Zealand's groundwater use, drilling technology, and research on our groundwater resources has unfolded slowly, keeping pace with our slow increase in population and the ups and downs of economic growth. This slow growth, however, may be an advantage–New Zealand may be able to foresee and avoid the problems that other countries have had with overuse and pollution of their groundwater resources.

MAORI USE OF GROUNDWATER

He huahua te kai?	Are preserved birds the best food?
E, he wai te kai.	Ah no! Water is!
	(Reed and Brougham 1978)

Wai means water–its importance to the Maori people is reflected in the many place names that include the word. Maori used groundwater long before Europeans arrived. *Waikari* or *waikeria* (water dug out) came from shallow dug wells; the other source of groundwater was *waipuna* (springs). The quality of the water was important: the best quality was *waiareka* (water of sweetness), *waiariari* (clear or gleaming water) and *waipiata* (glistening water). Water from hot springs or streams fed by hot springs however often wasn't suitable for drinking, and was known as *waipiro* (stinking water), a name the Maori later applied to the alcoholic brews of the Europeans.

Maori consider water to be a *taonga* (treasure) and believe water contains a *mauri* (life force) which joins the physical and spiritual elements of the natural world. Specific springs were often *tapu*. *Waitapu* was sacred water, and it could be used only by *tohunga* for ceremonies such as baptism and purification rites, or where cleanliness was essential, such as washing after child birth, cleaning and treating the wounds of warriors, and for mixing medicines.

Water with curative properties was known as *wairongoa*. Some mineral water springs were particularly valued because of their reputed medicinal properties. On the right bank of the Whanganui River about two kilometres upstream of Whakahoro is a mineral spring, *waipahi* (water of travellers) or *waitete* (water dripping from the ground) (Brown et al. 1987). People journeying along the river by canoe would stop to drink and collect the mineral water (Downes 1923).

Groundwater also features in Maori tradition. In Canterbury (Fig 2.1), eels (*tuna*) served as the *kaitiaki* or guardians of the waterways (The Press 21 January 1989). Maori people talked with nature. A Ngai Tahu *kaumatua*, Henare Te Raki Ihia Tau, says the *tuna* carried messages from Kaiapohia Pa (near Woodend) through underground waterways to caverns near Taumutu on the west shore of Te Waihora (Lake Ellesmere). Lakes Ellesmere and Forsyth (Wairewa) were known to Maori as *"ko te kete ika a tutekawa"* (the fish basket of Tutekawa). Tutekawa was the first Ngai Tahu chief to set-

Weeber J.H.; Brown L.J.; White P.A.; Russell W.J. and Thorpe H.R. 2001: A history of groundwater development in New Zealand. *In* Groundwaters of New Zealand, M.R. Rosen and P.A. White *(eds)*. New Zealand Hydrological Society Inc., Wellington. p5-44.

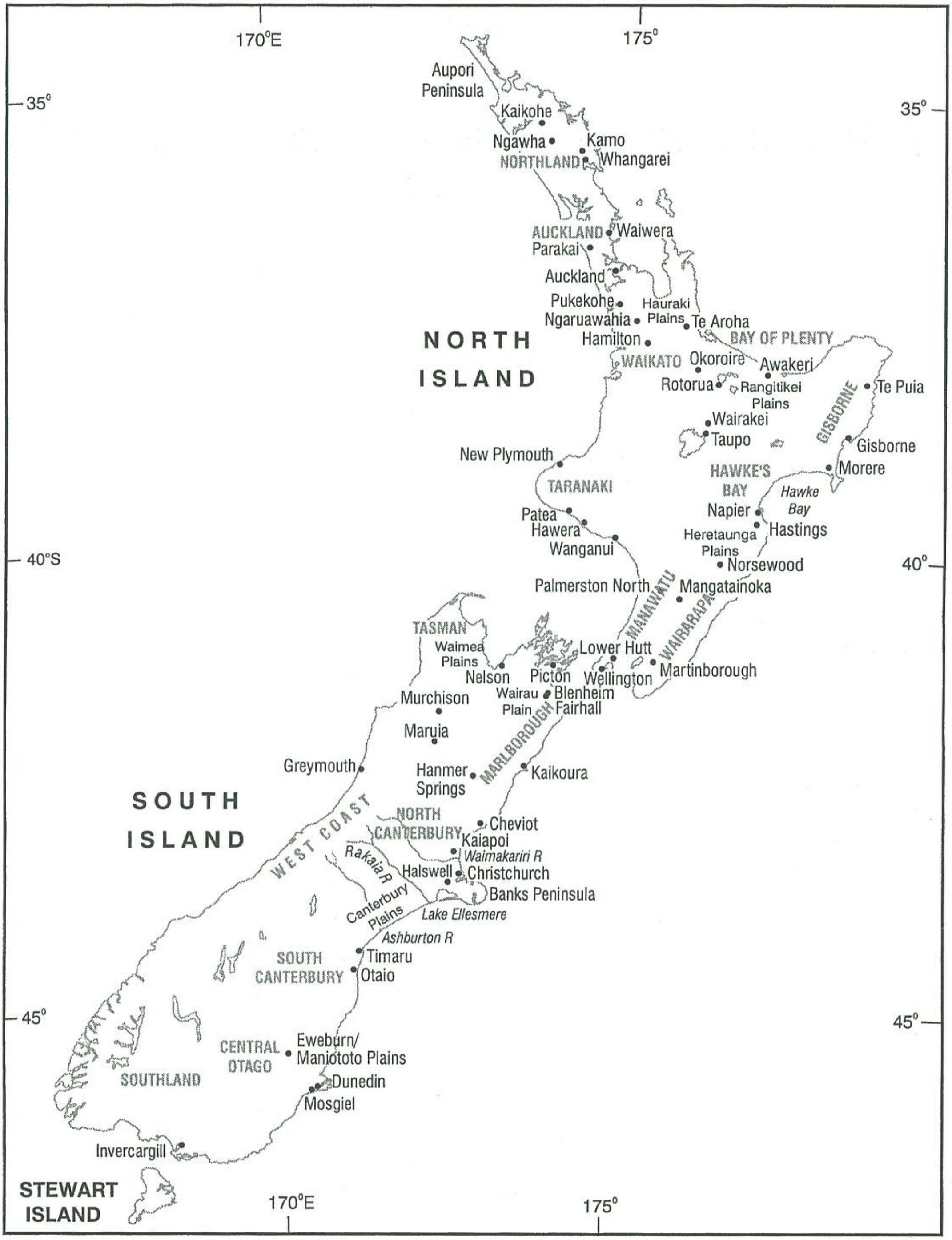


Figure 2.1 *Selected New Zealand localities used in Chapter 2.*

tle by the lakes, which teemed with fish (Beattie 1994). Both lakes are separated from the ocean by gravel bars that sometimes closed the lake outlets for several years. Beattie (1994) notes that minnows (*inaka*) spawn at the mouth of the Waihao River in South Canterbury, in brackish water at the bank of shingle across the river mouth. Here saltwater oozes through the shingle to mix with fresh water. *Tuna* and *inaka* are also thought to spawn at deep springs in Lake Ellesmere near Taumutu and Kuauwhiti (Beattie 1994) and the association of *tuna* with the ability to move underground in groundwater is perhaps derived from their need for brackish water for spawning.

Maori also practised irrigation. Before 1830 Maori cultivated extensive areas of kumara on the Waimea Plains, near Nelson. To make the soils of the Waimea River floodplain and delta more suitable for kumara growing, they burnt scrub to provide ash and charcoal, and added considerable quantities of fine gravel and sand. The soils they cultivated are distinct and now mapped as Maori gravelly sandy loam (Chittenden et al. 1966). Although there is no direct evidence, the kumara were probably irrigated with surface water or water from shallow wells (Dicker et al. 1992).

Waipatu, a settlement on the outskirts of Hastings, has a contemporary Maori name referring to groundwater; Reed and Brougham (1978) relate its origin. "In 1865 (sic. 1885) a well was being drilled near Tomoana at Waikoko, the homestead of William Nelson, the founder of the Tomoana freezing works. A local Maori was fascinated by the rig drilling the artesian bore. On the day the thumper struck water the Maori exclaimed, *waipatu*, *wai*: water, *patu*: struck, and thus the place was named."

Maori made extensive use of geothermal waters, which usually come from springs, for recreation and cooking, particularly in the central North Island. Hot springs, geysers and fumaroles were of interest to early European travellers and Maori often acted as guides to these features.

EUROPEAN USE OF GROUNDWATER

When European settlers arrived in New Zealand, they obtained water for domestic use, for their livestock, and for industry from the nearest river, stream or spring. In towns, industries were established on sites where water was readily available.

Contaminated surface water supplies soon became a problem in many areas of New Zealand. In 1865, when the New Zealand Geological Survey and the Colonial Museum and Laboratory were established in Wellington, James Hector was appointed the Director and William Skey the Colonial Analyst. Amongst Skey's many duties were analyses of water samples. He analysed samples from thermal and mineral springs to detect any chemical components that might be beneficial to human health through drinking or bathing in the water (Skey 1878a). Samples of suspect water supplies were analysed to find out what might be contaminating the water. In the 1877-78 Colonial Laboratory annual report Skey notes that "six waters have recently been forwarded here at the instance of the Education Board for the Hawke's Bay District. They were collected from different wells at Norsewood, a place where there had been just previously a great mortality among children. From a partial analysis of them it was clearly shown that No. (1) is decidedly a bad water, and that Nos. (5) and (6) are of doubtful quality, while the remaining ones were shown to be good waters." By the end of the century, however, Christchurch, Dunedin, and Wellington all had safe water supplies, comprehensive sewerage systems, and drainage by-laws. These amenities were established in Auckland by 1914 (McLean 1964).

Christchurch

Water quality was a recurring topic in the newspapers published in the early settlements. This letter to the editor of the Lyttelton Times 12 July 1851 is typical:

> "SIR, Allow me through your columns to call attention to what may sooner or later become a great evil to the town of Lyttelton. The cemetery occupies seemingly the spot most convenient for the inhabitants here, but I believe I am correct in saying that the spur on which it is placed is one of our principal sources of water, at all times not

too plentiful. If this our water supply should by circumstance become contaminated, the most disastrous results must inevitably ensue. I merely introduce the subject as one deserving the gravest consideration.

Yours Obediently

S."

The Press of 8 June 1861 notes that the water obtained from shallow wells at Christchurch was "very impure and unfit for domestic use".

At Christchurch, E. Dobson, the consulting engineer for the Christchurch Municipal Council, reported in December 1862 "springs below Christchurch which may be tapped by boring." The Canterbury Provincial geologist, Julius von Haast, and the city surveyor, W.F. Moore, on the other hand, advised against boring artesian wells "because it would be easier to obtain water from a surface source." The council followed Dobson's advice and a successful public water supply well was drilled in February 1864. Descriptions of successful water wells were published. Haast (1864, 1879) interpreted past environments from the geological information obtained from well logs, combined with surface geological observations. The concept of climate and sea level changes during glacial and interglacial periods was not known to Haast. He thought that a coastal lake formerly existed between the Rakaia and Waimakariri rivers (Haast 1864). This was filled with sediment and then uplifted, causing extensive swamps to develop. He suggested that incursions by the Waimakariri River dissected these deposits, leaving abandoned gravel-filled channels forming aquifers, and he constructed general cross-sections showing this mode of formation for the Canterbury Plains. Haast (1879) commented: "I need scarcely point out that it would be very important to have all the obtainable information as to the underground water supply of the district carefully collected, and mapped and sections prepared. Such documents would be of the greatest usefulness, their study leading us to conclusions the value of which cannot be overestimated." A paper by Mollet (1881) includes a log of the strata penetrated by an artesian well drilled at Avonside, Christchurch.

The Christchurch City Council and ratepayers debated for many years over whether they should obtain water for a reticulated system from artesian groundwater or from surface water. Several schemes were proposed, including diverting water from the Waimakariri River (e.g. McLeod 1882). At least 20 well drillers are known to have been active in Christchurch between 1864 and 1880. It is estimated (Environment Canterbury 2000) that 654 wells, with 630 wells for private consumers, had been drilled in Christchurch up until 1872. A reticulated public water supply began operating in June 1909, using water pumped from wells at Sydenham and Beckenham (Fig 2.2). The boroughs of Sumner, Lyttelton, Heathcote and Riccarton all obtained their reticulated water supplies from wells, as did people in the urban sections of the adjacent Halswell, Paparua and Waimairi Counties. Various boroughs and counties amalgamated with the Christchurch City Council in November 1989. Today the council supplies approximately 50 million cubic metres of water per year from 150 wells at 51 primary pumping stations. Page (1901), in New Zealand's first geochemical study of groundwater, compared groundwater chemistry to aquifer lithology for wells within the volcanic rocks of Lyttelton Harbour, and on the Canterbury Plains at the western margin of Banks Peninsula.

In 1902 the Christchurch City Council built a destructor to dispose of the city's refuse (Christchurch City Council 1928). Waste steam from the destructor boilers was used to generate electricity and to heat the artesian water in the municipal swimming baths, which opened in 14 May 1908. In 1910 a new artesian well was drilled to a depth of 450 feet ensuring the "purity of the water entering the baths" (Canterbury Times 24/8/1910). The council advertised that "The wonderful artesian water of Christchurch makes the municipal tepid bath the finest in the Southern Hemisphere" (Christchurch City Council 1928). By 1928 the destructor was put on standby, and the baths were heated by electricity supplied from Lake Coleridge.

Dunedin

J.T. Thompson (1859) proposed a gravity-fed supply from a reservoir on the Kaikorai Stream for the town's water source. His rea-

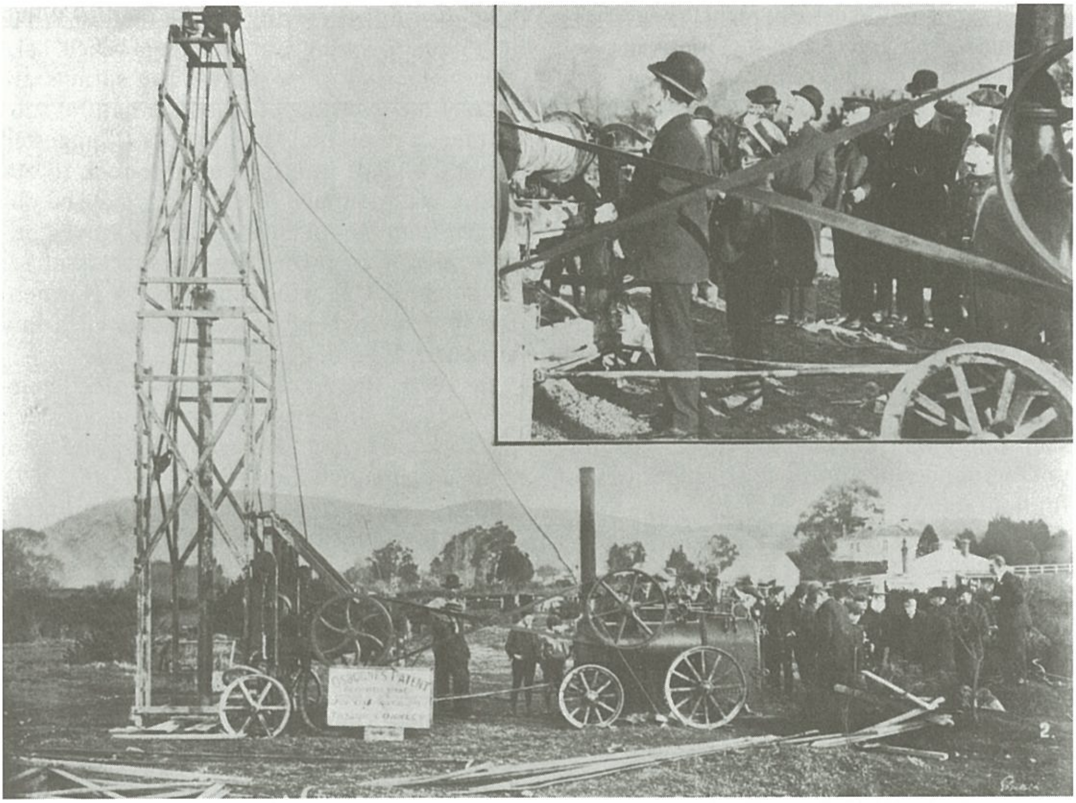


Figure 2.2 *Christchurch water supply – drilling the first pipe, Beckenham (Weekly Press 31/07/1907).*

sons for choosing the Kaikorai Stream were to avoid "the expense of steam power, with wear and tear of machinery, together with the cost of attendance," and to obtain a "pure" water supply. However, gold was discovered in Otago, and Dunedin's burgeoning population soon exceeded the capacity of the proposed water supply. Dunedin's public water supply system, based on an impounding reservoir at Ross Creek, began operating in December 1867. Supply sources were extended to other catchments, and in 1956 wells at Outram on the Taieri Plain were incorporated into the city water supply. Water for Mosgiel Borough came from wells.

Wellington

In 1868 Wellington's first public water supply was installed by the Government–it led from springs in Tinakori Road to Government buildings in Hill Street, Molesworth Street and Lambton Quay. This was superseded by a reservoir and dam–the lower Karori dam–in 1871. Groundwater was added in 1935, when water from wells at Petone in the Hutt Valley was piped into Wellington to supplement the surface water supplies. Petone (1962), Eastbourne (1928) and Lower Hutt (1908) borough water supplies in the Hutt Valley came from wells. The first municipal bore was installed by the Lower Hutt Borough Council in 1908, and through to the 1920s several other small bores were drilled in Williams Grove for a limited municipal supply (Roche 1915). The first large-scale artesian well pumping station, capable of supplying 22,750 m^3/day, began operation in 1935 at Gear Island. Initially there was resistance to using groundwater because many people believed that the underground water was polluted, and that it would cause goitre because of its low levels of iodine.

Old dug wells have often been discovered during inner-city redevelopment. They can be of considerable interest to historians because of the rubbish—now artefacts—that had been thrown into them. One such well was found at 76 Lambton Quay in Wellington. The well had been dug in the late 1840s when Baron von Alzdorfs's hotel occupied the site, and it was excavated and described (Chester 1988) before construction began on a new building on the site in 1987. An early artesian bore was drilled in the Lower Hutt valley in 1883 and by the late 1880s residents of Petone were reliant on private artesian wells for their water supply. A little later (c.1890) a limited reticulated artesian supply was provided in Petone, including underground tanks on some street corners for firefighting.

Auckland

The first water supplies for Auckland City during early times came from rainwater collected into tanks, and groundwater from private wells (Russell 1976). These supplies were supplemented in downtown areas by four public wells, two near Queen Street, one near Albert Street and one in Kitchener Street, and by small springs, one in Wellesley Street East, just outside the wall of the old barracks, and another in Official Bay.

A piped supply was inaugurated in 1866. This was a 6-inch (150 mm) gravity pipe line from the Domain Springs—now the Duck Pond in the Auckland Domain. By 1872, this supply was overtaxed and the newly formed City Council supplemented the ponds, via a small reservoir on Domain Hill, by pumping 30,000 gallons daily from Seccombe's well in Khyber Pass Road. These supplies were derived from groundwater in the basaltic bedrock of Auckland's many small volcanic centres. The possibility of springs or wells supplying Auckland with water was being discussed in 1873. Goodall (1874) notes, "We all know that in the vicinity of Auckland there is a vast tract of volcanic country, consisting of extinct volcanoes, tuff cones, and lava streams, extending over twenty or thirty square miles. Almost the entire rainfall over this large tract of country is being stored by Nature in the porous lava rocks, and being served out again through the many springs occurring on the road to Whau (the Western Springs), at Onehunga beach, Lake Takapuna, and other places. The springs are merely the overflow of what is a natural subterranean reservoir." Goodall (1874) suggested driving a shaft into the volcanic rock to obtain a water supply. "That water may be obtained from Mount Eden is already proved, independently of theory, by the success of Mr Seccombe's well, which supplies the Northern Brewery on Khyber Pass Road. This well is only a moderate depth down."

In 1875, the Auckland City Council purchased the property surrounding Western Springs and began to develop the springs as a main water supply (Russell 1976; Firth 1967). The Western Springs were brought into service on 10th July 1877 and served as the main city water supply until 1910, when upland catchment dams were brought on line. An early description of the Western Springs is given in the Weekly News of 3rd February 1872, where they were portrayed as:

> "... a large supply of water bubbling from a scoria bed with considerable force and in sufficient volume to supply a brook about 10 ft wide and from 1 ft to 18 inches deep. The water was pure and cold ..."

The scheme to utilise the spring water included the installation of a large steam-driven beam-engined pump (preserved now as a display in the Museum of Transport and Technology). This lifted water 235 feet through 140 chains of 21-inch pre-cast iron pipe to a reservoir at Ponsonby Road, on the first major ridge behind Auckland City. Records indicate that the maximum discharge when it was used as the main supply for Auckland City (1875 to 1910) was between 1.5 to 1.6 million gallons a day (6820 to 7270 m^3/day). During the 1920s the volume of water discharged from the lake amounted to some 6360 m^3/day. By 1943 it had been reduced to 4550 m^3/day, probably due to leakage through the embankment. By the 1890s, the combination of dry summers and Auckland's growing population were putting a considerable strain on the supply from Western Springs. The springs supply was augmented by pumped water from Edgecombe, Meola Stream, and a spring in the Oakley Hospital grounds. All water came from basaltic materials.

In 1896 a shaft was sunk at the rear of the engine house at Western Springs, 25 feet from the edge of the pond, to a depth of 38 feet (9 feet below sea level). A borehole drilled a further 8 feet was reported to still be "... tight rock ..." (17 feet below sea level). An 1898 report shows that the water supply was supplemented by 144,000 gallons/day (about 10% of the total pumped) from this shaft. From 1910 onwards, Western Springs was used only as an emergency supply until 1928, when the use of the old steam plant was finally discontinued. The old boilers were removed in 1939-1940. With the advent of wartime conditions, and subsequent shortages, it was found necessary to bring in water from the springs again around 1941. A diesel-driven pump unit was installed at the lake edge, but the diesel motor was soon replaced by an electric motor. This pump unit was finally dismantled in about 1950. In the most critical drought year in Auckland (1943), it was reported that with the pump delivering a steady 1 million gallons a day, the lake level was falling slightly after a prolonged period. Water from the pond continued to be used for industry until at least the mid 1970s, with the Auckland Steam Laundry Company taking approximately 373 m^3/day at that time.

The first public water supply scheme to be built by a suburban local body was completed in 1888 when the Onehunga Borough Council opened waterworks based around Bycroft's Springs (Water Care Services pers. comm.) Onehunga residents, at the time, relied on private tanks and shallow, surface-water fed wells. Night soil was commonly buried in the vicinity of these wells and typhoid and other water-borne diseases were a concern. The first public water supply well was sunk beside Bycroft's Springs and in September 1886 tenders were called for the construction of a brick pump house, a 250,000 gallon reservoir to be constructed on One Tree Hill, and service mains. Construction was completed in July 1888 before a loan was approved. Debate surrounding the raising of a loan to pay for the water works resulted in four rate-payer polls, all of which failed to gain a majority in favour of the public water supply. An 'anti-water party' became a political force and 'anti-water' extremists dynamited the One Tree Hill Reservoir and smashed mains. The final act of the 'anti-water' extremists was the discharge of a shotgun towards the mayor and councillors who were travelling in an open carriage along Manakau Road. Fortunately the only casualty was the mayor's umbrella. Consent for the loan was eventually given and the water supply remains in use today.

Nelson

In the Nelson district the discovery of artesian water is relatively recent. In 1883 S. Herbert Cox of the New Zealand Geological Survey had advised against drilling for artesian water at Motueka (Cox 1884). It was not until 1959 that a successful flowing artesian well was drilled at Lower Moutere on the Moutere River floodplain by Taylors Drilling of Oamaru. Flowing artesian groundwater was finally discovered in 1966 in wells drilled at Richmond on the Waimea Plains (Dicker et al. 1992). The deepest test bore for groundwater investigation in New Zealand was drilled to 895.5 metres on the Waimea Plains at Waimea West in 1992 (see Exploration Drillholes). In 1981 groundwater was discovered in aquifers in the Moutere Gravels, which form the Moutere Hills separating the Waimea Plains from the floodplain of the Moutere and Motueka rivers. Since then several successful wells have been drilled and they supply water for orchard trickle irrigation (Woodford 1996).

Invercargill

Proposals for water supply to Invercargill in 1878 and 1883 favoured a surface water-fed gravity system. The supply scheme favoured by the council, estimated to cost £100,000, was rejected in 1883 by the residents (Corkill 1932). The council then commenced a water supply scheme based on groundwater. The first well was sunk in 1885-6 to a depth of 96 feet. Problems were experienced with the quality of the water. The odour was described as 'vile' and householders would not take the water. The water was found to discolour clothing and a commercial laundry made complaints that were 'regular and violent'. Aeration at the pumping station improved the water quality. The Southland Times of 25 August 1897 noted "Mr Job Osborne's bore in the yard of the Southland Brewery, East Invercargill, is down 495 feet without striking water-bearing stratum, and it is said that operations are to be discontinued. It is a discouraging feature of boring in this and other districts of the colony that there are no geological data to work on. In the United States the Government has made the provision of these a national duty, the consequence being that in many of the States the depth at which bed-rock is to be found is known to within a few feet, and those boring for water know fairly well before they start how far they will have to go and approximately, what the work will cost."

New wells were required in 1910 and eventually six bores delivered water to a water tower, and then the city. The Invercargill water tower is 42.6 metres high, and used 224 000 bricks for its construction. Service pipes and street mains gradually became blocked, however, reducing the capacity of the supply system. The pipes were so encrusted that one four-inch pipe yielded 14+ tons of scale per mile of pipe during cleaning in 1928-9. The scale occupied 35% of the volume of one sample of pipe. Groundwater ceased to be used as a water supply in the 1950s. Invercargill's water now comes from the Oreti River. The water tower is presently used to maintain pressure during power outages. It has been restored to its former glory and is probably Invercargill's best known landmark (Carter 1993).

Napier and the Hawke's Bay

A successful well was drilled at Meeanee in February 1867 (Cuthbertson 1882). Captain F.W. Hutton, of the New Zealand Geological Survey (1871-74), described the confined aquifer encountered by artesian wells at Napier in a short paper accompanied by a cross-section based on well logs (Hutton 1871).

A major influence on 19th century New Zealand groundwater studies was Henry Hill. An inspector of schools for the Hawke's Bay Education Board, Hill had an enquiring mind and an educational background that included geography, geology and botany. He contributed scientific papers on diverse topics, including descriptions of the groundwater resources of the Heretaunga Plains, Hawke's Bay, with well logs and cross-sections based on well logs (Hill 1887, 1889, 1905). Hill (1923) urged that the flow of all artesian wells should be regulated to conserve groundwater, a somewhat visionary idea for 1923. He also recommended (44 years after Haast had made a similar recommendation for Christchurch), that artesian pressures should be monitored to provide information on how water levels responded to water usage. He suggested that "a properly constituted authority should collect, monitor and analyse information on wells and groundwater". Hill's papers also describe groundwater at Wanganui (Hill 1893a, 1893b), the Ruataniwha Plains, Hawke's Bay, (Hill 1893c) and Gisborne (1897). Napier's (in 1887), Hastings' (in 1912), Havelock North's and Taradale's town supplies became based on groundwater.

Other towns

Other settlements, on hearing about the discovery of artesian water at Christchurch, also looked at wells and groundwater as a potential water supply (Cuthbertson 1882). Successful wells were drilled at Gisborne (May 1875), Blenheim (1892), and Wanganui (1892).

In 1870, the Timaru community was warned that "unless a plentiful supply of pure water was obtained, Timaru would become the greatest 'pest hole' in the Colony" (Anderson 1916). The Poverty Bay Herald of 16 April 1875 reports "there are several cases of measles in the bay. We hear also typhoid has made its appearance. The majority of wells in Gisborne are dried up. In some parts of the town the water used for household purposes is not many removed from poisonous."

Haast also advised the Provincial Government regarding an artesian water supply for Timaru. This time, however, he recommended: "to have water sunk for, either by artesian wells or otherwise, on the highest locality of Timaru, so that the water obtained could be brought by gravitation over the whole town." (Collins 1948).

Blenheim (from 1946), Picton (1975) and

Richmond boroughs (1984) have changed from surface supplies to groundwater.

Industry and transport

In many towns reliable sources of good quality water were the exception and when available were extolled to promote commercial products. It was reported (Anon. 1898), that for the Egmont Brewery and aerated mineral water factory, Queen Street, New Plymouth, "the water used in the brewery is of admirable quality and is obtained from an Abyssinian well of great depth, thus ensuring an equable temperature all the year round." The European settlers also valued mineral water springs. For over 40 years until 1939, when transport charges made it uneconomic to continue the operation, Thomson's Mineral Water and Cordial Company, Dunedin, bottled "99.5% pure soda water" from Wairongoa springs, North Taieri (NZABC 1977). "The Cyclopedia of New Zealand," (1905) records, " a speciality of the business is the Wai-rongoa mineral water, which has a large sale in the Colony and is exported to Australia. The springs are situated at North Taieri, where the firm owns 160 acres of land, and where suitable buildings have been erected to conserve these natural medicinal waters, which are prepared for the market in large quantities."

The Official Record of the Otago Jubilee Industrial Exhibition 1898 records that in 1861 the Victoria Brewery was established at the corner of Pitt and Elder Streets in Dunedin because of the proximity of spring water. Another Dunedin brewery, the Red Lion Brewery, was built in 1862 between George and Great King Streets, on a block of land crossed by a spring-fed stream. By 1864, however, settlers living in the neighbourhood had contaminated the stream water. The stream supply was replaced by a well at the Red Lion Brewery, which provided a constant supply of pure spring water. In 1878, the supply of brewing water was improved by sinking the well to a greater depth (Anon. 1898).

An export trade in frozen meat began in 1882, and with the development of refrigeration, export of butter and cheese was also possible. Meat works and dairy factories required large quantities of good quality water for their operation, and wells were drilled to provide a water supply. These industries, as well as flaxmills, produced large volumes of polluted process water requiring disposal. The waste and used water was usually dumped into the sea or the nearest stream or river, or flooded onto adjacent farmland to drain away. This was the beginning of problems with industrial pollution of water, including groundwater.

In early New Zealand towns the risk of fire spreading through wooden buildings and houses was always very high. For many years in Christchurch there were serious problems maintaining a reliable water supply for fire fighting beyond easy reach of the Avon River. The small-diameter artesian wells could not sustain the pumping rate of the steam fire engines. Some surface reservoirs were constructed beside free-flowing artesian wells to store water. Underground storage tanks, each connected to an artesian well, were later installed in central Christchurch and New Brighton and remained in use until they were replaced by water reticulation schemes.

A substantial water supply was needed for the Glenbrook Steel Mill in South Auckland. Groundwater studies involved pump testing of thick Pleistocene shell-bed aquifers to depths of about 200 metres. The outcome was a consent to take 6000 m^3/day from a well-field adjacent to the Waiuku estuary. This well field was used for roughly two decades with no significant degradation of the groundwater.

Steam engines must have water to operate. Wells were needed to supply the locomotives for the railway system crossing the Canterbury Plains and other areas of New Zealand. Wells were dug or drilled at stations, and the Manager of Railways often submitted water samples to the Colonial Analyst to ascertain their suitability for use in locomotive boilers (Skey 1878b). The drilling of station wells often established that groundwater was available in an area, thus encouraging settlement and farming. A water tower was built at the former Addington Railway workshops, Christchurch, in 1883 (Brown and Weeber 1992). The tower was one of the first steel-reinforced concrete structures built in New Zealand–it has now been restored and features at the site of the new Christchurch Railway Station. It was designated an engineering heritage structure in 1990. Christchurch City Council generated its own electric power using coal-fired boilers (Christchurch City Council 1928) and water from an artesian well for the cooling tower (Fig 2.3).

The potential for irrigating the fertile soils of the Canterbury Plains was recognised as early as 1867 in the leading article in the Lyttelton Times (12 June 1867). "Practical

Figure 2.3 *Artesian well at the Power House, Falsgrave Street, Christchurch. This well supplied water to coal-fired boilers to generate power for the trams (Lyttelton Times 07/09/1904). Lantern slide, Canterbury Museum.*

farmers admit that were they sure of obtaining water it would be profitable to them to have an artesian well in every field. And everyone riding over our vast plains is forced to the conclusion that a sufficient supply of water is all that is needed to bring almost the whole extent under designation of arable land. But it is not to be supposed that individuals can risk the expense of deep artesian wells in those districts where it is already known that water is not to be had at even twice the depth at which it is obtained in Christchurch. On this account we think the Government might reasonably be asked to provide the sum required for obtaining an apparatus capable of working to a depth of, say 600 feet."

By the 1950s the potential for irrigation to increase productivity and maintain growth during droughts was firmly established. Conferences such as the Lincoln College Farmers' Conference in 1956 featured presentations promoting the use of groundwater for irrigation (Collins 1956), and potential and practising irrigators formed associations at the Halswell Irrigation conference (Oborn 1962). The question then became how to obtain groundwater for an irrigation supply.

The spa

Geothermal springs, which had long been a source of pleasure for Maori, were developed by early European entrepreneurs, and the New Zealand Government, into spas based on the European model. The first spa was at Waiwera, north of Auckland, and the two main nineteenth-century spas were at Rotorua and Te Aroha (Rockel 1986). Other nineteenth and early twentieth-century spas include Hanmer, Maruia, Tokaanu, Wairakei, Taupo, Morere, Te Puia, Awakeri, Okoroire, Parakai, Kamo, and Ngawha. Most of these still exist today, but their state of development is often somewhat less than that envisaged by the early advocates.

The Waiwera area near Auckland was purchased by Robert Graham, a Scottish businessman, in 1842. Graham had been fascinated by the sight of up to 3000 Maoris assembled on Waiwera's beach and bathing in holes in the sand ('Waiwera' means hot water in Maori). In 1872 the hotel was extended, bathhouses were built and the water was bottled to be sold in Robert Graham-owned hotels in Auckland (Rockel 1986).

The first systematic investigation of the Waiwera thermal area is described in Russell (1980). At that time the warm water was artesian, with a natural discharge to some 2 metres above ground level. During the 1950s, the proliferation of abstracting bores began to affect the thermal water supply, and the water levels fell. With the advent of better drilling equipment and methods, deeper wells were drilled to nearly the full depth of the warm water aquifer. In 1958 a bore reached 371 metres depth in Waitemata Group sandstones and siltstones. This bore was artesian and in 1959 was reported to flow to 3.7 metres above ground level, with a wellhead temperature of 49°C. During the 1960s, the effects of exploitation were beginning to be felt, as some bores periodically ceased to be artesian and required pumping for the first time. The last report of natural artesian flow was in 1969. By 1970 some 1245 m^3/day of thermal water was being pumped and natural springs on the beach dried up prior to 1978. The water board's investigations led to changes in the management of the thermal waters, resulting in some recovery of pressure and temperature.

Thermal water has been used for hot pools at Parakai, Auckland, at least as far back as 1900. The thermal activity at Parakai consisted originally of a hot spring situated in the Parakai Domain, close to the location of the well now providing hot water to the public hot pools. Herbert (1921) wrote:

> "... when I first knew it, one small hand pump which the bather worked himself, drew the water from the hot saline spring rising in a boggy field surrounded by mud flats and an estuary. The field has been drained and replaced by a garden, bores have been sunk for abundant additional mineral water, excellent baths have been built and boarding houses and private hotels have sprung up."

Wells were initially drilled in the Domain close to the site of the spring, and the artesian water was sold to the private hotels. At a later stage, as drilling methods and equipment improved, it was found that hot water could be obtained on adjoining properties. The first to be supplied from the springs was the Craigwell Guest House, which opened in 1908. The first baths were opened in the Parakai Domain in 1912. Two new boarding houses opened during the First World War. One of these was reported to have an "89 foot" (27 metre) deep bore capable of producing "75,000 gallons" per day (340 m^3/day) of hot water. Hay (1946) recorded 25 productive bores at temperatures of over 30°C, with water drawn both from wells at and outside the Domain. Artesian head had fallen by this time to about 5 metres above ground level. Healy (1955, 1957a, 1957b) undertook the first systematic investigation of the Parakai hot water resource. At that time artesian head was approximately 2.5 metres above ground level. By 1968, water levels had fallen to 5 metres below ground level, as a result of installation of larger wells and pumps. In 1979-80, the Auckland Regional Water Board began a further investigation, including an assessment of historic changes, geological evaluation, geophysical investigations, down-hole and production temperature measurements, down-hole conductivity measurements, and water level measurements. (Russell 1981) At the time water levels were consistently some 3 to 4 metres below ground level, with pumping volume averaging about 1040 m^3/day of water with temperatures of 33°C to 64°C.

One facet of the historic utilisation of the Parakai thermal water was that gas, mainly methane, was coming up with the hot water. The gas was collected and used for lighting and cooking at least in the Craigwell Guest House (Hay 1946). The Parakai hot waters come from a reservoir in the Waitemata Group sandstones and siltstones (Miocene). The reservoir is of tectonic origin–Parakai is sited at the junction of two or more fault zones.

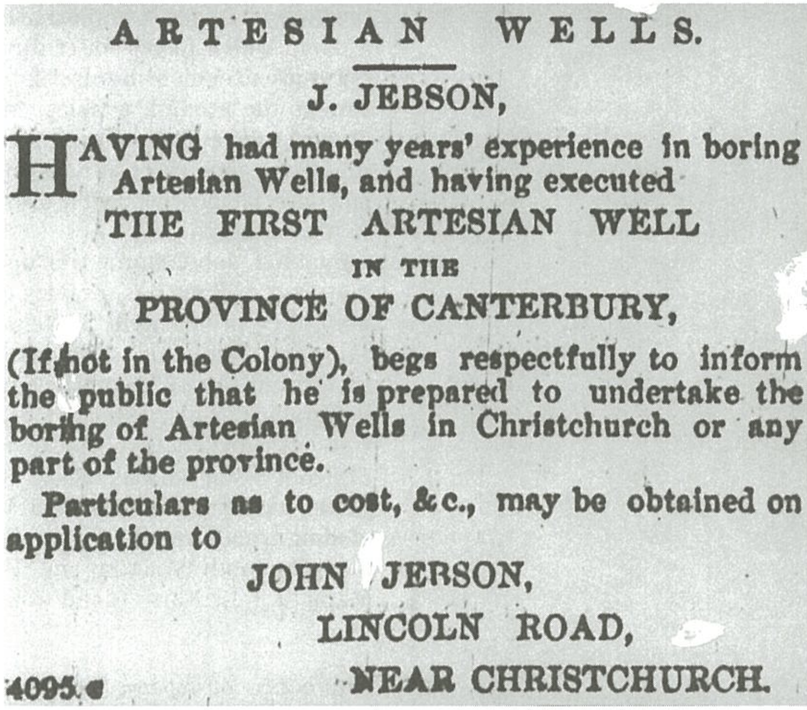
Drilling and pumping technology

Resourceful well drillers, and steady advances in drilling rigs and pumps, have played a major role in the development of New Zealand groundwater resources. The first wells were hand dug and some of these had reached surprising depths. At Otaio in South Canterbury a 60-metre-deep dug well is reported in the original New Zealand Geological Survey well files–it could be one of the deepest. Where sediments were loose, pipe wells were commonly drilled using the "Abyssinian" method, which involved driving a pointed pipe by means of a falling weight. An advertisement in the Lyttelton Times of 17 October 1863 for Josiah Hadley "to receive orders for all kinds of pump work, boring artesian wells, or any water, gas, or steam works," is the earliest Christchurch advertisement for well drilling found so far (Weeber 1995).

Wells penetrating hard consolidated sediments such as cemented gravel and rock weren't possible before drilling rigs become available. The first operational drilling rig was probably used for gold or coal prospecting. At Christchurch the first public water supply well was drilled by the Christchurch Municipal Council in January 1864 using a boring machine that had been purchased from the Kowai Coal Company in 1863. In July 1864, John Jebson was advertising "to undertake the boring of Artesian Wells in Christchurch or any part of the province" (Fig 2.4) (Weeber 1995). Jebson was formerly a manager of the Kowai Coal Company, which prospected for coal in the Malvern Hills area (Popple 1953). He would have acquired the skills of drilling, driving and boring needed for water well drilling, from his coal prospecting and mining engineering work. The technology, equipment and expertise used in drilling for oil was also transferred to water well drilling. In 1866 a successful 174-foot deep oil well had been drilled at Moturoa near New Plymouth (Henry 1911).

Christchurch-based water well drillers also drilled in other regions. From December 1866 to December 1867 Messrs Bennett and Ashworth from Christchurch drilled wells on the Heretaunga Plains in Hawke's Bay. However by 14 December 1867 these gentlemen had "made themselves scarce, leaving a few creditors in the lurch" (Weber 1868).

One of the most important contributors to the development of New Zealand's groundwater resources was Job Osborne (Fig 2.5). Osborne is described as a farmer, contractor



ARTESIAN WELLS.

J. JEBSON,

HAVING had many years' experience in boring Artesian Wells, and having executed

THE FIRST ARTESIAN WELL

IN THE

PROVINCE OF CANTERBURY,

(If not in the Colony), begs respectfully to inform the public that he is prepared to undertake the boring of Artesian Wells in Christchurch or any part of the province.

Particulars as to cost, &c., may be obtained on application to

JOHN JEBSON,
LINCOLN ROAD,
NEAR CHRISTCHURCH.

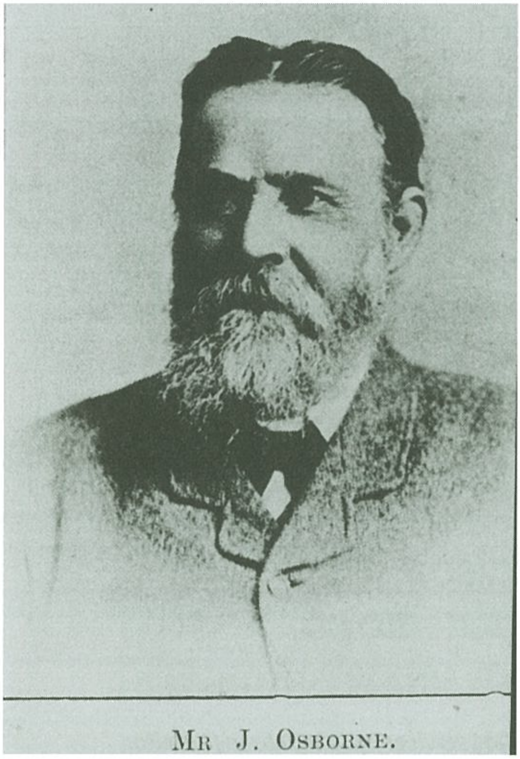
4095.

Figure 2.4 *Advertisement for well-drilling services by John Jebson (Lyttelton Times 09/07/1864).*

and well-sinker in "The Dictionary of New Zealand Biography" (Volume 2-1870 to 1900). Born in Somerset, England, in 1842, he came to Lyttelton as an assisted emigrant in 1859 and was employed on a farm at Halswell near Christchurch. A year at the Otago goldfields in 1861 increased his capital enough for him to buy farm land at Prebbleton in Canterbury in 1863. The following year he sold the Prebbleton farm and bought 100 acres of swampland at Doyleston. Around 1865 he established a road and railway foundation business, in partnership with John Rennie. By 1902, with drainage and the acquisition of adjacent land, Osborne's property "Winfield" was a prosperous cropping and grazing establishment of 2130 acres.

Osborne's contracting business diversified and prospered through his practical skills and inventiveness. He used the latest available machinery. He is credited with importing the first portable steam engine to New Zealand and one of the first steam-driven threshing machines. In 1879, he brought the first steam traction engine to the Doyleston area. Because they required water, the use of mobile steam engines was restricted, especially during hot dry summers when rivers and streams on the Canterbury Plains often dry up. Osborne solved this problem by diversifying his contracting business in 1881 to include well drilling.

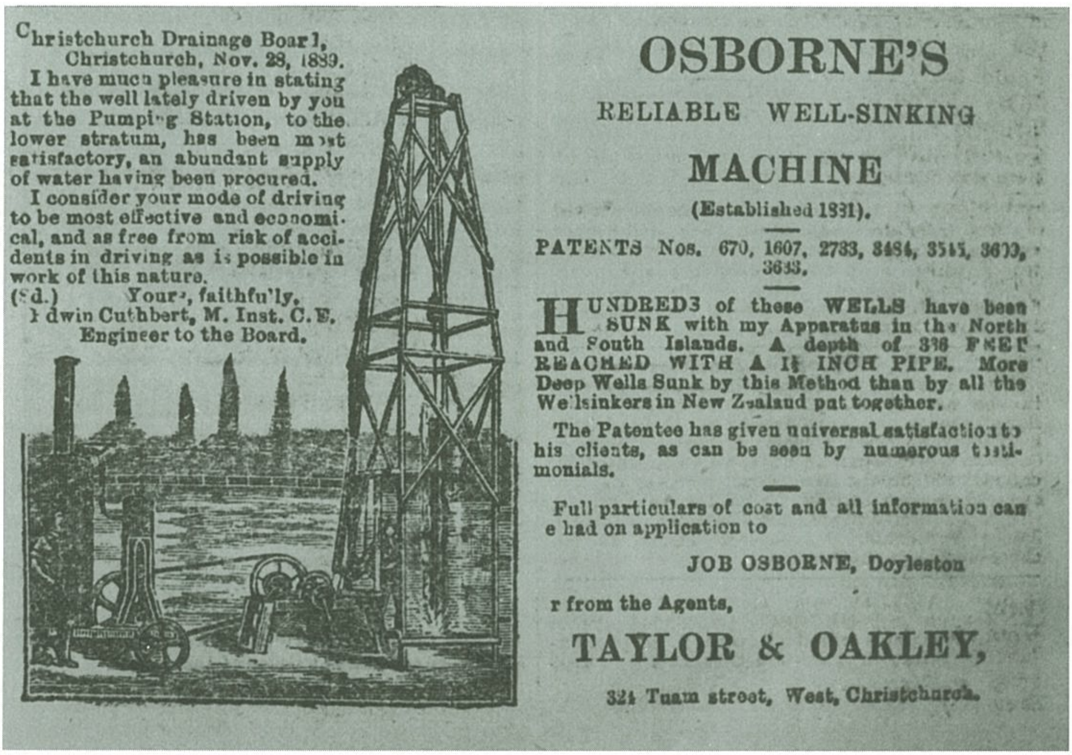
Osborne designed and patented several well-sinking machines including, in July 1882, a machine to be "driven by other than manual power for driving pipes for artesian wells". This machine was replaced in 1887 by a "double action well driving machine" operated by two men and powered by a portable steam engine. In New Zealand patent no. 2733 (Weeber 1995) Osborne describes the operation of this machine: "The improvement consists in making the machine so that it is double acting insomuch that the machine can be used simultaneously to drive the pipe and at the same time work a drill inside of the pipe which shall loosen and make a way for the pipes through

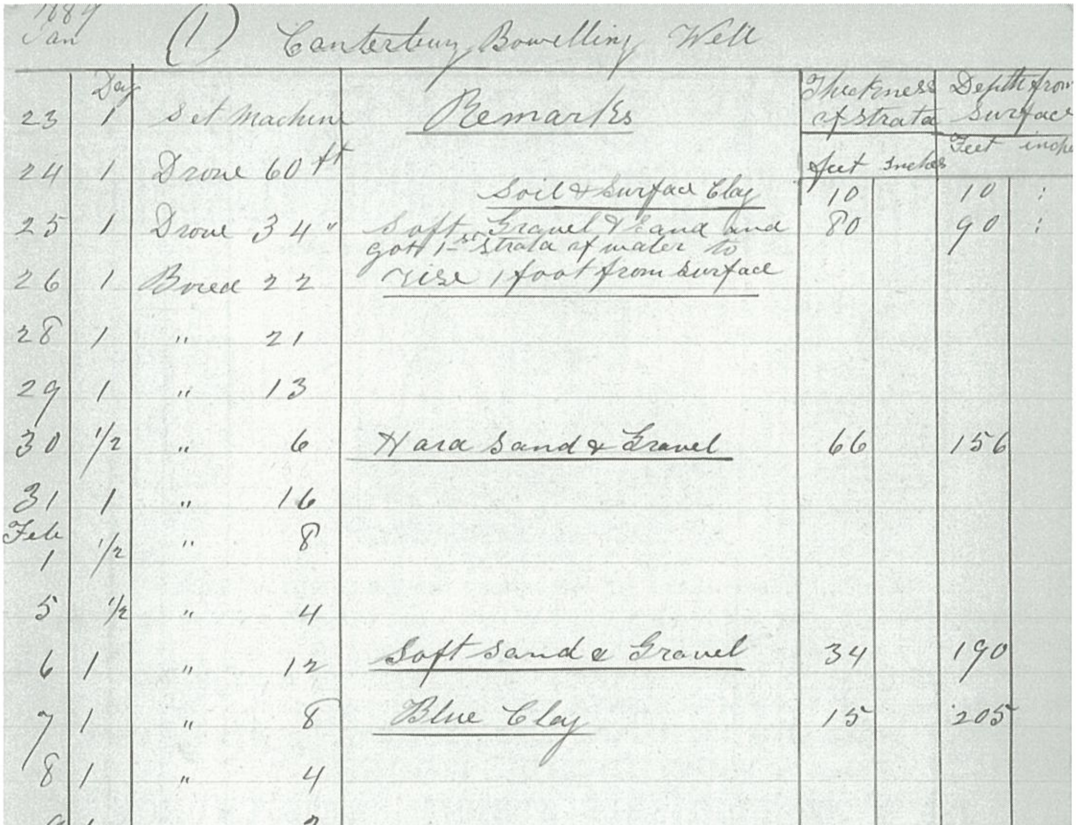


the ground. In addition the machine can work a pump which forces water through the hollow rods to which the drill is attached, this softens the ground, enables the pipes to be driven easier and the returning overflow at the top of the pipe being driven allows the mud and material loosened by the drill to be brought to the surface."

By 1902, Job Osborne was operating seven two-man drilling rigs. Besides North Canterbury, they drilled wells at Nelson, Blenheim, Timaru, Dunedin, Central Otago and Invercargill. In 1898, at Cheviot, North Canterbury, an unsuccessful 825 feet deep water well was drilled. Osborne-owned rigs also drilled wells at various localities in the North Island, including the Wairarapa, Manawatu (including Longburn), Wanganui, Patea, Hawera, New Plymouth (Waitara) and Gisborne areas. Many of these North Island wells were drilled

Figure 2.5 *Job Osborne (Cyclopedia of New Zealand 1903) and advertisement for well-drilling services (Canterbury Times 25/09/1890).*





1889 Jan (1) Canterbury Bowelling Well

	Day	Set Machine	Remarks	Thickness of strata (feet, inches)	Depth from Surface (feet, inches)
23	1	Set Machine			
24	1	Drove 60 ft	Soil & Surface Clay	10	10 :
25	1	Drove 34 "	Soft Gravel & Sand and gott 1st strata of water to rise 1 foot from surface	80	90 :
26	1	Bored 22			
28	1	" 21			
29	1	" 13			
30	1/2	" 6	Hard Sand & Gravel	66	156
31	1	" 16			
Feb 1	1/2	" 8			
5	1/2	" 4			
6	1	" 12	Soft Sand & Gravel	34	190
7	1	" 8	Blue Clay	15	205
8	1	" 4			
9	1	" 2			
11	1	" 1½			
12	1	" ½			
13	1	" 2½			
14	1	" 2			
15	1	" 1½	Hard yellow Sand containing Water & rise 7 ft but no quantity.	15	220
16	1	" 4			
19	1	" 2½			
20	1	" 8	Soft blue sand	40	260
21	1	" 8	Hard yellow sand	2	262
27		"	Clay & Peat	2	264
total 28					

Figure 2.6 *Job Osborne well log from January 1889.*

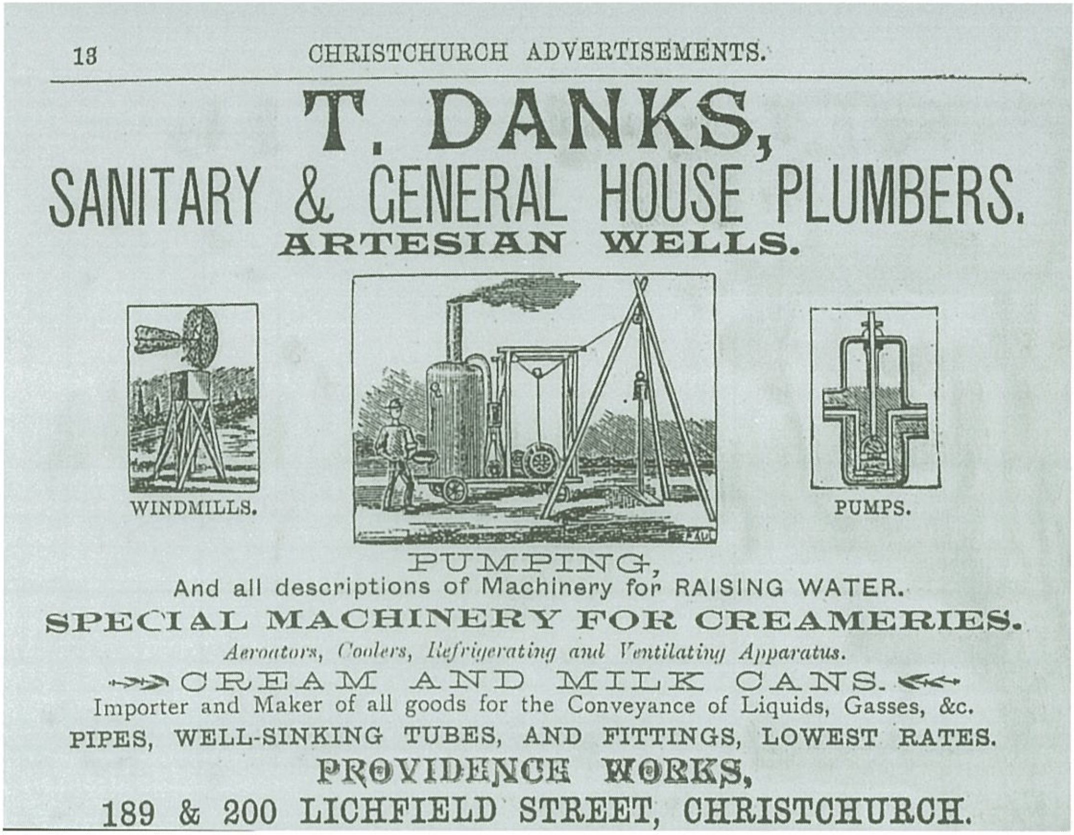


Figure 2.7 *Advertisement for well-drilling services by T. Danks (Wises Directory of Canterbury 1893).*

for water supplies for dairy factories and newly established freezing works. In 1909 Job Osborne sold the well drilling business to a former employee, Sam Taylor. Job Osborne and Co. Ltd. continued drilling wells until 1980, when the company was closed down (Weeber 1995).

Among the many advantages offered by the double-action well driving machine was the means for the driller to directly observe fragments of the strata being drilled (Fig 2.6). Job Osborne and his drillers logged the details of the strata penetrated by hundreds of wells, and the original log records in notebooks are deposited with Environment Canterbury. Many of these well records are incorporated in the computer-based well data file for the Canterbury region, operated by the Council.

Another major contributor to Canterbury well log data was James W. Horne. Horne was a former Osborne employee who established his own successful drilling business in 1893. He built his own drilling machines, based on Job Osborne's design with modifications. These two early well drillers recorded the details of hundreds of wells that they drilled during the 1880-1910 period when well-drilling activity was at a peak. Their foresight has considerably assisted the work of hydrogeologists, geologists and engineers in the study of Canterbury and New Zealand aquifers. A number of well drillers operated through this period (e.g. Fig 2.7) but limited records of their wells have survived. The log of an Osborne well drilled in April 1892 is in a paper describing artesian wells at Longburn near Palmerston North (Marchbanks 1899). The Canterbury well logs of Osborne and Horne first featured in the landmark paper by Speight (1911), which included 6 cross-sections, each with 17 well logs, covering coastal North Canterbury from Sefton to The Estuary and Gebbies Valley. Speight acknowledged that he examined the records of more than 500 wells to accurately construct the aquifer sequences. Subsequent groundwater, geology and engineering publications based on Canterbury well logs include Alley (1955, 1964), Suggate (1958, 1968), Oborn (1960), Wilson (1976), Bowden et al. (1986), Brown and Wilson (1988) and Brown and Weeber (1992, 1994).

During the early 1900s, American "Keystone" cable tool drilling machines were imported to New Zealand by water well drillers, including Job Osborne and J.M. Stewart of Dunedin. In 1907 Job Osborne, using a "Keystone borer," drilled an unsuccessful well (not enough water) to a depth of 365 feet at the new engine shed in Dunedin for the Railways Department. In the 1930s approximately 30 cable tool machines based on the "Keystone" design were made by the "Dispatch Foundry Co. Ltd." in Greymouth (Dispatch Engineering Ltd. pers. comm. 1985). These drills were initially used for gold exploration, but some later found their way into Canterbury for water well drilling and for foundation testing. To meet the demand for high-yielding wells for irrigation, public water supply and industry, the cable tool machine became the standard drilling method until 1983, when the first rotary percussion machine was used in Canterbury by McMillan Water Wells Ltd. Today, these drilling methods are widely used by the water well drilling industry throughout New Zealand.

Another engineering-related factor that has provided impetus to groundwater use in New Zealand has been the development of pumps. The original dug wells used a bucket to bring water to the surface. Stirrup or hand pumps were installed on pipe wells. These were suction lift pumps and required a water level within seven metres of the ground surface for pumping. Wind power provided a means of driving both surface suction pumps and deep well pumps, where the pump is below water level and pushes the water to the surface. Windmills, installed in conjunction with water storage tanks or troughs, were well suited to New Zealand's windy climate.

Driven pipes and drilled wells sometimes penetrated confined aquifers where the contained groundwater was under pressure. If the water pressure was sufficient to create flowing artesian wells with a water level above ground level, then no pump would be required. This was the ideal water supply that drillers of the first exploratory wells hoped to encounter. A hydraulic ram or impulse pump that utilised water pressure could be installed on a flowing artesian well to raise water to a storage tank, from whence it could be reticulated by gravity feed. Hydraulic rams provided the means to supply reticulated water from flowing artesian wells where the water levels were only a metre or two above ground level. The main disadvantages were water spillage and wastage, and the monotonous tapping noise created by the continuous pumping. Hilgendorf (1912, p.157) estimated that hydraulic rams waste seven times the amount of water actually pumped. An important development that encouraged the use of groundwater for irrigation was advances in pump technology, particularly submersible pumps. A turbine pump with a submersible electric motor was relatively easy to install in deep wells, compared with pumps driven by a power unit at the ground surface.

The provision of irrigation water supplies from wells is complex. The choice of screen slot size, the precise location of the screen in the well, and the subsequent development of the well relied on the skill and knowledge of both the well driller and the irrigation engineer (Crosby 1978; Bowden et al. 1983). E.V.R. (Russell) Harris of A.M. Bisley and Company Limited, had training in engineering (at the Massachusetts Institute of Technology) and in drilling that combined all of these skills. Harris successfully promoted and designed wells for town water supplies (including Christchurch, Palmerston North, Richmond (Nelson), and Blenheim) and irrigation wells throughout New Zealand. The firm of A.M. Bisley was a pioneering organisation in promoting groundwater for irrigation on the Wairau Plain in Marlborough and the Waimea Plains near Nelson in the 1960s. Well hydraulics and efficiency became important, and aquifer pumping tests became a standard requirement for high-capacity wells drilled for public and industrial water supplies.

Water divining

Much to the frustration of professionals engaged in research on groundwater, water diviners have been used to find a large number of the wells drilled in New Zealand. Some diviners claim not only to be able to find groundwater, but to predict its depth, quality, quantity and direction of flow. To this end diviners use a variety of devices, including forked sticks, L-shaped rods, keys, pendulums and electrical equipment. The earliest authenticated account in the literature of the use of a forked stick for divining occurs in 1556 (Vogt and Hyman 1959). By the end of the sixteenth century the practice was commonly used in Germany for locating underground minerals.

As groundwater became recognised as a widespread and convenient source of water in New Zealand, the number of diviners proliferated. Divining claims were not restricted to water. M. Ongley (1924) observed that "diviners in New Zealand claim to have found underground springs of water, subterranean streams and pools of oil, coalfields, lodes of gold, silver, etc., and to know the quality, extent, and depth of the deposits, to have found and counteracted the cause of goitre, tuberculosis, and cancer, etc., by the divining rod or by related means." A subjective test of New Zealand diviners by P.A. Ongley showed that "of 75 diviners thoroughly tested, none showed any reliability" (Ongley 1947).

The media have sometimes unwittingly reported nonsensical claims. Mary Bryan reported in the Wanganui Chronicle, on 12 October 1998:

> "Wanganui diviner David Watkin may feature in an Australian documentary on the potential for cities to use primary water. Julia Truebridge-Freebury of Sydney, who is doing research for the television documentary, has spent this week with David Watkin, a diviner for more than 50 years. He has located 20 primary water sites in the Wanganui city area. Primary water is continuously created from oxygen and hydrogen trapped within the earth's crust. The water has not been through the rainfall process and is virtually free from mineral and other pollutants. Ms Truebridge-Freebury said the significance of being able to tap into an endless supply of primary water for cities such as Sydney was immense. Primary water sites had been divined in Sydney, which if tapped would mean an end to that city's water supply problems she said."

Unfortunately, follow-up articles or reports on failures by water diviners are not common in newspapers. Some local government authorities have engaged the services of diviners to find a source of water for public supply, usually when traditional methods have failed. On 10 November 1993, the Timaru Herald reported that the Waimate District Council intended to drill at a site pinpointed by a diviner. He claimed that water flowing at a rate of 22 750 litres per minute would be found at a depth of only 23 metres. The well was drilled to 108 metres but only a small flow, estimated to be 455 litres per minute, was found at a depth of between 9 and 14 metres (Timaru Herald 2 February 1994).

Water diviners are often well meaning and believe in their art, but many also have a considerable knowledge of the local groundwater systems. There are extensive areas of gravel deposits where diviners cannot go wrong, and most localities in New Zealand overlie strata containing groundwater. There is no doubt that diviners have been associated with many successful wells in New Zealand. "In 1926 a water diviner from Manawatu by the name of Bill Brogden who was well known for his divining skill, was asked to test the factory site of the soft drink manufacturers, Thomson and Lewis Company, Tory Street, Wellington for artesian water. Mr Bill Brogden divined water, but could not estimate the depth other than that it was very deep. The geological experts in Wellington and a Professor of Geology at Victoria University rubbished the idea. Drilling began and it was only Mr Lewis's faith in Mr Brogden, and possibly his annoyance at the Professor's skepticism, that determined him to persevere. At 497 ft water was found in greywacke lithology, with a head of 10 feet, resulting in a flow at the surface of 500 gallons per hour. The water was tested and found to be of excellent quality and was used for 53 years for the manufacture of soft drinks. The flow never diminished. The only change ever noticed was after the Murchison earthquake when the water became slightly cloudy for a short period. It is believed the water comes underneath Wellington Harbour, its origin possibly the Wairarapa." (Lewis 1980). Henderson (1937) includes this well in a short paper on groundwater in Wellington greywacke. Isotope analyses (tritium and oxygen-18) of the groundwater from this Tory Street well show that the groundwater is more than 70 years old and derived from local rain.

Many people accept diviners as credible prospectors and divining as a valid method for indicating where groundwater might occur. The professional hydrologist is in a "no win" situation with regard to divining and this is recognised by well drillers (Brown 1998b). The diviner's mystique, extravagant claims and availability at no or low cost, cannot be replicated by hydrologists. Humans, by nature, are fascinated by claims of mysterious powers, and this means that divining will never be entirely refuted.

EXPLORATION AND RESEARCH

New Zealand Geological Survey and the Department of Scientific and Industrial Research (DSIR)

The description of the geologic materials that behave as aquifers and confining units has always been a fundamental aspect of hydrology (Leahy and Lyttle 1998). Early New Zealand groundwater workers commonly used geology in their search for flowing artesian aquifers, for aquifers remote from contamination sources, and for aquifers providing a sustainable yield of water for domestic and industrial use. New Zealand groundwater research, however, was largely independent of overseas influences until the 20th century, when projects of the U.S. Geological Survey established principles for regional groundwater investigations. The work of N.H. Darton (Darton 1901, 1905), describing the geology and the occurrence of groundwater in the central Great Plains, W.C. Mendenhall (Mendenhall 1905), who advanced the concept of groundwater mining, and O.E. Meinzer, whose books and papers (Meinzer 1923) established groundwater as a dynamic component of the hydrologic cycle, were to establish the pattern for New Zealand hydrogeology and groundwater studies.

Other researchers contributed to the theoretical understanding of hydrogeology. C.S. Slichter provided a major advance in 1899 in his paper entitled "Theoretical investigation of the motion of ground waters", which established the concept of a cone of depression forming at the site where groundwater is withdrawn (Slichter 1899). The experiments of Roche (1915), on interference between wells in the Lower Hutt Borough well field, are the first recorded groundwater flow and pumping experiments in New Zealand. Pumping interference between wells was also measured in the five wells of the Invercargill water supply (Corkill 1932). Research by C.V. Theis on non-equilibrium flow to wells (Theis 1935) built upon the concepts established by Slichter.

In the early part of this century the New Zealand Geological Survey concentrated on mapping, describing and identifying rock units, using techniques such as petrology, palaeontology and micropalaeontology, and on investigating mineral, coal and oil resources. The government's promotion of agriculture and improved farm production had created a demand for fertiliser, so surveys of phosphate and limestone deposits were also important. Geologists in the field, however, often found themselves called upon to address hydrological problems. Percy Morgan, the Director of Geological Survey, was in Kaikoura in December 1915 during a drought and was asked to advise on a water supply for the town (Morgan 1916). His recommendation that the town supply should be pumped from two springs however was never followed up (Sherrard 1966). Kaikoura's water supply is now based on an infiltration gallery augmented by wells (Brown 1988).

Political and economic conditions in New Zealand during and after World War 1 restricted any advances in groundwater resource research for several decades. In this period, the main developments in hydrology were related to engineering, pump development, hydroelectric power and water supply. Groundwater investigations were also focussed on engineering and supply aspects, for example Stewart (1902 Wanganui); Wood (1917 Whangarei); Holmes (1916 and 1917 Westshore, Napier); Williams (1920 Napier); Roche (1915 Lower Hutt); Corkill (1932 Invercargill); Chilton (1924), Dobson (1920), and Speight (1926), Christchurch. Chilton (1924) produced a 133-page booklet that summarised established knowledge of the Christchurch artesian system.

On 31 August 1926 the New Zealand Parliament passed the Scientific and Industrial Research Act. The Department of Scientific and Industrial Research (DSIR) became the central government scientific research organisation. The Geological Survey, the Dominion Laboratory and the Meteorological Service, along with the Dominion, Magnetic and Apia Observatories, were now part of DSIR.

Ernest Marsden became the permanent secretary of DSIR. Marsden had a natural affinity and feeling for people. He was very conscious of the plight of the unemployed during the depression, and searched vigorously for new projects that might provide jobs and increase the national income (Atkinson 1976). Irrigation was one of these projects.

The DSIR structure promoted multidisciplinary teams to investigate resources such as groundwater. Geology was the science on which research in groundwater, soil, coastal and land processes was based, and the Geological Survey was the division that initiated research. The DSIR had been established in the face of the thinly veiled hostility of departments that had been stripped of their scientific units, or were fearful of losing them (Atkinson 1976). The DSIR's view was that, as the central government research department, it should be the focus of all state research projects (Atkinson 1976). Subsequently these views were to prove both an advantage and an impediment to promoting and organising research. For example, in 1946, when the hydrological survey of New Zealand was to begin, Montague Ongley, the director of the Geological Survey, used the example of the US Geological Survey to advocate that his organisation had a prior claim to undertake this important work. He was overruled, as the 1941 Soil Conservation and Rivers Control Act stated that this was the role of the Soil Conservation and Rivers Control Council and the Catchment Boards (Roche 1994). Water, including groundwater, was now very much a political issue and management decisions would have to consider political influences.

Geological Survey geologists routinely answered groundwater-related enquiries from all over New Zealand. When major earthquakes struck Murchison on 16 June 1929 and Hawke's Bay on 3 February 1931, Survey geologists investigated and analysed the damage, including disruption of water supplies by the Hawke's Bay earthquake (Callaghan 1933). Concern had already been expressed over the treatment and disposal of wastewater from dairy operations (McDowall 1931). The first water supply bulletin by Taylor (1935) discussed hydrogeology in relation to the quality of water supplies for farms and dairy factories in the Hamilton Basin and Hauraki Lowland.

In 1926 the Geological Survey undertook a soil survey in Central Otago, the first systematic soil survey in New Zealand. The potential for irrigation in Central Otago had been noted 50 years previously by Hutton and Ulrich (1875): "the soils of Otago taken as a whole are decidedly above the average in quality, and this appears to be owing to the great extent of mica-schist exposed at the surface, the decomposition of which has supplied more or less directly almost all the soil in the province. That this schist contains a considerable amount of lime is proved by the incrustation in nearly all the caves occurring in it; and the good quality of the soil derived is well seen in the Dunstan district, which is remarkably fertile when irrigated." A well had been drilled at Eweburn, in the Maniototo Plains, by Job Osborne in 1893 to a depth of 199 metres, but had encountered no flowing artesian water (Gordon 1893). An 1897 report by T. Perham, Under Secretary, Mines Department, entitled "Water-conservation for mining and irrigation purposes, Otago and Westland Districts," concluded "that water is, both for mining and irrigation purposes, urgently required in Central Otago. I think water is required more for irrigation than mining." The Central Otago soil survey was published in a bulletin (Ferrar 1929) and sources of water for irrigation were also considered.

Groundwater beneath the Maniototo Plain had already been established (Gordon 1893), although Ferrar (1929) had recommended using surface water. Flowing artesian wells penetrated confined aquifers in Tertiary gravels underlying sand and silt deposits of the Miocene/Pliocene Wedderburn series (Williamson 1939), which had accumulated in the "Maniototo Lake" (Wood 1960). Geological Survey geologists (Harrington 1952; Wood 1960; Bishop 1979) thought that the regional structure, with gravel beds dipping gently away from the surrounding hills into a basin, had the potential for an extensive artesian aquifer system. Harrington (1952) cautioned however that the groundwater quality could be affected by dissolved minerals derived from the sediments filling the basin. In 1978, groundwater was found well below the sedimentary strata, when the construction of a canal near Patearoa for a combined power generation and irrigation scheme was impeded by groundwater pressure within the underlying schist rock (Christie et al. 1994). The availability of water, including groundwater, and recurring water supply problems and the difficulties in maintaining agricultural production during regular summer drought have still not been resolved for Central Otago.

In 1933 Les Grange began a soil survey of the Ashburton County sector of the Canterbury Plains in relation to irrigation (Grange 1935a), and in 1935 the survey was extended to Levels County in South Canterbury (Grange 1935b). In 1936 the Soil Survey Division (later the Soil Bureau) was separated from the Geological Survey, but the multidisciplinary team approach (often involving Department of Agriculture scientists) to water and groundwater research continued. It was recognised that flood irrigation methods could result in drainage problems further down the plains, and soil surveys were combined with water-level monitoring programmes on the Canterbury Plains. Soil survey bulletins considered water resources, including groundwater for irrigation supplies (Pullar 1962; Cox 1978; Ward et al. 1964) and land use (DSIR 1939). The impact of settlement and the role of deforestation in producing mass soil movement and soil loss were also considered (Gibbs et al. 1945) for geological and soil mapping.

In 1941 John Henderson, the Director of Geological Survey, reviewed "underground water in New Zealand" (Henderson 1942). Tony Collins wrote three important papers that reviewed and updated the knowledge of groundwater resources in New Zealand (Collins 1950, 1955a, 1955b). These were to be the most comprehensive reviews of New Zealand's groundwater resources. Subsequent "reviews" either repeated previous review papers (Grant-Taylor 1967) or dealt with specific regions or methods (Thorpe and Scott 1979).

From 1946, DSIR Annual Reports summarised research by the various DSIR divisions during the year. By 1946, six Geological Survey geologists were working on water-supply (DSIR Annual Report 1946). The following year, in the 1947 Annual Report, Ongley suggested a growing demand for water-supply guidance and research. "Problems in water-supply are becoming more and more urgent and require more investigation. If the geology of the district has already been done, it is easier to report on water-supply, but in many places scraps of evidence have had to be hastily searched for. Districts reported include Opua, Whangarei, and other parts of North Auckland, several parts of Auckland City and suburbs, Wairakei, Otahuhu, Mangatainoka, Blenheim, Picton, North Canterbury, Canterbury Plains, Goodwood, Southland, and Stewart Island". In 1948 the Geological Survey established a Water Resources Unit to study urgent problems of water supply, but coal surveys were given priority and groundwater investigations were restricted. Ongley, in DSIR Annual Report 1952, reports that "the Water Resources Section of the Geological Survey was established to investigate the underground water resources of Canterbury. Observation wells throughout Canterbury have been measured periodically and the fluctuations of water-level studied and interpreted. Irrigation areas and areas for future irrigation have been given special attention so that any possible harmful effects of the scheme may be detected and avoided. The occurrence of groundwater in connection with drainage and water-supply has been studied. Similar systematic investigations of water resources have been extended to Otago, Southland, Hawke's Bay, and the Waikato."

The first regional investigation of groundwater resources in New Zealand began in 1945, with data collation and monitoring of the Canterbury Plains aquifers. This was carried out by the Geological Survey, with Robin Oliver based in Ashburton (1945-46). The Canterbury groundwater surveys continued when the office moved to Timaru (1946-49) with Tony Collins, and then to Christchurch (1949 -92), initially with Tony Collins and Les Oborn. Les Oborn's (1955) thesis on "The hydro-geology of the Canterbury Plains between the Rakaia and Ashley Rivers" (School of Mines, University of Otago) was the first university thesis in New Zealand concerned with regional groundwater resources. Another Geological Survey groundwater investigation began in 1949, with Tom Grant-Taylor based at a Napier District Office (1949-1956) carrying out a groundwater survey of the Heretaunga Plains. The Napier office was closed in 1956 and the Heretaunga Plains groundwater survey was continued by Pat Grant, Ministry of Works, Napier, in conjunction with the Heretaunga Plains Underground Water Authority. Other Geological Survey district offices were established at Kaikohe (1950-55), at Ngaruawahia (1950-58), with Jim Schofield surveying the Hamilton Basin groundwater resources, at Rotorua (1946-1992), and at Invercargill (1942-1958), with Peter Chandler surveying Southland groundwater resources.

By 1955 the Geological Survey had eight geologists and technicians dedicated to groundwater studies. This was to be their peak earth science input into groundwater research. The Water Resources Section never really received enough resources to become firmly established. Most efforts of the staff were devoted to addressing the escalating number of enquiries for guidance in drilling wells for groundwater, as agriculture shifted from traditional dry-land farming toward irrigation-based pasture and cropping. The New Zealand economy was buoyant and agricultural processing was expanding along with other new industries, all of which required reliable water supplies.

Groundwater work however was relegated to servicing mode when Dick Willett became the Survey Director in 1956 and the 4-mile geological mapping project began. Only the Christchurch-based Canterbury groundwater surveys were continued. The Water Resources Section was disbanded. Several of the early 1950s groundwater research projects were never completed and publication of the results of others was delayed. Major publications on the Hamilton Basin by Schofield (1972), on Canterbury by Bowden et al. (1986) and on the Heretaunga Plains by Dravid and Brown (1997) eventually evolved from the original surveys. The application of hydrogeology to groundwater investigations and the establishment of well log data bases and water-level monitoring networks by the Geological Survey provided the model and foundation for present regional council work on groundwater resources.

Knowledge of the Quaternary stratigraphy of an area, and the geological processes involved in the formation of the strata, is often essential in groundwater investigations to map aquifers and determine groundwater flow paths.

Geological mapping in Westland in the 1940s by Wellman and Willett (1942a, 1942b) and by Gage (1945) had established that interbedded marine and terrestrial deposits and multiple river terraces were the product of both tectonic uplift and a number of glacial advances and retreats during the Quaternary. At Wanganui uplifted beach cliffs were correlated with high interglacial sea levels (Fleming 1953), and in the Rangitikei River valley terrace remnants across and down valley correlated with intermittent periods of uplift (Te Punga 1952).

The first application of Quaternary stratigraphy to the strata logged in water wells was for the Hutt Valley aquifer system. Stevens (1956a, 1956b) identified aquifers within the late Quaternary sediments penetrated by water wells. He recognized glacial and interglacial stratigraphic sequences and correlated the strata with surfaces in the Hutt Valley. Gage (1958) mapped multiple glaciations in the

Waimakariri Valley, and in a subsequent paper Gage and Suggate (1958) established a glacial chronology for New Zealand by correlating the Waimakariri Valley sequences with sequences in Westland, on the other side of the Southern Alps. Suggate (1958) also correlated the deposits underlying Christchurch, as identified by well logs, with the glacial sequence mapped in the Waimakariri River valley. Aquifers were associated with eroded surfaces on glacial outwash fans. Brown and Wilson (1988) and Brown and Weeber (1992) extended the correlation of the Christchurch aquifers and glacial and interglacial sequences as deeper wells were drilled and samples of fossiliferous marine and swamp deposits were obtained. Similar stratigraphic correlation techniques were applied to aquifers underlying the Wairau Plain (Brown 1981b) and Heretaunga Plains (Dravid and Brown 1997).

"The reports of the mining industry of New Zealand," presented to New Zealand Parliament in 1892, contained an article taken from the Australian Mining Standard on "A wonderful water indicator, by which subterranean water at any depth can be found with certainty." The construction of the apparatus was secret, but it was "constructed on strictly scientific principles, electricity being the detective medium." Geophysical survey methods had arrived, but were they as good for finding water as the article title suggested?

Geophysical exploration methods were first applied in New Zealand by overseas-based oil prospecting companies during oil exploration in Taranaki in 1927 (Burton 1965) and southern Hawke's Bay. DSIR (Geological Survey) geologists and geophysicist Norbert Modriniak tested various geophysical methods at sites on the Otago, Nelson and West Coast goldfields from 1934 to 1938 (Modriniak and Marsden 1938). The results were sufficiently encouraging for geophysical exploration to be incorporated into the expertise of the Geological Survey, and in 1951 a separate Geophysics Division of DSIR was formed.

In 1947 the resistivity method had been tested on the Canterbury Plains in the Methven-Ashburton area, where the water table is often deeper than 30 metres. The results however suggested that the lithology of the sediments (gravel, sand and silt) determined resistivity, rather than the water table (Risk 1974).

Seismic refraction surveys have provided important information on the broad structure of regional aquifer systems (e.g. the Heretaunga Plains), but are of limited use for detecting aquifers and groundwater recharge areas, especially in floodplains. The geophysical exploration methods were relatively coarse for detecting subtle lithological changes in fluvial deposits. The method was tested at the site of a 256.5-metre-deep testbore near Hastings on the Heretaunga Plains (Brown 1993). The seismic data couldn't be related to specific layers in the testbore, suggesting that the frequency range of the seismic data was not useful for delineating the shallow sequence (Melhuish 1993). To successfully apply geophysics to groundwater exploration in New Zealand, supporting geological data (well logs) are needed to aid interpretation. Downhole geophysical methods interpreting strata sequences, however, have been successful in New Zealand since the first trial of electrical self-potential logs in wells at Heathcote, Christchurch in 1950 (McKellar and Collins 1951).

Donaldson and Campbell (1977) applied five groundwater models to the Hutt Valley–Port Nicholson groundwater system. They used a steady-state one-dimensional model of the pressure profile from Taita Gorge to Somes Island to explain the system behaviour. They defined a 'critical' withdrawal rate, for which withdrawal and inflow are equal. The groundwater level at Petone was predicted to drop to sea level when withdrawal is 'critical'. A wave propagation model was used to estimate changes in the amplitude and phase of oceanic tidal variations in the groundwater system. A 'bucket and pipe' model was used to predict the relationship between groundwater levels and withdrawals during droughts. This model predicted that reducing pumpage by about 12% in the 1974/1975 drought would allow the ground-water system to be pumped for an extra month before a critical groundwater level was reached. A finite element model and a finite difference model were used to predict groundwater levels in wells in the unconfined aquifer at the Petone foreshore and Somes Island. These models were used to assist with policy decisions in times of drought. They estimated a safe summer withdrawal at about 73,000 m^3 /day and predicted that this withdrawal could be 20% higher if some water supply wells were to be moved further north.

National Water and Soil Conservation Authority (NWASCA)

The National Water and Soil Conservation Authority (NWASCA) was established in 1967 under the Water and Soil Conservation Act, and was administered by the Water and Soil Division of the Ministry of Works and Development (MWD). One of the statutory functions of NWASCA was to provide a capability for research on water and soil problems. As there were already a number of other government departments doing research in similar fields, there was some concern that the new group might intrude into somebody else's "patch".

With the exception of Hawke's Bay, Marlborough and Canterbury, very little groundwater investigation had been done before the 1970s by any of the regional water boards. Even in these regions groundwater was being tapped with minimal understanding of its magnitude, character or the effects of the abstractions.

Until this time the New Zealand Geological Survey (NZGS) had been doing a small amount of groundwater research, but over a long period the Survey had focussed largely on hydrogeological aspects. In 1972 an agreement was signed between NWASCA and NZGS—the geological parts of groundwater research would remain the prerogative of NZGS, while MWD, as agent for NWASCA, would be responsible for the water resource components. On the whole this agreement worked satisfactorily until 1988, when NWASCA was disestablished during government restructuring.

In fact NWASCA was slow to establish its research capability. Little groundwater research or investigation was done by MWD until 1976 when, under intense political and time pressure, a major study was initiated into the potential for contamination of the unconfined aquifers of the Heretaunga Plains. At the time Hastings City wanted more land for urban development. A stalemate developed between the City and the Hawke's Bay Regional Water Board over the wisdom of urbanising the area above the unconfined aquifer to the west of the City. Groundwater in this area is largely recharged from the Ngaruroro River and flows eastwards into the confined aquifers supplying the rest of the Heretaunga Plains. There was a perceived risk of polluting the entire system.

As was often the case in such situations, local authorities wrote to the Minister of Works and Development requesting that the matter be resolved urgently, and this was passed to NWASCA for action. The newly appointed Director of Research in the Water and Soil Division, Ken Mitchell, was trying to establish the credibility of his new organisation and he decreed, over considerable protest, that the job would be done in nine months! He further risked his reputation by making a bet with the Chairman of the Hawke's Bay Regional Water Board for two bottles of whisky that the task would be completed on schedule (he himself was a teetotaller)!

There had never, to this time, been an investigation of this type or size done in New Zealand, and MWD had minimal staff with groundwater expertise. The complex exercise was planned by pulling together a committee of the few experienced staff that existed in the various government departments in Wellington (mostly MWD and DSIR). The lack of experience was, to some extent, eased by the fact that in those halcyon days money was less of a problem. Ken Mitchell hired staff and arranged finance to ensure that the job was not hindered, at least in those respects. It was the first groundwater study in New Zealand that was truly multidisciplinary, co-ordinating the skills of engineers, geologists, geophysicists, physical and isotope chemists, drillers, technicians, a mathematician, a modeller and a microbiologist. After much intense effort, mostly by a group of dedicated people in Napier, the job was completed and the report presented—on time! The whisky went to the field staff!! The report concluded that urban expansion over the unconfined aquifer was acceptable, provided that the new developments were fully sewered and that certain high-risk industrial or service activities were controlled or precluded (Thorpe 1981; Thorpe et al. 1982). The recommendations were incorporated into the local planning provisions. Because of the huge pressure of this job and the lack of experience of those involved, some mistakes were made and time and money wasted. Nevertheless the final result was satisfactory and all those involved learned a lot about many facets of groundwater science in a very short time. It proved to be a good foundation for those of the group who went on to specialise in groundwater research and investigation.

The establishment of NWASCA Science Centres at Hamilton, Palmerston North and Christchurch led to the creation of research teams in a number of scientific fields, with the objective of providing scientific bases for soil and water operations in New Zealand, whether for catchment authorities, MWD or other government departments. In 1978 the groundwater research group was based in Christchurch, along with surface-water hydrology, alpine hydrology, land resource inventory mapping and a small water quality laboratory. At this time the group consisted of three civil engineers and two scientists. In due course two geophysicists were appointed, and the water quality group came to be heavily involved in groundwater quality research, both chemical and microbiological. The group, though, was still quite inexperienced, and the primary requirement was to develop its own expertise, then develop expertise within regional water boards and try to stay ahead!

The major task for the group in Canterbury was to assess the magnitude of groundwater resources between the Ashburton and Rakaia rivers. The government at this time was subsidising irrigation development throughout New Zealand. A major irrigation scheme, using water from the Rakaia River, was planned for the area bounded by the two rivers, State Highway 1 and the sea. Before this, community irrigation schemes in Canterbury were supplied from the Rangitata River via a diversion race, but the increasing awareness of environmental issues and the powerful influence of recreational salmon fishermen led to groundwater being incorporated in the scheme planning. The objective was to determine how much of the scheme area could be irrigated from groundwater, in order to minimise the take of water from the Rakaia River. This was a large task, but rather more orthodox than the Heretaunga Plains investigation, and it occupied the group for about four years. In addition to the usual groundwater investigation methods, several downhole geophysical logging techniques were used for the first time, and water chemistry was used to identify water provenance. A major groundwater model was developed to predict the response of the groundwater system to various scenarios for irrigation development. The reports (Scott and Thorpe 1983, 1986) were published about the time that a conservation order was placed on the Rakaia River, limiting the amount that could be taken for irrigation. At this time also the government discontinued subsidies for community irrigation schemes and so the scheme was deferred.

The third major study undertaken by the MWD groundwater group was of the aquifers of the Waimea Plains near Nelson. This 75 km^2 area of highly productive land is underlain by an interconnected three-aquifer system. It was being rapidly developed in the early 1980s, and becoming heavily stressed in dry years. There was a need for a model that could be used to examine development options for management, and there was enough information to begin modelling while continuing the data collection. The three aquifers interact with each other at discreet zones and also interconnect with the Wairoa, Waiiti and Waimea rivers that traverse the Plains. The Nelson Regional Water Board had an active programme of investigation and had accumulated sufficient geological, hydrological and, most importantly, water-use information that a quasi-three dimensional numerical model could be attempted. Modelling at this scale was possible only because of access to the MWD's IBM 360 mainframe computer in Wellington–it had, by the standards of the time, massive computing power. Calibrating the Waimea model was a big task, but it was satisfactorily achieved because of the information available from the Nelson Regional Water Board. At the peak of the calibration effort, the computer time required would have cost about $100,000 per month if charged at commercial rates, but fortunately it was a "paper" cost. The outcome of the study was reported by Fenemor (1988, 1989) and is still arguably the most successful attempt at modelling a three-dimensional aquifer system completed in New Zealand. In part this is because today few agencies would have the financial resources to devote to such a comprehensive study.

The MWD adopted three ways of developing the national groundwater skill base: the groundwater group organised and ran short training courses, they published small manuals and, with regional water boards, established technical groups to plan and oversee groundwater investigations. Regional, and local, groundwater investigations were often carried out and interpreted by groundwater group staff who would provide training to Regional Water Board staff. As far as possible each member of the groundwater group was given a liaison role with several regional water boards, so that the board staff had access to the skills of the whole group through a personal contact. There was thus a system of formal and informal support of the regional water board staff, who were often professionally very isolated.

At times almost no information was available to regional water boards at the beginning of an investigation. For instance, when the technical group sat around a table for the first time in 1980 to plan an investigation in the Wairarapa, the sum of the knowledge of the groundwater system in the lower plains was the inch-to-the-four-mile geological map and two borelogs! Pooling of the limited available expertise was generally successful in getting regional water boards underway in groundwater investigations. The expertise available outside of the boards resided in DSIR, MWD, and in Bruce Hunt at the University of Canterbury, and was available as a free government service. There were no groundwater consultants in New Zealand at this time. The first consultancy specialising in groundwater studies was Ground Water Consultants New Zealand Ltd. (GCNZ), which was established in 1983 as an offshoot of Australian Ground Water Consultants Ltd. The company was involved in studies for catchment boards and regional councils in areas including the Rangitaiki Plains, western Bay of Plenty, Wairau, and the Aupouri Peninsula in Northland.

In 1979 the groundwater group acquired the first suite of downhole (wireline) geophysical tools for groundwater investigation. They were intended primarily to help define aquifers in the thick alluvial sequences of the Canterbury Plains, but were also used in other parts of the country. The techniques included measurement of electrical resistivity, emission of natural gamma radiation, electrical potential differences at boundaries of strata, and back-scattering of gamma or neutron radiation. From these measurements, information could usually be derived on the density, porosity, silt content and hence permeability of the strata. Used in conjunction with the original lithological log and knowledge of the regional aquifer distribution and groundwater flow directions, this information could be used to construct the production well with the screen positioned at the precise depth for optimum hydraulic connection and groundwater intake. While this suite of equipment performed adequately in many areas around New Zealand with differing lithologies i.e. the Bay of Plenty, South Waikato, Wanganui, and Banks Peninsula, it was not successful in greywacke alluvium, because insufficient signal differences were measurable in cased wells drilled in the alluvium.

Surface electrical resistivity equipment was used to investigate groundwater problems throughout New Zealand (White 1985). In 1979 the MWD used the resistivity technique to map bedrock beneath the shallower sections of the unconfined aquifer sector of the Heretaunga Plains, Hawke's Bay. Resistivity surveys over the unconfined aquifers also detected a low-resistivity layer underlying the water table and the aquifer (McLellan 1988). The significance of this contrast was discovered when a testbore was drilled in 1991. The change to low-resistivity and hence low permeability sediments corresponded with the boundary between fluvial gravel and sand deposited during the last glaciation, and the underlying gravel and sand of the last interglacial, which have a higher silt and clay matrix content (Dravid and Brown 1997). Resistivity measurements to locate water and aquifers on the Canterbury Plains have had qualified success. Broadbent and Callandar (1991) comment that resistivity (Schlumberger soundings) cannot locate aquifers nor provide reliable hydrogeological parameters for the thick heterogeneous alluvium of the Canterbury Plains.

The demise of NWASCA occurred in 1988, and this was also the time when regional agencies such as water boards ceased to be directly supported or subsidised by the central government. The entire MWD water and soil research capability, which was by now well established, was transferred into DSIR, and at this time the groundwater group was split from the surface water hydrologists. In retrospect this split was a serious mistake for the advance of groundwater science in New Zealand. Initially the groundwater group was placed in the Geophysics Division of DSIR and subsequently in an amalgamated Geology and Geophysics Division.

Local investigations

Ever since groundwater was first used in New Zealand, deep well exploration has discovered substantial groundwater resources. Some of these exploration drillholes were "wildcat" bores; others were planned and sited after careful consideration of the geology. Drilling deep holes to acquire information on the sequence of subsurface strata and the contained aquifers is now a common part of groundwater resource investigations. Costs have been met by a variety of organisations, including drilling companies, catchment boards and councils, and central government departments and ministries, including DSIR, Forestry, Agriculture, Railways and Public works (subsequently Ministry of Works). Many exploration wells and successful deep water wells have also been funded by private organisations or individuals.

The 251.5-metre-deep well at Cheviot in North Canterbury drilled by Job Osborne in 1898 was the deepest nineteenth-century groundwater exploration well drilled in New Zealand. Unfortunately, the Cheviot testbore did not find any deep aquifers before the casing jammed, and the bore was abandoned with 175 metres of rods remaining in the ground. The deepest groundwater exploration well drilled in New Zealand is the 895.5-metre-deep Tasman District Council well (WWD 1500) drilled by Waimea Drilling Company Limited in 1992 at Waimea West on the Waimea Plains, Nelson. This well produced a small artesian flow from 770-790 metres depth (Woodford 1996).

In the 1980s regional development projects promoted by the central government helped to fund groundwater exploration drillholes. In areas such as Nelson, the Bay of Plenty, Gisborne, North Otago and Horowhenua groundwater resources had never been investigated and thus groundwater was under-utilised. Exploration drillholes were drilled for the catchment boards, with funding from regional and central government sources. The investigation programmes established that good quality reliable groundwater supplies were available, thus encouraging private development and the diversification of horticulture and orchards, leading to regional prosperity. In the Wanganui district, the Ministry of Works and Development funded an exploration drillhole in 1983 at Westmere and designed the pumping and reticulation system for the groundwater. The drillhole was 418 metres deep and drilled by Richardson Drilling Co. Ltd. Palmerston North. This was New Zealand's most expensive groundwater exploration well drilling project, with well drilling costs of $340,000 (Richardson Drilling Co. Ltd records). By the end of the 1980s, however, central government involvement in regional development had ceased and regional councils funded all groundwater exploration drillholes.

One important regional council exploration drillhole provided important information about the glacial stratigraphy and aquifers of the Canterbury Plains. The testbore, funded by the Canterbury Regional Council and Christchurch City

Council, was sited in the eastern Christchurch suburb of Bexley, about 1 kilometre from the Pegasus Bay coast. McMillan Water Wells Ltd., from January 1989 to March 1990, drilled the 433-metre-deep testbore (M35/w6038). At 163.2 metres it penetrated the base of the deepest artesian aquifer beneath Christchurch in use–the Wainoni Gravel (Brown and Wilson 1988). From 163.2 metres to 240.7 metres the bore penetrated strata from three interglacial and three glacial periods. The climatic environments were identified from shells and pollen. The glacial strata were predominantly gravel and were water-bearing, although less permeable than the Wainoni Gravel. At 240.3 metres depth an erosional unconformity was found between the overlying postglacial, glacial and interglacial deposits of the last 660,000 years (correlated with oxygen isotope stages 1-16) and the earlier Pleistocene Kowai Formation (Brown 1998a). Oil exploration well logs and the Offshore Canterbury DSDP 594 well also suggest a late Pleistocene unconformity (Field and Browne 1989; Nelson et al. 1986). The unconformity may mark the groundwater "basement" within the Pleistocene deposits forming the Canterbury plains.

In the last decade other regional councils have completed exploration drillholes to acquire hydrogeological data and to identify and test aquifers below those being used. These include the Tasman District Council Waimea West drillhole, three Hawke's Bay Regional Council drillholes on the Heretaunga Plains (Brown 1993; Brown and Gibbs 1996) and a Wellington Regional Council drillhole at Lower Hutt in the Hutt Valley (Brown and Jones 2000).

To establish the depth and thickness of aquifer systems, exploration drillholes are often sited and drilled to intersect the groundwater "basement" of an aquifer system. This basement can be a regional unconformity between permeable strata that may include aquifers, and strata or lithologies that are impermeable. A change in lithology indicating a break in deposition may be detectable, or fossils may indicate a transition to strata of an age that would preclude the inclusion of aquifers. The basement may be a structural feature indicating faulting or folding that would eliminate the possibility of significant aquifers. On the other hand, the basement may simply be the depth below which it is economically prohibitive to drill, construct a well or pump water, even if aquifers were present. "Economic basement" for groundwater aquifers isn't fixed and may depend on the income derived from the crop produced or from the process the water is used for. In the 1980s deep wells were commonly drilled for water for kiwifruit irrigation in the Bay of Plenty and Horowhenua areas. With low returns for kiwifruit this is no longer economical. In contrast deep wells are now drilled for irrigation water for grape production for wine. Wine-producing areas where deep wells (>150 metres) are now commonly drilled include Martinborough, Wairarapa, the Wairau Plain, Marlborough and Canterbury (e.g. Waipara).

Exploration drillholes do not need to locate high-yielding aquifers to provide important information on geology and groundwater resources. The 152.4-metre-deep New Zealand Railways drillhole at Timaru, drilled by A.M. Bisley and Co. Ltd. of Christchurch in 1959, demonstrated that groundwater in the Cannington Gravels at 125.8 to 126.8 metres was not suitable for railway locomotives or public supplies (Gair 1961). Similarly a 442-metre-deep drillhole at Dominion Breweries Ltd., Waitemata Brewery at Otara, Auckland, yielded groundwater from the Waitemata Formation that was "too salty for use in processing" and of insufficient quantity for the brewery's requirements (Petty 1971).

Exploration drillholes for oil and minerals, and foundation testbores, have encountered unexpected but useful groundwater supplies. At Hawera, a 914-metre-deep oil exploration well supplies groundwater from sandstone aquifers within the Matemateonga Formation for the Kiwi Dairy Company factory. This well is the deepest water well in New Zealand and was formerly an oil well. A coal and limestone testbore drilled for the Waitohi Valley Prospecting Association 3 kilometres south of Picton in 1902 encountered flowing artesian groundwater at a depth of 18.3 metres. The testbore now supplies farm stock and household water (Brown 1977).

Groundwater exploration drillholes do encounter other resources that may be useful, such as warm water and mineral water. In 1955 at Mount Maunganui a 137-metre-deep water supply well yielded water from rhyolite rock at a temperature of 44°C. The warm water was used for the public swimming pool. At Frankton, near Hamilton, a water well for a dairy factory encountered warm water (31.7°C) at a depth of 182.8 metres and more at 281.9 metres (Henderson and Grange 1926). This warm water was used for the public baths (Schofield 1972). Mineral water has been encountered by wells drilled for groundwater at Kamo, Northland (Petty et al. 1987) and at North Taieri near Wairongoa Springs.

The longest-term water level record available from wells in New Zealand is for two wells at the Canterbury Museum in Christchurch. Regular water level readings were started by F.W. Hutton, the curator of the museum, on 23 March 1894, shortly after the "deep" well (57.9 metres) was drilled. Hutton's 1895 paper is the first to describe and analyse hydrographs and water level fluctuations in New Zealand artesian wells. Water levels in the Canterbury Museum wells are now measured every Monday morning by Environment Canterbury staff. There are breaks in the record, but overall one hundred years are covered by these water level measurements. There are also periods when a continuous water recorder was installed on the museum deep well. Other long-term water level measurements have been made on wells at Lincoln College (1912 - 1986) and Rangiora (1930 - 1978) in Canterbury. Many of the current Environment Canterbury and Marlborough District Council water level monitoring wells on the Canterbury and Wairau plains have records extending back to the 1940s. Groundwater level monitoring was begun by the Public Works Department, using established wells, specially drilled wells, and gravel pits to monitor the effects of irrigation on the water table. Long-term water level measurements since 1940 were available from a Woodbourne Air Force base well, Wairau Plain. This monitoring programme was established by E.J. (John) Speight, when he was involved in the construction of Woodbourne aerodrome and several years before he was appointed "hydrologist" with the Ministry of Works, Blenheim, in 1949. Because of Speight's contributions to hydrology, which included organising the establishment of a hydrological monitoring network for the South Island, he is recognised as the "father of the Hydrological Survey in New Zealand" (Freestone 1985).

The installation of continuous water level recorders on wells is an essential component of groundwater monitoring. The first use of a continuous water level recorder in New Zealand was probably in 1914, when L.P. Symes and F.W. Hilgendorf of Lincoln College designed a float recorder and installed it on an artesian well at Papanui, Christchurch (Hilgendorf 1917; Symes 1917). The details of recorder construction are given in Hilgendorf (1926). Three recorders were constructed and installed on several wells at Christchurch and Lincoln from 1914 to 1924. In 1921 one of these recorders was used to monitor water levels in the Avon River just upstream of the hospital. Many interesting artesian water level fluctuations were observed, including the response to an earthquake and to a heavy water tanker passing by on a nearby tram line (Hilgendorf 1926). Probably the most important fact established from these records was that the artesian aquifers are fed by percolation from the Waimakariri River (Hilgendorf 1926). Ian McKellar of the Geological Survey reported on trials carried out with Bristol Pressure Recorders on two wells at the Mosgiel Woollen Mills, Mosgiel (McKellar 1952). Although the pressure recorders coped with water level fluctuations produced by pumping during the daytime on Monday to Friday, and overnight and weekend recovery, McKellar concluded that float recorders would be better for providing detailed long-term records. Continuous water level monitoring has become a routine operation by regional councils, mostly using float recorders and electronic pressure transducers. For example in 1995 the Hawke's Bay Regional Council had 23 recorders operating on wells on the Heretaunga Plains.

Universities

C. Chilton, who was a Professor of Biology at Canterbury College (Chilton 1924) followed Hill (1923) in advocating regulations to conserve groundwater—he also suggested that meters be installed to measure the water use of individual industries and households to discourage waste. Water-use charges remain a controversial issue to this day. Groundwater resources were now recognised as being limited. There was a shift toward estimating groundwater yields, and away from the simple concept of prospecting and drilling for groundwater. Chilton was also one of the first people in the world to study and describe the subterranean phreatic Crustacea that live in groundwater. Chilton lived near Eyreton on the northern Canterbury Plains about 10 kilometres inland from Kaiapoi. On his property was a 7.6-metre-deep pipe well with a stirrup-type suction pump. Chilton discovered that small Crustacea were pumped to the surface in the water. He collected and identified the first southern hemisphere phreatic and subterranean species of Isopoda and Amphipoda (Chilton 1881). Chilton was restricted to bathynellids that were big enough to be seen by the naked eye and those he described ranged from 7 to 16 millimetres. Consequently he may have failed to observe other small and transparent bathynellids and phreatic insects that might also have been present in the water.

In July 1972, Chilton's former property was revisited and a shallow disused pipe well was pumped in an attempt to recollect the phreatic Crustacea obtained by Chilton. No species were present in the groundwater. Other wells in Canterbury, Otago and Southland were also pumped. Beetles (Dytiscidae) were present in groundwater from a well at Seadown, South Canterbury, and these resembled species from Europe and Japan (Kuschel 1975). The range of South Island bathynellids was extended and the first discovery in New Zealand of *Notobathynella longpipes* was established from wells at Motueka (Schminke 1978).

The similarity of thriving present day New Zealand phreatic fauna with those from countries formerly connected to Gondwanaland and beyond is astonishing. A concern is that their survival in the water table aquifers in alluvial plain gravels, where they have thrived for millions of years, may now be threatened by contamination of the groundwater.

In 1965 the New Zealand Agricultural Engineering Institute was established at Lincoln College. Groundwater hydraulics was included in student courses, and senior students and teaching staff were encouraged to pursue groundwater research topics. Overseas irrigation and groundwater experts were brought to New Zealand as visiting Professors at the Institute. Professor Grant Huber (University of Calgary) and Professor Sam Mandel (Hebrew University, Jerusalem) made significant contributions to the progress of groundwater research in New Zealand (Huber 1973; Mandel 1974).

Research by Bruce Hunt and his students at the Department of Civil Engineering, University of Canterbury, was directed toward determining aquifer hydraulic characteristics (transmissivities and storativities) and comparing theory with field measurements (Hunt and Wilson 1974). Groundwater research was an accepted and important branch of hydrology and hydraulics at the University of Canterbury. Groundwater hydrology has also been taught at Auckland, Waikato, Victoria, and Otago Universities.

Foundation for Research, Science and Technology

Government research funding to a number of government departments, universities and non-governmental organisations was centralised under the Foundation for Research, Science and Technology in 1989/90.

With the establishment of the crown research institutes in 1992, groundwater research from the MWD was placed within the Institute of Geological and Nuclear Sciences Ltd. (GNS). When GNS closed its Christchurch office, most of the staff opted for voluntary redundancy and the groundwater expertise accumulated over the previous 16 years was scattered.

The groundwater research programme of the Institute of Geological and Nuclear Sciences Ltd (GNS) is called 'Understanding Groundwater Resources and Processes'. GNS is developing and testing new scientific techniques that will allow resource managers to assess the volumes, fluxes, quality, usage, and economics of groundwater resources. Techniques for measuring the recharge of groundwater by rainfall are being tried in Pukekohe and Canterbury. The relation between river scour and groundwater recharge from gravel-bed rivers is also being studied. Techniques for dating water are being used to validate a groundwater flow model of the Canterbury region. Isotopic and chemical techniques for monitoring the sustainability of groundwater withdrawal are being researched using the aquifers beneath the Waimea Plains, Nelson, as an example. The economic value of groundwater to agriculture, industry, and households in the Waimea Plains and Christchurch is being estimated. This GNS project is applying economic techniques to quantity and quality problems in groundwater resources. In collaboration with all the regional and unitary authorities in the country, the National Groundwater Monitoring Programme collects land-use and groundwater quality data from 113 wells in New Zealand (see Chapter 4). Samples are taken from wells in unconfined and confined aquifers in representative rock types, from areas with differing land use. The samples are taken quarterly and the data are used for research into key indicators of groundwater quality. A national survey of groundwater pesticide is undertaken every four years, measuring pesticide concentrations in a subset of the wells used for the National Groundwater Monitoring Programme (see Chapter 8).

Groundwater research at Lincoln Ventures Limited, which inherited the water resources staff from N.Z. Agricultural Institute, focusses on two main problems—the protection of groundwater quality and water allocation. The groundwater quality research is based on the premise that processes in both the unsaturated and saturated zones must be understood to manage the relationships between land-use practices and groundwater quality. One study is developing methods for predicting how much nitrogen is leached through the soil as a result of agricultural activities and applying wastes to land. Predicting the fate of contaminants, once they are in the groundwater, is another research project. This may be useful in identifying "risky" land uses that may contaminate water supply bores and springs, so they can be monitored. Research into managing applications of effluent or wastes to land aims to minimise leachate flux, to maximise the re-use of nutrients, and to meet groundwater quality standards. Lincoln Ventures' project on the design and management of bio-remediation systems aims to improve systems for cleaning up soil and groundwater at sites that are already badly contaminated. Lincoln Ventures is studying methods for predicting how aquifers will respond to both natural and controlled water input and output, to determine sustainable allocation limits for aquifers. This will aid in the integrated management of groundwater, surface water, and consumption.

Environmental Science and Research Ltd, which inherited staff from GNS, focuses on determining how contaminants are attenuated in New Zealand groundwater systems—they are developing models to predict their transport and fate. The breakdown of selected pesticides is studied under field conditions, as they pass through a range of New Zealand soils and into the underlying groundwater. The data are used to evaluate pesticide leaching models. The attenuation of groundwater contaminants is being modelled using a range of laboratory columns, field sites, and an artificial aquifer facility. Tracer studies are carried out to study the factors controlling dispersion, non-equilibrium transport and the movement of particulates in groundwater. The movement of pesticides, micro-organisms, organic compounds and heavy metals through the unsaturated zone is being modelled.

LEGISLATION AND GROUNDWATER

Much of the early water legislation in New Zealand was concerned with the water supply problems of regions. For example the Wellington City and Suburban Water Supply Act (1927), which resulted in the formation of the Wellington City and Suburban Water Authority in 1928, was aimed principally at coordinating water supplies in the Wellington region. No specific reference however was made to the management of underground water. Shortly after its enactment the Lower Hutt and Petone Borough Councils withdrew from the Authority in order to develop the Hutt Valley aquifer system for their water supplies.

The Soil Conservation and Rivers Control Act (1941) established Catchment Boards and Catchment Commissions to investigate and manage floods and promote soil conservation. These boards developed most of the flood protection works that we see today. The Waikato Valley Authority was established under the Waikato Valley Authority Act (1956) to manage and develop the Waikato River basin. Several catchment boards included groundwater and irrigation investigations in their activities (e.g. Nelson and Marlborough).

The Underground Water Act (1953) allowed the establishment of Underground Water Authorities to control the drilling and use of aquifers. These Authorities could also pass bylaws to protect groundwater from pollution. Any local authority could petition the Governor-General to set up an authority, and the Minister of Works would then appoint a commission to examine the proposal. Underground Water Authorities came into existence in the Hutt Valley, Franklin County, the Heretaunga Plains, Rotorua Borough, and Onehunga Borough. The establishment of an underground water authority in Christchurch however caused considerable debate up until 1966. The main disagreement was among the North Canterbury Catchment Board, the Christchurch City Council and the urban councils and boroughs, over who should control the authority. These disagreements had not yet been resolved when the Water and Soil Conservation Act 1967 became law. The Water and Soil Conservation Amendment Act 1973 repealed the Underground Water Act 1953, and revoked the Orders in Council establishing the Underground Water Authorities. The functions of the Underground Water Authorities and bylaws were transferred to the regional water boards that now covered all of New Zealand.

The Water and Soil Conservation Act (1967) was administered by the Water and Soil Division of the Ministry of Works. The Act provided for the establishment of regional water boards, which for most regions were incorporated within the established Catchment Boards and Catchment Commissions. The Boards' functions included the issuing of water rights. The Act also specified rights, in relation to natural water and water quality standards, designed to improve water quality in New Zealand. Substantial improvements were made to community water supplies and water and waste treatment schemes, often with the assistance of central government funding for investigation and engineering works.

When the Water and Soil Conservation Act (1967) was passed, Regional Water Boards were established with responsibilities to "exercise the functions, rights, powers, and duties of an Underground Water Authority" where no Underground Water Authority existed under the Underground Water Act 1953. An underground water authority had never been established in Christchurch, for example, so the North Canterbury Catchment Board assumed responsibility "for the conservation, allocation, use, and quality of natural water" from the Conway to the Rakaia rivers in North Canterbury, including the Christchurch artesian system.

Wellington had no Catchment Board or Catchment Commission. In 1973 the Wellington Regional Water Board was formed under the Wellington Regional Water Board Act (1972). The role of the board included the water supply functions of the former Wellington City and Suburban Water Supply Board, the engineering functions of the Hutt River Board, and the groundwater resource management functions of the Underground Water Authority. In February 1976, under Section 67 of the Act, the Hutt Valley Underground Water Authority bylaws were adopted, with a few minor changes, to become the Wellington Regional Water Board Bylaws. One provision of the Water Board Bylaws reads:

> "7.20. No person shall cause, permit or suffer any deleterious, dangerous, harmful, toxic, corrosive, unsightly or offensive substance whether liquid or solid to enter, seep, percolate or infiltrate either directly or indirectly and whether immediately or over a period of time into any underground water in the region whether in its original form or some other form as a result of biological action, chemical action, or by the decomposition of matter or otherwise."

Another two provisions refer to the exclusion of septic tanks within 30 metres of any bore and the prevention of backflow. These provisions, which have been around since the formation of the Underground Water Authority in 1959, may be one of the earliest attempts at legislating groundwater quality protection in New Zealand.

The Auckland Regional Water Board was established in 1973 under the Water and Soil Conservation Act (1967). Prior to this the Water and Soil Conservation Act (1967) was administered in Auckland by the Ministry of Works and Development.

The Resource Management Act (1991) integrated 59 enactments and 19 regulations relating to the environment and amended a further 53 enactments. The Water and Soil Conservation Act (1967) and its amendments were combined with legislation on air quality, geothermal energy, marine farming, town and country planning, noise, and other aspects of the environment to set up a system to promote "sustainable management of natural and physical resources" (Ministry for the Environment 1991). Sustainable management means "managing the use, development, and protection of natural and physical resources in a way, or at a rate, which enables people and communities to provide for their social, economic, and cultural wellbeing..." (Resource Management Act 1991). A hierarchy of standards that people are expected to follow is laid out in the Act. These standards include national environmental standards, national policy statements, regional policy statements, regional plans, and district plans. The Act specifies the process for granting resource consents, including assessment of the effects of resource use, permitted activities, controlled activities and discretionary activities. Water Conservation Orders exist under the Act to "recognise and sustain water bodies (including rivers, lakes, streams, ponds, wetlands, geothermal water or aquifer) of outstanding natural, amenity, or intrinsic value" (Ministry for the Environment 1991). The functions, powers and duties, of central and local government are outlined in the Act. Central government's role is overview and monitoring. Standards can be set by regulation by Central government. Regional government have the primary responsibility for the management of water, soil, air, geothermal resources, and for pollution control. District councils have primary responsibility for land use management. The Act also sets out the provisions of prosecution and fines for offences. Three unitary councils exercise the powers of districts and also administer the Act.

Underground water authorities

In 1953 the Underground Water Act was passed by Parliament "to provide for the control of the tapping, use and pollution of underground water." The Act was in response to a petition from the Hawke's Bay Catchment Board to the government in 1950 that it be granted power to regulate and control the sinking of artesian bores as a means of conserving water. In Napier, Dr J.T. Kingma of the Geological Survey, DSIR, warned the Chamber of Commerce in June 1950 of the damaging effects of deforestation on catchments and the wastefulness of artesian water flowing from hundreds of abandoned bores on the Heretaunga Plains (Dunlop 1992). In December 1955 the Soil Conservation and Rivers Control Council appointed a commission to enquire into the constitution of an underground water area in the provincial district of Hawke's Bay.

The commission recommended the setting up of an underground water authority and in July 1957 the Hawke's Bay Underground Water Authority was established for the Heretaunga Plains. "The Underground Water Authority had limited powers, its main functions being to compile records of existing bores, to issue permits to sink new bores and to persuade owners of leaking bores either to repair them or permanently seal them off. Leaking bores not only wasted water but also contributed to the flow of water in the drains. The repair or sealing of bores reduced the flow into nearby drains. Some of the leakage was caused by the bores having been broken off, in some instances several metres below ground level, during the 1931 earthquake. During prolonged periods of dry weather the Authority was often called upon to request bore owners to limit their taking of water. The approach was made directly to bore owners if the problem affected a small area, or by public notice if the dry conditions were more widespread. On a few occasions after a public notice appeared, a downpour immediately followed. This prompted some people to suggest that such notices may be useful as a method of breaking droughts. Increasing consumption of water and periodic spells of dry weather continued to cause problems. Efforts were made to educate industrial users and irrigators of cropping and orchard land on methods of reducing the quantity of water taken and on the recycling of water. However, the problem continued to cause concern. The Authority was financed from levies made on the constituent local authorities, excluding the Catchment Board. These levies were modest, ranging from $600 for 1958 to 1959 and gradually increasing to $7,200 for 1972 to 1973." (Dunlop 1992).

Other underground water authorities were established in Onehunga Borough (1955), Franklin County (1957), Hutt Valley (1959) and Rotorua Borough (1962). The Hutt Valley Underground Water Authority began regular measurements of artesian wells in the Lower Hutt Valley and undertook geological and hydrogeological investigations. The Authority developed a series of bylaws with provisions to control the use and development of groundwater including: rules on bore construction, permits for usage (and charges), record keeping, sampling, prevention of wastage, leakage between aquifers, construction activities (that might damage the aquifer structure), and the prevention of groundwater contamination.

Catchment Boards and Regional Water Boards

Catchment Boards, established in 1941, and Regional Water Boards, established in 1967, started groundwater investigation projects where groundwater was important to the region. In 1960 the Marlborough Catchment Board investigated the recharge of a sector of the Wairau Plain aquifer by the diversion of water from the Waihopai River into a dry creek bed. A well water level monitoring network that had been established by the Public Works Department was expanded to include wells to monitor the recharge project, and other river diversion and drainage projects. Well water level measurement began at Kaikoura in 1968. The Geological Survey and the Marlborough Catchment Board began a joint investigation of the region's groundwater resources in 1965. During the winter and spring of 1966 some 500 wells on the Wairau Plain were inspected, and the data were recorded to establish the Marlborough water well database (Brown 1972). In the 1970s a network of testbores was drilled on the Wairau Plain for the Marlborough Regional Water Board to assess the hydrogeology. Geological logs of testbores and wells drilled for irrigation water supplies provided the base data for geological maps, and for the stratigraphy, hydrogeology and groundwater resources of the Wairau Plain aquifers (Brown 1981a, 1981b; Rae 1987; Cunliffe 1988). A joint Geological Survey-Marlborough Regional Water Board groundwater investigation in southern Marlborough (Kaikoura) also involved testbore drilling, sampling and geological mapping (Brown 1988). The Marlborough groundwater investigations were to provide the lead for similar joint projects between the Geological Survey and other catchment and regional water boards. Projects with the Northland, East Cape, Hawke's Bay, Nelson and Canterbury Regional Water Boards were completed and the results published. These joint projects were funded from a combination of sources: the DSIR science vote, local catchment board ratings and Ministry of Works and Development operational survey (GA 38) allocations. The last of these joint projects—the Heretaunga Plains groundwater study (Dravid and Brown 1997)—was completed with funding by the Public Good Science Fund administered by the Foundation for Research, Science and Technology and the Hawke's Bay Regional Council.

When the Auckland Regional Water Board began in 1973, groundwater in the region was used principally for stock and domestic use, with some small communities and industries also using groundwater resources. In addition, hot groundwater was used at two resort areas. Interest in groundwater resources grew rapidly during the 1970s as the need for irrigation, particularly for kiwifruit, expanded. The competition for the available groundwater amongst historical and new users stimulated substantial investment in groundwater investigations.

The first systematic documentation of the groundwater resources of the Auckland Region (Tonkin and Taylor 1975) notes that "The groundwater potential of the various geological units can be assessed in general terms but insufficient data are available to accurately assess storage capacity, permeability or safe yield of the rock formations."

The first major study that the Auckland Regional Water Board became involved in was the Franklin District groundwater study. This study had been started by Phil Wharton, a hydrogeologist with the Waikato Valley Authority (Wharton 1974). In 1974 Wayne Russell, of the Auckland Regional Water Board, joined Phil Wharton on the study. A major focus became the Pukekohe Plateau. Market gardens in this area were competing with other well and spring water users for the groundwater moving through the region's basalt volcanic aquifer. Russell (1977) developed a conceptual model of the multiple-basalt aquifers of the Pukekohe plateau, and subsequent studies have updated and modified his model.

The results of this study also prompted the Pukekohe Borough council to drill through the basalt aquifers to intercept shell-bed aquifers. Water from these aquifers was used to dilute the high nitrate concentrations in the groundwater collected in galleries constructed in the upper basalts. The nitrate came from the nitrogenous fertilisers used on the market gardens developed on the rich volcanic soils of the Pukekohe plateau. Investigations of the Franklin district groundwater system are still continuing.

The Auckland Regional Water Board began a study of water resources in the Omaha-Leigh area because water was needed both for irrigation to allow the development of gardens on suitable soils and for community water supplies, in particular for the development of the Omaha Beach resort. There had been some previous work (in Field 1977), but the Water Board's investigation was the first comprehensive study, and it updated the earlier work. The groundwater came principally from fractured Waitemata Group sandstones and siltstones at depths of up to c. 300 metres, and the flow was artesian in low areas. Bores into the Waitemata Group rocks below the Omaha Spit were considered to be at risk from seawater intrusion. The sands of the spit may have a shallow aquifer, but this resource has not been evaluated. Some deep wells had water with elevated boron levels, indicating movement of water from the local basement greywacke rocks into the Waitemata Group rocks.

Regional councils

Regional councils established under the Resource Management Act (1991), took over, and expanded on, the roles of catchment authorities and water boards. There are 12 regional councils, plus four unitary councils in New Zealand: their boundaries are based on catchments and they have the primary responsibility for managing water, soil, and geothermal resources in their regions (Enterprise New Zealand Trust 1997). The responsibility for the mitigation of natural hazards is shared with territorial authorities. Regional councils are responsible for resource management, biosecurity, catchment control, harbour administration, regional civil defence, and regional land transport. The four unitary authorities are responsible for the above, and for community well-being and development, environmental health and safety, infrastructure, recreation, culture, land-use planning, and development control.

Councils must develop the plans and rules for resource use in their area—this allows flexibility and efficiency in managing local resources. The environmental effects of resource use (e.g. on water, soil, and air) can be considered together, and the councils and landowners have more flexibility in dealing with developments than under previous legislation. For example, potential land uses are not prescribed under the Resource Management Act (1991). This is quite a different approach from the Town and Country Planning Act (1977) which the Resource Management Act (1991) replaced. No central agency has had a co-ordinating role in water resources since the repeal of the Water and Soil Conservation Act (1967), and this has caused some problems for resource users who cross the boundaries of regional councils. In addition, regional councils interpret and apply the provisions of the Resource Management Act (1991) in different ways, with the possible result that the requirements and standards for groundwater resource management can vary from one region to another.

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REFERENCES

ALLEY, P.J. 1955: Foundation conditions in the Christchurch Metropolitan area. New Zealand Engineering November 1955: 430-432.

ALLEY, P.J. (Ed.) 1964: Subsurface bores in Christchurch. The Canterbury Branch, New Zealand Institution of Engineers and The Department of Civil Engineering, University of Canterbury, Christchurch.

ANDERSON, J.C. 1916: Jubilee History of South Canterbury. Whitcomb and Tombs Limited, Auckland, New Zealand.

ANON. 1898: Official record of the Otago Jubilee Industrial Exhibition 1898 and Otago Agricultural and Pastoral Societies Annual report.

ATKINSON, J.D. 1976: DSIR's first fifty years. Information series 115. Department of Scientific and Industrial Research, Wellington, New Zealand. 220p.

BEATTIE, J.H. 1994: Traditional lifeways of the southern Maori (edited by Athol Anderson). University of Otago Press, Dunedin, New Zealand.

BISHOP, D.G. 1979: Sheet S135, Ranfurly. "Geological Map of New Zealand 1:63360". New Zealand Department of Scientific and Industrial Research, Wellington.

BOWDEN, M.J.; HARRIS, E.V.R.; THORPE, H.R.; WILSON, D.D. 1983: Commissioning and maintaining a water well in New Zealand: a guide to good practice. National Water and Soil Conservation Organisation, Wellington. Water and Soil miscellaneous publication 61.

BOWDEN, M.J.; TALBOT J.T.; WEEBER, J.H.; FREEMAN, M.C.; MASON, C.R.; WILSON, D.D. 1986: The Christchurch artesian aquifers. North Canterbury Catchment Board and Regional Water Board, Christchurch.

BROADBENT, M.; CALLANDER, P.F. 1991: A resistivity survey near Waimakariri River, Canterbury Plains, to improve understanding of local groundwater flow and of the capabilities of the survey method. New Zealand Journal of Geology and Geophysics 34(4): 441-453.

BROWN, L.J. 1972: A preliminary account of the groundwater resources of the Wairau Plains, Marlborough. New Zealand Geological Survey Report No. 60, Lower Hutt New Zealand.

BROWN, L.J. 1977: 6. Canterbury – Marlborough coal region. 6.5 Picton coalfield. In: New Zealand Geological Survey report 38 part C: Coal reserves (unpublished).

BROWN, L.J. 1981a: Late Quaternary geology of Wairau Plain, Marlborough New Zealand. New Zealand Journal of Geology and Geophysics 24: 477-490.

BROWN, L.J. 1981b: Water well data Northern Marlborough, Part Sheet P28 Wairau Plain (Geology and water wells), 1:25000. New Zealand Geological Survey Report 93, Lower Hutt, New Zealand.

BROWN, L.J. 1988: Water well data, geohydrology and Quaternary geology, Southern Marlborough. New Zealand Geological Survey Report No. 111, Lower Hutt, New Zealand.

BROWN, L.J. 1993: Heretaunga Plains groundwater resource investigations – Flaxmere and Tollemache Orchard exploratory water wells. Institute of Geological and Nuclear Sciences client report.

BROWN, L.J. 1998a: Bexley groundwater testbore results. Institute of Geological and Nuclear Sciences client report 62698D.12, Canterbury Regional Council Report U98/26.

BROWN, L.J. 1998b: Contribution to "Water Divining: a case for objective tests." Water and Wastes in New Zealand, 102: 14-22, September 1998.

BROWN, L.J.; GIBBS, B.R. 1996: Heretaunga Plains groundwater resource investigations – Awatoto exploratory water well. Institute of Geological and Nuclear Sciences client report.

BROWN, L.J.; HOMER, D.L.; PETTY, D.R. 1987: Thermal and mineral water springs in the middle reaches of the Wanganui River. New Zealand Geological Survey Record 18:13-19.

BROWN, L.J.; JONES, A. 2000: Moera Gravel aquifer investigation bore. Wellington Regional Council publication number WRC/RINV-T-00/30.

BROWN, L.J.; WEEBER, J.H. 1992: Geology of the Christchurch urban area. Scale 1:25 000. Institute of Geological & Nuclear Sciences geological map 1. 1 sheet + 104p. Institute of Geological & Nuclear Sciences Limited, Lower Hutt, New Zealand.

BROWN, L.J.; WEEBER, J.H. 1994: Hydrogeological implications of geology at the boundary of Banks Peninsula volcanic rock aquifers and Canterbury Plains fluvial gravel aquifers. New Zealand Journal of Geology and Geophysics 37: 181-193

BROWN, L.J.; WILSON, D.D. 1988: Stratigraphy of the late Quaternary deposits of the northern Canterbury Plains, New Zealand. New Zealand Journal of Geology and Geophysics 31: 305-335.

BURTON, P. 1965: The New Zealand Geological Survey 1865 – 1965. New Zealand Department of Scientific and Industrial Research Information Series 52.

CALLAGHAN, F.R. 1933: The Hawke's Bay earthquake. New Zealand Journal of Science and Technology 15(1): 3-38.

CARTER, H. 1993: Utility and beauty. New Zealand Historic Places Trust 42: 14-15, July 1993.

CHESTER, P. 1988: The history and archaeology of Lambton Quay 76-84, Wellington. Site R27/84, (2nd Edition). Consultants report for Department of Conservation.

CHILTON, C. 1881: On some subterranean Crustacea. Transactions of the New Zealand Institute 13: 174-180.

CHILTON, C. 1924: The Christchurch Artesians and the City Water Supply. The Lyttelton Times Co. Ltd., Christchurch, New Zealand.

CHITTENDEN, E.T.; HODGSON, S.; DODSON, K.J. 1966: Soils and agriculture of Waimea County, New Zealand. New Zealand Soil Bureau Bulletin 30.

Christchurch City Council 1928: Christchurch City Council Diamond Jubilee. Sixty Years' Progress 1868-1928. Official Souvenir.

Christie, A.B.; Bishop, D.G.; Doole, M.H.; Morrison, A.D.; Field, B.D.; Brown, L.J. 1994: Sheet QM399 Waimate. Geological Resource Map of New Zealand. Institute of Geological and Nuclear Sciences science report 94/17.

Cyclopedia of New Zealand 1903: V3 p 697.

Cyclopedia of New Zealand 1905: V4, p 300

Collins, B.W. 1948: Ground water at Timaru. New Zealand Geological Survey Hydrological Report 11. Department of Scientific and Industrial Research, Christchurch, New Zealand.

Collins, B.W. 1950: Conservation and protection of underground water in New Zealand. Proceedings of First International Water Supply Association Congress, Amsterdam. pp 652-664.

Collins, B.W. 1955a: Fluctuations of ground-water levels in New Zealand and their significance. Association of International Hydrology Publication No. 37(2): 25-31.

Collins, B.W. 1955b: The occurrence and utilization of ground water in New Zealand. Association of International Hydrology Publication No. 37(2): 295-307.

Collins, B.W. 1956: Underground water supplies for irrigation. Lincoln College Farmers' Conference 1956.

Corkill, F.M. 1932: Invercargill water supply. Proceedings of the New Zealand Society of Civil Engineers 18: 230-262.

Cox, J.E. 1978: Soils and agriculture of part Paparua County, Canterbury, New Zealand. New Zealand Soil Bureau Bulletin 34.

Cox, S.H. 1884: On the probability of artesian water at Motueka. New Zealand Geological Survey report of geological explorations 1883-84 16: 87-88.

Crosby, C.J. 1978: Putting numbers on wells. Ministry of Agriculture and Fisheries, Christchurch, New Zealand.

Cunliffe, J.J. 1988: Water and soil resources of the Wairau. Water Resources, Volume Two, Groundwater. Marlborough Catchment and Regional Water Board, Blenheim.

Cuthbertson, J.R. 1882: On a source of water supply for Invercargill. Transactions of the New Zealand Institute 14: 121-122.

Darton, N.H. 1901: Preliminary description of the geology and water resources of the southern half of the Black Hills and adjoining regions in South Dakota and Wyoming. U.S. Geological Survey 21st Annual Report, pt. IV: 489-599.

Darton, N.H. 1905: Preliminary report on the geology and underground water resources of the central Great Plains. U.S. Geological Survey Professional Paper 32, 433p.

Department of Scientific and Industrial Research 1939: Land utilization report of the Heretaunga Plains. Department of Scientific and Industrial Research Bulletin 70.

Department of Scientific and Industrial Research Annual Reports: 1946, 1947, 1952.

Dicker, M.J.I.; Fenemor, A.D.; Johnston, M.R. 1992: Geology and Groundwater Resources of the Waimea Plains, Nelson. New Zealand Geological Bulletin 106, DSIR, Lower Hutt.

Donaldson, I.G.; Campbell, D.G. 1977: Groundwaters of the Hutt Valley-Port Nicholson alluvial basin - a resource evaluation. New Zealand Department of Scientific and Industrial Research Information Series No. 124. 78p.

Dobson, A.D. 1920: Notes upon the artesian water supply in Christchurch. Proceedings of the New Zealand Society of Civil Engineers 6: 166-168.

Downes, T.W. 1923: History of and guide to the Wanganui River (2nd Edition) Wanganui. Wanganui Herald Newspaper Company Limited.

Dravid, P.N.; Brown, L.J. 1997: Heretaunga Plains groundwater study. Hawke's Bay Regional Council, Napier, & Institute of Geology and Nuclear Sciences Ltd, Lower Hutt.

Dunlop, J.D. 1992: Catchment. A history of the Hawke's Bay Catchment Board and Regional Water Board. Hawke's Bay Regional Council, Napier. 84p.

Enterprise New Zealand Trust 1997: Local government in New Zealand. 40p.

Environment Canterbury 2000: Watering Christchurch. The story of well drilling and water supply in Christchurch. 25p.

Fenemor, A.D. 1988: A three dimensional model for management of the Waimea Plains aquifers, Nelson. Publication no.18 of the Hydrology Centre, DSIR, Christchurch. 133p.

Fenemor, A.D. 1989: Groundwater modelling as a tool for water management: Waimea Plains, Nelson. Journal of Hydrology (New Zealand) 28(1): 17-31.

Ferrar, H.T. 1929: The soils of irrigation areas in Otago central. New Zealand Geological Survey Bulletin 33.

Field, A.B. 1977: Omaha Leigh Water Resources Study - A Preliminary Assessment and Interim Water Management Plan. Auckland Regional Water Board Technical Publication No. 4.

Field, B.D.; Browne, G.H. 1989: Cretaceous and Cenozoic sedimentary basins and geological evolution of the Canterbury Region, South Island, New Zealand. New Zealand Geological Survey basin studies 2.

Firth, C.W. 1967: A century of water supply for Auckland, New Zealand. Auckland Regional Authority. 76p

Fleming, C.A. 1953: The geology of the Wanganui Subdivision. New Zealand Geological Survey Bulletin 52.

Freestone, H.J. 1985: Obituary: Mr E. J. Speight. Journal of Hydrology (NZ) 24(1): 47.

Gair, H.S. 1961: Drillhole evidence of the Pliocene - Peistocene boundary at Timaru, South Canterbury. New Zealand. Journal of Geology and Geophysics 4: 89-97.

Gage, M. 1945: The Tertiary and Quaternary geology of Ross, Westland. Transactions of Royal Society of New Zealand 75(2): 138-159.

Gage, M. 1958: Late Pleistocene glaciations of the Waimakariri Valley, Canterbury, New Zealand. New Zealand Journal of Geology and Geophysics 1: 123-155.

Gage, M.; Suggate, R.P. 1958: Glacial chronology of the New Zealand Pleistocene. Geological Society of America Bulletin 69(5): 589-598.

Gibbs, H.S.; Raeside, J.D.; Dixon, J.K.; Metson, A.J. 1945: Soil erosion in the High Country of the South Island, New Zealand. Department of Scientific and Industrial Research Bulletin 92.

Goodall, J. 1874: On the probability of a water supply being obtained for the City of Auckland from Mount Eden. Transactions of the New Zealand Institute 6: 35- 40.

GORDON, H.A. 1893: Artesian well boring, Maniototo Plains. Appendix to Journal of House of Representatives, New Zealand C-3: 132.

GRANGE, L.I. 1935a: Soils of Ashburton County in relation to irrigation. 9th Annual Report of the Department of Scientific and Industrial Research: 56-68.

GRANGE, L.I. 1935b: Field-work on soils of Levels Plain. 9th Annual Report of the Department of Scientific and Industrial Research: 46-47.

GRANT-TAYLOR, T.L. 1967: Groundwater in New Zealand. New Zealand Geological Survey Report 24.

HAAST, J. 1864: Report on the formation of the Canterbury Plains. The Press, Christchurch, New Zealand.

HAAST, J. 1879: Geology of the Provinces of Canterbury and Westland, New Zealand. A report comprising the results of official explorations. Lyttelton Times, Christchurch, New Zealand.

HARRINGTON, H.J. 1952: Geology of Naseby and Kyeburn Formation, Central Otago. Unpublished New Zealand Geological Survey report.

HAY, R.F. 1946: Helensville hot Springs Area. Unpublished Geological Survey Report, DSIR April 1946.

HEALY, J. 1955: Hot Water Resources, Parakai, Helensville. Unpublished Geological Survey Report, DSIR, October 1955.

HEALY, J. 1957a: Helensville Hot Springs. Unpublished Geological Survey Report, DSIR, September 1957.

HEALY, J. 1957b: Tests on Hot Water Wells at Parakai Helensville. Unpublished Geological Survey Report, DSIR, 1957.

HENDERSON, J. 1937: Underground water, Wellington Hospital. New Zealand Geological Survey 31st Annual Report.

HENDERSON, J. 1942: Underground water in New Zealand. New Zealand Journal of Science and Technology 13(3B): 97B-112B.

HENDERSON, J.; GRANGE. L.I. 1926: The geology of the Huntly - Kawhia subdivision, Pirongia and Hauraki divisions. New Zealand Geological Survey Bulletin 28.

HENRY, J.D. 1911: Oil fields of New Zealand with some critical notes on the colonial oil situation of to-day. Bradbury, Agnew & Co. Ltd., London.

HERBERT, A.S. 1921: The hot springs of New Zealand. Lewis, London.

HILGENDORF, M.A. 1912: Fluctuations in the level of the water in some artesian wells in the Christchurch area. Transactions of the New Zealand Institute 44: 142-159.

HILGENDORF, M.A. 1917: Fluctuations in the water-level of some artesian wells in the Christchurch area. Transactions of the New Zealand Institute 49: 491-493.

HILGENDORF M.A. 1926: Artesian wells of the Christchurch area. Transactions of the New Zealand Institute 56: 369-382.

HILL, H. 1887: On the artesian well system of Hawke's Bay. Transactions of the New Zealand Institute 20: 282-293.

HILL, H. 1889: Artesian wells: No.2. Transactions of the New Zealand Institute 22: 429-438.

HILL, H. 1893a: Artesian - water prospects at Wanganui, New Zealand. Transactions of the New Zealand Institute 25: 343-347.

HILL, H. 1893b: Artesian wells, Wanganui, New Zealand. Transactions of the New Zealand Institute 25: 348-350.

HILL, H. 1893c: Discovery of artesian water supply, Ruataniwha Plain. Transactions of the New Zealand Institute 25: 350-353.

HILL, H. 1897: On artesian water prospects in Poverty Bay and Gisborne. Transactions of the New Zealand Institute 29: 567-571.

HILL, H. 1905: The artesian water basins of the Heretaunga Plain, Hawke's Bay. Transactions of the New Zealand Institute 37: 431-444.

HILL, H. 1923: Water conservation and the Hawke's Bay artesian systems. Transactions of the New Zealand Institute 54: 143-147.

HOLMES, R.W. 1916: Artesian trial bore, Westshore, Napier. Proceedings of the New Zealand Society of Civil Engineers 2: 218-222.

HOLMES, R.W. 1917: Notes on an artesian trial bore Westshore, Napier. Transactions of the New Zealand Institute 49: 509-512.

HUBER, D.G. 1973: Water resource development for expanded irrigated agriculture on the Canterbury Plains. Lincoln Papers in Water Resources No.11, New Zealand Agricultural Engineering Institute, Lincoln College, Canterbury, New Zealand.

HUNT, B.W.; WILSON, D.D. 1974: Graphical calculation of aquifer transmissivities in northern Canterbury, New Zealand. Journal of Hydrology (N.Z.) 13(2): 66-80.

HUTTON, F.W. 1871: On the artesian wells near Napier. Transactions of the New Zealand Institute 3: 251.

HUTTON, F.W. 1895: On the behaviour of two artesian wells at the Canterbury Museum. Transactions of the New Zealand Institute 28: 654-664.

HUTTON, F.W.; ULRICH, G.H.F. 1875: Report on the geology and goldfields of Otago. Mills Dick, Dunedin.

KUSCHEL, G. 1975: Biogeography and ecology in New Zealand. Dr. W. Junk, Publishers, The Hague.

LEAHY, P.P.; LYTTLE, P.T. 1998: The re-emerging and critical role of geologic understanding in hydrogeology. In van Brahana, J. (ed.); Gambling with groundwater: physical, chemical and biological aspects of aquifer-stream interactions. Proceedings of XXVII Congress of International Association of Hydrogeologists, Las Vegas, Nevada, U.S.A. 19-24.

LEWIS, M.A. 1980: 'Artesian bore' - note supplied by Mr A.M. Lewis of Thomson and Lewis Co. Ltd, soft drink manufacturers.

MANDEL, S. 1974: The groundwater resources of the Canterbury Plains. Lincoln Papers in Water Resources No.12, New Zealand Agricultural Engineering Institute, Lincoln College, Canterbury, New Zealand.

MARCHBANKS, J. 1899: On the artesian wells at Longburn. Transactions of the New Zealand Institute 31: 551-554.

MCDOWALL, F.H. 1931: Treatment and disposal of dairy waste waters. New Zealand Department of Scientific and Industrial Research Bulletin 27.

MCKELLAR, I.C.; COLLINS, B.W. 1951: Self-potential logs of two Canterbury water wells. New Zealand Journal of Science and Technology, Section B, 32: (6)1-(6)4.

MCKELLAR, I.C. 1952: Performance of a Bristol's recording pressure gauge used in making ground water level measurements. Presentation at New Zealand Geological Survey Conference, Wellington, May 1952. 2p.

MCLEAN, F.S. 1964: Challenge of health - a history of public health in New Zealand. Government Printer, Wellington, New Zealand.

McLellan, C.H. 1988: Re-evaluation of basement contour beneath the Heretaunga Plains recharge area. Unpublished report, Hawke's Bay Catchment Board, Napier.

McLeod, D.A. 1882: Scheme for supplying the City of Christchurch and suburbs with water from the Waimakariri, to which is appended details as to general water supply and comparative merits of gravitational & pumping schemes. The "Press" Company Limited, Christchurch, New Zealand.

Meinzer, O.E. 1923: The occurrence of groundwater in the United States. United States Geological Survey water supply paper 485. Government Printing Office, Washington D.C.

Melhuish, A. 1993: Seismic reflection investigations near Tollemache Road and St Georges Road, Hastings. Institute of Geological and Nuclear Sciences Limited, Wellington. Client Report No. 1993/71.

Mendenhall, W.C. 1905: Development of underground waters in the eastern coastal- plain region of southern California. U.S. Geological Survey Water-supply Paper 137.

Ministry for the Environment 1991. Resource Management - Guide to the Act. Ministry for the Environment, Wellington, 38p.

Modriniak, N.; Marsden, E. 1938: Experiments in Geophysical Survey in New Zealand. New Zealand Department of Scientific and Industrial Research Memoir 4.

Mollet, T.A. 1881: Description of an artesian well sunk at Avonside. Transactions of the New Zealand Institute 13: 410- 412.

Morgan, P.G. 1916: Water supply for Kaikoura township. New Zealand Geological Survey 10th annual report.

Nelson, C.N.; Hendy, C.H.; Cuthbertson, A.M.; Jarrett, G.R. 1986: Late Quaternary carbonate and isotope stratigraphy, subantarctic site 594, southwest Pacific. In: Kennett, J.P.; von der Borch, C.C. et al. (editors). Initial reports of the deep sea drilling project volume XC: 1425-1436.

New Zealand Antique Bottle Collector 1977: 1(4) August 1977.

Oborn, L.E. 1955: The hydro-geology of the Canterbury Plains between the Rakaia and Ashley Rivers. MSc thesis, School of Mines, University of Otago, Dunedin.

Oborn, L.E. 1960: The incompetent and elastic nature of the Christchurch artesian system. New Zealand Journal of Geology and Geophysics 3: 81-97.

Oborn, L.E. 1962: Water resources. In proceedings of the Halswell conference "Sprinkler Irrigation". Department of Agriculture, Halswell, Canterbury. July 1962.

Ongley, M. 1924: The divining rod. New Zealand Journal of Science and Technology 7: 227-232.

Ongley, P.A. 1947: New Zealand diviners. New Zealand Journal of Science and Technology 30(1): 38-54.

Page, S. 1901: Notes on an artesian-well system at the base of the Port Hills. Transactions of the New Zealand Institute 33: 335-336.

Petty, D.R. 1971: Water supply test drillhole at Waitemata Brewery. Unpublished New Zealand Geological Survey Report.

Petty, D.R.; Brown, L.J.; Homer, D.L. 1987: Mineral and thermal waters and springs of North Auckland. New Zealand Geological Survey, Lower Hutt, New Zealand.

Popple, G.L. 1953: Malvern County. A Centennial History. Malvern County Council, Darfield, New Zealand.

Pullar, W.A. 1962: Soils and agriculture of Gisborne Plains. New Zealand Soil Bureau Bulletin 20.

Rae, S.N. (Ed.) 1987: Water and soil resources of the Wairau. Water Resources Volume 1. Marlborough Catchment and Regional Water Board, Blenheim.

Reed, A.H.; Brougham, A.E. 1978: The concise Maori handbook. A.H. & A.W. Reed, Wellington.

Risk, G.F. 1974: Papers on geophysical investigations of groundwater on the Canterbury Plains. Geophysics Division Report No. 94. Department of Scientific and Industrial Research.

Rockel, I. 1986: Taking the Waters. Early spas in New Zealand. Government Printing Office Publishing. 195p.

Roche, W.J. 1915: Raising of water from artesian wells, with special reference to the water supply of the Lower Hutt Borough. Proceedings of the New Zealand Society of Civil Engineers 1: 92-107.

Roche, M. 1994: Land and water. Historical Branch of Internal Affairs, Wellington, New Zealand. 219p.

Russell, W.J. 1976: Aspects of the Geology and Hydrology of the Western Springs Watershed, Auckland. Unpublished MSc Thesis, University of Auckland.

Russell, W.J. 1977: A Study of the Water Resources in Franklin County - A Progress Report on the Joint Water Resources survey of the Central Franklin County for the Auckland Regional Water Board and the Waikato Valley Authority.

Russell, W.J. 1980: Waiwera Water resource Survey – Preliminary Water Allocation/Management Plan. Auckland Regional Water Board Technical Publication No.17.

Russell, W.J. 1981: Parakai Water Resource and Management Proposals. Auckland Regional Water Board Technical Publication No. 20.

Schminke, H.K. 1978: *Notobathynella longipes* sp.n. and new records of other Bathynellacea (Crustacea, Syncarida) from New Zealand. New Zealand Journal of Marine and Freshwater Research 12: 457-462.

Schofield, J.C. 1972: Ground Water of Hamilton Lowland. New Zealand Geological Survey Bulletin 89.

Scott, D.M.; Thorpe, H.R. 1983: Ground water resources between the Rakaia and Ashburton Rivers, Canterbury, New Zealand. Papers of the international conference on groundwater and man. Sydney, Australia, December 1983. Vol. 3:245-254.

Scott, D.M.; Thorpe, H.R. 1986: Ground water resources between the Rakaia and Ashburton Rivers. Publication No. 6 of the MWD Hydrology Centre, Christchurch 105p.

Sherrard, J.M. 1966: Kaikoura – a history of the district. Kaikoura County Council, Kaikoura, 373p.

Skey, W. 1878a: On certain of the mineral waters of New Zealand. Transactions of the New Zealand Institute 10: 423-448.

Skey, W. 1878b: On the solubility of calcicarbonate in solutions of the alkaline chlorides. Transactions of the New Zealand Institute 10: 449-452.

Slichter, C.S. 1899: Theoretical investigations of the motion of ground waters. U.S. Geological Survey 19th Annual Report, pt 2: 295-384.

SPEIGHT, R. 1911: A preliminary account of the geological features of the Christchurch artesian area. Transactions of the New Zealand Institute 43: 420-436.

SPEIGHT, R. 1926: Results given by wells at Christchurch pumping station, Beckenham. Transactions of the New Zealand Institute 56: 363-368.

STEVENS, G.R. 1956a: Stratigraphy of the Hutt Valley, New Zealand. New Zealand Journal of Science and Technology B38(3): 201-235.

STEVENS, G.R. 1956b: Hutt Valley artesian system. Journal of Science and Technology B38(3): 149-156.

STEWART, J.T. 1902: Note on an artesian well at Aramoho. Transactions of the New Zealand Institute 34: 451-452.

SUGGATE, R.P. 1958: Late Quaternary deposits of the Christchurch Metropolitan area. New Zealand Journal of Geology and Geophysics 1: 103-122.

SUGGATE, R.P. 1968: Postglacial sea-level rise in the Christchurch Metropolitan area, New Zealand. Geologie en Mijnbouw 47(4): 291-297.

SYMES, L.P. 1917: Note on the fluctuation of water-level in a Christchurch artesian well. Transactions of the New Zealand Institute 49: 493-495.

TAYLOR, N.H. 1935: Water-supplies of farms and dairy factories in Hamilton basin and Hauraki Lowland. New Zealand Department of Scientific and Industrial Research Bulletin 48.

TE PUNGA, M.T. 1952: The geology of the Rangitikei Valley. New Zealand Department of Scientific and Industrial Research Geological Memoir 8.

THEIS, C.V. 1935: The relation between lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage. Transactions of American Geophysical Union 16: 519-524.

THOMSON, J.T. 1859: Report on the water supply of Dunedin. Otago Provincial Government Gazette 3(91): 283-285.

THORPE, H.R. 1981: Movement of contaminants into and through the Heretaunga Plains aquifers Hawke's Bay, New Zealand. Proceedings of the groundwater pollution conference, Perth, Western Australia, February 1979. pp225-241.

THORPE, H.R.; BURDEN, R.J.; SCOTT, D.M. 1982: Potential for contamination of the Heretaunga Plains aquifers. Water and Soil Technical Publication No. 24. 149p. Water and Soil Division, Ministry of Works and Development for the National Water and Soil Conservation Organisation.

THORPE, H.R; SCOTT, D.M. 1979: Groundwater - state of the art in New Zealand. Physical Hydrology - New Zealand Experience, New Zealand Hydrological Society (Inc) Toebes Memorial Volume: 84-96.

TONKIN AND TAYLOR 1975: Preliminary Survey of Water Resources. Auckland Regional Water Board.

VOGT, E.Z.; HYMAN, R. 1959: Water Witching USA. University of Chicago Press. 260p.

WARD, W.T.; HARRIS, C.S.; SCHAPPER, H.P. 1964: Soils and agriculture of Ellesmere County, Canterbury, New Zealand. New Zealand Soil Bureau Bulletin 21.

WEBER, 1868: Introduction of artesian wells into Hawke's Bay. Report of Provincial Engineer to Hawke's Bay Provincial Council.

WEEBER, J.H. 1995: An inexhaustable supply. Australasian Drilling 14(1): 37-39, 14(2): 36-37, and 14(3): 49-52.

WELLMAN, H.W.; WILLETT, R.W. 1942a: The Geology of the West Coast from Abut Head to Milford Sound - Part 1. Transactions of Royal Society of New Zealand 71(4): 282-306.

WELLMAN, H.W.; WILLETT, R.W. 1942b: The Geology of the West Coast from Abut Head to Milford Sound - Part 2. Glaciation. Transactions of Royal Society of New Zealand 72(3): 199-219.

WHARTON, P. 1974: Progress Report on the Franklin Underground Water Study. Unpublished report by the Waikato Valley Authority.

WHITE, P.A. 1985: Handbook on hydrogeological applications of earth resistivity measurements. Water and Soil Publication No. 90. Water and Soil Directorate, Ministry of Works and Development, New Zealand, 41p.

WILLIAMS, E.A. 1920: Artesian water supply of Napier. Proceedings of the New Zealand Society of Civil Engineers 6: 170-186.

WILLIAMSON, J.H. 1939: The geology of the Naseby Subdivision, Central Otago. New Zealand Geological Survey Bulletin 39.

WILSON, D.D. 1976: Hydrogeology of Metropolitan Christchurch. Journal of Hydrology (NZ) 15: 101-120.

WOOD, B.L. 1960: To examine the possibilities of artesian water on the farm of J. L. Falconer, Puketoi. Unpublished New Zealand Geological Survey Hydrological Report.

WOOD, J. 1917: Results obtained from artesian well bores, Oakleigh near Whangarei. Proceedings of the New Zealand Society of Civil Engineers 3: 216-219.

WOODFORD, C. 1996: Water for the Nelson and Marlborough areas of New Zealand. Australasian Drilling, September-October 1996, p69.

3

Groundwater Resources in New Zealand

PAUL A. WHITE

INTRODUCTION

A large portion of New Zealand's total water storage is in its groundwater resource – Toebes (1972) estimates 80%, or $1.7 \times 10^{12} m^3$, of the nation's water is held as groundwater. This water is an important water source for agriculture, industry, public water supply and recreation (see Chapters 2, 10, and 12 to 26). Groundwater, however, is not available everywhere because of the variety of geological environments where aquifers have formed and the structural complexity of geological units containing aquifers. Groundwater is scarce in some areas which has led to concerns about the long-term sustainability of the resource.

This chapter reviews the regional uses of groundwater for agriculture, industry, public water supply, and recreation. The uses of geothermal water for power generation and tourism are also discussed because they represent a significant use of groundwater. The locations of New Zealand aquifers are reviewed to place these systems in a geological context. Examples of aquifers in sedimentary, volcanic, and metamorphic lithologies illustrate the variety of geological environments that are used for water supply in New Zealand. These examples also represent differing tectonic and paleoclimatic histories in New Zealand. Tectonic and paleoclimatic histories are summarised to illustrate two fundamental causes of complex aquifer structure.

This chapter also reviews the concept of safe yield of an aquifer system, and summarises methologies used in New Zealand to estimate safe yield and the management needs for these estimates. The importance of determining the economic value of groundwater is demonstrated through an example from the Waimea Plains in Nelson. The aim of present groundwater management practise is to manage the resource sustainably, and as such the concept of sustainability is defined with an example of modelling the sustainability of an aquifer.

GROUNDWATER USE

Groundwater is used by agriculture for irrigation; by industry for washing, processing and bottled water; by communities for public water supply, and for irrigation of parks and gardens; and by tourists for recreation and adventure. New Zealand's thermal springs are used by bathers throughout the country and high temperature-volcanic geothermal systems are used for power generation and heating.

Groundwater allocation in New Zealand is approximately 30% (Robb 2000) of total consumptive water allocation (Table 3.1). This figure does not include individual domestic supplies and stock-water systems, of which there are thousands, because regional councils do not require consents for these groundwater users. Non-consumptive uses such as cooling and hydroelectric power are not included in the data. Allocations by Nelson City Council and the West Coast Regional Council are not included in the survey of water allocation. However, allocation of groundwater use in these two regions is not large (Chapter 21 and Chapter 24) The largest total volumetric allocation of groundwater is in Canterbury. Groundwater allocation, as a percentage of total allocation is lowest in Northland (3%) and highest in Marlborough (71%). Irrigation, with 74% of the total groundwater allocation, has the greatest demand for groundwater. Community water systems are allocated an average of 17% of the total allocation. The Bay of Plenty, Manawatu-Wanganui, Wellington, and Southland, have a groundwater allocation to community water schemes that is 40% or more

White P.A. 2001: Groundwater Resources in New Zealand. *In* Groundwaters of New Zealand, M.R. Rosen and P.A. White *(eds)*. New Zealand Hydrological Society Inc., Wellington. p45-75.

Table 3.1 *Total water allocation and groundwater allocation by region (Robb 2000).*

Region	Total consumptive water allocation ($m^3 s^{-1}$)	Groundwater allocation ($m^3 s^{-1}$)	% of groundwater allocation for:		
			Irrigation	industrial	community
Northland	7.9	0.3	64	18	18
Auckland	8.1	2.8	43	19	38
Waikato	10.3	4.0	13	59	28
Bay of Plenty	8.9	2.6	57	3	40
Gisborne	1.4	0.4	91	0	9
Hawke's Bay	16.8	11.3	66	15	19
Taranaki	3.4	0.1	25	50	25
Manawatu-Wanganui	5.2	2.9	32	26	41
Wellington	9.8	4.6	51	6	43
Tasman	6.7	4.2	85	5	10
Marlborough	8.2	5.8	75	15	10
Canterbury	249.8	82.4	85	3	12
Otago	90.1	4.9	33	33	33
Southland	2.4	0.6	20	28	52
TOTAL	428.9	126.9	74	9	17

of the total groundwater allocation. The groundwater allocation to industry is greater than, or equal to, 50% of total allocation in Waikato and Taranaki.

Groundwater is an important source of drinking water. An estimated 26% of the New Zealand population have groundwater as their sole source of drinking water. (Chapter 10) Cities that are totally dependent on groundwater include: Wanganui, Napier, Hastings, Lower Hutt and Christchurch (Thorpe 1992). A further 25% of the population drink water that is sourced from both groundwater and surface water (Chapter 10).

Water use is typically less than the allocation. Water allocation from the Lower Confined Aquifer, Nelson, is set at a maximum of

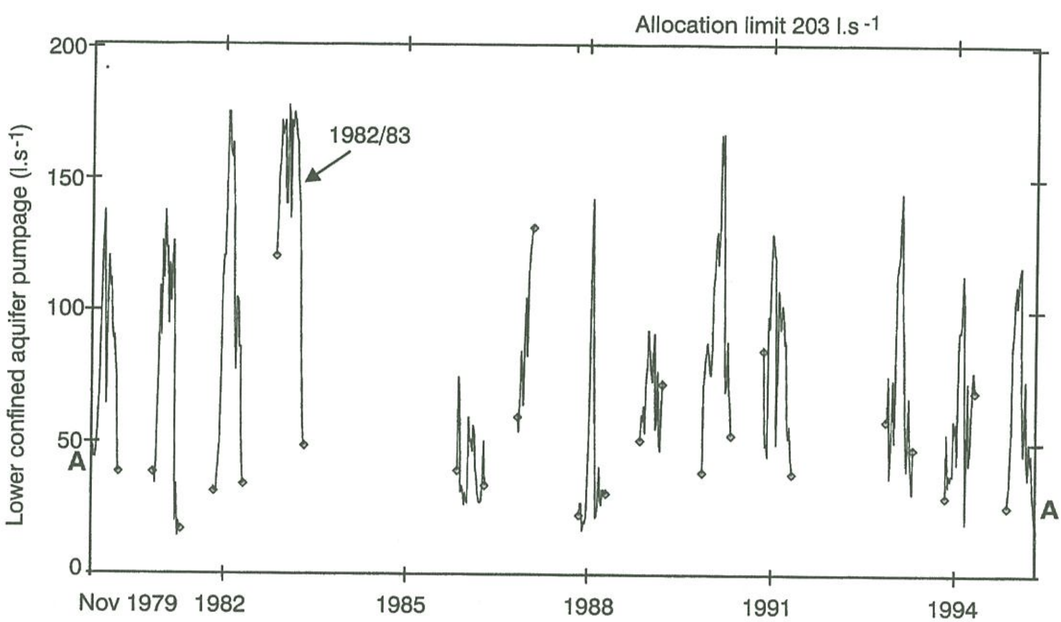


Figure 3.1 *Groundwater abstractions from the Lower Confined Aquifer, Nelson.*

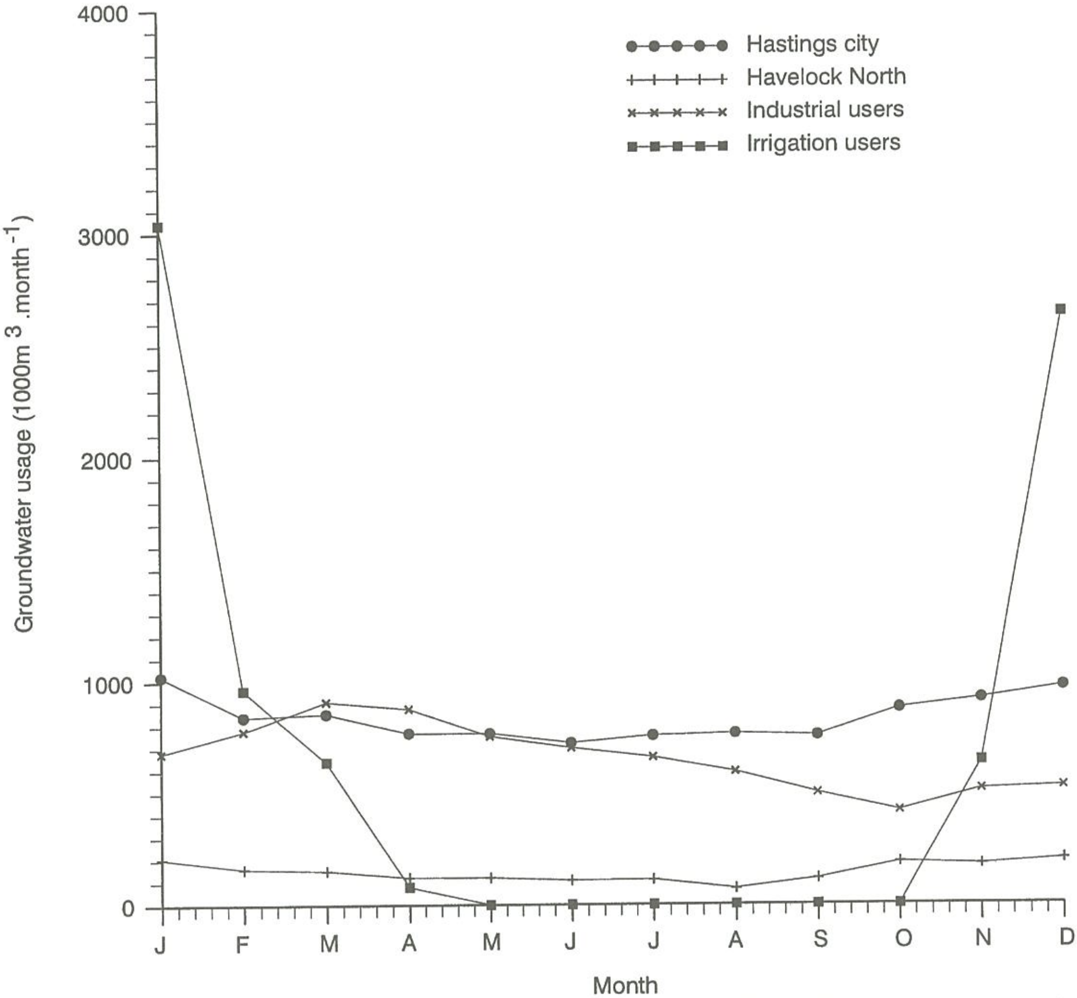


Figure 3.2 *Estimated irrigation, industrial and community use of groundwater in, and near, the unconfined aquifer, Heretaunga Plains (Dravid and Brown 1997).*

203 L s^{-1} (Tasman District Council 1991). Groundwater usage from the Lower Confined Aquifer is for irrigation and town supply. Recorded water abstraction from the aquifer (Fig. 3.1) was greatest during the 1982/83 drought (White 1997a) and usage was less than the allocation limit. Usage of the resource during the irrigation seasons between 1985 and 1995 averaged 68 L s^{-1} (White 1997b).

Irrigation typically reaches peak usage in December and January (Fig. 3.2). Community water use of groundwater commonly reaches a maximum in summer when residents are watering their gardens. Use of water by industry is also seasonal and is dictated by the timing of crop harvests in the crop-processing industries. The seasonal variation of groundwater use by irrigation is significantly greater than the seasonal variation of use by domestic and industrial users and total groundwater usage is typically greater in summer because of irrigation by agricultural and domestic users. The maximum requirement for groundwater over summer occurs when groundwater recharge is at a seasonal low. Therefore the links between natural recharge, usage, and groundwater level are of key interest when setting allocation limits.

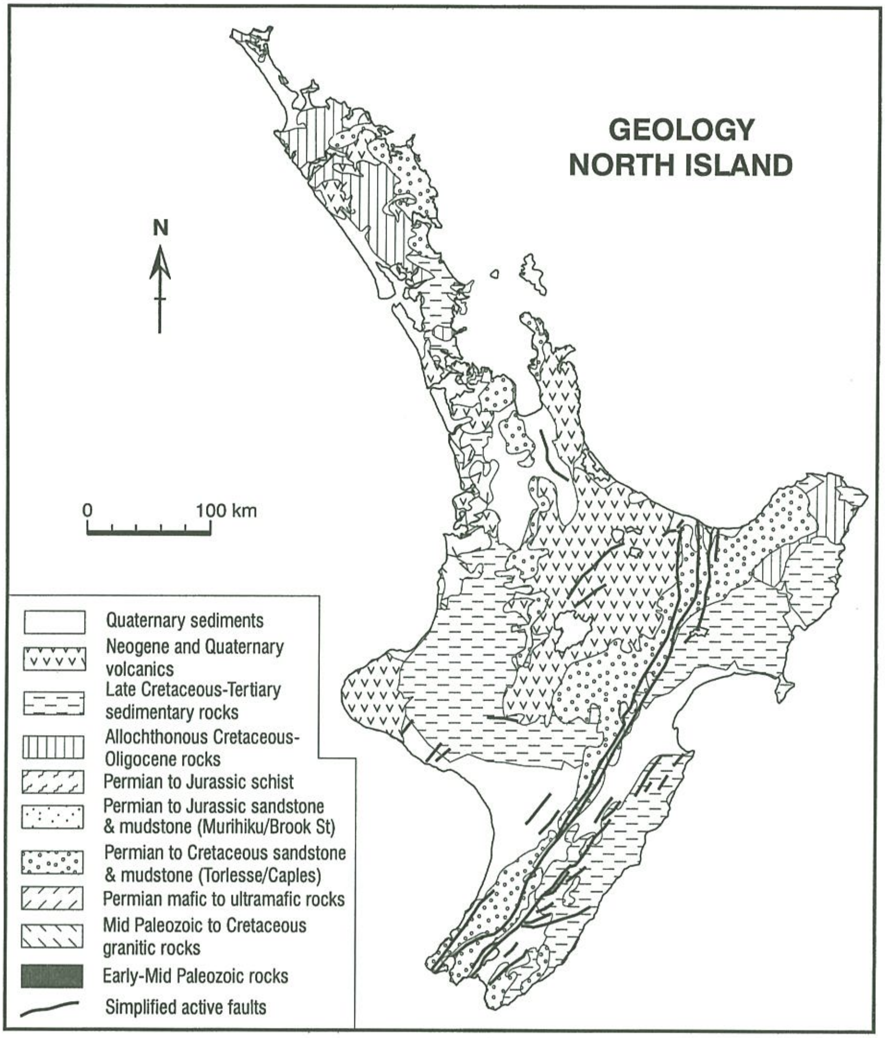


Figure 3.3 *Simplified geological map of North Island.*

Cold-water springs and caves are popular with tourists and adventurers. Springs can be popular visitor attractions, for example the Pupu Springs, northwest of Nelson attracted approximately 60,000 visitors a year in 1999 and 2000 (Department of Conservation pers. comm.). Visitors can view the springs from a platform and can use a mirror system to view underneath the spring water surface. Drift-diving in the springs and spring-fed streams is also popular. Approximately 250,000 people visit the Waitomo Caves each year (Waitomo Information Centre pers. comm.). They visit to view glow worms, to marvel at natural cave decoration, and to explore the cave depths by caving and 'black water rafting'.

Hot springs have been used since the habitation of New Zealand (Chapter 2) for bathing and cooking. Hot springs remain popular tourist destinations to this day. For example, Rotorua attracts approximately 1.3 million tourists per year (Rotorua District Council pers. comm.), largely to the geysers, springs, and hot pools associated with the Rotorua geothermal field.

High temperature-volcanic geothermal systems are used for electrical power generation. Electrical power generation from geothermal steam was 441 MW from the Wairakei, Ohaaki, Ngawha,

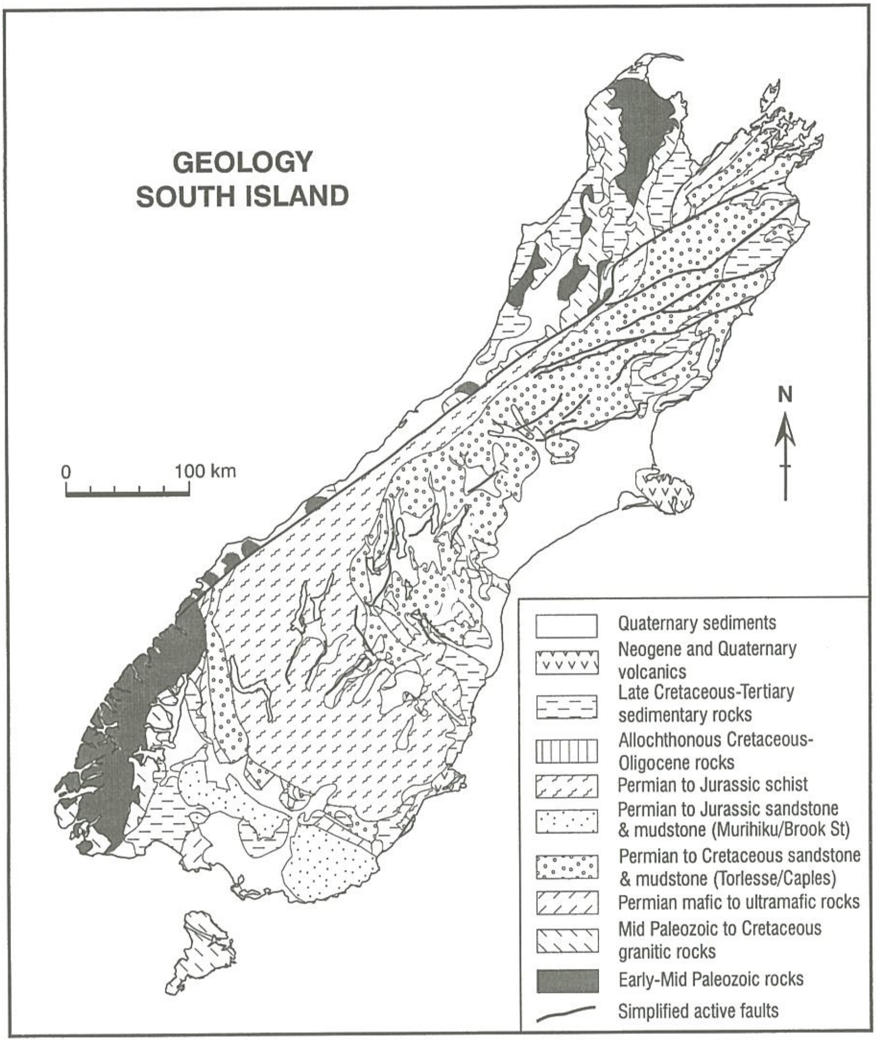


Figure 3.4 *Simplified geological map of South Island.*

Mokai and Rotokawa fields in 2000 (Thain and Dunstall 2000). Geothermal steam is also used directly for: paper drying at Kawerau; agricultural drying at Kawerau and Ohaaki; greenhouse and soil heating at Kawerau and Taupo; prawn farming at Wairakei; and space heating at Rotorua (Thain and Dunstall 2000).

AQUIFERS AND AQUIFER GEOLOGY

Recent, relatively shallow, sedimentary and volcanic lithologies (Fig 3.3 and Fig 3.4) contain the majority of North Island (Fig 3.5 and Table 3.2) and South Island (Fig 3.6 and Table 3.3) aquifers. Quaternary sediments are commonly associated with aquifers (Suggate et al. 1978). The Rangitaiki Plains, Heretaunga Plains, Manawatu Plains, Wairarapa Valley, Waimea Plains, Marlborough Plains, Canterbury Plains, Otago basins and Southland Plains are examples of aquifer systems in Quaternary sediments. Quaternary volcanic lithologies in Northland, Auckland, the Taupo Volcanic Zone, and Taranaki contain important aquifers. Examples of Tertiary-age sedimentary aquifers occur in: Auckland, Taranaki, Nelson, Otago and Southland. Volcanic lithologies of Tertiary age that are used for groundwater supply occur in Northland, Coromandel, Waikato,

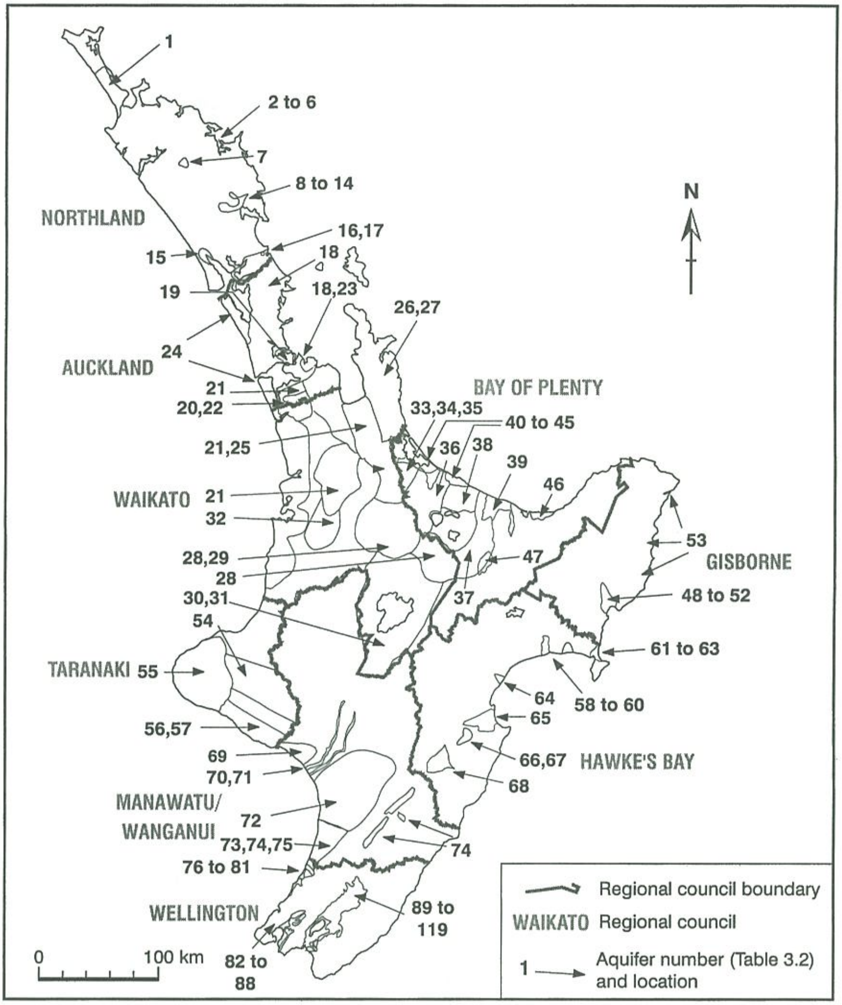


Figure 3.5 *Location of aquifers – North Island.*

Banks Peninsula, South Canterbury, and North Otago. Limited use is made of metamorphosed sediments for groundwater supply as these rocks are generally of low permeability and generally occur in mountainous regions.

The axial ranges of North Island are composed of greywacke (Fig. 3.3). South Island mountains are predominantly composed of Torlesse greywacke and Haast Schist (Fig. 3.4). These rock types are the important sources of sediment to New Zealand's alluvial plains. Aquifer systems including: Heretaunga Plains, Manawatu Plains, Wairarapa and Hutt Valley, Marlborough, Kaikoura, and Canterbury are mainly composed of greywacke gravel. Sedimentary aquifers in Otago contain schist clasts. Other South Island aquifer systems contain mixed clasts reflecting the varied geology of source rocks. Northland, Auckland, Waikato, Bay of Plenty, and Canterbury sedimentary aquifers contain clasts of volcanic rock.

Hunt and Bibby (1992) classified geothermal systems on the basis of temperature, geological location, and chemistry, into low temperature-tectonic geothermal systems (springs) and high-temperature volcanic geothermal systems. Forty-one low temperature-tectonic geothermal springs occur in the North Island (Fig. 3.7). Thirty-two low temperature-tectonic geothermal springs occur in a band between

Table 3.2 *Regions and names of North Island aquifers.*

Region and Aquifer Name	Number on Fig. 3. 5
Northland	
Aupouri	1
Kerikeri	2
Okaihau	3
Waimate North	4
Pakaraka	5
Ngawha	6
Kaikohe	7
Matarau	8
Glenbervie	9
Three Mile Bush	10
Maunu	11
Whatitiri	12
Maungatapere	13
Maungakaramea	14
Ruawai	15
Tara	16
Mangawhai	17
Auckland	
Waitemata Formation	18
Auckland volcanics	19
South Auckland volcanics	20
Tauranga Group sediments	21
Kaawa Formation	22
Greywacke	23
Auckland coastal aquifers	24
Waikato	
South Auckland volcanics	20
Tauranga Group sediments	21
Kaawa Formation	22
Hinuera Formation	25
Coromandel volcanic	26
Coromandel sand	27
Waiotapu Ignimbrite	28
Whakamaru ignimbrites	29
Taupo ignimbrites	30
Taupo sand	31
Otorohanga and Orahiri limestone	32
Bay of Plenty	
Aongatete Ignimbrite	33
Waiteariki Ignimbrite	34
Western Bay Rhyolite	35
Mamaku Plateau	36
Matahina Ignimbrite	37
Pongakawa Breccia	38
Rangitaiki Plains	39

Region and Aquifer Name	Number on Fig. 3. 5
Bay of Plenty *continued*	
Coastal Aquifers	
Waihi Beach Rhyolite	40
Katikati Gravel	41
Mt Maunganui sand	42
Matakana Island sand	43
Maketu warm water	44
Maketu Pumice	45
Opotiki	46
Galatea Basin	47
Gisborne	
Waipaoa Valley	
Te Hapara sand	48
Shallow fluvial	49
Waipaoa Gravel	50
Makauri Gravel	51
Matokitoki Gravel	52
Waiapu and Tolaga Bay flats	53
Taranaki	
Matemateaonga Formation	54
Taranaki Volcanic	55
Marine Terrace	56
Whenuakura Formation	57
Hawke's Bay	
Northern Coastal	
Wairoa Valley	58
Nuhaka coastal	59
Nuhaka limestone	60
Mahia sand	61
Mahia alluvium	62
Mahia	63
Esk Valley	64
Heretaunga Plains	65
Poukawa Basin	66
Papanui Stream Valley	67
Ruataniwha Plains	68
Manawatu-Wanganui	
Wanganui	69
Wangaehui-Turakina	70
Rangitikei	71
Manawatu	72
Horowhenua	73
Tararua	74
Coastal	75

Region and Aquifer Name	Number on Fig. 3. 5
Wellington	
Kapiti Coast	
Waiotohu	76
Otaki	77
Hautere	78
Coastal	79
Waikanae	80
Raumati-Paekakariki	81
Hutt Valley	
Lower Hutt	82
Upper Hutt	83
Black Creek	84
Wainuiomata	85
Mangaroa	86
Pakuratahi	87
Akatarawa	88
Wairarapa Valley	
Upper Opaki	89
Opaki	90
Rathkeale	91
Masterton	92
Te Ore Ore	93
Upper Plain	94
Fernridge	95
West Taratahi	96
East Taratahi	97
Mangatarere	98
Carterton	99
Parkvale	100
Matarawa	101
Fern Hill	102
Hodders	103
Greytown	104
Middle Ruamahanga	105
Moroa	106
Ahikouka	107
Battersea	108
Tauherenikau	109
Woodside	110
Te Maire Ridge	111
South Featherston	112
Riverside	113
Tawaha	114
Mangaroa	115
Martinborough Terraces	116
Huangarua	117
Lower Valley	118
Pirinoa Terraces	119

Kaikoura and Fiordland in the South Island (Fig. 3.8). These systems are commonly associated with faults and fractures in basement rocks where meteoric water circulates into the earth's crust to be heated and returned to the ground surface. Hunt and Bibby (1992) and McKinnon (1997) mapped 23 high-temperature volcanic geothermal systems in the Taupo Volcanic Zone between White Island and Mt Tongariro (Fig. 3.9). These fields are often associated with caldera structures and active volcanism.

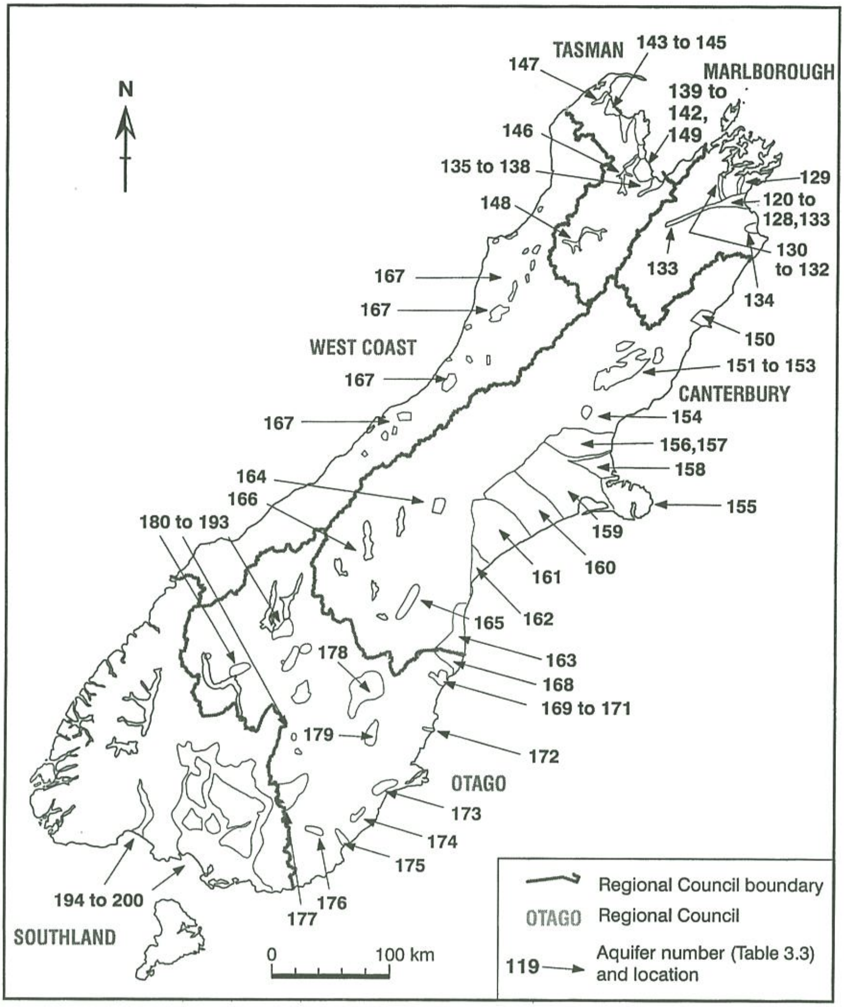


Figure 3.6 *Location of aquifers – South Island.*

Sedimentary aquifers - terrestrial depositional environment

Terrestrial sedimentation includes the depositional environments of: glacial, alluvial fan, aeolian, braided fluvial and meandering fluvial (Serra 1986). New Zealand sedimentary aquifer systems deposited within glacial, alluvial fan and fluvial sedimentary environments include the aquifer systems of Central Otago, the Galatea Basin, Wairau Valley, North Canterbury Plains, and North Otago. Aquifer systems in terrestrial aeolian dune deposits include the Aupori Peninsula and Auckland coastal aquifers.

The Wakatipu Basin (Fig 3.6 and Table 3.3) is an example of a sedimentary basin deposited in glacial, alluvial fan and fluvial terrestrial environments. (Barrell et al. 1994) Sediments in the Wakatipu Basin (Fig. 3.10) include fan, fan/delta, lake, terrace alluvium and glacial deposits. Sediments in the basin are believed to have formed during and after the Otira (last) glaciation. Glacial retreat left a blanket of tills and moraines on the schist basement and then lake sediments formed in an enlarged Lake Wakatipu. Alluvial fans developed and coalesced, in places, to form a piedmont and the Shotover River built a large fan/delta into Lake Wakatipu. Terrace alluvium and floodplain

Table 3.3 *Regions and names of South Island aquifers.*

Region and Aquifer Name	Number on Fig. 3.6
Marlborough	
Wairau	120
Southern Valleys	
Benmorven	121
Brancott	122
Fairhall River Gravels	123
Taylor - Burleigh	124
Omaka - Hawkesbury	125
Omaka River Valley	126
Deep Wairau	127
Rarangi Shallow	128
Tuamarino Valley	129
Rai Valley	130
Pelorus Valley	131
Kaituna Valley	132
Upper Wairau Valley	133
Lower Awatere Valley	134
Tasman	
Waimea Plains	
Appleby Gravel Unconfined	135
Hope Minor Confined and Unconfined	136
Upper Confined	137
Lower Confined	138
Moutere Valley	
Shallow Moutere	139
Middle Moutere	140
Deep Moutere	141
Motueka/Riwaka Plains	142
Takaka Valley	
Arthur Marble	143
Takaka Limestone	144
Takaka Valley Gravel	145
Motueka River Terraces	146
Aorere Gravel	147
Buller River Terraces	148
Marahau River	149

Region and Aquifer Name	Number on Fig. 3.6
Canterbury	
North Canterbury	
Kaikoura Plain	150
Hanmer Basin	151
Parnassus Basin	152
Culverden Basin	153
Waipara Basin	154
Banks Peninsula	155
Canterbury Plains	
Ashley Downs	156
Waimakariri-Ashley plains	157
Christchurch-West Melton	158
Central Plains	159
Rakaia-Ashburton plains	160
Ashburton-Rangitata plains	161
Rangitata-Levels plains	162
South Canterbury	163
Fairlie Basin	164
Hakataramea Basin	165
MacKenzie Basin	166
West Coast	
West Coast alluvial	167
Otago	
Lower Waitaki Alluvium	168
Papakaio	169
Waiareka and Deborah volcanic	170
Kakanui-Kauru Alluvium	171
Shag Alluvium	172
Lower Taieri Plain - East and West	173
Tokomairiro Basin	174
Lower Clutha Plain	175

Region and Aquifer Name	Number on Fig. 3.6
Otago *continued*	
Kuriwao Basin	176
Pomahaka Basin	177
Central Otago aquifers	
Maniototo Basin	178
Strath Taieri Basin	179
Ettrick Basin	180
Roxburgh East	181
Alexandra Basin	
Dunstan Flats	182
Earnscleugh Terrace	183
Manuherikia Alluvium	184
Springvale Terrace	185
Kingston	186
Pisa Terrace	187
Upper Clutha Valley	
Lindis Valley	188
Lowburn Valley	189
Wanaka Basin	190
Hawea Basin	191
Glenorchy	192
Wakatipu Basin	193
Southland	
Southland colluvial	194
Southland alluvial	195
Coastal aquifers	196
Tertiary lignite measures	197
Tertiary limestone	198
Chatton Formation	199
Caples and Murihiku Terrain	200

units have been deposited more recently by fluvial action.

The aquifers in the Wakatipu Basin are unconfined (Chapter 25) and have a thickness between 5 and 30m (Rosen and Jones 1998). Approximately 180 households use groundwater (Heller, pers. comm.) for domestic supply, stock water, and irrigation and there has been a general decline in groundwater level due to increasing use. Current usage of groundwater is approximately 1400 m^3 day^{-1}. Water quality problems in the Wakatipu Basin include bacterial contamination (up to 2400 faecal coliforms per 100mL) and nitrates (up to 14 mg L^{-1}) (Rosen et al. 1995). Management of this aquifer aims to improve the water quality with respect to these two problems.

Sedimentary aquifers - shallow marine depositional environment

Deltaic, siliclastic, carbonate and evaporite sediments can be deposited in a shallow marine environment (Serra 1986). The Whenuakura Formation in Taranaki (Fig. 3.5 and Table 3.2) contains aquifers with litholo-

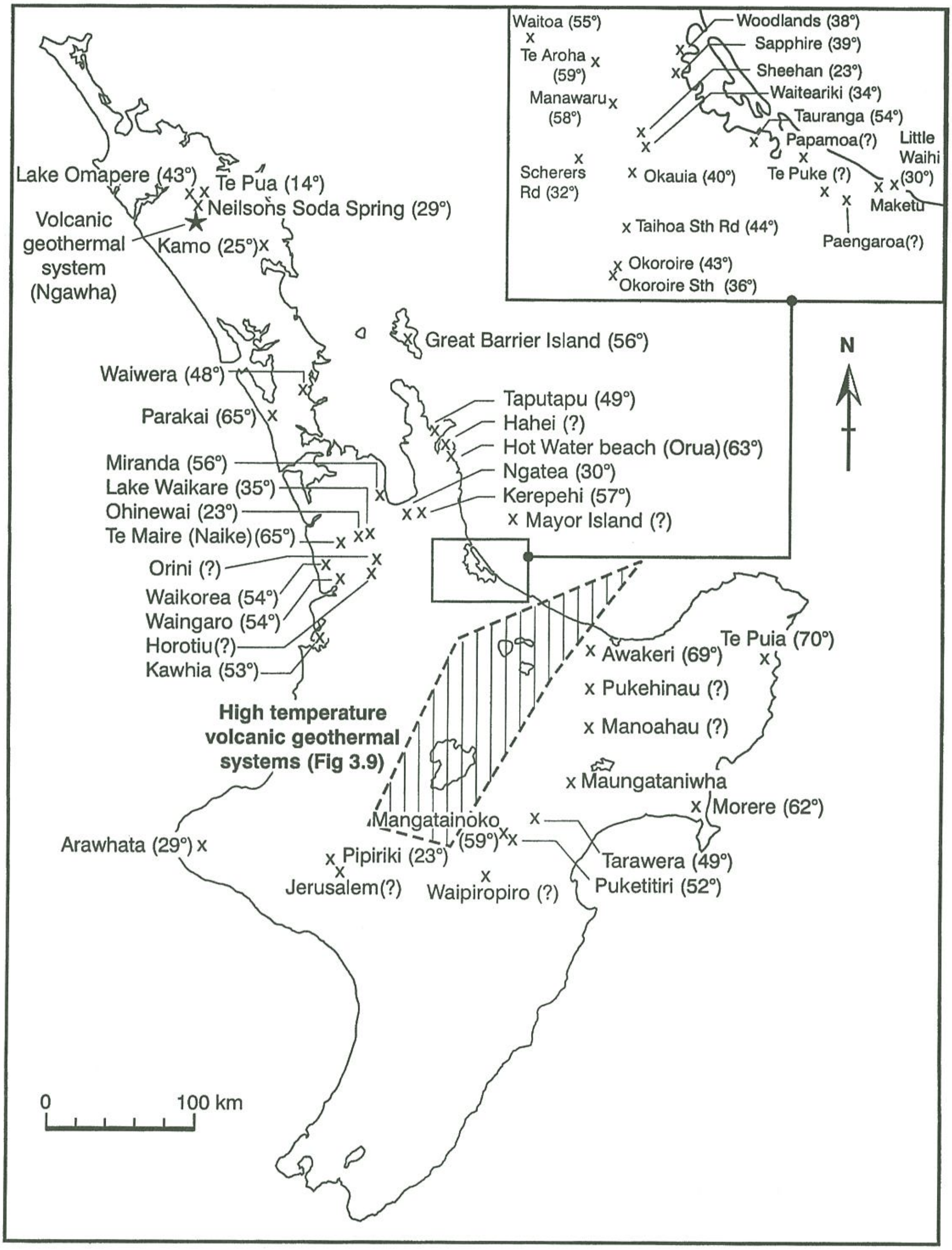


Figure 3.7 *Map of North Island showing the location and maximum temperature (°C) of low temperature-tectonic geothermal waters (after Mongillo and Clelland 1984).*

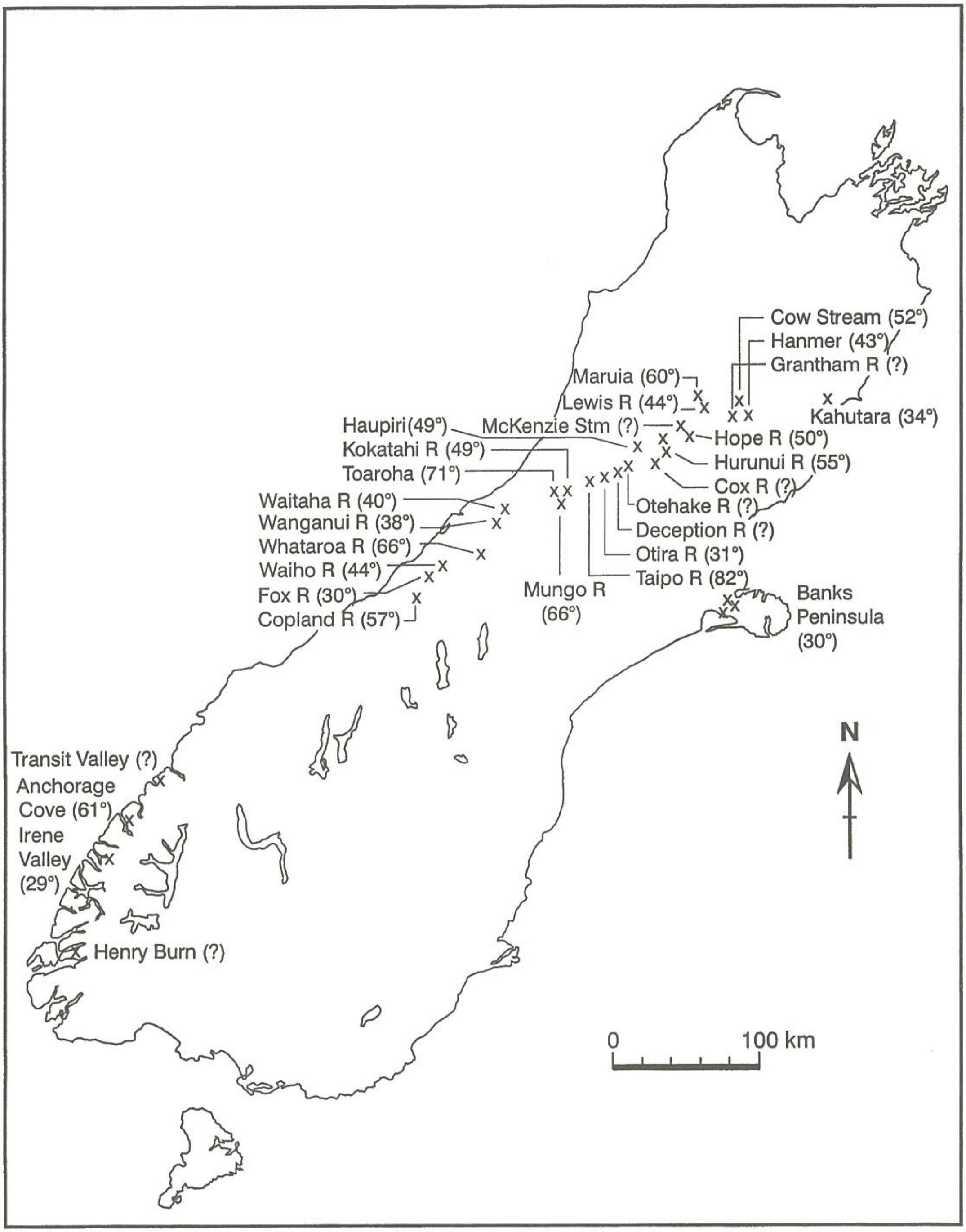


Figure 3.8 *Map of South Island showing the location and maximum temperature (°C) of low temperature-tectonic geothermal waters (after Mongillo and Clelland 1984).*

Figure 3.9 *Map of the central part of North Island showing the location of known high temperature-volcanic geothermal systems (after Mongillo and Clelland 1984 and McKinnon 1997).*

gies deposited in a shallow marine siliciclastic environment (Fleming 1953). This formation consists of: the Pepper Shell sand deposited not far below the position of low tide; the Rangikura Sandstone which consists of estuarine beds typical of a tidal channel, and beach deposits; the Waipipi Formation containing shell beds, sands and silts; and the Waverly

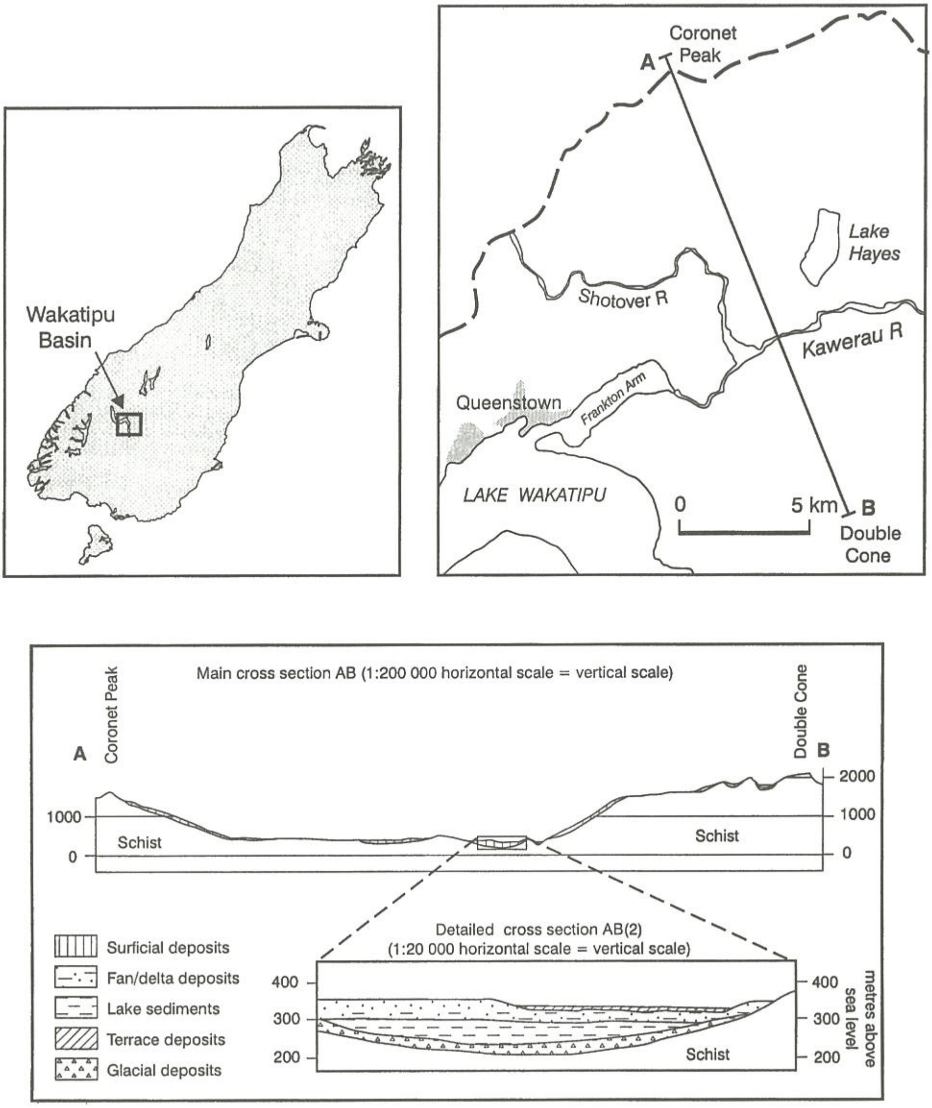


Figure 3.10 *The Wanaka Basin - an example of an aquifer system deposited in a terrestrial environment (after Barrell et al. 1994).*

Formation consisting of fine, massive blue-grey sandstone and siltstone approximately 60 m thick.

The Whenuakura Formation (Chapter 18) contains six aquifers that are mostly confined. The formation is approximately 400m thick and the aquifers within the formation are 5-10m thick. The majority of eighty-five groundwater users pump from four of the six aquifers (Stevens, pers. comm.). Resource consents allow the abstraction of approximately 5700 m^3 day^{-1} from the formation. Groundwater level measurements in the measurement period (1994 to 2001) are relatively consistent indicating that the aquifers are not under stress. Elevated boron concentrations, believed to be natural, have been measured in the Patea town supply well.

Uplifted marine limestones (Williams 1992) are important aquifers and are often associated with karstic landforms (sinkholes, fluted lime-

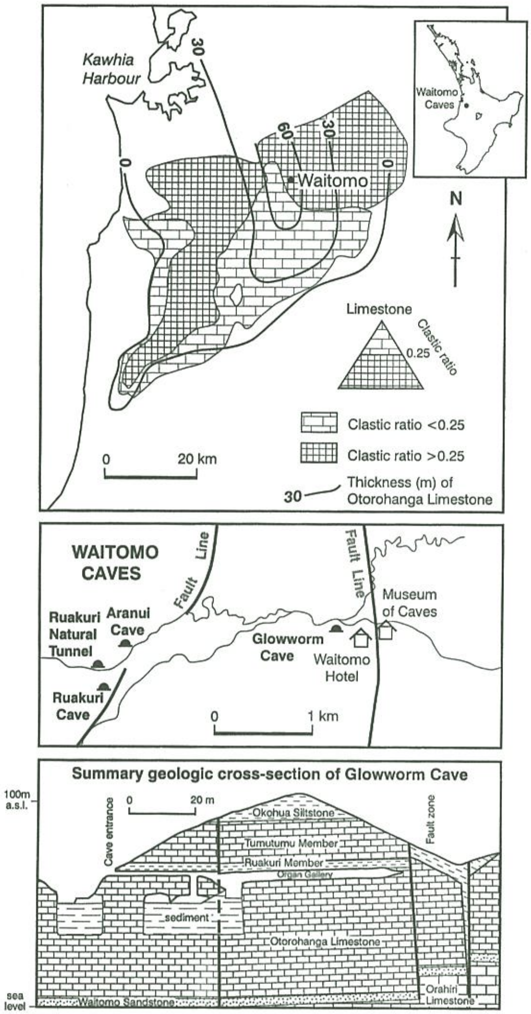


Figure 3.11 *Te Kuiti Group limestones (after: Kermode 1974a, Kermode 1974b, Nelson 1978) the Waitomo Caves, and geological cross section of the Glowworm Cave.*

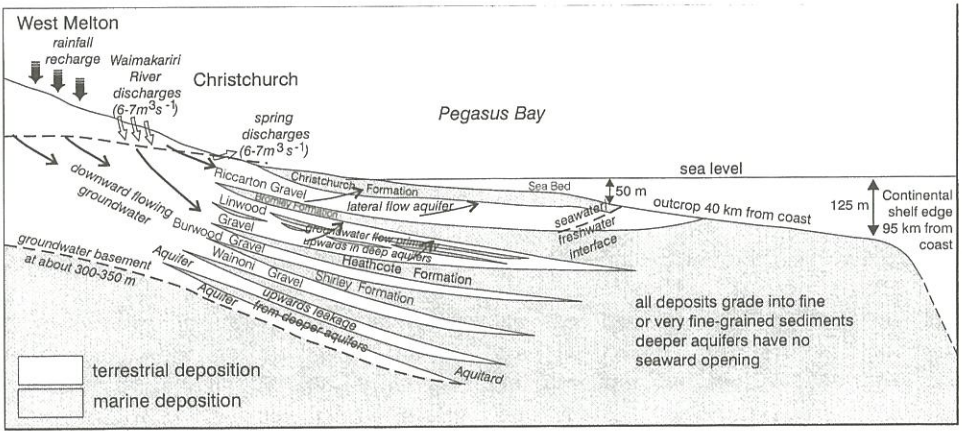
stones), caverns, and spring flow. These formations occur in Northland, Waikato, Hawkes Bay, Wairarapa, Nelson, West Coast, Canterbury, Otago and Southland. The Tertiary Te Kuiti Group of marine-deposited sediments (Suggate et al. 1978) in the Waikato includes the Otorohanga and Orahiri limestones (Nelson 1978). These limestones were deposited in a temperate climate (Nelson and Hume 1987) and predominantly consist of calcite derived from bryozoan, echinoid, foraminifera, mollusc, barnacle, and algae remains. Oyster-rich horizons are common although most skeletal remains are fragmented and partially, or fully, dissolved. Limestone grades into siliciclastic sandstones and mudstones towards the north and is approximately 75m thick at Waitomo (Fig 3.11). Cave systems at Waitomo developed in fractured limestone along or adjacent to major faults (Institute of Geological and Nuclear Sciences Ltd 1994). At least 45km of interconnected cave passages exist in the Waitomo area.

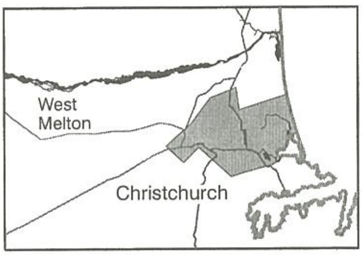
Sedimentary aquifers - terrestial and shallow marine depositional environments

Aquifer systems that were deposited in a terrestrial and shallow marine depositional environment often display transgressive/regressive sequences. Transgressive/regressive sequences occur where the environment of deposition changes with time due to sea level change.

This can result in a change in the physical characteristics of an aquifer, for example, terrestrial deposition in the up-dip section of an aquifer may grade into marine deposition in the down-dip section of an aquifer which may result in a significant permeability reduction in the down-dip direction. The aquifer system may take a layered structure, in vertical cross section, when a number of transgressive/regressive sequences have occurred and a basin is subsiding and/or uplifting due to tectonism. New Zealand sedimentary aquifer systems deposited in terrestrial and marine environments include North Island aquifers of: Waikato, Rangitaiki Plains, Heretaunga Plains, Manawatu Plains, and Lower Wairarapa Valley aquifers. South Island aquifer systems deposited in terrestrial and marine environments include: Wairau, coastal Canterbury Plains north of the Rakaia River and Southland.

The Christchurch-West Melton groundwater system in Canterbury (Fig 3.6 and Table 3.3) is dominated in the west by deposition of gravels, sands, silts and loess from the Waimakariri River. Gravels in this area are possibly up to 350m thick (Chapter 23). Beneath Christchurch, and to the east, is a succession of alternating gravel and marine deposits. (Fig 3.12) Marine deposition occurred during periods of relatively high sea levels in interglacial periods and these deposits





GEOLOGIC TIME SCALE					
INTERNATIONAL DIVISIONS					
PERIOD	EPOCH		CLIMATE (Pillans 1991)	BEGAN YEARS AGO	COASTAL GEOLOGICAL UNIT
QUATERNARY	HOLOCENE		ARANUI	10,000	Springston Formation / Christchurch Formation
	PLEISTOCENE	LATE PLEISTOCENE	OTIRA	70,000	Riccarton Gravel
			KAIHINU	120,000	Bromley Formation
			WAIMEA	200,000	Linwood Gravel
			KARORO	250,000	Heathcote Fromation
			WAIMAUNGA	310,000	Burwood Gravel
			UNNAMED	350,000	Shirley Formation
		EARLY PLEISTOCENE	NEMONA	380,000	Wainoni Gravel
					Undefined
					Undefined
					Early glacial and interglacial sequence
					Sequence uncertain

Figure 3.12 *Christchurch - West Melton - an example of an aquifer system deposited in terrestrial and marine environments (after Brown et al. 1995).*

form confining layers that separate the aquifers. For example the Christchurch Formation is the shallowest low permeability layer and represents the last marine incursion. The predominant sediment type in the Christchurch Formation is peat, clay, and marine mud (Brown et al. 1995). Concurrent deposition of the Springston Formation occurred to the west. The Springston Formation consists of gravels, sand and riverbank silts. The relatively impermeable sediments of the Christchurch Formation effect groundwater flow in the Springston Formation by controlling the locations of springs and wetlands. Recharge, from the Waimakariri River and rainfall, flows through the unconfined section of the aquifer to the confined aquifers. Aquifers deeper than the Riccarton Gravel are probably closed to the east. Groundwater in the deeper aquifers flows eastward, and then upward through the low permeability layers.

There are a total of 510 groundwater users in this area who are allocated approximately 300 million $m^3 year^{-1}$ from the unconfined and confined aquifers (Weeber pers. comm.). Users of groundwater include: farming, industry, rural domestic supply and urban domestic supply. No significant long-term changes in groundwater level have occurred in the period of record between 1894 and the present day (Chapter 23). An increase in the amplitudes of seasonal variation in the groundwater levels in Christchurch has occurred in the last 40 years but the groundwater does not appear to be overexploited. The groundwater is of good quality with, for example, a low chloride concentration (Chapter 6) in the region of the system where recharge from the Waimakariri River is important. Sea water intrusion is a problem in the Woolston area (Chapter 6) and potential effects of agricultural and industrial land uses on groundwater quality are a concern as contaminants could enter the confined system and Christchurch's drinking water supply. Iron and manganese concentrations are problems in some coastal areas (Hayward pers. comm.).

Sedimentary aquifers - deep sea marine depositional environment

Deep sea marine environments (Serra 1986) are characterised by sediments deposited in turbidite fans by a gravity flow mechanism. Examples of New Zealand aquifer systems in sediments deposited in deep sea marine environments include the Waitemata Group in the Auckland region. The Waitemata Group (Kermode 1992) sediments consists mainly of alternating mudstone and lithic sandstone with breccia and conglomerate. Volcanic-derived sediment is common as the sediments were deposited in a subsiding basin flanked by active volcanoes. Minor basal shallow water-deposited facies are included in this group. Deposition occurred in the Early Miocene and the succession is 1000 m to 2000 metres thick. Regional, and small-scale faults displace the Waitemata Group. Permeability sufficient for groundwater supply is often associated with fracture systems in the Waitemata Group.

Aquifers in the Waitemata Group sediments are generally confined (Chapter 13). Wells are generally 200m to 400m deep with typical yields of 30 $m^3 day^{-1}$ to 300 $m^3 day^{-1}$. Approximately 3.4 million $m^3 year^{-1}$ is allocated to 600 users of groundwater from the Waitemata Group sediments in six management areas (Crowcroft pers. comm.), exclusive of the 76 users of two low-temperature geothermal fields. Groundwater levels in the Waitemata Group sediments show seasonal variations. Longer-term groundwater level records show similar year-to-year groundwater levels. Groundwaters at less than 200m depth are typically hard calcium carbonate waters with high total iron (>1 g m^{-3}). Deeper groundwaters are typically soft sodium bicarbonate waters with pH >8.5 and low total iron (<0.2 g m^{-3}). Groundwater quality is consistent over time (Crowcroft pers. comm.) and the foremost management concern is the potential for seawater intrusion in coastal areas to be induced by pumpage.

Aquifers in volcanic lithologies

Basalts and ignimbrites are two classes of lithology of volcanic origin that contain aquifers. Basalt aquifers occur in Northland, Auckland, Waikato, Canterbury and Otago. Basalt deposits comprise weathered lava, scoriaceous rock, and basaltic ash. They are usually associated with tuffaceous rock. Fractures in hard, dense lava, produced by cooling (Petch et al. 1991) are the locations of highest permeability. Scoriaceous layers and lava tubes (Kermode 1992) are also zones of high permeability. Weathered basalt, ash, and tephra act as aquitards in the volcanic units. Basalt flow units often follow the ground topography (Kermode 1992). This results in the groundwater flow direction in basalt aquifers usually being in the direction of dip. Basalts are often associated with good quality soil, for example Pukekohe and North Otago, and groundwater from basalts can provide a water source for market garden irrigation. Two periods of basaltic volcanism have deposited up to 100 m of basalt in the vicinity of the Pukekohe cone (Auckland Regional Council 1991). Bombay Basalt, the older unit, is often over 30 m thick and is massive, jointed and more deeply weathered than the shallower

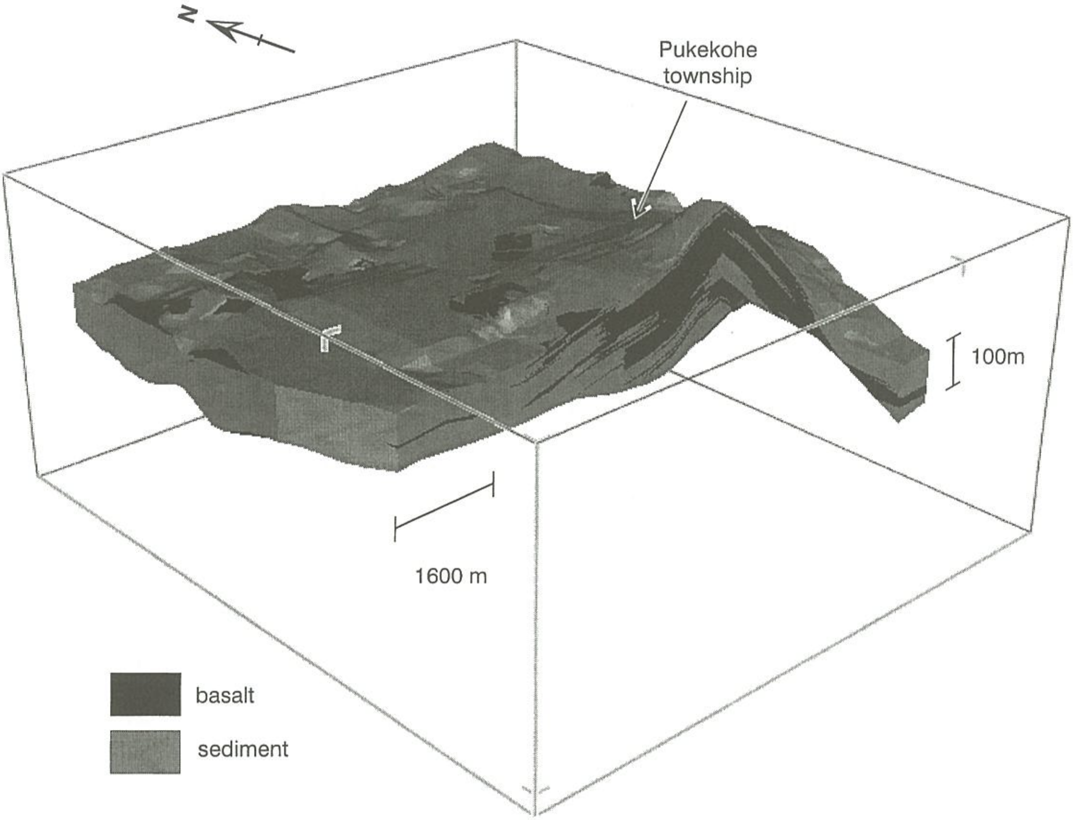


Figure 3.13 *Pukekohe basalts - an example of a basalt aquifer system.*

Franklin Basalt. Franklin Basalt consists of dense and vesicular basalt with fine and coarse tuffs. Basalt flow units are contiguous in the vicinity of Pukekohe Cone (White et al. 1996) and are separated by sedimentary deposits beyond the cone (Fig. 3.13).

Groundwater is taken from Bombay Basalt and Franklin Basalt in the Pukekohe area by wells that are typically 30m to 60m deep (Chapter 13) in both unconfined and confined aquifers. Approximately 1 million m^3 $year^{-1}$ is allocated to 76 consented users of groundwater from the two aquifers (Crowcroft, pers. comm.). A three-dimensional geological model of the Pukekohe area (Fig 3.13) estimates that approximately 300 million m^3 of water is stored in the basalt lithologies (White et al. 1996). Groundwater levels show seasonal variation, and can respond quickly to rainfall events. Water from these aquifers can have nitrate concentrations greater than the New Zealand drinking water standards of 11 mg L^{-1} because of land-use practises, including the irrigation of market gardens. The impact of possible urbanisation of the recharge area on groundwater quality is a potential management issue.

Ignimbrite sheets are associated with calderas in the Taupo Volcanic Zone. More than 34 caldera eruptions have generated ignimbrite sheets of volumes from 10 km^3 to 500 km^3 (Wilson et al. 1984). Ignimbrite sheets reach up to 200 km from their source and can be greater than 200 m thick. The central zone of an ignimbrite sheet is usually relatively permeable, and often contains aquifers, because of fracturing during cooling of welded eruptive material. The base of an ignimbrite sheet is commonly relatively impermeable due to a relative lack of fractures in the less welded material (Risk 1980). Examples of ignimbrites that contain viable water supplies includes the Waiotapu Ignimbrite which supplies water for agriculture, domestic supply and industry in the Tokoroa area of South Waikato; and the Mamaku Plateau which supplies water for agriculture and Rotorua City.

The Waiotapu Aquifer (Chapter 14) is typically 20-50m thick in the Tokoroa area. The aquifer is generally confined and approximately 40,000 m^3 day^{-1} is abstracted by approximately 210 users. A pulp and paper mill is the largest user of groundwater from the aquifer. Groundwater levels are relatively consistent from year-to-year indicating that the system is not overused. The natural quality of groundwater is good. Contaminated groundwater from the vicinity of a pulp and paper mill has been detected but contamination does not exceed drinking water guidelines in any drinking-water supply wells.

Aquifers in metamorphic lithologies

Metamorphic rocks that contain useable water supplies include metamorphosed Torlesse supergroup greywacke and Ordovician Arthur Marble.

The Arthur Marble (Fig 3.6 and Table 3.3) has a stratigraphic thickness of more than 1 km (Williams 1992). The marble varies in colour from cream to dark grey (Suggate et al. 1978) and contains graptolites and coral-crinoid fossil faunas. The outcrop is up to 7 km wide in places. An extensive cave system in the Arthur Marble is popular with cavers. Dry caves exist at least 350 m above the present water table in the Arthur Marble (Williams 1992) indicating that historic water levels were considerably higher than present. These caves were formed by the dissolution of rock material by water and most of the water flow through the Arthur Marble is likely to be occurring in caves and passages. The Takaka River loses approximately 11 m^3 s^{-1} of flow where the riverbed crosses the Arthur Marble. An outflow of the Arthur Marble is at Waikoropupu Springs (Chapter 21) located approximately 10 km from the location of recharge from the Takaka River. The Waikoropupu Springs are the largest springs in New Zealand and are protected as a scenic reserve (Williams 1992).

Geothermal systems

Low temperature-tectonic geothermal systems have temperatures in the range of about 20°C to 100°C and are often associated with active faults. These systems contain mainly meteoric waters that have percolated downwards and have been heated at depths as great as 5 km. The warm water rises along high permeability pathways, such as faults, to discharge at the ground surface in warm springs or seeps.

High temperature-volcanic geothermal systems are associated with active volcanism. Temperatures up to 280°C occur in these systems (Hunt and Bibby 1992). Meteoric waters percolate down to depths of 5-10 km where they are heated by hot rock, or magma, that obtain temperatures of up to 800°C. Hot water rises to the ground surface. Water and steam phases, which commonly occur in the high temperature systems, cause natural discharge features such as: hot springs, mud pots, geysers, fumaroles, and phreatic explosion pits. Hot geothermal fluid mixes with cold groundwater near the ground surface, which affects the distribution and chemistry of high temperature water discharge.

GEOLOGICAL HISTORY

New Zealand's geology (Fig. 3.3 and Fig. 3.4) is a result of a complex development history that is summarised as occurring in three phases (Suggate et al. 1978, Thornton 1995). The first phase, in the Precambrian to Devonian periods up to 355 million years ago, resulted in the deposition, metamorphism and emplacement of many North-west Nelson, West Coast, and Fiordland lithologies. Precambrian gneiss, Cambrian-Ordovician volcanics and sediments, granites, and gneisses occur in these areas. Marine sedimentation occurred in a range of shallow to deep marine environments. Fossils in these rocks include trilobites, graptolites, corals, crinoids and brachiopods. This phase ended with mountain-building, accompanied by metamorphism and igneous intrusion.

Large volumes of greywacke and argillite were deposited in a variety of tectonic settings during the second phase, from Carboniferous (355 million years ago) to mid-Cretaceous time (100 million years ago). Greywacke of the

Torlesse composite terrane forms the axial ranges in the North Island from East Cape to Wellington including the eastern Wairarapa. Superficially similar greywacke of the Waipapa composite terrane occurs in Northland, Auckland, and Waikato. Greywacke of these terranes makes up the Southern Alps (Fig. 3.4) between Marlborough and Lake Wakatipu. Permian to Jurassic-age volcanogenic sedimentary rocks of Nelson, West Otago, and Southland, include minor intrusive and volcanic rocks. Belemnites, ammonites, bilvalves, gastropods, and plant remnants are amongst the fossils found in these rocks. Sediments were deposited in marine environments adjacent to the Gondwana Supercontinent. Phase two ended with the Rangitata Orogeny when substantial mountain-building and metamorphism of the Haast Schist occurred.

Phase three of New Zealand's development began approximately 100 million years ago in the Cretaceous. The Tasman Sea began forming 85-55 million years ago separating the New Zealand portion from remainder of Gondwana (McKinnon 1997). Cretaceous, and Paleogene, rocks in New Zealand are associated with this rifting. New Zealand's relatively structurally complex sedimentary basins (King et al. 1999) have undergone different sedimentary histories on the western and eastern sides of the country in the last 65 million years. Basin development throughout western New Zealand has been dominated by the break-up of the Gondwana Supercontinent and associated plate boundary tectonism. The development of eastern New Zealand basins has been influenced by sedimentary processes on the margin of the New Zealand landmass. The advent of the Neogene saw a change from a passive margin setting to a transpressional regime that continues to the present day. This regime is characterised by active tectonic processes, including volcanism.

TECTONIC SETTING

Since Miocene time New Zealand's tectonic setting has been dominated by the gradual convergence of the Australian and Pacific tectonic plates. Tectonism has been dominated by uplift, subsidence, erosion, folding, faulting, and volcanism and has contributed significantly to the geomorphology of the New Zealand landscape as we see today. East and north east of Hawke's Bay the Pacific Plate is identified by earthquake foci to be subducting beneath the Indo-Australian Plate. (Adams and Ware 1977) Between the lower North Island and the West Coast (South Island) the relative plate motions are taken up by strike-slip faulting on the Alpine fault and other faults. (Bibby et al. 1986) South and south west of Fiordland the Indo-Australian Plate is identified by earthquake foci to be subducting beneath the Pacific Plate (Davey and Broadbent 1980).

Most of the present-day New Zealand landmass was under water 30 million years ago (McKinnon 1997). Peat and coastal swamps formed on the remnant of the country above sea level. The Pacific and Indo-Australian plates began converging about 26 million years ago to commence the phase of mountain-building, known as the Kaikoura Orogeny, that continues to this day. Rates of uplift associated with the Kaikoura Orogeny in the North Island (Fig. 3.14) and the South Island (Fig. 3.15) are greatest along the axial ranges. This uplift exposes greywackes and other basement rocks. The eroded debris from this uplift has been deposited as a series of flood plains. The majority of floodplains on the east coast of North Island and South Island are composed of alluvial greywacke gravels deposited in terrestrial depositional environments and it is in these materials that important aquifer systems are found.

Subsidence, also associated with tectonism, is occurring in many areas in New Zealand including: Taupo Volcanic Zone, Hamilton Basin, Gisborne, Heretaunga Plains, Manawatu Basin, and Wairarapa Basin in the North Island (Fig. 3.14). Marlborough Sounds, Canterbury Plains, and Taieri Plains are regions of subsidence in the South Island (Fig. 3.15). The coastal basins remain above sea level where the rate of sediment deposition is greater than the rate of subsidence. For example the Canterbury Plains are largely formed of greywacke gravel from the uplifted greywacke of the Southern Alps. Sedimentary deposition of up to 637 m of gravel (North Canterbury Catchment Board 1986 and

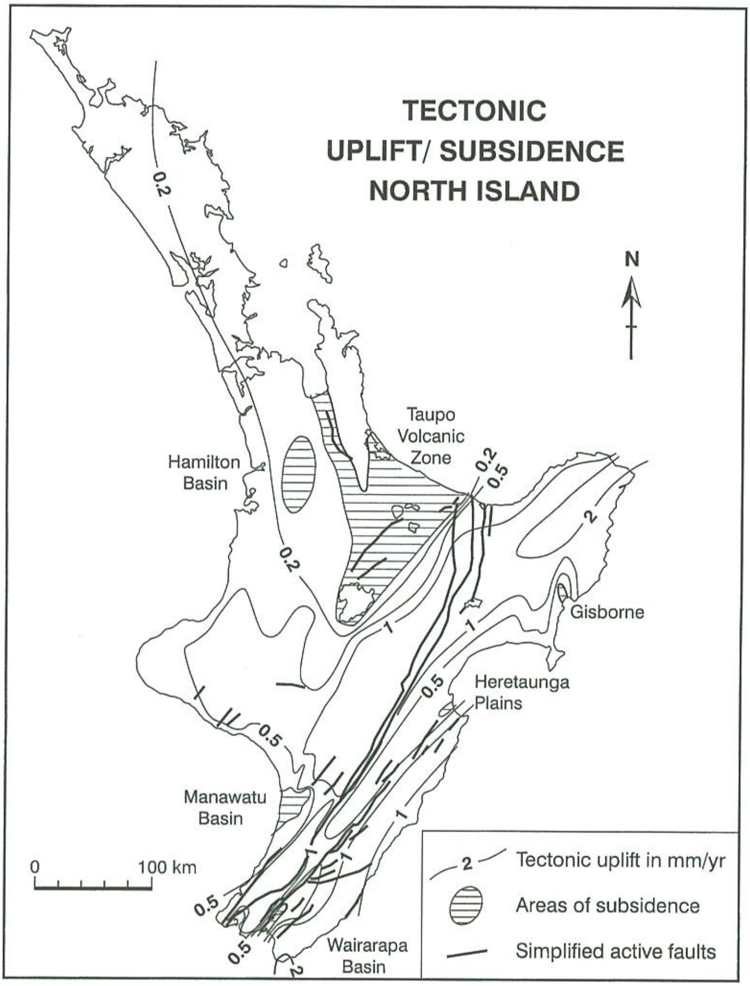


Figure 3.14 *Tectonic uplift and subsidence – North Island (after Pillans 1986).*

Weeber pers. comm.) on the Canterbury Plains began approximately 5 million years ago. The Taupo Volcanic Zone has been in-filled with up to 2700m of sedimentary, volcanic and intrusive units (Wood 1996). The drowned valley features of the Marlborough Sounds are an example where the subsidence rate exceeds the rate of sediment deposition.

Uplift and subsidence can be associated with active faulting. Uplift of up to 2.5 m occurred after the magnitude 7.9 1931 Napier earthquake approximately 30 km north of Napier (Eiby 1980) and an area of land approximately 3.5 x 10.5 km rose from the sea during the same earthquake event (Stevens 1974). Subsidence of up to 1 m occurred near Hastings after the earthquake. Subsidence of over 2 m was associated with the magnitude 6.6 Edgecumbe earthquake in 1987 (Ansell and Taber 1996). Horizontal and vertical off-sets are common on fault lines. Horizontal displacement up to 1.6m in the Edgecumbe earthquake and vertical displacement up to 2.4 m, occurred along a 7 km surface rupture. During the 1855 Wellington earthquake the southeast Wellington coastline rose 3 m to 6 m from the sea. Cumulative off-sets can be substantial. Approximately 600 km of horizontal movement has occurred on the Alpine Fault in South Island (Walcott 1979).

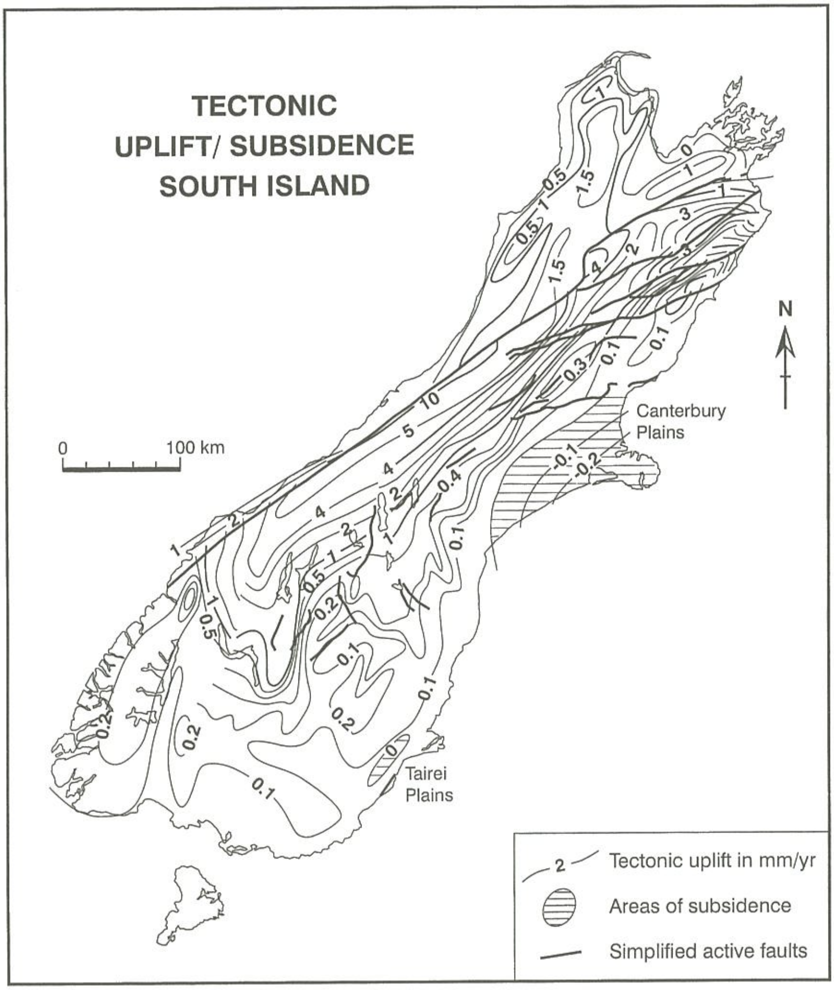


Figure 3.15 *Tectonic uplift and subsidence – South Island (after Wellman 1979).*

Fault lines commonly mark the boundaries of depositional basins because of the association of uplift, subsidence, normal faulting, reverse faulting and lateral off-set with active tectonism. Examples of fault-bounded basins include the eastern margin of the Taupo Volcanic Zone, which is bounded by the Kaingaroa Fault (Healy et al. 1964); the western boundary of the Hutt Valley basin (Kingma 1967), which is bounded by the Wellington Fault; and the western boundary of the Wairarapa basin (Kingma 1967), which is bounded by the Wairarapa Fault.

Tectonism is also associated with volcanic and geothermal activity. Volcanism commenced in the North Island approximately 22 million years ago in the Early Miocene period (McKinnon 1997). North Island volcanic rocks include rhyolite, dacite, ignimbrite, andesite, and basalt and tend to be young in the Taupo Volcanic Zone. Basaltic eruptive activity commenced in the Auckland region approximately 150,000 years ago (McKinnon 1997) and the last major eruption occurred on Rangitoto Island 200-600 years ago.

Volcanic activity in the South Island has resulted in the basaltic rocks of North Canterbury, Central Canterbury, Banks Peninsula, Otago Peninsula, Timaru and Oamaru. Volcanic landforms in New Zealand include cone volcanoes (e.g. Auckland volcanic cones, Mt Taranaki, Mt Ngauruhoe and Mt Ruapehu), rhyolite domes (e.g. Mt Tarawera) and calderas (e.g. Lake Taupo, Lake Rotorua, Reporoa and Lake Okataina). Volcanic deposits include rhyolite, dacite, ignimbrite, andesite, basalt, lahar and pumice (McKinnon 1997). These deposits usually contain aquifers containing cold and/or hot water.

PALEOCLIMATE

Paleoclimatic variations are a significant influence on the pattern of sedimentation (Ethridge et al. 1998). The last two million years is sometimes referred to as the 'Ice Age' (McKinnon 1997) when large ice sheets formed at high latitudes. In the New Zealand region over this period the climate has been generally cool. New Zealand has been affected by glaciations with glacial erosion carving South Island valleys, for example Fiordland, and leaving a diverse range of glacial landforms in the mountains of the North Island and South Island (Suggate et al. 1978). Oscillations between a cold and a warm climate have been proposed in the last two million years. Changes from cold, or 'glacial', to warm or 'interglacial' periods have occurred throughout the period (Pillans 1991, and Suggate 1990), Fig. 3.16, and in New Zealand have been determined from oxygen isotopes from deep sea cores, glacial deposits, alluvial deposits, loess and volcanic eruption marker beds. Four glacial periods are recognised, and named, in the last half million years using primarily a succession of glacial deposits near Hokitika in Westland (Suggate 1990).

Temperatures during glacial periods were up to 5°C cooler than present (McKinnon 1997). Northern Hemisphere ice sheets were extensive during glaciations and New Zealand glaciers were more extensive than at present, with West Coast South Island glaciers extending to the sea and the Canterbury glaciers extending to the plains. Glaciation also occurred in the North Island, for example in the Tararua Range (Stevens 1974). Sea levels were up to 120 – 130 m below present levels due to the volume of water held in ice sheets and glaciers. New Zealand's dry land area would have been about

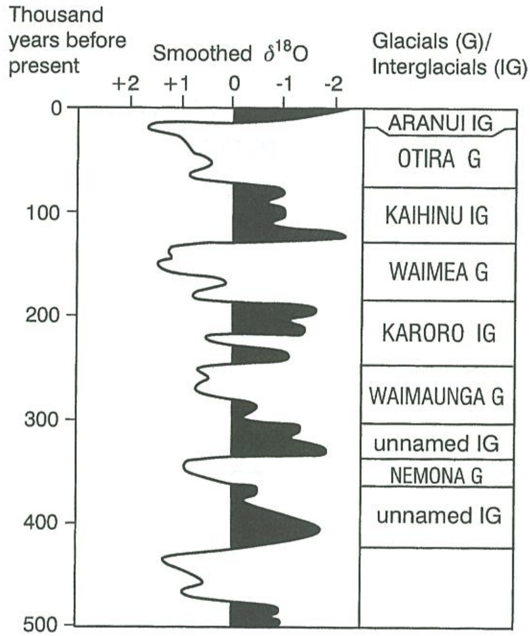


Figure 3.16 *Glacial and interglacial chronology in the last half million years (from Pillans, 1991).*

50% greater than present and North, South and Stewart islands were joined in a continuous land mass. The climate was generally drier (McKinnon 1997) with stronger winds. Continuous forest growth only occurred in the far north of the North Island. Beech, the most common tree at the time, was rare in the southern parts of the South Island. Shrub and grassland were the dominant vegetation south of Auckland. Sediment transport by glaciers, rivers and wind was greater during glacial periods due to the thin vegetation and relatively high erosion rate. Loess was deposited in many areas from wind-blown sediment (Raeside 1964, Brown et al. 1995). Terrestrial sedimentation occurred beyond the present shoreline because of the lower sea level. The climate during interglacial periods was probably much like the present day climate.

The change of climate between the last glacial period and the present interglacial period began about 18,000 years ago (Suggate et al. 1978). The climate began to warm and glaciers began to retreat. Sea levels began to rise separating North Island and South Island about

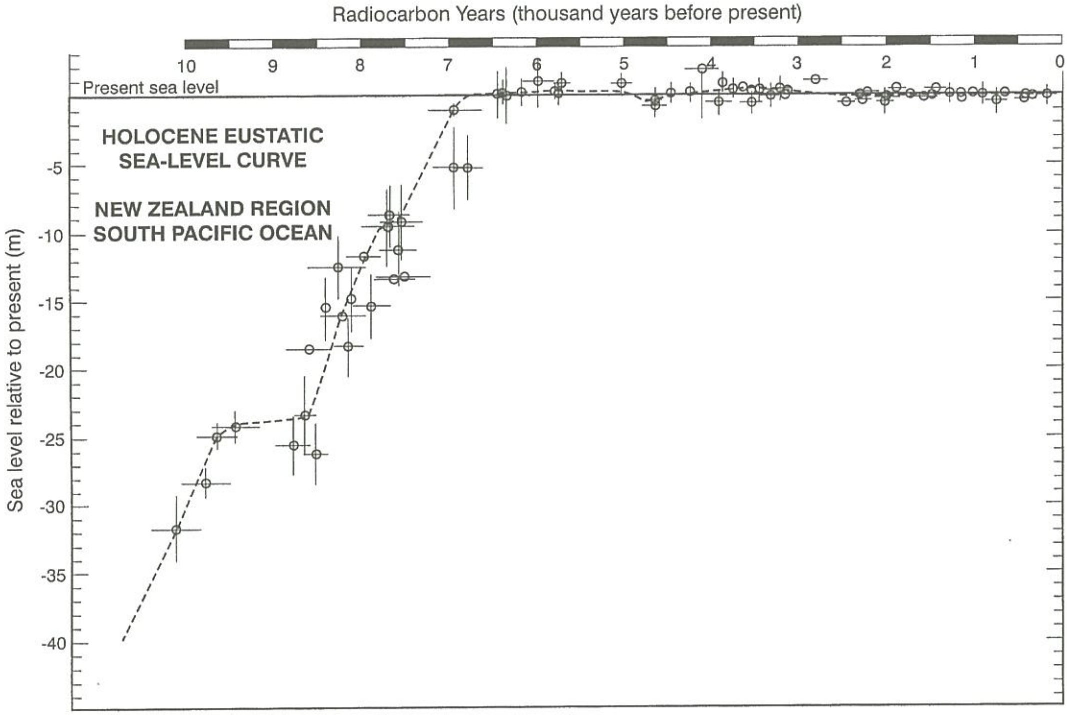


Figure 3.17 *Sea level in New Zealand in the last 10000 years (after Gibb 1986).*

12,000 years ago. Temperatures possibly reached 1-1.5°C greater than present between 9,500 and 5,000 years ago when glaciers reached their smallest. Sea levels rose to reach present levels about 6,000-7,000 years ago (Fig. 3.17).

Recent sedimentation in the Canterbury Plains demonstrates the effects of the transition between glacial and interglacial climate. The late Pleistocene Canterbury Plains shoreline is estimated to be about 90 km east of the present shore during the last glaciation (North Canterbury Catchment Board 1983). The Waimakariri River valley was glacial down to the confluence with the Poulter River (Suggate et al. 1978) and relatively undifferentiated gravels of the Burnham and Windwhistle formations were being deposited on the Canterbury Plains. Sea level rise brought the shoreline to 10 km west of the present coast (Brown et al. 1995) approximately 6,000-7,000 years ago. Sediment sorting by the rivers during the present interglacial period gave rise to the permeable Springston Formation. Rivers typically became incised during the present interglacial (Wilson 1985) with active channels approximately 2 km wide. Sediment deposition has resulted in an eastward movement of the coastline near Christchurch in the last 6,000-7,000 years.

SAFE YEILD OF GROUNDWATER SYSTEMS

Domenico and Schwartz (1990) present a definition of safe yield: "The rate at which water can be withdrawn from an aquifer for human use without depleting the supply to the extent that withdrawal at this rate is no longer economically feasible". Estimates of groundwater recharge, groundwater discharge, and groundwater storage are used to estimate the safe yield of an aquifer. Typically the estimates of flux and storage are firstly made on the basis of a conceptual model of the groundwater system, usually at a regional scale. Estimates are then improved by field measurement and modelling of individual components of the water balance and geological reconnaissance of the aquifers that make up the reservoir. Computer simulations of system inputs, storage, and outputs are used to refine safe yield estimates. Estimation of the safe yield of an aquifer system is a useful starting-point to determination of the sustainability of a groundwater resource. Sustainability, a concept that is wider in scope than the concept of safe yield, is the current aim of resource management (see last section of this chapter).

Groundwater recharge can be from rainfall, rivers, other aquifers, irrigation, and the ocean. Rainfall recharge (Chapter 5) is typically estimated from considerations of rainfall, evaporation, drainage, runoff, and soil water holding capacity. Direct measurements of rainfall recharge, usually with lysimeters, are possible but are generally restricted to calibration of recharge models in terms of climate and soil-type parameters. Rainfall recharge, for example, in the area of the recharge zone between Christchurch and the Waimakariri River is estimated at 30 x 10^6 m^3 yr^{-1} (North Canterbury Catchment Board 1986). Rainfall over the unconfined area of the Heretaunga Plains (Dravid and Brown 1997) is estimated to range between 7.4 x 10^6 m^3 yr^{-1} and 22.3 x 10^6 m^3 yr^{-1} between 1975 and 1995 using a model which considered drainage through three different soil types.

Recharge to groundwater from rivers (Chapter 6) is commonly assessed by measurement of low flow gaugings and calculation of flow losses. For example, Dravid and Brown (1997) estimated a recharge from the Ngaruroro River to the unconfined aquifer of 135 x 10^6 m^3 yr^{-1}. River recharge to groundwater can be difficult to assess in braided gravel rivers where the losses are a small proportion of the total flow and where there can be alternating losses and gains over quite short distances through pool and riffle sequences along the channel. The loss from the Waimakariri River to the Christchurch-West Melton groundwater system is estimated in the range 158 x 10^6 m^3 yr^{-1} to 252 x 10^6 m^3 yr^{-1}. Groundwater recharge from other aquifers occurs when piezometric gradients, combined with sufficient permeability, drive water across aquifer boundaries. The shallowest confined aquifer in the Christchurch-West Melton system (the Riccarton Gravel, Fig. 3.12) receives an estimated 32 x 10^6 m^3 yr^{-1} from inland Canterbury aquifers. Recharge can also have a substantial vertical component where upward or downward leakage is implied by head differences and permeability contrasts. The three deeper confined aquifers of the Christchurch-West Melton system receive an estimated 95 x 10^6 m^3 yr^{-1} from upward leakage through each aquitard (North Canterbury Catchment Board 1986).

Groundwater recharge to the onshore groundwater system can occur when groundwater levels are drawn below sea level for a sufficient period of time, or when inshore piezometric levels are naturally below sea level. Saltwater intrusion of freshwater aquifers has been recorded near Motueka (Thorpe 1994) and in Woolston, Christchurch (Chapter 6). Many aquifers in New Zealand are coastal and systems are managed to avoid the potential of salt water intrusion. Natural salt-water intrusion does occur, for example at Waikoropupu Springs (Chapter 7)

Discharges from groundwater systems occur through onshore springs, offshore springs, pumpage, and discharge to other aquifers. Groundwater discharge to onshore springs often maintains spring flow (Chapter 6) and habitat. Spring discharge in Christchurch is estimated at 220 x 10^6 m^3 yr^{-1} (North Canterbury Catchment Board 1986) and 119.8 x 10^6 m^3 yr^{-1} in the Heretaunga Plains (Dravid and Brown 1997). The presence of submarine springs that are presumed to represent outflow of the groundwater system have been mapped in New Zealand in Wellington Harbour (Donaldson and Campbell 1977) in Hawke's Bay (Dravid and Brown 1997) and Golden Bay (Williams 1992). The relatively poor knowledge about offshore springs, and groundwater discharge offshore generally, means that this component of the water balance is poorly known.

Discharge from a groundwater system by pumpage includes that made by abstractive users such as irrigators, domestic supply, and commercial/industrial users. Pumpage for dewatering purposes occurs in areas where high water tables are a problem (White 1997) such as the Heretaunga Plains (Dravid and Brown 1997).

Computer modelling of the inputs, outputs, and storage, of a groundwater system is commonly used to assess safe yield. Donaldson and Campbell (1977) used a two dimensional model of the Hutt Valley system to predict that moving the existing well field back from the coast could increase the average yield of the groundwater system by up to 60% without compromising groundwater level and quality. Fenemor (1988) investigated the effects on groundwater levels in one unconfined and two confined aquifers for four pumpage scenarios: no pumpage, domestic only pumpage, actual pumpage, and a high usage of 0.58 L s^{-1} ha^{-1}. The high usage model caused substantial dewatering of the aquifers and 'massive' salt-water intrusion. The Waimea Plains have been divided, subsequent to the work of Fenemor (1988) into ten water management zones. Zone-specific policies relating surface and groundwaters have been developed based partly on the groundwater flow model (Tasman District Council 1991). For example the allocation limit for the Lower Confined Aquifer is set at 203 L s^{-1} including 84 L s^{-1} allocated to Tasman District Council's Richmond supply. Allocation is monitored through a system of rights to take water under the Resource Management Act (1991).

Environmental effects of the withdrawal of fluid from the high temperature geothermal system (Hunt and Bibby 1992) include decline of pressure and temperature in the deep system leading to the formation and expansion of a two-phase zone containing steam and water; increase in surface heat flow due to the creation of a steam zone; decline in geyser activity due to the decline in reservoir pressure (Allis and Lumb 1992; White and Hunt 2000); ground subsidence where, for example, a section of the ground surface in the Wairakei field subsided by over 400 mm $year^{-1}$ between 1970 and 1980 (Hunt and Bibby 1992); and surface water quality effects due to the disposal of non-reinjected geothermal fluid. Potential environmental benefits of electricity generation from geothermal fields, when compared with fossil fuels, include the relatively low atmospheric releases of carbon dioxide.

ECONOMIC VALUE OF GROUNDWATER RESOURCES

Undervaluation of groundwater in the United States (National Research Council 1997) leads to misallocation of resources because: (1) the groundwater resource is not efficiently allocated relative to alternative current and future uses; and (2) authorities responsible for resource management and protection devote inadequate attention and funding to maintaining groundwater quality. The United States has spent billions of dollars cleaning up contaminated groundwater with 'little comparison of costs or technological difficulty to future benefits' (National Research Council 1997). The National Research Council (1997) describes the quantification of the groundwater resource's total economic value as the sum of two categories: the extractive services and the in-situ services. Extractive services are associated with direct water use by irrigators, industry and domestic users. In-situ services include: maintenance of groundwater quality including protection against seawater intrusion; maintenance of spring flow and therefore recreation and habitat protection; a guarantee of water supply when surface water is scarce and maintenance of habitat and ecological diversity.

Groundwater resources in New Zealand are highly valuable in an economic sense as they provide for a large proportion in the total water supply for agriculture, industry, and domestic supply. In areas such as the east coast of North Island and South Island the groundwater resource is the only viable year-round supply for many users. The economic value of a groundwater resource to a region, and to agriculture, industry and domestic supply is estimated for the Waimea Plains (Fig 3.6 and Table 3.3) groundwater system. (White et al. in press)

A random sample of forty-eight (approximately 16%) of the 260 Waimea Plains irrigators with groundwater consents were questioned in February 1999 about the value of groundwater to their enterprise. The total government valuation of the 48 properties is \$37 million and the water allocation to those properties is 29,000 m^3 day^{-1}. Statistics on government property values, property sizes and water allocations of the sample indicate a mean government valuation of $770,000 per property, $30,000 per hectare, and 23 m^3 ha^{-1} day^{-1} mean water allocation per hectare. Reduced groundwater availability usually means that production would decline, and this is usually reflected in the perception that reduced property values would result. Those surveyed predicted that government valuation of their property would reduce to an average of $560,000 per property, and $22,000 per hectare, with a 100% reduction in groundwater availability. The total government valuation for the 48 properties in the sample, with no groundwater availability, would probably reduce to $27 million. Thus an estimate of the value of the groundwater resources to the 48 irrigators is $10 million calculated from the difference between government valuations with the present operation and the government valuation with no groundwater. The value of the groundwater system to all 260 irrigators, calculated by scaling-up the sample, is $54 million.

All fifteen commercial/industrial users of groundwater in the Waimea Plains were approached in June 1999 and twelve contributed to the survey. The classes of industry that contributed to the survey include those who process timber, animal products, fruit, and gravel. The value of these businesses is a total of $517 million. Businesses were asked how their production, and therefore business values, would respond to a decline in groundwater availability. Eight of the businesses in the survey are relatively sensitive to groundwater availability, as a decline in water availability would lead to a significant decline in product output. The estimated total valuation of the twelve businesses in the survey with no groundwater availability is $379 million. This implies that the value of the groundwater resource to commercial/industrial users in the sample is about $138 million. The value of the groundwater resource to all commercial/industrial users is calculated as $173 million by scaling-up the results from the sample.

Tasman District Council is the bulk water supplier for householders in the Waimea Plains and for industry in Richmond and Stoke. The present scheme is estimated to have a capital value of $31 million, and annual running costs of approximately $1 million per year. Alternative schemes, should groundwater not be available for household supply, include water dams and piping water from Nelson Lakes. These two schemes are estimated to cost an extra $20 million of capital expenditure. The annual cost of these schemes is estimated at $2.3 million, for supply dams, and $2.6 million for piping Nelson Lake Water. An estimate of the value of the groundwater resource to the bulk water supplier is the sum of the capital expenditure required for a non-groundwater scheme ($20 million) plus the difference in annual running costs capitalised at 10%. The difference in annual running costs is taken as $1.3 million from which an estimate may be made of the value of the groundwater system to the bulk water supplier as being $33 million.

The combined value of the Waimea Plains groundwater system for abstractive users is estimated at $260 million, and this is for approximately 3% of New Zealand's groundwater allocation. This indicates the economic importance of the resource to the country. It also indicates the scale of potential economic loss resulting from mismanagement of the resource. The economic loss to a region, and the country, should aquifers become unusable through drawdown or pollution would be significant. It is therefore justifiable to manage aquifer systems on a sustainable basis for economic reasons alone. The provision of in-situ services is also a very important consideration in the sustainable management of groundwater reserves.

SUSTAINABILITY OF GROUNDWATER SYSTEMS

Sustainable management under the Resource Management Act (1991) Section 5(2), means 'managing the use, development and protection of natural and physical resources in a way, or at a rate, which enables people and communities to provide for their social, economic, and cultural wellbeing and for their health and safety while –

(a) sustaining the potential of natural and physical resources (excluding minerals) to meet the reasonably foreseeable needs of future generations; and
(b) safeguarding the life-supporting capacity

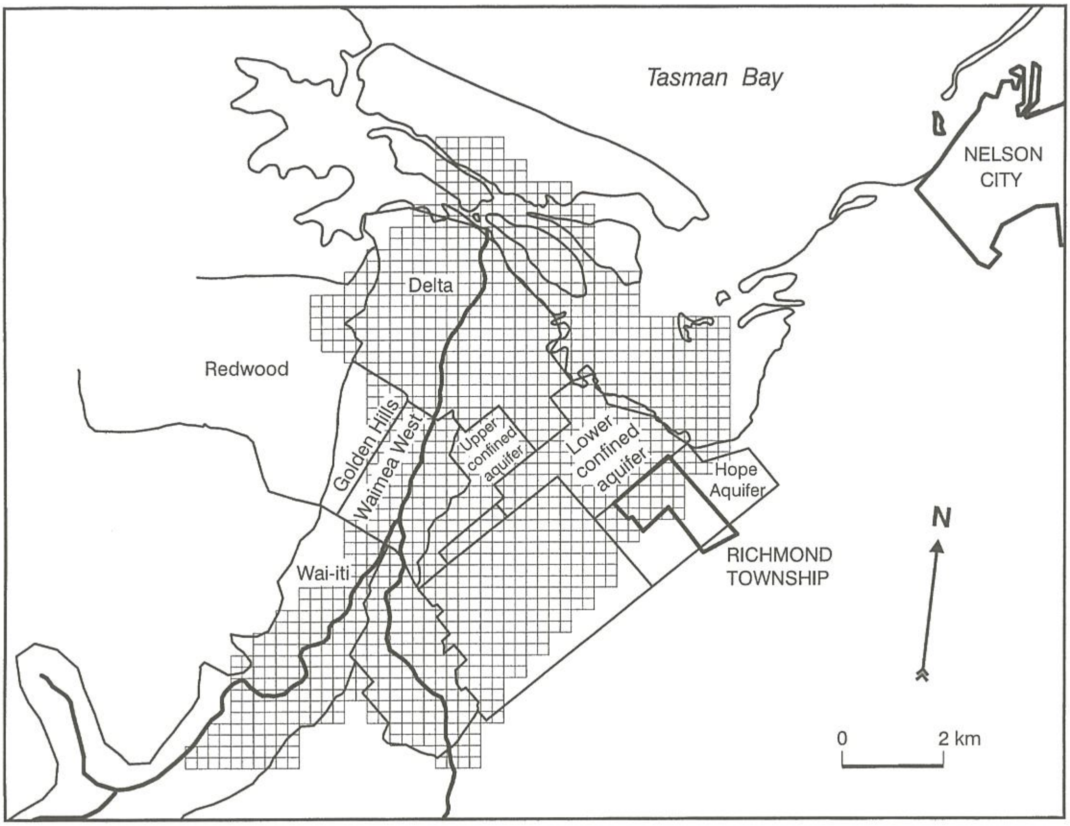


Figure 3.18 *Location of the Delta Zone, and other water usage zones, on the Waimea Plains with groundwater model grid.*

of air, water, soil, and ecosystems; and
(c) avoiding, remedying, or mitigating any adverse effects of activities on the environment'.

Groundwater management under the Resource Management Act (1991) is carried out by regional councils and unitary authorities mostly using regional plans that govern the management of water quality, water quantity, and water allocation. The definition of sustainability in the Resource Management Act (1991) goes beyond physical and biological resources to consider the human aspects of resource use. Integrated modelling of the physical, biological, and human aspects of a groundwater resource is an approach to understanding the sustainability of groundwater systems. Environmental usage invariably involves trade-offs between environmental quality, or quantity, and economic development. Integrated modelling is required to understand these trade-offs so that rational decisions can be made to allow human usage of the environment while maintaining acceptable environmental standards.

An approach to modelling the sustainability of aquifer systems is shown by linking models of the physical and human environment in the Delta Zone (Fig. 3.18) of the Waimea Plains groundwater system. Three-dimensional models of the aquifer structure (White and Reeves 1999), groundwater flow (Fenemor 1998), and groundwater quality, are used to predict environmental effects of four scenarios of groundwater usage. River flow, spring flow, groundwater level at the coast, and groundwater quality are potentially affected by pumpage of groundwater. The economic

Table 3.4. *Potential environmental effects of groundwater pumpage, Delta Zone, Waimea Plains in one week of March 1983.*

Effect	Pumpage Scenarios			
	Actual Pumpage	Allocated Pumpage	2 x Allocated Pumpage	5 x Allocated Pumpage
Waimea River flow at the coast, weekly average (L s^{-1})	280	260	0	0
Neiman Creek discharge, weekly average (L s^{-1})	70	70	30	0
Groundwater discharge across the estuary boundary (L s^{-1})	800	800	600	120
Area of land with groundwater chloride concentration above 200 ppm (ha)	0	0	0	481
Area of land with no groundwater (ha)	0	0	0	126

effects of increased irrigation, and the economic effects of changes in water quality, are assessed for four scenarios of groundwater usage. The level of employment related to irrigation can be assessed (White et al. in press). There is no biological component to this model, although biological effects are recognised as important considerations in the management of the resource as prolonged low flows in rivers and streams can lead to deleterious effects on biota.

Models of weekly average piezometric levels were predicted for the 1982/1983 year, when weekly Wairoa River flow was a 1-in-34 year low and 3-monthly rainfall was a 1-in-4 year low, with a MODFLOW groundwater flow model of the Waimea Plains system. Groundwater abstractions were at historic highs (Fig. 3.1), and groundwater levels reached low levels (White 1997a) during this period. The 1982/83 year represents a time when the groundwater system was at its most stressed and therefore is an appropriate period in which to examine the limits of water allocation and the environmental effects of water allocation.

Groundwater pumpage has potential for environmental effects on: river flow, spring flow, groundwater level near the coast, and groundwater quality. Potential effects are time-variant and the maximum predicted effect during the 1982/83 year occurs in one week of March 1983. The Waimea River is predicted to be dry when pumpage is two-times allocated and five-times allocated (Table 3.4). Spring-fed Neiman Creek is predicted to not be flowing in 23 weeks of the 1982/83 year when pumpage is five times the allocation. Groundwater discharge across the estuary boundary of the Delta Zone is predicted to occur in all four pumpage scenarios (Table 3.4). However, the simulation of five-times the allocated pumpage predicts that groundwater levels in a substantial area of the Delta Zone will be lower than mean sea level which could allow saltwater intrusion of the groundwater system.

It is predicted that 481 ha of the Delta Zone will have a groundwater Cl concentration greater than the World Heath Organisation 'maximum desirable' limit of 200ppm with five-times the allocated pumpage. It is also predicted that groundwater would disappear from under 126 ha of farmland with five-times the allocated pumpage.

Economic benefits of increased water availability are estimated by analysis of questionnaires completed by irrigators. Irrigated farms in the Delta Zone are estimated to be worth approximately $4,000 per hectare more than non-irrigated farms. A decline in groundwater quality is predicted by Waimea Plains irrigators to have an impact on property prices because groundwater may not be suitable for household use. Water quality for household use is a significant consideration in property purchase for most farmers including small-

Table 3.5 *Economic effects of four groundwater usage scenarios in the Delta Zone, Waimea Plains. The area of the model Delta Zone = 1513 ha.*

Modelled effects	Pumpage Scenarios			
	Actual Pumpage	Allocated pumpage pumpage	Two-times allocated pumpage	Five-times allocated
Area of irrigation (ha)	490	490	980	906
Area not irrigable because of no groundwater availability and/or saltwater intrusion (ha)	0	0	81	607
Non-irrigated land (ha)	1023	1023	452	0
Economic benefit of irrigation, from ($ million)	2	2	3.5	3.3
Economic effect of unavailability of groundwater and/or salt-water intrusion ($ million)	0	0	0	-2.6 (land prices) -2.0 (TDC relocation)
Estimated net economic benefit of irrigation ($ million)	2	2	3.5	-1.3

holders and irrigators. Farmers in the Delta Zone indicate that the mean difference of water property value between pristine groundwater and undrinkable groundwater is approximately equivalent to $4,400/ha.

The area of the Delta Zone under irrigation in four usage scenarios is predicted to increase to 980 ha (Table 3.5) with pumpage of two-times the present allocation. Increasing the pumpage to five-times the present allocation is predicted to result in 906 ha of irrigation. The land area under irrigation with five-times allocation is less than with two-times allocation because 607 ha of land would need to be retired from irrigation use with five-times allocated pumpage.

Net economic benefits of irrigation are estimated to be the same, at $2 million, with the actual and allocated pumpage scenarios. The net benefit of irrigation with a pumpage of two-times the allocated is estimated at $3.5 million. This is greater than the benefit for actual and allocated pumpage scenarios because more land is irrigated in the two-times allocation scenario. The net economic benefit with a pumpage of five-times allocated pumpage is estimated at -$1.3 million. The economic effect of saltwater intrusion and unavailability of groundwater for irrigation is estimated as a loss of $2.6 million in land values with five-times allocated pumpage. Saltwater intrusion in this scenario is also predicted to salinise the Delta Zone public water supply wells of the Tasman District Council (TDC). These would have to be moved to a new site, at an estimated cost of $2 million (Wareing pers.comm.).

The example of the Delta Zone indicates that actual and allocated pumpage scenarios cause similar environmental effects and produce similar economic benefits. Pumpage of two-times the allocated could cause the Waimea River to dry but produces a greater economic benefit than the two scenarios with lower pumpage. Pumpage of five-times the allocated could cause the Waimea River to dry, Neiman Creek to dry, and results in an economic loss. Ultimately the decisions on water allocation are often political and economic. Research, such as that outlined, plays a part in assessing the response of the physical, biological, and social environment and providing this information to the public, to users, and to decision-makers so that rational decisions on the sustainable development of groundwater resources can be made.

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REFERENCES

ADAMS, R.D.; WARE, D.E. 1977: Subcrustal earthquakes beneath New Zealand: locations determined with a laterally inhomogeneous velocity model. New Zealand Journal of Geology and Geophysics 20: 59-63.

ALLIS, R.G.; LUMB, J.T. 1992: The Rotorua Geothermal Field, New Zealand: its physical setting, hydrology, and response to exploitation. Geothermics special issue Rotorua Geothermal Field, New Zealand. V21, No. 1/2: 7-24.

ANSELL, R.; TABER, J. 1996: Caught in the Crunch. Harper Collins New Zealand. 188p.

AUCKLAND REGIONAL COUNCIL 1991: Pukekohe Plateau groundwater resource report water allocation and management plan. 67p.

BARRELL, D.J.A.; RIDDOLLS, B.W.; RIDDOLLS, P.M.; THOMPSON, R. 1994: Surficial geology of the Wakatipu Basin, Central Otago, New Zealand. Institute of Geological and Nuclear Sciences science report 94/39. 31p, 2 maps.

BIBBY, H.M.; HAINES, A.J.; WALCOTT, R.I. 1986: Geodetic strain and the present day plate boundary zone through New Zealand. In Recent Crustal Movements of the Pacific Region. The Royal Society of New Zealand. Bulletin 24: 427-438.

BROWN, L.J.; BEETHAM, R.D.; PATERSON, B.R.; WEEBER, J.H. 1995: Geology of Christchurch, New Zealand. Environmental and Engineering Geoscience 1(4): 427-488.

BROWNE, G.H.; THOMAS, J.T. 2001: Clast size characteristics of gravel within rivers of the Waimea Plains, Nelson. New Zealand Journal of Geology and Geophysics 44: 97-104.

CHAPPELL, J. 1983: A revised sea-level record for the last 300 000 years from Papua New Guinea. Search 15(3-4): 99-101.

DAVEY, F.J.; BROADBENT, M. 1980: Seismic refraction measurements in Fiordland south west New Zealand. New Zealand Journal of Geology and Geophysics 23: 395-406.

DICKER, M.J.I.; FENEMOR, A.D.; JOHNSTON, M.R. 1992: Geology and groundwater resources of the Waimea Plains, Nelson. New Zealand Geological Survey Bulletin 106. Department of Scientific and Industrial Research. 59p.

DOMENICO, P.A.; SCHWARTZ, W. 1990: Physical and Chemical Hydrogeology. J. Wiley and Sons, Inc. 824p.

DONALDSON, I.G.; CAMPBELL, D.G. 1977: Groundwaters of the Hutt Valley - Port Nicholson alluvial basin - a resource evaluation. New Zealand Department of Scientific and Industrial Research Information Series No. 124. 78p.

DRAVID, P.N.; BROWN, L.J. 1997: Heretaunga Plains Groundwater Study. Volume 1: Findings. Hawke's Bay Regional Council. 254p.

EIBY, G.A. 1980: Earthquakes. Heinemann Reed. 166p.

ETHRIDGE, F.G.; WOOD, L.J.; SCHUMM, S.A. 1998: Cyclic variables controlling fluvial sequence development: problems and perspectives. *In:* Shanley, K.W., McCable, P.J. ed. Relative role of eustasy, climate, and tectonism in continental rocks. Society of Economic and Petroleum Mineralogists Special Publication 59: 17-29.

FENEMOR, A.D. 1988: A three-dimensional model for management of the Waimea Plains aquifers, Nelson. Publication 18 of the Hydrology Centre, Department of Scientific and Industrial Research, Christchurch, New Zealand. 133p.

FLEMING, C.A. 1953: The Geology of Wanganui Subdivision. Bulletin n.s.52, New Zealand Geological Survey, New Zealand Department of Scientific and Industrial Research. 362p + 4 maps.

GIBB, J.G. 1986: A New Zealand regional Holocene eustatic sea-level curve and its application to determination of vertical tectonic movements: a contribution. In Reilly, W.I., Harford, B.E., (eds). Recent crustal movements of the Pacific region. The Royal Society of New Zealand Bulletin 24: 377-395.

HEALY, J.; SCHOLFIELD, J.C,; THOMPSON, B.N. 1964: Sheet 5 Rotorua (1st Ed.) Geological Map of New Zealand 1:250,000. Department of Scientific and Industrial Research, Wellington, New Zealand.

HUNT, T.M.; BIBBY, H.M. 1992: Geothermal Hydrology. In: Waters of New Zealand. New Zealand Hydrological Society, Wellington. 147-166.

INSTITUTE OF GEOLOGICAL AND NUCLEAR SCIENCES LTD 1994: Waitomo Caves. Institute of Geological and Nuclear Sciences Information series No. 30. 6p.

KERMODE, L.O. 1974a: Glowworm Cave, Waitomo, conservation study. New Zealand Speleological Bulletin, 5(91): 329-344.

KERMODE, L.O. 1974b: Geological setting of Glowworm Cave, Waitomo. New Zealand Speleological Bulletin, 5(92): 361-369.

KERMODE, L.O. 1992: Geology of the Auckland urban area. Scale 1:50 000. Institute of Geological and Nuclear Sciences geological map 2. 1 sheet +63p. Institute of Geological and Nuclear Sciences Ltd, Lower Hutt, New Zealand.

KING, P.R.; NAISH, T.R.; BROWNE, G.H.; FIELD, B.D.; EDBROOKE, S.W. 1999: Cretaceous to recent sedimentary patterns in New Zealand. Institute of Geological and Nuclear Sciences folio series 1. Folder with 39p and 1 enclosure.

KINGMA, J.T. 1967: Sheet 12 Wellington (1st Ed.). Geological Map of New Zealand 1:250,000. Department of Scientific and Industrial Research, Wellington, New Zealand.

MCKINNON, M. 1997: New Zealand Historical Atlas. Bateman. 290p.

MONGILLO, M.A.; CLELLAND, L. 1984: Concise listing of information on the thermal areas and thermal springs of New Zealand. Department of Scientific and Industrial Research Geothermal Report 9. 228p.

NATIONAL RESEARCH COUNCIL 1997: Valuing groundwater economic concepts and approaches. National Academy Press, Washington. 189p.

NELSON, C.S. 1978: Stratigraphy and paleontology of the Oligocence Te Kuiti Group, Waitomo County, South Auckland, New Zealand. New Zealand Journal of Geology and Geophysics, 21(5): 553-594.

NORTH CANTERBURY CATCHMENT BOARD 1983: Interim report on the groundwater resource of the central plains. 192p.

NORTH CANTERBURY CATCHMENT BOARD 1986: The Christchurch artesian aquifers, 206p.

Petch, R.A.; Bell, A.R.; Depledge, D.; Hadfield, J.C.; Maggs, G.R.; Ringham, K.L. 1991: An assessment of ground and surface water resources in the Pukekohe/Tuakau area. Waikato Regional Council Technical Report 1991/12. 141p.

Pillans, B. 1986: A late Quaternary uplift map for North Island, New Zealand. In Reilly, W.I., Harford, B.E., (eds). Recent Crustal Movements of the Pacific Region. The Royal Society of New Zealand Bulletin 24: 409-417.

Pillans, B. 1991: New Zealand Quaternary stratigraphy: an overview. Quaternary Science Reviews 10: 405-418.

Raeside, J.D. 1964: Loess deposits of the South Island, New Zealand, and soils formed on them. New Zealand Journal of Geology and Geophysics 7: 811-838.

Risk, G.F. 1980: Tests of the applicability of electrical prospecting methods for detecting underground seepage of pulp and paper mill effluent at Kinleith. Report No. 170, Geophysics Division, Department of Scientific and Industrial Research, Wellington. 12p.

Robb, C.A. 2000: Information on water allocation in New Zealand. Lincoln Environmental Client Report 4375/1 to Ministry for the Environment. 180p.

Rosen, M.R.; Jones, S. 1998: Controls on the groundwater composition of the Wanaka and Wakatipu basins, Central Otago, New Zealand. Hydrogeology Journal 6: 264-281.

Rosen, M.R.; Reeves, R.; Stewart, M.K.; Taylor, C.B. 1997: Ground water quality of the Wanaka and Wakatipu basins, Central Otago, New Zealand. Institute of Geological and Nuclear Sciences Science Report 97/1. 98 p.

Serra, O. 1986: Fundamentals of well-log interpretation, 2. The interpretation of logging data. Developments in Petroleum Science 15B. Elsevier. 684p.

Stevens, G.R. 1974: Rugged landscape: the geology of central New Zealand, including Wellington, Wairarapa, Manawatu, and the Marlborough Sounds. Reed. 286p.

Suggate, R.P.; Stevens, G.R.; te Punga, M.T. eds. 1978: The Geology of New Zealand. New Zealand Geological Survey. New Zealand Department of Scientific and Industrial Research. Two volumes, 820p.

Suggate, R.P. 1990: Late Pliocene and Quaternary glaciations of New Zealand. Quaternary Science Reviews 9: 175-197.

Tasman District Council 1991: Waimea Catchment Water Management Plan. 73p.

Thain, I.A.; Dunstall, M. 2000: 1995-2000 update report on the existing and planned use of geothermal energy for electricity generation and direct use in New Zealand. Proceedings World Geothermal Congress, Kyushu-Tohuku, Japan, May 28 - June 10. 481-489.

Thornton, J. 1995: The Reed Field Guide to New Zealand Geology. Reed, Auckland. 226p.

Thorpe, H.R. 1992: Groundwater - the hidden resource. In M. Paul., Mosley, (ed) Waters of New Zealand. New Zealand Hydrological Society, Wellington. 167-186.

Thorpe, H.R.; Scott, D.M. 1979: Groundwater - state of the art in New Zealand. In Physical Hydrology - New Zealand Experience. Murray, D.L. and Ackroyd, P., eds. New Zealand Hydrological Society. 84-96.

Toebes, C. 1972: The water balance of New Zealand. Journal of Hydrology (New Zealand) 11(2): 127-139.

Walcott, R.I. 1979: Plate motion and shear strain rates in the vicinity of the Southern Alps. In R.I. Walcott and M.M. Cresswell eds. The Origin of the Southern Alps. Royal Society of New Zealand Bulletin 18: 5-12.

Wellman, H.W. 1979: An uplift map for the South Island of New Zealand, and a model for uplift of the Southern Alps. In Walcott, R.I. and Cresswell, M.M. (eds). The Origin of the Southern Alps. The Royal Society of New Zealand, Wellington. Bulletin 18: 13-20.

White, P.A. 1997a: Hydrological extremes and the groundwater system. In M.P. Mosley and C.P. Pearson (eds), Floods and Droughts: the New Zealand Experience. New Zealand Hydrological Society, Wellington. 143-157.

White, P.A. 1997b: A postaudit study of the Waimea Plains aquifer model. Institute of Geological and Nuclear Sciences Science Report 97/17. 91p.

White, P.A.; Hunt, T.M. 2000: Simple models for changes in spring flows at Wairakei. Proceedings of the 22nd New Zealand Geothermal Workshop, Auckland. 203-208.

White, P.A.; Reeves, R.R. 1999: Waimea Plains aquifer structure as determined by three-dimensional computer modelling. Journal of Hydrology (New Zealand) 38(1): 49-75.

White, P.A.; Reeves, R.R.; Zhan, X. 1996: Geological and fracture flow modelling of the Pukekohe aquifer system. Institute of Geological and Nuclear Sciences science report 96/8. 64p.

White, P.A.; Sharp, B.M.H.; Kerr, G.N. In press: Economic valuation of the Waimea Plains groundwater system. Journal of Hydrology (New Zealand).

Williams, P.W. 1992: Karst hydrology. In M. Paul Mosley (ed), Waters of New Zealand, New Zealand Hydrological Society, Wellington. 187-206.

Wilson, C.J.N.; Rogan, A.M.; Smith, I.E.M. 1984: Caldera Volcanoes of the Taupo Volcanic Zone, New Zealand. Journal of Geophysical Research 89 (B10): 8463-8484.

Wilson, D.D. 1973: The significance of geology in some current water resource problems, Canterbury Plains, New Zealand. Journal of Hydrology (New Zealand) 12(2): 103-118.

Wilson, D.D. 1985: Erosional and depositional trends in rivers of the Canterbury Plains, New Zealand. Journal of Hydrology (New Zealand) 24(1): 32-44.

Wood, C.P. 1996: Basement geology and structure of TVZ geothermal fields, New Zealand. Proceedings of the 18th New Zealand Geothermal Workshop. 157-162.

4

Hydrochemistry of New Zealand's aquifers

MICHAEL R ROSEN

INTRODUCTION

Groundwater chemistry on a national scale has never been studied in New Zealand apart from a few studies on nitrate concentrations (Burden 1982; Dillon et al. 1989; Lincoln Environmental 1998) and pesticides (Close 1993, 1996). These studies are covered in Chapter 8 of this book. However general studies of groundwater chemistry, groundwater-rock interaction and regional characteristics of water quality have not been previously addressed in much detail. This is partly because New Zealand aquifers are relatively small on a world scale and are geologically and tectonically diverse (see Chapter 3). But New Zealand has also recently lacked a centralised agency responsible for groundwater quality, and therefore, no national assessments have been undertaken.

In recent years, the Institute of Geological and Nuclear Sciences has managed a programme of collecting and analysing the groundwater chemistry of key New Zealand aquifers (Rosen 1997, 1999). This programme is called the National Groundwater Monitoring Programme (NGMP) and is funded by the New Zealand Public Good Science Fund. The programme started in 1990 using only 22 wells, with four regional authorities of the country participating. The NGMP now includes all 15 regional and unitary authorities that use groundwater and over 100 monitoring sites (Fig 4.1). The NGMP is considered a nationally significant database by the New Zealand Foundation for Research Science and Technology.

The NGMP allows a national comparison of aquifer chemistries because the samples are all analysed at one laboratory in a consistent manner and undergo stringent quality control checks. Poor quality analyses are thus minimised. In addition, samples are collected quarterly so that long-term seasonal trends in water quality can be analysed, and the effects of changes in land use and the vulnerability of aquifers to contaminant leaching can be assessed.

This chapter summarises the water quality data collected for the NGMP over the past 10 years. Some records are much shorter than others, but most are greater than three years. Additional information is taken from regional authority "State of the Environment" reports and from detailed reports on central Canterbury (Burden 1984; Close 1987; Close et al. 1995). The chapter summarises the major element chemistry and relates this to aquifer geology and land use. Nutrient chemistry and an analysis of some heavy metals are also included and this information is related to land use. Pesticides and nitrate are discussed in Chapter 8 and nitrate is only briefly mentioned here under nutrients. A brief discussion of hydrocarbons and other organic chemicals is included for areas that have available data, but a discussion of microbial contamination of groundwater is reserved for Chapter 9.

Limitations of the data set

Compared to the number of wells throughout New Zealand, the NGMP data set is relatively small, approximately 110 wells. Although no accurate number of wells for the country is readily available, the Environment Canterbury well database alone contained 19,304 wells as of 30 June 1996 (Canterbury Regional Council 1997).

Therefore, there are likely to be over 100,000 wells used for groundwater supply and monitoring throughout New Zealand. However, there is little geological information or well

Rosen M.R. 2001: Hydrochemistry of New Zealand's aquifers. *In* Groundwaters of New Zealand, M.R. Rosen and P.A. White *(eds)*. New Zealand Hydrological Society Inc., Wellington. p77-110.

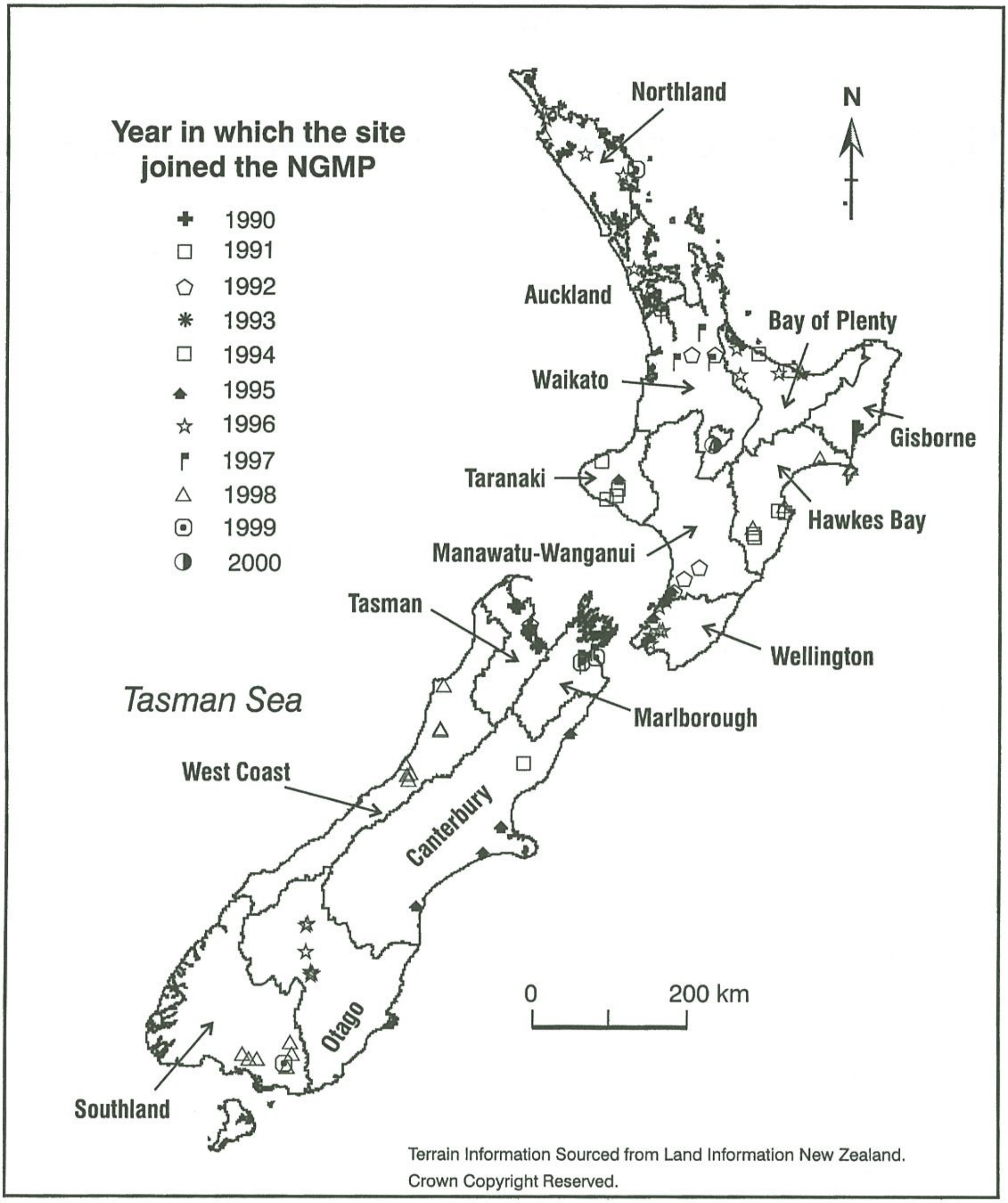

Figure 4.1 *Location of wells monitored for the NGMP. Symbols represent the year when the first samples were taken at the sites. Boundaries are regional council and unitary authority boundaries.*

construction information for most of these wells, so many are of little use in interpreting water quality information.

An important concern of the project has been the scale of sampling in each region and throughout New Zealand. Groundwater samples are, by necessity, collected from points and there is always some uncertainty as to spatial variability and how representative the sampling location is of the whole aquifer. Most NGMP wells have been strategically located to be near recharge areas or in up-gradient positions, to give an early indication of possible contamination.

The NGMP data set includes a wide variety of aquifer types and geological materials, and has a wide geographical distribution, so the selection of a small number of good quality wells is a reasonable way to assess general trends on a national scale. It is recognised however that a larger data set would be useful for refining the estimates made in this chapter, but until more wells are incorporated into the NGMP, the present data will have to suffice.

Geology of the aquifers

All of the large aquifers in New Zealand are sedimentary (see regional summaries for more detail). The aquifers in Canterbury, Hawke's Bay, Wellington, Gisborne and West Coast are composed of gravels and sands, mostly derived from greywacke material brought down by rivers and deposited in valley bottoms or on alluvial fans. In the Tasman District, many of the sedimentary aquifers have been derived from granitic material. All the major volcanic aquifers (either volcanic sediments or fractured basalt) are in the upper North Island (Northland, Auckland, Taranaki, Waikato and Bay of Plenty), although the volcanic rocks that form Banks Peninsula near Christchurch and parts of Otago on the South Island have limited supplies (see Chapters 23 and 25). Most of the wells included in the NGMP are in sedimentary lithologies (Table 4.1), but other important aquifers are composed of fractured basalts (Waikato, Auckland, Bay of Plenty, Taranaki), pumice (Bay of Plenty), and limestones (Tasman), although these aquifers are minor in comparison to the alluvial gravel aquifers. Limited use is made of water from fractured metamorphic rocks in central Otago for single-family rural domestic supplies (Rosen and Jones 1998), but these wells are not included in the NGMP. Table 4.1 shows the principal lithologies for aquifers in the NGMP. Many wells penetrate multiple lithologies, so the totals are greater than the number of wells in the database. Gravel and sand make up 76% of the lithologies recorded; no other category is greater than 5%. Many of the aquifers sampled in the NGMP are unconfined and shallow (54%), 13% are semi-confined, but 33% are confined and deep. The average thickness of the aquifers is 27 m, and the average depth to the top of the aquifers is 29 m, however, 26% of the wells have water levels ≤10 m below the surface.

It is apparent from the information supplied by the regional councils that detailed geochemical information on the aquifers is lacking. Most sediments are reported by grain size (i.e. silt, sand or gravel) rather than by lithology (i.e. quartz sand, granitic or graywacke gravels etc.). Although it is relatively simple to predict the major chemical components of limestone aquifers (Ca and HCO_3), predicting the chemical composition of water derived from sands and gravels is more difficult. In addition, because many of the aquifers are derived from river sediments, the aquifer material may be a mixture of many different lithologies. Furthermore, many New Zealand groundwater systems have relatively high flow rates and low residence times, and may not have come to equilibrium with aquifer lithologies. Therefore, determining the predominant controls on water chemistry can be difficult. Nevertheless an attempt has been made at correlating the hydrochemical composition of aquifer water with lithologies from the spatial distribution of chemical abundances.

Land uses

There are 16 different land-use designations in the NGMP. Land uses were determined for radii of 10 m and 200 m around each well. Those wells in confined aquifers also had land-use designations for the recharge area. Using this system, most wells had more than one land-use designation (Table 4.2). Most of the land-use designations reflect the rural nature of the database, because the network is designed to detect non-point source contamination. However, approximately 10% of the wells are in urban settings (Table 4.2). Land uses can

Table 4.1 *Geological and aquifer characteristics of NGMP wells**

Hole ID	Top of aquifer (m)	Bottom of aquifer (m)	Aquifer thickness (m)	Aquifer Name	Aquifer Type	Geology
Auckland Region						
6475015	1	16	15	Shallow Waitemata Sandstone	Semi-Confined	sand
6485070	UNKNOWN	78	<78	Deep Waitemata Sandstone	Semi-Confined	sandstone, siltstone
7417023	UNKNOWN	103.2	<103.2	Waitemata Sandstone	Confined	sandstone, siltstone
7418027	UNKNOWN	65.1	<65.1	Kaawa Shellbed	Confined	silt, gravel, shell
7428103	UNKNOWN	UNKNOWN	UNKNOWN	Deep Pukekohe Basalt		volcanic
7428105	0	UNKNOWN	UNKNOWN	Shallow Pukekohe Volcanics	Unconfined	volcanic
WATSON_AVE_1	0	38.4	38.4	Three Kings Basalt	Unconfined	volcanic sediment, basalt
Canterbury Region						
J39/0109	13	13.7	0.7	Cannington Gravel	Unconfined	gravel
L36/871	1	12	11	Springston Gravel	Unconfined	na, na
M35/1382	10	34	24	Riccarton Gravel	Unconfined	gravel, greywacke-derived
M35/6791	1	13	12	Aquifer 5	Confined	gravel, greywacke-derived
N33/205	23	30	7	Not Defined	Semi-Confined	gravel, greywacke-derived
O31/0156	20	31	11	Aquifer 2 (Kaikoura)	Confined	gravel, greywacke-derived
Bay of Plenty Region						
ALLEN	3	10	7	Maketu Pumice Aquifer	Unconfined	volcanic sediment
BEEK	2	9	7	Rangitaiki Plains Sand	Unconfined	sand
FERNLANDSPA	96	176.8	80.8	No Name	Unconfined	volcanic sediment, rhyolite
LAING	281	319.5	38.5	Matahina Ignimbrite	Confined	sand, gravel, volcanic sediment
OHOPEGC	5.8	7.4	1.6	Ohiwa Spit Sand Aquifer	Unconfined	sand, gravel, shell
PEMBERTON	103.6	134.1	30.5	Mamaku Ignimbrite	Confined	volcanic sediment, ignimbrite
Waikato Region						
COROMANDEL	1.6	6	4.4	Holocene Beach Barrier Dune	Unconfined	sand
GRAHAM	14	33	19	Franklin Basalt	Confined	volcanic sediment
HAMBASIN	3	6	3	Hinuera Formation	Unconfined	gravel
HANDCOCK	9	28	19	Franklin Basalt	Unconfined	volcanic sediment, basalt
HAURAKIGRABEN	14.58	21.98	7.4	Tauranga Group Sediments	Confined	sand, gravel, volcanic sediment
PUKEKOHE	23.8	35	11.2	Franklin Basalt	Semi Confined	volcanic sediment, basalt
REIDS	4.5	8.5	4	Tauranga Group	Unconfined	gravel
SPRINGDALE_SCH	2	6	4	Hinuera Formation	Semi Confined	gravel, volcanic sediment
WILCOX	14	66	52	Hinuera Formation	Unconfined	sand, gravel, volcanic sediment

Table 4.1 *Geological and aquifer characteristics of NGMP wells** (continued)

Hole ID	Top of aquifer (m)	Bottom of aquifer (m)	Aquifer thickness (m)	Aquifer Name	Aquifer Type	Geology
Gisborne Region						
GPB102	81	94	13	Matokitoki	Confined	sand, gravel, shell
GPC031	1.5	10	8.5	Te Hapara	Unconfined	sand
GPC062	2.7	9.8	7.1	Te Hapara	Semi To Unconfine	sand, gravel, shell
GPD130	61	65	4	Makauri (Bilnd End)	Confined	silt, sand, greywacke-derived
GPE006	17	24	7	Waipaoa	Semi-Confined	sand, gravel
GPF090	45.7	51.8	6.1	Makauri (Recharge End)	Confined	gravel, volcanic sediment
Hawkes Bay Region						
WAIPUKURAU	2.8	25.19	22.39	Ruatauwha Plains Aquifer	Unconfined	gravel, greywacke-derived
WELL#1450	46	UNKNOWN	UNKNOWN	Heretaunga Plains	Confined	gravel, greywacke-derived
WELL#1558	UNKNOWN	22.6	<22.6	Ruatauwha Plains Aquifer	Semi Confined	gravel, greywacke-derived
WELL#1940	59.74	66	6.26	Heretaunga Plains Aquifer	Confined	sand, gravel, greywacke-derived, limestone, shell
WELL#3697	36	66	30			silt, sand, gravel, greywacke-derived
WELL#3697	70	84	14	Heretaunga Plains Aquifer	Confined	silt, sand, gravel, greywacke-derived
WELL#3697	112	126	14			silt, sand, gravel, greywacke-derived
WELL#3697	145	164	19			silt, sand, gravel, greywacke-derived
WELL#3697	193	210	17			silt, sand, gravel, greywacke-derived
WELL#3699	36	64.5	28.5	Fluvial Postglacial Gravel	Confined	gravel, greywacke-derived
Marlborough Region						
P28W/0371	21	40	19	Wairau-Coastal Confined Zone	Confined	gravel, greywacke-derived
P28W/0426	0	25	25	Wairau-Recharge Zone	Unconfined	sand, gravel
P28W/0612	10	25	15	Wairau	Transitional	sand, gravel
P28W/1634	0	10	10	Rarangi Shallow Aquifer	Unconfined	na
P28W/1873	30	83.5	53.5	Omaka	Semi To Confined	silt, sand, gravel
P28W/1879	30	91.5	61.5	Brancott	Semi To Confined	gravel
P28W/1945	22	60	38	Omaka	Semi To Confined	gravel

Table 4.1 *Geological and aquifer characteristics of NGMP wells** (continued)

Hole ID	Top of aquifer (m)	Bottom of aquifer (m)	Aquifer thickness (m)	Aquifer Name	Aquifer Type	Geology
Manawatu-Wanganui Region						
HINDE	32	34	2	No Name	Confined	gravel
MCALOON	33.5	36.5	3	No Name	Confined	gravel
REESBY	0	4	4	Horowhenua	Unconfined	sand
YULE	27	29	2	No Name	Semi-Confined	gravel
Northland Region						
AHIPARA	5.6			Ahipara Sand	Unconfined	sand
COLVILLE	20	45	25	Alpuri Sand	Confined	sand
FARNORTH	65	75	10	Alpuri Shell Bed	Confined	sand, shell
GREEN	25	45	20	Whangarei Basalt	Confined	volcanic sediment
KAIKOHEHILL	0	30	30	Whangarei Basalt	Confined	volcanic sediment, basalt
TARA_MANGAWHAI	18	48	30	Tara Basalt	Unconfined	volcanic sediment, basalt
Otago Region						
G400120	UNKNOWN	16	<16	Hawea Outwash	Unconfined	sand, gravel
G400129	5	26.4	21.4	Hawea Outwash	Unconfined	gravel
G410103	UNKNOWN	29.4	<29.4	Cluther Outwash Alluvium	Unconfined	sand, gravel
G420119	UNKNOWN	40	<40	Cluther Recent Outwash	Unconfined	sand, gravel
G420150	UNKNOWN	35	<35	Cluther Recent Outwash	Unconfined	sand, gravel
G420160	UNKNOWN	32.3	<32.3	Cluther Recent Outwash	Unconfined	sand
G420190	UNKNOWN	21.3	<21.3	Clutha Recent Outwash	Unconfined	sand
Tasman Region						
PUPU	30	500	470	Takaka Marble Aquifer	Confined	limestone
WWD3108	6	10	4	Motueka Gravel Aquifer	Unconfined	sand, gravel
WWD3115	0	9.4	9.4	Central Riwaka Plains		gravel
WWD3115	5	10	5	Motueka Gravel Aquifer	Unconfined	gravel
WWD32	25	38.1	13.1	Lower Confined Aquifer	Confined	sand, gravel
WWD3216	7	20	13	Motueka Gravel Aquifer	Unconfined	gravel
WWD3314	3	24	21	Motueka Gravels Aquifer	Unconfined	gravel
WWD37	11	20.5	9.5	Upper Confined Aquifer	Confined	sand, gravel
WWD6601	30	55	25	Takaka Limestone Aquifer	Confined	limestone
WWD802	3	11	8	Appleby Gravel Unconfined	Unconfined	gravel
WWD8404	UNKNOWN	236	<236	Shallow & Middle Moutere Aquifer	Confined	sand, gravel
WWD8407	70	337	267	Lower & Middle & Deep Moutere	Confined	gravel

Table 4.1 *Geological and aquifer characteristics of NGMP wells** (continued)

Hole ID	Top of aquifer (m)	Bottom of aquifer (m)	Aquifer thickness (m)	Aquifer Name	Aquifer Type	Geology
Taranaki Region						
BAYLY	72.2	77.7	5.5	Matemateaonga Formation	Confined	sand, shell
CARRINGTONRD	0	8.6	8.6	Taranaki Volcanics Formation	Unconfined	volcanic sediment
CORRIGAN	UNKNOWN	234.6	<234.6	Whenuakura Formation	Confined	sandstone
ELTHAMDAIRY	UNKNOWN	271.3	<271.3	Matemateaonga Formation	Confined	sandstone
HANN	55.49	86.59	31.1	Matemateaonga Formation	Confined	siltstone
MCCALLUM-2	92	97	5	Whenuakura Formation	Confined	siltstone
MCCALLUM-2	159	161.3	2.3	Whenuakura Formation	Confined	siltstone
MCCALLUM-WELL	0	8.54	8.54	Taranaki Volcanics Formation	Unconfined	gravel
Wellington Region						
AVALONSTUDIOS	0	50	50	Taita Alluvium	Unconfined	sand, gravel
BETTYS	0	10	10	Otaki	Unconfined	gravel
BOFFA	0	20	20	Waikanae	Unconfined	sand
COCACOLA	UNKNOWN	30.5	<30.5		Unconfined	na
EDHOUSE	18	30	12	Waitohu Groundwater Zone	Semi-Confined	sand
LIDDLENURSERIES	UNKNOWN	12.9	<12.9		Unconfined	na
MAHOEST	14.2	39.2	25	Waiwhetu Artesian Aquifer	Confined	gravel
MANGAROA	0	24.5	24.5	Mangaroa	Unconfined	sand, gravel
PENRAY	10	32	22	Hautere Groundwater Zone	Unconfined	gravel
QEPARK	5	60	55	Raumati/Paekakariki Gw Zone	Unconfined	sand
SPTYRES	5	50	45	Upper Hutt Aquifer	Unconfined	gravel
WAINUIOMATAGC	2	15	13	Wainuiomata	Unconfined	gravel

*South Island and West Coast wells are all gravel aquifers, but detailed information on aquifer characteristics is currently not available.

Table 4.2 *Summary of land-use information. Some wells are in areas with multiple land uses.*

Land use	Number and percentage* (in parentheses) of wells within areas with the specified land use (general)	Number and percentage* (in parentheses) of wells in unconfined aquifers within areas with the specified land use (10-m radius)	Number and percentage* (in parentheses) of wells in unconfined aquifers within areas with the specified land use (200-m radius)	Number and percentage* (in parentheses) of wells in confined aquifers with the specified land use in the recharge area
Dairy	24 (19)	24 (17)	25 (16)	6 (13)
Drystock	25 (20)	28 (19)	36 (24)	15 (32)
Cattle	4 (3)	4 (3)	4 (3)	2 (4)
Sheep	16 (13)	17 (12)	17 (11)	3 (6)
Deer	1 (1)	1 (1)	1 (1)	0 (0)
Horse	3 (2)	3 (2)	3 (2)	0 (0)
Cropping	3 (2)	3 (2)	3 (2)	1 (2)
Fallow	1 (1)	1 (1)	1 (1)	0 (0)
Horticulture	10 (8)	10 (7)	13 (9)	4 (9)
Orchard	19 (15)	19 (13)	21 (14)	4 (9)
Rural residential	0 (0)	16 (11)	4 (3)	0 (0)
Lifestyle	0 (0)	2 (1)	2 (1)	0 (0)
Urban	13 (10)	11 (8)	15 (10)	1 (2)
Golf course	4 (3)	4 (3)	4 (3)	0 (0)
Native	2 (2)	2 (1)	2 (1)	5 (11)
Forestry	0 (0)	0 (0)	1 (1)	6 (13)
TOTAL	125 (99)	145 (101)	152 (102)	47 (101)

*Percentage totals do not equal 100% due to rounding.

be broadly categorised as animal husbandry (deer, dry stock, sheep, cattle, dairy, horses), agricultural (horticulture, cropping, fallow, orchard), residential (rural, lifestyle, urban, golf course), native vegetation and forestry. Dairy and dry stock farming make up a significant proportion of land use around the wells, as do horticulture, orchards and sheep. The distribution of land-use categories is a reasonable reflection of the dominant rural land uses in New Zealand, particularly those that may affect groundwater quality. In this chapter, land-use information is compared with lithological information to determine the main influences on the chemical composition of water for specific wells and as a basis for comparison for the heavy metal data.

General chemistry of New Zealand's aquifers

In the figures presented in this chapter, thousands of chemical analyses of groundwater in the NGMP are summarised as median values for all wells. The data used for these figures is available on the National Groundwater Monitoring Programme Database held at the Institute of Geological and Nuclear Sciences Ltd. Interested readers who would like to obtain portions of the data should contact the institute's web site at www.gns.cri.nz.

The major ions can be plotted using a Piper diagram (Fig 4.2) that shows the diversity of different groundwater "classes" present in New Zealand. Analyses in this diagram are plotted as percentages on an equivalent basis. Water types can also be determined using equivalents (a method that takes into account the molecular weight and ionic charge of each ion). Water types or "chemical facies" are calculated by first converting the milli-equivalents per litre of the major cations (Na, Ca, Mg, K) and anions (Cl, SO_4, HCO_3) to percentages. The water type expression is formed by listing the ions with concentrations greater than 10% in decreasing order (the cations are listed first). Table 4.3 shows the top nine groups of water types determined from median concentrations using the AquaChem computer software package. Forty-two different water types were determined for the 108 monitoring sites included in the NGMP, 28 of which were unique to one sample.

The most common single type of water found

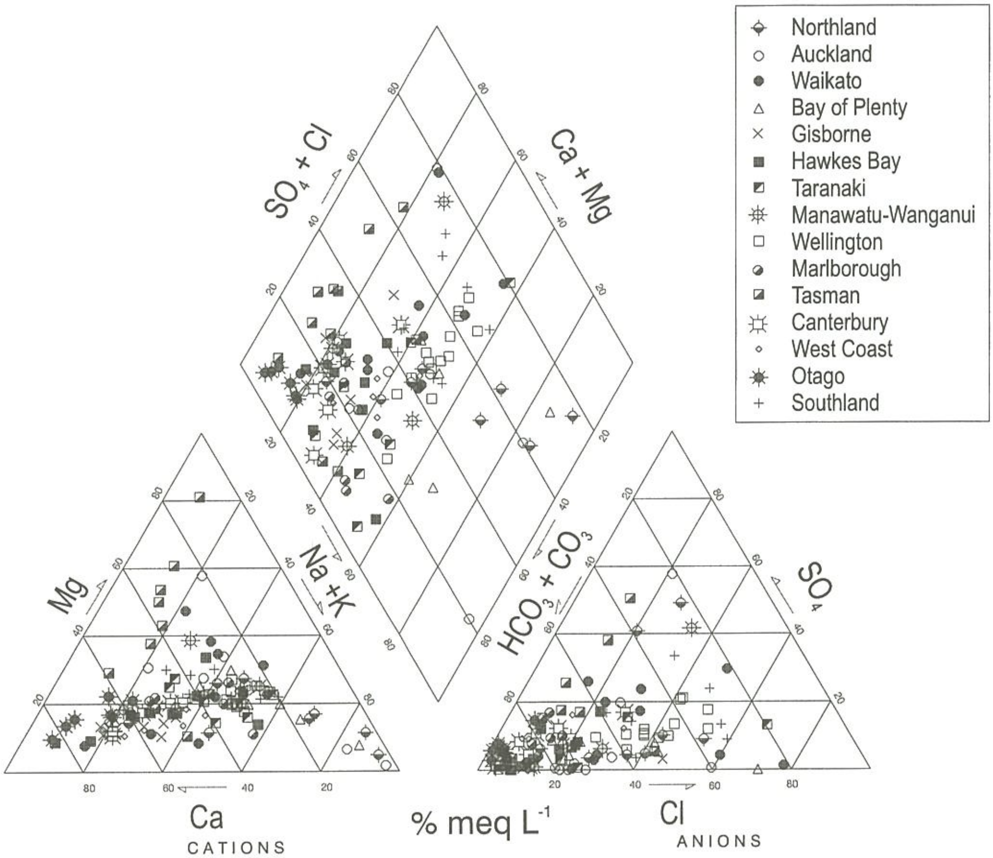

Figure 4.2 *Piper diagram of NGMP wells.*

Table 4.3 *Principal water types in NGMP wells. The number of wells of each type are in parentheses.*

	Water type	No. of wells
1	$Na-Ca-HCO_3-Cl$ (6)	19
	$Na-Ca-HCO_3$ (4)	
	$Na-Ca-Mg-HCO_3-Cl$ (5)	
	$Na-Ca-Mg-HCO_3$ (4)	
2	$Ca-Na-HCO_3$	15
3	Ca-HCO3	14
4	$Ca-Na-HCO_3-Cl$ (7)	14
	$Ca-Na-Mg-HCO_3$ (7)	
5	$Na-Mg-Ca-HCO_3-Cl$	6
6	$Ca-Mg-HCO_3$ (3)	5
	$Ca-Mg-Na-HCO_3$ (2)	
7	$Ca-Na-Mg-HCO_3-Cl$	3
8	$Na-HCO_3-Cl$	3
9	$Mg-Ca-HCO_3-SO_4$	2

is a $Ca-Na-HCO_3$ solution (15 wells), followed closely by $Ca-HCO_3$-dominated water (14 wells), only one of which was from a limestone aquifer. Five of the wells were from central Otago, and located in alluvial gravel aquifers derived from metamorphic rocks. Rosen and Jones (1998) documented the importance of finely disseminated calcite in the host metamorphic rocks as a source of Ca and HCO_3 in the Wanaka and Wakatipu basins. They demonstrated that dissolution of this calcite constituted 80% of the dissolved ions in solution, even though calcite made up <5% of the rock. The aquifers in these basins were also the $Ca-HCO_3$ water type. Nineteen other wells have Na, Ca and HCO_3 as the most common ions, plus or minus Mg or Cl. All of the top groups include bicarbonate (HCO_3) as the most abun-

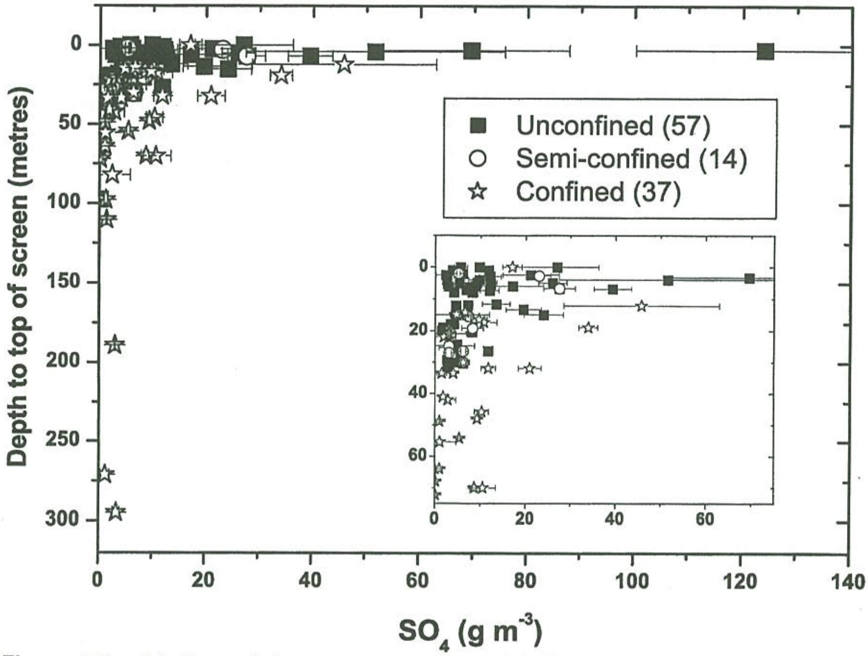

Figure 4.3 *Median sulphate concentrations with depth in NGMP wells plotted by aquifer condition. Sulphate is low and relatively constant with depth below about 40 m depth (see inset). Error bars represent one standard deviation. Numbers in the legend refer to the number of points for each aquifer condition.*

dant anion. Chloride is the dominant anion in a number of other wells, but SO_4 and NO_3 are only rarely dominant (two wells each), and it can be demonstrated that these wells are influenced by land uses near the well. It is not surprising that HCO_3 is the dominant ion, given that most groundwater monitored in the NGMP is relatively young and near the surface. The interaction of dissolved atmospheric CO_2 with organic matter in the soil zone washes HCO_3 into the groundwater (see *Alkalinity* below).

It has been recognised for almost 50 years that anions in groundwater tend to evolve towards the composition of seawater in the following sequence, known as the Chebotarev sequence (Chebotarev 1955) or the Ignatovich and Souline sequence (Freeze and Cherry1979):

Travel along flow path →→

$HCO_3 \rightarrow HCO_3 + SO_4 \rightarrow SO_4 + HCO_3 \rightarrow$
$SO_4 + Cl \rightarrow Cl + SO_4$
$\rightarrow Cl$

Increasing age →→

This sequence rarely goes to completion, except in large basins, and in many cases it may be interrupted or changed due to chemical or biochemical reactions within the groundwater system. New Zealand groundwater rarely evolves past the HCO_3 stage, but when it does, SO_4 is rarely present. The absence of SO_4 in the sequence is most likely due to sulphate reduction in confined sluggish aquifers, particularly in coastal areas such as Gisborne. The concentration of SO_4 decreases with depth (Fig 4.3), suggesting that sulphate reduction is occurring. Aquifers that are dominated by Cl are not necessarily more evolved than other aquifers, but may simply be closer to the coast, or may be affected by land uses at the surface or by geothermal water.

Calcium and Na are the dominant cations in solution. Calcium is dominant in 55 wells, and sodium in 43 wells. Sodium is dominant in groundwater that is near the ocean or near geothermal areas, or in areas that are affected by certain land uses (such as land application of sewage effluent). Ion exchange reactions with clays may also increase Na in solution. Calcium dominates in areas where limestone or marble is the major lithology of the aquifer (i.e. parts of the Tasman district), or where carbonate pebbles, cements, and shell material are present in the aquifer rock matrix or in the recharge area.

Mg dominates the chemistry of 10 wells in the NGMP. Orchard and market gardens are the principal land uses around these 10 wells, and most of the wells also have relatively high nitrate concentrations. This suggests that the dominance of Mg is not due to water-rock interaction, but is related to land use, possibly fertiliser applications. Rosen (1999) documented rising and falling Mg trends in Waimea Plains (Tasman District) groundwater. Although some Mg may come from the weathering of serpentinite in the recharge area, the rising and falling trends suggest that land use plays some role in the dominance of Mg in the groundwater.

MAJOR IONS

Sodium and chloride

Median sodium (Na) concentrations range from 2.2 g m^{-3} in central Otago to 306 g m^{-3} in coastal Northland, with most falling below 50 g m^{-3} (Fig 4.4). Many of the samples analysed for the NGMP fall on the seawater concentration-dilution line (SCDL) for sodium and chloride (Cl) (Fig 4.4). The SCDL represents water with the same proportional concentration of Na and Cl as seawater. Water evaporated from the ocean will contain dissolved salts from seawater that are in the same ratio as in the ocean. As the water is rained out over land, it will flush out Na and Cl from the cloud and contribute Na and Cl to recharge water. Therefore groundwater collected closer to the ocean will tend to have Na:Cl ratios similar to seawater and will fall along the SCDL. Figure 4.3 shows that many groundwater samples in New Zealand fall close to or directly on the SCDL. This indicates that these groundwaters receive most of their sodium (Na) and chloride (Cl) from the ocean. In other areas, Na may be enriched relative to Cl either due to water-rock interaction, mostly with sodium feldspars, and ionic exchange with clays, or input from various land uses. The only natural sink for Na is reverse ion exchange, which occurs when saline water comes in contact with calcium-rich clays (Hounslow 1995), however, this does not commonly occur in New Zealand groundwaters.

There are only two cases of Na depletion in the New Zealand aquifers studied. One of the wells is located in Gisborne and the other in the Waikato (Fig 4.4). The Waikato well is in the Franklin Basalt, and its water is relatively close to the SCDL, but another well in the Franklin Basalt has a much lower chloride concentration and does not plot below the SCDL. Rosen et al. (1999) showed that the shallow Franklin Basalt aquifer in the Pukekohe region is greatly influenced by rainfall with a seawater signature. This suggests that although the Na concentration is slightly below the SCDL, the main source of Na is seawater. Both wells are located in or near market gardens, so the cause is unlikely to be differing land uses. The Gisborne well is well below the SCDL line and situated in a shallow coastal aquifer. Reverse ion exchange reactions may cause sodium to be adsorbed onto clay particles in the aquifer, lowering the sodium concentration (Hounslow 1995). However, the geology of the aquifer is not well enough known to prove this.

There are limited sources of chloride ions in New Zealand that can provide Cl to groundwater. Most rocks do not contain appreciable Cl, and those that do, such as halite or other evaporites, do not occur in New Zealand. Geothermal fluids may provide some sodium and chloride, but these fluids are limited to certain areas of the Taupo Volcanic Zone. Chloride is relatively conservative in groundwater and once it is in solution is difficult to remove. The dominant source of chloride in New Zealand groundwater is from salts carried in clouds that have been evaporated from seawater (sea spray). Sources of sodium in New Zealand include sea spray, geothermal springs, plagioclase feldspars (albite and nepheline) and ion exchange reactions with Na-montmorillonite clays. An additional source of both Na and Cl (and other seawater-derived ions) in confined, slow-moving coastal aquifers could be paleo-

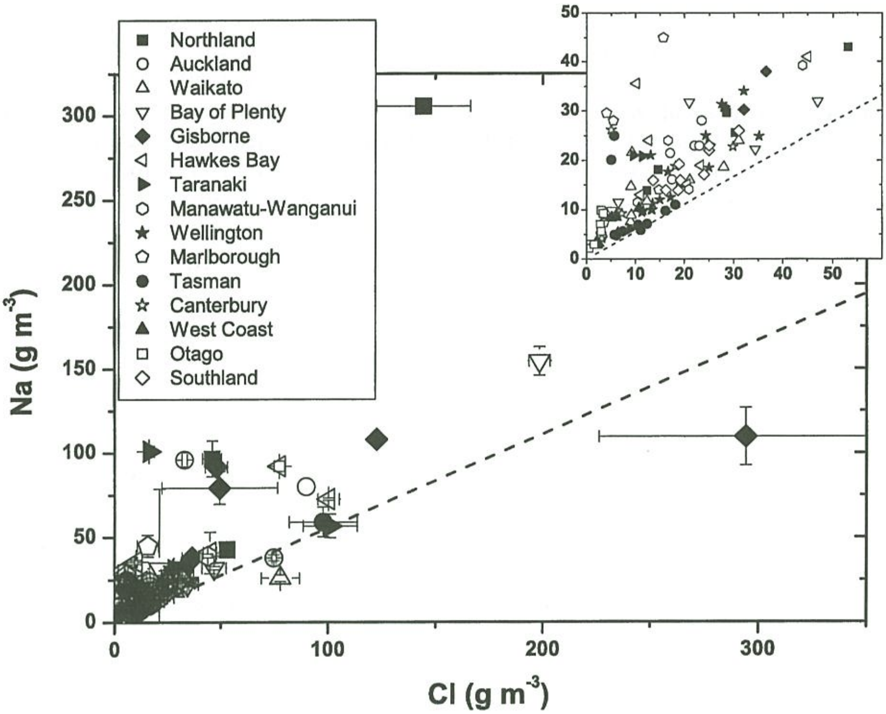

Figure 4.4 *Median sodium concentration plotted against median chloride for each region. Dashed line is the seawater concentration-dilution line (SCDL). Error bars represent one standard deviation. Inset shows detail for the lower concentrations without error bars plotted.*

seawater trapped in marine-derived sediments when they were deposited. Deep coastal aquifers in Canterbury and Gisborne may be likely places where salts could be derived in this manner. Non-natural sources of sodium and chloride include human and animal sewage, some types of industrial wastes and landfill leachate. Sodium and Cl are not generally dominant ions in fertilisers.

Potassium

The concentration of potassium (K) is generally low in New Zealand groundwaters, generally <10 g m^{-3}. This is because there are many sinks for K, both in the soil zone and within aquifers, that remove large amounts of K from solution, e.g., plant uptake of K, ion exchange reactions and the formation of clays (illite). Common anthropogenic sources of K include fertilisers and human and animal waste. However, because plants utilise most of the fertiliser K and reactions with clay minerals in the soil zone take up the remainder, it does not readily accumulate in solution. Gisborne appears to be an area of New Zealand that has higher K concentrations than most places. One median value is 16 g m^{-3} (well GPC062) and all median values are above 5 g m^{-3} (Fig 4.5). For well GPC062, the high K concentrations may be due to extensive fertiliser applications in the plains, exceeding the soils' capacity to take up the potassium. The well draws water from a shallow aquifer (Te Hapara Aquifer) that is <10 m deep, and is semi-confined to unconfined. But some of the other wells in Gisborne with high K concentrations are located in confined aquifers that contain old water (>3000 years, see *Ammonium* below), so that modern land uses would not have affected the composition of the aquifer water. In general, K concentrations are less than 3 g m^{-3}, particularly in groundwater that has low Na as well (Fig 4.5).

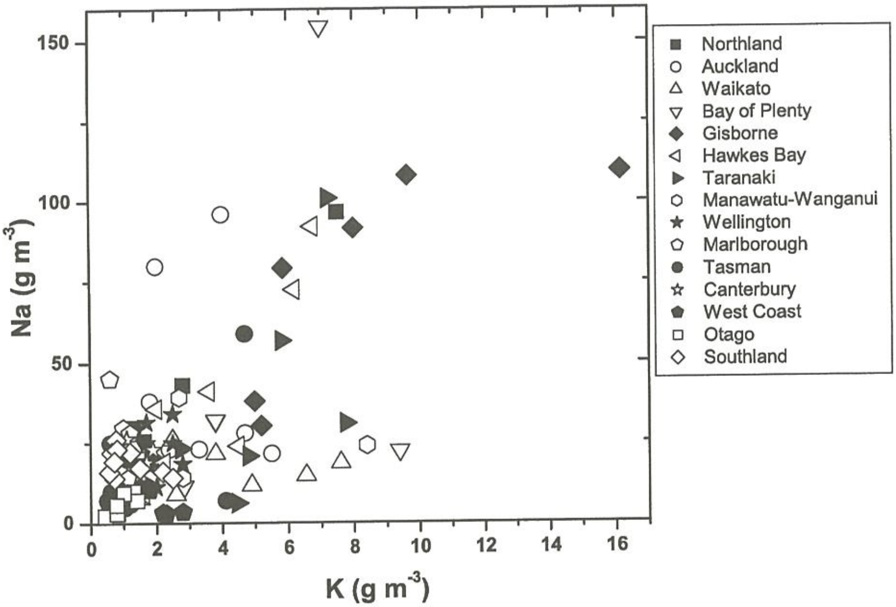

Figure 4.5 *Median potassium (K) plotted against median sodium (Na). Note: one well with a Na concentration >300 g m^{-3} from Northland is not plotted; it has a median K concentration of 15.9 g m^{-3}.*

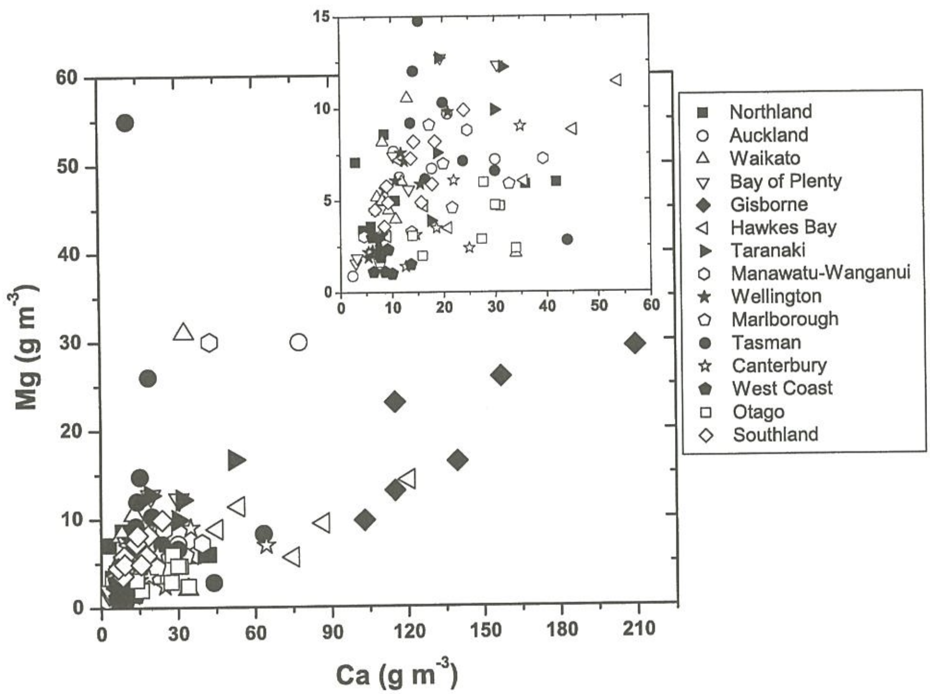

Figure 4.6 *Median calcium plotted against median magnesium for NGMP wells. There is a general trend of increasing magnesium with increasing calcium.*

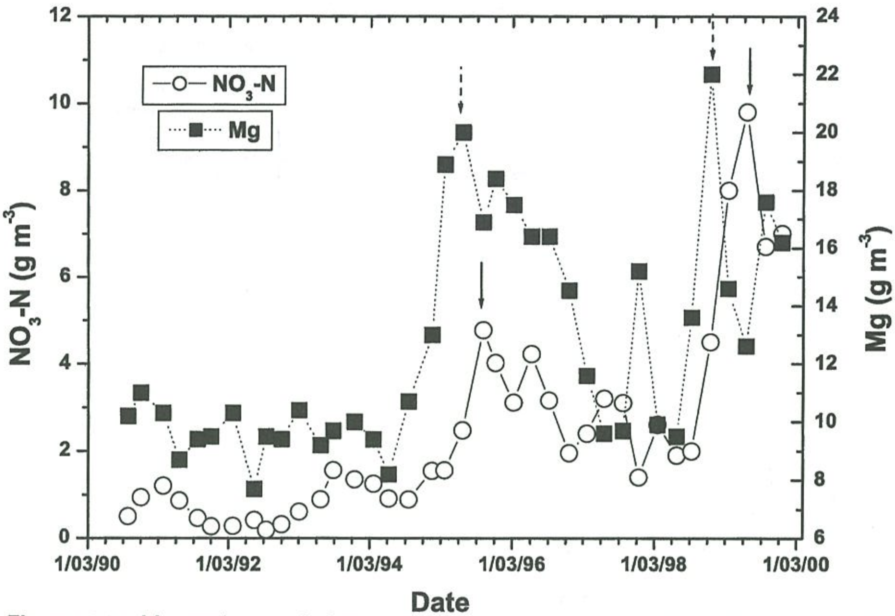

Figure 4.7 *Magnesium and nitrate concentrations plotted against time for a well in the Tasman District. Higher nitrate concentrations occur when fertiliser is applied to market gardens. Magnesium concentrations peak (dashed arrows) three to six months before the nitrate peaks (solid arrows).*

Calcium and magnesium

Sources of calcium include dissolution of carbonates (aragonite, calcite and dolomite), sulphates (gypsum, anhydrite), fluorite, plagioclase feldspars, pyroxene and amphiboles (Hounslow 1995). However, bedded sulphates do not occur in New Zealand. Limestones are relatively rare in New Zealand, but carbonate cement, pebbles and shells are relatively common, particularly in coastal aquifers. Large quantities of calcium oxide (CaO) are added as lime to pastures and other agricultural areas to adjust soil pH. Sources of Mg include dolomite and silicates (olivine, pyroxene, amphibole and mica). Dolomite aquifers are rare in New Zealand and Mg concentrations rarely exceed 15 g m^{-3}, suggesting that the silicates are the main source of Mg in New Zealand aquifers.

High Mg concentrations associated with some wells in the Tasman District (Fig 4.6) may be derived from dissolution of serpentinite, but the application of fertilisers that include Mg cannot be discounted (see above). One shallow well near the coast shows increases in Mg at about the same time that nitrate concentrations increase in the groundwater (Fig 4.7). The nitrate increases are related to fertiliser that is applied when a market garden is operating. The Mg concentrations actually increase slightly before the nitrates, indicating that Mg is moving faster through the aquifer than the nitrate, or that some time is needed to convert fertiliser applied as urea or NH_4 to nitrate.

The main sink for Ca and Mg is adsorption (ion exchange) onto montmorillonite clays.

Alkalinity (HCO_3)

Alkalinity is measured by titration of a solution with a known concentration of acid to a pH end point of 4.5. Alkalinity is a measure of those chemicals in the solution that buffer the pH and is defined as the capacity of a solution to react with strong acid (Hounslow 1995). The main components that buffer pH and contribute to alkalinity are carbonate (CO_3^{2-}), bicarbonate (HCO_3^-) and carbonic acid ($H_2CO_3^*$). For the total analytical concentration of dissolved CO_2, which is equal to $[CO_{2(aq)}] + [H_2CO_3]$, we abbreviate this as H_2CO_3* (Stumm and Morgan 1981). Other compounds can contribute to alkalinity, such as borate, hydroxide, silicate, and organic ligands, but in most New Zealand groundwater these elements are insignificant. For water with a pH between 4.5 and 8.3, bicarbonate (HCO_3) is the main contributor to alkalinity. All groundwater samples in the NGMP have median pH values between 5.8 and 8.5, so that in this chapter alkalinity will be referred to as HCO_3.

The main sources of bicarbonate and carbonate are from reactions with water and CO_2 in the atmosphere: $H_2O + CO_2 \Leftrightarrow H_2CO_3 \Leftrightarrow H^+ + HCO_3^-$, from sulphate reduction (see *Sulphate* below), and from the dissolution of carbonate rocks (calcite, aragonite, and dolomite). Rosen and Jones (1998) showed that if dissolution of calcite controls the chemistry of the groundwater, then Ca and HCO_3 will fall on a 1:1 regression line on a milli-equivalent basis (Fig 4.8). This is because the dissolution of calcite yields 1 mole of Ca for every 2 moles of HCO_3: $CaCO_{3(s)} + CO_2 + H_2O \Leftrightarrow Ca^{2+} + 2HCO_3^-$. On an equivalent basis (because of the charge difference), one mole of Ca is given an equal weight to 2 moles of HCO_3. However, the weathering of anorthite (plagioclase feldspar) will also lead to the same Ca and HCO_3 relationship in the solution as the dissolution of calcite. However, anorthite is much less common than calcite and is much less soluble under New Zealand conditions. Therefore the dissolution of anorthite is not considered a major source of Ca and HCO_3 in New Zealand groundwater.

Groundwater from Pupu Springs and the Takaka Limestone falls directly on the 1:1 regression line, and the shallow Te Hapara coastal aquifer in Gisborne, which contains significant shell material (see Chapter 16), plots near the line (Fig 4.8). However, most wells in the NGMP have a greater proportion of HCO_3 compared to Ca. This suggests that HCO_3 is derived more from reactions involving soil organic matter than from calcite dissolution. The most common sink of bicarbonate is the precipitation of calcite. However, only more arid regions of the country such as parts of central Otago are likely to precipitate calcite (c.f. Rosen and Jones 1998).

Sulphate

Sulphate mainly comes from the oxidation of pyrite, the dissolution of sulphate minerals (gypsum and anhydrite), and from sea spray. There are no significant bedded sulphate deposits near groundwater aquifers in New Zealand, so this source of sulphate can be discounted. Pyrite is relatively ubiquitous in silicate rocks and can be important in some carbonate sequences. Sulphate concentrations in the NGMP wells are enriched relative to the concentration to be expected if the sulphate were all derived from seawater. However, when SO_4 is plotted against Mg, it appears that only those wells with significant land use inputs of sulphate (mostly added as gypsum in fertiliser) plot above the seawater concentration-dilution line for Mg and SO_4 (Fig 4.9). Rekker (1998) showed a similar plot for sulphate concentration in Oteramika groundwater in Southland. In this study, groundwater near the recharge area had SO_4 concentrations that plotted along the seawater concentration-dilution line (SCDL), but down-gradient groundwater was significantly enriched, probably due to fertiliser application. In many wells Mg is enriched relative to the SCDL even when plotted against SO_4. This may be due to enrichment of Mg because of land uses, ion exchange reactions, or to lower levels of sulphate due to sulphate reduction. Sulphate concentrations decrease with depth and in general are lower in confined aquifers (Fig 4.3). This suggests that sulphate reduction is occurring at least in some aquifers (it is difficult to make generalisations for all aquifers). The reaction is as follows:

$$SO_4^{2-} + 2CH_2O \rightarrow 2HCO_3^- + H_2S$$

The reaction produces bicarbonate and hydrogen sulphide as the product. This indicates that the water may have a hydrogen sulphide smell when sampled.

However, this may not always be the case, as it depends on reducing conditions within the aquifer. If sulphate reduction is occurring, bicarbonate should increase with depth. This relationship holds for Gisborne aquifers: generally the confined aquifers have higher bicarbonate concentrations than the shallow unconfined aquifers, but a definitive relationship, particularly for some of the deeper wells

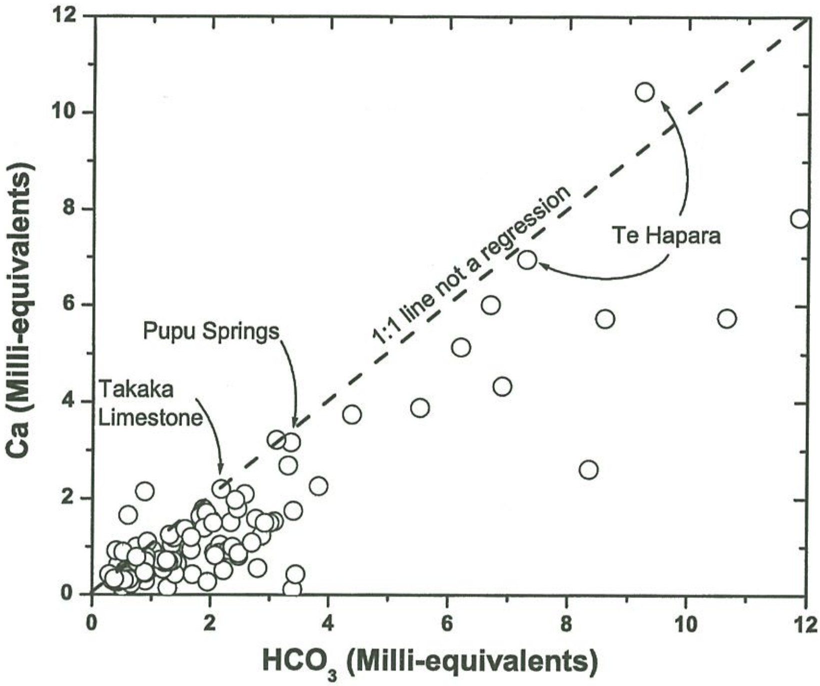

Figure 4.8 *Median calcium plotted against median bicarbonate as milli-equivalents. Calcium carbonate-dominated aquifers tend to plot on the 1:1 line.*

has not been proven. Another possible sink is the precipitation of pyrite, which may occur in aquifers that have undergone sulphate reduction. Precipitation of gypsum and anhydrite is unlikely given the low concentrations of dissolved ions that are present in New Zealand groundwater.

Silica

Monomeric silica (SiO_2) concentrations (all concentrations reported as SiO_2) in many of the wells in the NGMP are high. The highest concentrations are from the Waikato and Bay of Plenty regions, with concentrations greater than 80 g m^{-3} SiO_2 in the Bay of Plenty region. Concentrations greater than about 30 g m^{-3} are considered to result from mixing with geothermal water or dissolution of volcanic glass (Hounslow 1995). Widespread shallow pumice aquifers and relatively recent volcanic deposits are common on the North Island of New Zealand, particularly in the Waikato and Bay of Plenty regions. Therefore, it is not surprising that New Zealand groundwaters should reflect the importance of volcanic glass or pumice dissolution, particularly in regions with recent volcanism.

Na and SiO_2 appear to be relatively well correlated at low Na (<30 g m^{-3} Na) and low SiO_2 concentrations (<30 g m^{-3}). But at higher concentrations of either ion the relationship doesn't hold (Fig 4.10). High SiO_2 concentrations usually reflect dissolution of volcanic glass, and high Na concentrations contributions from seawater, which is low in SiO_2. The correlation between the two ions at low concentrations probably reflects the equilibrium dissolution of Na-feldspars and ion exchange reactions in the aquifers. However, it should be noted that high SiO_2 concentrations (>30 g m^{-3}) have been measured in some South Island wells in Canterbury, Southland, Marlborough and Tasman District, where the distribution of pumice and geothermal fluids are limited. The only regions with no groundwater silica concentrations >30 g m^{-3} are central Otago, and West Coast.

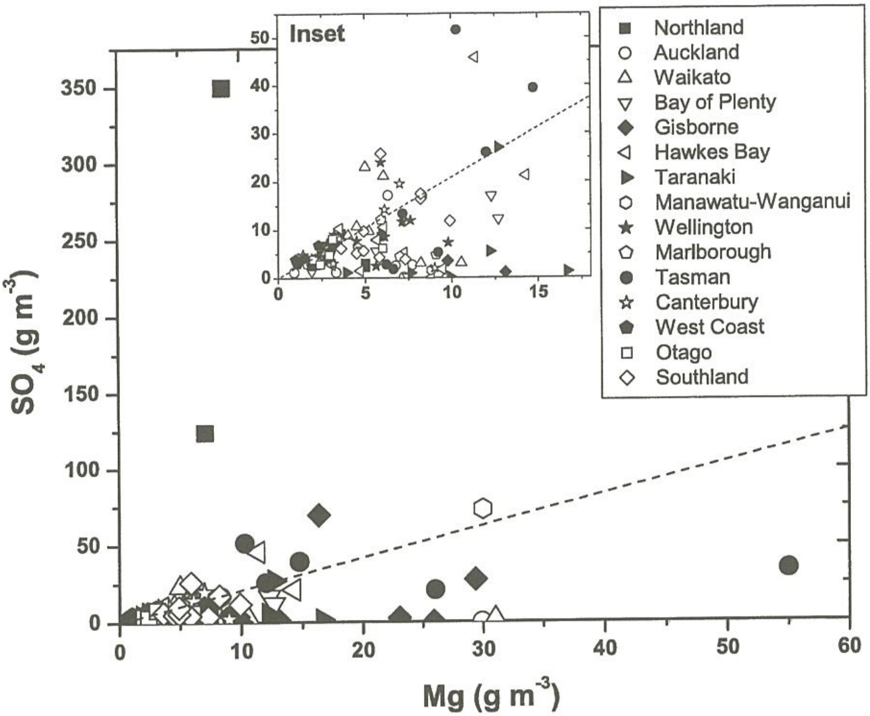

Figure 4.9 *Median sulphate plotted against median magnesium. Most wells plot to the right of the seawater concentration-dilution line (dashed line).*

NUTRIENTS

Nitrate

Nitrate concentrations are discussed in detail in Chapter 8, however one additional point not covered in that chapter is made here. Figure 4.11 shows a plot of nitrate versus ammonium for NGMP wells. This plot shows that relatively high ammonium concentrations are associated with low nitrate concentrations and vice versa. This is expected because nitrate is the oxidised form of nitrogen, while ammonium occurs essentially under anaerobic conditions.

Nitrogen in the form of ammonium is also detrimental to the environment, as it will cause eutrophication of surface water bodies, and when oxidised at the surface may be detrimental to human and animal health. This suggests that monitoring only nitrate in a system may provide a false sense of security if nitrate concentrations are low. Knowledge of the aquifer conditions (i.e. redox conditions, dissolved oxygen, confinement of the aquifer, and pH) is essential to determine which form of nitrogen should be monitored.

In general, organic nitrogen concentrations in groundwater are low, but elevated organic nitrogen may occur near contaminated sites.

Ammonium

Ammonium concentrations (NH_4-N) have not been measured frequently in most of the NGMP wells. The exception to this is in the Manawatu-Wanganui region, where ammonium concentrations have been measured since 1992, and in Taranaki, where they have been recorded since December 1994. Ammonium has been routinely measured in all the NGMP wells since 1996.

Some indication of the oxidising or reducing nature of an aquifer can be deduced from its ammonium concentrations, coupled with total Fe and total Mn concentrations. This is because significant concentrations of ammonium (greater than about 0.1 g.m^{-3} NH_4-N) and total dissolved Fe and Mn in solution occur

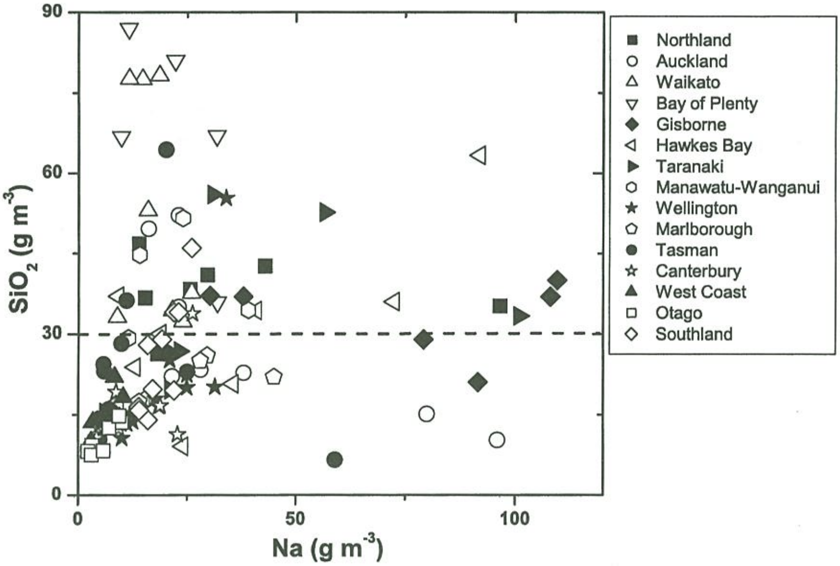

Figure 4.10 *Median silica (as SiO_2) plotted against median sodium. Dashed line represents equilibrium concentration of silica for dissolution of silicate rocks. Concentrations of SiO_2 much >30 g m^{-3} are usually the result of dissolution of volcanic glass (Hounslow 1995). Note: one well with a Na concentrations >300 g m^{-3} is not plotted (from Northland).*

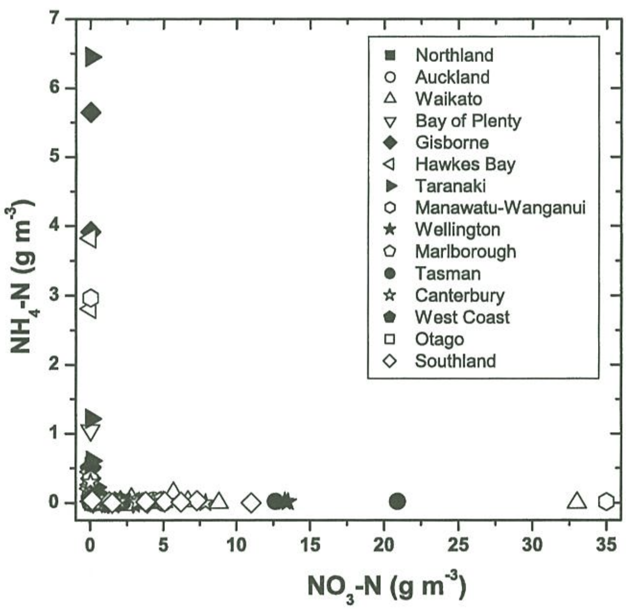

Figure 4.11 *Median nitrate plotted against median ammonium. When nitrate concentrations are high, ammonium concentrations are low and vice versa. This suggests that in some reducing aquifers measuring nitrate may not be as useful as measuring total inorganic nitrogen or ammonium.*

only under anaerobic conditions (no oxygen present). Mildly reducing anaerobic conditions are indicated by an absence of dissolved oxygen and hydrogen sulfide (H_2S). Iron and manganese in their reduced forms (Fe^{2+}, Mn^{2+}) may be abundant, but nitrogen species will be present as nitrate (NO_3). Under strongly reducing anaerobic conditions, oxygen is absent, but H_2S and methane (CH_4) are present (Hounslow 1995). Under these very reducing conditions nitrate is reduced to ammonium, although H_2S and CH_4 may or may not be present.

A total of 17 wells in the NGMP have NH_4-N concentrations >0.3 g m^{-3}, and four of those wells are in the Taranaki region, and five in Gisborne. Of the remaining eight wells, two are located in the Manawatu-Wanganui region, one in the Bay of Plenty, three in Hawke's Bay, and two in Canterbury. Eight of the 17 wells have NH_4-N concentrations >1.0 g m^{-3}, with the maximum median concentration recorded of 6.5 g m^{-3} NH_4-N from a well in Taranaki. Almost all of the wells with high NH_4-N concentrations are located in confined aquifers, although NH_4-N concentrations >1 g m^{-3} have been recorded from a well in the Bay of Plenty, which draws water from a shallow unconfined aquifer.

The two highest NH_4-N concentrations from Gisborne come from well GPB102 (median concentration of 5.7 g m^{-3} NH_4-N) located in the Matokitoki Gravel Aquifer and well GPD130 in the discharge end of the Makauri Gravel Aquifer (median concentration of 3.9 g m^{-3} NH_4-N). The Matokitoki Gravel Aquifer is a deep (>80 m) confined aquifer of limited extent. Water movement in the aquifer is relatively slow and the age of the groundwater is thought to be >3000 years old (Barber 1993). Ammonium concentrations in this aquifer are so high that chloramines, dichloromines and trichloramines are formed instead of free chlorine when the water is chlorinated (Barber 1993). The source of ammonium in the aquifer has not been studied in detail, but due to the age of the water in the aquifer, it is suspected that the ammonification of organic matter trapped in pockets of organic-rich sediments is responsible for the observed high concentrations. Changes in land use in the last 100 years have not contributed to the high ammonium concentrations.

Phosphate

Phosphate concentrations in NGMP wells are generally low, with only three wells having PO_4-P concentrations >0.2 g m^{-3}, and only 18 wells >0.1 g m^{-3}. Many wells have PO_4-P concentrations below the detection limit (approximately 0.03 g m^{-3}). The maximum PO_4-P concentration recorded is from a Taranaki well, which has a median concentration of 0.62 g m^{-3}. The aquifer that is being monitored by this well is confined, but the land use around the well is dairying, and the recharge area is in sheep and cattle pasture land. Abundant natural sources of phosphate are limited in New Zealand, as there are no phosphorite deposits associated with groundwater aquifers. Inclusions of apatite minerals in soils and igneous rocks may be a source of phosphate to groundwater. For example, it has been demonstrated that phosphate may leach from fresh rhyolitic pumice, probably from hydroxyapatite inclusions, in the Taupo catchment (Timperley 1983). This source of phosphate is significant, so aquatic plant growth in Lake Taupo is limited mainly by the amount of nitrogen available rather than by the amount of phosphorus (White 1983).

The most common source of phosphorus pollution in New Zealand groundwater is from fertiliser use in agricultural areas. Like nitrogen (see Chapter 8), phosphorus is an essential plant nutrient. However, a major sink for phosphate is uptake by organic matter within the upper metre of the land surface. Phosphate is also highly reactive and will adsorb onto clay particles, Fe and Al oxides, and organic matter in the soil and aquifer materials, so its mobility in most aquifers is relatively low. In addition, high Ca, Al or Fe concentrations will reduce P solubility (Haygarth 1997). The concentration of phosphorus necessary to cause nuisance weed growth or eutrophication in surface water bodies depends on the ratio of nitrogen to phosphorus in the aquatic system. The natural vegetation of a lake or stream may have adjusted to the particular N:P ratio of an area, so that disturbance of this ratio, even by a small amount, may cause changes to the habitat (Vollenweider 1968). Therefore, even small changes to the phosphate (or nitrate) concentration of groundwater systems should be viewed with some concern if down-gradient surface water bodies are susceptible to eutrophication.

TRACE METALS

Iron and manganese

Iron and manganese are not dissolved in solution in large quantities if oxygen is abundant in solution. Generally, moderately reducing and anoxic conditions are required before appreciable dissolved iron and manganese are found. This is because the oxidised forms of iron and manganese, Fe(III) and Mn(IV), are virtually insoluble except in very acidic waters. The oxidation of organic matter by a progression of increasingly weaker oxidising agents is the basis of the oxidation-reduction (redox) model (Stumm and Morgan 1981). In natural aquatic systems the oxidising agents are, in order of decreasing strength: molecular oxygen, nitrate ions, manganese (IV) oxide, iron (III) oxide, sulphate ions, carbon dioxide and molecular nitrogen (Stumm and Morgan 1981). If the reactions occur in thermodynamic equilibrium, each of the oxidants must be consumed (or nearly consumed) before the reduction of the next strongest oxidant begins. This may not occur if reactions are kinetically controlled. However, from the thermodynamic reactions it can be seen that the reduction of Mn(IV) to Mn(II) would occur before the reduction of Fe(III) to Fe(II). This indicates that high concentrations of dissolved Mn and Fe may not always occur at the same time (if all Mn (IV) has not been consumed). For example, Downes (1985) used the principles of redox reactions to explain the observed chemical composition of the Hutt Valley aquifer, which culminates in very reducing conditions (low sulphate and nitrate) at the distal end of the aquifer offshore at Somes Island. Although the main purpose of this study was not to determine the controls on iron and manganese in solution, the study is one of the few in New Zealand that uses redox conditions to suggest management options for groundwater use.

In New Zealand, shallow unconfined aquifers mostly are low in iron unless the water is relatively slow moving and oxygen is consumed along the flow path by reactions with organic matter or other chemicals. However, high iron and manganese concentrations are relatively common in New Zealand groundwater, particularly in rural domestic water supplies. This is because individual farms may be tapping convenient aquifers (i.e. a shallow aquifer directly under the house) rather than the best aquifer available in the area. High iron concentrations occur in virtually all regions of New Zealand (Fig 4.12) and are a problem for water managers in Otago, Bay of Plenty, Southland, Marlborough and Waikato regions (Hodges 1994; MacTavish et al. 1997; Otago Regional Council 1999; Gisborne Distict Council 1997; Marlborough District Council 1994; Rekker 1994). Twenty-nine wells in the NGMP (27%) have median total dissolved iron concentrations ≥0.2 g m^{-3}. The 1995 Drinking Water Standards for New Zealand (DWSNZ 1995) indicate that concentrations greater than 0.2 g m^{-3} will stain laundry. Similarly for manganese (Mn), the DWSNZ (1995) indicates that concentrations >0.05 g m^{-3} will stain laundry, but there is a potential health risk if concentrations are >0.5 g m^{-3}. Thirty-five wells in the NGMP (32%) have median total dissolved Mn concentrations >0.05 g m^{-3}, and 16 wells (15%) have median total dissolved Mn concentrations >0.5 g m^{-3} (Fig 4.12). High Mn concentrations are found in most parts of the country, but Gisborne aquifers appear to be particularly high in Fe and Mn. This is because the aquifers are largely confined and deep, with slow-moving water, and they contain pockets of organic matter (Barber 1993). This allows the utilisation of dissolved oxygen along the flow path and leads to reducing conditions that are conducive to mobilisation of iron and manganese.

Fe and Mn are derived from water-rock interaction, and there are few land uses that would contribute soluble Fe and Mn to solution except for certain types of mining activities (i.e. induced low redox and pH conditions caused by acid mine drainage), industrial activities, or landfills. For example, Pang (1995) demonstrated high Fe and Mn concentrations

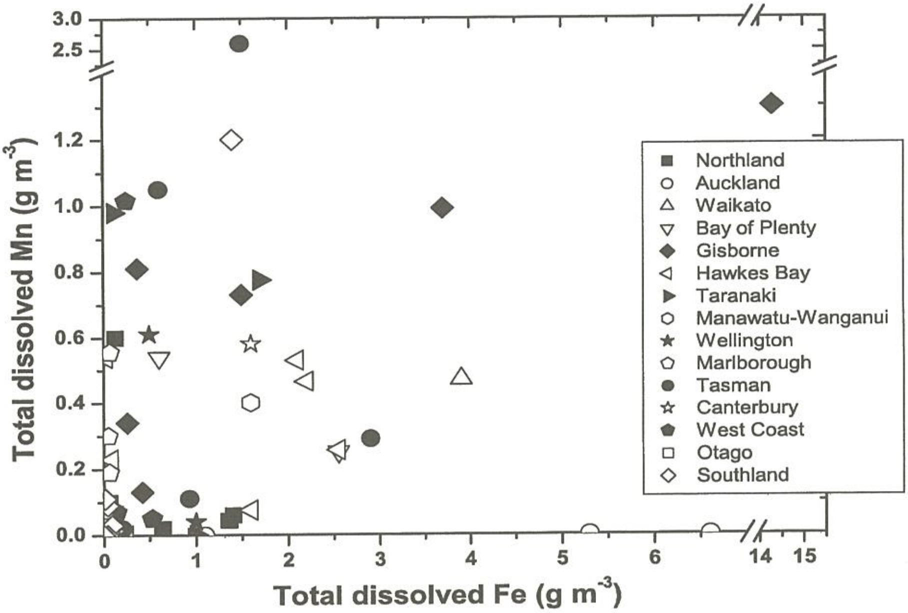

Figure 4.12 *Median concentrations of total dissolved Fe plotted against median total dissolved Mn. There is no apparent correlation between the concentrations of the two elements. Note the break in values on both axes.*

(along with other heavy metals) in the down-gradient aquifer from the leaching of mine tailings in the Coromandel. However, in New Zealand these types of induced high iron concentrations are localised.

The natural or induced redox conditions of the aquifer control the amount of dissolved Fe and Mn in an aquifer. However, there appears to be little correlation between concentrations of Fe and Mn in New Zealand aquifers (Fig 4.12). The lack of correlation may reflect several possibilities. One possibility is that because Mn is reduced before Fe (see redox sequence above), the aquifer has not reached a sufficient reduction potential to reduce Fe(III) to Fe(II), leading to high Mn(II) in solution and low Fe(II). Another possibility is that the abundance of Fe in rocks is much greater than Mn and there may be little Mn available to go into solution. This also explains why dissolved Fe concentrations are generally much greater than dissolved Mn concentrations when both are present in solution. Similarly, where Mn oxides are available in some rocks, Fe oxides may not be available.

Fluoride

Most fresh water contains <1 g m^{-3} of fluoride (F) (Hem 1985), and in New Zealand most wells contain <0.5 g m^{-3}, although one well in Northland is very close to 1 g m^{-3} (Fig 4.13). Sources of F include the dissolution of fluorite, apatite or fluoride-bearing micas and amphiboles. Groundwater associated with volcanic fumarolic gases and hydrothermal fluids depleted in calcium may also contain appreciable F concentrations (Hem 1985). A common sink for F is adsorption onto clay minerals (kaolinite, gibbsite and halloysite) via ion exchange. Adsorption is greatest at a pH of 6, and negligible below 4 and above 7.5, when desorption occurs (Hounslow 1995). This results in high alkalinity waters with high F concentrations. In NGMP samples, there are no samples with median pH values less than about 6. But a general increase in F concentrations does occur as the groundwater becomes more alkaline (Fig 4.13). Precipitation of $Al(OH)_3$ also effects the concentration of F in groundwater (Flühler et al. 1982). Not many land-use activities involve the application of fluoride to

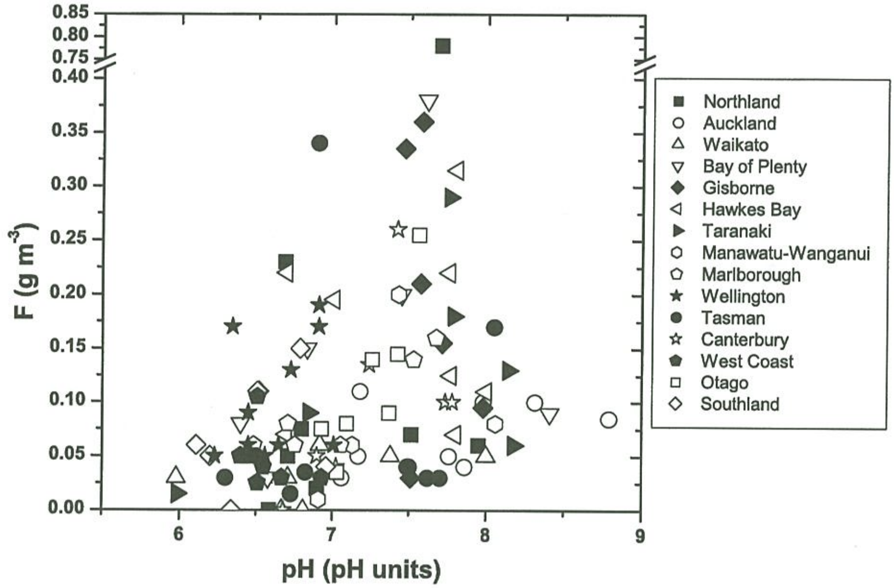

Figure 4.13 *Median fluoride plotted against median lab pH. Fluoride concentrations generally increase as pH increases (see text for explanation). Note the break in values on the vertical axis.*

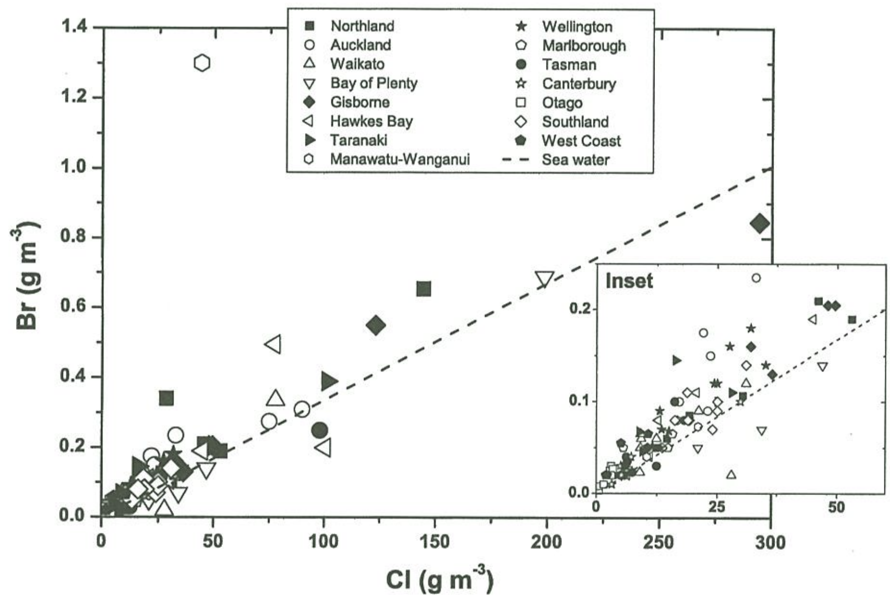

Figure 4.14 *Median bromide plotted against median chloride. Virtually all wells plot near the sea-water concentration dilution line (marked as sea water on the graph).*

land. However, wastewater from cities or towns that use fluoridated water may help to increase F concentrations slightly (Vengosh and Pankratov 1998). Seawater has an F concentration of 1.3 g m^{-3}, so coastal areas may have slightly elevated F concentrations. The maximum acceptable value for fluoride in New Zealand for drinking water is 1.5 g m^{-3} (DWSNZ 1995); no wells in the NGMP exceed this value.

Bromide

The main source of bromide in New Zealand aquifers is from evaporation from sea water or sea-water spray. The mechanism of transferring Br to the aquifer is the same as for Na and Cl. Figure 4.14 show that the relationship of Br to the SCDL is similar to that of Na and Cl (Fig 4.4). In some cases, Br plots just below the SCDL. This may be due to bromine uptake in the soil zone or volatilisation of Br before it reaches the soil zone (Gerritse and George 1988). In addition, Br is often at low concentrations in the groundwater. This means that the concentration is near the detection limit of the method (0.02 g m^{-3}). Although Br is generally considered to be conservative in dilute groundwater (very few exchange reactions occur) it is not necessarily conservative in the soil zone or in open water bodies (Gerritse and George 1988). One well from the Manawatu-Wanganui region plots a long way off the SCDL line. This well also has the highest median nitrate concentrations in the NGMP database (median = 35 g m^{-3} NO_3-N). This suggests that land-use activities have affected the hydrochemistry of the groundwater in this area.

HEAVY METALS

The mobility of heavy metals in the unsaturated zone above the water table has been studied extensively by many workers (Alloway 1990). However, the fate of heavy metals below the water table has not been studied to the same extent because some soil studies indicated that many heavy metals are retained in the soil and do not pass into the groundwater easily. In addition, determining the fate of heavy metals in both the unsaturated and saturated zones is complex and requires a thorough knowledge of the aquifer conditions expected before their mobility can be predicted (Allen et al. 1993). However, because the mobility of heavy metals is dependent on a wide range of common, and often competing, environmental factors (including pH, Eh, and competition from other elements for adsorption sites) it is important to stress the interdependence of the mobility of each element on these environmental factors.

There are a number of conditions that affect the mobility or retention of heavy metal species in the environment in general, and in groundwater specifically. Tanji and Valoppi (1989) outlined the possible biotic and abiotic processes that affect the reactivity and mobility of trace elements. They stated that the speciation and reactivity of the trace element, and mobility and transport processes, influence the presence or accumulation of trace elements in groundwater. The rate and extent of these reactions are influenced by many environmental conditions that are in most cases specific to an individual site. Furthermore, the mobile forms of the trace elements are subjected to many competing reactions. Because of this complexity, few generalisations can be made about the reactivity and mobility of heavy metals in groundwater. For example, cationic trace elements, such as copper, tend to be strongly retained by earth materials due to ion exchange, sorption, and mineral solubility, but anionic elements (e.g. CrO_4 and AsO_4) are more mobile (Tanji and Valoppi 1989).

Although generalisations about the mobility of heavy metals may be limited, a few basic processes seem to control many of the metal species present in groundwater. The most important processes are: 1) ion exchange and adsorption onto mineral surfaces, 2) oxidation-reduction state of the groundwater, 3) pH, and 4) formation of organic ligands. For example, both cationic and anionic trace elements that form complexes with organic and inorganic ligands have greater mobilities that those that do not. Reaction rates involving metals tend to increase with increasing temperature, and the solubility of minerals containing cationic metals increases as pH decreases, while that of anionic minerals increases with increasing pH. The application of equilibrium concepts to metal migration in groundwater is appropriate if the residence time of groundwaters exceeds the rates of reaction (Langmuir and Mahony 1985). For most important reactions Langmuir and Mahony (1985) suggested that the reaction rates vary from a fraction of a second (hydration, acid-base complexation, adsorption and desorption), to minutes to hours (oxidation-reduction, gas solution and exsolution), weeks (precipitation and dissolution), months (polymerisation and hydrolysis, isotopic exchange) and years (mineral crystallisation). Because the residence times of groundwaters range from a few days to thousands of years in deep or slow-moving aquifers, chemical reactivity in most groundwater systems may be described by equilibrium concepts. An excellent review of all the processes listed above can be found in Tanji and Valoppi (1989).

Because most heavy metals are readily adsorbed onto oxides and clays in soils, it is generally considered that heavy metals become immobilised in the soil zone and do not contribute greatly to groundwater contamination. However, preferential flow paths in an aquifer may allow greater transport of metals than is predicted by uniform-flow contaminant transport models (Pang and Close 1999). In addition, there are many competing reactions taking place in the soil zone and in the aquifer that may mobilise heavy metals. In particular the redox and pH conditions in the aquifer, and the association of heavy metals with organic substances and colloids (Pang and Close 1999), may create an environment conducive to heavy metal transport. For example, a study of an agricultural site in the Netherlands indicated that high concentrations of nitrate in manure applications gave rise to a series of chemical reactions in the soil matrix that released heavy metals (including As) to the shallow groundwater (van Beek et al. 1989).

In February to April 1998, samples were collected from all NGMP wells in 13 regions of the country for heavy metal analyses (copper, chrome, arsenic, and lead). No samples were collected from Southland and West Coast because they were not part of the NGMP at the time. Samples were analysed by inductively coupled plasma mass spectroscopy to detect low concentrations. Samples were collected in special acid-washed bottles, but were collected during the normal NGMP Autumn sample collection by regional council staff. Samples were filtered in the field and acidified with ultra-pure nitric acid on-site, so that results represent total dissolved metals and not total metal concentrations. Blind duplicates were collected at some sites, but no special sampling techniques were used, so atmospheric or handling contamination may have occurred in some samples. However, the sampling gives an overall picture of metal concentrations in the NGMP and provides the first national coverage of metals in New Zealand (Rosen 1998).

Eighty-seven samples were analysed for As, Cr, Cu, and Pb. Detection limits for each element were As: 1 ppb, Cu: 0.5 mg m^{-3}, Cr: 0.5 mg m^{-3}, and Pb: 0.1 mg m^{-3}. As was detected in 23% (n=20) of the samples, Cu in 89% (n=77), Cr in 17% (n=15), and Pb in 93%(n=81) of the samples. Median values for As and Cr are equal to the detection limit of the method, indicating that these elements are rare in the groundwater sampled. However, of the 20 samples that had detectable As, eight were from the Bay of Plenty (4) and Gisborne (4) out of 12 bores sampled. Concentrations of As were low, between 12 and 1 mg m^{-3} (Fig 4.15), but because As was found in such a large percentage of samples compared to other areas, it suggests that the trend is real. The highest concentration of As recorded was from Canterbury at 54 mg m^{-3}, and three other wells had As concentrations above the New Zealand drinking water standard of 10 mg m^{-3} (Fig 4.15), only one of which (Bay of Plenty) was located near geothermal activity. Because the concentration in the Canterbury well was anomalously high compared to all the other wells sampled, the well was sampled again by Environment Canterbury. They again found high concentrations of As in the groundwater. This led to an intensive study by Environment Canterbury to determine the reason for the high As concentrations. The investigations revealed that the soil near the well was also contaminated with As and that other wells in the area were also contaminated (Hayward and Smith 2000).

The source of the As was found to be an old sheep foot trough site (used for controlling foot rot in sheep) located just up-gradient of the well, although other potential As sources may also exist in the area. Even though the aquifer is confined, and the foot trough has not been used in over 50 years, the persistence of As in the soil and the potential for it to leach into the groundwater is high.

Arsenic-bearing chemicals were used extensively in sheep and cattle dips for the control of parasites in the first half of the twentieth century (Hadfield and Smith 1999), and many thousands of these sites still exist throughout the country. In addition, later preparations for dipping sheep in the mid-twentieth century also included organochlorine compounds (such as dieldrin, hexachlorocyclohexane, DDT, DDE, aldrin, and endrin), which are environmentally persistent. Dipping sites were often located adjacent to water supplies. Hadfield and Smith (1999) estimated that the Waikato region alone contains over 10,000 sheep dip sites. Given the number of sites and the persistence of As in soil and groundwater, it is likely that future investigations like the one in Canterbury will turn up further contamination.

The highest recorded concentration of Cr in the groundwater was 6 mg m^{-3}. Most samples were below 1 mg m^{-3}, and no trends can be discerned from these data. Cr concentrations are unlikely to be a good indicator for groundwater quality due to the generally low concentration of Cr in New Zealand groundwater. However monitoring of Cr concentrations may be important in determining groundwater plumes from timber treatment sites or other localised industrial activities that used chrome.

Although the number of wells with detectable Pb was high, the concentrations were low, (most <1 mg m^{-3}, high of 6 mg m^{-3}). Because clean sampling techniques were not used, it is likely that the lead detected was from atmospheric contamination during the sampling process.

Copper was detected in all regions at low levels (Fig 4.16). The maximum concentration was 31 mg m^{-3} in the Manawatu-Wanganui region. The average concentration is 3 mg m^{-3} and the median is 1 mg m^{-3}. In urban areas concentrations were often below the detection limit, but low concentrations were common in rural areas, suggesting that agrichemicals may influence Cu concentrations. However, further work needs to be done to substantiate this apparent relationship. No other relationship to land uses could be determined from the data.

Heavy metals are routinely measured in the Bay of Plenty groundwater monitoring network (Hodges 1994, 1995). Four of the five sites monitored for the NGMP were analysed for heavy metals under the Environment Bay of Plenty (EBOP) survey. The results of the 1995 EBOP survey indicated that two of the wells had higher arsenic concentrations at that time than those found in the NGMP survey. However, it is not clear in the report whether the results are for total metal concentrations (which include sediment in the sample) or for total dissolved metals (filtered samples). The concentrations found by EBOP were above the MAV for arsenic (Hodges 1995).

Viljevac (1998) and Rosen et al. (2000) studied both the total metal and total dissolved metal concentrations of groundwater that was sampled after rainfall events in the Mount Eden area of Auckland. The groundwater is recharged by storm water runoff into soak holes that may have a direct connection to the shallow fractured-rock basalt aquifer. The results indicated that, even with more than 60 years of storm-water infiltration into the Mt Eden aquifer, there has been only a minor effect on groundwater quality. Particulate organic matter adsorbs much of the contaminant load. Although long-term binding of contaminants to particulate matter is not certain, the soak holes appear to be cleaned frequently enough to remove much of the adsorbed contaminants. The possibility of leaching of Pb, Zn and Cu from the sediments appears to be the most likely cause for concern. Total Pb and Zn concentrations in groundwater are higher than natural background concentrations and total Pb concentrations are greater than the DWSNZ (1995) in some bores at certain times. Dissolved and total Zn concentrations are also relatively high.

Pang (1995) studied the concentration, transport and adsorption/desorption kinetics of

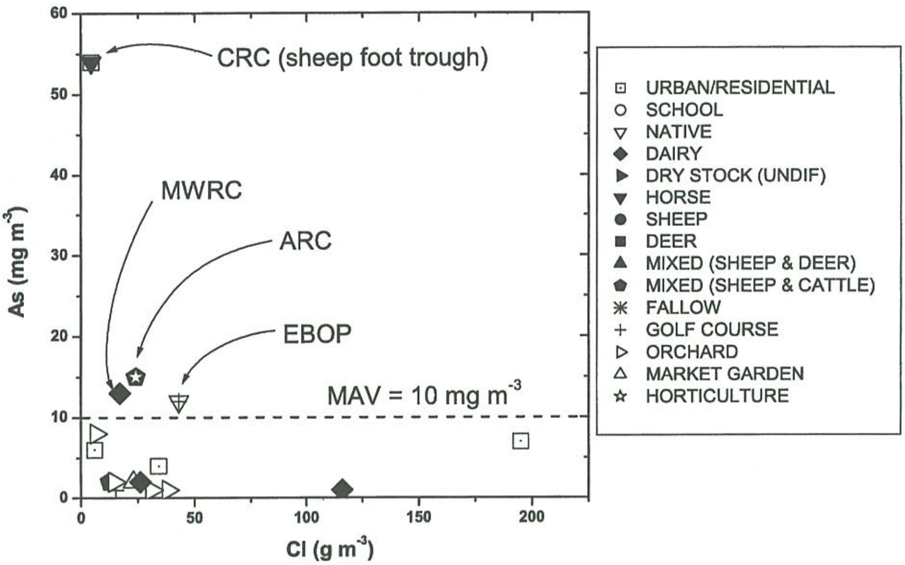

Figure 4.15 *Arsenic concentrations plotted against chloride for those wells with As concentrations above the detection limit of the method. CRC = Canterbury Regional Council (now Environment Canterbury), ARC = Auckland Regional Council, MWRC = Manawatu-Wanganui Regional Council (now Horizons.mw), and EBOP = Environment Bay of Plenty.*

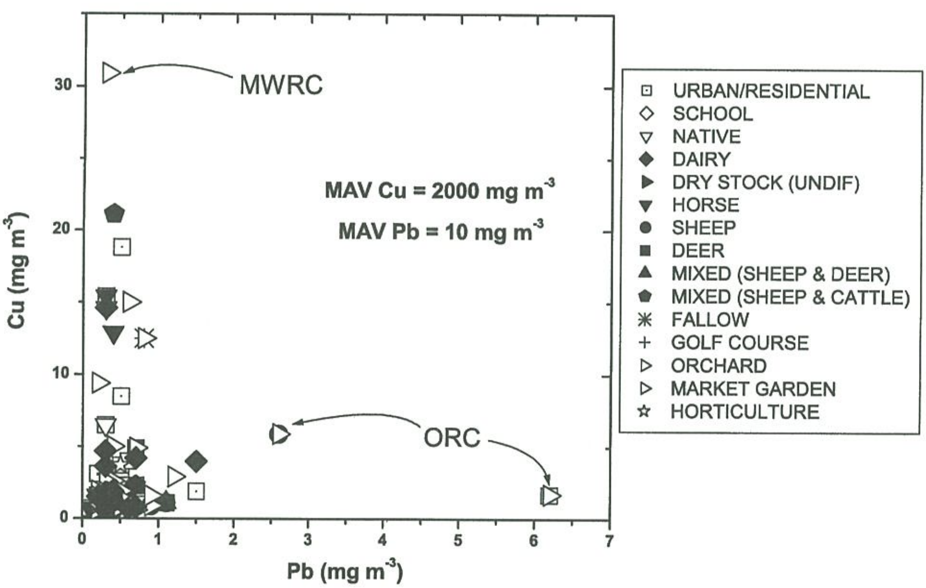

Figure 4.16 *Copper concentrations plotted against lead. All samples of both elements are below the New Zealand MAV. ORC = Otago Regional Council.*

heavy metals (Zn, Cu, Pb, Cd, Fe, Mn) in groundwater that was affected by acid drainage from an abandoned mine in the Te Aroha area of the Coromandel. She found that toxic concentrations of heavy metals were located near the old tailings ponds and around the old mine shafts, although the natural composition of the groundwater in the Te Aroha area is enriched in heavy metals. The groundwater flow paths indicated that the plume of contaminated groundwater derived from the tailings pond was likely to be limited to the mountain area about 1 km down-gradient of the pond.

Modelling of the metal adsorption/desorption kinetics of the metals indicated that, if no corrective measures were undertaken, more than 16 tonnes of various metals would be released to the groundwater and streams over hundreds to thousands of years (Pang 1995). The study shows that although acid mine drainage is not as severe a problem in New Zealand as it is in other parts of the world, it can have a significant local impact here.

HYDROCARBONS

Hydrocarbons are a type of organic compound that can pose a significant risk to aquifer systems because of their mobility, persistence and detrimental health effects at even low concentrations. Hydrocarbon contaminants do not dissolve particularly well in water and form non-aqueous phase liquids (NAPLs). If the compound is less dense than water it will float on the surface of the water table. These compounds are known as light non-aqueous phase liquids (LNAPLs). Compounds such as benzene (a common compound in unleaded petrol) and vinyl chloride are LNAPLs. Compounds that are denser than water are dense non-aqueous phase liquids (DNAPLs). These compounds will sink to the bottom of the aquifer and can be difficult to detect with monitoring because they will migrate down the slope of the bottom of the aquifer and not necessarily in the direction of groundwater flow.

NAPLs are generally immiscible, but a small fraction of the compound will dissolve in water, and this dissolved fraction may exceed concentrations for drinking-water standards for a particular compound because the drinking water MAVs for these compounds are also low.

A detailed review of sources and sinks of hydrocarbons is beyond the scope of this chapter. Hydrocarbons enter groundwater systems almost exclusively through anthropogenic activities, although natural seeps of hydrocarbons do occur in some areas of New Zealand, particularly where geothermal maturation of organic matter is occurring near the ground surface. Industrial areas and leaking petrol storage tanks are the most common sources of hydrocarbons in shallow groundwater. Relatively few areas of the country have undertaken extensive regional monitoring of hydrocarbons, and hydrocarbon monitoring is not included in the NGMP. Environment Waikato lists hydrocarbons as a parameter that they monitor in groundwater, but no results are given (Environment Waikato 1998). The only region with an extensive hydrocarbon monitoring programme is Canterbury (Hayward and Smith 1999). This programme has been in existence for 11 years and is the most comprehensive regional monitoring of hydrocarbons in the country.

Hayward and Smith (1999) found 23 different hydrocarbon contaminants (including chlorinated and aromatic hydrocarbons) in Canterbury groundwater over the 11-year period of monitoring (1988 – 1999), 22 of which were found in the Christchurch area (Table 4.4). The concentrations of these contaminants are well below the relevant New Zealand drinking-water standards, indicating that the risk to Canterbury groundwater users is presently low. However because monitoring concentrates on the detection of ambient hydrocarbons (i.e. no monitoring of known contaminated sites is done), there is concern about the persistent presence of hydrocarbons over an extensive area of the Canterbury aquifers.

There is a clear pattern of hydrocarbon detections down-gradient of industrial areas where solvents and other hydrocarbons are used, or where poorly designed (both historic and current) landfills are located. Hayward and Smith (1999) concluded that it is difficult to determine the source(s) of hydrocarbon contamination in Canterbury because of the multitude of potential sources, the dynamics of the aquifer system, and the limited availability of wells in the appropriate locations to pinpoint sources of contamination.

The Environment Canterbury monitoring network has also occasionally analysed for polynuclear (or polycyclic) aromatic hydrocarbons (PAHs) and some detection of various PAH compounds has been reported (Hayward and Smith 1999), but these concentrations were well below DWSNZ (1995) maximum acceptable values (for those compounds listed). PAHs are a group of organic compounds formed during the incomplete combustion of organic matter. Sources include gas works, burning at landfills and incomplete combustion of fossil fuels in motor vehicles.

The solubility of PAH compounds is very low, but their solubility in water can be significantly increased in the presence of dissolved organic carbon, at environmentally feasible concentrations (Magee et al. 1991). Furthermore, this dissolved organic carbon also has the ability to enhance desorption of PAHs from sediments low in organic carbon (Johnson and Amy 1995). Studies of PAH concentrations in groundwater have been undertaken in the Mt Eden area of Auckland (Roberts 2000; Rosen et al. 2000). In these studies, the PAH contribution from storm-water infiltration to the Mt Eden fractured basalt aquifer was measured during baseline conditions and after rainfall events. Various PAH compounds were detected but no concentrations were above the DWSNZ (1995) MAV, and no readily interpretable pattern of PAH distribution could be obtained (Roberts 2000).

RELATIONSHIPS WITH DEPTH AND AQUIFER CONDITIONS

The relationship between sulphate and depth has already been discussed (see Fig 4.3). If decreasing sulphate is truly related to sulphate reduction, there should be a corresponding increase in HCO_3 concentration as a by-product of the sulphate reduction reaction. Figure 4.17 shows the relationship between HCO_3 and depths for the NGMP wells. In general, HCO_3 concentrations are higher in confined aquifers and at greater depths, but there is considerable scatter in the data, making the relationship doubtful. However, not all of the low sulphate concentrations are caused by sulphate reduction, given the variety of aquifer conditions represented in the NGMP aquifers. In fact, there is no inverse correlation between SO_4 concentrations and HCO_3 concentrations for the data.

As the many different weathering reactions take place in an aquifer, hydrogen ions (H^+) are consumed (as in the case of the reduction of iron) or liberated (many incongruent dissolution reactions involving aluminosilicates). In many of the deeper groundwater systems in New Zealand reduction of iron may be important (see *Iron and manganese*) and this may help to increase the pH of deeper aquifers. Figure 4.18 demonstrates this relationship relatively well, even though the pH of samples was measured in the laboratory rather than in the field. There is an increase in pH with depth in a general sense, and confined wells are in general more alkaline than unconfined wells.

There are no other correlations with depth or aquifer condition (confined versus unconfined) except for a decrease in nitrate concentrations with depth (see Chapter 8).

SUMMARY

New Zealand aquifers are diverse in their lithology, water flow, aquifer conditions and size, and in land use in their recharge areas. It is therefore not surprising that the hydrochemistry of these aquifers is also diverse. The geology of the aquifers is dominated by sedimentary rocks, generally as either gravel or sand aquifers. The lithology of many aquifers is poorly known, so that relating specific hydrochemical signatures to certain types of rock weathering is difficult. The hydrochemistry of New Zealand's aquifers is dominated by sodium-calcium and bicarbonate ions. As New Zealand is an island nation, most sites in the NGMP are relatively near the ocean, and a significant portion of many elements and compounds have been derived from sea water or sea spray. In particular sodium, chloride and bromide have been derived from ocean water. Agricultural land uses have had an effect on the concentrations of sulphate, po-

Table 4.4 *Hydrocarbon detections in the Christchurch area during an 11-year monitoring programme (From Hayward and Smith 1999).*

SAMPLING PERIOD		88/89	MID 89	89/90	MID 90	90/91	91/92	92/93	93/94	94/95*	95/96*	MID 96	96/97*	97/98*	98/99*
HALOGENATED ALKANES AND ALKENES															
1,1,1-Trichloroethane (1,1,1-TCA)	Maximum Concentration	2.8	6.5	4.2	7.5	6.9	8.2	2.1	5.7	3.6	4.3	2	4.4	4.3	3.8
	Detection limit	0.2	0.2	0.3	0.4	0.4	0.4	0.2	1	1	0.5	0.5	0.5	1	1
	No. of sites	4	32	9	14	7	11	13	9	7	15	6	13	8	8
Trichloroethene (TCE)	Maximum Concentration	14	16	0.6	11	0.7	8.2	11	5.5	8.8	9.7		11	10	10
	Detection limit	0.1	0.3	0.2	0.6	0.6	0.6	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	No. of sites	1	3	4	3	2	1	2	3	3	3	0	3	2	3
Tetrachloroethene (PCE)	Maximum Concentration		0.1			0.9									
	Detection limit	-	0.1	0.1	0.2	0.2	0.2	0.2	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	No. of sites		1	0	0	1	0	0	0	0	0	0	0	0	0
1,1-Dichloroethane (1.1-DCA)	Maximum Concentration								0.8		0.7	1.4	0.8	0.6	0.8
	Detection limit	-	-	-	-	-	-	-	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	No. of sites								2	0	2	5	3	2	2
Dichloromethane	Maximum Concentration								79		6.8				
	Detection limit	-	-	-	-	-	-	-	5	5	5	8	8	8	8
	No. of sites								3	0	1	0	0	0	0
Vinyl chloride (VC)	Maximum Concentration									2.2					
	Detection limit	-	-	-	-	-	-	-	0.5	1	1	1	1	1	1
	No. of sites								0	1	0	0	0	0	0
Trichloromethane	Maximum Concentration		8.2												
	Detection limit	-	0.6	0.6	0.9	0.9	0.7	0.7	1	1	0.5	0.5	0.5	0.5	0.5
	No. of sites		1	0	0	0	0	0	0	0	0	0	0	0	0
1,1-Dichloroethene (1,1-DCE)	Maximum Concentration								4.8						
	Detection limit	-	-	-	-	-	-	7	0.5	1	0.5	0.5	0.5	0.5	0.5
	No. of sites							0	1	0	0	0	0	0	0

Table 4.4 *Hydrocarbon detections in the Christchurch area during an 11-year monitoring programme (From Hayward and Smith 1999).* (continued)

SAMPLING PERIOD		88/89	MID 89	89/90	MID 90	90/91	91/92	92/93	93/94	94/95*	95/96*	MID 96	96/97*	97/98*	98/99*
AROMATICS															
Benzene	Maximum											0.7	0.8	0.5	
	Concentration														
	Detection limit	-	-	-	4	4	4	4	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	No. of sites				0	0	0	0	0	0	0	1	1	1	0
Toluene	Maximum								11			1.8	4.6	1.8	1.2
	Concentration														
	Detection limit	-	-	-	11	11	11	11	1	1	1	1	1	1	1
	No. of sites				0	0	0	0	1	0	0	1	2	1	1
Ethylbenzene	Maximum								5.5						
	Concentration														
	Detection limit	-	-	-	3	3	3	3	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	No. of sites				0	0	0	0	5	0	0	0	0	0	0
m+p-Xylene	Maximum								19			1.2	1.2	0.8	0.6
	Concentration														
	Detection limit	-	-	-	3	3	3	3	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	No. of sites				0	0	0	0	6	0	0	1	1	2	1
o-Xylene	Maximum								7			0.6	0.6		
	Concentration														
	Detection limit	-	-	-	3	3	3	3	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	No. of sites				0	0	0	0	5	0	0	1	1	0	0
1,2,4-	Maximum											0.5			
trimethylbenzene	Concentration														
	Detection limit	-	-	-	-	-	-	-	-	-	0.5	0.5	0.5	0.5	0.5
	No. of sites										0	1	0	0	0
POLYNUCLEAR AROMATIC HYDROCARBONS															
Naphthalene	Maximum													1	
	Concentration														
	Detection limit	-	-	-	-	-	-	-	-	-	0.5	0.5	0.5	0.5	0.5
	No. of sites										0	0	0	1	0
Benzo[a]anthracene	Maximum					0.04									
	Concentration														
	Detection limit	-	-	-	-	0.02	0.02	-	-	-	-	-	-	-	-
	No. of sites					4	0								

Table 4.4 *Hydrocarbon detections in the Christchurch area during an 11-year monitoring programme (From Hayward and Smith 1999). (continued)*

SAMPLING PERIOD		88/89	MID 89	89/90	MID 90	90/91	91/92	92/93	93/94	94/95*	95/96*	MID 96	96/97*	97/98*	98/99*
Fluoranthene	Maximum Concentration					0.04									
	Detection limit	-	-	-	-	0.02	0.02	-	-	-	-	-	-	-	-
	No. of sites					4	0								
Pyrene	Maximum Concentration					0.08									
	Detection limit	-	-	-	-	0.02	0.02	-	-	-	-	-	-	-	-
	No. of sites					5	0								
Chrysene	Maximum Concentration					0.04									
	Detection limit	-	-	-	-	0.02	0.02	-	-	-	-	-	-	-	-
	No. of sites					4	0								
NO. OF SITES SAMPLED		13	62	21	19	30	24	23	37	28	27	20	28	28	26

Concentrations and detection limits are reported as mg m^{-3}
A "-" represents no sampling for a particular compound in that year
* Includes highest value of quarterly sampling

tassium, magnesium, nitrate, and possibly calcium and ammonium for some wells.

Relatively few regional programmes routinely monitor heavy metals and hydrocarbons. This makes a national assessment of these compounds and elements difficult. One national survey conducted for the NGMP shows some elevated concentrations of arsenic in some areas of the country. Arsenic may be found naturally in the groundwater near geothermal areas, but high concentrations in other areas may reflect former agricultural land uses, such as areas used as sheep dips and sheep foot troughs. The extent to which these land uses are responsible for high arsenic concentrations throughout the country is unknown. In general, sulphate and nitrate concentrations decrease with depth, and pH and alkalinity increase with depth. Sulphate reduction may be responsible for the decrease in sulphate in some cases, but other mechanisms may also reduce sulphate concentrations. The weathering of calcium carbonate minerals, even in areas where they may occur in only trace amounts, may control the chemical concentration of the groundwater because the dissolution rate of calcium carbonate is so much greater than most silicates.

The National Groundwater Monitoring Programme provides a basis for the comparison of the hydrochemistry of New Zealand's aquifers on a national level. The small size of the data set and the lack of well-documented geological information limits the utility of the programme to some degree. It is hoped that this chapter illustrates the importance of the NGMP as a nationally significant database and that support for the further analysis of the data collected and for the collection of a much wider range of data will bring about future refinements of the information presented here.

ACKNOWLEDGEMENTS

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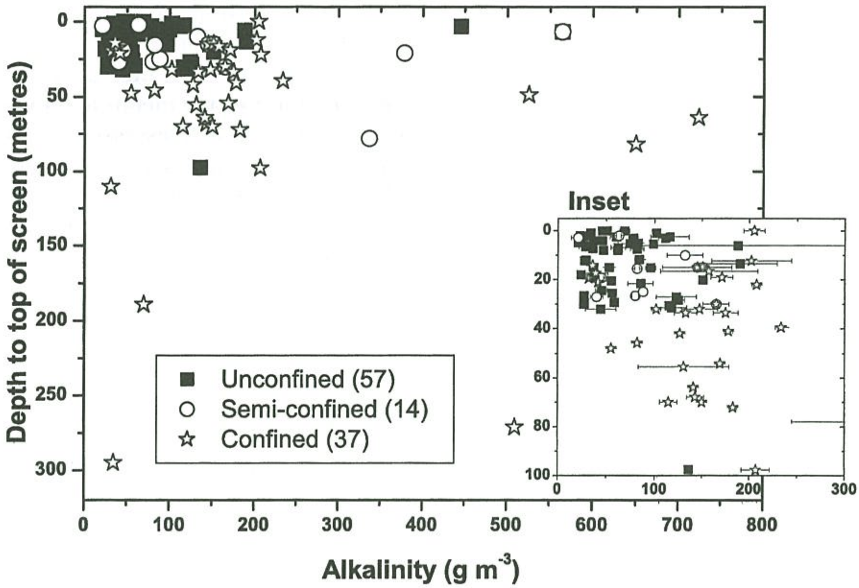

Figure 4.17 *Median alkalinity (HCO_3) plotted against the depth of the top of the screen in NGMP wells. There is a tendency for higher alkalinities with greater depth. Error bars represent one standard deviation. Numbers in the legend refer to the number of points for each aquifer condition.*

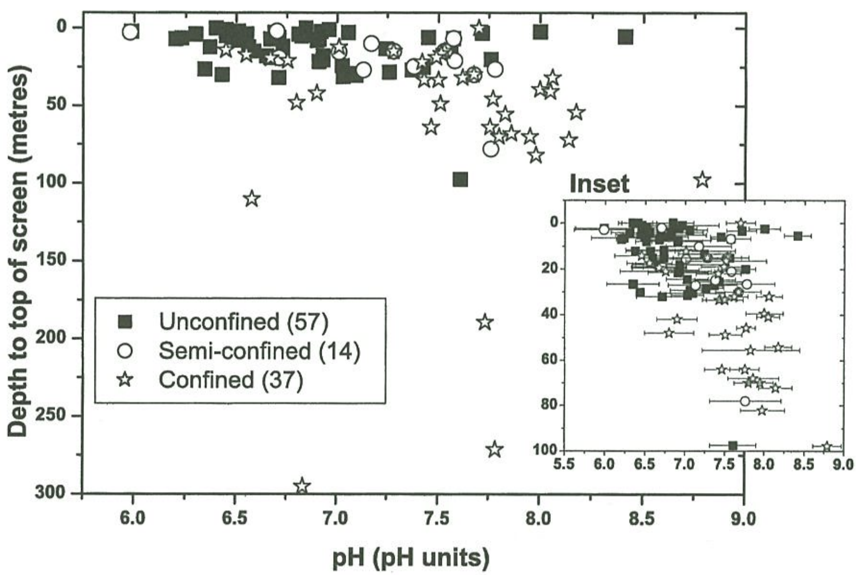

Figure 4.18 *Plot of median lab pH versus depth to top of screen for NGMP wells. There is a general increase in pH with depth. Error bars represent one standard deviation. Numbers in the legend refer to the number of points for each aquifer condition.*

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Support for the NGMP by the regional authorities is essential for the success of the programme. The programme would not be a success without their help in collecting samples. Reviews by Murray Close and Tim Charleson greatly contributed to this paper.

REFERENCES

ALLOWAY, B.J., ed. 1990: Heavy Metals in Soils. Blackie Publishing, Glasgow, 339 p.

ALLEN, H.E.; PERDUE, M.E.; BROWN, D.S. eds. 1993: Metals in Groundwater. Lewis Publishing, Chelsea, 437 p.

BARBER, J.L. 1993: Groundwater of the Poverty Bay Flats - a brief synopsis. Environment and Planning Department Report, Gisborne District Council, 54 p.

BURDEN, R.J. 1982: Nitrate contamination of New Zealand aquifers: a review. New Zealand Journal of Science 25: 205-220.

BURDEN, R.J. 1984: Zonation in groundwater of the Central Plains, Canterbury. New Zealand Journal of Hydrology 23: 100-119.

CANTERBURY REGIONAL COUNCIL 1997: Canterbury Regional Council Regional Environment Report 1995/96. Report 97(10).

CHEBOTAREV, I.I. 1955: Metamorphism of natural waters in the crust of weathering. Geochimica et Cosmochimica Acta 8: 22-48.

CLOSE, M.E. 1987: Effects of irrigation on water quality of a shallow unconfined aquifer. Water Resources Bulletin 23: 793-802.

CLOSE, M.E. 1993: Assessment of pesticide contamination of groundwater in New Zealand. II Results of groundwater sampling. New Zealand Journal of Marine and Freshwater Research 27: 267-273.

CLOSE, M.E. 1996: Survey of pesticides in New Zealand groundwaters, 1994. New Zealand Journal of Marine and Freshwater Research 30: 455-461.

CLOSE, M.E.; TOD, J.L.; TOD, G.J. 1995: Effect of recharge variations on regional groundwater quality in Mid-Canterbury, New Zealand. New Zealand Journal of Hydrology 33:1-16.

DOWNES, C.J. 1985: Redox reactions, mineral equilibria, and groundwater quality in New Zealand aquifers. In: C.H. Ward; W. Giger and P.L. McCarty (Eds.) Ground Water Quality: John Wiliey & Sons. p 94-121.

DILLON, P.J.; CLOSE, M.E.; SCOTT, R.I. 1989: Diffuse-Source Nitrate Contamination of Groundwater in New Zealand and Australia. Hydrology and Water Resources Symposium, Christchurch, New Zealand. p 351-355.

DRINKING WATER STANDARDS FOR NEW ZEALAND 1995: Compiled by the National Drinking-Water Standards Review Expert Working Group, Ministry of Health. 87p.

ENVIRONMENT WAIKATO 1998: Waikato state of the environment report 1998. 244 p.

FLÜHLER, H.; POLOMSKI, J.; BLASER, P. 1982: Retention and movement of fluoride in soils. Journal of Environmental Quality 22: 747-758.

FREEZE, R.A.; CHERRY, J.A. 1979: *Groundwater*, Prentice Hall, Englewood Cliffs, 604 p.

GERRITSE, R.G.; GEORGE, R.J. 1988: The role of soil organic matter in the geochemical cycling of chloride and bromide. Journal of Hydrology 101: 83-95.

GISBORNE DISTRICT COUNCIL 1997: The state of our environment. Conservation Division, Gisborne District Council, 72 p.

HADFIELD, J.; SMITH, D. 1999: From gasworks to sheep dips: Site contamination in the Waikato Region, New Zealand, Contaminated Site Remediation Conference proceedings, Perth, Australia.

HAYGARTH, P. 1997: Agriculture as a source of phosphorus transfer to water: sources and pathways. SCOPE Newsletter 21: 16 p.

HAYWARD, S.A.; SMITH, V.R. 1999: Groundwater contamination by hydrocarbons in Canterbury: A review of monitoring data from April 1988 to June 1999. Canterbury Regional Council, Environmental Monitoring Group, Technical Report R99/11, 55 p.

HAYWARD, S.A.; SMITH, V.R. 2000: Arsenic contamination of soil and groundwater in Kaikoura associated with historic sheep farming practices. Environment Canterbury, Environmental Monitoring Group, Technical Report, (Draft).

HEM, J.D. 1985: Study and interpretation of the chemical characteristics of natural water. 2nd edition. U.S. Geological Survey Water-Supply Paper 2254.

HODGES, S. 1994: Non-geothermal groundwater natural environment regional monitoring network annual report 1992-1994. Environment Bay of Plenty, Environmental Report 94/7, 98 p.

HODGES, S. 1995: Groundwater natural environment regional monitoring network annual report 1995. Environment Bay of Plenty, Environmental Report 95/14, 107 p.

HOUNSLOW, A.W. 1995: Water Quality Data: Analysis and Interpretation. CRC Lewis Publishers, Boca Raton, 397 p.

JOHNSON, W.P.; AMY, G.L. 1995: Facilitated transport and enhanced desorption of polycyclic aromatic hydrocarbons by natural organic matter in aquifer sediments. Environmental Science and Technology 29: 807-817.

LANGMUIR, D.; MAHONY, J. 1985: Chemical equilibrium and kinetics of geochemical processes in ground water studies. *In*, First Canadian/American Conference on Hydrology: Practical applications of Ground Water Geochemistry, 1984, Banff, 69-95.

LINCOLN ENVIRONMENTAL 1998: A survey of nitrate contamination of NZ aquifers. Report to Ministry of Agriculture and Forestry, Draft Report No. 4309/1, 8 p.

MACTAVISH, D.; CLOSE, M.E.; THORPE, H.R. 1997: Lower Taieri Groundwater Study. Prepared for Otago Regional Council.

MAGEE, B.R.; LION, L.W.; LEMELY, A.T. (1991): Transport of dissolved organic macromolecules and their effect on the transport of phenanthrene in porous media. Environmental Science and Technology 25: 323-331.

MARLBOROUGH DISTRICT COUNCIL 1994: Groundwater resources and issues of the Omaka and Brancott valleys. Unpublished Report .

Otago Regional Council 1999: Taieri River catchment monitoring report. Report No 99/316, 248 p.

Pang, L. 1995: Contamination of groundwater in the Te Aroha area by heavy metals from an abandoned mine. Journal of Hydrology (NZ) 33: 17-34.

Pang, L.; Close, M.E. 1999: A field study of nonequilibrium and facilitated transport of Cd in an alluvial gravel aquifer. Ground Water 37: 785-792.

Rekker, J.H. 1994: Southland region groundwater resource; scoping study. Report to Southland Regional Council from AquaFirma Ltd.

Rekker, J.H. 1998: Oteramika trial catchment groundwater studies. Studies into non-point source groundwater effects in Southland. Report to Southland Regional Council from AquaFirma Ltd. 86 p.

Roberts, K. 2000: Effect of storm water infiltration on a fractured rock aquifer, Western Springs, Auckland. Unpublished Masters Thesis, The University of Auckland, 76 p.

Rosen, M.R. 1997: The national groundwater monitoring network (NGMP): Structure, implementation and preliminary results. Institute of Geological and Nuclear Sciences, Science Report 97/26, 47 p.

Rosen, M.R. 1998: Construction of an environmental indicators database for groundwater quality: preliminary results of a heavy metal survey of NGMP wells. Abstracts of the joint conference of the Meteorological Society of New Zealand and the New Zealand Hydrological Society, November 1998, Dunedin, 90-91.

Rosen, M.R. 1999: The importance of long-term, seasonal monitoring of groundwater wells in the New Zealand National Groundwater Monitoring Programme (NGMP). Journal of Hydrology (NZ) 38: 145-169.

Rosen, M.R.; Bright, J.; Carran, P.; Stewart, M.K.; Reeves, R. 1999, Estimating rainfall recharge and soil water residence times in Pukekohe, New Zealand, by combining geophysical, chemical and isotopic methods. Ground Water 37: 836-844.

Rosen, M.R.; Jones, S. 1998: Controls on the groundwater composition of the Wanaka and Wakatipu basins, Central Otago, New Zealand. Hydrogeology Journal 6: 264-281.

Rosen, M.R.; Sheppard, D.S.; Roberts, K.; Viljevac, Z.; Smaill, A.; Reeves, R. 2000: Effects of storm water infiltration on groundwater quality in a fractured rock aquifer in Auckland. New Zealand Water and Waste Association, Storm water Conference and Workshop Proceedings, 12-14 April 2000.

Stumm, W.; Morgan, J.J. (1981): Aquatic Chemistry, 2nd edition, Wiley-Interscience, New York.

Tanji, K.; Valoppi, L. 1989: Groundwater contamination by trace elements. Agricultural Ecosystems and Environment 26: 229-274.

Timperley, M.H. 1983: Phosphorus in spring waters of the Taupo volcanic zone, North Island, New Zealand. Chemical Geology 38: 287-306.

Van Beek, C.G.E.M.; Hettinga, F.A.M.; Straatman, R. 1989: Release of heavy metals in groundwater due to manure spreading. In Water-Rock Interaction 6, Miles (ed.), Balkema, Rotterdam, 703-706.

Vengosh, A.; Pankratov, I. 1998: Chloride/Bromide and Chloride/Fluoride ratios of domestic sewage effluents and associated contaminated ground water. Ground Water 36: 815-824.

Viljevac, Z. 1998: Western Springs aquifer. Hydrological characteristics and computer model. Masters Thesis, Department of Geology, University of Auckland, 144 p.

Vollenwieder, R.A. 1968: Scientific fundamentals of the eutrophication of lakes and flowing waters, with particular reference to nitrogen and phosphorus as factors in eutrophication. OECD Water Management Research DAS/CSI/68.27, 159 p.

White, E. 1983: Chemicals and their importance to the lake, In: D.J Forsyth and C. Howard-Williams (Eds.) Lake Taupo, Ecology of a New Zealand Lake, DSIR Information Series 158, Wellington, pp. 63-72.

5

Rainfall and irrigation recharge to groundwater

HUGH R. THORPE

INTRODUCTION

The movement of water through the vadose zone is of interest for several reasons. The vadose zone is a point of entry for water into the aquifer and the flux through it, below the root zone, is an upper bound of the magnitude of the resource. Information on this water movement is also needed as part of studies of irrigation efficiency and of mass transport in unsaturated materials where water is the agent of transport for pollutants.

As this is intended to be a description of current research in groundwater recharge in New Zealand, only a brief mention is made of earlier work.

There are two modes of water movement through an unsaturated soil. Darcian flow, as the name suggests, obeys Darcys law and can be well described, assuming soil hydraulic parameters are isotropic and homogeneous. The less well understood mode of movement is through larger openings in the soils such as shrinkage cracks, worm holes or old root openings. Such macropores transmit water only when the soil is very wet.

Natural soils are neither isotropic nor homogeneous, and macropores with variable diameters occur randomly in position. The research described here makes no distinction between these modes, and the models described have not allowed for macropore flow.

The first reported study of rainfall recharge to groundwater in New Zealand was by H.E. Annett (1953), using data from two lysimeters constructed at the former Soil Fertility Research Station at Rukuhia. Annett reported on drainage through a Hamilton clay loam. Over the years 1948 to 1952, when the average yearly rainfall was 1170 mm, the average yearly drainage (i.e. recharge) was 445 mm. Annett was interested in the loss of water and nutrients from the soil, so recharge, as such, was incidental to his research.

The same design was used in constructing two more lysimeters, for the same purpose, in Lismore stony silt loam, at the Winchmore Irrigation Research Station in Mid-Canterbury. These two lysimeters began operating in 1952 and were supplemented by four more in 1961, with daily data collection carrying on until 1978 (Thorpe and Scott 1999).

In the following years further short runs of recharge data were collected during research into land disposal of animal wastes (Fraser et al. 1994; Cameron et al. 1995; Carey et al. 1997; Barkle et al. 1998), leaching of pesticides (Pang et al. 2000) and irrigation efficiency (Close 1985; Evans 1999).

Only in more recent years has research been carried out specifically to measure and understand recharge, without including measurements of leaching processes (Bekesi and McConchie 1999; Thorpe and Scott 1999; Evans 1999; Rosen et al. 1999).

STUDIES OF RECHARGE AT A POINT

G.F. Barkle, T.N Brown, D.J. Painter and P.L. Singleton

Barkle et al. (1998) established a suite of nine lysimeters, 600 mm in diameter and 1200 mm deep, in undisturbed Te Kowhai silt loam at the Ruakura Research Station on the outskirts of Hamilton City in the North Island of New Zealand. There were three replicates of three

Thorpe H.R. 2001: Rainfall and irrigation recharge to groundwater. *In* Groundwaters of New Zealand, M.R. Rosen and P.A. White *(eds)*. New Zealand Hydrological Society Inc., Wellington. p111-131.

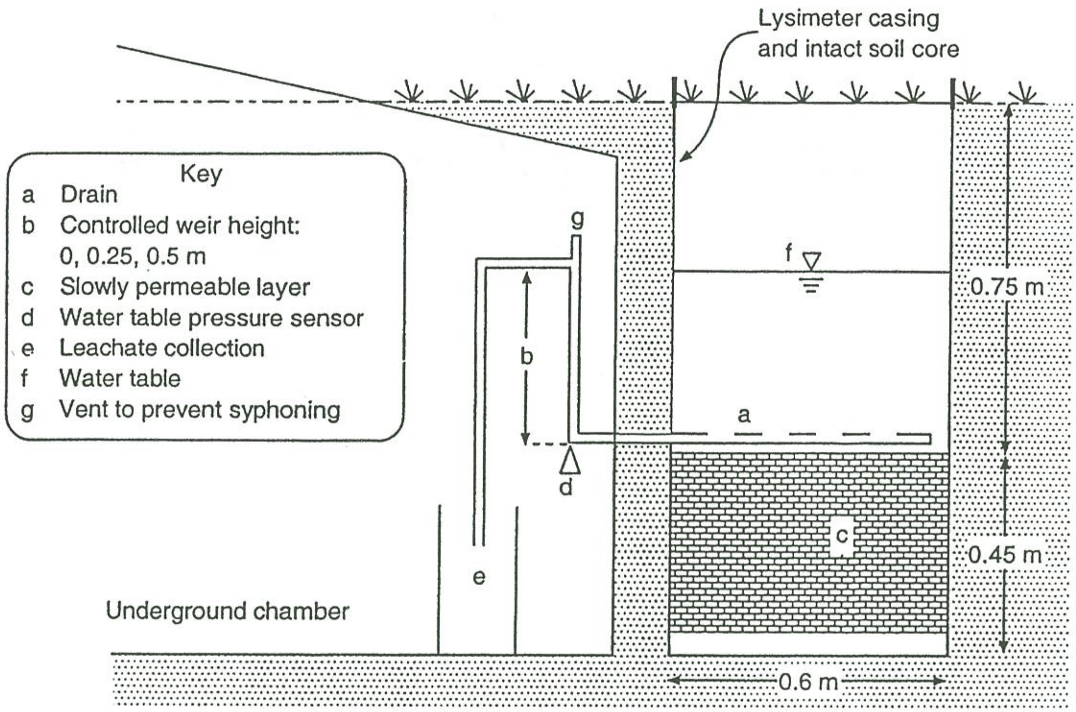

Figure 5.1 *Lysimeter configuration used by Barkle et al. (1998).*

controlled drainage treatments (Fig 5.1); the objective of the study was to measure nutrient leaching and validate two models of soil water distribution. Although the lysimeters were 1200 mm deep, the Te Kowhai soil contains a layer of slowly permeable material at about 750 mm and this was the greatest depth from the soil surface at which the water table was controlled throughout the four-year experimental period. The other two replicate sets controlled the water table at depths of 500 mm and 250 mm. (Barkle et al. 1998) (Fig 5.1). The lysimeters were spray irrigated weekly over 3.5 hours with 17 mm of very dilute organic slurry, from September to May, 1992-1996. Leachate (recharge) was generally collected on a daily basis. A ryegrass-clover mix *(Lolium perenne* L. *Trifolium repens* L.) was grown on the lysimeters, and cut and removed every 28 days.

Hourly meteorological data were obtained from the Ruakura station and used to calculate the potential evaporation (PET), using the Priestly-Taylor method. Annual quantities of rainfall, irrigation, PET and calculated drainage from this site are given in Table 5.1 (Barkle et al. 1998).

Data from these lysimeters were used to evaluate two soil moisture models, DRAINMOD (Skaggs 1980a, b) and SWIM (Ross 1990).

DRAINMOD is widely used in the United States for managing the water table in agricultural

Table 5.1 *Annual rainfall (R), irrigation (I), and potential evapotranspiration (PET) at the Ruakura lysimeter site. All measurements are in mm (Barkle et al. 1998).*

Year	R	I	Inputs (R+I)	PET (P)	Drainage (R+I-P)
1992A	770	301	1071	488	583
1993	872	691	1563	1030	533
1994	1047	705	1752	1065	687
1995	1341	894	2235	1016	1219
1996B	737	69	806	524	282

A Last 6 months
B First 6 months

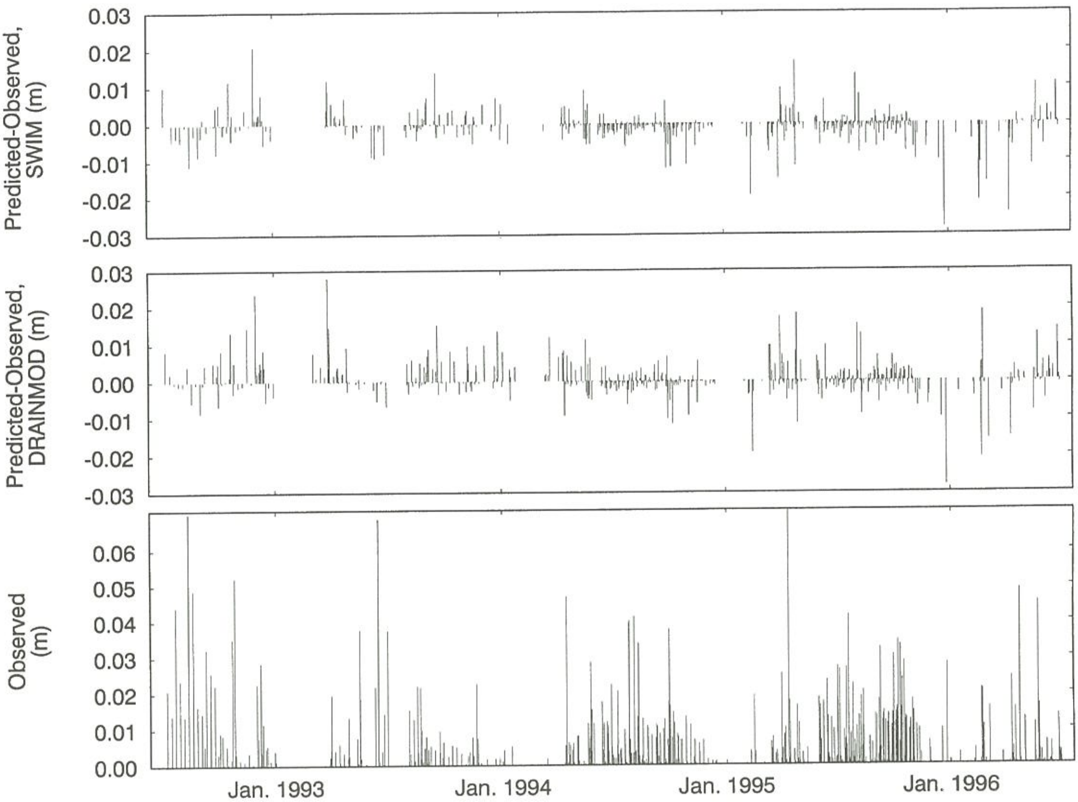

Figure 5.2 *Residual plot of (predicted-observed) drainage values for the controlled low-drainage treatment for both DRAINMOD and SWIM over a 4-year period (Barkle et al. 1998).*

areas where a system of parallel subsoil drains is to be installed. It is based on a water balance in the soil profile midway between the parallel drains and developed specifically for areas where the water table is shallow.

The hydrological computations in DRAINMOD are largely empirical and approximate. With the water table usually fairly close to the surface evapotranspiration is largely unrestricted, but provision exists within the model for limiting evapotranspiration for conditions in which the soil is dry or water demands are high.

For the unsaturated zone, a 1:1 relationship is assumed between matric potential and height above water table. A table is given relating the height above water table to the air-filled porosity or drainage volume for specific soils.

DRAINMOD requires hourly rainfall data and simulation steps vary from daily for drier conditions to hourly when rainfall or surface ponding occurs.

SWIM is a CSIRO hydrology package used to simulate Soil Water Infiltration and Movement (Ross 1990). It is built around a numerical solution of the Richards equation. Water is added to the model as precipitation and removed by runoff, drainage, evaporation from the soil surface and transpiration by vegetation. The soil is assumed to be uniform horizontally, but up to 101 layers within the profile may be specified. Soil hydraulic properties required for SWIM are more detailed than for DRAINMOD, but these have been measured and published for a number of New Zealand soils. (Watt and Burgham 1992).

The comparison of measured and simulated annual data from Barkle et al. (1998) is given in Table 5.2.

Table 5.2 *Comparison of observed and predicted drainage for three drainage treatments. Data shown for 1992 and 1996 are for the last and first six months respectively; the first two replicates ran for only 2 months in 1996. The observed mean is an adjusted value to account for some data loss due to equipment failure. Replicate variation is the drainage depth variation about the mean; data for only one replicate was collected for the final 4 months of 1996, so variation is not shown for this period. Error is the standard error of deviation; ratio is actual/predicted values (Barkle et al. 1998).*

Year	Observed mean (mm	Replicate variation Plus %	Minus %	DRAINMOD Drain. Depth (mm)	Error (mm)	Ratio	SWIM Drain. Depth (mm)	Error (mm)	Ratio
Free drainage									
1992	616	5.9	5.7	649	5.4	0.95	668	6.0	0.92
1993	562	9.9	8.2	672	3.2	0.84	664	2.9	0.85
1994	923	2.4	3.5	885	2.9	1.04	870	2.8	1.06
1995	1341	2.3	3.8	1390	3.9	0.96	1280	3.2	1.05
1996	355			371	4.1	0.96	295	4.0	1.20
1992-6	3798	4.5	2.9	3967	3.6	0.96	3777	3.4	1.01
Drainage controlled by 0.25 m weir height									
1992	569	11.4	6.1	649	5.2	0.88	572	5.5	0.99
1993	498	3.3	3.1	672	3.3	0.74	526	2.2	0.95
1994	894	2.8	2.1	885	2.6	1.01	731	2.5	1.22
1995	1373	1.9	3.6	1380	3.9	0.99	1186	3.6	1.16
1996	334			367	4.0	0.91	237	4.8	1.41
1992-96	3667	0.6	0.4	3953	3.6	0.93	3253	3.4	1.13
Drainage controlled by 0.5 m weir height									
1992	580	5.9	4.9	605	4.8	0.96	558	4.2	1.04
1993	532	8.6	13.0	643	3.2	0.83	504	2.5	1.06
1994	893	5.3	4.4	847	2.7	1.05	719	2.6	1.24
1995	1279	3.6	2.7	1319	3.8	0.97	1154	3.4	1.11
1996	367			309	3.4	1.19	222	5.4	1.65
1992-96	3651	4.9	4.6	3724	3.4	0.98	3156	3.4	1.16

Both models gave excellent estimates of total drainage on an annual basis under all three drainage conditions, without any need to adjust the model calibration or parameters. Over the four years of the experiment, the ratio of actual to predicted recharge ranged from 0.93 to 1.16.

DRAINMOD generally overestimated recharge (mean annual / predicted = 0.95) while SWIM underestimated recharge (mean annual / predicted = 1.10).

Drainage fluxes over summer and autumn were the most difficult for both models to predict and the greatest errors were associated with events in these seasons. Simulation errors accumulated over periods of no drainage and only became apparent when the next drainage event occurred. In replicate lysimeters recharge differences were greatest during soil rewetting after dry periods. (Fig 5.2).

Despite relatively high rainfall and regular summer irrigation, there were periods of up to eight weeks when no recharge occurred.

DRAINMOD is simpler, so when its assumptions are met, i.e. shallow water table or drainage depth control, it is preferable. If soil moisture data is needed then SWIM is better. Barkle et al. (1998) suggest that SWIM may give better estimates for drainage in areas with drier climates and low permeability soils.

M.R. Rosen, J. Bright, P. Carran, M.K. Stewart and R. Reeves

Rosen et al. (1999) used four methods to estimate ground water recharge at Pukekohe, an

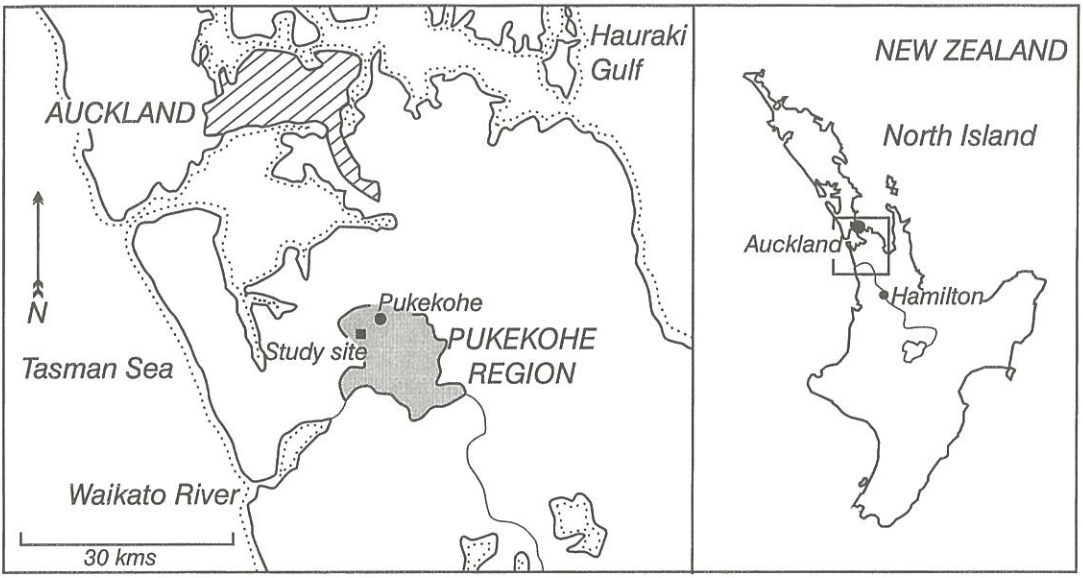

Figure 5.3 *The Pukekohe region showing the recharge study site (Rosen et al. 1999). Reprinted by permission of Ground Water ©1999. All rights reserved.*

area of intensive irrigated vegetable production, about 35 km south of Auckland (Fig 5.3). They also used isotopic and chemical techniques to estimate residence times in the aquifers. The experimental period was from January 1997 to May 1998.

The four methods of estimating recharge were:

- a water balance based on time series measurements of soil moisture by time domain reflectometry (TDR, Lincoln Environmental 1998),
- a single-layer daily soil-water balance model, CSMM (Heiler 1982),
- the monthly difference between rainfall and potential evapotranspiration (PET),
- using the equation:

$$R = \frac{Cp \,.\, P}{Cr}$$

where R and P are recharge and precipitation, and Cp, Cr are the mean monthly chloride concentration of these fluxes.

The sum of monthly totals from the first three methods all gave an annual recharge of about 680 mm from an annual rainfall of 1318 mm, with most recharge occurring in winter and spring, as expected. The first two methods gave weekly, monthly and seasonal totals and the third method only monthly and seasonal (Fig 5.4.). The chloride method gave an estimate of 730 mm, but with a high monthly error because of the incidence of westerly storms sweeping in at random intervals from the Tasman Sea. Data from a nearby well showed a lag of recharge of about a month between rainfall and the water table response at a depth of 12-16 metres (Fig 5.5).

The TDR technique measured soil moisture and allowed changes in the root zone (top 600 mm) to be determined. Recharge was then calculated with the simple water balance

$$R = P - AET \pm \delta S \qquad (5.1)$$

where: AET = actual evapotranspiration
δS = change in soil moisture.

Lincoln Environmental (1998) comment that this method does not give an absolute measure of recharge because the actual evapotranspiration (AET) is derived from PET, which in turn is calculated from measured climate data. Thus the accuracy of the method will be reduced in summer when AET is often less than PET, but this is not of great significance because most recharge occurs in the other seasons. The method bias will be to un-

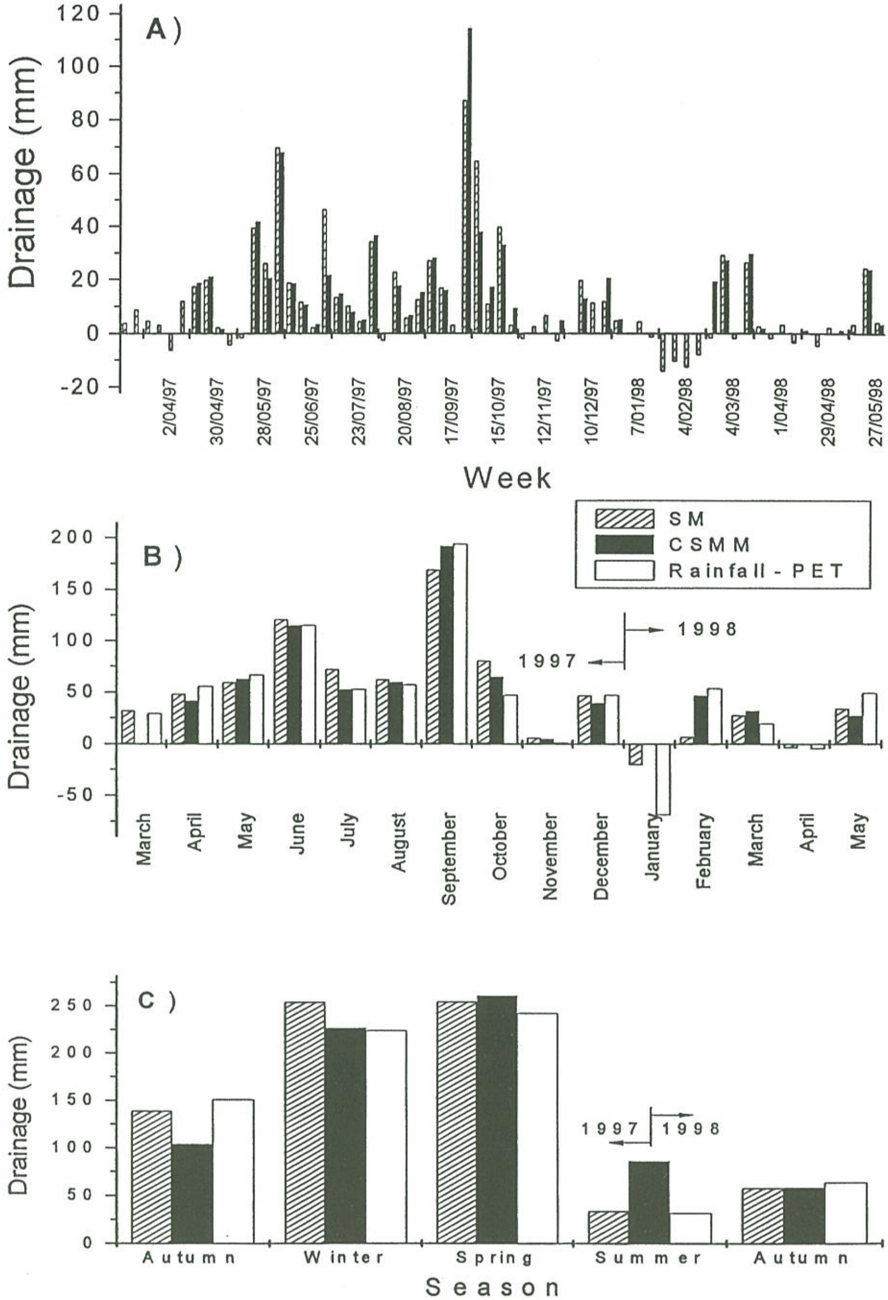

Figure 5.4 *A) Weekly drainage data estimated using soil moisture measurements (SM Balance) and the simple water balance model (CSMM). B) Monthly recharge (drainage) depths estimated using soil moisture measurements (SM Balance), the simple water balance model (CSMM), and based on rainfall minus potential evapotranspiration. (Rain - PET). C) Seasonal recharge (drainage) for the methods shown in 4B (Rosen et al. 1999). Reprinted by permission of Ground Water ©1999. All rights reserved.*

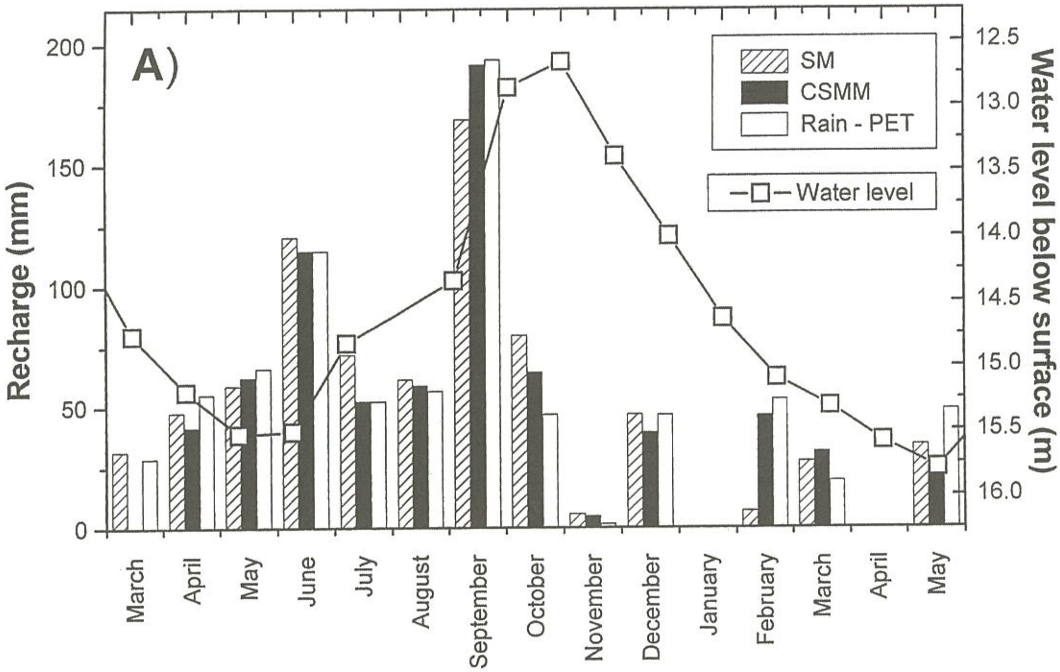

Figure 5.5 *Monthly recharge (drainage) estimates (from Fig 5.4B) compared to water level fluctuations in a nearby bore. Negative drainage is not plotted (Rosen et al. 1999). Reprinted by permission of Ground Water ©1999. All rights reserved.*

derestimate, but annual values should be accurate to within a few percent.

The simple soil water balance model (Heiler 1982) uses only measured climate data and soil hydraulic properties to estimate daily soil moisture values. AET is calculated by factoring PET according to the estimated soil moisture value for that day. Rainfall in excess of the drained upper limit of the soil is assumed to become recharge on the day of occurrence. No allowance is made for upward flux. The method will overestimate recharge in areas where drainage is impeded to the point where evapotranspiration demands can be met from soil moisture levels greater than the drained upper limit, or where significant upward flux can occur.

The difference between rainfall and PET is a crude method of estimating recharge that assumes a reasonably uniform distribution of rainfall and PET throughout the year. In New Zealand areas where rainfall is relatively uniformly distributed and there is typically a summer soil moisture deficit, the method will slightly underestimate annual recharge but should be quite accurate in the winter, and to a lesser degree in autumn and spring.

Lincoln Environmental (1998) comments: "It can be seen that none of the methods could be considered to provide an absolute estimate of the drainage volume and to this extent the comparisons are somewhat artificial. Evapotranspiration and rainfall are the major factors in the soil water balance equation and these are used in all the techniques compared. To some extent all three methods just provide slightly different means of manipulating the same basic inputs."

H.R. Thorpe and D.M. Scott

Thorpe and Scott (1999) used an extensive set of lysimeter data from the Winchmore Irrigation Research Station (now AgResearch Winchmore) in mid-Canterbury (Fig 5.6) to evaluate four soil moisture models for estimating natural recharge.

The objective of the early research at Winchmore was to examine leaching of ferti-

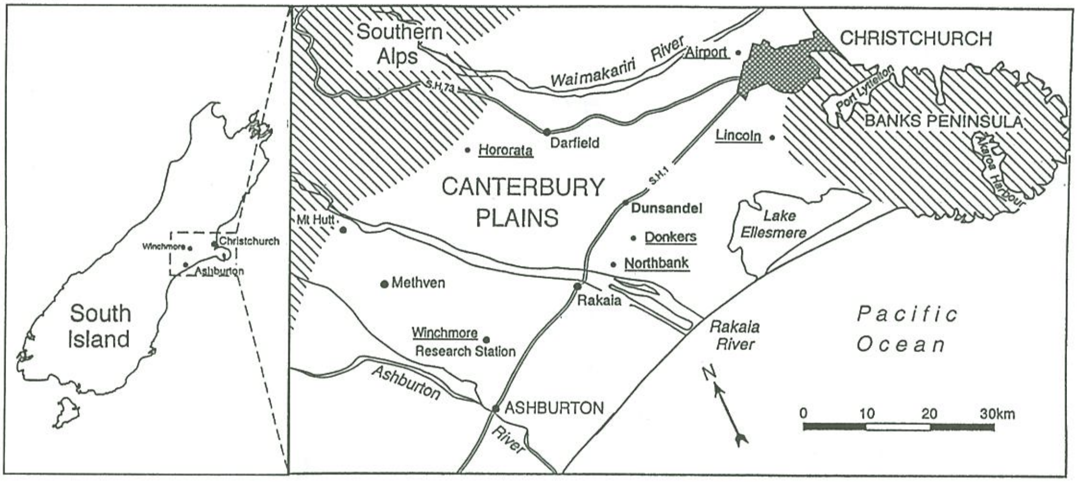

Figure 5.6 *Locations (underlined) of the lysimeters on the Canterbury Plains, South Island, New Zealand (Thorpe and Scott 1999).*

lisers under irrigation, and during the period 1955-60, one lysimeter was irrigated and a second used as a control. Only data from the control was used in this study.

These lysimeters were essentially the same design used by Annett (1953) at Rukuhia (Fig 5.7). They consisted of spun concrete pipes, 1220 mm diameter and 1000 mm long, sunk 900 mm into the soil, and containing an undisturbed column of Lismore stony silt loan soil. A perforated steel plate was driven horizontally across the base of the pipe and sealed to it with a mastic. Beneath the perforated plate, a collection cone and pipe carried the drainage to measuring tanks. Access to the tanks and the base of the lysimeters was via a concrete-lined trench. Two such lysimeters were commissioned in 1953 and operated with a bare soil surface for two years. They were then sown in grass and operated until 1960, when four more lysimeters were added in another cluster within the same paddock.

From 1961 until about 1972 six identical lysimeters were used with bare soil and then they were re-grassed. Data collection was nominally daily (i.e. except weekends) and continued until 1978. Meteorological data was available from a station about 100 metres from the lysimeter paddock.

This data was carefully transcribed to a data disk from paper records and cross checked. Replicated data from up to six lysimeters gave added confidence in data quality. Figure 5.8 shows data from 1961-71 and illustrates the consistency of the daily records from three lysimeters. Figure 5.9 plots annual values of rainfall and recharge under bare soil through the 1960s and shows the inter-lysimeter variability. Figure 5.10 shows, for one lysimeter, the increase in recharge through a bare soil as compared to a grassed surface. It also suggests that the relationship of annual rainfall and recharge could be linear.

In September 1994, three of the old lysimeters were checked for leaks and fitted with tipping-bucket rain gauges in place of the collecting tanks (Fig 5.7). A fourth gauge measured rainfall. Data were logged at 5-minute intervals until December 1997.

Over this period soil moisture profiles were also obtained by the neutron-scattering technique. Thorpe and Scott (1999) showed that, of the four soil moisture models evaluated, SWIM (Ross 1990, described above) and SOILMOD (Scott and Thorpe 1986) provided a good simulation of natural recharge. The strength of this work was the availability of a unique daily recharge data set extending over a 25-year period, with replication of lysimeters and with both pasture and bare soil cover. This set was extended with data logged at 5-minute

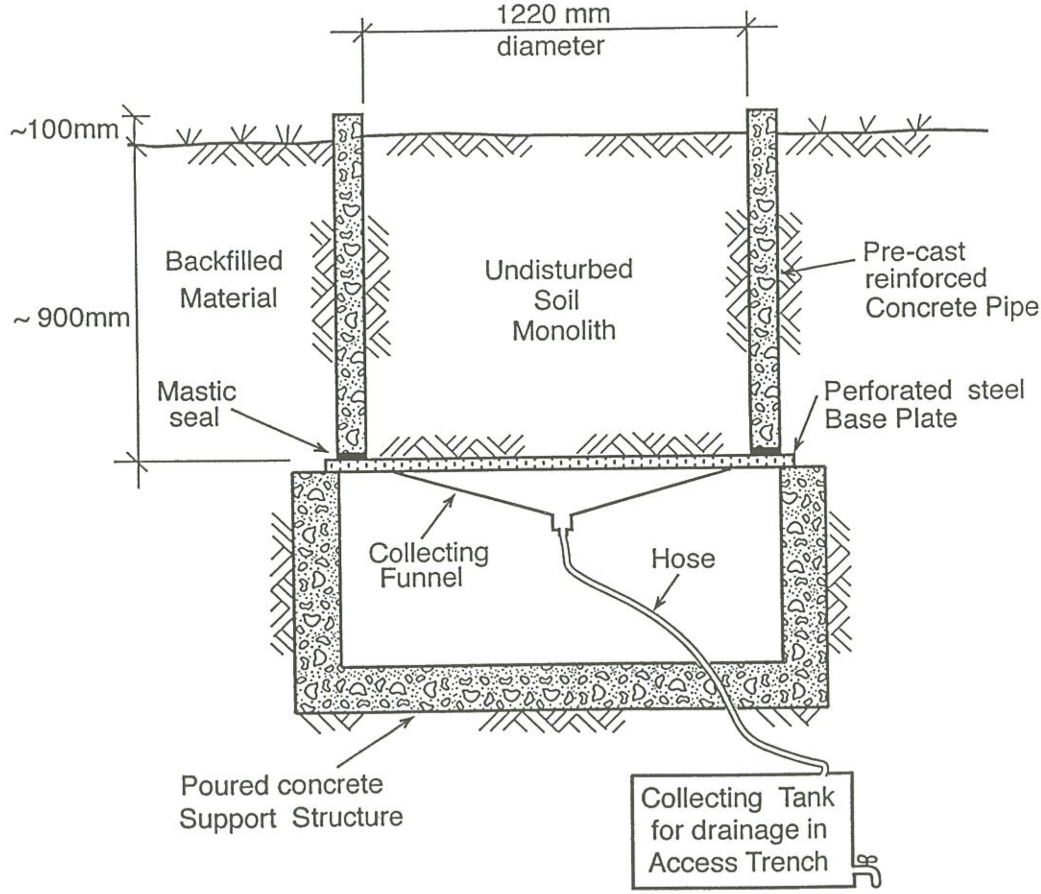

Figure 5.7 *A Winchmore lysimeter as originally constructed, with a rim protruding above ground (Thorpe and Scott 1999).*

intervals from three grassed lysimeters over the years 1995-97.

SOILMOD is a single-layer (lumped parameter) model based on a simple soil moisture balance, assuming no surface runoff, i.e.

$$S_i = S_{i-1} + R_i + I_i - AET_i - D_I \qquad (5.2)$$

Where Si = soil moisture on day i, i-1 etc.
R_i = rainfall on day i
I_i = irrigation on day i
AET_i = actual evapotranspiration on day i
D_i = drainage on day i.

In this equation AET is the most difficult of the independent parameters to quantify. The calculation of AET is based on the soil field capacity, level of soil moisture and evaporative demand on the day. Thus for higher soil moistures, where Si exceeds Sc, the critical moisture level at which AET begins to fall below PET (Fig 5.11):

If $S_{i-1} > S_c$ i.e. $S_{i-1} > FC\ \ U$, then

$$\frac{AET_i}{PET_i} = 1 \qquad (5.3)$$

while for drier soil;

$$\frac{AET_i}{PET_i} = \frac{S_i}{S_c} = \frac{S_i}{FC\text{-}U} \qquad (5.4)$$

where a vegetation cover factor, VC, is defined by:

$$VC = \frac{U.PET_i}{FC} \qquad (5.5)$$

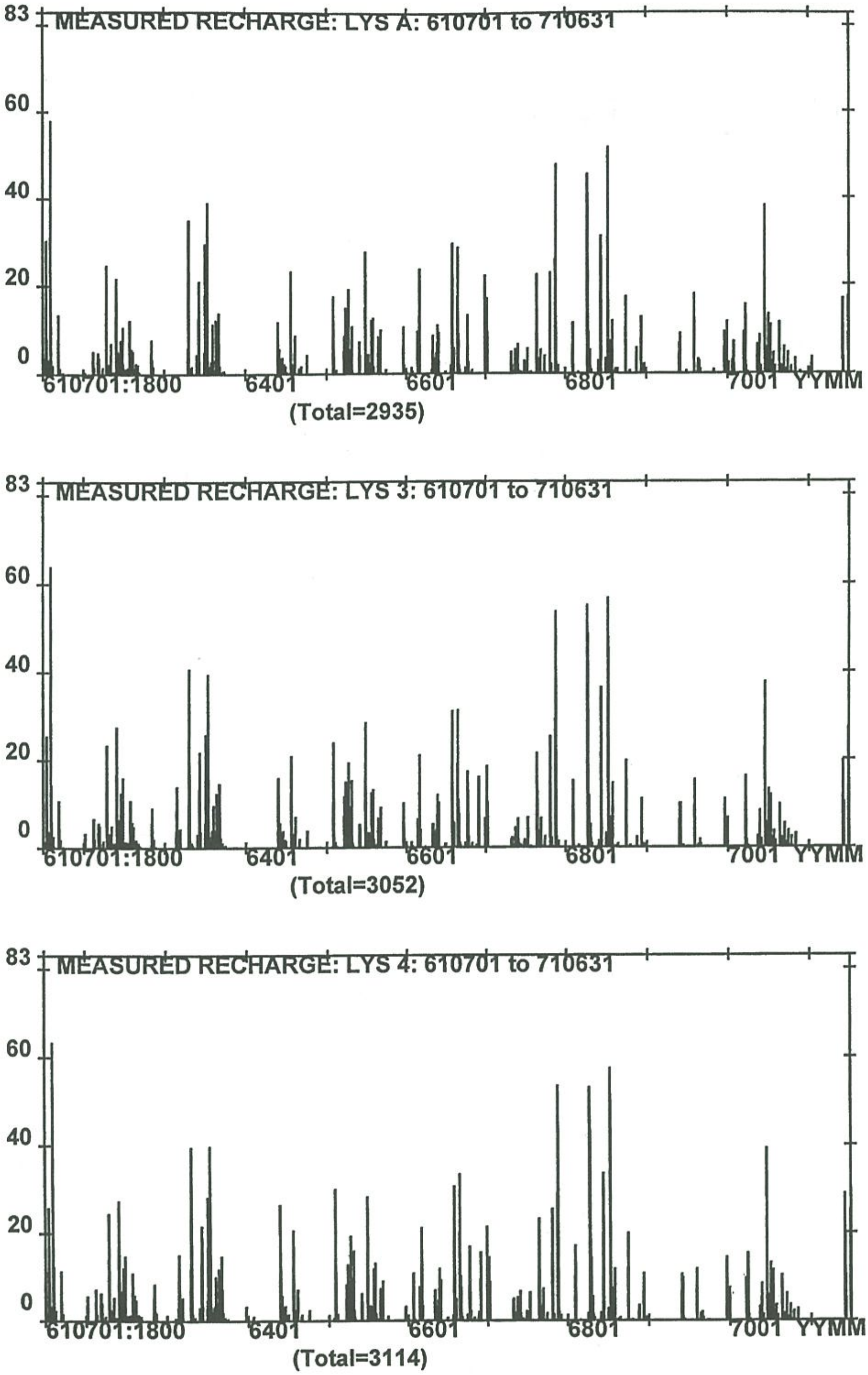

Figure 5.8 *A 10-year record of recharge through three Winchmore lysimeters without vegetation cover (Thorpe and Scott 1999). Totals are in mm.*

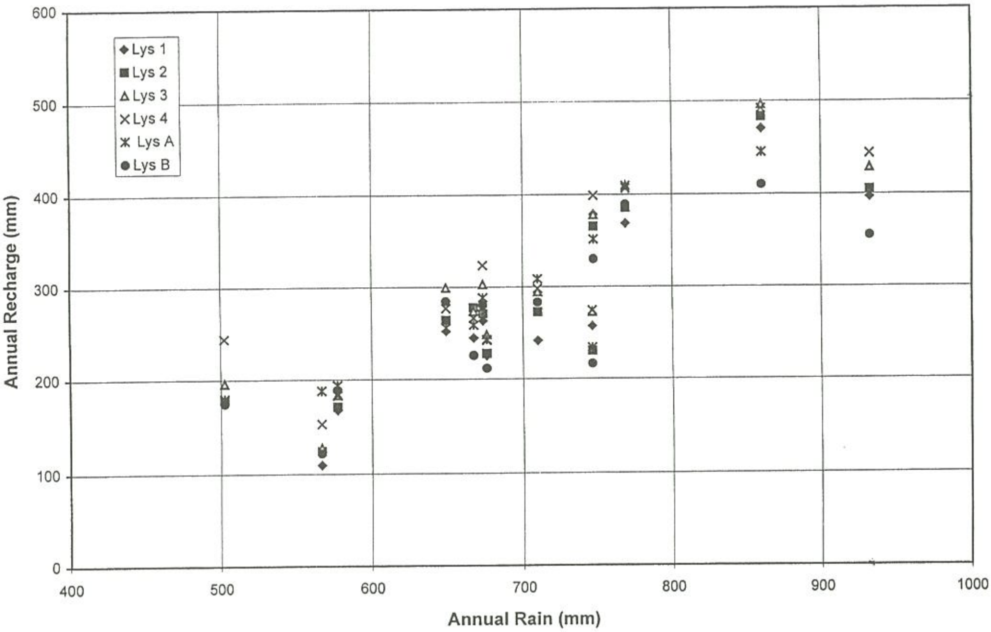

Figure 5.9 *Annual values of rainfall and recharge through the 1960s for six lysimeters, showing inter-lysimeter variability. Lysimeter B is thought to have leaked slightly and lysimeter 4 was occasionally spray irrigated by accident (Thorpe and Scott 1999).*

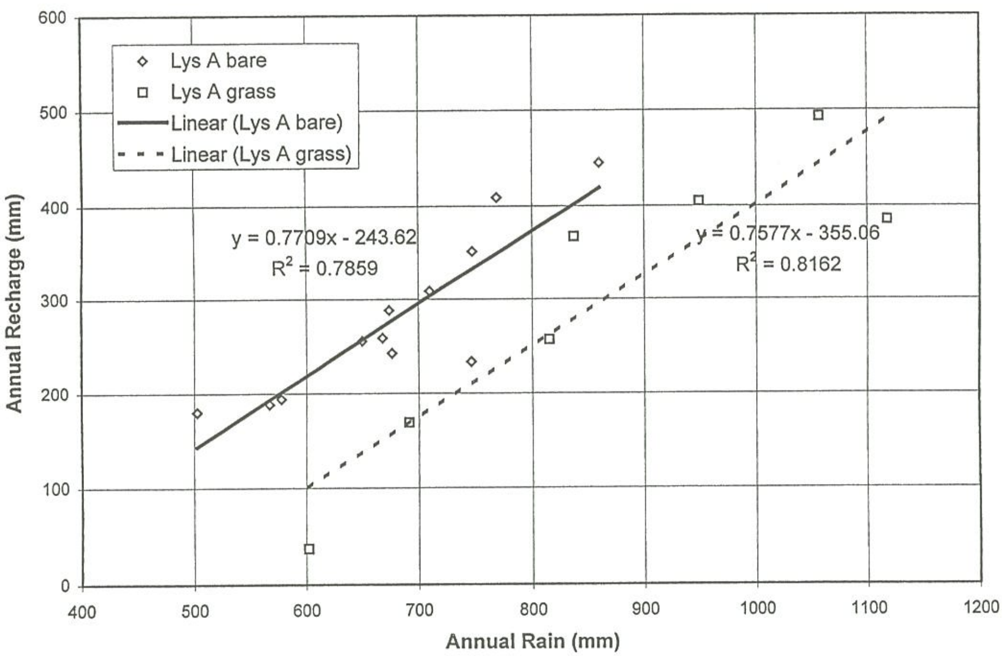

Figure 5.10 *A comparison of annual recharge through one lysimeter under pasture and bare soil conditions (Thorpe and Scott 1999).*

substituting this into (5.4) results in:

$$\frac{AET_i}{PET_i} = \frac{S_i/FC}{(1-VC/PET_i)} \qquad (5.6)$$

Where:

FC = soil moisture field capacity,

Sc = critical moisture level below which AET is less than PET

U = a root factor analagous to the Penman root constant (Penman 1949)

All the data and parameters used in the simulations were either measured at Winchmore or derived from New Zealand values in the literature. They were modified in two ways. Firstly, the official Winchmore rain data is probably an underestimate, as in very wet periods the lysimeters were producing more recharge than rain was apparently falling. Such underestimation of rainfall is commonly reported and is considered to be caused by exposure of the gauge to wind. Installation of a ground level rain gauge at the meteorological station to measure this effect indicated that the underestimate was about 10% and all rain data input to both models was increased by this amount. Secondly, although the recharge simulations with the SWIM model gave good results, there was a marked difference between the simulated and measured soil moisture profiles in the gravel subsoils. The hydraulic parameters used in SWIM for the gravel in a Lismore soil profile were noted by Watt and Burgham (1992) to be regarded with caution so there was justification to modify them to improve the simulation of the soil moisture profile.

SOILMOD gave good results over longer periods when the lysimeters had a grass cover. Figure 5.12 compares the simulated results with measured recharge for one lysimeter over a five-year period from 1955-60. The ratio of mean annual measured/ simulated recharge is 0.88, i.e. the model overestimated. However when the lysimeters were without vegetation the simulation consistently underestimated recharge. For a typical five-year simulation with one bare soil lysimeter, mean annual measured/ simulated recharge was 1.10.

SWIM underestimated recharge under grass cover slightly. For the same lysimeter and five-year time period as SOILMOD the ratio mean annual measured/simulated recharge was 1.06, which is an excellent result (Fig 5.13). However for bare soil conditions SWIM also underestimated recharge in all lysimeters, the ratio ranging from 1.47-2.0 over various five-year intervals.

Neither model (as used) incorporated macropore flow nor soil hysteretic behaviour under wetting and drying conditions. Desiccation and shrinkage at the bare soil surface may cause extra cracking, so macropore flow may account for the underestimation of recharge under such conditions. The long-term measurements showed greater recharge under bare soil than under grass (Fig 5.10), so models would need to be modified.

Other complicating factors in measuring recharge in small lysimeters are micro-topography and soil surface compaction by stock trampling. Throughout the period of earlier data collection, the lysimeter walls stood about 100 mm above ground (Fig 5.7), which prevented flow on or off the catch area. From 1995 onward, the lysimeters were cut down to just below ground level so there was no hindrance to flow on or off the catch area. During hand-applied spray irrigation in the course of the later research, water flowed off if the application rate was too high. It was also noted that relative lysimeter behaviour changed markedly over one period in 1996, after the paddock had been heavily stocked with sheep for several weeks in winter when the soil was soft, with an observed reduction in soil infiltration capacity. Normal recharge patterns were observed in 1997, presumably because natural plant and worm activity restored infiltration capacity over the growing season. Table 5.3 showing the annual data for these three years, illustrates how anomalous the 1996 simulations were compared to 1995 and 1997.

Sensitivity analyses showed that, with respect to long-term recharge, both models were very sensitive to rain input, which is significant given the uncertainty of rainfall measurement mentioned above. On the other hand, neither model was particularly sensitive to evapotranspiration, and the models were rather insensitive to soil water holding capacity.

Table 5.3 *Annual values of measured recharge under pasture cover compared with SOILMOD and SWIM simulated drainage for the three years 1995-97 (Thorpe and Scott 1999).*

Year	Rain (mm)	Irrigation (mm)	Total water (mm)	Lys A meas. (mm)	Lys. 3 meas. (mm)	Lys. 4 meas. (mm)	Average meas. (mm)	SOILMOD (mm)	SWIM (mm)
1995	803	210	1013	493	592	508	531	568	588
1996	806	312	1118	385	611	375	457	649	594
1997	699	0	699	169	186	174	177	186	174
Total	2308	522	2830	1047	1389	1057	1165	1403	1356

These observations relate to long-term recharge and are thought to result from the strongly seasonal recharge pattern (Thorpe and Scott 1999). Model sensitivities over shorter periods when the soil is generally wetting or drying out (autumn and spring) have not been examined and may be different. Both models performed less well during autumn.

SOILMOD is computationally more efficient than SWIM by an order of magnitude, a factor to be considered if a regional recharge model is needed.

C.J. Evans

As a study of irrigation efficiency, Evans (1999) carried out field measurements of recharge under two irrigation regimes, in an Eyre stony silt loam near Dunsandel (Fig 5.6). He used the same basic lysimeter design as Barkle et al. (1998) but 500 mm diameter by 700 mm deep, with unrestricted drainage. There were two lysimeters at each site. One site on a deer farm was irrigated by the border-strip (flood) method and the other site on a dairy farm by spray irrigation. Evans defined irrigation efficiency as the percentage of the applied water that was retained in the top 700 mm of soil and thus available for pasture growth. Given that water application rates and intervals are usually fixed, irrigation efficiency varies throughout the season depending on the antecedent soil moisture levels. Evans found that, for the site chosen, overall border-strip irrigation efficiency ranged from 5-13%, averaging about 10% over the season. The amount draining through the lysimeters to recharge averaged 167 mm per 185 mm average application.

Under spray irrigation, the efficiency ranged from 26-90% with an average of 61% and average recharge per irrigation of 19 mm.

Spray irrigation in Canterbury is usually with groundwater so there is no foreign water, whereas border-strip irrigation usually involves imported river water. In addition, border-strip irrigation is inherently more difficult to manage for water efficiency because usually a set amount is supplied on a fixed roster and water application depths per irrigation are much greater.

STUDIES OF REGIONAL RECHARGE

The flat terrain of Canterbury allows simpler methods of estimating regional recharge to be used and, given the greater utilisation of the resource in this region of New Zealand, it is not surprising that this is where the first attempts were made. Donaldson (1977), Cooper (1980) and Bowden et al. (1983) all estimated rainfall recharge in the Central Plains area using variations of a basic soil moisture water balance.

The first published attempt in New Zealand at estimating regional recharge of ground water on a daily basis was by Scott and Thorpe (1986) in their study of groundwater resources between the Rakaia and Ashburton Rivers. This was done using both a simple method based on excess rainfall and also the original version of SOILMOD, incorporated into an unsteady regional ground water model. This regional model compared the response of the groundwater system to various scenarios for irrigation development.

Close (1985) used a water balance approach for the partially constructed Waiau Irrigation Scheme in North Canterbury, to calculate both natural recharge and recharge enhanced by irrigation. He used this to predict changes to the water table caused by completion of the

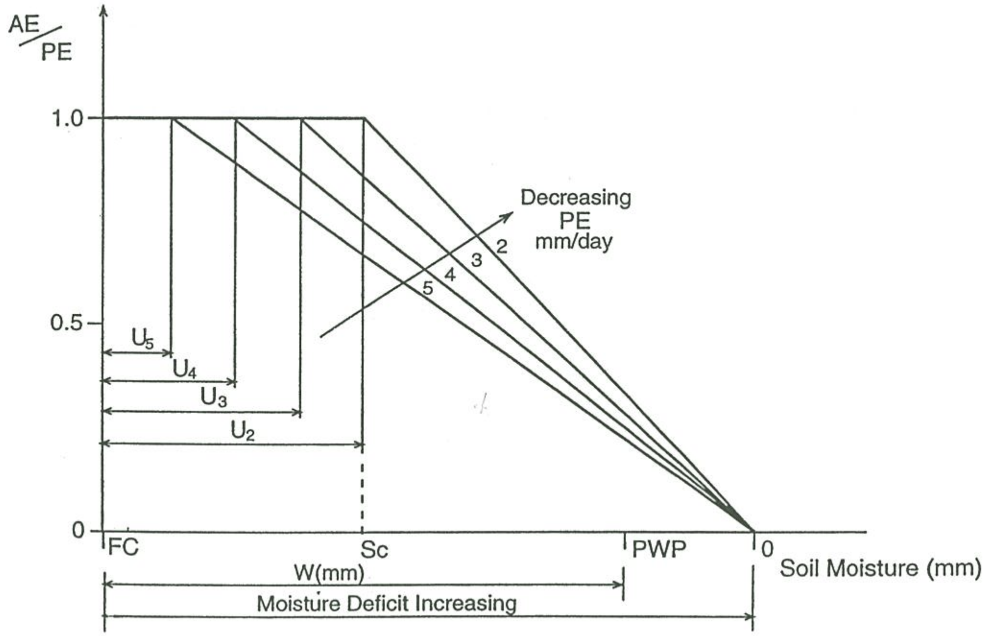

Figure 5.11 *The relationship between AET/PET ratio and soil moisture (Thorpe and Scott 1999).*

irrigation scheme and suggested that waterlogging could result in some areas.

G. Bekesi and J. McConchie

Bekesi and McConchie (1999) also adopted a simple soil moisture model but coupled this with a Monte Carlo simulation to produce a regional recharge estimate for the Manawatu Plains, and to provide an objective measure of the uncertainty of estimate. This approach was adopted because there was not enough detailed soil data for a more sophisticated study of the entire region. Fixed model inputs were rainfall and pan evaporation, while soil properties were the randomised variables. Ranges of values were most conservatively assigned for available water, readily available water, wilting point and pan factor, and for each scenario values were randomly selected within these ranges. The model then calculated daily recharge over a 28-year period, and calculated mean annual recharge and input values and stored these for statistical analysis. A map of recharge over the entire Manawatu Plains was produced (Fig 5.14), together with maps of uncertainty and sensitivity to the random inputs. Bekesi and McConchie (1999) comment that their model is relatively insensitive to estimates of available water but very sensitive to pan factor. Perhaps this is because pan factor is fairly well defined anyway and so should not have been included as a random variable. The authors further note that the modelled recharge is essentially linear with respect to annual rainfall, which can therefore be used as an estimator. They ar-

Table 5.4 *Estimates of water applied and recharge in the Ashburton-Rakaia district in 1978/79 and 1990/91 (Close et al. 1995)*

	Water applied (mm)		Recharge (mm)		
Rain	Spray	Border-strip	Rain only	Rain+Spray	Rain+Border-Strip
1141	60	650	672	677	1105
665	165	780	184	229	792

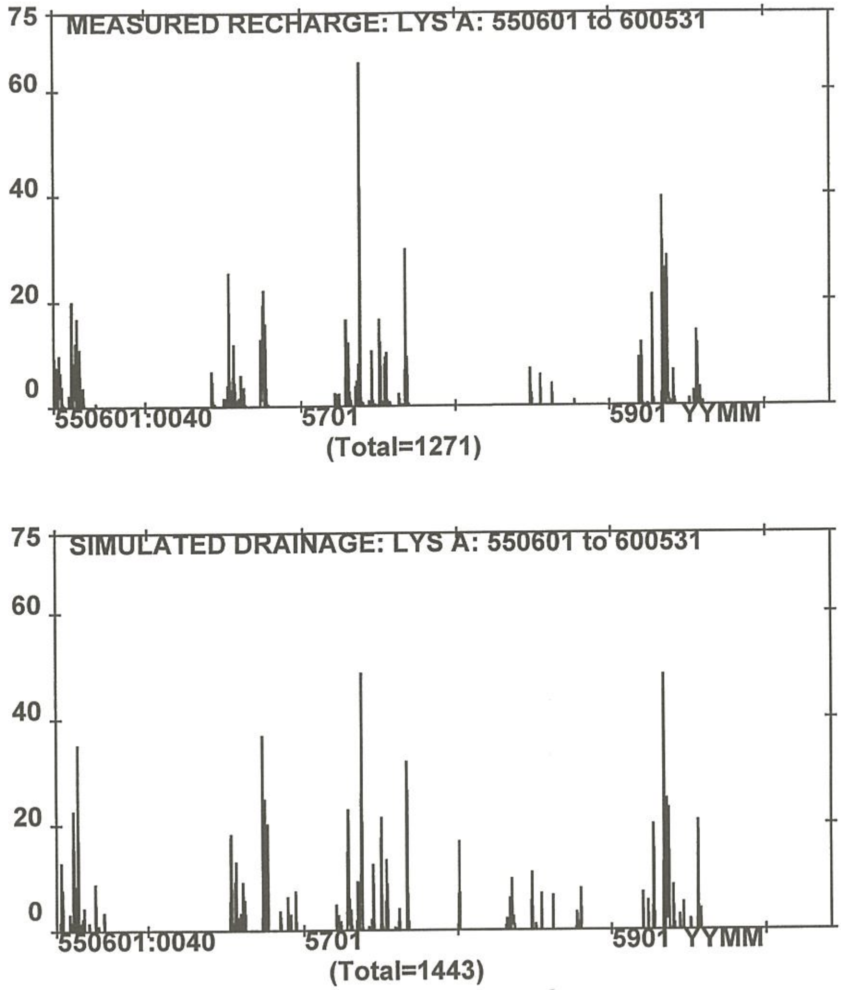

Figure 5.12 *Comparison of SOILMOD simulated drainage with measured recharge for lysimeter A under pasture cover from 1 June 1955 to 31 May 1960. Units are mm. Dates are shown as [yymmdd] (Thorpe and Scott 1999).*

gue that this type of model is consistent with the actual physical processes operating in flat, high rainfall areas where it is realistic to expect that recharge should increase as a linear function of precipitation.

Validation of the model was attempted by simulating groundwater levels using the modelled recharge and the method of Bidwell et al. (1991). While this satisfactorily reproduced the seasonal pattern over a two-year period, the modelled variations were significantly less than measurements indicated.

Since the mid eighties the use of soil moisture models to estimate recharge has become routine and these models have often been incorporated into sophisticated regional ground water studies. However there has been little work done in New Zealand to check the validity of the basic soil moisture models until the work of Barkle et al. (1998) and Thorpe and Scott (1999).

EFFECTS OF RECHARGE ON GROUNDWATER QUALITY

M.E. Close, J.L. Tod and G.J. Tod

Close et al. (1995) sampled a network of 22 wells between the Rakaia and Ashburton Riv-

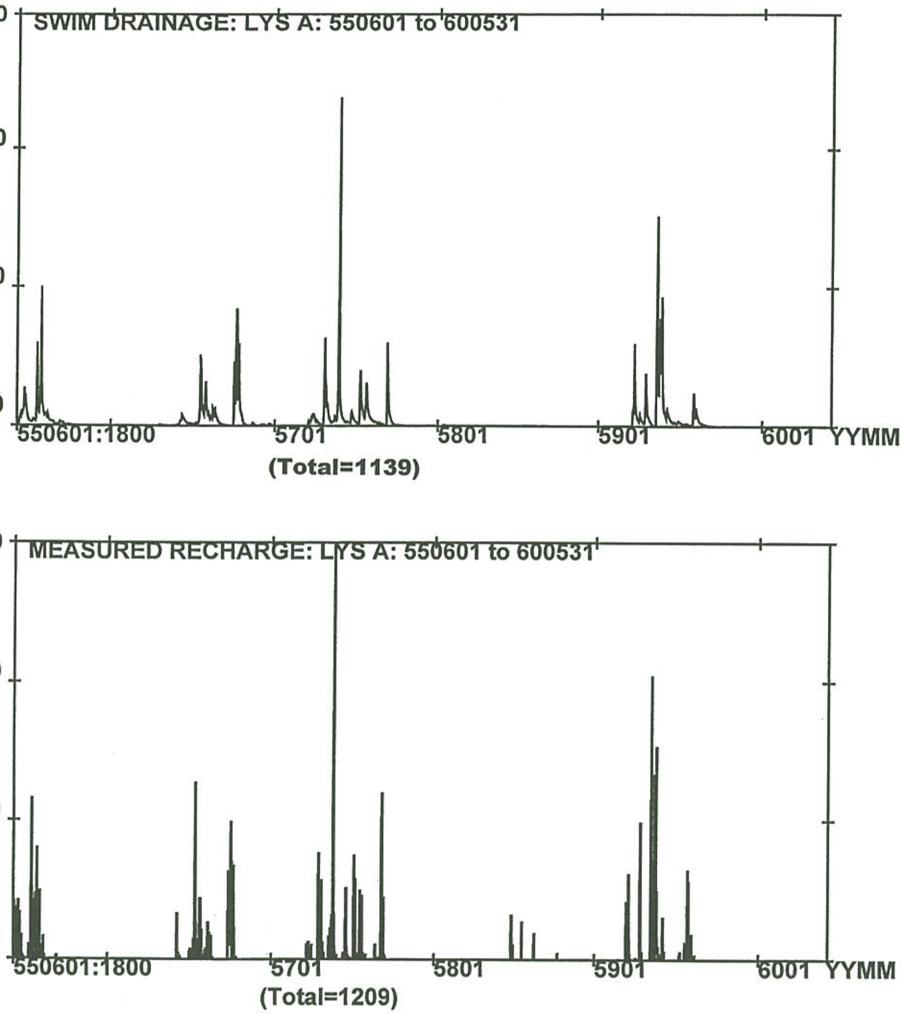

Figure 5.13 *Comparison of SWIM simulated drainage with measured recharge for lysimeter A under pasture cover from 1 June 1955 to 31 May 1960. Dates are shown as [yymmdd] (Thorpe and Scott 1999).*

ers at monthly intervals for 12 months over 1991/92 and analysed for nitrates and other major ions. This was a resurvey of most of the wells used by Burden (1982), to see if changes of water quality could be detected and related to increased agricultural activity and the development of irrigation. The study area is extensively irrigated with both river water imported for border-strip irrigation and groundwater for spray irrigation. There are however, still areas of dryland farming. Despite the considerable increase in irrigated land and hence artificial recharge over the intervening decade, the second survey did not reveal any systematic shifts in groundwater quality. Nitrate levels generally decreased or differed little and the number of wells with significant increases in concentrations of contaminants about equalled the number with significant decreases. The effects of changes in land use were less than the differences in recharge, because more rain fell in 1978/79 (1141 mm) than in 1990/91 (665 mm) so more irrigation water was applied over the later period. (Table 5.4). Changes in water quality caused by localised change in land use were detectable in

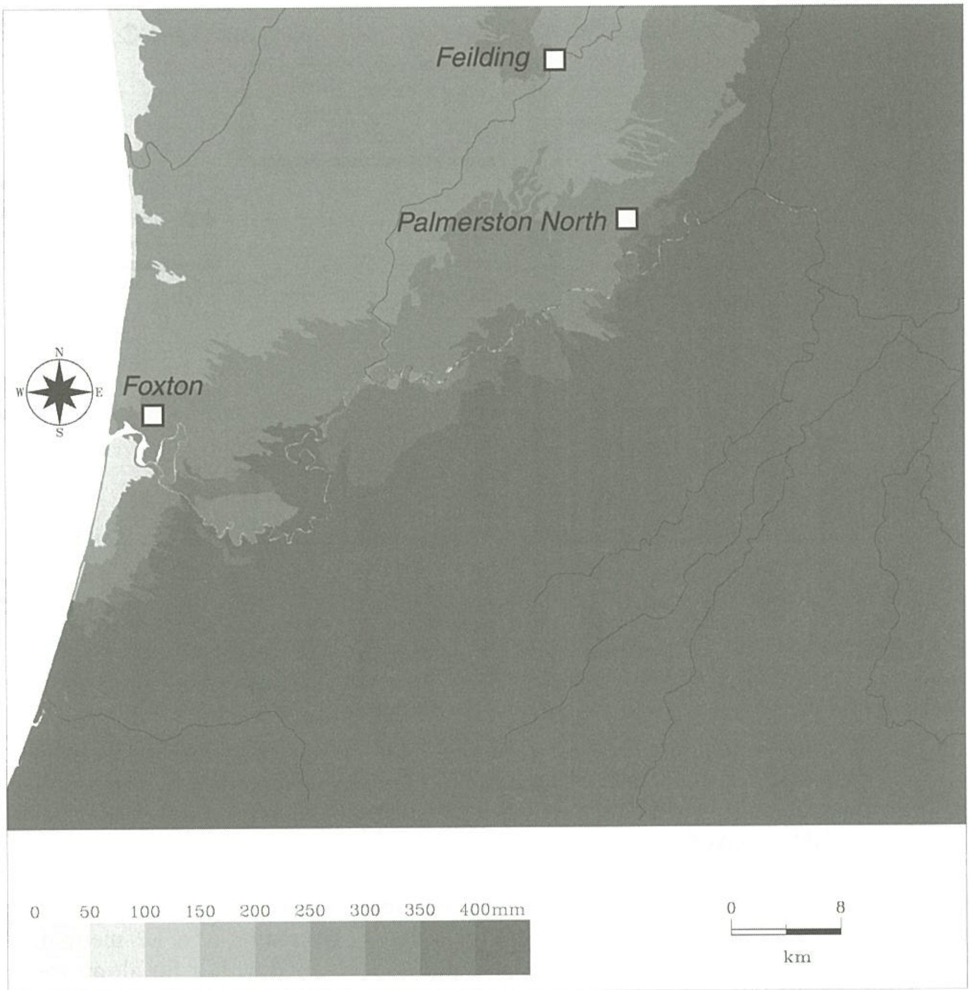

Figure 5.14 *Regional map of simulated average annual recharge in the Manawatu Plains using the Monte Carlo technique, after Bekesi and McConchie (1999). Reprinted with permission from Elsevier Science © 1999.*

only two of the 22 wells surveyed. Groundwater quality was affected more by changes in recharge than changes in land use.

M.E. Close and P.H. Woods

Close and Woods (1986) used non-weighing lysimeters to study leaching of solutes from irrigated pasture in the Waiau Irrigation Scheme, North Canterbury. This, at the time, was a partially developed border-strip scheme, and pre- and post-irrigation data were available. As would be expected, greater leaching of most nutrients resulted from a greater amount of drainage. However, at least for nitrate, the average concentration in groundwater significantly decreased with the onset of irrigation because of the huge (about six-fold) increase in recharge.

M.R. Rosen, J. Bright, P. Carran, M.K. Stewart and R. Reeves

Rosen et al. (1999), as part of their Pukekohe study, measured nitrates within the deep soil profile and in local unconfined groundwater. These measurements indicated that nitrogen is mineralised in the soil over the summer and

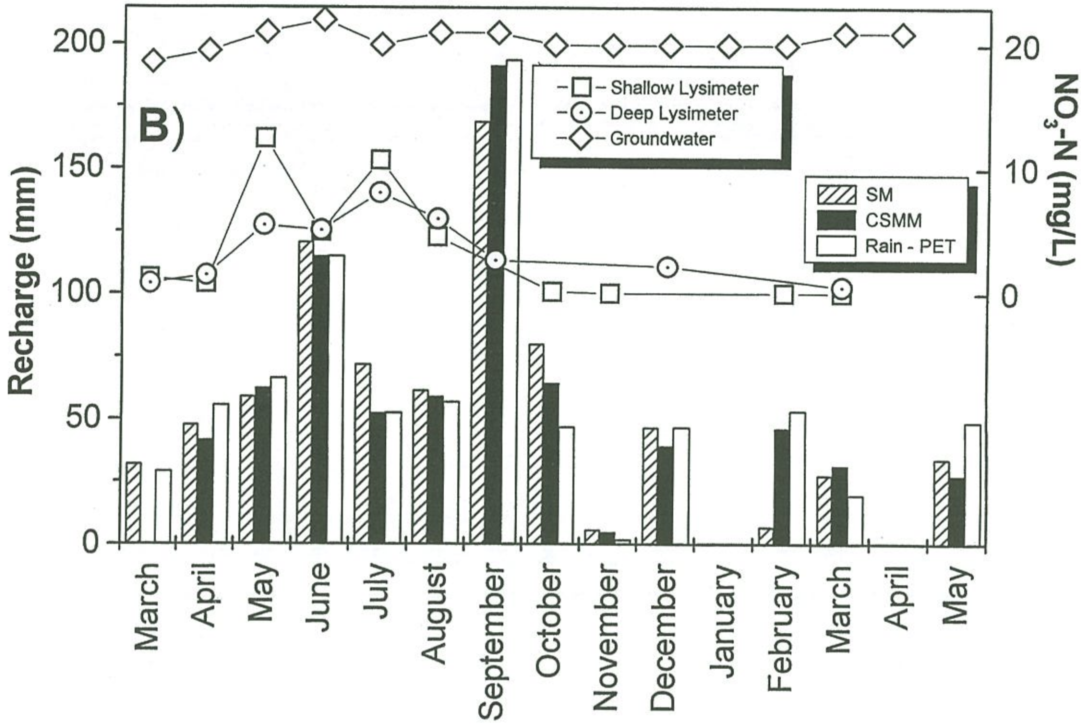

Figure 5.15 *Monthly recharge (drainage) estimates (Fig 5.4B) compared to nitrate concentrations from shallow (1.0 m depth) and deep (2.8 m depth) soil lysimeters and ground water. Negative drainage is not plotted (Rosen et al. 1999). Reprinted by permission of Ground Water ©1999. All rights reserved.*

nitrate is flushed past the root zone at the beginning of the recharge season in autumn and early winter (Fig 5.15). The lysimeters extracted soil-water from a non-fertilised site whereas the groundwater was derived from a heavily fertilised horticultural area, hence the big difference in nitrate concentrations. Although considerable recharge occurs later in winter and spring, the concentrations are much less because the nitrate stored in the upper soil profile over summer has been depleted. Therefore to maintain groundwater quality, fertilisers should be applied in spring and early summer.

WORK IN PROGRESS

Lincoln Environmental

Lincoln Environmental (1999) have constructed a large non-weighing lysimeter to monitor the effects on inputs to groundwater of changes of land use from dry-land sheep grazing to irrigated dairying. The lysimeter, located near Dunsandel (Fig 5.6) in Canterbury, is of an unusual design, consisting of a 1.2-metre diameter stainless steel pipe with a fin along each side, giving an overall width of 1.5 metres. The 8 metre long pipe was placed horizontally in a pit with 1.5 metres of soil above the highest point. It was then jacked lengthways into a Lismore stony silt loam while, from within the pipe, the gravel was hand-excavated just ahead of the advancing rim. When completed this gave a collection area 8 metres long and 1.5 metres wide which was divided into 12 equal zones, each separately instrumented. This allows examination of leachate quantity and quality with temporal and spatial variability. The focus is on nitrate leaching in a freely draining soil.

IGNS, H.R. Thorpe and Environment Canterbury

In 1999, the Institute of Geological and Nuclear Sciences and H.R. Thorpe, with the assistance of Environment Canterbury established a network of six lysimeter sites around North Canterbury (Fig 5.6). The locations were chosen to cover as many of the major soil types as possible and the range of climatic variability experienced in the province. The network includes four of the old lysimeters at Winchmore plus five new sites, each of these with two lysimeters 500 mm in diameter and 700 mm deep. Rainfall and other meteorological data are available at each site and the water table is also being recorded. This data is intended for calibration of a regional recharge model and the data will also be used to examine the optimum network for reliable estimates of regional recharge.

L. Pang, M.E. Close, J.P.C. Watt and K.W. Vincent

Pang et al. (2000) measured and modelled the movement of three pesticides at two sites through a 4.5 metre vadose zone and into an underlying gravel aquifer on the Heretaunga Plains in Hawkes Bay. The soils at the sites were a Te Awa silt loam, which is a shallow soil overlying a heterogeneous coarse sand and sandy gravel, and a Twyford fine sandy loam, which is a thicker, more homogeneous soil. At both sites the water table was about 4.5 meters deep.

The model used was HYDRUS-2D (Simunek et al. 1996), which simulates both unsaturated and saturated flow. The work was focussed on pesticide movement rather than recharge and showed that over a 2.2-3.5 year period the pesticide picloram could be tracked through the unsaturated zone. At one site it was followed 53 metres through the aquifer. Two other pesticides, atrazine and simazine, were measured and reasonably modelled in the unsaturated zone, but did not appear in the aquifers.

The same data set has been used (Close et al. 1999) to evaluate the models LEACHM and GLEAMS.

SUMMARY

This review of recent groundwater recharge research in New Zealand illustrates the diversity of approaches among the various workers. Some useful and interesting points of agreement are apparent.

In evaluating soil moisture models against multi-year recharge measurements made in very different soils and rainfall areas, Barkle et al. (1998) and Thorpe and Scott (1999) reach similar conclusions. Both find that for pasture conditions, without recourse to model calibration, SWIM (Ross 1990) slightly underestimates cumulative recharge. Thorpe and Scott did however increase rainfall by 10% to allow for measured undercatch of rain caused by wind exposure at the Winchmore Research Station. When Thorpe and Scott modified soil hydraulic parameters (measured in a sandy gravel) to reproduce measured soil moisture profiles, the agreement was further enhanced. Since SWIM, as used, did not account for macropore flow (nor hysteresis), these appear to be excellent simulations of unsaturated porous medium flow.

DRAINMOD (Barkle et al. 1998) and SOILMOD (Thorpe and Scott 1999), although written by different workers with different algorithms, behaved very similarly with different data sets. Both models overestimate cumulative recharge slightly for pasture conditions.

Both groups observed that recharge fluxes in the summer and autumn were most difficult to simulate accurately and under pasture there were extended periods without recharge ranging up to two months at Ruakura (under irrigation) and seven months at Winchmore (without irrigation).

However both SWIM and SOILMOD significantly underestimate measured recharge through bare soil (Thorpe and Scott 1999). For a given annual rain more recharge occurs through bare soil than through pasture (Fig 5.10). Barkle (pers comm.) has also noted that when pasture growth is stronger there is less recharge.

Measurements made in confined but buried lysimeters appear to be susceptible to run-on or run-off errors caused by microtopography and random stock trampling. To minimise these, the lysimeter surface area should be as large as practicable, and the area immediately around the lysimeter should be kept smooth, as soil settlement occurs after construction. Consideration should be given to excluding stock and maintaining a "standard" lysimeter surface in terms of smoothness and vegetation length.

Bekesi and McConchie's (1999) model, like SOILMOD and SWIM, proved to be "relatively resistant to changes in available water". They also report that "the recharge model is essentially linear and that rainfall provides a good estimate of recharge". This comment is supported by the plot of Winchmore annual values of rainfall and recharge. (Figs 5.9 and 5.10).

None of the soil moisture models evaluated for recharge predictions were very accurate over time intervals of days, but all performed reasonably over longer periods. Rosen et al. (1999) observe that even the crude approach of calculating the difference between rainfall and potential evapotranspiration provides recharge totals that are comparable with those derived from more sophisticated methods. This is probably because the great bulk of recharge occurs over late autumn, winter and spring when soils are wetter, vegetation water demand is low, and actual and potential evapotranspiration are usually the same.

The work of Close et al. (1995) and Close and Woods (1986) illustrates the difficulty of assessing changes in ground water quality caused by changes in land use, when recharge varies so widely from year to year under natural rainfall, let alone irrigation.

FUTURE DIRECTIONS

The previous studies suggest that several readily available models will provide good estimates of recharge under both natural rainfall and irrigation. Nevertheless some further validation work is warranted for different soil types and rainfall regimes. For free-draining soils, simple, affordable lysimeters can be built to provide the validation data (Cameron et al. 1992). In fact these lysimeters should be considered as basic parts of a hydrological data collection network where ground water resource management is important.

Further work needs to be done to measure recharge through bare soil and to develop algorithms to model the processes. As confidence builds in the ability to measure and model recharge, more attention should be paid to mass transport processes through soils and validating the models that are presently being used.

Success in these ventures will provide essential input to regional models which are increasingly required for the management of vital ground water resources.

ACKNOWLEDGEMENTS

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REFERENCES

Annett, H.E. 1953: Water in relation to pasture production. Journal of the New Zealand Institute of Chemistry 17(5): 114-127.

Barkle, G.F.; Brown, T.N.; Painter, D.J.; Singleton, P.L. 1998: Hydrology models DRAINMOD and SWIM applied to large soil lysimeters with artificial drainage. Australian Journal of Soil Research 36: 783-797.

Bekesi, G.; McConchie, J. 1999: Groundwater recharge modelling using the Monte Carlo technique, Manawatu region, New Zealand. Journal of Hydrology 224: 137-148.

Bidwell, V.J.; Callander, P.F.; Moore, C.R. 1991: An application of time-series analysis to groundwater investigation and management in central Canterbury, New Zealand. Journal of Hydrology, New Zealand 30(1): 16-36.

Bowden, M.J.; Talbot, J.H.; Ayrey, R.B.; Curtis, J.; Glennie, J.M.; Lineham, I.W.; Mason, C.R.; Thompson, D.A.; Weeber, J.H. 1983: Interim report on the groundwater resource of the central plains. Report prepared for the North Canterbury Catchment and Regional Water Board. 124p

Burden, R.J. 1982: Hydrochemical variation in a water table aquifer beneath grazed pastureland. Journal of Hydrology, New Zealand 21(1): 61-75.

Carey, P.L.; Rate, A.W.; Cameron, K.C. 1997: Fate of nitrogen in pig slurry applied to a New Zealand pasture soil. Australian Journal of Soil Research 35: 941-59.

Cameron, K.C.; Rate, A.W.; Carey, P.L.; Smith, N.P. 1995: Fate of nitrogen in pig slurry applied to a shallow stony pasture soil. New Zealand Journal of Agricultural Research 38: 533-542.

Cameron, K.C.; Smith, N.P.; McLay, C.D.A.; Fraser, P.M.; McPherson, R.J.; Harrison, D.F.; Harbottle, P. 1992: Lysimeters without edge flow: an improved design and sampling procedure. Soil Science Society of America Journal 56: 1625-8.

Close, M.E. 1985: Simulating the effects of the Waiau Irrigation Scheme on recharge and groundwater levels. Journal of Hydrology, New Zealand 24(2): 49-63.

Close, M.E.; Woods, P.H. 1986: Leaching losses from irrigated pasture: Waiau Irrigation Scheme, North Canterbury. New Zealand Journal of Agricultural Research 29: 339-349.

Close, M.E.; Tod, J.L.; Tod, G.J. 1995: Effect of recharge variations on regional groundwater quality in Mid-Canterbury, New Zealand. Journal of Hydrology, New Zealand 33(1): 1-16.

Close, M.E.; Watt, J.P.C.; Vincent, K.W. 1999: Simulation of picloram, atrazine and simazine transport through two New Zealand soils using LEACHM. Australian Journal of Soil Research 37: 53-74.

Cooper, K.J. 1980: Groundwater recharge in North Canterbury. Unpublished report to the north Canterbury Catchment Board, Christchurch. 34p

Donaldson, I.G. 1977: An analysis of ground-water data from the Waimakariri-Rakaia region of the Canterbury Plains. Paper presented to the New Zealand Hydrological Society annual symposium, Christchurch. 13p

Evans, C.J. 1999: Effects of irrigation on groundwater recharge between the Rakaia and Selwyn Rivers, Canterbury, New Zealand. Unpublished MSc thesis, University of Canterbury, New Zealand. 148p + 5 app.

Fraser, P.M.; Cameron, K.C.; Sherlock, R.R. 1994: Lysimeter study of the fate of nitrogen in animal urine returns to irrigated pasture. European Journal of Soil Science 45: 439-447.

Heiler, T.D. 1982: Simulation based design of water harvesting schemes for irrigation. Unpublished PhD dissertation, University of Canterbury, New Zealand.

Lincoln Environmental 1998: Pukekohe groundwater recharge-soil moisture monitoring 1997-98. Report to Institute of Geological and Nuclear Sciences. Report No. 2887. 21p

Lincoln Environmental 1999: Monitoring the effects of land-use change on inputs to groundwater-linear lysimeter construction and testing. Report No. 2775/1. Prepared for Ministry of Agriculture and Forestry and Canterbury Regional Council. 34p + 1 app.

Pang, L.; Close, M.E.; Watt, J.P.C.; Vincent, K.W. 2000: Simulation of picloram, atrazine and simazine leaching through two New Zealand soils and into groundwater using HYDRUS-2D. Journal of Contaminant Hydrology 44(1): 19-46.

Penman, H.L. 1949: The dependence of transpiration on weather and soil conditions. Journal of Soil Science, Oxford 1: 74-89.

Ross, P.J. 1990: SWIM: a simulation model for soil water infiltration and movement: reference manual. CSIRO Division of Soils, Davies Laboratory, Townsville, Qld 4814, Australia. 38p

Rosen, M.R.; Bright, J.; Carran, P.; Stewart, M.K.; Reeves, R. 1999: Estimating rainfall recharge and soil water residence times in Pukekohe, New Zealand, by combining geophysical, chemical, and isotopic methods. Ground Water 37(6): 836-844.

Scott, D.M.; Thorpe, H.R. 1986: Ground water resources between the Rakaia and Ashburton Rivers. Publication No. 6 of the Hydrology Centre, Ministry of Works and Development, Christchurch. 105pp.

Simunek, J.; Sejna, M.; van Genuchten, M. Th. 1996: HYDRUS-2D. Simulating water flow and solute transport in two-dimensional variably saturated media. US Salinity Laboratory, US Department of Agriculture/ARS Riverside, California. Distributed by International Ground Water Modelling Centre. 167p

Skaggs, R.W. 1980A: DRAINMOD: reference report methods for the design and evaluation of drainage-water management systems for soils with high water tables. US Department of Agriculture, Soil Conservation Service: Fort Worth, Texas. 270p

Skaggs, R.W. 1980B: A water management model for artificially drained soils. Technical Bulletin No. 267. North Carolina Agricultural Research Service. 54p

Thorpe, H.R.; Scott, D.M. 1999: An evaluation of four soil moisture models for estimating natural ground water recharge. Journal of Hydrology (NZ) 38: 179-209.

Watt, J.P.C.; Burgham, S.J. 1992: Physical properties of eight soils of the Lincoln area, Canterbury. DSIR land resources technical record 103, DSIR Land Resources, Department of Scientific and Industrial Research, Lower Hutt, New Zealand. 134p

6

Groundwater-surface water interaction

PAUL A.WHITE, BENTE CLAUSEN, BRUCE HUNT, STEWART CAMERON AND JULIAN J. WEIR

INTRODUCTION

Groundwater is commonly linked to surface water. Groundwater can be recharged by surface water from rivers, wetlands, and lakes, and by seawater; surface waters in turn receive groundwater through springs, seeps and subterranean flow. These interactions between ground and surface water resources mean that management of the two must be integrated to ensure the sustainability of both. However, the linkages between groundwater and surface water bodies are complex, with processes of recharge and discharge often taking place simultaneously. The complexity of flow between groundwater and surface water bodies is due to the intricacy of the geological formations through which the water flows, and the distributions of hydraulic pressures driving the flow. Groundwater investigations are commonly more expensive than surface water investigations, so our knowledge of the hidden resource is usually much less complete than our knowledge of the visible resource. In addition, interactions between groundwater and surface water are dynamic; recharge can interchange with discharge as groundwater levels change relative to surface water levels.

This chapter discusses natural and modified interactions between groundwater and surface water. Theory on recharge to groundwater from rivers is introduced, and the relative importance of groundwater recharge from rivers is illustrated with an example from the Ngaruroro River, Hawke's Bay. Some of the techniques used to identify and measure recharge to groundwater from gravel-bed rivers will be outlined, with examples from the Ngaruroro River, where the recharge reach is relatively well defined, and from the Rakaia River, where it is poorly defined. Groundwater recharged from rivers can have characteristic chemical and isotopic signatures, as shown by Waimakariri River water in the Christchurch-West Melton groundwater system. The incorporation of groundwater-river interaction in a regional groundwater flow model is outlined for the Waimea Plains, and relationships between river scour and groundwater recharge are examined for the Waimakariri River.

Springs are the result of natural discharge from groundwater systems and are important water sources. The interactions between groundwater systems, springs, and river flow for the Avon River in New Zealand will be outlined.

The theory of depletion of stream flow by groundwater pumpage will be introduced with a case study from Canterbury, and salt-water intrusion into groundwater systems with examples from Nelson and Christchurch. The theory of artificial recharge to groundwater systems is introduced with a case study from Hawke's Bay. Wetlands are important to flora, and the relationship of the wetland environment to groundwater hydrology will be discussed, with an example from the South Taupo wetland.

NATURAL INTERACTIONS BETWEEN GROUNDWATER AND SURFACE WATER

Recharge to groundwater from rivers

McDonald and Harbaugh (1984) introduce the theory of recharge to groundwater from a river, using Darcy's law, as:

$$Q_{RIV} = C_{RIV} (H-h) \qquad (1)$$

where Q_{RIV} is the recharge to groundwater through a reach of river bed (m^3/s), C_{RIV} is the conductance of the river bed (m^2/s), H is elevation of the river water surface (m), and h is the hydraulic

White P.A.; Clausen B.; Hunt B.; Cameron S. and Weir J.J. 2001: Groundwater-surface water interaction. *In* Groundwaters of New Zealand, M.R. Rosen and P.A. White *(eds)*. New Zealand Hydrological Society Inc., Wellington. p133-160.

head of the aquifer (m) when the porous material adjacent to the river bed is fully saturated. Recharge to groundwater is modelled as:

$$Q_{RIV} = C_{RIV} (H-R_{BOT}) \quad (2)$$

where R_{BOT} is the elevation of the bottom of the river bed (usually constant), when the porous material adjacent to the river bed is not saturated (perched river). Assuming a constant river bed conductance, Q_{RIV} in Equation 1 is a function of both river water level and groundwater level and can be either positive (recharge to groundwater) or negative (recharge to river). However, Q_{RIV} is a function solely of river water level in Equation 2, assuming a constant river bed conductance and assuming that it is greater than R_{BOT}. Equations 1 and 2 indicate some of the complexities of measuring and understanding groundwater-surface water interaction. These interactions are dynamic, as river levels and groundwater levels are changing constantly. River bed conductance probably also changes with time as sediment deposition and erosion affect the active channels of New Zealands rivers.

The groundwater budget and river management

Water from rivers and rainfall are the predominant inputs into groundwater systems, so identifying and measuring recharge both from rivers and from rainfall (Chapter 5) are important for groundwater resource allocation.

Groundwater in the Heretaunga Plains aquifer system, for example, is derived from rivers and rainfall in the unconfined section of the aquifer (Dravid and Brown 1997), with the Ngaruroro River contributing an estimated 84% (or 158 million m³/yr) of the total recharge to the aquifer system. Measurements of the river's recharge to groundwater, and the identification of the zones where recharge is occurring, allows groundwater recharge to be taken

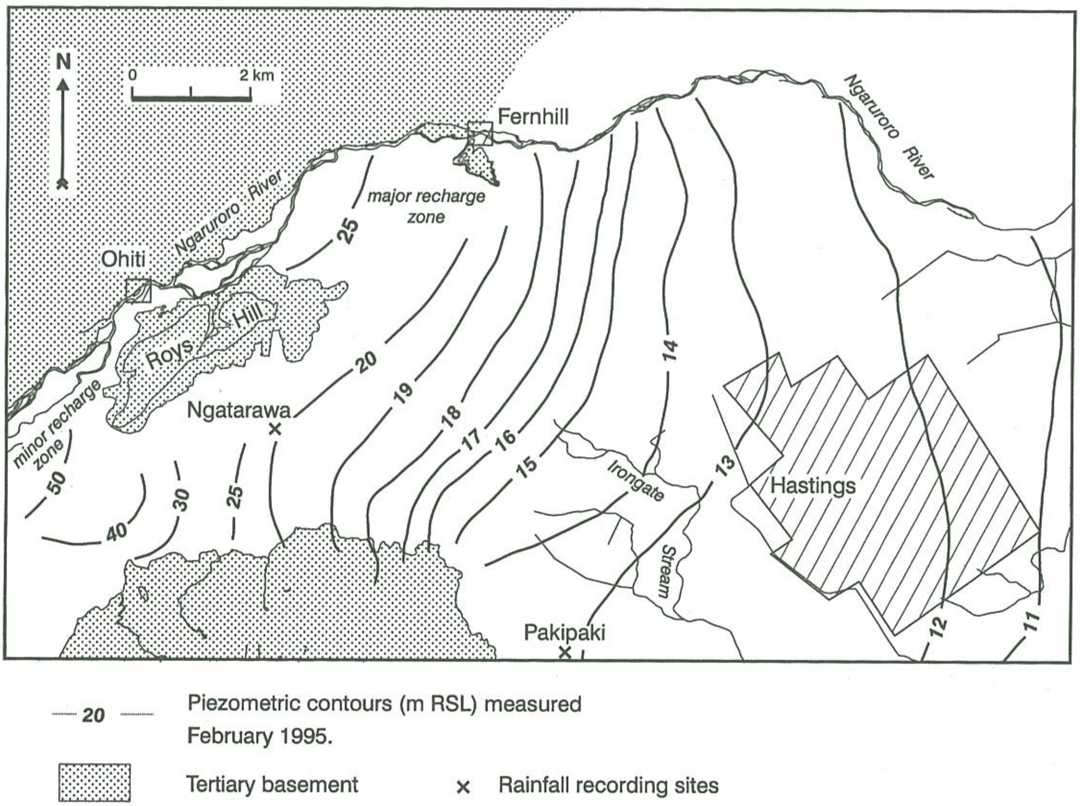


Figure 6.1 *Location of recharge zones from the Ngaruroro River and groundwater contours in the Heretaunga Plains aquifer system.*

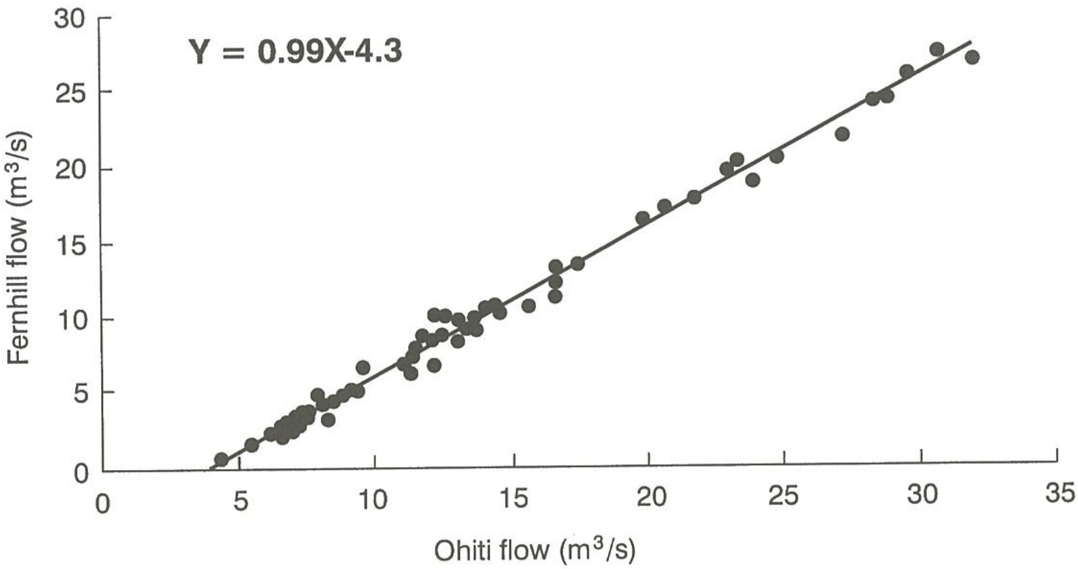


Figure 6.2 *Ngaruroro River, Ohiti and Fernhill discharge relationship, 1957 to 1999 (after Dravid and Brown 1997).*

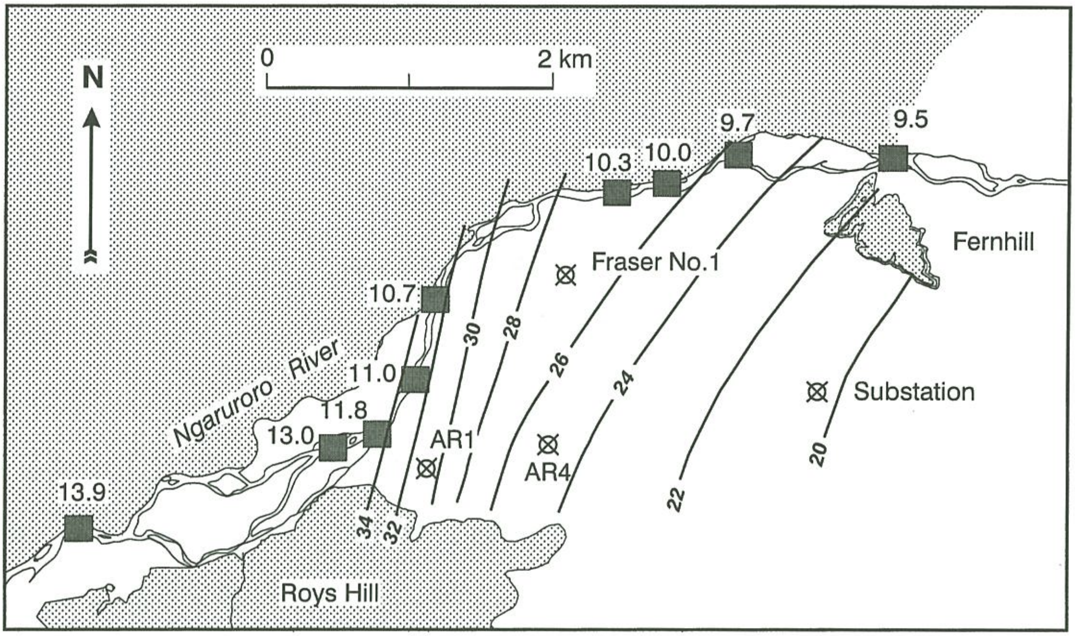
into consideration in river management. During periods of low flow, the minimum flow in the Ngaruroro River (2400 L/s at Fernhill, Wood, pers. comm.) is set to ensure that groundwater recharge is maintained and instream use of the river is possible.

Estimation of recharge

A number of techniques are used to identify and measure recharge to groundwater from rivers, including river gaugings, well drilling and well logging, measurement of groundwater levels, piezometric maps, groundwater velocity measurements using tracers, groundwater pump tests, and identification of the effects of river stage change on groundwater level. These techniques are applied here to two gravel-bed rivers: the Ngaruroro River, where groundwater recharge occurs over a well-defined reach, and the Rakaia River, where it is difficult to identify recharge locations and measure volumes of recharge.

Roys Hill and Fernhill (Fig 6.1) define the upstream and downstream boundaries of the major recharge zone of the Heretaunga Plains aquifer system from the Ngaruroro River. Relatively impermeable Tertiary sediments, which form Roys Hill and Fernhill, also occur below and west of the Ngaruroro River. Sediments deposited by the Ngaruroro River between Roys Hill and Fernhill are coarse permeable gravels up to 125 m thick that allow discharge from the Ngaruroro River to enter the groundwater system. Ninety discharge measurements at the Ohiti and Fernhill flow recorder sites between 1957 and 1995, during times when the flow at Ohiti ranged between 4.4 m^3/s and 31.8 m^3/s (Fig 6.2), show a consistent loss of 4.3 m^3/s between these two sites. This water is discharging into the groundwater system.

Piezometric contours within the recharge zone (Fig 6.3) indicate that the steepest gradient between the river and the groundwater system is in the northeast-trending section of river near Roy's Hill. Piezometric contours in Figure 6.3 combine Ngaruroro River water levels measured on eleven cross-sections in March 1992 (Hawke's Bay Regional Council pers. comm.) with contours of groundwater levels during October 1974 (Ministry of Works and Development 1974). Nine river gaugings in January 1991 (Dravid and Brown 1997) indicate that the majority of groundwater recharge occurs in the section of river passing over the area where groundwater gradients are greatest. The gauged flows (Fig 6.3) drop from 13.9 m^3/s at Ohiti to 10.7 m^3/s at the



— 20 — Piezometric contour (m) derived from October 1974 groundwater levels and March 1992 river water levels.

13.9 ■ River flow measurement January 1991 (m^3/s)

⊠ Well location

Tertiary basement

Figure 6.3 *Piezometric contours and gauged river flow in the major recharge zone.*

fourth gauging site downstream of Ohiti. The river flow reduces further to 9.5 m^3/s at Fernhill, in the section of river passing over the area of lower groundwater gradient.

The transient effect of changes in river stage on groundwater levels can also be used to indicate groundwater flow direction and recharge sources. Suspected river recharge events must be discriminated from other possible causes of groundwater level variation. Rainfall and increased river stage do not always coincide in the Hawke's Bay. For example, a 1.1 m rise in Ngaruroro River stage (Fig 6.4) appears to be unrelated to rainfall on the Heretaunga Plains at the Ohiti, Ngatarawa, and Pakipaki rainfall recording sites (Fig 6.1): it is caused by rainfall in the mountains. This increase in Ngaruroro River stage, and three other events of varying magnitude between 1989 and 1994, showed that groundwater levels in four wells (Fig 6.3) in the recharge zone respond to river stage change. It is estimated that a 1 m stage change in the Ngaruroro River at Ohiti will cause the following rises in water level: Fraser No. 1 (0.8 m), AR1 (1.5 m), AR4 (1.2 m), and Substation (0.04 m). Water levels in wells further from the river than the Substation well (Fig 6.3) did not respond to these river stage events, which indicates that at some distance beyond the Substation well, the river recharge is largely independent of transient changes in river stage.

Groundwater recharge from the Rakaia River, Canterbury (Fig 6.5), is not constrained by a

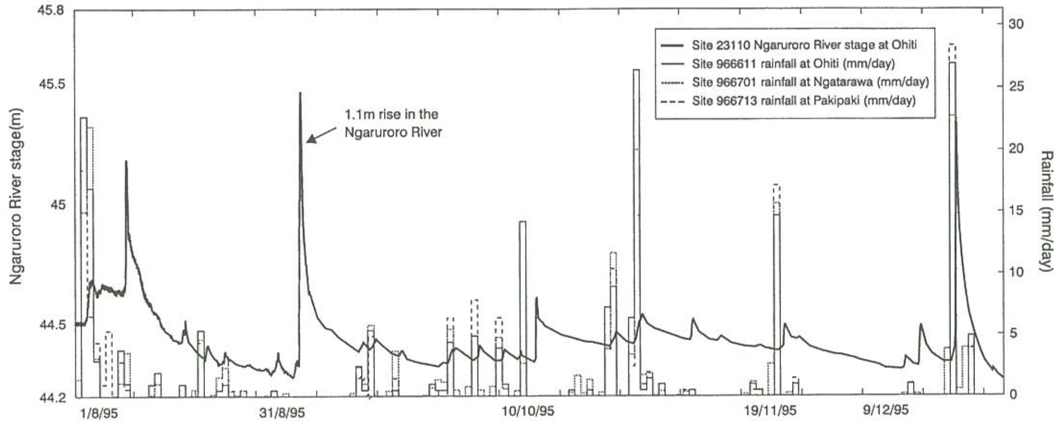


Figure 6.4 *Example of a 1.1 m river stage change of the Ngaruroro River at Ohiti when no rainfall was measured on the Heretaunga Plains.*

low-permeability barrier such as the Tertiary sediments around the Ngaruroro River. The Rakaia River, once it leaves the gorge, is a braided gravel-bed river flowing down the Canterbury Plains through a gravel fan. The location of groundwater recharge is difficult to identify because the adjacent geological formations lack large permeability contrasts with the gravels. Groundwater recharge is difficult to quantify: river gaugings in braided rivers require flow measurements in a large number of channels, giving rise to errors in the total flow calculation of at best 5% to 8%. River channel positions and channel depths can change significantly between successive measurements, leading to uncertainty in the hydraulic relationships between the river and groundwater. Not all river water flow losses move laterally into the groundwater system to be available to users adjacent to the river: the volume of water flowing directly beneath the river bed must be estimated by measuring groundwater flow velocities and the cross-sectional area of permeable sediments beneath the bed. The error in the estimate of net recharge to groundwater combines the errors of river flow loss measurements with the errors of estimating the volume of water flowing directly under the river bed.

The difficulty of estimating recharge to the groundwater system from the Rakaia River gauging data is discussed by the North Canterbury Catchment Board (1983), and by Anderson (1994). Flow-gauging measurements on the Rakaia River (Fig 6.5) identify a consistent pattern of losses of flow above and below State Highway 1 bridge (Table 6.1). Losses from the Rakaia River channel are potentially due to water entering the river

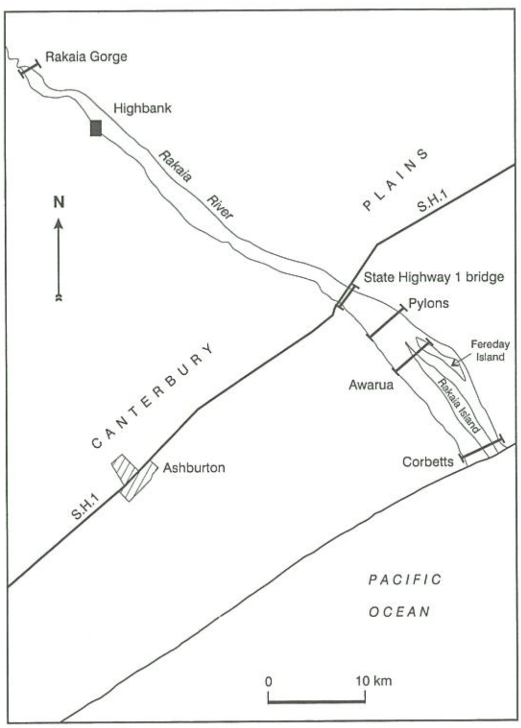


Figure 6.5 *The Rakaia River and gauging sites.*

Table 6.1 *Rakaia River flow gaugings between the gorge and Corbetts. Locations of gauging sites are shown in Figure 6.5.*

Date	Flow (m^3/s)							
	Rakaia Gorge	Highbank Input	SH1 Bridge	Pylons	Awaroa	Corbetts	Loss(-) or gain (+) in surface flow between the gorge and SH1	Loss(-) or gain(+) in surface flow between SH1 and Corbetts
05.05.59	-	-	137	-	122	120	-	-17
25.08.71	77	21	93	-	-	-	-5	-
22.09.71	159	20	158	-	-	-	-21	-
09.11.71	Gorge and Highbank = 183		169	-	-	-	-14	-
07.12.71	141	4	121	-	-	-	-24	-
11.01.72	130	4	114	-	-	-	-20	-
01.03.72	125	6	107	-	-	-	-24	-
05.05.79	123	25	137	-	-	-	-11	-
14.02.80	Gorge and Highbank = 185		176	-	-	-	-9	-
14.07.80	135	25	152	137	128	126	-8	-26
17.07.81	109	26	126	115	114	113	-9	-13
24.03.82	Gorge and Highbank = 111		102	103	96	90	-9	-12

bed. The river bed is approximately 100m wide, with a gravel cross-sectional area of 1700m^2 (Broadbent 1978), at the Rakaia Gorge Bridge. The river bed widens, at approximately 8km upstream of State highway 1 bridge, to be 1.5km wide at State Highway 1 bridge and 3.5km wide at the pylons. Geological logs of wells on the river bank between the State Highway 1 bridge and the pylons indicate that the permeable gravels are approximately 15 m thick. This layer is underlain by a thick layer of clay-bound gravels that is 'extensive and continuous' (Scott and Thorpe 1986). A cross-sectional area of saturated, highly permeable gravels is estimated from the width of river bed and saturated thickness (13m) as 45500m^2.

The volume of river water travelling in the highly permeable gravels under the river bed could increase as the cross-sectioned area of highly permeable gravels becomes greater which could explain the measured losses in the river. Scott and Thorpe (1986) therefore drilled eight 6-m-deep wells and two 15-m-deep wells across the river bed in the vicinity of the pylons aiming to estimate the volumetric flow in the highly permeable gravel under the river bed. Tracer tests in the ten wells indicated Darcy velocities in the range 0.1 m/day to 140 m/day, with mean velocities in the range 23 m/day to 36 m/day. Groundwater flow in the highly pereable gravels is calculated to range from 12 m^3/s to 19 m^3/s. This is a significant component of the measured flow losses in the Rakaia River (Table 6.1). White (1988, 1994) measured horizontal seepage velocities of between 260 ± 40 m/day and 720 ± 140 m/day at the water table in the vicinity of four wells in the Rakaia River bed using resistivity and salt water injection. Recharge to the groundwater system, considering the volume of groundwater flowing below the river bed between State Highway 1 bridge and the coast, is estimated by Scott and Thorpe (1986) as 3 to 8 m^3/s.

Chemical signatures

Chemical and isotopic signatures may also identify river recharge to groundwater systems. An example is the Christchurch-West Melton groundwater system (Fig 6.6), where the chemical similarity of groundwater, in a well near Halkett, to Waimakariri River water (Fig 6.7) is evidence of recharge to groundwater from the Waimakariri River (North Canterbury Catchment Board 1986). Changes in water chemistry between the river and a Halkett well, including an increase in Cl^-, HCO_3^- and nitrate-nitrogen, are probably due to the cumulative effects of through-soil drainage. The concentrations of chloride (Fig 6.8) and nitrate-nitrogen in the shallow aquifer are relatively low in the area of

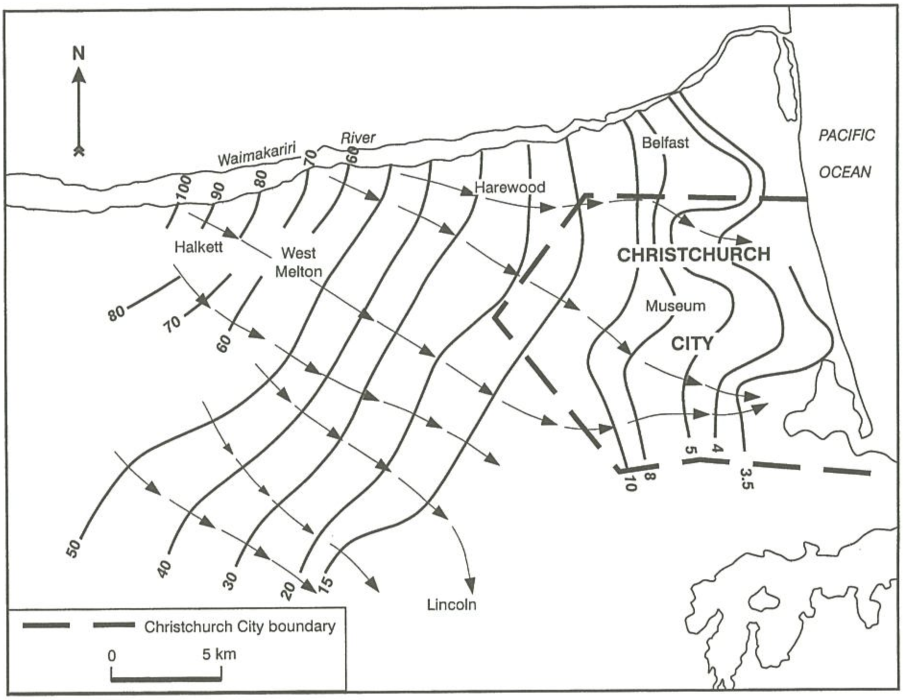


Figure 6.6 *Waimakariri River, groundwater contours (m), groundwater flow directions and Christchurch City.*

the aquifer where Waimakariri River water is a recharge source. Chloride and nitrate concentrations increase to the southwest, which probably reflects an increasing contribution of through-soil drainage to groundwater volumes. River water also has an isotope signature and Taylor et al. (1989) used $\delta^{18}O$ measurements to show that much of the shallow unconfined groundwater between the Waimakariri River and Christchurch is derived from the Waimakariri River. The groundwater had $\delta^{18}O$ values of -8.6 to -9.3%. They calculated that rainfall recharge cannot contribute more than 10% to the ground water discharge of the spring-fed city streams, based on the $\delta^{18}O$ values of river- and rainfall-derived groundwater being more negative than -8.9‰, and -7‰ respectively. Nitrate-nitrogen and $\delta^{18}O$ measurements are also used to identify recharge from the rivers on the Waimea Plains (Chapter 7).

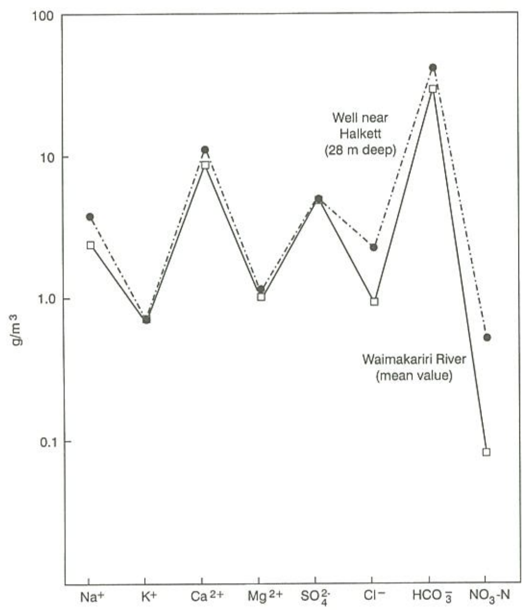


Figure 6.7 *Major anion and cation concentrations in Waimakariri River water and shallow groundwater near Halkett (after North Canterbury Catchment Board 1986).*

Modelling

A model of the interaction of rivers and groundwater is an important component of any

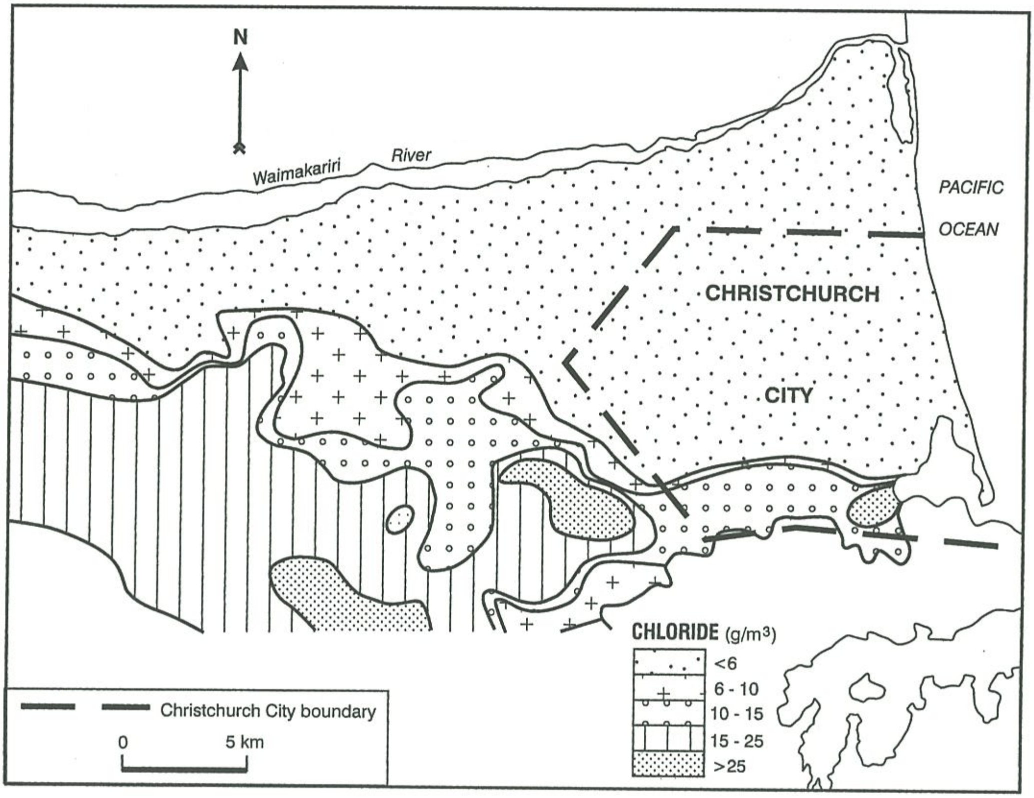


Figure 6.8 *Chloride contours for shallow groundwater 1977-1982 (after North Canterbury Catchment Board 1986).*

computer model of transient groundwater flow. Such a model was set up for the Wairoa, Waimea and Wai-iti Rivers (Fig 6.9) which are in direct hydraulic contact with the unconfined gravel aquifer in the Waimea Plains, Nelson (Fenemor 1988). These rivers interact with the unconfined aquifer and recharge the confined aquifers (Dicker et al. 1992). Sections of these rivers that consistently either lose or gain water from the aquifer have been identified by low-flow gaugings. Gaugings in the Waimea-Wairoa River between 1975 and 1993 (White 1997) show that the river generally loses water from the Wairoa Gorge (Fig 6.10) to a distance of 6-8 km from the coast, and always loses water in the reach from the gorge to 13 km from the coast. Losses are typically 200 to 600 L/s and have been as high as 1300 L/s (Fenemor 1984). The Waimea River typically gains flow in the 6-8 km reach before the coast.

Fenemor (1984) observed that river losses in the reach between the Wairoa Gorge and 13 km from the coast were reduced when groundwater levels in the adjacent aquifer were higher. Gauging measurements in this section of river (Fenemor 1988) indicated that river flow lost at the top of a riffle would often emerge in a downstream pool. River losses in the reach between 13 km and 6 km, however, appear unrelated to groundwater levels (Fenemor 1984) because the river is perched relative to the groundwater system (Equation 2).

The computer model of the river used nodes for each 500 m section of river bed, each node having a bed conductance value (Equation 1), a river bed level, and a specified thickness of strata between river bottom and the aquifer. Recharge to ground-water was calculated using bed conductance and the difference between river head and groundwater

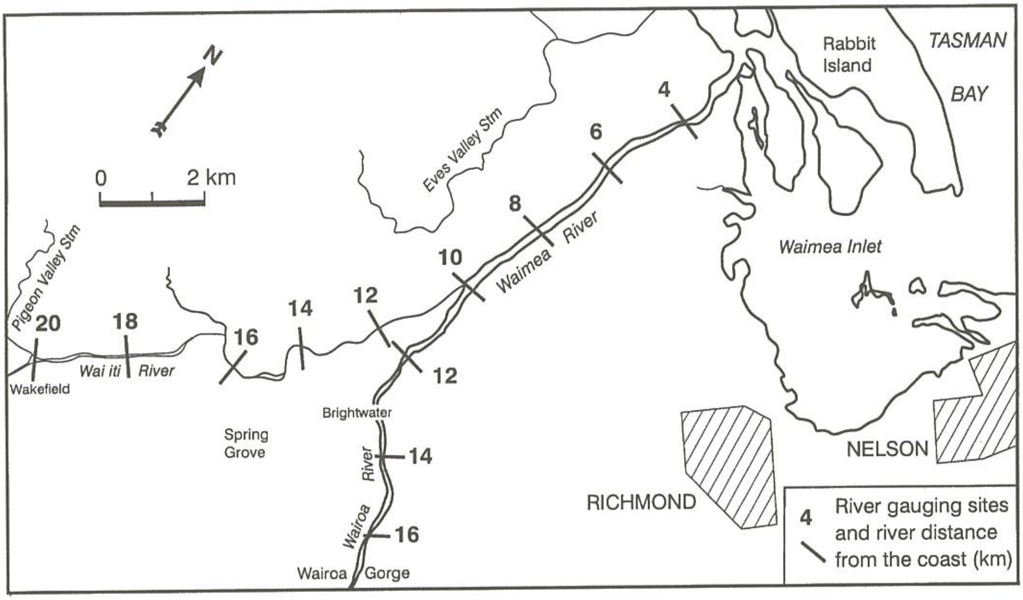


Figure 6.9 *The Wairoa, Waimea, and Wai-iti rivers, with river gauging sites and distance from the coast (km).*

head. River flow was calculated as the difference between flow in the upstream river cell and leakage. Calibration of the model of groundwater discharge aimed to match observed river discharge by adjusting river bed elevations and bed conductance values. Groundwater levels under the river bed were interpolated from observations in the unconfined aquifer adjacent to the river during river gauging measurements in October 1982 and March 1983. River losses were matched in four reaches of the Wairoa-Waimea River and three reaches of the Wai-iti River.

Fenemor (1988) found the calibration of river-groundwater interaction to be time-consuming and summarised some of the problems of calibration. Leakage was sensitive to small differences in river level and underlying groundwater head, but groundwater levels under the river are not easily measured, and aquifer levels were unknown on the dates of river gaugings. River bed elevation and conductance are assumed constant with time, but this is unlikely to be the case. Each model node represents 500 m of river bed, so the selection of a realistic river bed level and water depth is difficult. The finite-difference model of groundwater flow in the Waimea Plains was used to predict groundwater level variations for groundwater usage scenarios, including no usage, domestic pumpage only, and various irrigation regimes (Fenemor 1988). Operation of the Waimea East Irrigation Scheme, where a surface water scheme replaced groundwater pumpage, was predicted to result in higher groundwater levels, by up to 3.3 m in a dry summer. The Waimea East Irrigation scheme was predicted to reduce minimum flow in the Waimea River to 160 L/s.

River sedimentary processes and recharge

The relationship between river sedimentary processes and groundwater recharge is presently being assessed using two arrays of wells monitoring groundwater levels adjacent to the Waimakariri River. One array is adjacent to a zone of river aggradation and the other to a zone of river degradation. This work is currently in progress.

Griffiths (1979) defined three reaches of the Waimakariri River and summarised changes in gravel storage between five bed-level surveys

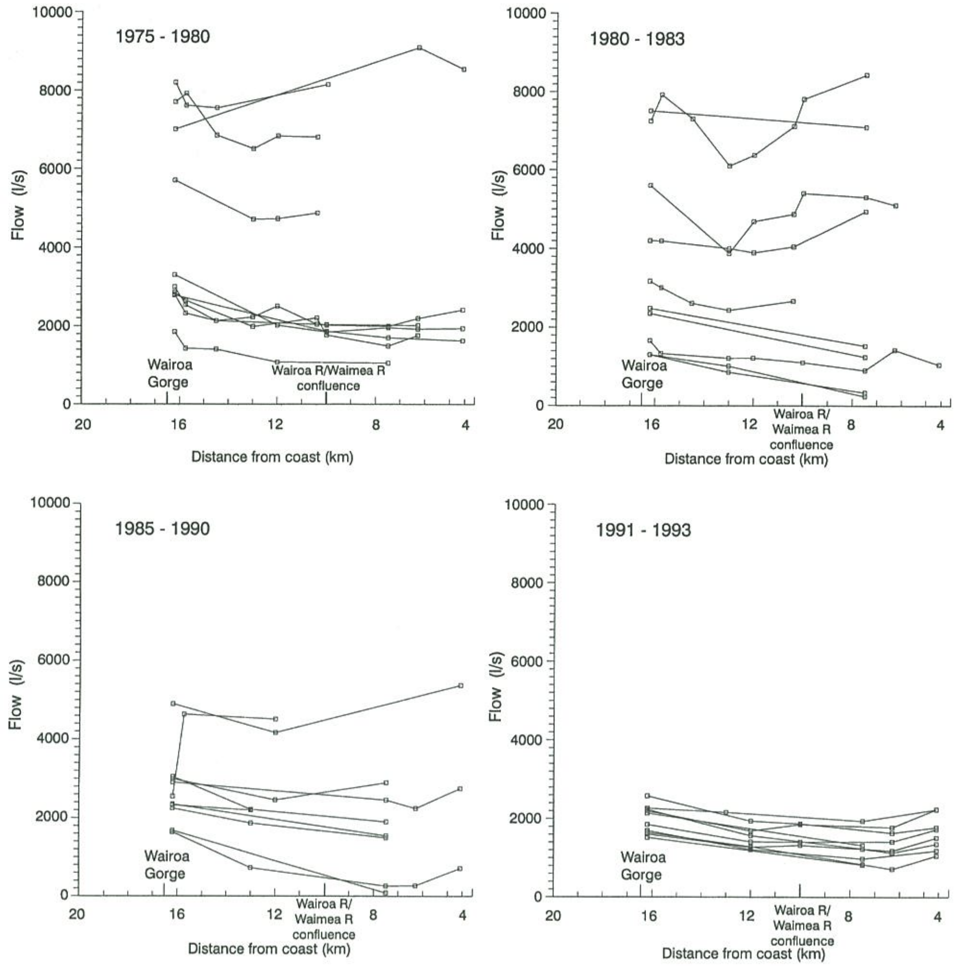


Figure 6.10 *River gauging data, Waimea and Wairoa Rivers.*

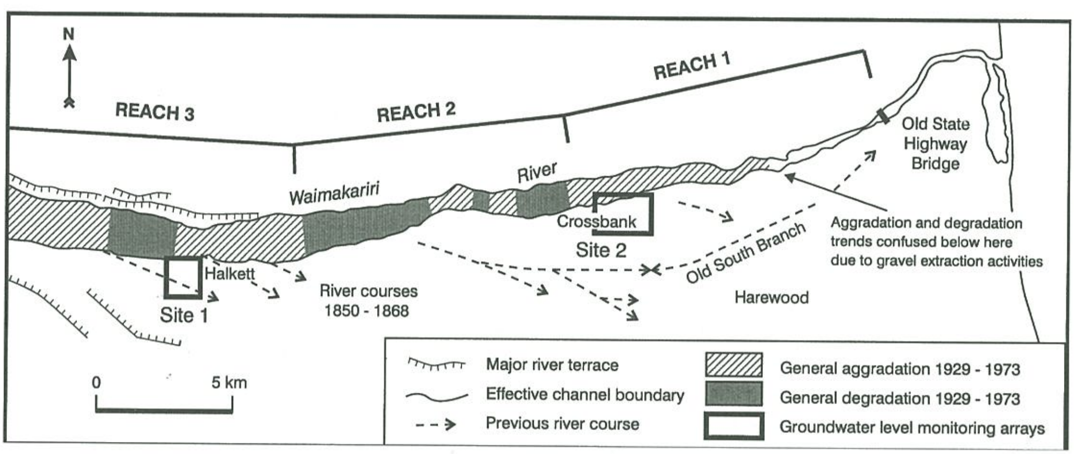


Figure 6.11 *Location of aggradation and degradation zones (after Griffiths 1979), with groundwater monitoring array locations, Waimakariri River.*

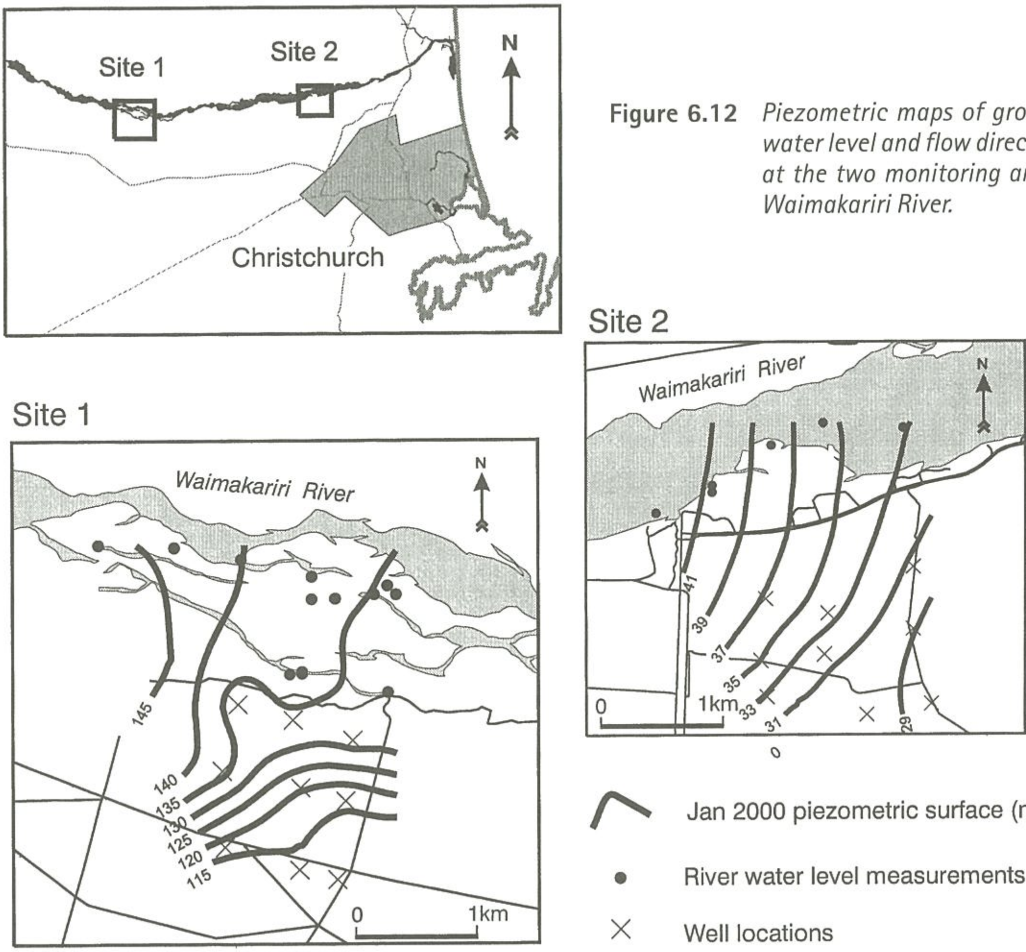


Figure 6.12 *Piezometric maps of groundwater level and flow directions at the two monitoring arrays, Waimakariri River.*

in the period 1929 to 1973. River aggradation and degradation (Fig 6.11) occurs within all three reaches. Reach 1 consistently gains gravel due to river sedimentation. It is estimated that this reach has gained 3.57 x 10^6 m^3 of gravel and silt in the period. Gravel and silt volumes in Reach 2 are estimated to have declined by 2.78 x 10^6 m^3 between 1929 and 1973. The majority of the loss (2.27 x 10^6 m^3) occurred between the 1929 and 1954 surveys. The surveys of 1960 and 1969, however, indicated that this reach had gained gravel and silt. Reach 3, adjacent to Halkett, showed a consistent gain in gravel in the period 1929 to 1973, with the gravel volume increasing by 1.77 x 10^6 m^3 in this period. This reach is the most active of the three reaches in terms of bank erosion.

Dalmer (1971) assessed Waimakariri River gaugings as showing an average river flow loss of 11 m^3/s in the channel adjacent to Halkett. Recharge in the area around Halkett (Vant Woudt et al. 1979) follows a pathway from the river to the groundwater through a low-permeability zone on the side and bottom margins of the river bed. Laboratory measurements show the formation of low-permeability zones is due to the movement of find sand and silt within the gravel matrix. Seepage from the river to the gravels beneath the river bed takes place along all channels except below riffles, where groundwater discharges to the river channel. Vant Woudt and Nicolle (1978) found that scarifying the channel bed surface, or the surface of a stratified river bed sample in the laboratory, produced a five-fold increase in the infiltration rate. Water levels, measured in ap-

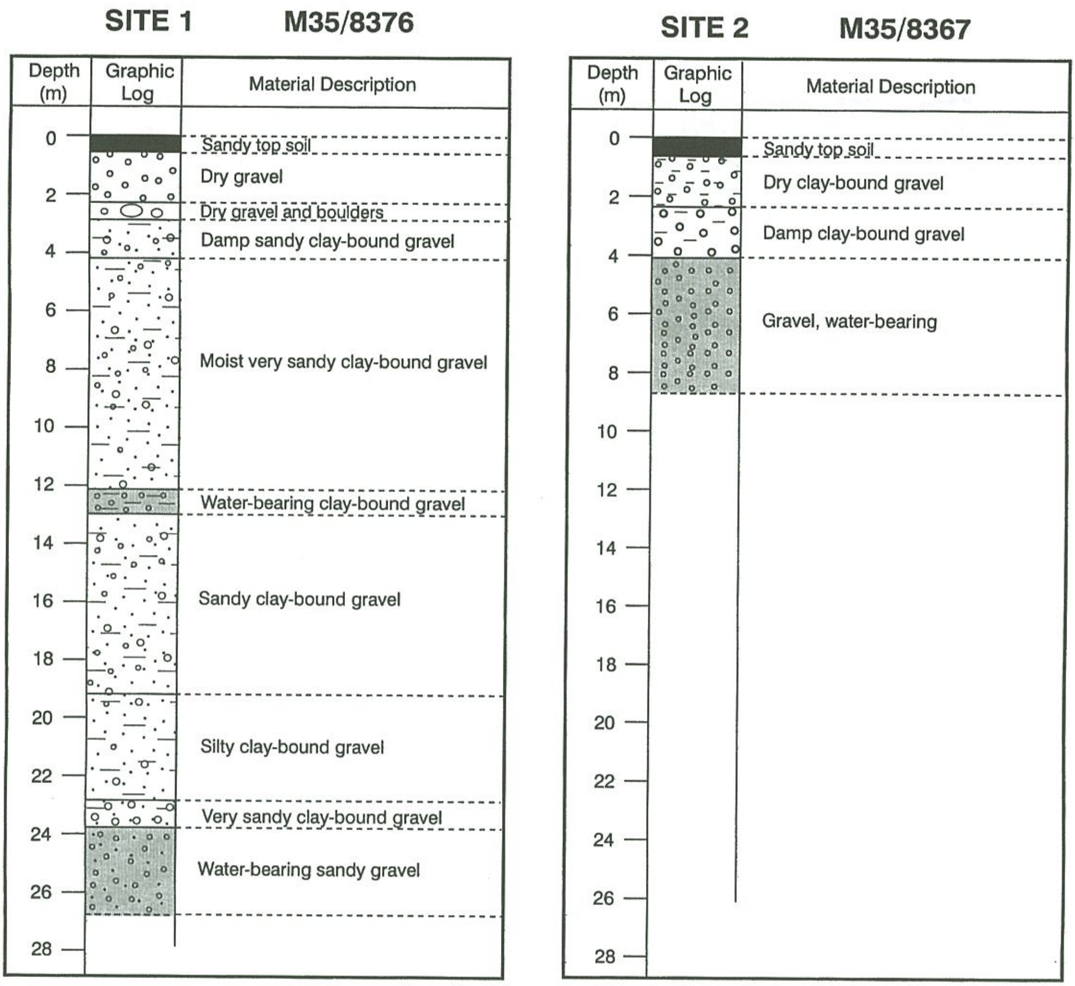


Figure 6.13 *Typical geological logs of wells in the two monitoring sites, Waimakariri River.*

proximately 40 wells in the river bed, are generally one to three metres below the ground surface. Seepage velocity measurements in the Halkett area suggest that flow in the river bed is about 4.2 m^3/s. This is a small portion of the total river flow and approximately 50% of this flow goes to groundwater recharge.

Wells within 500 m of the river at Site 1 (Fig 6.12) were drilled through approximately 4 m of gravel, or sand and gravel. Clean water-bearing gravel with minor sand occurs between approximately 4 to 6 m below ground surface. The gravel aquifer at this locality is unconfined, with the water table approximately 4 m below ground surface. At the wells more than 500 m from the river, dry gravel with sand occurs from the ground surface to approximately 3 m below the surface, and from approximately 3 m to 24 m (Fig 6.13) the gravel is clay-bound with a minor silt and/or sand component. Clean water-bearing gravel occurs between approximately 24 m to 30 m below ground surface. The groundwater level in this aquifer is approximately 5 m below ground surface at the middle line of wells and approximately 20 m below ground surface at the line of wells furthest from the river.

The groundwater monitoring array of nine wells located downstream from Crossbank (Site 2) measures groundwater level changes asso-

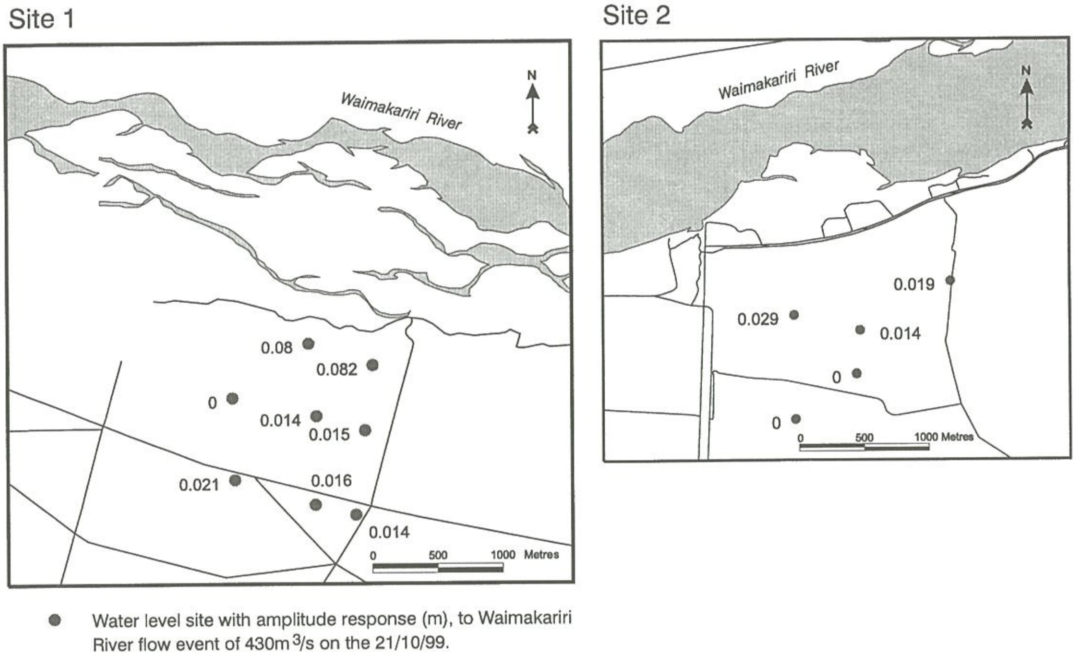


Figure 6.14 *Response of groundwater levels to an increase in Waimakariri River flow on 21 October 1999.*

ciated with an aggrading section of the river. Sandy gravel, with occasional clay-bound gravel deposits, occur from the ground surface down to approximately 4 m below ground surface (Fig 6.13) at all well sites. Water-bearing gravel, or sandy gravel, occur below approximately 4 m below ground surface. The gravel aquifer is unconfined, with the water table between approximately 3 to 4.5 m below ground surface.

Inferred groundwater flow directions at Site 1 and Site 2, using groundwater levels and river levels measured in January 2000 (Fig 6.12), are consistent with the regional pattern of groundwater flow (Fig 6.6). The groundwater piezometric gradient in the river-groundwater system in this area is approximately 0.02 m/m at Site 1 and averages 0.006 m/m at Site 2.

Changes in river flow during seven events in the Waimakariri River in the period October to December 1999 are consistently reflected in groundwater level changes at Site 1. Groundwater levels at Site 1 react more frequently to river flow changes than levels at Site 2, and the magnitude of the changes are usually greater at Site 1 than Site 2 (Fig 6.14). The greater amplitude of response of groundwater level at Site 1 may be because a number of wells there are in a semi-confined aquifer. Groundwater is unconfined in the three wells nearest the river at Site 1. The responses to five changes in Waimakariri River flow in the three wells closest to the river at Site 1 averaged 0.025 m, 0.032 m, and 0.033 m, while the three wells nearest the river at Site 2 averaged 0.022 m, 0.013 m, and 0.016 m. These observations are not inconsistent with seepage, and therefore recharge, through the river bed being greater at Site 1 than Site 2.

SPRINGS

The discharge of groundwater to the surface through springs has formed an important source of human water supply in New Zealand in both the past (Chapter 2) and present. The communities of Whangarei, Pukekohe, Rotorua (Thorpe 1992) and others use springs as water supplies. Other economic uses of springs include the bottled water industry, and water supplies for fish farming in Nelson and Canterbury. Some springs

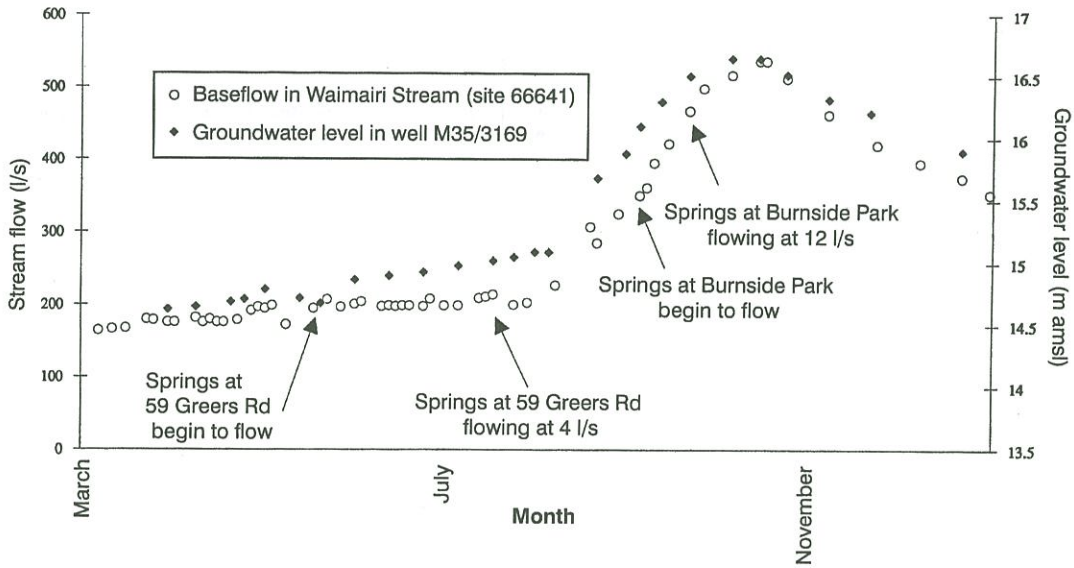


Figure 6.15 *Waimairi Stream flow, spring flow, and groundwater level.*

are popular tourist destinations for example Waikoropupu Springs in Nelson (Williams 1992) and Haumoana Springs in Rotorua. Spring discharges maintain the flow in the Avon River in Christchurch, which is very important to the character and amenity of the city. Tourist and recreation operations are based around the karst systems that feed springs in the Waikato, Nelson, and the West Coast. Caving and black-water rafting are popular in these areas. Water quality is extremely important where springs have economic uses, so land use around springs and travel paths for recharge are concerns to water managers (Williams 1992).

Spring flow and more diffuse groundwater seepage are important in maintaining baseflow (Duncan 1992), particularly in New Zealand's relatively steep catchments (Petch 1984). The baseflow of the Avon River, Christchurch, originates from groundwater-fed springs and the drainage of wetland areas (Cameron 1992). A seasonal fluctuation in the contribution by springs to the Avon River occurs due to the summer decline in groundwater levels caused by natural groundwater drainage, abstraction, lower summer rainfall and increased evapotranspiration. The occurrence of springs and their flow rate (Fig 6.15) fluctuate in response to groundwater level (Cameron 1992). The contributing channel length changes in response to the seasonal and long-term fluctuations in groundwater levels, so the summer decline in groundwater levels leads to a downstream migration of stream headwaters. As a result there is a seasonal fluctuation in stream baseflow.

Groundwater enters the headwater reaches of the Avon River both by discrete artesian spring flow through a confining layer and by groundwater seepage through stream bed gravels. Artesian spring flow occurs where the water-bearing gravels are overlain by less permeable fine-grained sediments (i.e., silty sand, silt and/or clay). These sediment acts as a confining layer, facilitating the development of an artesian head in the underlying gravel aquifer. Artesian spring flow occurs through pipes in the fine sediment, and water discharges into the stream through vents in the stream bed. Artesian springs do not occur where the thickness or the composition of the overlying fine-grained material is such that the hydraulic head of the underlying gravel aquifer is insufficient to develop pipes. Flow begins by indiscernible seepage through fine sediment in the streambed immediately upstream of the springs in the area where stream flow originates in artesian springs. Downstream, the flowing artesian springs become progressively larger and more numerous.

The diameter of measured vents in the Avon River varies from several millimetres up to 0.3 m. Vents typically occur in groups, with up to several dozen being present in an artesian spring section of the stream. The number of vents in a stream section and the diameter of the vents progressively increase from autumn, when groundwater levels and stream flow are at a minimum, to late winter when the groundwater levels and stream flow are at a maximum. Artesian spring discharge increases with vent size, and larger vents occur where there is a greater depth to underlying gravel. This is possibly due to increasing hydraulic head with depth in the Christchurch aquifer system. However, no artesian springs were observed where the depth to gravel exceeds 10 m. This implies that there is a maximum depth to gravel (approximately 10 m) beyond which artesian springs cannot develop.

Stream flow is augmented by groundwater entering the stream through seepage faces. The quantity of flow is a function of the gradient between the aquifer and the streams, the bank storage, the hydraulic properties of the aquifer, and the hydraulic properties of the material connecting the aquifer and the stream (Jorgensen et al. 1989). The location of seepage faces is related to the depth to gravel in the headwaters of the Avon River. Groundwater seepage from the unconfined aquifer through streambed gravel occurs where the gravel is within 1 m of the ground surface. In historical times springs were known to have occurred further west than present-day spring localities. Spring occurrence and flow has decreased due to the drainage of Christchurch, increased groundwater abstraction and the construction of impermeable surfaces that inhibit the infiltration of local rainfall. Residents who have springs on their property noticed a decline in spring flow when subdivisions were developed upstream of their properties; this decline is attributed to the drainage of new subdivision areas and reduced infiltration due to an increase in impermeable surface area and a more efficient removal of runoff.

MODIFIED INTERACTIONS BETWEEN SURFACE WATER AND GROUNDWATER

Stream depletion from groundwater pumping

The natural interaction between groundwater and streamflow can be greatly influenced by human activities. The impact of groundwater pumping on streamflow is an important issue which has been dealt with through analytical and numerical tools. The analytical method has the longest history. The follwing sections review previous methods and describes a new analytical solution that can be used to estimate the hydraulic parameters of the aquifer and the stream depletion caused by groundwater pumping.

Development of analytical models

The first unsteady solution for stream depletion caused by groundwater abstraction was given by Theis (1941) for the simplest

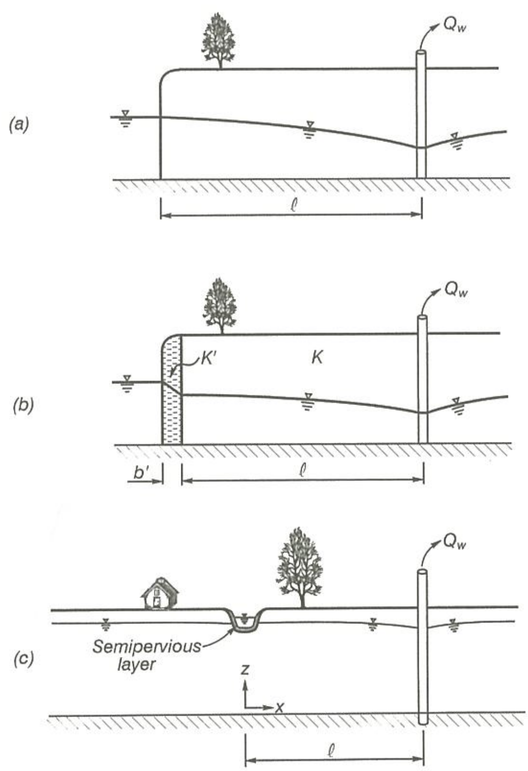


Figure 6.16 *Hydrogeologic setting considered by (a) Theis (1941), (b) Hantush (1965) and (c) Hunt (1999).*

hydrogeologic setting (Fig 6.16a): a straight river fully penetrating a homogeneous, isotropic aquifer of semi-infinite extent, which can be either confined or unconfined. Water is abstracted at a constant rate from a fully penetrating well. The solution assumes that changes in free surface elevations in the aquifer are small enough to allow linearisation of the governing equation and that water is released instantaneously from aquifer storage. Glover and Balmer (1954) rewrote the Theis (1941) solution in terms of the complimentary error function, erfc:

$$\frac{\Delta Q}{Q_w} = \mathrm{erfc}\left(\sqrt{\frac{S\ell^2}{4Tt}}\right) \qquad (3)$$

where ΔQ is the stream depletion rate (m^3/s), Q_w is the constant flow of groundwater abstracted from the well (m^3/s), S is the storage coefficient (or effective porosity for an un confined aquifer), T is transmissivity (m^2/s), ℓ is the shortest distance between the well and the stream edge (m), and t is time(s).

Later, using Equation 3, Jenkins (1968) developed dimensionless graphs for volume and rate of stream depletion; this is often referred to as Jenkins method. This method is still used today by some water administrators to assess stream depletion (see for example Scott and Callander 1995; Sanders 1996; Environment Canterbury 2000).

Jenkins also used superposition and time translation to calculate the stream depletion for more general pumping schedules. This is possible because the differential equations are linear, with coefficients that do not depend on time. Thus, the stream depletion caused by pumping a well from times $t = 0$ to $t = t_p$ can be found as the difference of solutions for two pumping scenarios: one where pumping starts at $t = 0$ and continues infinitely, and one where pumping starts at $t = t_p$ and continues infinitely (Fig 6.17). Thus, the stream depletion can be expressed as:

$$\frac{\Delta Q}{Q_w} = \begin{cases} \mathrm{erfc}\left(\sqrt{\frac{S\ell^2}{4Tt}}\right) & \text{for } 0 \le t \le t_p \\ \mathrm{erfc}\left(\sqrt{\frac{S\ell^2}{4Tt}}\right) - \mathrm{erfc}\left(\sqrt{\frac{S\ell^2}{4T(t-t_p)}}\right) & \text{for } t_p \le t \le \infty \end{cases} \qquad (4)$$

Stream depletion resulting from cyclic pumping can be found in a similar way by adding further components (Jenkins 1968; Wallace et

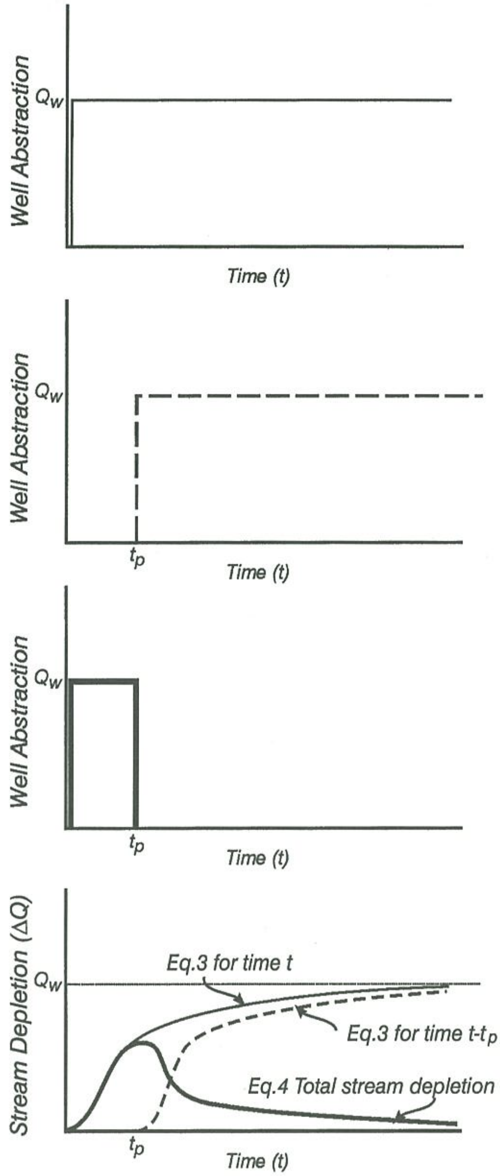


Figure 6.17 *Stream depletion (bold line) after pumping stops can be calculated as the stream depletion resulting from pumping an infinite time from t = 0 (solid line) minus the stream depletion resulting from pumping an infinite time (with the same rate) from t = t_p (dashed line).*

al. 1990). This entire procedure is identical with the use of superposition and time translation in applications of unit hydrograph theory.

The Theis/Balmer/Jenkins solution, although extensively used for administering water rights, suffers from the fact that many of the simplifying assumptions on which the solution is based are practically never fulfilled. Spalding and Khaleel (1991) and Sophocleous et al. (1995) used numerical modelling to evaluate the errors associated with the various assumptions. They found that significant errors were related to three phenomena not included in Theis's idealised setting (Fig 6.16a): the existence of a semipervious layer (also called a clogging layer) between the stream and the aquifer, partial stream penetration, and aquifer heterogeneity.

The importance of the first of these factors was acknowledged early and incorporated in an analytical solution by Hantush (1965). He considered a hydrogeologic setting similar to that of Theis, but with a semipervious layer along the stream edge (Fig 6.16b). Hantush's solution is given by:

$$\frac{\Delta Q}{Q_w} = \mathrm{erfc}\left(\sqrt{\frac{S\ell^2}{4Tt}}\right) - \exp\left(\frac{Tt}{SR^2} + \frac{\ell}{R}\right)\mathrm{erfc}\left(\sqrt{\frac{Tt}{SR^2}} + \sqrt{\frac{S\ell^2}{4Tt}}\right) \quad (5)$$

where R is called the 'retardation coefficient' and is defined as

$$R = \frac{K}{K'} b' \quad (6)$$

where K is the hydraulic conductivity of the aquifer, and K' and b' are hydraulic conductivity and thickness, respectively, of the semipermeable layer. When b' approaches zero, R approaches zero, and Equation 5 reduces to Equation 3. Jenkins (1968) developed user-friendly dimensionless graphs of Equation 5 in the same manner as he had for Equation 3.

Numerical models

The development of numerical models in the 1970s and 1980s overcame some of the simplifying assumptions on which Equations 3 and 5 are based. The flexibility of 3-D numerical modelling allows the representation of general hydrogeologic settings that include heterogeneous aquifers, river bends, and partly penetrating rivers and wells. Models became increasingly complex and the most difficult part of the modelling was to obtain enough accurate input data for the model. It therefore became time-demanding and relatively expensive to set up, calibrate and verify the models. Numerical groundwater models have been used to assess effects on streamflow. Spalding and Khaleel (1991), Sophocleous et al. (1995) and Clausen et al. (1993) evaluated analytical solutions and carried out sensitivity analyses with respect to abstraction regimes. Lanen and Weerd (1993) evaluated the effects of land-use change and climatic changes. Although numerical models are particularly valuable for sensitivity analysis or for rivers of special interest, it is difficult to see them being incorporated into standard routines for issuing water consents.

New analytical solution

A further step towards an analytical solution based on more realistic assumptions was taken by Hunt (1999), who found a solution for situations in which the stream only slightly penetrates the aquifer and has a semipervious stream bed, or clogging layer (Fig. 6.16c). Whereas before the aquifer was assumed to be of semi-infinite extent, it was now assumed to extend infinitely in all horizontal directions. Otherwise the assumptions are the same as in the previous cases (the stream is straight, the aquifer is homogeneous and isotropic, and Dupuit's approximation is valid). Finally, it is assumed that leakage between stream and aquifer per unit length of stream (Δq) is linearly proportional to the change in hydraulic head across the semipervious layer, as expressed in Equation 1. Thus, the leakage per unit length Δq (m^2/s) can be expressed as

$$\Delta q = \lambda\,(H - h(0,y,t)) \quad (7)$$

where H is the elevation of the stream water surface, h is the hydraulic head of the aquifer (which may be either confined or unconfined), and λ is the leakage coefficient (in m/s). The leakage, or stream depletion, is positive when water flows from the stream to the aquifer and negative when it flows in the opposite direction. It is helpful to remember that λ is a modified conductivity. The higher the value of λ, the higher the leakage.

If Darcys law is valid for flow across the semipervious stream bed, we also have

$$\Delta q = W K' \frac{(H - h(0, y, t))}{b'} \qquad (8)$$

where W is stream bed width and K' and b' are the hydraulic conductivity and thickness, respectively, of the semipermeable stream bed. By combining Equations 7 and 8 we obtain another expression for λ:

$$\lambda = W \frac{K'}{b'} \qquad (9)$$

Equation 9 is only an approximation, since the mathematical model assumes that the stream bed width, W, is infinitesimal. Therefore, applications of the mathematical solution should also satisfy the requirement $W << \ell$.

The Hunt (1999) solution for stream depletion is

$$\frac{\Delta Q}{Q_w} = \mathrm{erfc}\left(\sqrt{\frac{S\ell^2}{4Tt}}\right) - \exp\left(\frac{\lambda^2 t}{4ST} + \frac{\lambda \ell}{2T}\right) \mathrm{erfc}\left(\sqrt{\frac{\lambda^2 t}{4ST}} + \sqrt{\frac{S\ell^2}{4Tt}}\right) \qquad (10)$$

As expected, the expression approaches zero and one as t approaches zero and infinity, respectively. A comparison between Equations 5 and 10 shows that they are identical if we choose

$$R = 2\frac{T}{\lambda} \qquad (11)$$

This shows clearly that λ and R have an inverse relationship. While λ is a modified conductivity for leakage, R is a modified resistance.

The solution given by Equation 10 is plotted in dimensionless form in Figure 6.18. The upper curve ($\lambda\ell/T=\infty$) is the Theis solution (Equation 3), which is approached when b' approaches zero (no semipermeable stream bed). These curves also give the Hantush solution (Equation 5) if λ is calculated from Equation 11. The graphs in Figure 6.18 show that the stream depletion is overestimated for any finite value of t if an existing clogging layer (a value of λ lower than infinity) is ignored. Thus, to obtain a relatively accurate estimate for stream depletion it is important to obtain an accurate value for λ.

There are different ways of obtaining estimates for λ, T and S from Hunt's solution (see detailed explanations in Hunt et al. 2001). One way is to compare data on streamflow (and stream depletion) with the graphs in Fig 6.18. This requires specification of either λ, T or S to solve for the other two parameters. However, it will not often be possible to obtain sufficiently accurate field measurements of $\Delta Q/Q_w$ to carry out this calculation. A second method is to use drawdown data from observation wells and compare these with the theoretical solution given by Hunt (1999). This allows determination of all three parameters. However, the most accurate method is to include both drawdown and streamflow data, if both are available. This involves a stepwise refining of λ, T and S by

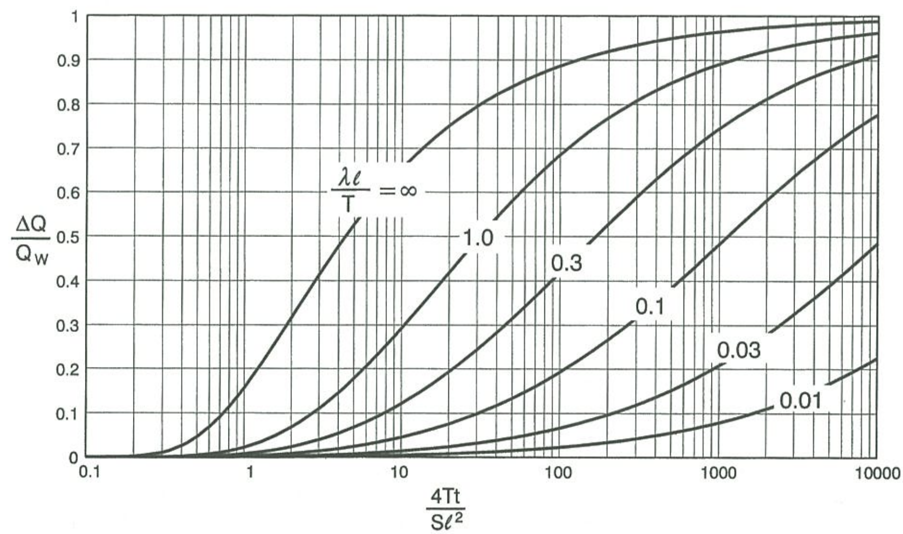


Figure 6.18 *Dimensionless graphs of the Hunt (1999) solution for stream depletion, calculated from Equation 10.*

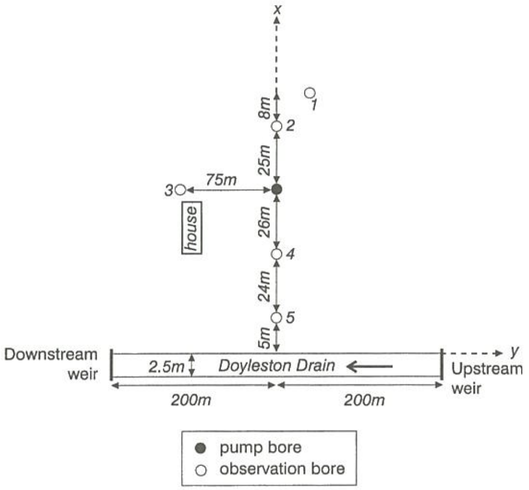


Figure 6.19 *Sketch of the Doyleston pump test site.*

alternating between the stream depletion match-point plot and the drawdown match-point plot.

Application

The methods described above were first tested by Weir (1999). A pump test was carried out near the Doyleston Drain (Fig 6.19), approximately 40 km south of Christchurch near Lake Ellesmere, in a gravel aquifer that was either confined or semi-confined. The abstraction bore was pumped at a rate of 17.5 L/s for 10 hours. Water levels were observed in five observation wells and the streamflow was monitored at two V-notched weirs during these 10 hours and also during the following 12 hours of recovery.

The streamflow in the Doyleston Drain at both the upstream and the downstream weirs decreased approximately 5 L/s after ten hours of pumping (Fig 6.20). The stream depletion between the two weirs (the difference between the two flow hydrographs at maximum depletion) was small (approximately 1 L/s). The lesson learned was that for the next pump test it would be enough to install only one weir next to the test site, and the stream depletion could be estimated. Since the theoretical cone of depression is symmetrical, stream depletions upstream and downstream from the test site should be equal at all times. If the streamflow at the test site has dropped by X L/s at a given time, then the total stream depletion should be 2 times X. This method of estimating stream

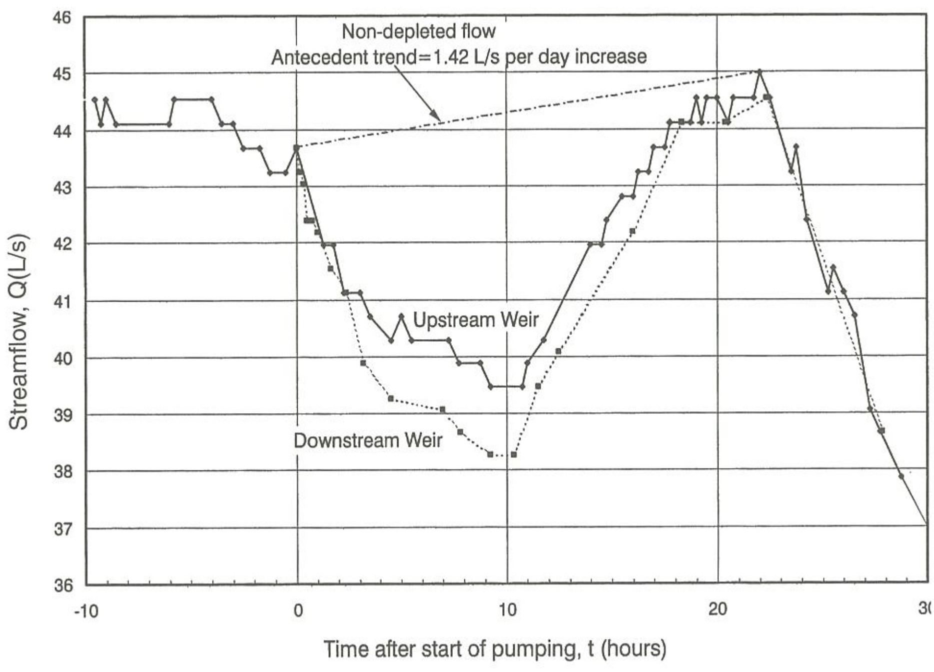


Figure 6.20 *Recorded streamflow at the upstream and downstream weirs in the Doyleston Drain during and after the pump test.*

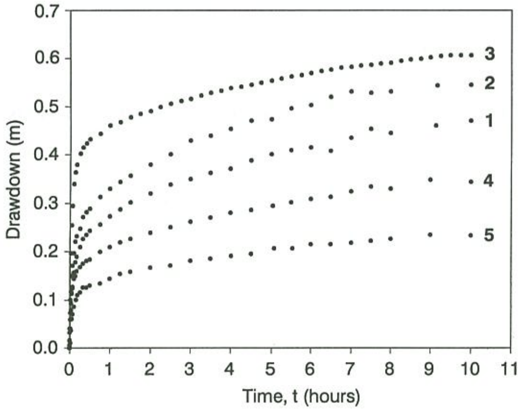


Figure 6.21 *Drawdown (ϕ) versus time (t) in five observation bores (for their locations see Figure 20).*

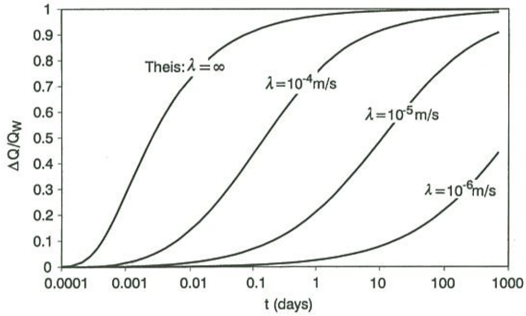


Figure 6.22 *Stream depletion (ΔQ) as a ratio of abstraction rate (Q_w) versus time (t) from observation bore 5, using different values of λ. Values of T and S were 0.019 m²/s and 1.6 x 10⁻⁴, respectively.*

depletion requires that there is a clear change in streamflow from the unaffected flow that can be measured accurately.

For the test in Doyleston Drain there was a significant drop in streamflow at both weirs. The undisturbed streamflow was simulated by a straight line (Fig 6.20) from the time when the pump started until the end of recovery, which occurred about 12 hours after pumping ended. From this time the streamflow started to drop again (as it had done before the pumping started). Thus, the total stream depletion was found to be approximately 4 L/s after 1 hour, 6 L/s after 3 hours, 9 L/s after 7 hours, and 11 L/s after 10 hours.

From streamflow and water level observations prior to the test it was clear that there was a good hydraulic connection between the stream and the aquifer. When water levels in the bores were high, the streamflow was high and vice versa. Also, differences in water level between the stream and bores were small (around 20 cm). This connection explains why drawdowns during the pump test (Fig 6.21) were lower in bores 5 and 4 closer to the stream and higher in bores 2 and 1 away from the stream. Bore 3 behaved somewhat unexpectedly by having the highest drawdowns, even though it was further from the pumped bore than the other observation bores were. This inconsistent behaviour of bore 3 has never been satisfactorily explained.

Table 6.2 lists the final estimates of T, S and λ for the five observation bores found from using both streamflow and drawdown data. Again, bore 3 showed anomalous behaviour by having smaller values than the other bores. The results from bores 1, 2, 4 and 5 were remarkably consistent. The average value for the leakage coefficient is close to 1×10^{-4} m/s.

Figure 6.22 shows the stream depletion calculated from Equation 10 using three different λ values: 10^{-4} m/s, 10^{-5} m/s, and 10^{-6} m/s. For comparison the stream depletion using the Theis

Table 6.2 *Estimated values of transmissivity (T), storativity (S) and leakage coefficient (λ), Doyleston Drain site.*

Parameter	Bore 1	Bore 2	Bore 3	Bore 4	Bore 5	Average Bores 1,2,4,5
T m²/s	0.019	0.019	0.011	0.033	0.025	0.024
S -	1.5×10^{-3}	1.7×10^{-3}	0.13×10^{-3}	1.7×10^{-3}	1.6×10^{-3}	1.6×10^{-3}
λ m/s	0.70×10^{-4}	0.76×10^{-4}	0.13×10^{-4}	0.95×10^{-4}	0.82×10^{-4}	0.81×10^{-4}

solution for stream depletion (Equation 3) was also included. It is inferred that the Theis solution overestimates the stream depletion by 20% after one day of pumping, 6% after ten days, and only a few percent after 100 days of pumping, when λ is 10^{-4} m/s. When λ is 10^{-5} m/s, the overestimation is more significant, approximately 75% after one day of pumping, 50% after ten days, and 22% after 100 days. For an even smaller value of λ, 10^{-6} m/s, the overestimation is 95% after one day, 91% after ten days, and 78% after 100 days of pumping. The stream depletion is also very sensitive to the distance between the pumped well and the stream.

Estimation of leakage coefficient

There are ways of estimating λ other than using pump tests and analytical solutions, although the accuracy of these methods is unknown. One method is to directly measure the conductivity of the stream bed sediments. This can be done using an infiltrometer pushed down into the stream bed. Water is poured into the infiltrometer and the water level is measured and plotted as a function of time. The slope of the line indicates the infiltration rate. One type of infiltrometer is the double-ring infiltrometer described and used by Brooks et al. (1998) to measure stream bed conductivity (K') in the Doyleston Drain. For a stream location close to the test site (Fig 6.19), K' was measured to lie in the range 3.4 – 6.0 x 10^{-4} m/s. Using Equation 9 and the values b' = 1.7 m and W = 2.5 m, λ is calculated as 5.0 – 8.8 x 10^{-4} m/s. These values are one order of magnitude higher than the results found from the pump test.

Another way of estimating λ is to measure the difference in head between the groundwater and the stream (H-h) and the stream leakage (Δq) over a reach. Thus λ can be calculated using Equation 7. This method was attempted for the Doyleston Drain by measuring the water level in wells near the stream not affected by pumping. However, measured values of (H-h) and Δq were too small to give reliable estimates: (H-h) varied between 4 and 36 mm, and Δq varied between 1 L/s and 7 L/s over 1.5 km reaches. Thus, errors in these measurements were probably of the same order as the measurements themselves. This method might be more suitable at a different time of year when the difference in head is larger.

In general, more accurate estimates of the groundwater head below the stream might be obtained by using piezometers directly in the stream bed or by constructing a detailed map of groundwater head. The latter was attempted in a recent study of the Ohoka stream by Sanders and Lovell (1999); they also used infiltrometers and seepage meters and found reasonable agreement between the results from all three methods. Environment Canterbury (2000) discussed other examples of the measurement of stream depletion.

Sea water intrusion

Aquifers that are open to the sea are potentially susceptible to sea water intrusion. Bear and Verruijt (1987) presented conceptual and mathematical models for predicting sea water intrusion into coastal aquifers. They discussed the Ghyben-Herzberg approximation to the interface between sea water and fresh water in static equilibrium and dynamic equilibrium conditions. A hydraulic approach was used to model regional sea water intrusion in an unconfined aquifer using two equations, one for horizontal flow of fresh water and another for horizontal flow of salt water, together with appropriate initial conditions and boundary conditions.

Sea water intrusion occurs naturally in New Zealand groundwater, for example under Tiwai Peninsula, Southland, and under reclaimed land in southern Wairarapa (White 1985). Induced sea water intrusion occurs when groundwater abstraction reduces piezometric levels sufficiently on the seaward side of a well to cause a wedge of relatively dense sea water to extend inland from the coast to the well. Induced seawater intrusion has been recorded (Thorpe 1992) near Motueka in the summer of 1990. Groundwater level drawdown below sea level induced seawater intrusion onto an area of approximately 1.5 km by 0.4 km and this disrupted orchard irrigation. The salt water was apparently flushed seawards in winter when groundwater levels were above sea level. Irrigation wells near the coast were replaced with wells approximately 2 km inland to prevent a re-occurrence of induced seawater intrusion.

Salinity has increased over the last 20 to 30 years in wells abstracting groundwater in the Heathcote/Woolston area in Christchurch (Environment Canterbury 1998; Hertel 1998). Brown and Weeber (1994) suggested that seawater intrusion and mixing with groundwater derived from the underlying volcanic rock are responsible for the salinity of the area. Groundwater levels can be below sea level in the Heathcote/Woolston area. Wells with groundwater levels below sea level yield water with chloride concentrations of up to 1600 g/m^3. Six industries, and the Christchurch City Council, pump water from this area. The problem, and remedial options, were discussed by groundwater managers and Heathcote/Woolston groundwater users. All ground-water users agreed to reduce groundwater abstraction and the Christchurch City Council reduced its groundwater take from the area by 90% (Ettema pers. comm.). Average daily usage for all users reduced from approximately 8000 m^3/day in 1995-1998 to approximately 5500 m^3/day in 1999-2000. An improvement in groundwater level is attributed to the reduced groundwater abstractions. For example, groundwater levels were above high-tide level in an indicator well for just 5% of the time in 1997-1998, but for 72% of the time in 1999-2000. Groundwater quality has, on average, improved during the period of reduced pumping. Monitoring is continuing in the area.

Artificial recharge

Asano (1985) states that the purposes of artificial recharge to groundwater are to reduce, stop, or even reverse declining levels of groundwater; to protect underground freshwater in coastal aquifers against saltwater intrusion from the ocean; and to store surface water, including flood or other surplus water, imported water, and reclaimed wastewater for future use. The use of artificial recharge is most imperative in arid climates (Asano 1985). Infiltration through the unsaturated zone is modelled (Asano 1985) as:

$$I = \frac{K(H_C + H + Z_f)}{Z_f} \qquad (12)$$

where I is the infiltration rate, K is the unsaturated hydraulic conductivity at a given water content, H_C is the effective capillary drive (expressed as an equivalent depth of water), H is the water depth in the infiltration basin, and Z_f is the depth of the sharp wetting front. Recharge to groundwater starts when the wetting front reaches the water table.

New Zealand, with its relatively high rainfall and low population density, has had limited experience with the practice of artificial recharge. One scheme exists on the Heretaunga Plains and trials of artificial recharge have occurred near Christchurch (Moore 1992).

Koutsos (1988) describes the artificial groundwater recharge scheme on the Heretaunga Plains, which is based on taking water from the Ngaruroro River and flood-irrigating four shallow infiltration ponds. The aim of this project was to augment Heretaunga Plains groundwater recharge and to reduce water level decline in the unconfined and confined aquifers. The infiltration ponds, covering an area of 4 ha, together with a sediment settling pond of 3 ha, were sited in the main recharge area of the Heretaunga Plains aquifers between Roys Hill and Fernhill (Fig 6.3). The ponds were used in rotation, which allows the drying of algae and the clearing of fines in ponds that were not being used. The total capital cost of this project was NZ$200 000, with annual maintenance and running costs estimated to be NZ$15 000. Infiltration rates of 1 m^3/sec were achieved in a 16-day test. Water level in a well situated 50 m from the artificial recharge system rose by approximately 1.6 m during the test, and the water level in a well 2 km downstream of the recharge system rose by approximately 0.2 m. The artificial recharge scheme now takes its water from a trench in the Ngaruroro River bed. The scheme has been run at a continuous flow of 0.6-0.7 m^3/sec for most of the period since 1995 (Adye pers. comm.).

Recharge events can be identified and their effects on groundwater levels in wells estimated from records of use of the artificial recharge system and stage measurements in the artificial recharge system. Wells AR1 and AR4 Fraser No.1, and Substation wells (Fig 6.3), were used to assess the effectiveness of artificial recharge. Between July and December 1991 the artificial recharge system operated during three periods (Fig 6.23). Between 10 September and 16 October 1991 the recharge system was used during a period of relatively uniform river stage. In response to its use the groundwater level in well AR1 rose by 3 m, in AR4 by 5.6 m, in Fraser No. 1 by 0.6 m and in Substation well by 0.9 m. The maximum response of the level in the Substation well to artificial recharge was delayed by approximately 22 days from the commencement of recharge, equivalent to a seepage velocity of 90 m/day over the 2 km distance.

The groundwater level effect of artificial recharge appears to be greater when natural groundwater levels are relatively low (Fig 6.24). For example, artificial recharge caused groundwater levels in the AR4 well to rise by 5.6 m when the water table elevation was 24.8 m, before recharge between 10 September 1991 and 16 October 1991. A level rise of 1.6 m in AR4 occurred when the water table elevation was 26.5 m, before artificial recharge on 28. April 1996. Groundwater level rises on 10 September 1991 and 10 December 1991 may be due to artificial recharge and increased rainfall, but removing these points from the graphs would not significantly change the best-fit lines to the data for AR4, Fraser No. 1 and Substation wells.

Return-period analysis of the Substation groundwater level record predicts minimum groundwater elevations and their return periods (Table 6.3), from which level increases due to artificial recharge can be estimated. Estimated level increases are based on an average artificial recharge event duration of one month. Return-period and groundwater elevation statistics are calculated by a normal distribution fit to monthly minimum elevations recorded in the Substation well between 1968 and 1997. Predicted increases in groundwater level due to artificial recharge are greater than 1.2 m for a 1 in 10 year, or greater, minimum level. Predicted level increases are less than 0.1 m for 1 in 5 year, or less, minimum levels.

Wetlands

Wetlands are economic, biological, and recreational resources that are commonly linked to groundwater systems. They are important economically (Environmental Council 1983) because they are the source of peat and sphagnum moss, which are used in horticulture; kauri gum, which has been mined; and ironsands and coal, which are mined. Wetlands, when drained, form some of the best agricultural land in Waikato, the Hauraki Plains, the Bay of Plenty, Hawke's Bay and Southland. Wetlands provide food for humans. Eel fisheries, whitebait fisheries, and marine farming of oysters and mussels are often closely associated with wetlands. Wetlands are important biological assets. They are some of the nearest approaches to total wilderness that we have left (Stephenson 1986), and are important to: bird life both New Zealand native species and trans-equatorial migratory birds, to fish, and to plants (Johnson 1998). They are important for recreational bird-watching, fishing, and hunting. The Environment Council (1983) map 169 terrestrial wetlands and 299 coastal wetlands in the North Island, South Island and Stewart Island.

Wetlands commonly store flood waters, thus attenuating flood severity. The wetlands are often a source for river baseflow, helping to maintain river flow in dry weather. Wetlands can also be a source of groundwater recharge where the wetland lies above the water table. Groundwater systems in turn are commonly a source of water for wetlands, and the water surface in a wetland can be the surface expression of the groundwater level. Activities that affect groundwater quantity and quality can therefore affect wetlands.

Coastal wetlands are common at the coastal margin of a groundwater system and therefore become the receiving environment for the cumulative effects of land use on groundwater quality. For example, the areal extent of eelgrass in an estuary in Massachusetts, USA , decreased significantly between 1951 and 1987 because of increased inputs of nitrogen from groundwater (United States Geological Survey 1998).

Wetland vegetation and ecosystem productivity are significantly related to hydrological conditions in a wetland (Eser and Rosen 1999). In the Stump Bay section of the South Taupo wetland, Lake Taupo (Fig 6.25), the distribu-

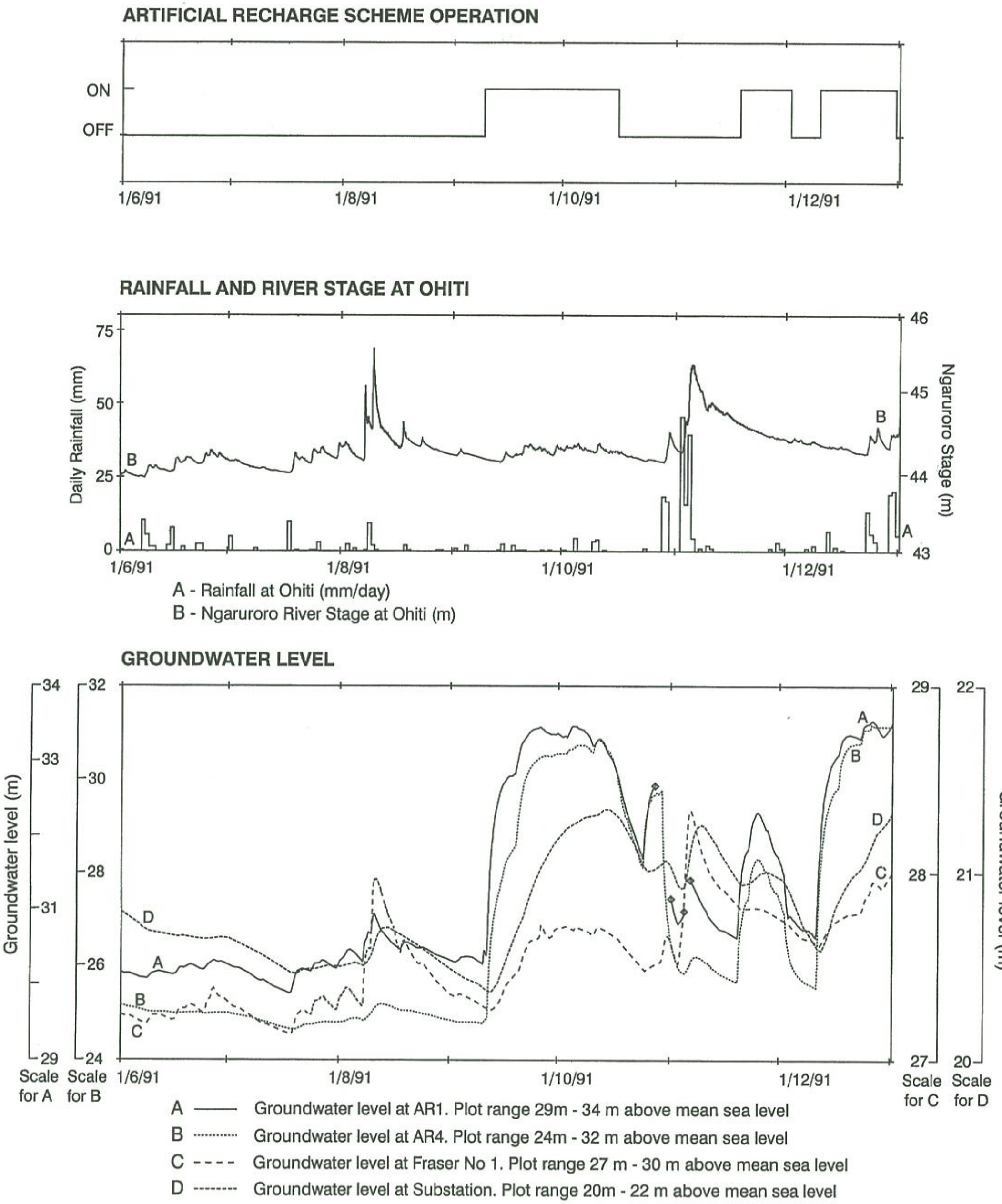


Figure 6.23 *Operation of the Heretaunga Plains groundwater artificial recharge scheme: Ngaruroro River flow, rainfall and groundwater levels in AR1, AR4, Fraser No. 1 and Substation wells in the period July to December 1991.*

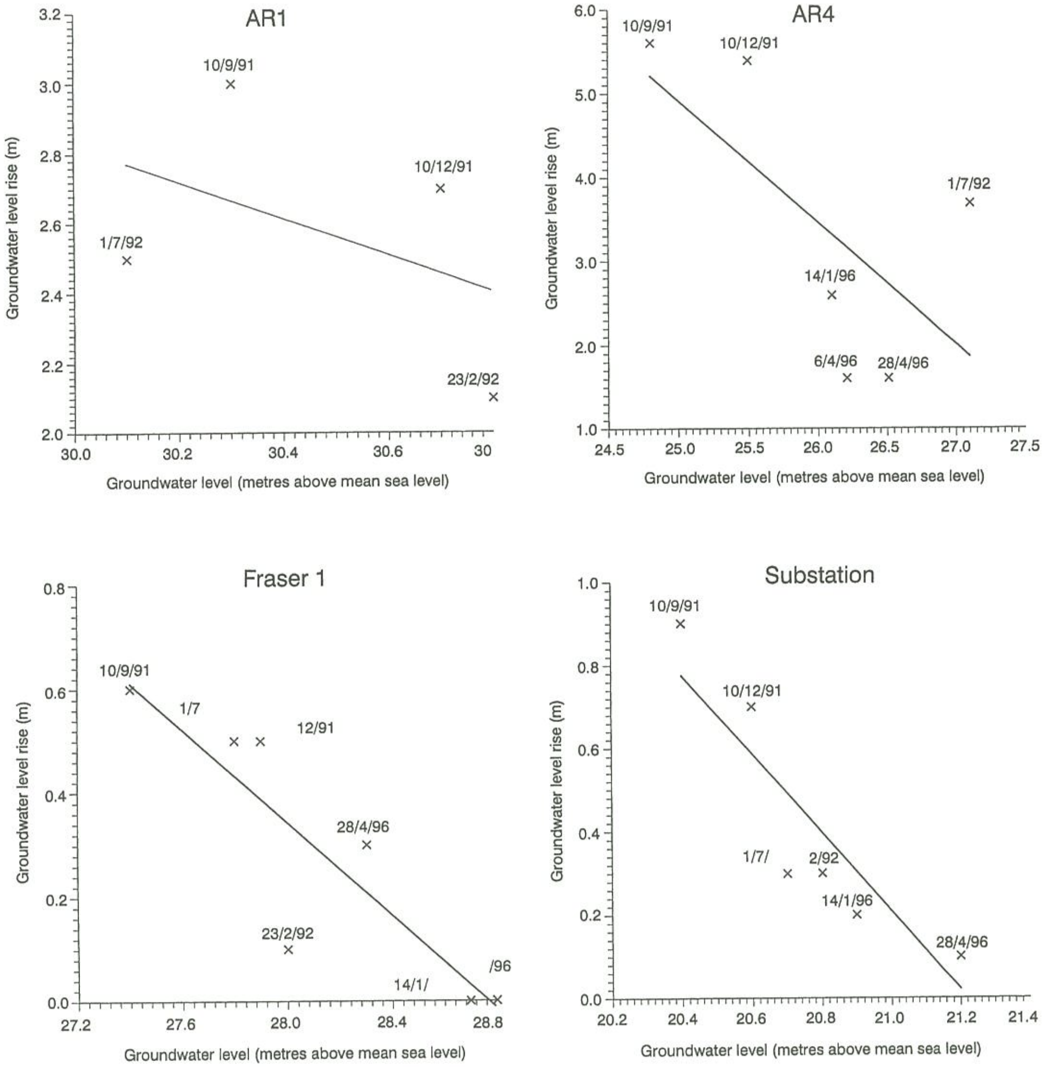


Figure 6.24 *Groundwater level rise induced by artificial recharge versus groundwater elevation before recharge began: AR1, AR4, Fraser No. 1 and Substation wells.*

Table 6.3. *Return period of monthly minimum groundwater levels and the potential of artificial recharge to increase levels, Substation well 1968–1997.*

Return period for monthly minimum elevation (years)	Groundwater elevation (m)	Predicted groundwater elevation increase due to artificial recharge (m)
1	21.3	0
5	21.2	0.1
10	20.0	1.2
20	19.9	1.3
50	19.7	1.5
100	19.6	1.6

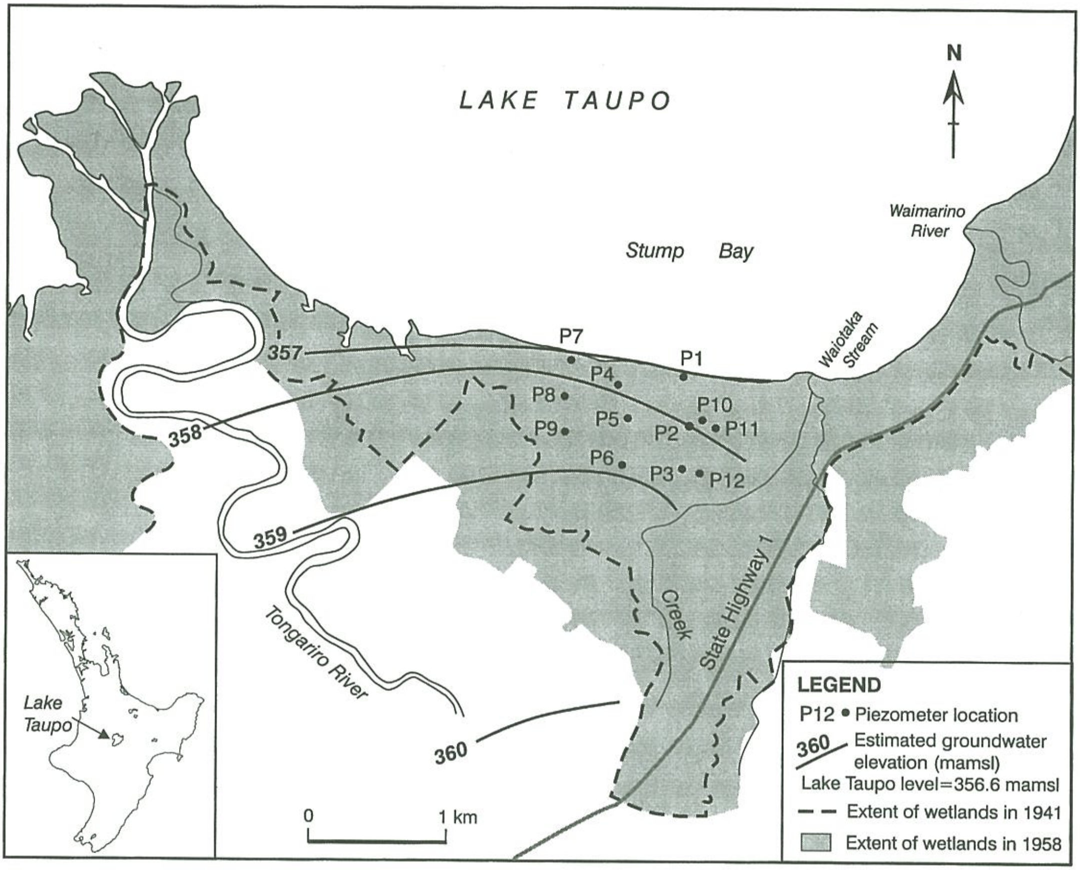


Figure 6.25 *The Stump Bay section of the South Taupo wetland, with wetland extent in 1941 and 1958 (after Eser and Rosen 2000). Estimated groundwater levels in March 1996.*

tion of plant communities varies with water height above ground surface, the soil water content, and soil organic matter content (Eser and Rosen 2000). Artificial regulation of the lake level, which has caused a 2 cm rise in the mean annual lake level and a 20 cm rise in summer level, is likely to have caused an increase in wetland groundwater levels and wetland area between 1941 and 1958 (Fig 6.25). Groundwater flows in a north-south direction and the chemical signature of water from the Tongariro River is recognisable in the groundwater in twelve monitoring wells. Some farmland has been abandoned because of drainage problems and this land was colonised by manuka, crack willow and blackberry. Grey willow has colonised the wetland in the last 20 years and is a threat to the native species.

CONCLUSIONS

Groundwater and surface waters are often linked. Recharge to ground water from rivers can be a significant component of total groundwater recharge and a significant influence on groundwater chemistry. The processes of recharge to groundwater from rivers were illustrated using case examples, and the main methods for measuring and modelling groundwater recharge were outlined. Groundwater in turn maintains spring flow and stream base flow. Examples demonstrate the complexity of groundwater-surface water interactions. The relationship between groundwater and surface water can be affected by humans: groundwater pumpage can reduce stream flow or induce seawater intrusion; methods for estimating stream depletion were outlined. Artificial recharge in turn can be used to replenish groundwater: several New Zealand engineered systems have caused local groundwater levels to increase. Groundwater level is also a major factor affecting the distribution of wetland flora.

Integrated management of groundwater and surface water resources is necessary where these resources are linked (United States Geological Survey 1998). For example, low flow limits on rivers must take into account the location and amount of river water discharge to groundwater. Conversely large abstractions from groundwater may cause streams to dry up. Integrated management of water quality is also required. For example, excessive application of fertiliser could lead to high concentrations of nutrients in groundwater, which may then cause eutrophication and a change in flora and fauna in surface water bodies connected to the groundwater system.

ACKNOWLEDGEMENTS

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REFERENCES

Anderson, B. 1994: Groundwater between the Selwyn and Rakaia Rivers, Canterbury, New Zealand. A hydrogeological modelling study. MSc thesis, Department of Geography, University of Otago.

Asano, T. 1985: Artificial Recharge of Groundwater. Butterworth, Boston. 767 p.

Bear, J.; Verruijt, A. 1987: Modelling Groundwater Flow and Pollution. Reidel, Dordrecht. 414 p.

Broadbent, M. 1978: Seismic refraction surveys for Canterbury groundwater research. Geophysics Division, Report No. 131. Department of Scientific and Industrial Research, 91 p.

Brooks, T.; Earl, P.; Rossiter, P. 1998: Observations of the Doyleston Drain area in a drought JanuaryMay, 1998. Report no. U98/41, Canterbury Regional Council, Christchurch, 32 p.

Brown, L.S.; Weeber, J.H. 1994: Hydrogeological implications of geology at the boundary of Banks Peninsula volcanic rock aquifers and Canterbury Plains fluvial gravel aquifers. New Zealand Journal of Geology and Geophysics 37: 181-193.

Cameron, S.G. 1992: A hydrogeological study of the interaction between Avon River baseflow and shallow groundwater, Christchurch, New Zealand. MSc. Thesis, Department of Geology, University of Canterbury.

Clausen, B.; Young, A.R.; Gustard, A. 1993: Modelling the impact of groundwater abstraction on low river flows. IAHS publication no. 221, 77-85.

Dalmer, E.B. 1971: The Waimakariri River as a water resource. North Canterbury Catchment Board and Regional Water Board, Christchurch.

Dicker, M.J.I.; Fenemor, A.D.; Johnston, M.R. 1992: Geology and groundwater resources of the Waimea Plains, Nelson. New Zealand Geological Survey Bulletin 106, 59 p.

Dravid, P.N.; Brown, L.J. 1997: Heretaunga Plains Groundwater. Study Volume 1: Findings, Hawke's Bay Regional Council, 254 p.

Duncan, M.J. 1992: Flow regimes in New Zealand Rivers. In Waters of New Zealand. New Zealand Hydrological Society, 13-28.

Environment Canterbury 1998: Background report for the Woolston-Heathcote groundwater users meeting of 7 September 1998. Report U98/60. 38 p + appendices.

Environment Canterbury 2000: Guidelines for the Assessment of Groundwater Abstraction Effects on Stream Flow. Report R00/11. 81 p + appendices.

Environmental Council 1983: Wetlands: A diminishing resource. Water and Soil Miscellaneous Publication 58, National Water and Soil Conservation Organisation, Wellington, 62 p + appendices.

Eser, P.; Rosen, M.R. 1999: The influence of groundwater hydrology and stratigraphy on the hydrochemistry of Stump Bay, South Taupo Wetland, New Zealand. Journal of Hydrology 220: 27-47.

Eser, P.; Rosen, M.R. 2000: Effects of artificially controlling levels of Lake Taupo, North Island, New Zealand, on the Stump Bay wetland. New Zealand Journal of Marine and Freshwater Research 34: 217-230.

Fenemor, A.D. 1984: Groundwater interaction and low flow behaviour of the Wairoa-Waimea River, Nelson. Unpublished Internal Report W5846 of the Hydrology Centre, Department of Scientific and Industrial Research, Christchurch, 44 p.

Fenemor, A.D. 1988: A three-dimensional model for management of the Waimea Plains aquifers, Nelson. Publication No. 18 of the Hydrology Centre, Department of Scientific and Industrial Research, Christchurch, 133 p.

Glover, R.E.; Balmer, C.G. 1954: River depletion from pumping a well near a river. American Geophysical Union Transactions 35(3): 468-470.

Griffiths, G.A. 1979: Recent sedimentation history of the Waimakariri River, New Zealand. Journal of Hydrology (New Zealand) 18(1): 6-28.

Hantush, M.S. 1965: Wells near streams with semipervious beds. Journal of Geophysical Research 70(12): 2829-2838.

Hertel, I. 1998: Groundwater contamination in the Heathcote/Woolston area, Christchurch, New Zealand. M.Sc. thesis, University of Canterbury. 260 p.

Hunt, B. 1999: Unsteady stream depletion from ground water pumping. Ground Water 37(1): 98-102.

Hunt, B.; Weir, J.J.; Clausen, B. 2001: A stream depletion field experiment. Ground Water 39(2): 283-289.

JENKINS, C.T. 1968: Techniques for computing rate and volume of stream depletion by wells. Ground Water 6(2): 37-46.

JOHNSON, P.N. 1998: Wetland Plants in New Zealand. Manaaki Whenua Press, Lincoln. 320 p.

JORGENSEN, D.G.; SIGNOR, D.C.; IMES, J.L. 1989: Accounting for intercell flow in models with emphasis on water table recharge and stream-aquifer interaction 1. Problems and concepts. Water Resources Research 25(4): 669-676.

KOUTSOS, P.T. 1988: Artificial recharge of the Heretaunga Plains aquifer, Hawke's Bay, New Zealand. Artificial Recharge of Groundwater. Johnson, A.I. and Finlayson, D.J. (eds), American Society of Civil Engineers, 644 p.

LANEN, H.A.J. VAN; WEERD, B. VAN DE. 1993: Groundwater flow from a Cretaceous Chalk plateau: impact of groundwater recharge and abstraction. IAHS publication no. 221, 87-94.

MCDONALD, M.G.; HARBAUGH, A.W. 1984: A modular three-dimensional finite-difference groundwater flow model. United States Department of the Interior, United States Geological Survey, Reston, Virginia. Open-file report 93-875. 528 p.

MINISTRY OF WORKS AND DEVELOPMENT 1974: The unconfined aquifer area of the Heretaunga Plains groundwater system. Progress report, 11 p.

MOORE, C. 1992: West Melton aquifer recharge trial. Canterbury Regional Council report R92(38), 10 p + appendices.

NORTH CANTERBURY CATCHMENT BOARD 1983: Interim report on the groundwater resource of the Central Plains. A report prepared by the resource investigations division of the North Canterbury Catchment Board and Regional Water Board. 187 p.

NORTH CANTERBURY CATCHMENT BOARD 1986: The Christchurch Artesian Aquifers, Christchurch, 196 p.

PETCH, R.A. 1984: Studies of source area hydrology under indigenous forest and pastoral agriculture in the Hapuakohe Range, North Island, New Zealand. Ph.D. dissertation, University of Waikato, New Zealand. 454 p.

SANDERS, R. 1996: Effects of groundwater abstractions on surface water flows in the Lower Waimakariri River and its tributaries. Report R96(1), Canterbury Regional Council, 69 p.

SANDERS, R.; LOVELL, M. 1999: Observations of the Ohoka stream system in a drought. Report U99/32, Canterbury Regional Council, 114 p.

SCOTT, D.M.; THORPE, H.R. 1986: Groundwater resources between the Rakaia and Ashburton Rivers. Publication No. 6 of the Hydrology Centre, Ministry of Works and Development, Christchurch.

SCOTT, D.M.; CALLANDER, P. 1995: Effect of groundwater abstractions on surface water flows in the Opihi River catchment. Report U95/37, Canterbury Regional Council, 21 p.

SOPHOCLEOUS, M.; KOUSSIS, A.; MARTIN, J.L.; PERKINS, S.P. 1995: Evaluation of simplified stream-aquifer depletion models for water rights administration. Ground Water 33(4): 597-609.

SPALDING, C.P.; KHALEEL, R. 1991: An evaluation of analytical solutions to estimate drawdowns and stream depletion by wells. Water Resources Research 27(4): 597-609.

STEPHENSON, G. 1986: Wetlands. Discovering New Zealands shy places. Government Print, Wellington. 117 p.

TAYLOR, C.B.; WILSON, D.D.; BROWN, L.J.; STEWART, M.K.; BURDEN, R.J.; BRAILSFORD, G.W. 1989: Sources and flow of North Canterbury Plains groundwater, New Zealand. Journal of Hydrology 106: 311-340.

THEIS, C.V. 1941: The effect of a well on the flow of a nearby stream. American Geophysical Union Transactions 22(3): 734-738.

THORPE, H.R. 1992: Groundwater. In Waters of New Zealand. New Zealand Hydrological Society, 167-186.

UNITED STATES GEOLOGICAL SURVEY 1998: Groundwater and surface water: a single resource. United States Geological Survey Circular 1139. 79 p.

VANDT WOUDT, B.D.; WHITTAKER, J.; NICOLLE, K. 1979: Ground water replenished from river flow. Water Resources Bulletin. American Water Resources Association 15(4): 1016-1027.

VANDT WOUDT, B.D.; NICOLLE, K. 1978: Flow processes below a gravelly river bed. Journal of Hydrology (New Zealand) 17(2): 103-120.

WALLACE, R.B.; DARAMA, Y.; ANNABLE, M.D. 1990: Stream depletion by cyclic pumping of wells. Water Resources Research 26(6): 1263-1270.

WEIR, J.J. 1999: Stream depletion from groundwater pumping. ME thesis. Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand.

WHITE, P.A. 1985: Handbook on hydrogeological applications of earth resistivity measurements. Water and Soil Miscellaneous Publication No. 90, 41 p.

WHITE, P.A. 1988: Measurement of groundwater parameters using salt-water injection and surface resistivity. Groundwater 26: 179-186.

WHITE, P.A. 1994: Electrode arrays for measuring groundwater flow direction and velocity. Geophysics 59(2): 192-201.

WHITE, P.A. 1997: A post-audit study of the Waimea Plains aquifer model. Institute of Geological & Nuclear Sciences science report 97/17, 91 p.

WILLIAMS, P.W. 1992: Karst Hydrology. In Waters of New Zealand. New Zealand Hydrological Society, 187-206.

7

Age and Source of Groundwater from Isotope Tracers

MIKE STEWART AND UWE MORGENSTERN

INTRODUCTION

As methods for analysing isotopes and chlorofluorocarbons continue to develop, increasingly useful information is being gained on groundwater systems (Clarke and Fritz 1997; Kendall and McDonnell 1998; Cook and Herczeg 1999). Stable isotopes are used as fingerprints to reveal groundwater sources and sources of dissolved nitrate and other constituents. Radioactive isotopes and dissolved chlorofluorocarbons (CFCs) are used as clocks to determine the residence times of water underground.

Stable isotopes in the water molecule are conservative tracers and have been used mainly to determine the sources of groundwater. Meteoric processes, for example, modify the stable isotope composition of water so that recharge waters from a particular environment have a characteristic isotopic signature. This signature serves as a natural tracer for the provenance of the groundwater. Likewise, the distinctive isotopic compositions of nitrogen, carbon and sulphur from different sources help to identify sources and processes affecting dissolved species such as nitrate, bicarbonate and sulphate in groundwater.

The decay of radioactive isotopes (such as tritium and carbon-14) provides a measure of the underground residence time of groundwater, and thus its sustainability. Tritium has become the standard for definition of "modern groundwater". Modern groundwater contains tritium and therefore has been recharged in the past few decades. This means it is part of an active hydrological cycle and exploitation of the resource is potentially sustainable. Dating by CFCs is an exciting new development, which complements tritium dating in the ten to fifty-year age range (Plummer and Busenburg 1999).

Groundwater containing zero tritium is submodern or older; it is not being actively recharged or simply has long flow paths and low flow velocities. Carbon-14 dating is the method used most often for dating tritium-free groundwater. Dating in this age range is important to establish the long-term potential for aquifer recharge.

Stable isotopes, radioactive isotopes, and CFCs have been used in New Zealand in a number of studies. The purpose of this chapter is to give a short background of isotopic techniques used in New Zealand and to illustrate the recent studies that have been undertaken to address the following aspects of groundwater movement, recharge and contamination.

Sources of groundwater and constituents - determining recharge sources for Canterbury, Takaka and Waimea Plains groundwater, and sources of nitrate for Canterbury and Waimea Plains groundwater.

Groundwater residence times - studies from Canterbury, Lower Hutt Valley, Takaka and Waimea Plains show whether water is being actively recharged or being mined.

Better conceptual and digital flow models of systems - age and source data help to elucidate the nature of the groundwater flow system at Canterbury, Lower Hutt Valley, Takaka and Waimea Plains, and validate digital flow models in Canterbury.

History of contamination - combining better dating methods with groundwater contami-

Stewart M. and Morgenstern U. 2001: Age and Source of Groundwater from Isotope Tracers. *In* Groundwaters of New Zealand, M.R. Rosen and P.A. White *(eds)*. New Zealand Hydrological Society Inc., Wellington. p161-183.

nation studies gives exciting prospects of determining contaminant-input histories, as well as transport and degradation rates of contaminants. Canterbury and Waimea Plains examples are described.

Young water fraction - a groundwater drinking water supply is considered secure against bacteriological contamination if it is of sufficient age for bacteria and viruses to have decayed. Examples from Canterbury are given.

Isotopic research commenced in New Zealand in the late 1940s in the then Department of Scientific and Industrial Research. A team led by T. Athol Rafter and Gordon J. Ferguson established one of the first successful carbon-dating laboratories in the world (Rafter 1953; Ferguson 1953). State-of-the-art stable isotope and tritium measurement capabilities followed (Hulston and McCabe 1962; Taylor et al. 1963). These facilities have been maintained and developed in the Institute of Nuclear Sciences (created in 1959 with Athol Rafter as its first director) and since 1992 in the Institute of Geological and Nuclear Sciences. The University of Waikato set up an Isotope Unit in 1973 with radiocarbon and stable isotope measurement capabilities.

STABLE ISOTOPE TRACERS

Oxygen and hydrogen isotopes in water

Oxygen-18 (^{18}O) and deuterium ($^{2}H \equiv D$) are ideal tracers for water because they are constituent atoms of water molecules. ^{18}O and D concentrations in water are expressed as δ values with respect to a water standard in units of per mil (‰), where

$$\delta(‰) = (R_{sample} / R_{VSMOW} - 1) \times 1000 \qquad (1)$$

and R is the $^{18}O/^{16}O$ or D/H ratio of the sample or standard. The standard (VSMOW or Vienna Standard Mean Ocean Water) is held at the International Atomic Energy Agency in Vienna. Measurement errors are ±0.10‰ for $\delta^{18}O$ and ±1.0‰ for δD (one standard deviation).

Compared to all other water bodies, the ocean is relatively uniform in isotopic composition and therefore a good starting point for discussing the hydrological cycle of ^{18}O and D. Temperature-related separation or fractionation during evaporation or condensation cause variations in ^{18}O and D in environmental waters (Craig 1961; Dansgaard 1964). As water evaporates from the ocean surface, its heavy and light isotopes separate appreciably and oceanic vapour becomes strongly depleted in ^{18}O and D relative to the ocean. The balancing increase in the ^{18}O and D concentration of the ocean is negligible, owing to the immense water content of the ocean relative to the amount of water evaporated.

This isotopic separation (described by a separation factor α) is made up of two parts. The first is an equilibrium separation factor $\alpha_e = R_c/R_v$ at the ocean surface (where R_c refers to the condensed phase, in this case liquid water, and R_v to water vapour). The second is a kinetic separation factor α_k due to different rates of diffusion of the isotopic water molecules away from the ocean surface. These are related by

$$\alpha = \alpha_k . \alpha_e \qquad (2)$$

Marine vapours sampled at Baring Head, near Wellington (Fig. 7.1) illustrate the consequence of kinetic fractionation; these samples are all depleted in ^{18}O and D compared

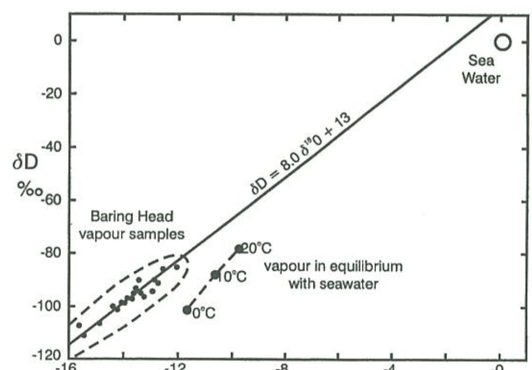

Figure 7.1: *Plot of δD versus $\delta^{18}O$ values for sea water, water vapour in isotopic equilibrium with sea water at the indicated temperatures, and actual atmospheric vapour sampled at Baring Head, near Wellington. The line is an average straight line through points (not shown) for many New Zealand precipitation samples.*

to equilibrium vapour. Fig. 7.1 is an example of the linear δ-diagram commonly used to show isotope relationships in hydrological studies, with $\delta^{18}O$ plotted as the x-axis and δD as the y-axis. Ocean water occupies a small region close to the origin, and most other waters occupy the negative quadrant as they have negative $\delta^{18}O$ and δD values.

The condensates from marine vapours, such as those shown in Fig. 7.1, plot nearer the origin of the δ-diagram, while the remaining vapour plots further away. The fractionation factors applying in atmospheric condensation processes are close to the equilibrium factors, so the relative changes of $\delta^{18}O$ and δD correspond to the ratio $(\alpha_e(D) - 1)/(\alpha_e(^{18}O) - 1)$, which is close to 8 for the range of temperatures in the atmosphere. As a consequence, condensates and depleted vapours plot near a straight line of slope of about 8 in the δ-diagram. However, the 'memory' of the extra kinetic fractionation during evaporation from the ocean surface is not lost, so that this line does not pass through the origin, but has a positive intercept (symbol d) on the δD axis, i.e.

$$\delta D = 8\delta^{18}O + d \qquad (3)$$

From global measurements Craig (1961) determined d to be +10‰ on average. We have found that d is about +13‰ for New Zealand (Stewart and Taylor 1981).

As rainfall is extracted from atmospheric vapour by condensation due to reduction in temperature, the ^{18}O and D concentrations of the remaining vapour become more and more depleted. This is the basis of the general rule that the δ values of precipitation are more negative at lower temperature. Consequently, δ values of precipitation vary with season, with more negative δ values in winter, and with altitude and latitude, with more negative δ values at higher altitudes and latitudes. Climate change also causes variations, with more negative δ values during colder periods.

Fig. 7.2 shows contours of the average annual δD values of precipitation throughout New

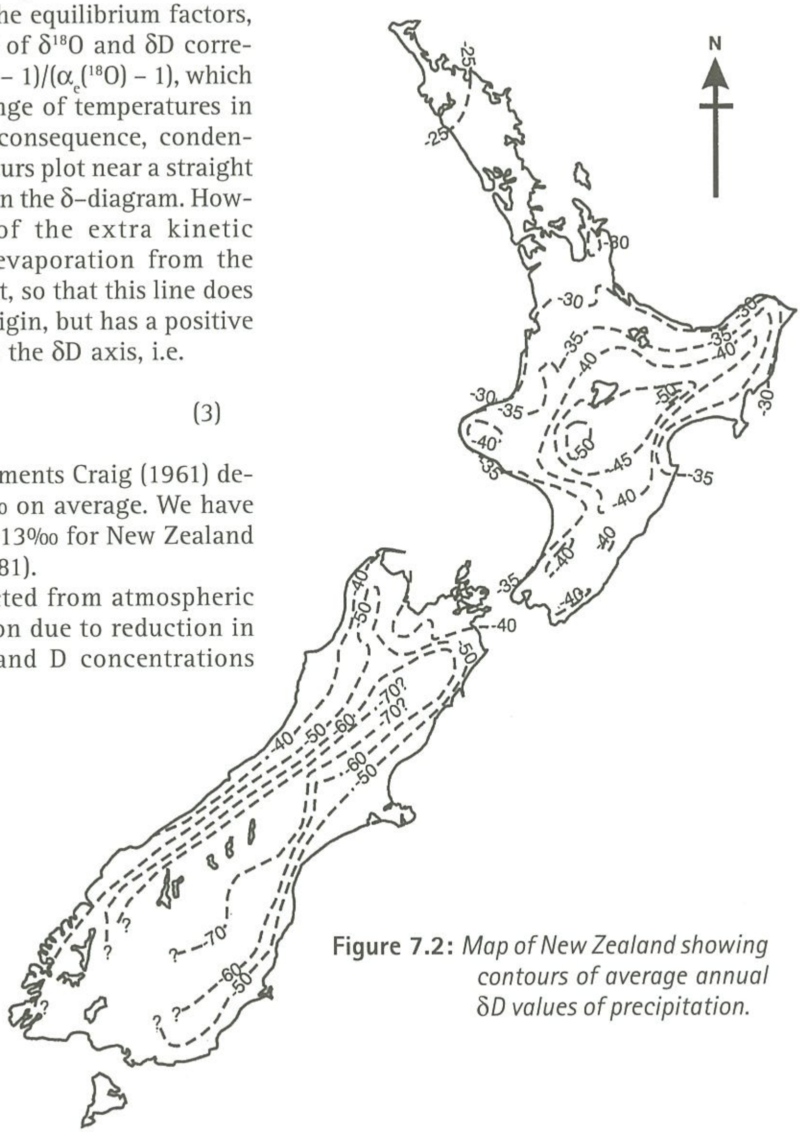

Figure 7.2: *Map of New Zealand showing contours of average annual δD values of precipitation.*

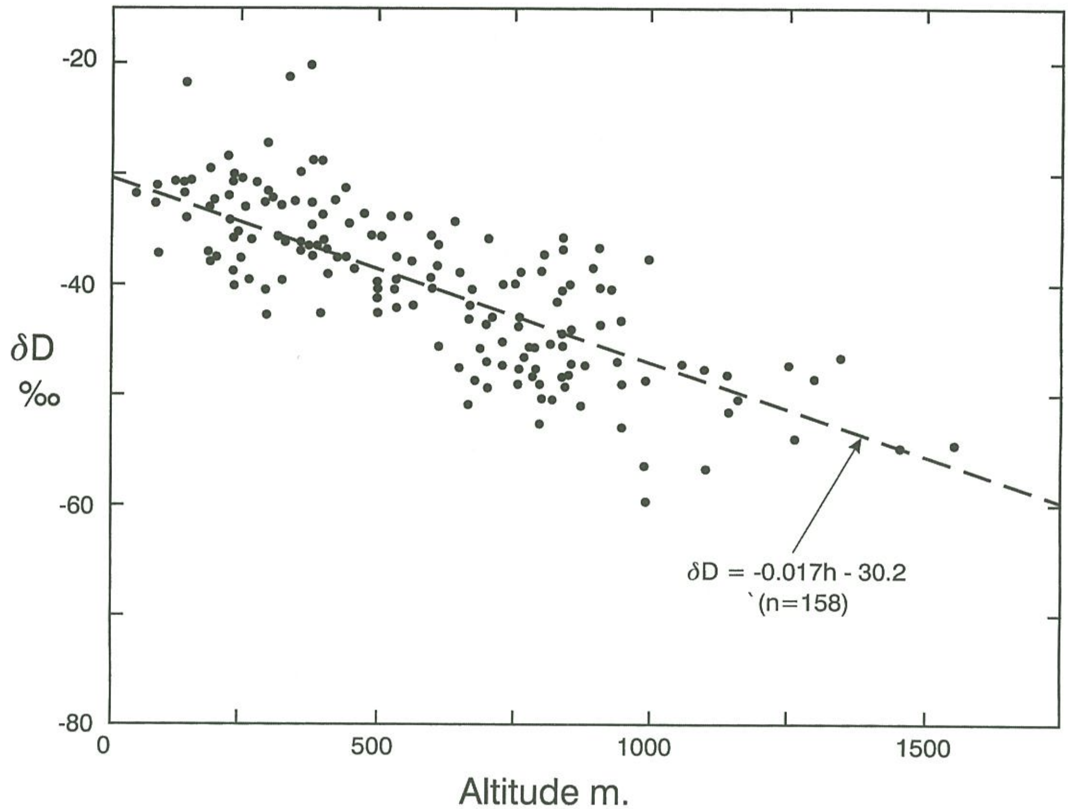

Figure 7.3: *δD values of river samples plotted against estimated mean altitudes of their catchments in the North Island and westerly zones of the South Island of New Zealand.*

Zealand (Stewart et al. 1983). Average annual δD values smooth out the seasonal variations. The highest (least negative) δD values are found at low elevations north of Auckland and the lowest (most negative) δD values at the highest elevations in the South Island, reflecting the effects of altitude and latitude.

Good correlations are found between δD and altitude, and δD and latitude for river samples (Figs. 7.3 and 7.4), as proxies for annual precipitation samples for westerly climatic zones (i.e. all of the North Island and all areas except Canterbury and Otago in the South Island). The equations of lines fitted to the data are:

$$\delta D = -0.017h - 30.2 \text{ and } \delta D = -1.76L + 41.6, \quad (4)$$

where h is the altitude in metres, and L is the latitude South in degrees. On average, δD decreases by 1.7‰ for each 100-m increase in altitude, and by 1.8‰ for each degree increase in latitude. The data used for the latitude correlation had first been adjusted to sea level using the altitude correlation.

Correlations for $\delta^{18}O$ in westerly zones are:

$$\delta^{18}O = -0.0021h - 5.40 \text{ and } \delta^{18}O = -0.22L + 3.58, \quad (5)$$

showing that $\delta^{18}O$ decreases by 0.21‰ for each 100-m increase in altitude, and by 0.22‰ for each degree increase in latitude. The relatively uniform behaviour of $\delta^{18}O$ and δD in westerly zones is due to the prevailing westerly circulation over the Tasman Sea. The d value of +13‰ results from the influence of dry air from Australia, which picks up moisture rapidly (and moisture with a higher α_k) as it passes over the Tasman Sea before reaching New Zealand.

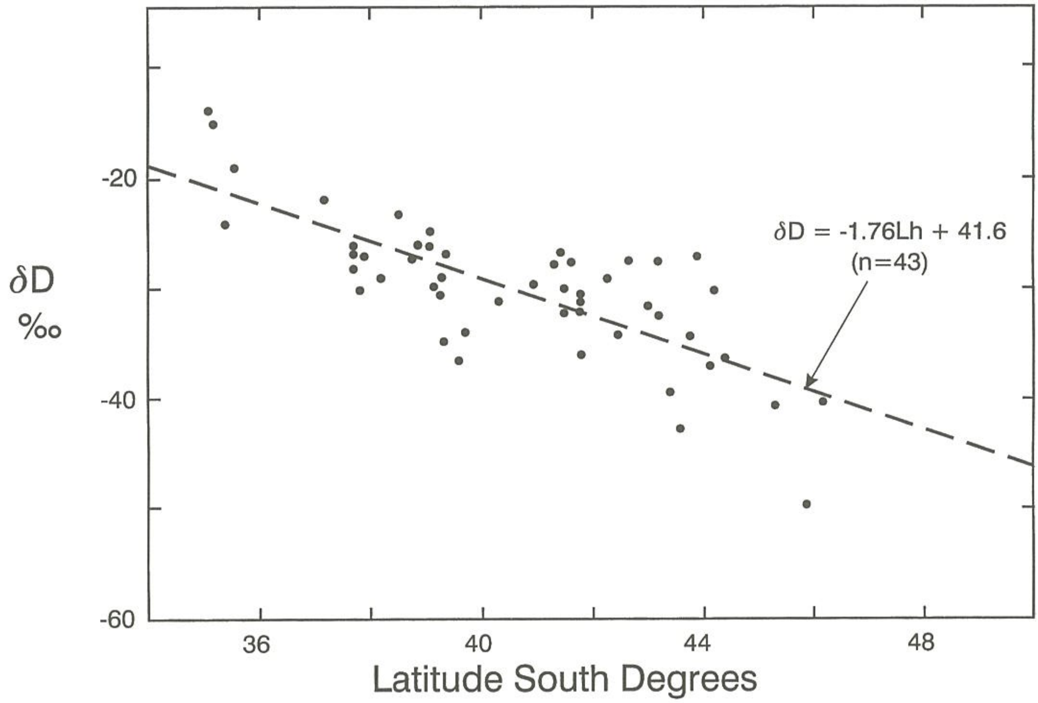

Figure 7.4: *δD values of river samples plotted against mean latitudes of catchments in westerly zones of New Zealand at sea level.*

Easterly climatic zones (Canterbury and Otago) do not fit the relationships derived for westerly rainfall (Stewart et al. 1983). The δ values are more negative for a given altitude or latitude than they are for westerly rainfall: this is because easterly rainfall is from southeasterly sources or from westerly air masses that have been 'wrung out' on passing over the main divide in the South Island. The relationship between the δ values is also different, with

$$\delta D = 8\ \delta^{18}O + 10 \qquad (6)$$

applying more closely for Canterbury and Otago precipitation.

The δ values of groundwater can be useful indicators of the source of recharge to a groundwater system. Two main sources of recharge are seepage from rivers or infiltration of rainfall. The average δ value of a river can be significantly different from the average δ value of low altitude rainfall, if the rivers derive their water from high altitude catchments (e.g. rivers on the Canterbury Plains). This enables the groundwater recharge source to be identified from $\delta^{18}O$ or δD.

Variations in $\delta^{18}O$ and δD in rainfall are used to study transport times of water through a catchment into a stream or through a soil to an underlying aquifer. Studies at Maimai Catchment on the West Coast (Stewart and McDonnell 1991; McDonnell et al. 1999) showed that during storms headwater streams predominantly discharged the water resident in the catchment rather than the current rainfall, even though their response to the rainfall was very rapid. The mean residence time of water in the catchment was three months. Another study in the Pukekohe region near Auckland (Rosen et al. 1999) showed that soil water residence times were at least six months.

Carbon, nitrogen and sulphur isotopes

Carbon has two stable isotopes (^{12}C and ^{13}C) and one radioactive isotope (^{14}C, see below). Carbon-13 is an excellent tracer of carbonate evolution in groundwaters, because there are large variations in the various carbon reservoirs (Clarke and Fritz 1997). Carbon isotope ratios are given as per mil (‰) relative to a marine carbonate standard (VPDB); marine carbonates have only limited variations in carbon isotope ratios.

$$\delta^{13}C\ (‰) = [(^{13}C/^{12}C)_{Sample}/\ (^{13}C/^{12}C)_{VPDB} - 1] \times 1000 \quad (7)$$

Carbon and oxygen isotopes in carbonate minerals have been used very successfully to reveal past temperatures, because long sequences of carbonates are preserved in chronological order in sediments and chemical deposits. Temperature-related variations, most commonly in the oxygen isotope ratios, are used to extract temperature records covering the period when the deposit was being laid down. The oxygen-isotope record from foraminifera in ocean cores has revealed in unparalleled detail the multiple succession of glacials and interglacials that have occurred in the Pleistocene (see, for example, Emiliani 1966). Hendy and Wilson (1968) pioneered the application of the method to stalactites from several New Zealand cave systems. They derived a detailed temperature record that revealed differences between Northern and Southern Hemisphere temperature histories.

Nitrogen has two stable isotopes (^{14}N and ^{15}N) that have been used to evaluate the sources and processes affecting nitrates in groundwater. This knowledge assists the development of effective management practices to preserve water quality and remediation plans for sites that are already polluted.

The average abundance of ^{15}N in air is constant, with $^{15}N/^{14}N = 1/272$. Nitrogen isotope ratios are reported in per mil (‰) relative to N_2 in atmospheric air, where

$$\delta^{15}N\ (‰) = [(^{15}N/^{14}N)_{Sample}/\ (^{15}N/^{14}N)_{AIR} - 1] \times 1000 \quad (8)$$

and AIR is the internationally accepted gas standard. Oxygen isotopes can also be measured in nitrate, and can sometimes provide more definite information on sources and cycling of nitrate in combination with nitrogen isotopes (Kendall and Aravena, 1999). New Zealand examples of the use of nitrogen isotopes to determine the source of nitrate in groundwater are described below for Canterbury and Waimea Plains.

Sulphur isotopes have been used particularly to determine the origin and fate of sulphate in groundwater, which is a subject of great interest in relation to the effect of "acid rain" on the environment (Krouse and Mayer 1999). Sulphur has four stable isotopes (^{32}S, ^{33}S, ^{34}S and ^{36}S), of which the two most abundant (^{32}S, ^{34}S) are chosen for measurement on the delta scale, defined as

$$\delta^{34}S\ (‰) = [(^{34}S/^{32}S)_{Sample}/\ (^{34}S/^{32}S)_{VCDT} - 1] \times 1000 \quad (9)$$

The standard is VCDT (Vienna Canon Diablo Troilite).

Robinson and Bottrell (1997) used sulphur isotopes to identify sources of sulphate in a number of New Zealand river catchments. Pristine rivers in the South Island (Buller, Wairau) and North Island (Hutt) contained two end-member mixtures of marine sulphate from rainwater and sulphate from oxidation of bedrock sulphides. Some Wairarapa rivers showed input of fertiliser sulphate (from "superphosphate"); in particular, results for the Ruamahanga River showed that the river removes 20% of the sulphate applied as fertiliser to the catchment. The Whangaehu River was shown to contain mainly volcanic sulphate from the Crater Lake of Ruapehu. Geothermal and rainwater sulphates were the main sources to Lakes Taupo and Rotorua via their tributary streams; Lake Rotorua outlets had a higher geothermal sulphate content than the inlets, showing an underwater geothermal input to the lake.

DATING MODERN GROUNDWATER

Good understanding of recharge, flow and storage volume is necessary for sustainable management of groundwater resources. One of the most important pieces of information for understanding groundwater resources is the age, or residence time, of the water underground. The age can give information on groundwater flow rates and paths, the sustainable yield of the resource, and buffering against drought. Furthermore, the age information al-

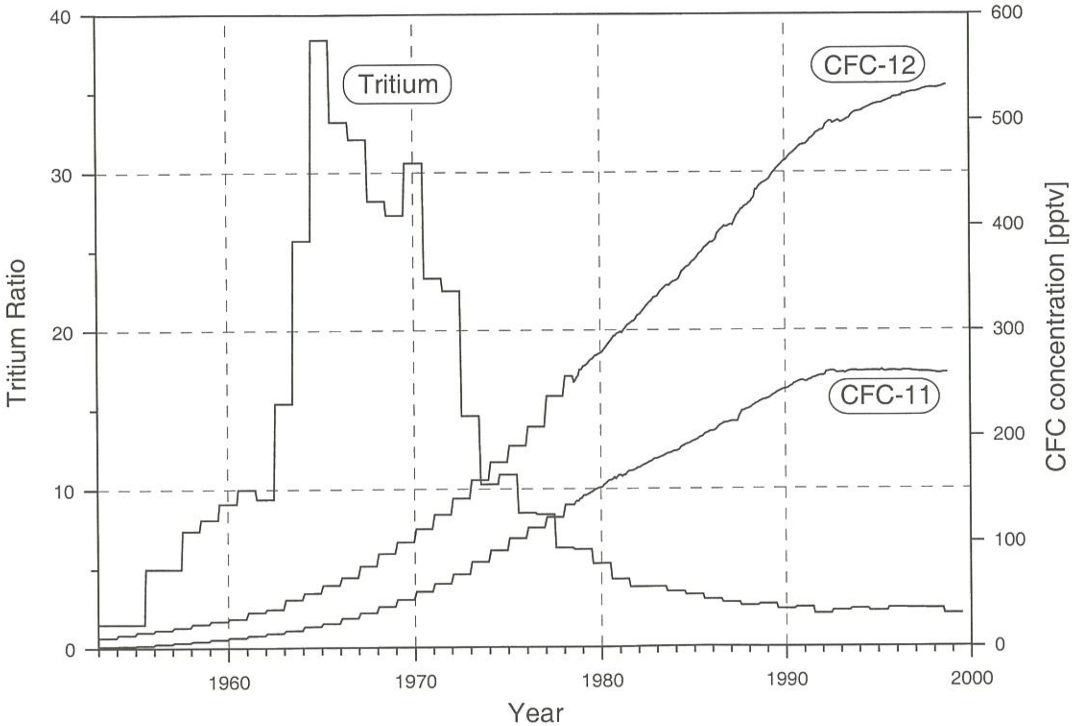

Figure 7.5: *History of tritium concentration in precipitation at Kaitoke, near Wellington, and CFC-11 and CFC-12 concentrations in the atmosphere in the Southern Hemisphere.*

lows assessment of the vulnerability of a groundwater resource to contamination; the fraction of young water gives a quantitative measure of the security of a groundwater resource against bacteriological contamination or against disasters (e.g. floods or volcanic ash). To obtain age information from groundwater, various isotopic and chemical tracers can be applied, depending on the age range and hydrogeologic conditions.

Tritium

The radioisotope tritium (half-life 12.3 years) is the standard dating tool for groundwater in the age range of recent to 100 years. It is the ideal tracer for groundwater because it is a component of the water molecule, and the age information is not distorted by any processes occurring underground, i.e. tritium is not affected by chemical or microbial processes, or by reactions between the groundwater, soil sediment and aquifer material. Tritium is naturally produced in the atmosphere by cosmic rays, but large amounts were also released into the atmosphere in the early 1960s during nuclear bomb tests, giving rain and surface water a high tritium concentration (Fig. 7.5). Surface water becomes separated from the atmospheric tritium source when it infiltrates into the ground, and the tritium concentration in the groundwater then decreases over time due to radioactive decay. The tritium concentration in the groundwater is therefore a function of the time (t) the water has been underground, i.e.

$$C_t = C_o \cdot e^{-\lambda t} \text{ or } t = (1/\lambda) \cdot \ln (C_o / C_t) \qquad (10)$$

where C_o is the initial tritium ratio (in the rain water), C_t the tritium ratio in the groundwater after time t, and λ (= ln2 / $T_{1/2}$) the tritium decay constant.

Most applications of the tritium method involved tracing the tritium from nuclear weapons tests through the hydrological cycle. However, since the mid-1980s, atmospheric tritium has declined to the natural cosmogenic level in most parts of the world. This allows tritium to be used now for groundwaters more straightforwardly as a "natural clock", using the decay equation (10), in combination with realistic age distribution models. Additional age information can be gained for very young groundwaters from the seasonal tritium variation, as peaks occur in spring due to an enhanced movement of tritium from the stratosphere to the troposphere.

As a result of the nuclear test peak in atmospheric tritium in the 60s, ages from single tritium determinations can be ambiguous (i.e. the tritium concentration can indicate any of three possible groundwater ages). This ambiguity can be overcome by making a second tritium determination after about 2 years, or by combining the single tritium determination with a second independent dating technique such as chlorofluorocarbons. The bomb tritium peak gives, on the other hand, waters with ages of 20-40 years a very distinct tritium signature that can be used to obtain very precise age information.

Very clear understanding of groundwater flow processes can be gained when historic tritium data (high tritium concentrations in the 60s and 70s) can be combined with recent data (natural levels). Such historic data are available from most of the main aquifers in New Zealand.

Further information about the tritium method is available in Clark and Fritz (1997) or Cook and Herczeg (1999). The tritium method has been applied to New Zealand groundwaters in several studies. In the first study, tritium data prior to the bomb-peak was used to indicate groundwater flow directions and residence times in the Heretaunga Plains aquifer (Grant-Taylor and Taylor 1967). This study also determined the residence time of groundwater in the main supply well in the Hutt Valley aquifer by tracing the tritium from individual bomb-test series. In Taylor and Stewart (1987), tritium data were used in a mixing model to derive mean residence times in the Rotorua geothermal aquifer. Following the bomb-peak period, tritium data were mainly used to distinguish between water recharged before and after1960, and attempts began to calculate groundwater ages for piston flow conditions (Taylor et al. 1989, 1992; Taylor 1994a). Tritium was also used to identify any fraction of recently derived water in old groundwater for carbon isotope studies (Taylor and Fox, 1996; Taylor and Evans 1999).

Sensitive and accurate methods for detecting tritium are needed to use low-level natural tritium as a tracer of the hydrologic cycle. Because of particularly low tritium concentrations in the Southern Hemisphere, a tritium measurement system with extremely high detection sensitivity is required. In New Zealand, the tritium measurement system has a lower detection limit of 0.03-0.04 TU (2-sigma criterion), using ultra low-level liquid scintillation spectrometry, and electrolytic enrichment prior to detection. Reproducibility of standard enrichment is 2%, and an accuracy of 1% can be achieved via deuterium-calibrated enrichment (Taylor 1994b). Tritium concentrations are expressed as tritium units (TU) or as a tritium ratio (TR). One TU (TR = 1) corresponds to one tritium atom per 10^{18} hydrogen atoms. The radioactivity equivalent for one TU in one kg of water is 0.118 Bq. The sampling procedure for tritium involves filling a one-litre bottle (avoiding air contact as much as possible because there is tritium in the air) and securely tightening the cap. No cooling of the sample during collection or transport is necessary.

Tritium – Helium-3 (^3H – ^3He)

Tritium-helium dating is a variant of tritium dating that allows unambiguous ages to be determined from tritium concentrations by using its daughter (helium-3) to eliminate the complicated tritium input function (Torgersen et al. 1979). The method gives good results and generally shows agreement with CFC dates (Ekwurzel et al. 1994), but is expensive and has not been used in New Zealand.

Chlorofluorocarbons and SF_6

Chlorofluorocarbons (CFCs) are entirely man-made contaminants of the atmosphere and hydrological systems. CFCs are used industrially for refrigeration, air conditioning and pressurising aerosol cans. Their concentrations in the atmosphere have gradually increased from zero in 1940 to the present levels of several hundred pptv (1 pptv is one part per trillion by volume or 10^{-12}). CFC-11 and 12 concentrations in the Southern Hemisphere are shown in Figure 7.5. Because the gases (CFC-11, CFC-12 and CFC-113) are relatively long-lived, they are widely distributed in the atmosphere. CFCs are slightly soluble in water and enter groundwater systems during recharge. Their concentrations in groundwater record the atmospheric concentrations when the water was recharged, thus allowing the recharge date of the water to be determined.

CFCs have three main advantages as dating tools. Firstly, CFC dating gives unambiguous ages because atmospheric concentrations of CFCs have risen monotonically from zero, in contrast to concentrations of tritium. Secondly, three dates are obtained (because there are three CFC species) and these can be compared, giving additional information. Thirdly, CFC concentrations can be measured accurately and relatively easily by modern gas chromatography. The main disadvantage is the relatively difficult sampling techniques required, because air must be rigorously excluded from the sample.

CFCs are now being phased out of industrial use because of their destructive effects on the ozone layer. Thus rates of increase of atmospheric CFC concentrations slowed greatly in the 1990s. This means that CFCs are not as effective for dating water recharged after about 1990.

A number of factors can modify apparent CFC ages (called "model" ages below); the following factors have the greatest effect on water recharged later than 1990 (see Plummer and Busenburg (1999) for more information).

Recharge temperature - The solubilities of CFCs in water are affected by temperature, hence errors in the estimated recharge temperature for a site affect the model age: too low a recharge temperature gives model ages that are too old and vice versa. An error of ±2°C results in an error of ±1 year for water recharged before 1970 and ±1-3 years for water recharged between 1970 and 1990. (Plummer and Busenburg 1999).

Thickness of the unsaturated zone - CFCs can be transported more rapidly than water through the unsaturated zone because CFCs mainly inhabit vapour-dominated pores. Transport times for CFCs are expected to be less than two years for unsaturated zones with thicknesses of up to 10 m, and 8-12 years for thicknesses of 30 m (Plummer and Busenburg 1999).

Local CFC sources - CFC contamination from local anthropogenic sources can occasionally occur in urban areas, and more rarely in rural environments. Local contamination causes "excess CFC" in the water, i.e. the CFC concentrations are higher than could normally be gained by solution from the atmosphere, so no age can be calculated. However, the ages may appear to be too young when very slight contamination occurs. CFC-12 is more susceptible to local contamination than CFC-11.

Loss of CFCs - Microbial degradation of CFCs in anaerobic environments or sorption onto organic matter causes removal of CFCs, giving model ages that are too old. Neither process is expected in aerobic conditions, since organic matter tends to remove oxygen. The dissolved oxygen concentration in the water can be used to assess the likelihood of these effects. CFC-11 has been found to be more susceptible to such losses than CFC-12.

Despite these potential problems, CFC measurements have given good results in New Zealand. Figure 7.6 shows CFC-derived recharge years for groundwater in Canterbury (Stewart et al. 1997, 1999). The CFC-11 ages are compared with the CFC-12 ages for data collected in 1997-2000. The dates when recharge occurred ranged from 1940 to 1999, with a small number of samples containing excess CFCs from local sources. An approximately linear trend between the results is observed, but the CFC-11 ages tend to be older than the CFC-12 ages.

The CFC results are compared with tritium

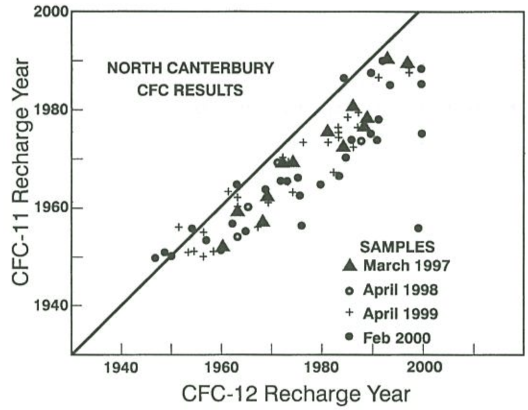

Figure 7.6: *Plot of CFC-11 recharge year versus CFC-12 recharge year for Canterbury groundwater.*

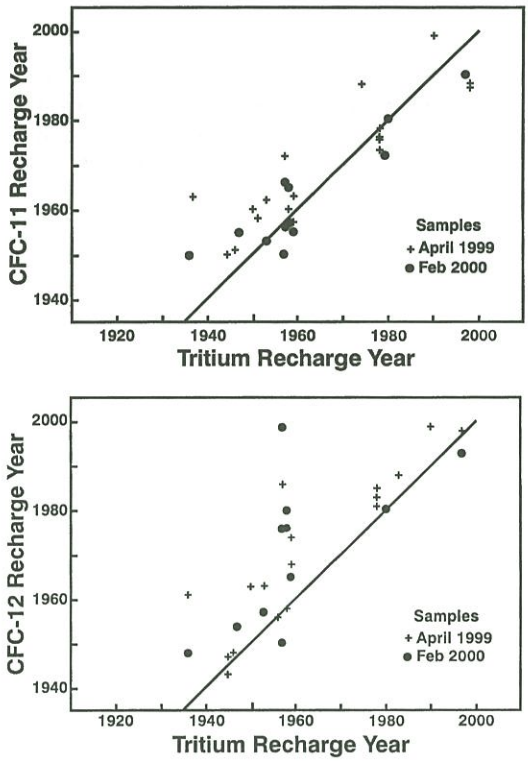

Figure 7.7: *Plot of CFC-11 and CFC-12 recharge years versus tritium recharge years for Canterbury groundwater.*

results in Figure 7.7. Ages were calculated for the tritium results assuming a mixing model with 80% piston flow and 20% exponential flow (see below for an explanation of these terms); ambiguous tritium ages were resolved by considering the hydrogeological conditions or by comparison with the CFC ages. CFC-11 and tritium ages show reasonable agreement, with points scattered about the concordant line, while the CFC-12 ages are generally younger than the tritium ages. This is probably due to a very slight contamination of the CFC-12 concentrations by local sources (at less than the "excess" levels).

Methods for dating groundwater using SF_6 are now being developed. SF_6 concentrations in the atmosphere have increased from zero in 1970 to the present. Concentrations are likely to continue to increase for some time because SF_6 is widely used in electrical switch gear. This should mean that SF_6 is especially useful for dating very young groundwater.

DATING OF OLD GROUNDWATER

Radiocarbon

Radiocarbon is the major tool for dating old groundwater (i.e. groundwater that has no tritium). ^{14}C (half-life 5730 years) is generated by cosmic rays in the atmosphere and introduced into living biomass by photosynthesis, and into the hydrosphere by CO_2 exchange reactions. Consequently, any carbon compound derived from atmospheric CO_2 since the late Pleistocene can potentially be dated by radiocarbon. Radiocarbon dating has provided the chronology used by archaeologists to decipher the history of humanity in the Holocene. It has also been used to provide the chronology of climate change in the late Pleistocene and Holocene.

^{14}C concentration or activity (a) is expressed as percent modern carbon (pmC), where the activity of "modern carbon" is taken as 95% of the activity in 1950 of the NBS oxalic acid standard. Groundwater dating by ^{14}C is complicated both by changes in ^{14}C activity in the atmosphere during the late Pleistocene and Holocene, and by dilution of ^{14}C in groundwater by dead (i.e. ^{14}C-free) carbon derived from soils and rocks where carbon-bearing solutions penetrate underground.

Most of the ^{14}C in groundwater is gained from the soil, where CO_2 accumulates by root respiration and decay of vegetation. The ^{14}C in dissolved inorganic carbon (DIC) is susceptible to reaction and dilution with dead carbon from carbonate and other minerals in the soil and groundwater zones. A dilution factor q is used to take account of the resulting dilution of ^{14}C. The age equation is therefore written (in analogy with equation 10)

$$t = (1/\lambda) \cdot \ln (q \cdot a_o / a_t) \qquad (11)$$

where a_o is the initial ^{14}C activity ($q.a_o$ the diluted initial activity in the groundwater), a_t is the ^{14}C activity in groundwater after time t (i.e. when measured) and λ is the carbon-14 decay constant ($1/\lambda = T_{½} / \ln2 = 8267$ years). The apparent simplicity of this equation is deceptive. Numerous methods have been proposed for estimating q, based on the chemical and ^{13}C composition of the groundwater. A widely accepted modern method involves modelling the geochemical and isotopic evolution of groundwater between initial and final points along a flow path using the *NETPATH* geochemical code (Plummer et al. 1994). This is best suited for regional confined systems where changes between sampling points can be observed.

New Zealand groundwater systems are often recharged by rivers, which impart a different initial ^{14}C signature and dilution factor to the groundwater. This is illustrated by ground-water in deep aquifers under Christchurch, which are recharged by the Waimakariri River (Taylor and Fox 1996). Because the water is recharged from the riverbed, thus largely bypassing the soil, it has low DIC (and other chemical) concentrations. Ages of up to several thousand years were determined for the deep groundwater beneath Christchurch.

Taylor (1997) developed a method for estimating a_o and q, based on the ^{13}C and DIC concentrations in the groundwater. This is applied in a study of deep groundwaters in Taranaki (Taylor and Evans 1999). The study identified Mt Taranaki as the major recharge area both today and for several tens of thousands of years in the past. Residence times of groundwater in the confined Tertiary sandstone/mudstone/shellbed aquifers ranged up to several tens of thousands of years.

APPLICATIONS TO NEW ZEALAND GROUNDWATER SYSTEMS

Isotopic studies of New Zealand hydrological systems have been carried out since the early 1960s, using most of the isotopic methods outlined above. In the following we have selected some New Zealand groundwater systems to illustrate the variety of problems that can be addressed using isotopic methods.

Canterbury Plains

Glacial outwash deposits of the major rivers have built up the Canterbury Plains from the Southern Alps, and fluvial episodes then redistributed the sediments. The plains extend over a 50 km wide by 150 km long area from Timaru to the Waipara River. Quaternary gravel aquifers are widespread and their thicknesses range from 250 m up to 600 m. Groundwater aquifers are unconfined or semi-confined under much of the inner plains, becoming confined near the coast, around Kaiapoi, Christchurch and Lake Ellesmere. Isotope methods are contributing greatly to understanding the recharge sources, residence times, nature of flow, and chemical history of the groundwater system.

Alpine rivers crossing the plains have high-altitude catchments and therefore low $\delta^{18}O$ values (c.f. equation 5) compared to the higher $\delta^{18}O$ values of precipitation on the plains (Taylor et al. 1989). $\delta^{18}O$ therefore serves as a fingerprint to distinguish river from rainfall-recharged groundwater via the equation:

$$f = (\delta_g - \delta_r)/(\delta_p - \delta_r), \qquad (12)$$

where f is the fraction of groundwater derived from precipitation, and δ_g, δ_r and δ_p are the $\delta^{18}O$ values of the groundwater, rivers and precipitation respectively. Note that δ_r and δ_p are the δ values of groundwater derived from the rivers and precipitation, rather than those of the rivers and precipitation themselves. Average $\delta^{18}O$ values of the alpine rivers (in brack-

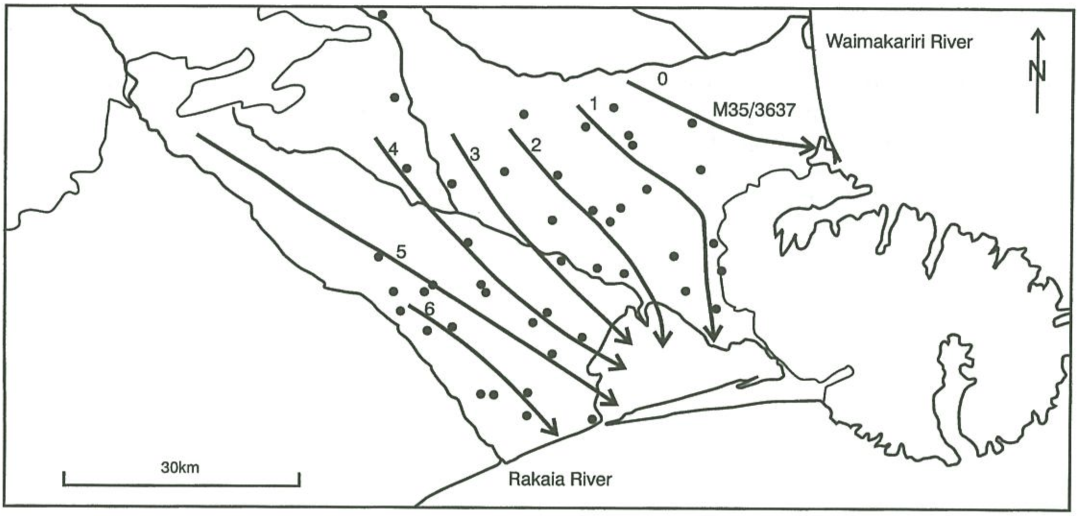

Figure 7.8: *Flowlines in shallow groundwater and sampling locations of CFC concentrations between the Waimakariri and Rakaia Rivers, Canterbury.*

ets) are, from north to south, Ashley (–9.4‰), Waimakariri (–9.4‰), Rakaia (–9.5‰) and Ashburton (–9.6‰) (Taylor et al. 1989). Their compositions are not expected to change much as they infiltrate the ground. Rainfall $\delta^{18}O$ values, however, are affected by soil processes because of higher evapotranspiration in summer than in winter, so δ values measured in water draining through the soil have been used for δ_p rather than the precipitation itself. These are about –7.7‰ near the coast (measured at Harewood Airport and Lincoln) and –9.0‰ inland (Hororata and in foothills rivers such as the Eyre and Selwyn) (Stewart 2001, unpublished data).

Fractions determined from equation 12 show that recharge from the alpine rivers dominates in fluvial gravel aquifers towards the coast, whereas recharge from rainfall and foothill rivers is predominant in the inter-fan areas. In particular, the deeper Christchurch aquifers are recharged by infiltration from the Waimakariri River in its Central Plains reaches, and are consequently protected from pollution as long as the river retains its present pristine condition (Taylor et al. 1989). On the other hand, shallow groundwater (including the unconfined and first confined aquifers under Christchurch) and water recharged to depth by precipitation and irrigation on the unconfined western areas of the Plains are susceptible to agricultural and other pollutants.

Residence times determined from tritium, carbon-14 and CFC concentrations reveal the flows in the groundwater systems (Taylor et al. 1989; Taylor and Fox 1996; Stewart et al. 1997, 1999). Horizontal flows in the near-surface layers are rapid, with very young waters emerging in springs on the west side of Christchurch and Kaiapoi. Vertical flows are more gradual, as they are driven by recharge rates. Taylor et al. (1989) showed that ground-water from deep aquifers under Christchurch had zero tritium. The isotopic and other evidence showed that old artesian groundwater underlying Christchurch ascends from deeper aquifers into the shallowest confined aquifer via gaps in the confining layers or by diffuse flow. Carbon-14 measurements have shown that the residence time of the deepest water under Christchurch is of the order of thousands of years (Taylor and Fox 1996).

Well M35/3637 is a deep well (140 m) located on the western edge of Christchurch, where the groundwater system becomes confined (flowline 0 in Fig. 7.8). It is ideally situated to help reveal the nature of water moving

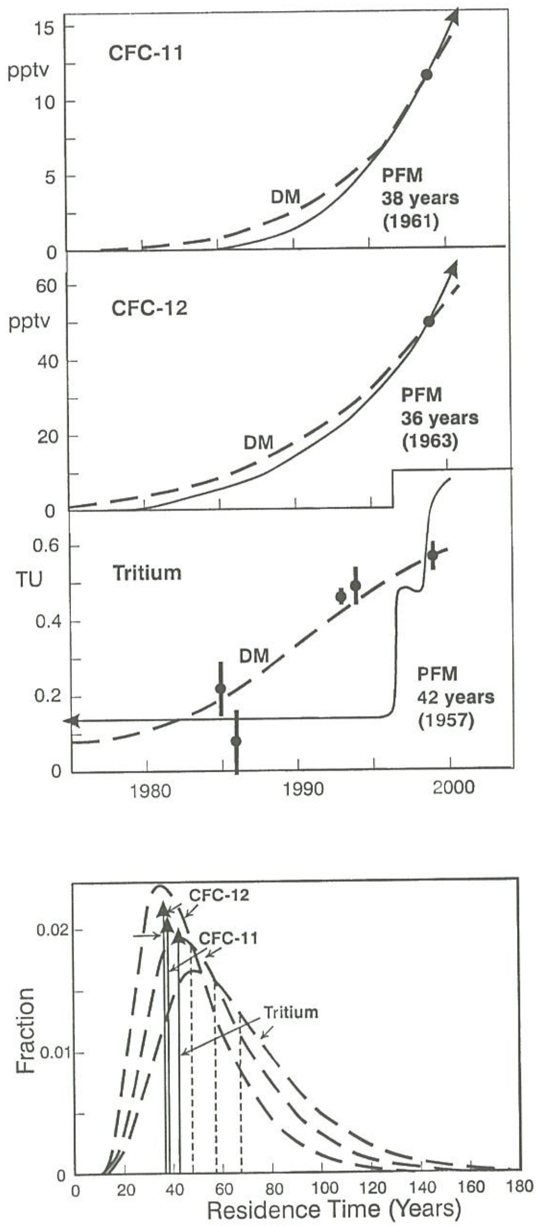

Figure 7.9: *Upper figure: Tritium, CFC-11 and CFC-12 concentrations versus time for well M35/3637. The dots are measured data, curves simulated data. PFM - piston flow model, DM - dispersion model. Lower figure: Residence time distributions for piston flow and dispersion models for well M35/3637.*

towards the important deep confined aquifers under Christchurch and how that water will change in the future. The $\delta^{18}O$ value of –9.33‰ shows that the water is derived from the Waimakariri River. It has very low concentrations of nitrate (0.21 mg/L NO_3-N) and other chemicals.

Five tritium measurements are available for this well between 1985 and 1999, so the age distribution of the water can be defined quite well. These are supplemented by CFC measurements in 1999. The measurements are plotted in Figure 7.9 (upper figure), along with simulations using the dispersion and piston flow models. The dispersion model (with τ = 68 years, D_p = 0.1) gives a reasonable match to all of the tritium points, whereas the piston flow model does not ($\tau \sim$ 42 yr). Figure 7.9 (lower) shows the distribution of residence times (i.e. age spectra) of the models. The peak residence times of the dispersion models are about 40 years (in agreement with the piston flow models), but a considerable proportion of older water is also present, probably derived from a greater depth in the system. The results show that good quality but relatively young water (40 years old) is penetrating into the system en route to the deep aquifers under Christchurch. This will preserve the good quality of deep Christchurch water in the future.

CFC measurements have been made on groundwater in the areas between the Waimakariri and Rakaia Rivers (Fig. 7.8), Waimakariri and Ashley Rivers, and Rakaia and Ashburton Rivers (Stewart et al. 1997, 1999). Figure 7.8 shows the locations of wells sampled for CFCs, chemical compositions and other isotopes between the Waimakariri and Rakaia Rivers in 1999. The figure shows flow directions for the shallow aquifers. The CFC age data have been used to define constant age surfaces, showing that young water penetrates more deeply i.e. recharge is greater near the alpine rivers.

The source and age information from $\delta^{18}O$ values and CFCs have been used to validate a large-scale model of Canterbury groundwater flow (White et al. 1999). CFC measurements on eight pairs of wells allowed the travel times of the groundwater between the wells to be determined. These were compared with flow-model predictions of the travel times. The CFC travel times ranged between 2 and 26 years, with a mean of 10.4 years, in good agreement with the flow-model predicted travel times of 4 to 25.5 years, with a mean of 9.9 years.

The history of chemical contamination of the groundwater is stored within the system and can be accessed by making age and chemical measurements on well waters. An increase in nitrate concentrations is apparent in the early 1950s, as shown by measurements on groundwaters of this age and younger; older groundwaters have low nitrate concentrations. The cause is likely to have been the intensification of farming in the post-war period. This early 1950s nitrate front is passing through the groundwater systems in accordance with their natural flow rates. While it is still observable in the Waimakariri–Rakaia and Waimakariri–Ashley groundwater regions, the front has already essentially passed through the more-rapidly flowing Rakaia–Ashburton groundwater region. Other fronts passing through the systems are those from the "nuclear weapons test" tritium peak in the mid-1960s and the CFC fronts of more recent years. $\delta^{15}N$ values indicate that the increase in nitrate concentrations in the 1950s was due to an increased use of inorganic fertilisers or to clover fixation. It is probable that increased dairy farming in recent years is introducing nitrate with $\delta^{15}N$ reflecting a larger proportion of manure sources.

Lower Hutt Valley

The Lower Hutt groundwater zone is an unconfined/confined aquifer system. The sediments infilling the Lower Hutt Basin include a thick sequence of alluvial gravels deposited by the Hutt River during successive Quaternary glaciations. Layers of fine sediments, which form confining layers for the artesian aquifers, break the succession of alluvial gravels. The major source of recharge to the Lower Hutt groundwater zone is flow loss from the Hutt River. Due to the large number of chemical and microbial analyses undertaken on municipal water supplies, groundwater quality is well defined and generally very good in terms of the drinking water standards (Ministry of Health 2000).

The artesian aquifers of the Lower Hutt basin provide about 35% of the greater Wellington region's water supply. They are recharged by the Hutt River, whose catchments extend 40 km north of Wellington, including the Kaitoke Regional Park at the southern end of the Tararua mountain range. This hydrological system has played an important role in the history of environmental isotope hydrology in the Southern Hemisphere. Environmental isotope data encompassing the period following atmospheric H-bomb tests (mainly 1952-62) are available from rainwater, rivers and groundwater. The long-term observation of tritium allows for understanding the water flow throughout the whole hydrological system from catchment to river, to aquifer, to outflow (Morgenstern, unpublished data).

The tritium signature in the Hutt River is smoothed compared to rain, and is very dependent on the preceding rainfall history. After heavy rain, the tritium signature in the river follows that of the rain, indicating that in rain periods the main component of the river water is derived directly from surface run-off. However, in periods of low rainfall, the main component of the river water at Kaitoke is up to 6 months old. The river water consists mainly of this old component after several days without rain.

The Lower Hutt groundwater system is recharged from the Hutt River between Taita Gorge and Kennedy-Good Bridge, about 7 km from the coast. Groundwater in the upper artesian aquifer (Waiwhetu Gravel) reaches wells at the coast in the centre of the valley after about 3.5 years, based on comparison of tritium records in the river and in a supply well at Hutt Park (Grant-Taylor and Taylor 1967). This is confirmed by matching the measured long-term tritium data from Hutt Park well with the output calculated with a mixing model. The best fit of the data is for groundwater flow mainly described by piston flow, with a portion of approximately 20% mixed flow represented by an exponential model. Modelling the tritium data from different wells results in the following groundwater flow pattern and age structure. The age of the groundwater in the upper artesian aquifer in the centre of the valley is 0.5±0.2 years close to the recharge area at Avalon; 1.0±0.7 years 3 km from the coast at Waterloo; 3.5±0.5 years near the coast at Hutt Park; and 20±1 years 3 km offshore at Somes Island, in the aquifer extension under Wellington Harbour. The much older groundwater age at Somes Island, compared to onshore data, demonstrates slower flow beneath Wellington Harbour, which can be explained by a combination of lateral widening of the aquifer downvalley and leakage holes within Wellington Harbour near the Hutt River mouth i.e. less water flows through a wider aquifer cross section in the offshore section of the aquifer. The groundwater age near the coast on the western side of the valley is 22±1 years, much older than in the centre, and indicates a slower rate of groundwater flow along the western margin of the Hutt Valley. The age of the water in the deeper artesian aquifer (Moera Gravel) is older than 50 years at both the centre and the side of the valley near the coast.

Waikoropupu Springs, Takaka Valley

The Waikoropupu Springs, comprising the Main Spring and Fish Creek Springs, are the principal outflows from the Arthur Marble Aquifer (Chapter 21). The springs are New Zealand's largest and an impressive sight. They are karstic, tidal and slightly brackish. The springs emerge from Arthur Marble through a cover of Motupipi Coal Measures approximately 4 km south of Golden Bay and 13 m above sea level (Fig. 21.12a in Chapter 21). $\delta^{18}O$ is used to determine the sources of the water in the springs. Dating then helps to gain an understanding of the nature of the system.

Mueller (1992) identified three recharge sources to the Arthur Marble Aquifer–the Takaka River, tributary creeks in Central Takaka including the Waingaro and Anatoki Rivers, and rainfall on Arthur Marble where it outcrops or is covered by permeable rocks. The annual and overall average $\delta^{18}O$ values of these are given in Table 7.1, based on three and a half years of monthly sampling (Stewart and Williams 1981). There is a large difference between the $\delta^{18}O$ values of the Takaka River and rainfall on the Takaka Valley floor, providing a very effective means of discriminating between these sources

Mueller (1992) and Edgar (1998) gave estimates of the net flows to the aquifer (Table 7.2). Mueller estimated total recharge to be 23.4 m^3/s, of which 15.0 m^3/s was discharged by the Waikoropupu Springs and 8.40 m^3/s by submarine springs in Golden Bay. Edgar estimated that total recharge was 14.5 m^3/s (approximately matching the outflow from the springs) and there were no submarine springs (see also Doyle and Edgar 1998). Their recharge models are given in Table 7.2.

Average discharges from the Main Spring and Fish Creek Springs are 10.0 m^3/s and 3.2 m^3/s respectively (Chapter 21). Their average $\delta^{18}O$ values are consistently different: -7.38‰ for Main Spring and -7.64‰ for Fish Creek Springs (Table 7.1). This means that the two springs contain different proportions of the source waters. In particular, Fish Creek Springs contain proportionately more Takaka River water than the Main Spring.

We can calculate the $\delta^{18}O$ values expected for the spring waters from the flows and $\delta^{18}O$ values of the source waters (Stewart, Rosen and Thomas, unpublisahed data; see Table 7.2). Results for the Mueller (–7.72‰) and Edgar (–

Table 7.1 *Mean oxygen-18 concentrations of waters from the Takaka Valley.*

	$\delta^{18}O$ ‰				
Feature sampled	1976	1977	1978	1979*	Mean
Takaka River	-8.73	-8.75	-8.66	-8.53	-8.67
Rainfall	-5.41	-5.43	-5.27	-5.50	-5.40
Main Spring	-7.24	-7.31	-7.48	-7.50	-7.38
Fish Creek Spring	-7.53	-7.67	-7.69	-7.66	-7.64

* *Samples collected January to June only.*

Table 7.2 *Recharge models to the Arthur Marble Aquifer and resulting oxygen-18 values.*

Recharge Source	$\delta^{18}O$ ‰	Mueller Net flow m^3/s	Edgar Net flow m^3/s	Preferred Model: Main Spring m^3/s	Fish Creek Spring m^3/s	Total flow m^3/s
Takaka River sinks	-8.67	11.0	8.0	3.3	4.7	8.0
Sinks in tributary creeks	-7.20	10.2	4.3	5.0	3.3	8.3
Takaka Valley rainfall	-5.40	2.2	2.2	1.7	1.5	3.2
Total recharge flow (m^3/s)		23.4	14.5	10.0	9.5	19.5
Weighted mean $\delta^{18}O$ (‰)		-7.72	-7.74	-7.38	-7.64	-7.51

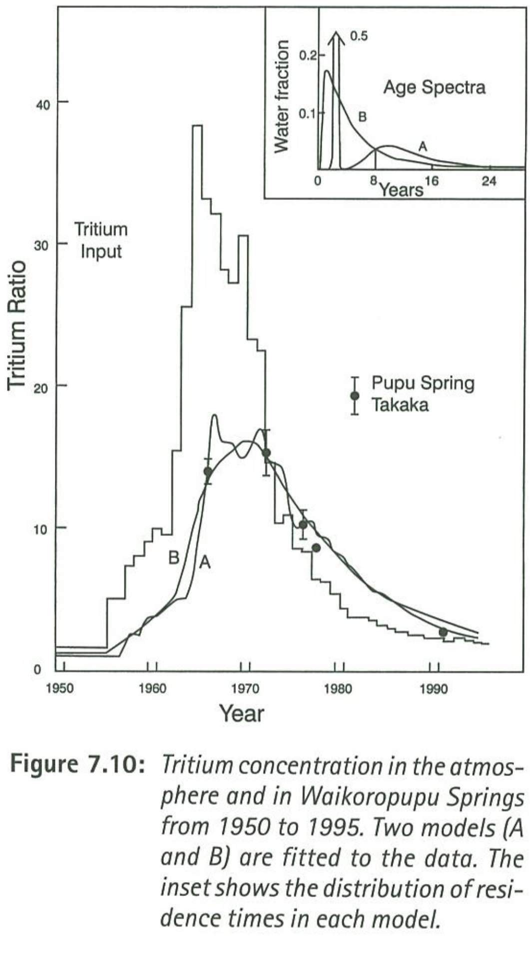

Figure 7.10: *Tritium concentration in the atmosphere and in Waikoropupu Springs from 1950 to 1995. Two models (A and B) are fitted to the data. The inset shows the distribution of residence times in each model.*

7.74‰) recharge models do not agree with the measured values for either the Main Spring or Fish Creek Springs and therefore the models are not feasible. A new model that matches the output of the Main Spring and the observed $\delta^{18}O$ values of the springs, and keeps the input of Takaka River water to the measured amount (8.0 m^3/s; see Chapter 21), produces too much Fish Creek-type water (9.5 m^3/s instead of 3.2 m^3/s). The remainder of at least 6.0 m^3/s must be discharged offshore via submarine springs or seeps.

At low flows, when the Fish Creek Springs dry up and the Main Spring flow is reduced, the $\delta^{18}O$ value of the Main Spring becomes more negative, like that of the Fish Creek Springs (Stewart and Downes 1981). In combination with the $\delta^{18}O$ difference between Main and Fish Creek Springs, this suggests that Takaka River-derived water flows preferentially over the top of the Arthur Marble aquifer and/or through larger solution cavities that occur in the upper parts of karstified carbonate rocks.

Measurements of the tritium concentrations in the Main Spring show that the peak residence time of the water is about one year (Stewart and Downes 1981). Figure 7.10 shows the input, measured, and simulated tritium concentrations for two mixing models. The inset shows the residence time distributions of the mixing models, both of which show a high degree of mixing. Such high mixing reflects dual porosities in the aquifer and is typical of karst systems (e.g. Rank et al. 1992). Connected porosity occurs in the small-scale fissures and the porous matrix that provides much of the storage in the system and contributes to baseflow. This provides a large fraction of much older water, so that the mean residence time of the water is eight years. A second porosity is demonstrated by the peaks at about one year in Fig. 7.10, which show that part of the Main

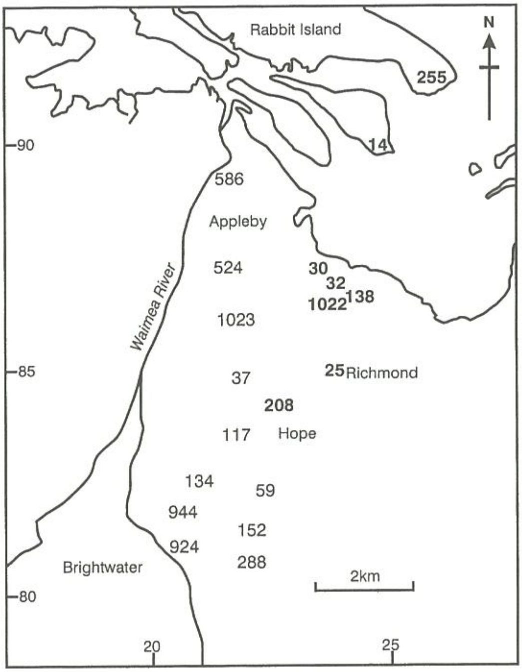

Figure 7.11: *Map of the Waimea Plains, Nelson, showing locations of wells referred to in the text. Wells penetrating the Lower Confined Aquifer are in bold.*

Spring discharge is delivered to the springs through a high-velocity conduit system in the upper levels of the Arthur Marble Aquifer. Takaka River contributes to this flow of young water.

A short flow-through time for Takaka River water is corroborated by the monthly $\delta^{18}O$ measurements (Stewart and Downes 1981). Fish Creek $\delta^{18}O$ showed a recognisable decrease 1.2 years after the $\delta^{18}O$ of the Takaka River went through a pronounced decrease in the winter of 1977. No corresponding decrease was found in the $\delta^{18}O$ of the Main Spring, but this is to be expected if the Takaka River contributes much less water proportionately to the Main Spring than to Fish Creek Springs, as concluded above.

The conceptual model that arises from the isotopic work is one of water penetrating deeply into the Arthur Marble Aquifer from recharge on both sides of the valley where the marble outcrops or is covered by permeable rock. The sources are the mid-valley tributary streams and direct rainfall. Flow is driven by the higher water levels on the flanks of the valley and the water has long residence times in the very large marble reservoir. On this "floats" water from Takaka River, which passes more rapidly through the larger solution cavities in the upper part of the karstified marble. Some of this reaches the springs, but much of it travels down the valley and is discharged in seeps or springs offshore. The Main Spring draws water from deeper in the aquifer than the Fish Creek Springs and hence discharges more of the water from the flanks of the valley.

Waimea Plains

The Waimea Plains, southwest of Nelson City, is an area of intensive farming and horticulture (Fig. 7.11). Groundwater from unconfined and two major confined aquifers are used extensively for irrigation. The Lower Confined Aquifer also supplies a large part of the Richmond Borough Council water supply. Water quality is generally good, except for nitrate concentrations, which exceed the Ministry of Health's recommended upper limit for potable waters (50 g/m^3 nitrate, or 11.3 g/m^3 nitrate-nitrogen). We have used $\delta^{18}O$ to determine the sources of recharge to the groundwater and $\delta^{15}N$ to investigate the source of the nitrate–knowledge that is important for management of the groundwater resource.

The hydrogeology of the area is summarised in Fig. 21.4 of Chapter 21. The unconfined aquifers are within the Appleby Gravel and the Pugh Gravel Member, adjacent to the coast between the Waimea River delta and Richmond. Hope Minor Confined and Unconfined Aquifers occur to the east of the plains. Two large lenses of sorted gravel within the Hope Gravel are, on the basis of their depth beneath the surface, divided into two major units: the Upper Confined Aquifer and the Lower Confined Aquifer (Dicker et al. 1992).

The predominant source of recharge for each well was assigned on the basis of its $\delta^{18}O$ value (Stewart et al. 1981). Wells with river recharge have $\delta^{18}O$ values in the range -6.8 to -7.4‰ with a mean of -7.02 ± .19‰: this is the same as the Waimea, Wai-iti and Wairoa Rivers,

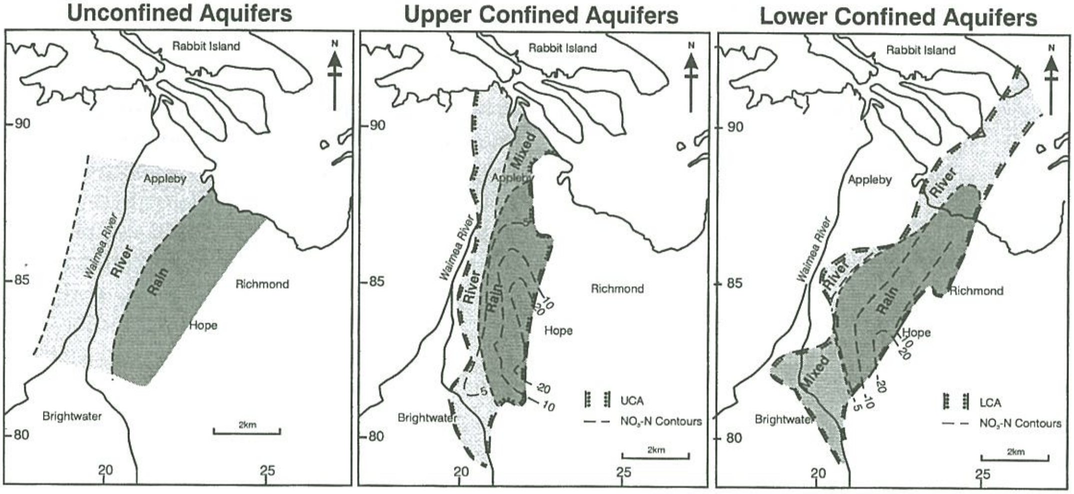

Figure 7.12: *Recharge sources of groundwaters in the Unconfined aquifers, Upper Confined Aquifer and Lower Confined Aquifer of Waimea Plains, Nelson, based on $\delta^{18}O$ to identify river, rainfall or mixed recharge, indicated by shading. Dashed lines show NO_3-N contours for the Upper Confined and Lower Confined aquifers.*

which have $\delta^{18}O$ = -7.1‰ on average. These wells have low nitrate-N concentrations (mean 2.9 ± 2.4 g/m^3). Wells with rainfall recharge have $\delta^{18}O$ values in the range -6.0 to -6.6‰ with a mean of -6.44 ± .15‰, in comparison with a measured value for rainfall of -6.2‰. Nitrate-N concentrations vary widely, but contain the highest values observed in the plains (mean: 10.1 ± 6.5 g/m^3). Wells with mixed river and rainfall recharge have intermediate $\delta^{18}O$ values (range: -6.6 to -7.0‰, mean: -6.79 ± .12‰) and more equal quantities of river and rainfall recharge. Mean nitrate-N concentration is 7.1 ± 0.7 g/m^3.

Fig. 7.12 shows the areal distributions of these recharge sources for each aquifer unit. The unconfined aquifers are recharged by river water near the Waimea and Wairoa rivers, and by rainfall to the east of them. The Upper Confined Aquifer is recharged by the Waimea River in a narrow strip along the river, then gains mixed recharge in the north, where there is no distinction between the Upper Confined Aquifer and the unconfined aquifers. Recharge is mainly from rainfall on the east, away from the rivers. The pattern of recharge for the Lower Confined Aquifer is more complicated. The south zone, adjacent to the Wairoa River, has mixed recharge, showing that the aquifer is not connected to the surface and recharge is from the overlying Upper Confined Aquifer from both river and rain sources. The Waimea River recharges a zone in the middle of the Valley, where the Upper and Lower Confined Aquifers are in contact, and the water flows northeast to the offshore part of the Lower Confined Aquifer (Bells and Rabbit Islands). Rainfall recharge is received from the Upper Confined Aquifer near the Hope area. This water also flows northeast, but does not reach far offshore, probably because of water extraction by wells near the coast and inland. Some influence from this water is seen at Bells Island, however.

Understanding the recharge sources sheds light on the sources of nitrate in the Upper and Lower Confined Aquifers. Clearly nitrate is low in the river-recharged parts of the aquifers and high in rainfall-recharged parts near Hope and northeast of it.

Further understanding can be gained from other geochemical parameters (Fig. 7.13). Sulphate shows a good correlation with nitrate-N for most of the area shown in Fig. 7.11, including all of the Lower Confined Aquifer samples. The correlation can be explained by mixing of groundwater enriched in nitrate and sulphate with groundwater low in nitrate and sulphate. Furthermore, the enriched end mem-

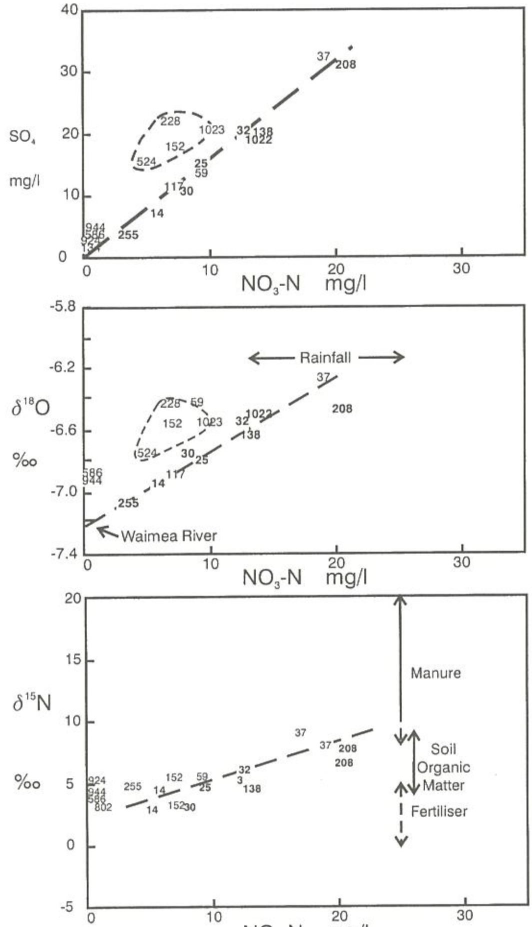

Figure 7.13: *Plots of sulphate, $\delta^{18}O$ in water and $\delta^{15}N$ in nitrate versus nitrate-nitrogen concentration for Waimea Plains groundwaters. The numbers are TDC well numbers (Lower Confined Aquifer wells are in bold). The $\delta^{15}N$ ranges of possible nitrate sources are shown.*

ber must be a body of water that has a uniform composition and therefore has been resident in the aquifers for a considerable time. The samples that deviate from the line are from the unconfined aquifers or Upper Confined Aquifer in areas away from Hope.

$\delta^{18}O$ versus nitrate-N shows a similar correlation to that with sulphate. The mean $\delta^{18}O$ values of rainfall and Waimea River are shown. Rainfall-derived groundwater enriched in NO_3-N mixes with river water low in NO_3-N to produce the correlation. The sources of the elevated levels of nitrate are clearly distributed on the ground surface in the general region of Hope. Rainfall infiltrating into the Upper Confined Aquifer in the vicinity of Hope carries nitrate at consistent concentration levels through to the Lower Confined Aquifer.

The $\delta^{15}N$ values of possible nitrate sources are shown in the third diagram in Figure 7.13. The sources can be clearly distinguished by their $\delta^{15}N$ values. Inorganic fertilisers have low $\delta^{15}N$ values (0-5‰), natural soil organic matter has values of 4-9‰ and manure has values of 8-20‰ (Sheppard and Lyon 1996). The plot shows that nitrate is from soil organic matter or inorganic fertilisers at low nitrate concentrations, but $\delta^{15}N$ trends towards manure values as nitrate increases. This shows that the high nitrate concentrations are derived mainly from manure sources. In the Hope region, market gardening is widespread and large quantities of chicken manure have been applied to the soil to improve growth, particularly in the 1970s and 1980s. There was also a large piggery in the area until recent years. The market gardens and piggery are the likely sources of much of the nitrate.

Tritium and CFC concentrations have shown that the waters in the Lower and Upper Confined Aquifers have very wide age distributions, as extensive mixing has occurred (Stewart, Thomas and Rosen 2001). The current nitrate concentrations reflect events that occurred in the 1970s and 80s. Refinement of the age dating will give more information on the history of nitrate contamination.

Security of groundwater drinking water supplies

The age of groundwater is a good indicator of its likely biological safety for drinking water. During the time spent underground bacteria and viruses decay, and in addition are affected by filtration and dilution due to flow of the groundwater through a porous medium.

Groundwater comprises a mixture of water of different ages due to mixing processes underground. Therefore the groundwater doesn't usually have a discrete age, but has an age distribution or spectrum. Various mixing models with different age distributions describe different hydrogeological conditions (Maloszewski and Zuber 1982). The piston-flow model describes systems with little mixing (such as confined aquifers and river recharge), while the one-box, or exponential model, describes fully mixed systems (more like unconfined aquifers and local rain recharge). Real systems, which are partially mixed, lie between these two extremes. They can be described by the dispersion model, which is based on a solution to the dispersion equation (the fundamental equation for groundwater flow), or by a combination of the exponential and piston-flow models, representing the recharge and flow parts of a groundwater system respectively.

The dispersion model can simulate a wide variety of realistic groundwater conditions with only two parameters (the first is the average residence time (τ) and the second the dispersion parameter (D_p), which is a measure of the spread of ages). Those parameters applying to a particular well are chosen to give the best match to the measured data. If information about the hydrologic conditions (and therefore the degree of mixing) is scarce, a minimum of two measurements of either tritium or CFC concentrations, separated in time, is needed to determine the parameters and uniquely specify the age spectrum.

The degree of mixing is specified by the dispersion parameter. A small dispersion parameter (e.g. 0.01) describes a system with a small degree of mixing, as in piston-flow. The distribution of residence times in this case is a symmetrical but very narrow bell-shaped curve. An intermediate value of the dispersion parameter (e.g. 0.1) describes a medium degree of mixing and the distribution of residence times looks like a skewed bell-shaped curve (Fig. 7.9b). A high dispersion parameter (e.g. 1.0) describes a highly mixed groundwater and the distribution of residence times has similarities to an exponential distribution i.e. the distribution is very skewed towards young ages (Fig. 7.10 inset).

What is important for drinking water safety is the fraction of water that is less than one year old, because one year or more is long enough for bacteria and viruses to decay (Ministry of Health 2000). This fraction can be determined from the parameters of the dispersion model fitted to tritium or CFC data. It is denoted by the symbol yf (for "young fraction") and given by

$$yf=\int_0^1 g(t)\,dt \qquad (13)$$

where g(t) describes the age spectrum (Maloszewski and Zuber 1982). A yf of 100% means that all of the water has been underground for less than one year and a yf of 0% means that none of the water has been underground for less than one year. The value of yf for a particular well characterises its security for supplying drinking water; the current criterion is that a well is considered secure if yf is less than 0.005% (Ministry of Health 2000). This gives yf = 0.00% on rounding to two decimal points.

Wells from the Canterbury region with two or more tritium measurements show the use of the method. The Environment Canterbury well numbers are M35/0443, M35/0444, M35/0480 and the tritium results and dispersion model simulations are given in Figure 7.14. Wells M35/0443 and M35/0444 had high tritium concentrations in the 1970s, showing that the waters have mean residence times of 4 and 5 years respectively and a dispersion parameter (D_p) of 0.6. These give young water fractions (yf) of 7.5% and 5.1%, so the well water supplies are not secure. The two tritium measurements from well M35/0480 are fitted with a dispersion model, with a mean residence time of 16 years and D_p of 0.001. The young water fraction is yf = 0.00% and the well water supply is thus secure. Tritium measurements in the 1980s, when much higher tritium concentrations occurred, are especially diagnostic of the model parameters (Fig. 7.14). The dating techniques demonstrate differences in groundwater flow and security, even though all three wells are in the same coastal Waimakariri-Ashley region.

Well M35/3637, on the western edge of Christchurch, is more typical of deeper wells

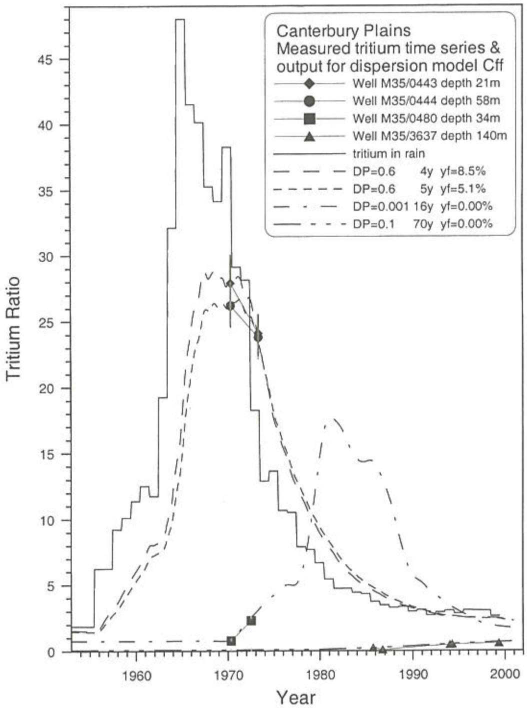

Figure 7.14: *Simulated tritium series for selected age and dispersion parameters compared to measured tritium data for four Canterbury wells.*

between the Waimakariri and the Rakaia Rivers. Five tritium measurements were made between 1985 and 1999, and CFC measurements were made in 1999. The mean residence time of water is 68 years and D_p is 0.1. These give yf = 0.00% and the well water supply is secure

The tritium concentration of a sample from the Waimarino well (5D) from the Lake Taupo Basin gave an ambiguous age; the age could have been 2, 22 or 40 years (Fig. 7.15; all three simulations pass through the tritium measurement marked by a filled circle). In contrast, only the 40-year simulation fits the CFC-12 measurement; waters younger than this have higher CFC concentrations and older waters have lower concentrations. The CFC-12 result thus shows that the tritium age of 40 years is the correct one. This gives yf = 0.00% and shows that the well water supply is secure. In this example, we have assumed a particular age distribution model because there was only

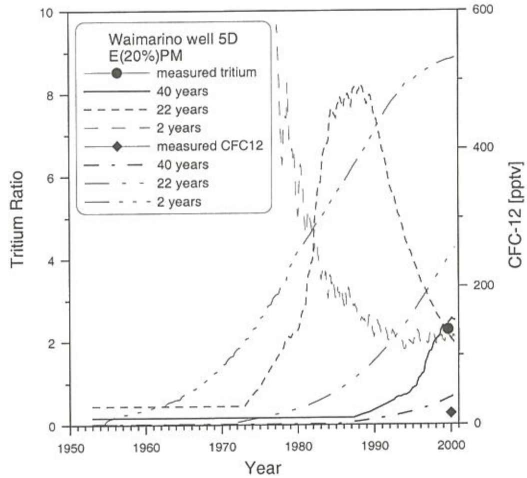

Figure 7.15: *Plot of tritium and CFC-12 measured concentrations and simulated time series for Waimarino well 5D.*

one tritium and one CFC measurement. The model (labelled E20%M) was assumed to be fully mixed in 20% of its volume (representing the recharge portion of the hydrological system) and non-mixed in the remaining 80% of the volume. This is roughly equivalent to a dispersion model with $D_p \sim 0.2$.)

SUMMARY

Isotope studies are coming of age and beginning to fulfil their promise as probes of groundwater systems, both because of gradual improvement in analysis methods and because of the introduction of new methods such as CFC dating. This chapter has described the background and application of environmental isotopes and CFCs that have found most use in New Zealand. Improvements in measuring tritium, combined with the decay of the nuclear testing peak, have improved the effectiveness of tritium for dating recent groundwater. CFC dating has also proven effective, and CFC and tritium dates have shown agreement for Canterbury groundwater. Radiocarbon dating has been applied to some old groundwaters in a number of New Zealand groundwater systems.

Stable isotopes have been used to help identify recharge sources of groundwaters in Canterbury, Takaka Valley and Waimea Plains, and the source of nitrate in Canterbury and Waimea Plains groundwater. Age-dating has proven to be a reliable method of determining flow rates in groundwater systems. The results are contributing to improved conceptual models of the systems and have assisted validation of a large-scale groundwater flow model of the Canterbury Plains. The history of water quality changes in the groundwater systems can be investigated by combined age-dating and chemical measurements, as illustrated for Canterbury and Waimea Plains groundwaters. Age-dating is proving to be a reliable method of establishing whether a groundwater supply is secure against contamination by pathogens and thus suitable for drinking water supplies.

As more data is accumulated, monitoring of environmental isotope data is expected to become more valuable, because trends in water ages will reveal changing flow patterns resulting from exploitation of the resource. For example, a trend of decreasing ages in water from deep aquifers under Christchurch over time could show recharge by young water, while increasing ages over time could show that older water is being drawn from greater depth or from offshore parts of the aquifer. Also improvements in techniques such as development of SF_6 dating will allow more precise information to be gained.

ACKNOWLEDGEMENTS

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REFERENCES

Clark, I.D.; Fritz, P. 1997: Environmental isotopes in hydrogeology. Lewis Publishers, New York. 328 p.

Cook, P.G.; Herczeg, A.L. (eds.) 1999: Environmental tracers in subsurface hydrology. Kluwer Academic Publishers, London. 529 p.

Craig, H. 1961: Isotopic variations in natural waters. Science 133: 1702-1703.

Dansgaard, W. 1964: Stable isotopes in precipitation. Tellus 16: 436-488.

Dicker, M.J.I.; Fenemor, A.D.; Johnston, M.R. 1992: Geology and groundwater resources of the Waimea Plains, Nelson. New Zealand Geological Survey Bulletin 106, 59 p.

Doyle, M.; Edgar, J.E. 1998: There are no springs in the water balance. Metorological Society of New Zealand and New Zealand Hydrological Society 1998 Symposium Proceedings, p 27. Dunedin, 24-27 November.

Edgar, J.E. 1998: Hydrogeology of the Takaka Valley. M.Sc. Thesis, University of Canterbury. 303 p.

Ekwurzel, B.; Schlosser, P.; Smethie, JR.; Plummer, N.; Busenberg, E.; Michel, R.L.; Weppernig, R.; Stute, M. 1994: Dating of shallow groundwater: comparison of the transient tracers $^3H/^3He$, chlorofluorocarbons and ^{85}Kr. Water Resources Research 30: 1693-1708.

Emiliani, C. 1966: Isotopic palaeotemperatures. Science 154: 851.

Fergusson, G.J. 1953: Activity measurement of samples for radiocarbon dating. New Zealand Journal of Science and Technology B 35: 91-108.

Grant-Taylor, T.L.; Taylor, C.B. 1967: Tritium hydrology in New Zealand. Isotopes in Hydrology. IAEA Vienna, STI/PUB/141, pp. 381-400.

Hendy, C.H.; Wilson, A.T. 1968: Palaeoclimatic data from speleothems. Nature 216: 48.

Hulston, J.R.; McCabe, W.J. 1962: Mass spectrometer measurements in the thermal areas of New Zealand. 2. Carbon isotope ratios. Geochimica et Cosmochimica Acta 26: 399-410.

Kendall, C.; Aravena, R. 1999: Nitrate isotopes in groundwater systems. Chapter 9 in Environmental Tracers in Subsurface Hydrology. Eds: P.G. Cook and A.L. Herczeg. Kluwer Academic Publishers. pp. 261-297.

Kendall, C.; McDonnell, J.J. (eds.) 1998: Isotope tracers in catchment hydrology. Elsevier, Amsterdam. 839 p.

Krouse, H.R.; Mayer, B. 1999: Sulphur and oxygen isotopes in sulphate. Chapter 7 in Environmental Tracers in Subsurface Hydrology. Eds: P.G. Cook and A.L. Herczeg. Kluwer Academic Publishers, pp. 195-231.

McDonnell, J.J.; Rowe, L.K.; Stewart, M.K. 1999: A combined tracer-hydrometric approach to assess the effect of catchment scale on water flow path, source, and age. Integrated Methods in Catchment Hydrology - Tracer, Remote Sensing and New Hydrometric Techniques. Proceedings of IUGG 99 Symposium HS4, Birmingham, July. IAHS Publication No. 258.

Maloszewski, P.; Zuber, A. 1982. Determining the turnover time of groundwater systems with the aid of environmental tracers: I.: Models and their applicability, Journal of Hydrology 57: 207-231.

Ministry of Health 2000: Drinking-water standards for New Zealand 2000. Ministry of Health, Wellington. 130 p.

MUELLER, M. 1992: Geohydrology of the Takaka Valley. Report for the Tasman District Council. 38 p.

PLUMMER, L.N.; BUSENBURG, E. 1999: Chlorofluorocarbons. Chapter 15 in Environmental Tracers in Subsurface Hydrology. Eds: P. Cook and A.L. Herczeg. Kluwer Academic Publishers. pp. 441-478.

PLUMMER, L.N.; PRESTEMON, E.C.; PARKHURST, D.L. 1994: An interactive code (NETPATH) for modelling net geochemical reactions along a flow path, version 2.0. U.S. Geological Survey Water Resources Investigations Report 94-4169, U.S.G.S., Reston, VA.

RAFTER, T.A. 1953: The preparation of carbon for ^{14}C age measurements. New Zealand Journal of Science and Technology B 35: 64-89.

RANK, D.; VÖLKL, G.; MALOSZEWSKI, P.; STICHLER, W. 1992: Flow dynamics in an alpine karst massif studied by means of environmental isotopes. Isotope Techniques in Water Resources Development 1991, IAEA Symposium 319, March 1991, Vienna, pp. 327-343.

ROBINSON, B.W.; BOTTRELL, I. 1997: Discrimination of sulfur sources in pristine and polluted New Zealand catchments using stable isotopes. Applied Geochemistry 12: 305-319.

ROSEN, M.R.; BRIGHT, J.; CARRAN, P.; STEWART, M.K.; REEVES, R. 1999: Estimating rainfall recharge and soil water residence times in Pukekohe, New Zealand, by combining geophysical, chemical and isotopic methods. Groundwater 37(6): 836-844.

SHEPPARD, D.S.; LYON, G.L. 1996: The usefulness of nitrate isotope measurements in groundwater contamination studies. Institute of Geological and Nuclear Sciences Report. 17 p.

STEWART, M.K.; COX, M.A.; JAMES, M.R.; LYON, G.L. 1983: Deuterium in New Zealand rivers and streams. Report INS-R—320, Institute of Nuclear Sciences, Lower Hutt, New Zealand. 32 p.

STEWART, M.K.; DICKER, M.J.I.; JOHNSTON, M.R. 1981: Environmental isotopes in New Zealand hydrology. Part 4. Oxygen isotope variations in subsurface waters of the Waimea Plains, Nelson. New Zealand Journal of Science 24: 339-348.

STEWART, M.K.; DOWNES, C.J. 1981: Isotope hydrology of Waikoropupu Springs, New Zealand. In Isotope studies of hydrologic processes. Eds.: E.C. Perry and C. Montgomery. Northern Illinois University Press, DeKalb, IL. pp. 15-23.

STEWART, M.K.; FOX, V.; SMITH, V.; HAYWARD, S. 1997: New groundwater dating technique applied to the Christchurch groundwater system. 24th Hydrology and Water Resources Symposium Proceedings, p. 546. Poster. Auckland, 24-27 November.

STEWART, M.K.; FOX, V.; VAN DER RAAIJ, R. 1999: Conceptual model of the groundwater resource between the Ashley and Rakaia rivers, Canterbury, using the CFC dating technique. New Zealand Hydrological Society 1999 Symposium Proceedings, p 76. Napier, 23-26 November.

STEWART, M.K.; MCDONNELL, J.J. 1991: Modeling baseflow soil water residence times from deuterium concentrations. Water Resources Research 27(10): 2681-2693.

STEWART, M.K.; TAYLOR, C.B. 1981: Environmental isotopes in New Zealand hydrology. Part 1. Introduction: The role of oxygen-18, deuterium and tritium in hydrology. New Zealand Journal of Science 24: 295-311.

STEWART, M.K.; WILLIAMS, P.W. 1981: Environmental isotopes in New Zealand hydrology. Part 3. Isotope hydrology of the Waikoropupu Springs and Takaka River, N.W. Nelson. New Zealand Journal of Science 24: 323-337.

TAYLOR, C.B. 1994a: Hydrology of the Poverty Bay Flats aquifers: New Zealand; recharge mechanisms, evolution of the isotopic composition of dissolved inorganic carbon and groundwater ages. Journal of Hydrology 158: 151-185.

TAYLOR, C.B. 1994b: The relationship between electrolytic deuterium and tritium separation factors, and attainment of improved accuracy in radiometric low-level tritium measurement. Journal of Applied Radiation and Isotopes 45(6): 683-692.

TAYLOR, C.B. 1997: On the isotopic composition of dissolved inorganic carbon in rivers and shallow groundwater: a diagrammatic approach to process identification and a more realistic model of the open system. Radiocarbon 39: 251-268.

TAYLOR, C.B.; BROWN, L.J.; CUNLIFFE, J.J.; DAVIDSON, P.W. 1992: Environmental tritium and ^{18}O applied in a hydrological study of the Wairau Plain and its contributing mountain catchments, Marlborough, New Zealand. Journal of Hydrology 138: 269-319.

TAYLOR, C.B.; EVANS, C.M. 1999: Isotopic indicators for groundwater hydrology in Taranaki, New Zealand. Journal of Hydrology (NZ) 38(2): 237-270.

TAYLOR, C.B.; FOX, V.J. 1996: An isotopic study of dissolved inorganic carbon in the catchment of the Waimakariri River and deep groundwater of the Canterbury Plains, New Zealand. Journal of Hydrology 186: 161-190.

TAYLOR, C.B.; POLACH, H.A.; RAFTER, T.A. 1963: A review of the work of the tritium laboratory –Institute of Nuclear Sciences – New Zealand. Tongiorgi E. Ed.: Nuclear Geology in Geothermal Areas. Consiglio Nazionale Delle Ricerche, Pisa, pp.185-233.

TAYLOR, C.B.; STEWART, M.K. 1987: Hydrology of the Rotorua Geothermal Aquifer, New Zealand. In: Isotope Techniques in Water Resources Development (Publication: IAEA-SM-299/95), International Atomic Energy Agency, Vienna, pp. 25-45.

TAYLOR, C.B.; WILSON, D.D.; BROWN, L.J.; STEWART, M.K.; BURDON, R.J.; BRAILSFORD, G.W. 1989: Sources and flow of North Canterbury Plains groundwater, New Zealand. Journal of Hydrology 106: 311-340.

TORGERSEN, T.; CLARKE, W.B.; JENKINS, W.J. 1979: The tritium/helium-3 method in hydrology. Isotope Hydrology 1978, Vol.II, IAEA Symposium 228, June 1978, Neuherberg, Germany. pp. 917- 930.

WHITE, P.A.; HONG, T.; MURRAY, D.C. 1999: Validation of the Canterbury groundwater flow model using CFC-derived ages. New Zealand Hydrological Society 1999 Symposium Proceedings, p 82. Napier, 23-26 November.

8

Fate and transport of nitrates and pesticides in New Zealand's aquifers

MURRAY E. CLOSE, MICHAEL R. ROSEN, AND VIVIENNE R. SMITH

INTRODUCTION

Nitrogen is a vital component of plant growth, either as nitrogen fertiliser or as nitrogen fixed by plants such as clovers. Pesticides are also an important part of agriculture and horticulture in New Zealand, and are used to eradicate or control animal and plant pests. However, the very characteristics they are valued for in controlling organisms, i.e., their toxicity, mobility, and persistence, are those that pose potential problems when pesticides leach through the soil and enter the groundwater. The challenge for our farming community and resource managers is to maintain the benefits of using nitrogen and pesticides while minimising any adverse effects such as contamination of lakes, rivers, and groundwaters. This chapter focuses on the occurrence, transport and fate of these compounds in our ground-water systems.

There are several reasons why any contamination of our groundwater systems is of concern. The major reason is the importance of groundwater as a drinking water source. Around 50% of community water supplies use groundwater as either a sole or partial source, as well as many domestic wells in the rural community. Another reason is the need to demonstrate good water quality to show that our agricultural systems are environmentally responsible. This has implications with respect to trade and non-tariff barriers. A third reason is the impact of these compounds when contaminated groundwaters recharge surface waters: nitrate can cause algal blooms and eutrophication, and pesticides can cause behavioural and growth changes in aquatic plant and animal life exposed to water or sediment contamination.

NITRATE OCCURRENCE IN NEW ZEALAND AQUIFERS

In this section we look at why nitrate is a problem in groundwater systems, the forms of nitrogen that commonly occur, and how they fit into the nitrogen cycle. Natural levels of nitrate in groundwater are discussed and the various man-made sources of nitrogen are detailed, together with nitrate loading and leaching rates from various land uses. The historical information on nitrates in New Zealand groundwater systems is presented and current trends are discussed, followed by a look at modelling nitrate transport and fate in groundwater and various options for treating high concentrations of nitrate.

The concentrations of nitrogen compounds can be reported either as nitrogen or as the ion of interest. For example a nitrate concentration of 50 g m^{-3} is equal to 11.3 g m^{-3} NO_3-N (nitrate-nitrogen). In this chapter, unless specifically mentioned, all concentrations are as nitrogen. SI units are used in this chapter: mg/L ≡ g m^{-3} ≡ ppm; mg/L ≡ mg m^{-3} ≡ ppb.

THE PROBLEM

Over 50 years ago, in a classic paper by Comly (1945), it was recognised that high concentrations of nitrogen, specifically nitrate, in drinking water supplies could cause health problems. Methemoglobin is a form of hemoglobin in which the reduced iron in hemoglobin

Close M.E.; Rosen M.R. and Smith V.R. 2001: Fate and transport of nitrates and pesticides in New Zealand's aquifers. *In* Groundwaters of New Zealand, M.R. Rosen and P.A. White *(eds)*. New Zealand Hydrological Society Inc., Wellington. p185-220.

is transformed to its ferric state and is unable to deliver oxygen. In the disease called Methemoglobinemia amounts of methemoglobin in the blood become so high that the skin shows a bluish discoloration (cyanosis). Infants under the age of 6 months are more susceptible to this disease because they lack the enzyme methemoglobin reductase, which converts methemoglobin back to hemoglobin (Avery 1999). Because the disease has a name that is hard to pronounce and it is most prevalent in infants, the condition has been commonly known as "blue-baby disease" because of the cyanosis. Comly (1945) provided information on infantile methemoglobinemia victims exposed to nitrate-contaminated drinking water. He proposed that because nitrites (NO_2^-) are known to react with hemoglobin to form methemoglobin, nitrates from the water must be converted to nitrite within the intestinal tract of infants. His theory was reinforced by the observation that the blue colour of the skin subsided after the affected infant was switched to low-nitrate water.

Comly's hypothesis became widely accepted when subsequent research indicated a consistent pattern of high-nitrate drinking water in infantile methemoglobinemia cases. In 1975, the United States Environmental Protection Agency established a maximum contaminant level for nitrate-nitrogen in drinking water of 10 g m^{-3}. The World Health Organisation (WHO) also established this level based on similar research, but the current WHO guideline (World Health Organisation 1993) has since been revised to 50 g m^{-3} as nitrate, which is equivalent to 11.3 g m^{-3} NO_3-N. Although most cases of infant methemoglobinemia have been reported for drinking water with nitrate-nitrogen concentrations greater than 20 g m^{-3}, a margin of error was considered necessary and the concentration of 10 g m^{-3} NO_3-N or 50 g m^{-3} NO_3 has been adopted by many countries around the world.

High nitrate concentrations have also been linked to hypertension (Malberg et al. 1978), central nervous system birth defects (Dorsch et al. 1984), certain cancers (Hill et al. 1973), non-Hodgkin's lymphoma, (Weisenburger 1991; Ward et al. 1996), and diabetes (Parslow et al. 1997). However, definitive relationships are lacking and more research is needed to confirm the links (Spalding and Exner 1993).

More recently there has been debate about whether the 10 g m^{-3} drinking water standard is appropriate (Lehr 1985; Fan and Steinberg 1996; Avery 1999). Lehr (1985), argued that, considering the relatively few cases of methemoglobinemia reported in the past 20 years, the high cost of treating or finding alternative water sources for whole communities, and small numbers of individuals that were affected by the high concentrations of nitrate in groundwater, alternative sources of water could be found for those individuals affected. Fan and Steinberg (1996) argued that because there are uncertainties in the database used to construct the maximum contaminant level (MCL) for nitrate that the MCL might not be low enough. Avery (1999) has suggested that the correlation between high nitrate concentrations and reported cases of methemoglobinemia is not related to nitrate specifically, but to the bacterial contamination that is often associated with high nitrate concentrations in rural areas (i.e. from septic tanks and farm animal waste). He suggested that the MCL in drinking water could be raised to 15 or 20 g m^{-3} NO_3-N without putting infants at risk. Most recently, McKnight et al. (1999) suggested that dietary nitrate (either dissolved in water or in food) is important as a host defence against gastrointestinal pathogens. They suggested that nitrate is beneficial in controlling intestinal infections, particularly for those with compromised immune systems and those who are unavoidably exposed to contaminated food and water. They also suggested a re-evaluation of the limitations on nitrate intake, but indicated that the safety of children under one year of age required further study before such a review could begin.

The above discussion illustrates the controversy surrounding the health implications of high nitrate concentrations in both surface and groundwater. Articles such as one in the Dominion newspaper in 1994 entitled "Toxic bore water alert" illustrates the emotive reaction of the public to nitrate contamination (Bell 1994). It may be some time before these questions are resolved, and because of this, high nitrate concentrations may be used as a political argument to control related (or unrelated) issues of farming or water supply.

Baber and Wilson (1972) and Baber (1977) recognised early on in New Zealand that high concentrations of nitrogen in groundwater could lead to eutrophication of lakes and streams. They estimated that in the Waikato region water draining from the soil (as recharge) would have a concentration of 51-86 g m^{-3} NO_3-N, and this would lead to shallow aquifers that were significantly contaminated with nitrate. Recently, Spalding and Exner (1993) in a review of nitrate in groundwater worldwide have expressed similar concerns. Nitrate concentrations in groundwater well below the current WHO or New Zealand drinking water guidelines may still be high enough to have serious environmental effects. Growth in some plant communities may be limited by the amount of nitrogen available. For example, biological activity in Lake Taupo has been considered to be limited by nitrogen availability (White 1983). Additional nitrogen introduced by human activities around the lake may cause algal blooms and change the ecology of the lake. In addition, Saffigna (1977) reported that concentrations of 0.3 g m^{-3} NO_3-N increase algal growth and may lead to eutrophication of surface waters.

THE NITROGEN CYCLE

A discussion of nitrogen in the hydrologic cycle would not be complete without some discussion of the nitrogen cycle (Fig 8.1a,b). The nitrogen cycle has been presented in numerous publications, for example Canter (1997) and Lincoln Environmental (1997b). Interested readers should consult these publications for more details, particularly for details of vadose zone nitrogen transformations.

Nitrogen (N) in natural groundwater is usually measured as one of three forms: nitrate-nitrogen (NO_3^--N), ammonium-nitrogen (NH_4^+-N) or organic nitrogen (Org. N). Other forms exist, such as nitrite (NO_2^--N), which is an intermediate form in the transformation of ammonium to nitrate (nitrification), or in the transformation of nitrate to nitrogen gas (denitrification). However, nitrite occurs in significant concentrations only near contaminated sites (i.e. sewage or organic waste disposal areas). Un-ionised ammonia (NH_3) also occurs in equilibrium with ammonium, but this equilibrium is influenced by pH and temperature and is usually significant only in water with a pH greater than 9.2 (Mueller et al. 1995). In aquifers with abundant oxygen, NO_3-N is the stable form; where oxygen is depleted in the aquifer (usually in confined aquifers), NH_4-N is the stable form. Organic-N can occur in either type of aquifer, however, abundant organic-N is rarely found in significant quantities in uncontaminated New Zealand aquifers.

Nitrogen in the atmosphere (the atmosphere is 79% nitrogen gas) enters at the land surface naturally either by fixation of N_2 gas by lightning strikes or as nitrate dissolved in rain. In the Southern Hemisphere these contributions are small compared to anthropogenic sources. Nitrate from igneous rocks, deep geothermal fluids or dissolution of nitrate minerals are additional sources of N but are rare in New Zealand (Dillon et al. 1989). Anthropogenic sources (fertilisers, grazing animals, sewage disposal, mineralisation due to tillage, landfills, horticulture etc.) are the main sources of nitrate contamination of groundwater.

The fate and transport of nitrogen in the subsurface environment depends on the form of nitrogen (i.e. organic or inorganic nitrogen) and the various biochemical and physicochemical processes that occur when nitrogen is transformed from one form to another (Canter 1997). Organic nitrogen is composed of compounds from amino acids, amines, proteins, and humic substances (Reddy and Patrick 1981). Nitrogen from un-treated human wastewater may be either organic nitrogen or ammonium, and nitrogen from chemical fertilisers is generally either NH_4 or NO_3. Nitrogen from grazing animals (sheep, deer or cattle) is in the form of urea (H_2NCONH_2) from urine or organic N in faecal material, which are converted to ammonium through hydrolysis reactions (urea) or decomposition (faecal material). Organic nitrogen may enter directly into aquifers if the water table is near the surface or if direct access is available due to poor wellhead protection, deep excavations or leakage from landfills. Nitrogen transformations are complex at the land surface, in the soil zone, and vadose zone (Fig 8.1b), but become simpler below the water table. In oxidising groundwater environments, nitrate is the dominant form of nitrogen and is persistent along a flow path as long as anaerobic conditions are not encountered. Denitrification and dissimilatory nitrate reduction may occur below the water table via the following reactions:

Denitrification:

$$4NO_3^- + 5CH_2O = 2N_{2(g)} + 5HCO_3^-$$

Dissimilatory nitrate reduction:

$$NO_3^- + H_2O + 2CH_2O = NH_4^+ + 2HCO_3^-$$

where CH_2O represents organic material. The key to both of these reactions is that they occur under oxygen-deficient conditions only when organic material is present (Freeze and Cherry 1979). Typically oxygen-deficient conditions occur in confined aquifers, but may also occur in shallow unconfined aquifers associated with wetlands (Rosen et al. 1998; Eser and Rosen 1999) or contaminated with organic waste.

Autotrophic chemolithotrophic denitrification

Ottley et al. (1997) demonstrated experimentally that nitrate can be reduced to NH_4 by Fe(II) in the presence of Cu(II). The rate of reaction systematically increased with pH in the range of 7-8.5. Copper was present mainly in the solid phase, either adsorbed to precipitated iron oxides or as a saturated solid. The solid phase of copper was catalytically active rather than the dissolved Cu^{2+} in solution. Other solid phase forms also act as catalysts, including Ag(I) Cd(II), Ni(II) and Hg(II). Eppinger and Walraevens (1998) have shown that in Belgian Eocene aquifers nitrate reduction could be caused by a similar mechanism. They termed this type of denitrification as autotrophic chemolithotrophic denitrification. In this model, nitrate is reduced by oxidation of pyrite, which may be bacterially catalysed (Postma et al. 1991), following a number of possible reactions, but which is best described by the following two reactions:

$$5FeS_{2\ (pyrite)} + 14NO_3^- + 4CO_2 + 2H_2O \rightarrow 7N_2 + 5Fe^{2+} + 10SO_4^{2-} + 4HCO_3^-$$

or

$$2FeS_{2\ (pyrite)} + 6NO_3^- + 2HCO_3^- \rightarrow 3N_2 + 2FeOOH + 4SO_4^{2-} + 2CO_2$$

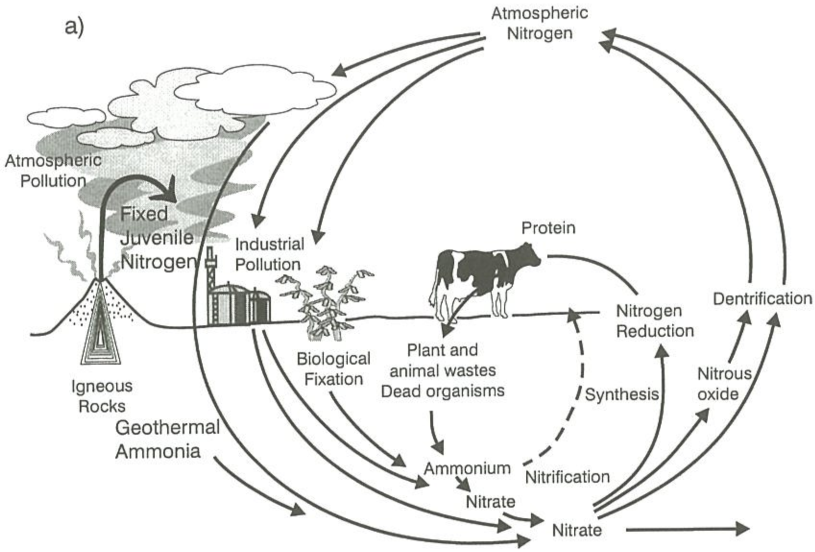
The inorganic reactions are slow unless they are catalysed in the way described by Ottley et al. (1997). Both Eppinger and Walraevens (1998) and Ottley et al. (1997) indicate that both bacterial processes and chemical nitrate reduction may be occurring at the same time. Other than the study by Eppinger and Walraevens (1998), we are not aware of further evidence of this type of nitrate reduction from natural aquifers, and this process has not been demonstrated in New Zealand aquifer systems.

Natural nitrogen concentrations

The natural concentration of N in New Zealand aquifers has not been studied in detail. Although Burden (1980a) suggested concentrations above 1 g m^{-3} NO_3-N in groundwater do not occur naturally, he did not provide any scientific basis for this cut-off value. In general, natural NO_3-N concentrations in New Zealand are low due to the high flow rates in many New Zealand aquifers and high rainfall in many parts of the country. In the United States of America, it has been determined that concentrations above 3 g m^{-3} of NO_3-N indicate contamination of the aquifer from anthropogenic sources (Madison and Brunett 1985), but in New Zealand natural concentrations of nitrate would rarely be higher than 1 g m^{-3}. However, further research would be required to determine natural background levels of nitrogen in New Zealand aquifers. In some deep confined aquifers in Gisborne and Taranaki naturally-occurring ammonium concentrations of up to 6 g m^{-3} NH_4-N have been found associated with the degradation of organic matter from marine deposits (see Chapter 4).

Anthropogenic sources of nitrogen

The non-natural sources of nitrogen in rural areas generally are from animals (sheep, cattle, pigs and deer) on both irrigated and non-irrigated pasture, fertilisers (crop and horticul-



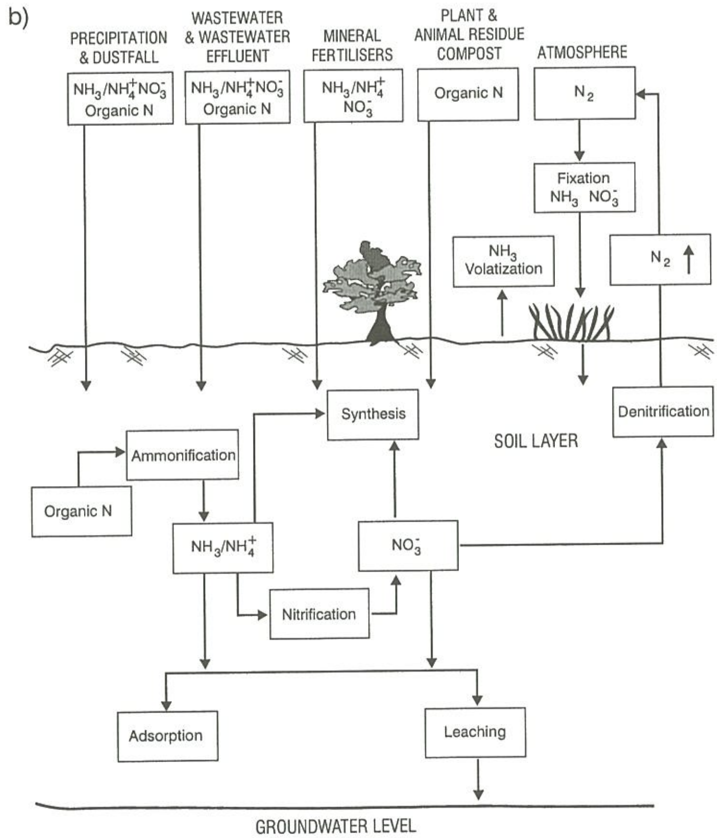


Figure 8.1 *a) The nitrogen cycle, including a contribution from geothermal sources, which may be important in New Zealand. b) Nitrogen transformations in the soil zone. Both figures modified from Canter (1997).*

tural lands) and human wastes (septic tanks and land treatment systems). In New Zealand, urine patches from animals are more important sources than fertiliser applications in pasture because clover is commonly used to fix nitrogen in the soil. But fertilisers are becoming more important in high-production pasture areas and are important sources of nitrogen in market garden areas such as Pukekohe, North Otago, and parts of Tasman District and Hawkes Bay. Tilling of soils for crops also mineralises natural organic nitrogen stored in the soil to nitrate, which can then be leached to groundwater during recharge events. In urban areas, leaking sewer pipelines may be the main cause of increased nitrogen concentrations in the shallow groundwater of New Zealand cities (Rosen et al. 2000a). Localised high nitrogen concentrations occur down-gradient of landfills and other types of industrial waste sites.

NITROGEN LOADING AND LEACHING RATES

Permitted nitrogen loading rates for controlled activities (such as land disposal of dairy or animal effluent, and fertiliser applications) currently range from 150-300 kg ha^{-1} yr^{-1}, although these rates have been higher (up to 600 kg ha^{-1} yr^{-1}) in the past (Lincoln Environmental 1997b). Regional councils specify the loading rates and the rate permitted varies from region to region. Fertiliser application may have a separate loading rate to animal wastes, but this is true for only a few regions.

Lincoln Environmental (1997b) summarised an extensive list of nitrate leaching rates for different agricultural land uses found in the New Zealand literature. Land use has a large effect on nitrate leaching, with leaching increasing as land use intensifies. Nitrate leaching from areas in natural vegetation is small, but leaching from pastoral areas can be high. Typical nitrate leaching rates range from 0 to 110 kg N $ha^{-1}yr^{-1}$ for sheep and dairy farms (Lincoln Environmental 1997b). Higher rates are associated with dairy farms and lower rates with non-irrigated sheep farms. Pig farms show relatively low leaching rates (12 kg N ha^{-1} yr^{-1} for a pig farm in Canterbury - Cameron et al. 1995), but measurements of nitrate leaching rates from crop areas in Pukekohe show relatively large losses (18 to 240 kg N ha^{-1} yr^{-1}). Spreading community sewage effluent on land may result in leaching rates of up to 205 kg N ha^{-1} yr^{-1}, but other systems may be much more effective at capturing nitrogen. For example, Rosen et al. (2000b) estimated that annual nitrogen leaching under the Taupo Land Treatment Facility, which is on free-draining pumice soils, is approximately 55 kg N ha^{-1} yr^{-1} or 10% of the nitrogen applied.

NITRATES IN GROUNDWATER

Historical information

Lincoln Environmental (1997a,b) compiled a lengthy review of the effects of nitrogen inputs on groundwater quality and a bibliography of New Zealand references to nitrogen contamination of groundwater. The bibliography listed 165 publications on the land application of nitrogenous wastes and nitrates in New Zealand groundwater (Lincoln Environmental 1997b). Table 8.1, modified from the report produced by Lincoln Environmental (1997b), summarises measured nitrate concentrations in New Zealand groundwater up to the end of 1999.

The first published study of nitrate contamination in New Zealand groundwater was conducted by Baber and Wilson (1972) in the Waikato region. At this time, awareness of increasing nitrate concentrations in groundwater was growing world-wide. Baber and Wilson found that some groundwater supplies in the Waikato were badly polluted by nitrate and that the nitrate originated from the highly productive clover/grass system of agriculture used in the region. Soon after this paper was published numerous other studies were conducted, primarily in the Canterbury region (Saffigna 1977; Quin and Burden 1979; Adams et al. 1979; Adams 1981; Sinton 1982), but also in the Waimea Plains (Stanton and Martin 1975), Hawkes Bay (Burden 1980b), and Rotorua (Grinsted and Wilson 1978). Of particular concern was the observed increases in nitrate concentrations in some areas.

Four major national surveys have been made

Table 8.1 *References dealing with nitrate contamination in New Zealand groundwater. Modified from Lincoln Environmental (1997b).*

Location	Groundwater properties	Nitrate concentration (g NO_3-N m^{-3})	Suggested major sources of nitrate	Reference
Amuri Plains, North Canterbury	Shallow, unconfined aquifer (1-5m depth)	2.0-10.7	Grazed pasture	Close (1987)
Ashburton	Shallow and unconfined aquifers	4-8 and in places >10	Grazed pasture, cropland	Burden (1984)
Ashley Catchment, North Canterbury	4% wells 32% wells	>10 >5	Grazed pasture, cropland	Bowden et al. (1982)
Aupouri Peninsula, Northland	-	<0.01-3.50	-	Smith et al. (1993)
Bay of Plenty	-	<0.001-4.3	-	Smith et al.(1993)
Canterbury	Shallow (24.4m) Deep (178.3m)	5 0.1	- -	Canterbury Reg. Council (1995)
Canterbury	Wells <40m deep	0.1-15	-	Smith (1993c)
Christchurch	Shallow and unconfined	Often >10 Deep <1	Grazed pasture, cropland, some point sources	Talbot et al. (1986)
Clutha Valley, Otago	-	<10	-	Close and McCallion (1988)
Clutha Valley, Otago	-	<0.2-5.3	Increased irrigation	Smith et al. (1993)
Wakatipu Basin aquifer	Unconfined shallow	Average = 1.8	Agricultural practices	Rosen and Jones (1998)
Wanaka Basin	Unconfined shallow aquifer	Average = 1.8 High = 42	Agricultural practices	Rosen and Jones (1998)
Gisborne	-	0-0.01	-	Smith et al. (1993)
Hamilton Basin	Shallow wells (<15m)	30% >10	Grazed pasture, dairy factory waste	Hoare (1986)
Hamilton Basin	Shallow bores	50% >10	Intensive dairying	Selvarajah et al. (1994)
Hauraki Plain	Wells	Most <10 (range up to 37)	Grazed pasture	Dewhurst (1981)
Heretaunga Plains	Unconfined aquifer	20-57	-	Burden (1980b)
Heretaunga Plains	Unconfined aquifer	0.3 - >100	Sheep feedlot	Rosen (1996)
Levels Plain, Canterbury	Unconfined shallow aquifer; 3-47m deep	0.4-14	Fertiliser works	Smith (1993a; 1993b)
Lincoln	Shallow wells	>10	Grazed pasture, cropland	Adams et al. (1979)
Mid-Canterbury	Wells 4-90m (<30m below water table)	0.1-10.0		Close et al. (1995)
Mid-Canterbury	Recharge by foothills run off and river seepage	0-3.5	Grazed sheep pasture	Quin and Burden (1979)
	Recharge by drainage from surface irrigation	6-12	Grazed sheep pasture	Quin and Burden (1979)
	Recharge from rainfall, river seepage and irrigation	5-20	Grazed sheep pasture	Quin and Burden (1979)
Manawatu	Wells 0-30m Wells >30m	3-13 <2	- -	Brougham et al. (1985)
Manakau, Horowhenua	Unconfined shallow gravel and sand aquifers	<0.5 to over 30	Septic tanks	McLarin et al. (1999)

Table 8.1 *References dealing with nitrate contamination in New Zealand groundwater. Modified from Lincoln Environmental (1997b). (continued)*

Location	Groundwater properties	Nitrate concentration (g NO_3-N m^{-3})	Suggested major sources of nitrate	Reference
Pukekohe	Upper unconfined aquifer	17-26	Intensive market gardens	Cathcart (1994) Rosen et al. (1999)
South Taranaki	-	0-28	Stock wastes	Smith et al. (1993)
Takapau Plains, Hastings	>6m deep	10-60	Meatworks effluent irrigation	Smith et al. (1993)
Waimea	-	97% >1 53% >10	Intensive horticulture	Cited in Burden (1982)
Waimea Plains	Unconfined aquifer	>10	Market gardening (N fertiliser), piggery waste	Fenemor (1987)
Waimea Plains	Lower confined aquifer	9.6	Piggeries and intensively fertilised land	Smith et al. (1993)
	Upper confined aquifer	12.6		
	Hope gravel aquifers	10.5		
	Appelby gravel unconfined aquifer	5.6		
Wairarapa	Deep confined aquifers	<7.5	-	O'Dea (1980)
National Groundwater Monitoring Network (NGMP) - 111 sites nationally	Varied, many of which included in the above aquifer listings	43% >1.0 26% >3.0 5% >11.3	Various sources	Rosen (1997) Rosen (1999) This chapter

of nitrate contamination in New Zealand groundwater (Askew 1985; Burden 1982; Dillon et al. 1989; Lincoln Environmental 1998), although Askew (1985) concentrates more on the economic and social implications of nitrate contamination rather than a full review of nitrate occurrence in New Zealand. The importance of nitrate contamination on a national scale is highlighted by the fact that no other single compound has been the subject of national surveys for its occurrence in groundwater. Although pesticide surveys have been conducted on a national scale (see below), the surveys have been conducted for a group of compounds.

The three published surveys (excluding Askew 1985) indicate that nitrate contamination of New Zealand groundwater systems is a problem in some areas of the country. The Waikato, Manawatu–Wanganui, Taranaki, Wairarapa, Tasman, and North Otago areas are all mentioned as problem areas in the latest report (Lincoln Environmental 1998). Additional areas of concern are Canterbury, Wellington (west coast), Southland (Hamill 1999) and Pukekohe (Cathcart 1995; Rosen et al. 1999). All of these areas have intensive agricultural land uses (dairy and horticulture) that contribute to the regional contamination. However, McLarin et al. (1999) recently blamed high nitrate concentrations in shallow unconfined aquifers around Manakau, Horowhenua on contamination from septic tanks systems and not agricultural practices in the area. In addition to land-use factors, local contamination related to poor well-head protection and large-diameter wells have been blamed for high nitrate concentrations in Southland (Hamill 1999).

Current national trends

Current trends in groundwater nitrate concentrations are difficult to evaluate. This is because historic data is patchy for many areas of the country, and regular sampling of the same wells over an extended period has not been carried out in most regions. Lincoln Environmental (1998) suggested that there is insufficient data to determine if nitrate contamination is becoming a problem in all regions of the country. Overall, the report suggested that incidences of "nitrate hot spots" would increase in the future.

The National Groundwater Monitoring Programme (NGMP) provides some indication of trends throughout the country (Rosen 1997, 1999). Quarterly monitoring of all regions of the country using 111 wells has taken place over the past two years, but some regions such as Tasman, Waikato, Manawatu-Wanganui and Bay of Plenty have participated in the NGMP for 10 years (see Chapter 4 for details).

Data from the NGMP database indicates that the average NO_3-N concentration in these wells is 2.6±5.4 g m^{-3}, but the median concentration is 0.7±5.3 g m^{-3} (See Table 4.3 in Chapter 4). The average and median concentrations were determined from the average and median values for each individual well, because some wells have considerably more measurements than others. Results of individual sampling events could not be used, as this would have biased the results. The concentrations range from below the detection limit (which is variable but generally <0.05 g m^{-3}) to 35 g m^{-3} NO_3-N. Greater concentrations have been recorded in New Zealand (>100 g m^{-3} NO_3-N from an unlined sheep feedlot in Hawkes Bay that has since been closed) in other datasets (Rosen and McNeill 1996), but the range in the NGMP is typical for most New Zealand aquifers. The high standard deviation of both the median and average values indicates that spatial variability in nitrate concentrations is high in New Zealand because of the variety of land uses and aquifer conditions (i.e. confined or unconfined) that have been sampled.

Five percent of the 111 wells sampled have nitrate concentrations greater than the New Zealand Maximum Acceptable Value (MAV), and 26 percent have average nitrate concentrations greater than 3.0, indicating a greater likelihood of anthropogenic causes for the high nitrate concentrations. The percentage of wells in the NGMP with concentrations greater than 10 g m^{-3} is the same as that for wells greater than 11.3 g m^{-3}. Although the size of the sample is small compared to the number of groundwater wells used for drinking water supplies nationwide, the percentages of contaminated wells are comparable to studies from other countries (Spalding and Exner 1993). For example, Madison and Brunett (1985) reported that about 6% of wells from the United States Geological Survey's National Water-Data Storage and Retrieval System (WATSTORE) database and Texas Natural Resources Information System (a combined sample of almost 124,000 wells) had NO_3-N concentrations greater than 10 g m^{-3}. About 13% had concentrations greater than 3.0 g m^{-3} NO_3-N. However, this study was conducted 15 years ago and the observed trends toward increasing nitrate concentrations in U.S.A. groundwater suggest the percentage of contaminated wells may have increased.

Many European countries and parts of the United States deliver groundwater to community supplies that may be above the WHO drinking water guidelines for nitrate (Spalding and Exner 1993). In New Zealand, the Ministry of Health does not permit water that is above New Zealand MAVs to be supplied to communities. Therefore, all municipal supplies in New Zealand are below the 11.3 g m^{-3} NO_3-N MAV, although some supplies, such as the Richmond water supply, must be mixed with low nitrate surface water to comply with this standard.

The Lincoln Environmental (1998) survey of nitrate contamination in New Zealand aquifers included a much larger database of nitrate concentrations than the NGMP and reported that a significant proportion of wells had nitrate concentrations greater than 50% of the New Zealand MAV. However, the report does not provide enough statistical information to compare the data with other studies or the NGMP data, which is included in the database used for the report. The report suggests that historical information on nitrate concentrations is lacking in many regions of the country, so that long-term comparisons cannot be made. However, the report also indicates that there is much more monitoring of nitrate presently (both regionally and nationally) and this will help in defining trends for the future.

Long-term records show variable trends in nitrate concentrations ranging from improving to deteriorating (Fig 8.2a-d). Land-use changes can lead to rapid increases in nitrate concentrations in shallow unconfined aquifers. Figure 8.2a shows an example of a change to market gardening in a very shallow (3 m deep) coastal aquifer in the Tasman District. During some market gardening operations the nitrate concentration increases dramatically over a short period of time. When the market gardening operations stop the nitrate concentration is reduced. Figure 8.2b illustrates a slow increase in nitrate concentrations over time that may not be recognised with infrequent monitoring. In this case the increase in NO_3-N over a six-year period has been small (less than 1 g m^{-3}). If only two measurements had been taken, one at the start and one at the end of the record, the difference in concentration could be attributed to analytical error. But with consistent sampling, the increasing trend is apparent. Seasonal patterns of increased nitrate concentrations after winter recharge are also apparent at a number of sites (Fig 8.2c and d), and from other studies (e.g. Rosen 1996). Figure 8.2c shows opposite seasonal trends in alkalinity and nitrate-nitrogen concentrations in a well at the Wainuiomata golf course. Both denitrification and dissimilatory nitrate reduction produce HCO_3 (alkalinity) as a product of the reaction. It is possible that nitrate is not increasing over the long term because of some form of denitrification. However, it is unusual for denitrification to occur in shallow unconfined aquifers such as this one. Seasonal variations may occur even when the overall trend is to lower nitrate concentrations. In the example shown in Figure 8.2d, nitrate concentrations have dropped from 4 g m^{-3} to less than 1 g m^{-3} in a well near a kiwifruit orchard in the Bay of Plenty, yet winter increases are still apparent, probably related to fertiliser applications.

Even relatively deep wells in confined aquifers may show significant variations in nitrate concentrations. A well in the confined area of the Heretaunga Plains aquifer (Hawkes Bay) at about 70 m depth shows variations of over 3 g m^{-3} (Fig 8.3). This well is located in an area of apple orchards and sheep grazing, but the recharge area has mixed land uses. Therefore, the source of nitrogen to this well is difficult to determine.

Burden (1984) showed nitrogen concentrations decreasing with depth in the central plains of Canterbury; this was also shown for the Amuri Plains (Close 1987). A similar relationship has been shown in other countries (Spruill 1983; Madison and Brunett 1985). The relationship between nitrate concentration and depth for NGMP wells in New Zealand is not clear (Fig 8.4), but the data suggest that nitrate concentrations do generally decrease with depth. Confined and semi-confined aquifers are less likely to have high nitrate concentrations (Fig 8.5), but they are not immune to nitrate contamination. In general, aquifers deeper than about 50 m tend to have lower nitrate concentrations, due either to dilution or to denitrification within the deep aquifers, which are commonly confined.

Modelling nitrate transport

Nitrate transport in groundwater has not been modelled frequently in New Zealand. Most researchers treat nitrate as a conservative ion and assume that all nitrate entering the aquifer from the vadose zone will remain in the aquifer (with some dilution) and exit the aquifer at the discharge area. While this is a reasonable assumption for most unconfined aerated aquifers, it does not apply to all conditions. However, it is often difficult to prove that denitrification or dissimilatory nitrate reduction is taking place in an aquifer without intense investigation of a system at a relatively fine scale.

One example of nitrate transport modelling in New Zealand is illustrated by Wang et al. (1998) for a shallow unconfined aquifer at Waitahanui, near Taupo, that receives wastewater from a sequential batch reactor sewage treatment plant. Sewage is disposed of directly into groundwater through a soakage trench after treatment in the plant. Using field measurements of nitrate, ammonium and chloride and NO_3/Cl ratios, Hadfield (1995) determined that denitrification was the main mechanism

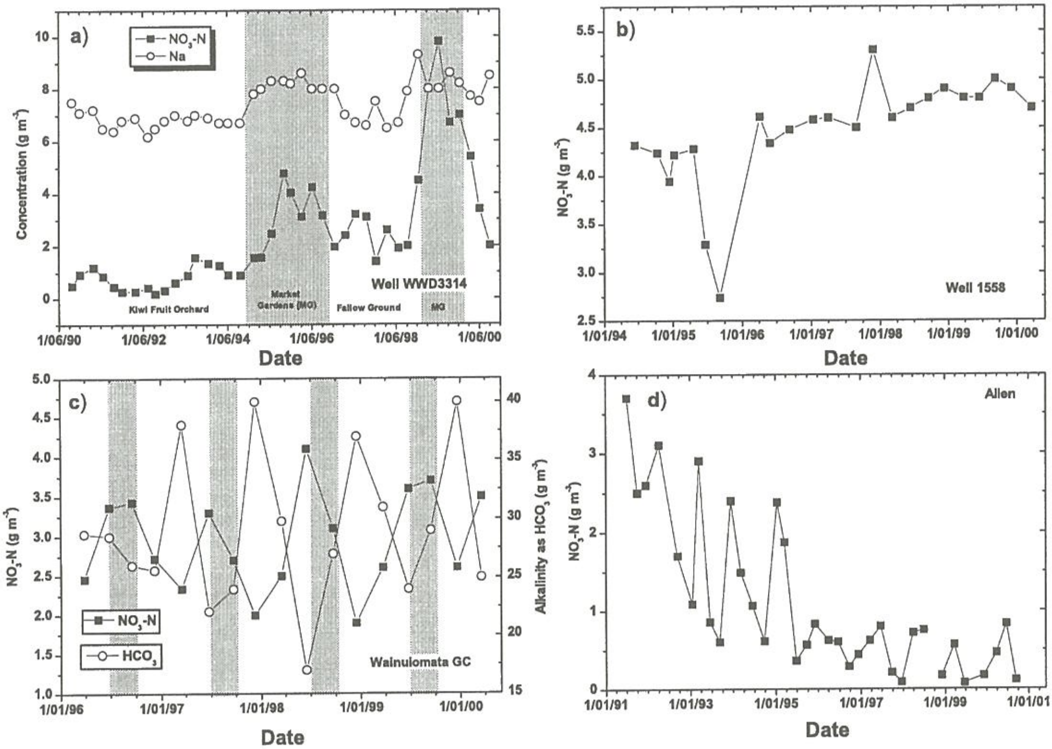


Figure 8.2 *Examples of nitrate-nitrogen concentrations plotted against time for four wells in the NGMP. a) Rapidly increasing nitrate concentrations for a shallow well (3 m depth) in the Tasman District caused by changing land use. Over the same period sodium concentrations change only marginally. Shaded areas represent periods of market gardening activity. b) Small but consistent increases in nitrate-nitrogen near a dairy farm in the Hawkes Bay. c) Seasonal variation in nitrate-nitrogen concentrations and alkalinity near a golf course well in Wainuiomata. The variations are almost exactly opposite to each other. Shaded areas represent the winter months. d) Seasonal variation in nitrate-nitrogen concentrations, but with a decreasing concentration trend, near a kiwi fruit orchard in the Bay of Plenty.*

that explained the decrease in nitrate within a short distance of the disposal trench. A mathematical model describing nitrogen dynamics in groundwater and the unsaturated zone was used by Wang et al. (1998) to model nitrogen transformations. The model simulated transport and transformations of oxygen, substrate, and organic and inorganic N species. They used both first-order kinetic and comprehensive denitrification models to simulate denitrification. Relatively good agreement was found between simulated and measured concentrations of nitrate using both the first-order and comprehensive models during a one-year monitoring period. However, the first-order denitrification model may not be suitable for simulating nitrogen dynamics over long periods of time (Wang et al. 1998).

The comprehensive denitrification model uses the measured oxygen status of the groundwater and the availability of substrate (as a carbon source) to calculate the rate of denitrification. However, because data on the dissolved oxygen and total organic carbon concentrations were not available when this study was done, estimates of these parameters were used in the comprehensive denitrification model (J. Hadfield pers comm., June 2000). These data have subsequently been collected and simulations will be rerun to determine if

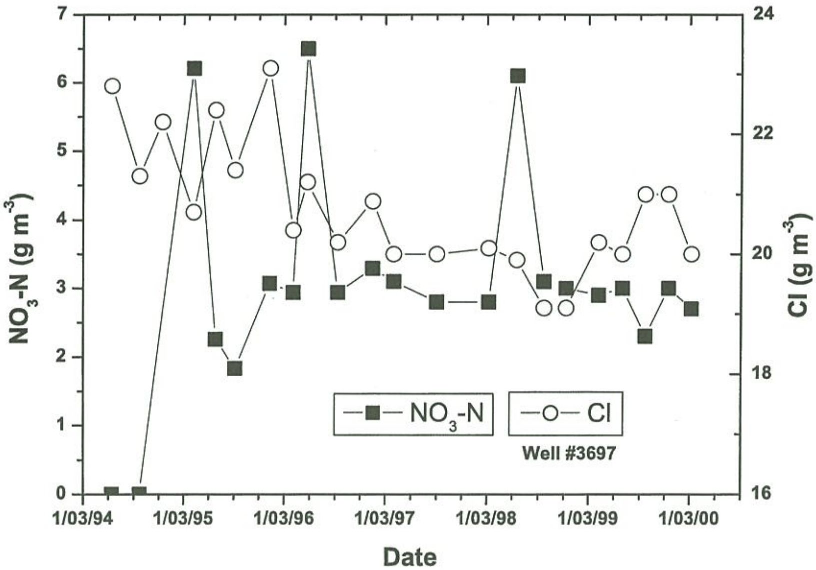


Figure 8.3 *Changes in nitrate-nitrogen concentration with time in Well 3697 located in the confined area of the Heretaunga Plains The aquifer is at about 70 m depth. Chloride concentrations do not show the same variations as the nitrate.*

the comprehensive denitrification model is more suitable, and if field data support the inference that denitrification is taking place in a shallow unconfined aquifer.

The simulations showed that the size and peak concentrations of the nitrate plume from the soakage trench under the given hydraulic conditions are mainly controlled by the rate of effluent discharge, the N concentration of the treated effluent and the rate of denitrification. The annual amount of rainfall recharge does not appear to significantly affect the vertical distribution of nitrogen in the aquifer.

The advantage of using computer model simulations is that denitrification processes can be explored, even for aquifers where intuition would leave one to believe that denitrification was unlikely, i.e. where the aquifer is shallow, unconfined and well oxygenated. Wang et al. (1998) have shown that denitrification cannot be ruled out in these aquifers if the right conditions are present.

Treatment

Nitrogen is very expensive to remove from groundwater once it has penetrated to the water table. Ion exchange mechanisms are the most effective way of removing nitrate from groundwater, but are expensive (Canter 1997). Other methods of reducing nitrate concentrations include biological denitrification, algal ponds, reverse osmosis, electrodialysis, chemical reduction, distillation and blending (Burden 1982). Blending–mixing in low-nitrate water–is currently being used to reduce nitrate concentrations in the Richmond water supply (Tasman District). Recent work in New Zealand and overseas has shown that shallow groundwater (less than a few metres depth) can be renovated using permeable reactive barriers (Robertson and Cherry 1995; Schipper and Vojvodić-Voković 1998, 2000). These barriers are constructing by trenching down to 1-2 metres below the water table using a backhoe. The trench is then filled with a combination of untreated sawdust and soil taken from the trench. The sawdust acts as a source of organic matter that stimulates the conversion of nitrate to nitrogen gas by denitrification (Schipper and Vojvodić-Voković 1998). Other fill materials can be used in the trench, including zeolites, bark, or other types of organic matter.

The key elements to the success of the trench system are that the groundwater must be shal-

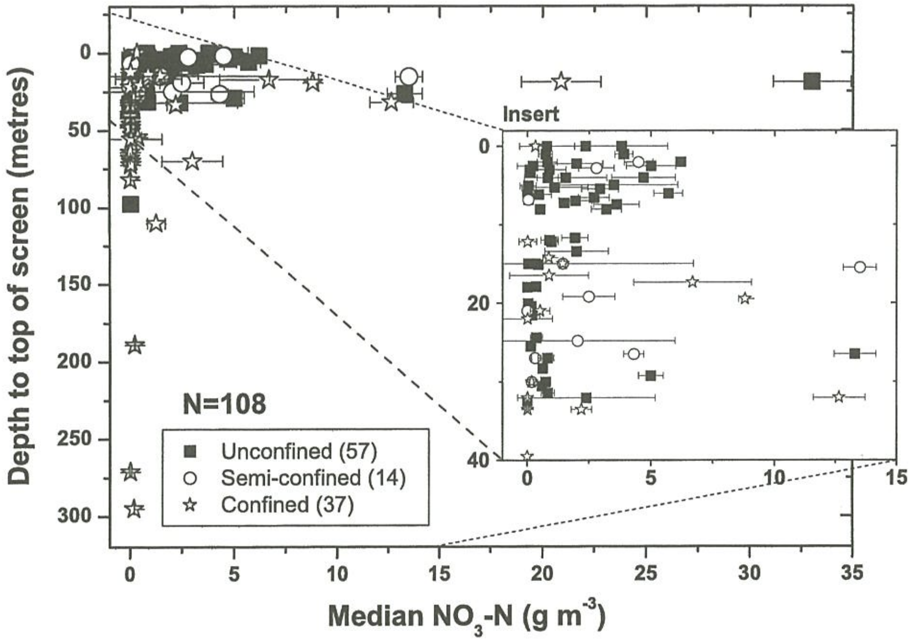


Figure 8.4 *Median nitrate concentration of wells in the NGMP plotted versus depth to the top of the screen. Samples from depths shallower than about 50 m have higher nitrate concentrations than those from deeper wells.*

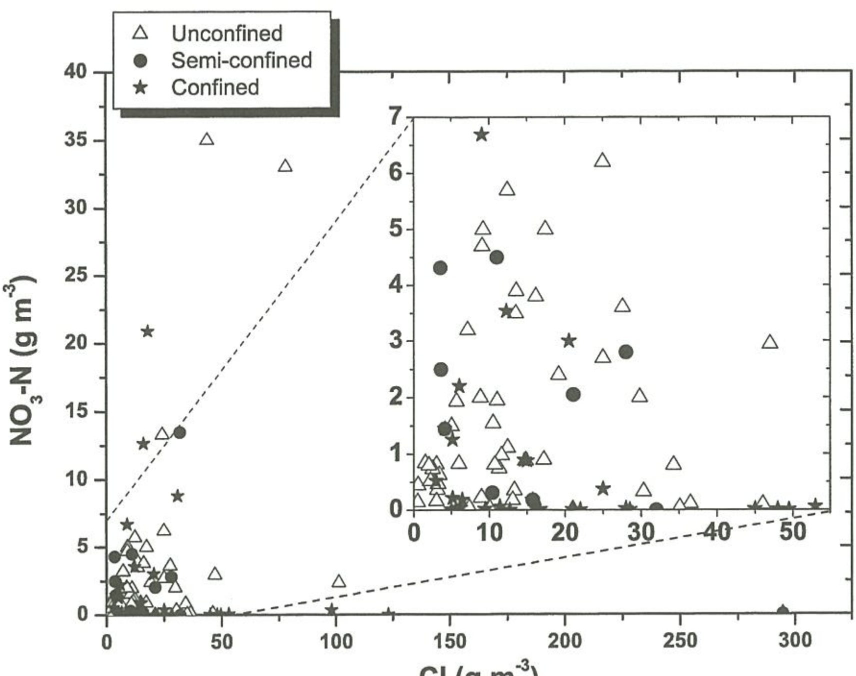


Figure 8.5 *Median nitrate concentration of wells in the NGMP plotted versus median chloride concentrations, grouped as confined, unconfined and semi-confined wells.*

low (less than 2 m below the surface), sufficient organic matter must be present in the wall to promote denitrification over a long period of time, and the barrier must be permeable enough so that groundwater will not travel around or under the wall. Ideally, the wall should be placed to a depth that will not allow groundwater to travel below the wall, but in many cases this is not practical because the aquifer thickness is too great. Therefore, the most appropriate places to use denitrification trenches are at groundwater discharge zones (i.e. near rivers, lakes or the coast) where the nitrate plume can be well defined. The technique is relatively inexpensive to implement, but because it can only be used in limited situations it is not the solution to all nitrate contamination problems.

It is best to prevent nitrate contamination before it occurs rather than to remediate the results of poor land management, because the most effective technologies available to remove nitrate from a drinking-water supply are expensive.

FATE AND TRANSPORT OF PESTICIDES IN NEW ZEALAND'S AQUIFERS

In this section we consider the types and usage of pesticides in New Zealand. The factors controlling the entry of pesticides through the soil and into and through the groundwater systems are discussed, followed by a critical review of New Zealand studies which have examined pesticide fate and transport in a range of New Zealand soils and groundwater systems. The monitoring and occurrence of pesticides in New Zealand groundwater systems is described, followed by a discussion of temporal variability, point sources, and remediation of contaminated sites. A few examples of interactions of contaminated groundwater with surface water are given and the relationship between nitrate and pesticides in groundwater is discussed.

A variety of types of pesticides are in common use in New Zealand, and their active ingredients have been detected in groundwaters. The active ingredients can be found in a number of commercial formulations, mixed to a variety of ratios. In addition, pesticides formulations are often combined; for example a herbicide to kill existing weeds will be mixed with another to prevent the emergence of new growth. Active ingredients can also metabolise into daughter degradation products with different characteristics to the parent. Consequently, when a pesticide is detected it can be difficult to attribute it to a single source or formulation, or even to know if it is the original compound.

Use and types of pesticides in New Zealand

New Zealand does not have a system in place to gather detailed records on pesticide usage and it is reasonably difficult to obtain good information that can be used for research, policy and management decisions. Wilcock (1989) and Wilcock and Close (1990) carried out surveys of pesticide usage in the North and South Islands, respectively, in the late 1980s. Their data were reported by district for individual pesticides and were based on land use data for each district combined with average pesticide spray schedules for each land use. They indicated that around 4000 tonnes of active ingredients (ai) were applied annually, with around 60% of this amount being herbicides. Most of the pesticide use (72%) was in the North Island.

However, over a period of time the use of some pesticides will decline as other newer pesticides come into widespread use and as land use patterns change in some areas. In 1999 the Ministry for Agriculture and Forestry (MAF) commissioned a survey on pesticide use in New Zealand (Holland and Rahman 1999). They found that total pesticide use (excluding mineral oil) grew from about 3300 tonnes (ai) per annum in 1983 to a peak of about 3700 tonnes (ai) per annum in 1994 and then declined to the 1998 total of 3300 tonnes. Herbicides continue to dominate pesticide use (68%), followed by fungicides (24%) and insecticides (8%).

There are several ways of classifying pesticides. The first classification is by the biota they control, for example, herbicides control plants and insecticides control insects. A second classification is the chemical group to which they belong. Triazine pesticides all have a triazine ring with three nitrogen atoms at the centre of the molecule, with other chemical groups added on. Organochlorine pesticides have chlorine atoms in their structure. Some of these chemical groups are more general than others, so there can be overlaps and subsets. For example, the triazines are a subset of the organonitrogen pesticides. A third classification is a broader chemical classification according to the method of their analysis. Pesticides can be referred to as neutral pesticides, which refers to the extraction method used in their analysis. Each classification has advantages in certain conditions, with the first two probably more useful than the third. The herbicide-insecticide-fungicide system is useful when considering what pesticides are likely to be used for a given land use. The chemical group classification is useful for considering whether certain pesticides are likely to leach into groundwater or persist in the environment, and the analytical method classification can indicate the range of pesticides that are likely to be detected by a particular screening method. Weber (1994) has a good discussion of pesticide properties for 16 chemical classes of pesticides.

Pesticides have a wide range of toxicity for humans. Insecticides tend to be more toxic than fungicides and herbicides, reflecting the greater similarity of the target organisms to humans. The Ministry of Health (2000) has derived Maximum Acceptable Values (MAV) for most pesticides found in groundwater. The values are set on the basis of no observable effects on humans for a lifetime consumption. They vary from 0.03 mg m^{-3} for aldrin + dieldrin (organochlorine insecticides) to 400 mg m^{-3} for hexazinone (triazine herbicide).

ENTRY OF PESTICIDES INTO GROUNDWATER

Pesticides can enter groundwater systems in several ways:

- by leaching of pesticides applied during normal agricultural and horticultural operations through the soil and unsaturated zones;
- by leaching of pesticides used in industry, including spraying along roads, railways, and around buildings. In some of these operations, soakholes are used to dispose of excess runoff, and pesticides may gain easier access to groundwater;
- by recharge of groundwater by contaminated surface water;
- point-source entry of pesticides into groundwater due to inappropriate storage near wells and inadequate well-head protection.

As the use of pesticides in some circumstances is beneficial or even necessary, there is need to manage their application to maintain the benefits while minimising or eliminating any leaching. The third mode is not generally a problem in New Zealand but has been noted overseas, where surface water is often polluted due to intensive agricultural and industrial land use. Well maintenance practices and the management and storage of pesticides should be improved to eliminate the fourth route of pesticide contamination of groundwater. DeMartinis and Cooper (1994) suggests several management options, including well inspections, proper storage and disposal of pesticide containers, rinsing of spray equipment away from wells and appropriate disposal of rinsate, mixing and loading pesticides away from wells, and protection of features such as sinkholes from runoff containing pesticides.

Table 8.2 summarises different modes of direct entry for pesticides into groundwater and indicates management options for preventing or minimising these sources of contamination.

The factors controlling the entry of pesticides into groundwater need to be understood before groundwater contamination by pesticides can be reliably assessed. Most research to date has focused on the factors controlling the transport and fate of pesticides in the soil, particularly the topsoil, as this largely determines the amount of pesticides entering the groundwater. Two important factors in pesticide leaching to groundwater are how fast the pesticide moves and how long it persists. Related topics, such as pesticide efficacy on target organisms and toxicity to other non-target plants and biota, and pesticides in surface run-off, will not be covered here.

Factors controlling pesticide transport and fate in soil

The mobility of a pesticide is determined by the movement of soil water and the retardation

Table 8.2 *Modes of direct entry of pesticides to groundwater and means of preventing their entry (compiled from information in DeMartinis and Cooper (1994).*

Direct entry pathways		
Man-made	Natural	Prevention methods
• Faulty well casings and/or screens • Poor well-head protection (including seals at the land surface and protection from runoff) • Corroded or damaged well pumps or pipes • Drainage wells • Improperly abandoned wells (including those located under cultivated land) • Site-specific farm management practices • Back siphoning	• Sink-holes • Macropores created by roots • Fissured clay soils (shrink-swell processes) • Animal & insect burrows • Solution cavities • Surface runoff from treated crops and oils • Contaminated surface water recharging groundwater	• Inspections and maintenance of well-head protection • Old wells properly decommissioned • Empty or partially filled containers should be stored away from wells and disposed of so they do not pose a threat to groundwater • Spray equipment rinsed as far as practicable away from wells • Mixing of chemicals should be away from wells • No storage of chemicals in well sheds or shelters • New wells constructed above flood plains and streams and away from potential contaminant sources • Monitoring and maintenance of chemigation wells equipped with back-flow prevention devices • Buffer zones (grass filter strips) created around sinkholes and other natural features to protect wells against surface runoff or re-routing surface water flow away from them

of the pesticide by adsorption to organic material and soil. For most pesticides, most adsorption takes place on soil organic matter, and adsorption will dominate when the mass fraction of organic matter in the soil exceeds 0.1% (Barbash and Resek 1996). Adsorption is measured by the adsorption or distribution coefficient, K_d, defined as the ratio of the pesticide concentration in soil to the pesticide concentration in water. Because organic matter is so important, the soil organic carbon adsorption coefficient, K_{oc}, is used to standardise between soils for comparisons. K_{oc} is defined as K_d divided by the fraction of organic carbon in the soil. As the organic matter content is usually greatest in the topsoil, pesticides will be adsorbed, and hence retarded, to the greatest extent in the topsoil, and will move more quickly once they pass below this layer. K_{oc} values can range from close to 1 for a very mobile pesticide such as picloram (K_{oc} = 16 mL g^{-1}), to very high values for immobile pesticides such as DDT (K_{oc} = about 400,000). Soil pH can be important for ionisable pesticides, which can become positively or negatively charged and bind strongly to clay and other minerals in the soil.

The movement of soil water is the transport mechanism for pesticide leaching. Thus pesticide leaching will be much greater in high rainfall areas with high infiltration and little runoff. Water movement pathways are important as well. If the water moves uniformly through the entire soil then there is opportunity for the pesticides to interact with all the organic matter. However, if some of the water moves through macropores in the topsoil, such as cracks or wormholes, then any pesticides in the water will also bypass the soil matrix, where the organic matter and micro-organisms are concentrated, and thus the pesticides will travel further and persist longer. Macropore or preferential flow affecting pesticide leaching has been identified both overseas (e.g., Barbash and Resek 1996) and in New Zealand (e.g., Close et al. 1999a). Pesticide adsorption to colloidal particles may also increase the mobility of strongly sorbed pesticides.

Pesticides become degraded in three main ways: photodecomposition, chemical transformation, and microbial degradation. Other ways for pesticides to be lost are by volatilisation, spray drift, and uptake by plants. These losses can be quite significant in some conditions and need to be considered when assessing the amounts of pesticide likely to leach into the groundwater system.

Photodecomposition can occur while the pesticide is on the surface of plants or soil. It is very dependent on the application method, sunlight intensity, rainfall and irrigation practices, and on the properties of the pesticide. There are many chemical transformations that can take place in the subsurface (Barbash and Resek 1996). Soil pH, ionic strength, temperature, redox-active species such as dissolved oxygen, and surface-active substances such as organic matter can all influence the reaction rates. As microorganisms mediate most of these transformations, the reaction rates will also be affected by soil moisture, by the size, health and species composition of the microbial population, by the availability of nutrients, and by the chemical structure and concentration of the pesticide itself. The factors affecting bacterial degradation of pesticides have been reviewed by Aislabie and Lloyd-Jones (1995). Sparling et al. (1998) measured degradation of atrazine in three New Zealand soils and demonstrated that temperature, soil moisture content, and the number of atrazine-degrading microbes present in the soil significantly affected mineralisation rates. They also showed that the total microbial population is not as important as the population of organisms able to degrade the particular pesticide.

Degradation rates are usually reported as field half-lives—to a first approximation, pesticides exhibit exponential decay in soils. There is generally a wide range in reported rates of field degradation and this parameter is the most uncertain of those affecting pesticide transport (Hornsby et al. 1996). This reflects the wide range of factors that influence pesticide transformations and the complex nature of the transformations. In addition, a single half-life value may apply for only a few half-lives and then the compound exhibits increasing persistence, as the more rapidly degraded fractions are lost.

Although degradation generally results in decreased pesticide concentrations, intermediate breakdown products or metabolites can be formed that may be more or less toxic, mobile and persistent than the parent compound. For example, aldicarb rapidly breaks down to form aldicarb sulfoxide and aldicarb sulfone, which are more persistent and also more mobile than aldicarb. One of the commonly observed metabolites of atrazine, desethylatrazine, is more mobile than atrazine and has been detected at low concentrations in both field studies in New Zealand and in the 1998/99 national groundwater survey (Close and Rosen 2001).

The extent and rate of transformation and the mobility of a pesticide are interdependent: adsorption can reduce bioavailability, and movement from a zone of high microbial activity to one of lower microbial activity will also slow degradation, while degradation reduces the amount of the pesticide with a potential for movement.

Factors controlling pesticide transport and fate in the groundwater

The factors controlling pesticide transport and fate in the groundwater are largely the same as in the soil but, because the environment is quite different, the rates of the process can be very different. In particular, levels of organic carbon in groundwater systems are usually very low. There are relatively few measurements available, but levels of 0.04% have been measured in Canterbury alluvial gravels and 0.11% in Hamilton coarse sand (ESR, unpublished data). In the overseas studies, values often range between 0.02 and 0.2 % organic carbon for British aquifer systems (up to 2% for limestone - Foster et al. 1991); between 0.1 and 0.3% for three aquifers systems in the United States (Levy and Chester 1995; Rodriguez and Harkin 1997), and less than 0.05% in three Dutch aquifer systems (Weijnen et al. 1990). This compares with mean values of organic carbon of about 5-6% (range 0.4 to 20%) for topsoils and around 2% for subsoils in New Zealand (Tate et al. 1997; Kevin Tate pers. comm. 2000). This indicates that adsorption to clay and other minerals will be as or more important than to organic matter in groundwater systems. The usefulness of K_{oc} as a parameter for adsorption will be limited for comparisons between groundwater systems and also between some subsoils. Pang et al. (2000) found that K_{oc} was not a useful parameter for subsoils in Hawkes Bay, probably because of

Table 8.3 *Mobility and degradation of pesticides in New Zealand soils.*

Soil Type	Depth (cm)	Pesticide	Half-life (days)	Mobility (K_{oc})	Field or Lab.	Reference
Horotiu sandy loam	0-20@	hexazinone	113	50-60	Field	Close et al. (1999b)
		procymidone	28	138		
		atrazine	59	123		
		terbuthylazine	104	62		
		picloram	no degrad	22		
		triclopyr	no degrad	25		
		2,4-D	45	28		
Horotiu sandy loam	0-10	Nicosulfuron	9.8	nd	Field	James et al. (1999)
8 soils from Nelson Marlborough & Hawkes Bay	not given	Amitrole	2.1 (1)*	200		McNaughton et al. (1999)
		Diuron	65 (14)	530	Lab	
		Linuron	33 (14)			
		Procymidone	34 (23)	580		
		Simazine	24 (7)			
		Terbuthylazine	46 (7)			
Te Awa silt loam#	0-30	Picloram	200-1270	19-30	Field	Close et al. (1998, 1999a); Pang et al. 2000
		Atrazine	57-126	29-60		
		Simazine	59-145	50-100		
	30-70	Picloram	$986\text{-}3.9\times10^6$	23-43		
		Atrazine	139-348	29-222		
		Simazine	67-80	50-390		
Twyford fine sandy loam#	0-30	Picloram	244-480	45-47	Field	Close et al. (1998, 1999a); Pang et al. (2000)
		Atrazine	20-35	7-67		
		Simazine	15-16	0-16		
	30-110	picloram	>2000	45-64		
10 soils with a total of 32 horizons	mean of up to 4 horizons	metsulfuron methyl	nd	14 (5)*	Lab	Baskaran et al. (1996)
		atrazine	nd	61 (31)		
		2,4-D	nd	110 (48)		
		phorate	nd	368 (92)		
		terbufos	nd	425 (95)		

no degrad : no degradation   nd : not determined   * : mean with standard deviation in brackets
: parameters for these soils were estimated using 3 different models - see references for further details.
@ : degradation values were also estimated for the subsoil.

the low organic carbon content and adsorption to mineral surfaces.

The microbial population is much lower in groundwater systems and thus degradation is much slower. Pothuluri et al. (1990) measured degradation half-lives in the laboratory for alachlor of 23 days for soil, 73 to 285 days for subsoil, and 320 to 324 days for aquifer material, under aerobic conditions. They found that degradation for alachlor under anaerobic conditions was much slower, indicating that the effect of redox potential on pesticide degradation in groundwater systems can be significant. Levy and Chesters (1995), in a 2.5 year field study of a shallow sandy-till aquifer in Wisconsin, estimated degradation half-lives for atrazine and desethylatrazine of 3470 and 2770 days, respectively. These field-based rates are much slower than degradation rates indicated by laboratory measurements. The long time period for their study was necessary to obtain these estimates, and a number of other studies over shorter time periods have detected little or no degradation in groundwater of the pesticides under study (e.g., Rodriguez and Harkin 1997). Temperature has an effect on pesticide degradation, with lower degradation rates at lower temperatures. The effect of pH on pesticide degradation varies with the chemical structure of the pesticide, with generally greater persistence of pesticides at low pH (United States Environmental Protection Agency 1992).

The degradation of pesticides in groundwater is likely to be slow, and the pesticides may be only slightly retarded by the aquifer material. Pesticides in groundwater become attenuated mainly by mixing due to advection and dispersion. This effect can be quite large, particularly for groundwater systems in coarse alluvial gravels, which often have additional recharge from nearby rivers. Such groundwater systems are common throughout New Zealand.

NEW ZEALAND STUDIES ON TRANSPORT AND FATE OF PESTICIDES

The majority of New Zealand studies on the transport and fate of pesticides have focused on topsoil, and are predominately laboratory-based, e.g., Rahman and Holland (1985), Bolan and Baskaran (1996), and Baskaran et al. (1996). These studies are useful in assessing the relative likelihood of leaching among different pesticides and soil types and have the additional advantage of being relatively cheap and easy to carry out. These types of studies have been carried out on a wide range of New Zealand soils and pesticides (Table 8.3). Laboratory degradation rates, however, may differ significantly from those measured under field conditions, due to differences in factors such as moisture and temperature that affect degradation greatly (Di et al. 1998). Rahman et al. (1991) developed a bioassay method for assessing mobility and persistence of pesticides. This method is useful for assessing pesticides such as sulfonylurea herbicides, which have high levels of activity and thus low application rates, making them difficult to detect at levels that are still herbicidal. The main limitation with this method is that it is not quantitative. The pesticides in Table 8.3 have generally been selected on the basis of common usage, detection in groundwater, and a high likelihood of leaching. In some cases a pesticide has been selected so that a wider range of leaching characteristics is available to assist in model evaluation.

The number of field-based studies in New Zealand is very small (Table 8.3). In a joint research programme, ESR, Landcare Research, GNS, and various regional councils have carried out field-based studies on the transport and fate of selected pesticides at three sites. These studies include a Te Awa silt loam and a Twyford fine sandy loam in Hawkes Bay (Close et al. 1999a), and a Horotiu allophanic soil near Hamilton (Close et al. 1999b). They have involved application of selected pesticides and tracers to a 15 by 15 m field site, followed by monitoring of pesticides using suction cups and, at the Hamilton site, soil sampling. Groundwater was also monitored at each site using an array of shallow wells.

The mobility and degradation characteristics of each pesticide were determined by inverse modelling using several readily available pesticide leaching models and are given in Table 8.3. There is a lot of variability in pesticide attenuation characteristics and the studies showed that, in New Zealand soils, values for these characteristics could be quite different from average values in the literature (Close et al. 1999a).

Picloram was observed in the groundwater monitoring wells at both Hawkes Bay sites following major recharge events (Pang et al. 2000). The highest concentrations were detected immediately beneath the application areas, as would be expected, with lower concentrations in wells up to 22 and 53 m down-gradient at the Twyford and TeAwa sites, respectively. At the Horotiu site hexazinone and procymidone were detected in several wells about 10-15 m down-gradient of the site, with desethylatrazine, a degradation product of atrazine, also detected on two occasions.

Groundwater tracing experiments were carried out to assess the attenuation of atrazine and picloram in an alluvial gravel aquifer (Pang and Close 1999). They found no retardation or degradation of either pesticide in the aquifer over a distance of 90 m within a period of 49 hours. Longer batch experiments indicated significant degradation of atrazine with time, but little, if any, degradation of picloram. Tracer experiments in a coarse sand aquifer near Hamilton, using tritiated water as a conservative tracer, indicated little retardation of hexazinone, with more retardation of atrazine and procymidone (ESR, unpublished data). Degradation was least for hexazinone, followed by atrazine, then procymidone.

James et al. (1994) undertook a study of the movement of atrazine in soil and groundwater in the Waikato region. The site was on a Horotiu sandy loam soil and was used for maize. Atrazine was applied at a rate of 1.5 kg ha^{-1}. Groundwater samples were collected monthly from two shallow wells installed at the site. Atrazine was detected at concentrations between 0.06 and 0.26 mg m^{-3}, 2-5 months after the application. The MAV for atrazine is 2 mg m^{-3} (Ministry of Health 2000).

James (1995) carried out a field study on the movement of bromacil in soil and groundwater. Bromacil was applied to a field of asparagus at a rate of 2 kg ha^{-1} at two sites in the Waikato region. One site had six wells available for monitoring and the other had four wells. Bromacil was found in five wells on all sampling dates at site 1, with concentrations of up to 84 mg m^{-3}. Bromacil persisted, at decreasing concentrations, for at least two years after application. At site 2 groundwater concentrations were much lower, with a maximum of 0.34 mg m^{-3}. Site 2 had high levels of organic matter in the soil, which presumably reduced the leaching of bromacil. The provisional MAV for bromacil is 400 mg m^{-3} (Ministry of Health, 2000). Thus, although the levels of bromacil were quite high, they were still significantly below the MAV for drinking water.

Several pesticide leaching models have been used to simulate pesticide movement under New Zealand conditions. These include GLEAMS (Close et al. 1998); LEACHM (Close et al. 1999a; Webb and Lilburne, 2000); HYDRUS-2D (Pang et al. 2000) and RZWQM (Rahman et al. 1999). Green et al. (1999) report the development of a leaching model called PESTRISK, which uses a database of pesticide properties, to assist in the assessment of current pesticide use in the environment. These models vary in complexity, the processes that are considered, and in the amount of input data they require. HYDRUS-2D is the only 2-dimensional model so far used that is able to simulate the linkage with the underlying groundwater system. The lack of consideration of the effects of preferential flow on pesticide movement is a limitation in most of the available models.

DETECTION OF PESTICIDES IN NEW ZEALAND'S GROUNDWATER SYSTEMS

In New Zealand pesticides in groundwater have been monitored mainly in the last 10 years. Monitoring in the early 1990s was briefly reviewed by Close (1995). There have been three main purposes for such monitoring: (1) monitoring of public water supplies for comparison with Maximum Acceptable Values (MAVs) in the drinking water standards; (2) surveys of "at risk" wells to assess the likely magnitude of pesticide contamination (worst case situation); and (3) general monitoring of the groundwater resources in a region. Each type of survey targets a different group of wells and can be expected to show different levels of pesticide contamination.

The Ministry of Health co-ordinates monitoring of registered community drinking water supplies. It concentrates monitoring for pesticides in drinking water supplies on areas where pesticide use is significant and the water is considered "vulnerable". To date, only one pesticide, dieldrin, has been detected at over half of its MAV, which is 0.03 mg m^{-3} (Ministry of Health 2000), in one small rural supply. Pesticides have been detected at very low concentrations in only four other supplies out of a total of 483 assessed registered groundwater supplies, indicating that the occurrence of pesticides in drinking water supplies is very low. These results are covered more extensively in chapter 10 on Groundwater and Health by Helen Davies. Other surveys of groundwater have tended to focus on "at risk" wells, as sampling and analysis for pesticides is very expensive and it is usually necessary to restrict sampling to obtain the most information for the available funds.

Nationally co-ordinated surveys of pesticides in groundwater have been carried out in 1990, 1994 and 1998/99. Little monitoring of pesticides in groundwater had taken place before the first of these surveys, and its main purpose was to assess whether any pesticides were entering the groundwater and what, if any, was the likely magnitude of the contamination. A worst case approach was taken (Close 1993a) and 17 regions throughout New Zealand were ranked using an index of potential pollution that considered pesticide usage, mobility, and persistence, and relative groundwater vulnerability, based on the DRASTIC ranking. The DRASTIC ranking considers Depth to water table, Recharge, Aquifer media, Soil media, Topography, Impact of the vadose (unsaturated) zone and hydraulic Conductivity. Six of the higher-ranked regions were selected for sampling. A total of 82 wells were sampled, with 6 wells (7%) having detectable levels of pesticide (Close 1993b). Seven different pesticides were detected, mostly at concentrations < 1 mg m^{-3} (Table 8.4). However, one well had 37 mg m^{-3} of atrazine, which is significantly higher than the MAV of 2 mg m^{-3} (Ministry of Health 2000). Thus, although the levels found in the 1990 survey were generally very low, the survey established that unconfined groundwater systems in New Zealand could be contaminated by pesticides, and in some cases there could be significant contamination. This survey set the scene for subsequent national surveys and the more intensive regional monitoring carried out by many of the Regional and District Councils.

The national surveys in 1994 (Close 1996) and in 1998/99 (Close and Rosen 2001) aimed to provide a more even spatial distribution, with sampling in most regions throughout New Zealand. Within each region there was a balance between shallow unconfined wells in areas of high pesticide use and aquifers of importance to the region. In 1994, 79 wells were sampled throughout New Zealand, with an additional 39 wells sampled in a more intensive survey in Marlborough. No wells had pesticide levels above the Maximum Acceptable Value (MAV) for drinking water (Ministry of Health 2000). Pesticides were detected in 16 out of the 118 wells sampled (13.6%), with most (78%) levels below 1 mg m^{-3}. Ten different pesticides were detected, with the triazine group being the most frequent (Table 8.4). In 1998/99 a total of 95 wells were sampled in 15 regions. The detection limits for this survey were significantly lower than those for the 1990 and 1994 surveys. Pesticides, including triazine metabolites, were detected in 33 wells (35%), with 18 wells (19%) having two or more pesticides detected. Most concentrations were less than 0.1 mg m^{-3}. There were one or more wells with pesticides detected in 11 out of the 15 regions (Fig 8.6). About 76% of the pesticides detected were triazines, with 9% of these being above 1 mg m^{-3} and 74% below 0.1 mg m^{-3}. If detection limits comparable to the earlier surveys are used, then the percentage of wells with detectable pesticides would be 11%, which is slightly lower than the 1994 survey (13.6%) and slightly higher than the 1990 survey (7%). Thus the change in analytical detection limits resulted in a large difference in detection rates (11 to 35% for the 1998/99 survey) and this highlights the need to ensure that comparisons between surveys not only have the same sampling strategy and focus, but also have comparable detection limits. A total of twenty different pesticides were detected, as well as two triazine metabolites (Table 8.4). Only one well (K38/0172) had any pesticides that were above a MAV for drinking water. This well had a history of previous contamination and was down-gradient from a point source of contamination. It is discussed in more detail later.

The results from the 1994 New Zealand national survey of pesticides in groundwater were examined for relationships between groundwater from contaminated and from un-contaminated wells (Close 1996). He found that contaminated groundwater was abstracted from wells that were significantly shallower, and were screened closer to the water table, than wells where groundwater was not contaminated. Groundwater from contaminated wells also had slightly lower temperatures than that from uncontaminated wells. This may be because of lower degradation rates at lower temperatures, but is more likely associated with other climatic factors such as higher recharge rates.

The significant relationships between pesticide detections and shallow depths and amounts of water above the well screen were also found in the 1998/99 national groundwater survey (Close and Rosen 2001). The survey also found significant differences for pH and nitrate, with pesticide detections being associated with higher nitrate and lower pH values. The United States Environmental Protection Agency National Survey of Pesticides

Table 8.4 *Summary of pesticides detected in the three national surveys.*

Pesticide	1990 survey (n=82)	1994 survey (n=118)	1998/99 survey (n=95)	Range (mg m^{-3})	MAV (mg m^{-3})
2,4-D	2		1*	0.05 - 0.9	40
2,4,5-T	1			0.1	10
Alachlor		2	2	0.02 - 0.8	20
Atrazine	1	3	7	0.01 - 37#	2
Chlorpyrifos	1			0.03	70
Cyanazine			1*	1	0.7
DEA			9	0.01 - 0.15	NA
DIA			3	0.02 - 0.26	NA
Diazinon	1		4	0.01 - 0.03	10
Hexazinone			2	0.12 - 0.23	400
MCPA			1*	61	2
MCPB			1*	2.1	NA
Mecoprop		1**	1*	420	10
Metolachlor		1	1	0.1 - 0.21	10
Metribuzin			2	0.14 - 1.2	70
Pendamethalin			1	0.03	20
Phenylphenol		1		0.1	NA
Picloram			1*	0.3	200
Pirimiphos methyl	1		1	0.01 - 0.06	100
Procymidone	1		1	0.1 - 1.7	700
Propazine		1	4	0.01 - 2.5	70
Simazine		7	18	0.01 - 1.6	2
Terbuthylazine		2	10	0.01 - 3.5	8
Triclopyr		1	2	0.02 - 0.3	100
Trifluralin		1	1	0.02 - 0.3	30

* these pesticides were only detected in well K38/0172.
** detected in landfill monitoring well.
\# Value of 37 mg m^{-3} detected in well PF32; next highest value in a different well is 0.09 mg m^{-3}
NA = not available.
DEA = Desethyl atrazine; DIA = Desisopropyl atrazine.

also found a significant relationship between low pH and pesticide detections and attributed this to generally greater persistence of pesticides at low pH (United States Environmental Protection Agency 1992). In addition to being involved in the national surveys, a number of the regional and district councils, have undertaken more intensive monitoring on a regional scale, including Auckland (Scoble pers. comm. 1998), Waikato (Hadfield and Smith 1997, 1999a), Taranaki (Taranaki Regional Council 1995), Manawatu-Wanganui (Bekesi pers. comm 1997), Wellington (Hughes 1997), Marlborough (Close 1994), and Canterbury (Canterbury Regional Council 1997).

Results are shown in Table 8.5. The intensive quarterly sampling carried out by Environment Canterbury and Environment Waikato is not included in Table 8.5 but is discussed later.

The monitoring by different regional councils has varied between surveys of "at risk" wells, for example, by Environment Waikato (Hadfield and Smith 1999a), and more general monitoring of the groundwater resource in a region, for example, by Taranaki (Taranaki Regional Council 1995). The type of wells targeted, together with the wide variability in pesticide usage and groundwater vulnerability between regions, results in the differences between regions shown in Table 8.5. The follow-up surveys carried out by Environment Canterbury, which sampled areas where pesticides had been detected, have had mixed results. Those undertaken in 1993 and 1994 showed much higher detection rates, as would be expected, but some follow-up surveys have not detected any pesticides in the groundwaters sampled. The most extensive general moni-

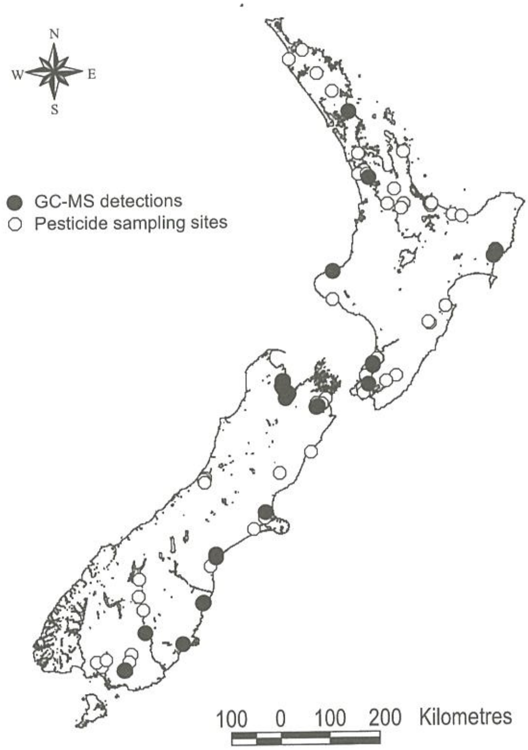


Figure 8.6 *Pesticide sampling sites and detections for 1998/99 national survey.*

toring survey is that undertaken by Environment Canterbury in the summer of 1995/96, in which groundwater samples were collected from 125 sites throughout the central and southern parts of the region. This number excludes 6 wells with a history of pesticide detections that had been monitored quarterly. These 125 sites are used annually to detect broad trends in groundwater quality, with wells included for ease of access and to fill "geographic gaps", irrespective of land use. This non-targeted survey provides the most reliable indication of the background level of pesticide contamination in New Zealand's aquifers. Pesticides were detected in samples from 18 (14%) of the 125 sites but only one sample, containing dieldrin at 0.06 mg m^{-3}, exceeded its respective MAV. The majority of the wells sampled (109, 87%) were shallow, at less than 30 m depth. All except two pesticide detections were in groundwater from wells shallower than 18 m. The pesticides detected were simazine (at 13 sites), atrazine (9), terbuthylazine (6), hexazinone (3), diuron (1), and dieldrin (1). The two exceptions were from relatively deep wells at 54 and 66 m deep, with atrazine and simazine found in each at, or close to, the detection limit.

The general survey was completed in the summer of the following year, 1996/97, with sampling of 25 locations in North Canterbury, along with 18 sites elsewhere in the region. Pesticides were detected at 3 (12%) of the North Canterbury sites, with one pesticide detected at each site: atrazine at 0.02 mg m^{-3}, simazine at 0.08 mg m^{-3}, and dieldrin at 0.06 mg m^{-3}. The dieldrin concentration was twice its MAV, and although the 7.1-m-deep well was only used to supply water to a garden, there was concern about the source of the pesticide, its distribution within the aquifer, and its effects on the groundwater users. Repeat sampling of this well and 5 others surrounding it was undertaken in January 1997. Neither dieldrin nor any other pesticides were detected in the follow-up sampling.

The detection rate found in the non-targeted sampling in Canterbury (circa 12-14%) is similar to the detection rate in the 1994 and 1998/99 national surveys. The area where pesticides were most commonly detected was the Levels Plains in South Canterbury. While it is not clear whether this is because of specific land uses, pesticide applications, or accidental release or burial of pesticide residues, the Levels Plains typifies areas vulnerable to contamination, especially by triazines. The silt loam soils are thin and free-draining, the greywacke alluvium aquifer is unconfined and thin (less than 12 m) with a near-surface water table, and recharge is high (in this case from spray and border strip irrigation). Irrigation is undertaken in spring and summer following the optimum period of herbicide application, and groundwater levels are subsequently raised.

The increasing detection of pesticides in groundwater over the last 5 years does not necessarily imply that pesticide contamination of groundwater has increased over this period. The effect of lower detection limits is significant, as noted earlier, and another major factor is the increase in monitoring. In their review of pesti-

Table 8.5 *Results from monitoring wells for pesticide contamination by Regional and District Councils.*

Region	Year	# of wells	# of detections (%)	Total # of pesticides	Pesticides > MAV
Auckland	1998	11	5 (45%)	3	0
Waikato	1995-96	35	19 – 26 (54-74%)	17	1
Taranaki	1995	32	2 (6%)	2	0
Manawatu-	1996	20	2 (10%)	2	0
Wanganui	1997	32	1 (3%)	1	0
Wellington	1996	14	3 (21%)	2	0
Marlborough	1994	39	3* (8%)	3	0
Canterbury	1988-90	32	0	0	0
	1990/91	22	0	0	0
	1991/92	27	0	0	0
	1992/93	25	1 (4%)	1	0
	1993 @	38	30 (79%)	2	0
	1993/94	29	3 (10%)	4	0
	1994 @	15	8 (53%)	3	0
	1994/95	40	9 (23%)	3	0
	1995 @	14	2 (14%)	2	0
	1995/96	131	23 (18%)	6	1
	Mar 96 @	25	4 (16%)	7	0
	April 96 @	5	1 (20%)	1	0
	June 96 @	6	0	0	0
	Sept 96 @	8	0	0	0
	Oct 96 @	4	0	0	0
	1996/97	48	14 (29%)	5	1
	1997/98	30	0	0	0
	Mar 98 @	2	0	0	0
Southland	1996@	5	2(40%)	3	0
	1999/00@	12	10(83%)	8	0

Note :* one of these wells was a landfill monitoring well.
@ these were follow-up surveys which focused on areas where pesticides were detected to assess the spatial extent of any contamination. The data for Canterbury include the quarterly monitoring wells.

cide monitoring in the USA, Barbash and Resek (1996) state that the increase in numbers of pesticides detected is "more likely to reflect the expansion of sampling efforts across the nation over this period". To assess long-term trends, the design, spatial coverage and analytical scope of the monitoring programmes must have remained stable over the survey period.

Temporal Variation of Pesticides in Groundwater

Long-term monitoring of pesticides in selected groundwater wells has been carried out by Environment Waikato and Environment Canterbury. Following an initial survey of 35 wells by Environment Waikato in 1995/96, 20 wells were selected for quarterly sampling over a 3-year period (Hadfield and Smith 1999a). They found significant variations in pesticide concentrations over time. At some sites pesticides were consistently at similar concentrations, while at others they were detected only sporadically. Examples of variations are shown in Figures 8.7 to 8.9. At site 61.113 (Fig 8.7) both procymidone and metribuzin were detected on all but occasion, with the levels varying by a factor of 10 to 20. Alachlor was detected at the start of the monitoring period and then decreased, while dieldrin and propazine were detected only once. At site 69.357 (Fig 8.8) six different pesticides were detected, but the levels varied widely. Detections of bromacil and diuron appeared to be related to applications in the 6 months prior to sampling. Atrazine was detected on most sampling occasions, with diuron detected in about half of the samples. The other four pesticides were only detected between 1 and 3 times. Figure 8.9 gives data for a site contaminated with dieldrin (discussed later). Dieldrin was detected on 9 out of 12 sampling occasions, with concentrations within a factor of 10. This is expected for a persistent compound such as dieldrin. There appears to be some relationship between pesticide contamination and parameters such as nitrate, water level and conductivity at some sites (Fig 8.9) but not at others (Fig 8.7). These examples indicate the complexity involved in the leaching, degradation and groundwater transport processes.

Six wells in and close to the Levels Plain area in South Canterbury (Fig 8.10) have been monitored regularly, usually at quarterly intervals, between 1993 and 1999. They too show variations over time in pesticide patterns (Table 8.6). The pesticides have generally been at low concentrations, well below the relevant MAV. An example of variability over 6 years in one of these wells (K38/0268) is shown in Figure 8.11a and b. It is interesting to note that the different pesticides do not show the same pattern of temporal variation, even within the same well.

In the national groundwater survey in December 1998, carboxylic acidic herbicides were found in groundwater from well K38/0172 at high concentrations: MCPA at 61.0 mg m^{-3}, MCPB at 2.1 mg m^{-3}, and MCPP (Mecoprop) at 420 mg m^{-3}. These pesticides have a similar chemical structure and MCPB can be converted to MCPA in susceptible plants. These active ingredients are commonly combined in commercial pesticide formulations and it is possible they are derived from leaching or release of a single formulation to groundwater. These compounds leach at a moderate rate through soils, but are short-lived, with half lives of 25 and 21 days for the first two respectively (Weber 1994). MCPA has been detected in two of the subsequent monitoring rounds, but at substantially lower concentrations (0.09 and 0.16 mg m^{-3}), as has dicamba and other pesticides (Fig 8.12; Table 8.6), while the other pesticides have not been detected at all. Notably, these compounds were not detected in the well immediately down-

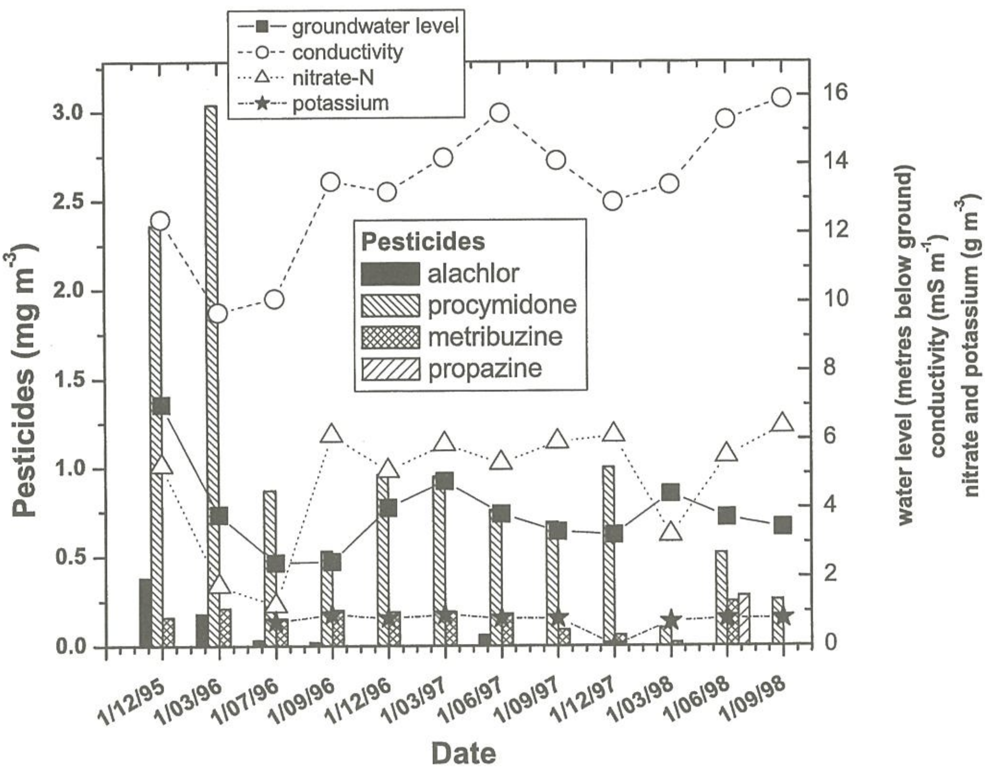


Figure 8.7 *Pesticide variability at site 61.113, Waikato (after Hadfield and Smith 1999a).*

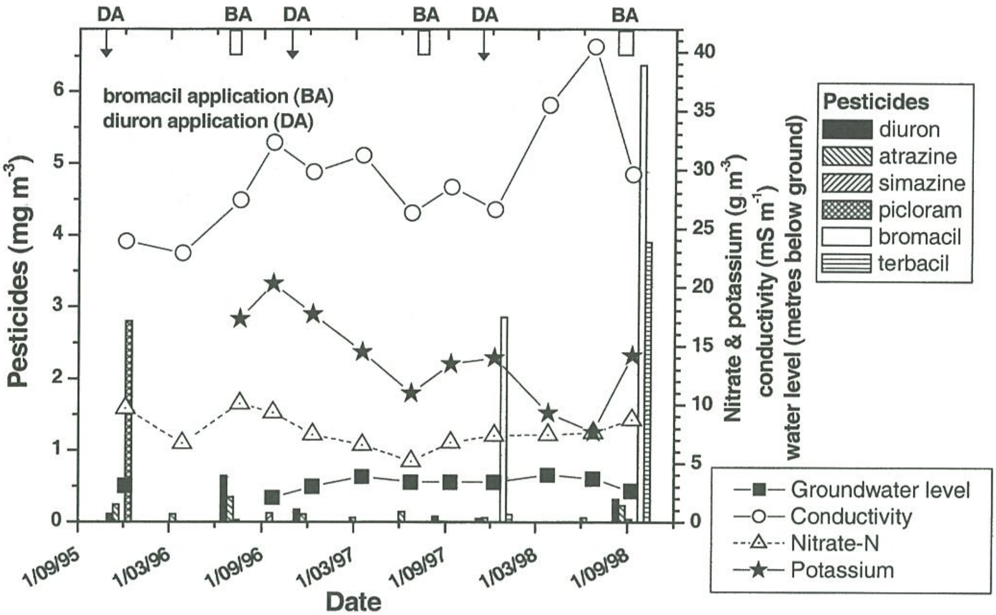


Figure 8.8 *Pesticide variability at site 69.357, Waikato (after Hadfield and Smith 1999a).*

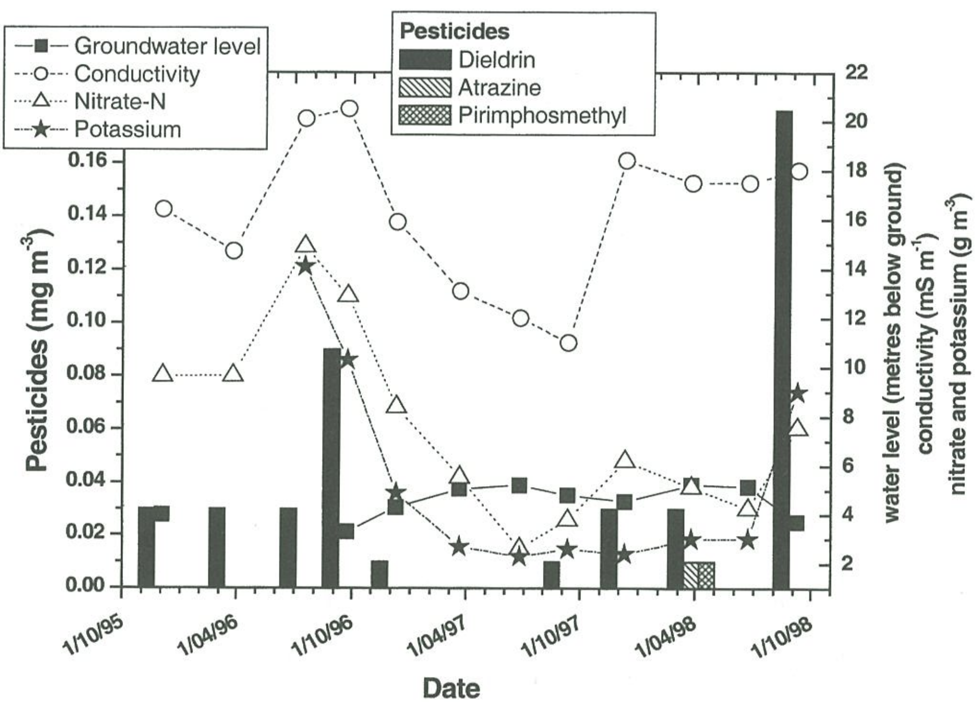


Figure 8.9 *Pesticide variability at site 70.69, Waikato (after Hadfield and Smith 1999a).*

gradient (K38/0430), although the triazines have been regularly detected at this site (Table 8.6).

There is little long-term data available in New Zealand other than that discussed above. The existing data show high levels of variability, which may be a function of many factors: changes in recharge patterns, numbers and rates of application, crop rotations, and timing of recharge events in relation to pesticide applications. In addition, the behaviour of individual pesticides will differ because of differing chemical characteristics and application histories. Long-term trends are thus difficult to assess, even with considerable sampling and analysis over a long period of time. Barbash and Resek (1996) give an example of atrazine concentrations from Big Spring, Iowa, which increased over the first 4 years of monitoring, then fluctuated for the next 10 years. This demonstrates the difficulties of predicting long-term trends in pesticide concentrations using comparatively short periods of record.

Point sources and remediation

For many of the pesticides detected in the above surveys it is uncertain if the contamination came from a point source or from leaching associated with normal agricultural practices. Remediation of contaminated groundwater is feasible only for point source contamination. Some examples of pesticide contamination in groundwater from point sources are given in this section. This list is not exhaustive, but illustrates the sort of contamination that can occur and, in some cases, possible remediation options.

Disposal of pesticide containers, particularly if they are partially full, can result in point source contamination of groundwater. An example is a monitoring well downstream from

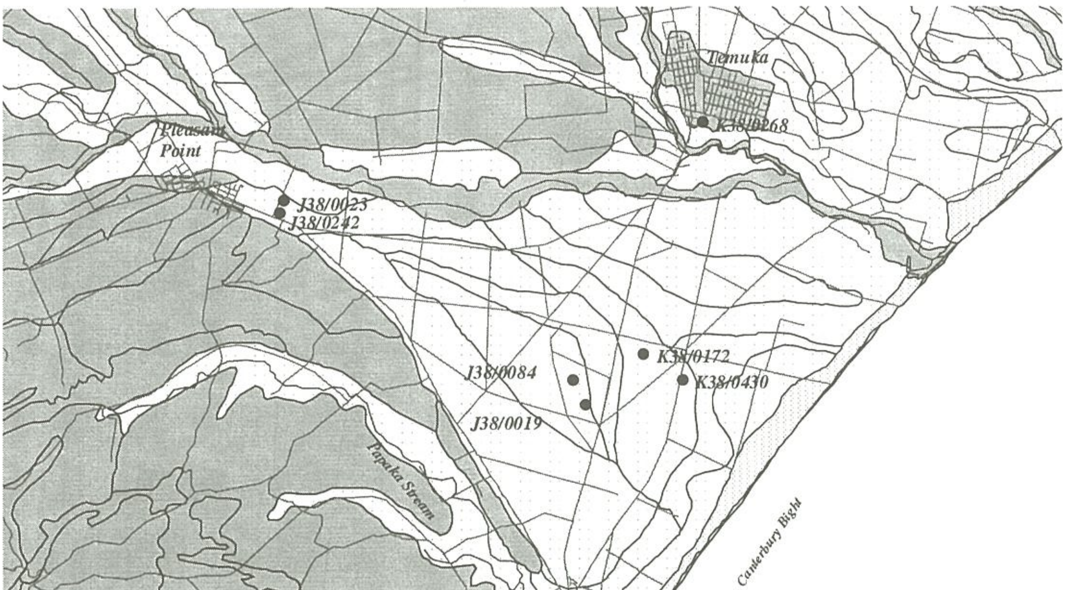


Figure 8.10 *Location map of Levels Plains monitoring wells.*

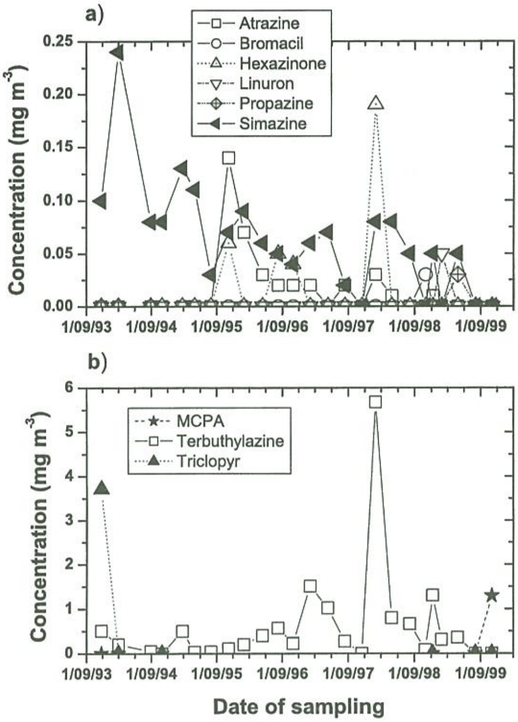


Figure 8.11a and b *Concentrations of different pesticides in groundwater from well K38/0268 in Temuka.*

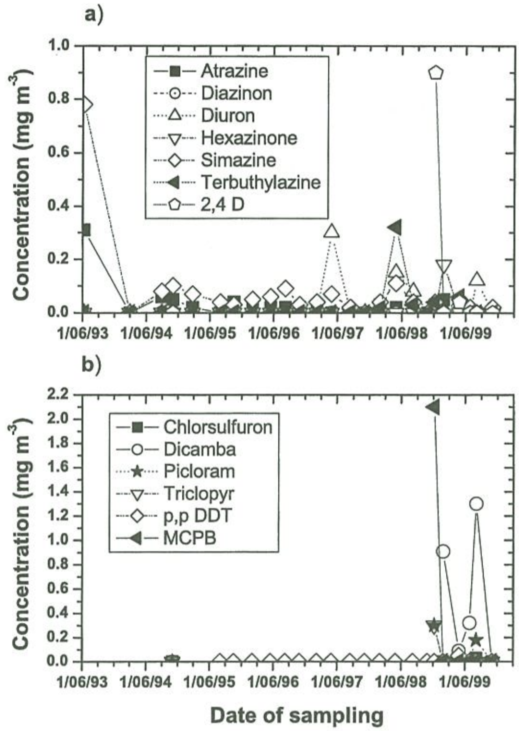


Figure 8.12a and b *Concentrations of different pesticides in groundwater from well K38/0172, Levels Plains.*

a landfill near Blenheim, in which mecoprop was detected on two occasions at levels of 2.4 and 3.2 mg m^{-3} (Close 1996). This contamination had definitely come from pesticide disposal in the landfill.

Residual concentrations of triazine herbicides have been detected in the Edendale Aquifer in eastern Southland since the 1994 national pesticide survey. Products detected include propazine, terbuthylazine, hexazinone, metribuzin, simazine, atrazine and bromacil.

The maximum concentrations are generally well below drinking water standard MAV. On some occasions simazine and atrazine have been detected at concentrations of up to 50 and 30 percent of MAV respectively. All other products are generally found at concentrations of less than 10 percent of MAV. There are several potential sources for the pesticides detected: horticultural operations (forest nursery, potatoes) as well as roadside spraying and weed control around railway yards. Pesticides appear to be introduced into groundwater via soak holes for stormwater disposal, bypassing the natural processes of adsorption and degradation associated with infiltration through the soil profile. The exact area affected by the pesticide contamination is uncertain. Current monitoring indicates transport of propazine, simazine and terbuthylazine over 3 kilometres down-gradient of the likely source.

A contamination event in Canterbury was reported by Smith (1993d), in which pesticides from a spray tank were accidentally back-siphoned into a household water well. Bromoxynil, ioxymil and chlorpyrifos were found in the holding tank. Chlorpyrifos, detected at a concentration of 23 g m^{-3} in the holding tank, equated to less than 0.5% of the original spray mix. Water taken from the zip in the kitchen contained 0.5 g m^{-3} chlorpyriphos. The pesticides were not found in water samples taken at the well when it was first

Table 8.6 *Temporal monitoring of wells in Levels Plains and Temuka. All units are in mg m^{-3}; numbers in square brackets are numbers of detections out of number of samples analysed. Monitoring in J38/0019 began after use of J38/0084 was discontinued. Includes the national monitoring round in December 1998.*

	K38/0172	K38/0430	K38/0268	J38/0023	J38/0019 and J38/0084	J38/0242
Atrazine	0.02 – 0.31 [15/24]	0.01 – 0.05 [12/27]	0.01– 0.14 [10/26]	0.04 – 0.10 [3/5]		0.01 – 0.09 [4/11]
Cyanazine	0.07 – 4.75 [4/24]	0.04 [1/27]				
Diazinon	0.03 [1/24]					
Diuron	0.08 – 0.3 [4/22]					
Hexazinone	0.18 [1/24]		0.04 – 0.79 [5/27]			
Metribuzin	0.02 – 0.78 [20/25]					
Simazine	0.02 – 0.78 [20/25]	0.02 – 0.22 [22/27]	0.03 – 0.24 [21/27]	0.04 – 0.24 [3/5]	0.02 – 0.40 [12/21]	0.01– 0.03 [5/11]
Terbuthylazine	0.016 – 0.32 [5/24]		0.02 – 5.68 [22/27]	0.03 – 0.11 [3/5]	0.02– 0.10 [12/21]	0.04 – 0.07 [5/11]
2,4 D	0.04 – 0.9 [2/6]	0.02 [1/6]			0.04 [1/2]	0.04 [1/1]
Chlorsulfuron*	0.03 [1/5]	0.04 [1/6]				
Dicamba*	0.09 – 1.3 [4/5]				0.32 [1/2]	
MCPA	0.09 – 61 [3/6]		1.29 [1/6]		0.13 [1/4]	
Picloram	0.18 – 0.3 [2/6]					
Triclopyr	0.3 [1/5]		3.7 [1/5]			
p,p DDT	0.05 [1/19]					
MCPB	2.1 [1/6]					
MCPP	420 [1/6]					
Linuron*			0.05 [1/27]			
Propazine			0.03 [1/7]			
Bromacil			0.03 [1/27]			

* = no MAV available in Ministry of Health (2000).

turned on or 15 minutes later. Therefore, almost all of the back-siphoned pesticide had either been diluted and spread into the aquifer system at very low concentrations or had been pumped into, and through, the house reticulation system. Pesticides were not detected in the house well nor in the three closest down-gradient wells several days later.

Dieldrin has recently been detected in two shallow groundwater sites in the Waikato adjacent to old sheep dip sites (Hadfield and Smith 1999a). Calcium arsenite, or arsenic pentoxides, have been used in New Zealand as sheep dips to control lice, ticks, and maggots from the mid 1800s until about the late 1950s. For part of this time annual sheep dipping was compulsory under The Stock Act (1908) and subsequent legislation (McBride et al., 1998). In 1947, lindane was introduced as an alternative sheep dip compound. Dieldrin, the first of the organophosphate pesticides, was introduced in the 1950s and became widely used, replacing the arsenic-based dips, but was deregistered in 1966. Arsenical pesticides were voluntarily withdrawn from the market in 1977. However, this historical pesticide use has had a continuing environmental impact, as it was a common practise to drain the spent dip into a nearby ditch or creek, or dispose of it directly onto the surrounding land. Most livestock farms probably had a sheep or cattle dip, and it is estimated that over 10,000 old dip sites exist in the Waikato region. Similar contaminated sites are expected elsewhere in New Zealand. Hadfield and Smith (1999a) investigated one such site. They found that a localised plume of dieldrin extended about 40 m from the dip site, and passed through a well used for domestic water supply. Concentrations in the groundwater ranged up to 2.18 mg m^{-3}, with levels in the well varying with time between 0.03 and 0.18 (Fig 8.9). The Maximum Acceptable Value (MAV) for dieldrin is 0.03 mg m^{-3} (Ministry of Health 2000). Significant levels were found in the soil profile and it is likely that this contamination will persist for many years. Hadfield and Smith (1999b) also found lindane and arsenic contaminating soils, surface water and groundwater around sheep dip sites. In an investigation in Canterbury, soil and groundwater were found to be contaminated by arsenic from a sheep dip site that has not been used for over 50 years (Environment Canterbury, unpublished data), reflecting the non-decaying nature of elemental arsenic.

Pentachlorophenol (PCP), a timber preservation chemical, was used in the timber industry for about 40 years to prevent fungal staining of sawn wood. It has been detected at the Waipa sawmill in a groundwater plume that was discharging into a nearby stream and then into Lake Rotorua. Remediation of the contaminated groundwater started in 1994. The contaminated water was pumped and treated using an advanced oxidation technology that uses hydrogen peroxide and UV light to break the PCP down into CO_2 and NaCl. Contamination levels of 4600 mg m^{-3} PCP are commonly reduced to less than 1 mg m^{-3} after treatment (Gavin Williamson Fletcher Challenge Forest pers. comm. 2000).

Another contaminated pesticide site is the Fruitgrowers Chemical contaminated site at Mapua, Nelson. A range of chemicals were manufactured at the site between 1955 and 1988 but the only ones that remain in the soil at medium to high concentrations are the persistent organochlorine pesticides, namely DDT, DDE, DDD, dieldrin, aldrin, and lindane (Easton 1996). These contaminants have been detected in the groundwater at the site at variable concentrations. Clean-up options used in Europe and the United States include removal and storage of the contaminated material in special hazardous waste landfills, destruction in high temperature incinerators, extraction with solvents followed by combustion, thermal desorption and bioremediation. The options being considered for this site include thermal desorption, bioremediation and sealing the wastes into a permanent purpose-built landfill. This site is an "orphan" site. The Tasman District Council owns the land and they are working with the government to clean up the site. An "Orphan Contaminated Sites Fund" has been created by the government and the Mapua site is the first to be cleaned up using this fund.

Interactions between ground and surface waters

In some cases a relationship clearly exists between pesticides in groundwater and contamination of associated surface waters. In January 1995 simazine was detected at 0.02 mg m^{-3} in the spring-fed L2 river at Pannetts Rd bridge in Canterbury between Lincoln township and Lake Ellesmere. Three months later simazine was not detected, but it was present at 0.14 mg m^{-3} in November 1995 along with 2,4-D at 0.26 mg m^{-3}, MCPA at 0.24 mg m^{-3}, and terbuthylazine at 0.37 mg m^{-3}. In April 1996 a concurrent programme of groundwater and surface water sampling was undertaken in the area to determine the extent of pesticides in the water bodies. Groundwater was sampled from five wells, with pesticides detected in only one sample from a 9.7-m-deep unused well up-gradient of the oxidation ponds. Here 2,4-D was found at 0.05 mg m^{-3} and 2,4,5-T at 5.9 mg m^{-3}, the latter just over half its MAV. The well is close to the spring-fed headwaters of the L2. Stream samples were collected at five sites along the length of the L2. Four of the five surface water samples contained 2,4-D at concentrations of between 0.04 and 0.20 mg m^{-3}. These sites were all down-gradient of the well and the town's oxidation ponds. The only uncontaminated surface water sample was up-gradient of the oxidation ponds and the well. In September 1996 groundwater from the well was sampled and neither 2,4-D or 2,4,5-T were detected. Six subsequent sampling rounds at the Pannetts Rd bridge between the April 96 detection and September 1999 have not detected 2,4-D, but simazine was found in September 1999 at 0.04 mg m^{-3}, along with terbuthylazine at 0.02 mg m^{-3} and triclopyr at 0.05 mg m^{-3} (Environment Canterbury unpublished data).

While the L2 receives discharges from the oxidation pond and overland runoff from the silty soils along its length, its quality has, at least periodically, been affected by contaminated groundwater discharge. For the pesticides detected in the L2, the acceptable concentration for drinking water is substantially lower than that for protection of aquatic ecosystems, but this is not always the case. There is a general pattern of longer pesticide persistence in groundwater relative to surface water.

The vulnerability of spring catchments to contamination is demonstrated by the detection of triclopyr, at a concentration of 0.63 mg m^{-3}, in a spring in the Kaituna Valley on the Banks Peninsula volcanic deposits in Canterbury in December 1992. It is unclear whether this resulted from overspraying near the spring, or whether the pesticide entered the groundwater from higher up in the catchment via a fractured or very permeable volcanic outcrop and travelled rapidly through the groundwater system to the spring. Triclopyr was also detected in another spring-fed catchment at Allandale at concentrations of 60 mg m^{-3} around 5 metres from the springhead and 180 mg m^{-3} in a sample collected from a residential tap. Both contaminations resulted from herbicide spraying in the catchment up-gradient of the springs; in the Allandale case there was evidence of overspraying near the spring itself.

Correlation of nitrate and pesticide concentrations in groundwater

As analyses for pesticides are quite expensive it would be useful to have another parameter that could be used as an indicator of likely pesticide contamination. One such possible indicator is nitrate, as nitrates and pesticides often share a common source. Close and Rosen (2001) examined data from the 1998/99 national groundwater survey for any relationship between nitrate and pesticide detections. They found a significant difference for nitrate (after log transformation) in wells with and without detectable pesticides. Pesticide detections were associated with higher nitrate values (mean=8.6 g m^{-3}; SD = 12.4), compared to wells with no pesticides detected (mean = 3.2 g m^{-3}; SD = 4.9), but there was significant variability in nitrate concentrations within both groups of wells. There was no relationship between concentrations of pesticides detected and nitrate concentrations. The United States Environmental Protection Agency carried out a National Survey of Pesticides in 1990 (United States Environmental Protection Agency 1992). They found weak support for an association between nitrate and pesticide detections, but it was not a significant relationship. Even though there was a significant difference in nitrate concentrations for wells with and without pesticide detections, the relationship was not strong enough for it to be used as an indicator or for prediction. While some land uses might lead to leaching of both nitrate and pesticides, many sources, such as effluent irrigation systems and septic tanks, would contribute only nitrate. Some pesticide uses such as spraying around roads or buildings would not contribute to nitrate leaching. In addition, because of the differences in leaching characteristics among the various pesticides and between pesticides and nitrates, a common single input of pesticides and nitrate could be spread out over a 2-3 year time period by the time it reached a well.

SUMMARY AND CONCLUSIONS

Nitrate in groundwater is a difficult contaminant to control because it is difficult to remediate and it is associated with many different land uses. The health implications of high nitrate concentrations are still being debated, but it is clear that high nitrate concentrations will cause environmental problems due to its ability to promote eutrophication of surface water bodies. In New Zealand, areas of intense agricultural land use are the areas most likely to have high groundwater nitrate concentrations. These areas include the Waikato, Manawatu-Wanganui, Taranaki, Wairarapa, Tasman, and North Otago. Additional areas of concern are Canterbury, Wellington (west coast), Southland and Pukekohe. All of these areas have intensive agricultural land uses (dairy and horticulture) that contribute to the regional contamination, but local contamination may also be related to poor well-head protection and large diameter wells.

Current trends in groundwater nitrate concentrations are difficult to establish because good, long-term records of nitrate are hard to come by and are non-existent in some parts of the country. Recent emphasis in monitoring nitrate will help to alleviate this problem in the future. Based on current information, the best way to prevent nitrate contamination is to responsibly manage land and water resources so that nitrate is not leached to the groundwater. It is important to minimise sources of contamination because remediation of any nitrate contamination to groundwater caused by poor land management will be expensive.

Pesticide monitoring of groundwater since 1990 has indicated that low levels of pesticides can be detected in around 10-15% of shallow, unconfined wells, with higher detection rates in targeted and follow-up surveys. Virtually no pesticides however have been found in community drinking water supplies. The most commonly detected pesticides have been the triazine group. The pesticides detected have usually been at very low concentrations (less than 0.1 mg m^{-3}) and there have been only a few detections at levels greater than the MAV for drinking water, generally associated with point sources. There is a growing concern about dieldrin from old sheep dip sites, which has been detected in groundwater in Canterbury and Waikato at concentrations greater than the MAV for drinking water of 0.03 mg m^{-3}. The long-term data is reasonably limited, but pesticides show a high level of variability. This, together with changes in recharge patterns and analytical detection limits, makes the assessment of long-term trends of pesticide contamination very difficult.

Management options include the prevention of direct entry of pesticides into groundwater by appropriate storage and disposal of pesticide containers, ensuring that the wellhead is secure and properly maintained, and the use of pesticides with lower mobility and persistence than those in current use, particularly in areas of high groundwater vulnerability.

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REFERENCES

Adams, J.A.; Campbell, A.S.; McKeegan, W.R.; McPherson, R.J.; Tonking, P.J. 1979: Nitrate and chloride in groundwater, surface water and deep soil profiles of central Canterbury, New Zealand. Prog. Water Technology 11(6): 351-360.

Adams, J.A. 1981: Influence on land use on nitrate movement through soil properties in Paparua County. A research report prepared for the North Canterbury Catchment Board, New Zealand.

Aislabie, J.; Lloyd-Jones, G. 1995: A review of bacterial degradation of pesticides. Australian. Journal. Soil Research 33: 925-942.

Askew, C.C. 1985: Nitrate in Groundwater - A review of the issue with emphasis on the New Zealand situation. Masters thesis, University of Canterbury, New Zealand.

Avery, A.A. 1999: Infantile Methemoglobinemia: Reexamining the Role of Drinking Water Nitrates. Environmental Health Perspectives, Vol. 107(7): 583-586.

Baber, H.L. 1977: A study of some nitrate and phosphate problems in New Zealand agriculture. Unpublished Ph.D. dissertation, Dept. Chemistry, University of Waikato, 303 p.

Baber, H.L.; Wilson, A.T. 1972: Nitrate pollution of groundwater in the Waikato region. Journal of the

New Zealand Institute of Chemistry, Vol. 36(6): 179-183.

Barbash, J.E.; Resek, E.A. 1996: Pesticides in Ground Water: Distribution, trends, and governing factors. Ann Arbour Press Inc. 588 p.

Baskaran, S.; Bolan, N.S.; Rahman, A.; Tillman, R.W. 1996: Pesticide sorption by allophanic and non-allophanic soils of New Zealand. NZ Journal of Agricultural Research 39:297-310.

Bell, S. 1994: Toxic bore water alert. Article from the Dominion newspaper, 24 November 1994, New Zealand.

Bolan, N.S.; Baskaran, S. 1996: Biodegradation of 2,4-D herbicide as affected by its adsorption-desorption behaviour and microbial activity of soils. Australian Journal of Soil Research 34(6): 1041-1053.

Bowden, M.J.; Ayrey, R.B.; Duffield, D.N.; Glennie, J.M.; Harrison, N.; Hurd, N.; Mason, C.R.; Talbot, J.D.; Weeber, J.H. 1982: The water resources of the Ashley Catchment. North Canterbury Catchment Board and Regional Water Board, Christchurch.

Brougham, G.C.; Kampman, I.; Caldwell, K.J. 1985: Groundwater resources of the Waitohu, Otaki and Mangaone. Report 65. Manawatu Catchment Board and Regional Water Board.

Burden, R.J. 1980a: Nitrate contamination of New Zealand groundwater. Proceedings of the New Zealand Hydrological Society Symposium held in Palmerston North.

Burden, R.J. 1980b: Distribution of Nitrate-N concentrations in groundwater beneath intensively grazed pastureland in the Ngatarawa Valley, Hawke's Bay. Journal of Hydrology (NZ), 19(2): 94-105.

Burden, R.J. 1982: Nitrate contamination of New Zealand aquifers: a review. New Zealand Journal of Science, Vol. 25: 205-220.

Burden, R.J. 1984: Chemical zonation in groundwater of the central plains, Canterbury. Journal of Hydrology (NZ), 23(2): 100-179.

Cameron, K.C.; Rate, A.W.; Carey, P.L.; Smith, N.P. 1995: Fate of nitrogen in pig effluent applied to a shallow stony pasture soil. New Zealand Journal of Agricultural Research 38: 533-542.

Canter, L.W. 1997: Nitrates in Groundwater. Lewis Publishers, Boca Raton, New York.

Canterbury Regional Council 1995: Canterbury Regional Council regional environment report 1993-1994. CRC Report 95(5), Christchurch, 76 p.

Canterbury Regional Council 1997: Canterbury Regional Council Regional Environment Report (1995/96) CRC Report 97(10).

Cathcart, S.N. 1994: Fertiliser and its role in the contamination of Pukekohe ground water. *In* L.D. Currie and P. Loganathan (eds.), The efficient use of fertilisers in a changing environment: reconciling productivity and sustainability, Fertiliser and Lime Research Occasional Report No. 7, Massey University, Palmerston North, 374-381.

Cathcart, S.N. 1995: An investigation of the nitrate contamination of an unconfined, shallow fractured, basaltic aquifer at Pukekohe, South Auckland, New Zealand, Unpublished Masters Thesis, University of Auckland.

Close, M.E. 1987: Effects of irrigation on water quality of a shallow unconfined aquifer. Water Resources Bulletin 23(5): 793-802.

Close, M.E.; McCallion, R.F. 1988: Groundwater quality and the likely effects of the proposed Hydroelectric Development, Clutha Valley, Otago. Publication No 16. Hydrology Centre, Christchurch.

Close, M.E. 1993a: Assessment of pesticide contamination of groundwater in New Zealand. I Ranking of regions for potential contamination. New Zealand Journal of Marine and Freshwater Research 27: 257-266.

Close, M.E. 1993b: Assessment of pesticide contamination of groundwater in New Zealand. II Results of groundwater sampling. New Zealand Journal of Marine and Freshwater Research 27: 267-273.

Close, M.E. 1994: Wairau Plains groundwater quality results: May 1994 survey. ESR report C94/26. Prepared for Marlborough District Council. 23 p.

Close, M.E. 1995: Pesticides in New Zealand's groundwater? In "Proceedings of the First AgResearch/Landcare Research Pesticide Residue Workshop 15-16 September 1994" Eds. L Boul & J Aislabie. Lincoln, New Zealand. p 47-52.

Close, M.E.; Tod, J.L.; Tod, G.J. 1995: Effect of recharge variations on regional groundwater quality in mid-Canterbury, New Zealand. New Zealand Journal of Hydrology 33: 1-16.

Close, M.E. 1996: Survey of pesticides in New Zealand groundwaters, 1994. New Zealand Journal of Marine and Freshwater Research 30: 455-461.

Close, M.E.; Pang, L.; Watt, J.P.C.; Vincent, K.W. 1998: Leaching of picloram, atrazine and simazine through two New Zealand soils. Geoderma 84 (1-3): 45-63.

Close, M.E.; Watt, J.P.C.; Vincent, K.W. 1999a: Simulation of picloram, atrazine and simazine transport through two New Zealand soils using LEACHM. Australian Journal of Soil Research 37: 53-74.

Close, M.E.; Pang, L.; Magesan, G.N.; Stewart, M. 1999b: Field study of pesticide leaching in an allophanic soil in New Zealand - model simulations using GLEAMS. In Abstracts of the workshop on Environmental Aspects of Pesticide Use, November 1999, Hamilton.

Close, M.E.; Rosen, M.R. 2001: 1998/99 National Survey of Pesticides in Groundwater using GCMS and ELISA. NZ Journal of Marine and Freshwater Research 35: 205-219.

Comly, H.H. 1945: Cyanosis in infants caused by nitrates in well water. Journal of the American Medical Association 29: 112-116.

Demartinis J.M.; Cooper S.C. 1994: Natural and Man-made modes of entry in agronomic areas. In: Mechanisms of pesticide movement into ground water. RC Honeycutt and DJ Schabacker (Eds.) Lewis Publishers 165-175 p.

Dewhurst, R.H. 1981: Thames Valley groundwater investigations. Technical Report No. 106, Hauraki Catchment Board.

Di, H.J.; Aylmore, L.A.G.; Kookana, R.S. 1998: Degradation Rates of Eight Pesticides in Surface and Subsurface Soils Under Laboratory and Field Conditions. Soil Science 163(5): 404-411.

Dillon, P.J.; Close, M.E.; Scott, R.I. 1989: Diffuse-Source Nitrate Contamination of Groundwater in New Zealand and Australia. Hydrology and Water Resources Symposium, Christchurch, New Zealand. p 351-355.

Dorsch, M.M.; Scragg, R.K.R.; Mc Michael, A.J.; Baghurst, P.A.; Dyer, K.F. 1984: Congenital malformations and maternal drinking water supply in rural South Australia: A case-control study. American Journal of Epidemiology 119: 474-486.

EASTON, J. 1996: Remedial works at the Mapua site, Waimea Inlet. Water and Wastes in New Zealand, July 1996: 53-65.

EPPINGER, R.; WALRAEVENS, K. 1998: Mobility and removal of nitrate in heterogeneous Eocene aquifers. Groundwater Quality: Remediation and Protection (Proceedings of the GQ'98 Conference held at Tübingen, Germany, September 1998) IAHS Publication No 250, 11-18.

ESER, P.; ROSEN, M.R. 1999: The influence of groundwater hydrology and stratigraphy on the hydrochemistry of Stump Bay, South Taupo Wetland, New Zealand. Journal of Hydrology, 220: 27-47.

FAN, A.M.; STEINBERG, V.E. 1996: Health Implications of nitrate and nitrite in drinking water: An update on methemoglobinemia occurrence and reproductive and developmental toxicity. Regulatory Toxicology and Pharmacology 23, Article No. 0006: p 35-43.

FENEMOR, A.D. 1987: Water quality of the Waimea Plains aquifers, 1971-86. Nelson Regional Water Board.

FREEZE, R.A.; CHERRY, J.A. 1979: Groundwater, Prentice-Hall, Englewood Cliffs, 604 p.

GREEN, S.R.; CLOTHIER, B.E.; MILLS, T.M.; HOLLAND, P.T.; CUNLIFFE, J.; HAMILL, P. 1999: Modelling the transport of pesticides through soil. In Abstracts of the workshop on Environmental Aspects of Pesticide Use, November 1999, Hamilton.

GRINSTED, M.J.; WILSON, A.T. 1978: Nitrate concentrations in the groundwater around Lake Rotorua. NZ Journal of Marine and Freshwater Research 12(4): 463-6.

HADFIELD, J. 1995: A groundwater contaminant tracer study at Waitahanui, Taupo. Unpublished Masters Thesis, University of Waikato, New Zealand.

HADFIELD, J.; SMITH, D. 1997: Pesticide Contamination of Groundwater: An investigation in the Waikato Region, New Zealand., 24th Hydrology and Water Resources Symposium, Auckland, pp. 246-251.

HADFIELD, J.; SMITH, D. 1999a: Pesticide Contamination of Groundwater in the Waikato Region. 1999/9, Environment Waikato. 52 p.

HADFIELD, J.C.; SMITH, D.J. 1999b: From gas works to sheep dips: site contamination in the Waikato region, New Zealand. Contaminated Site Remediation: Challenges posed by urban and industrial contaminants. Proceedings of the 1999 Contaminated Site Remediation Conference. C D Johnston (Ed). Centre for Groundwater Studies March 1999. 805 – 813

HAMILL, K. 1999: Nitrate in Southland's Groundwater: Hot spots in your back yard. Water and Wastes in NZ: July issue, p30-32.

HILL, M.J.; HAWKSWORTH, G.; TATTERSALL, G. 1973: Bacteria, nitrosamines and cancer of the stomach. British Journal of Cancer, 28: 562-567.

HOARE, R.A. 1986: Groundwater nitrate in the Hamilton Basin. Waikato Valley Authority Technical Report 1986/16.

HOLLAND, P.; RAHMAN, A. 1999: Review of trends in Agricultural Pesticide Use in New Zealand. MAF Policy Technical Paper 99/11. 53 p.

HORNSBY, A.G.; WAUCHOPE, R.D.; HERNER, A.E. 1996: Pesticide Properties in the Environment. Springer, New York. 227 p.

HUGHES, B. 1997: Pesticide contamination of groundwater in the Western Wellington region. WRC/RINV-T-97/33, Wellington Regional Council.

JAMES, T.K.; LAUREN, D.R.; RAHMAN, A. 1994: Measurement of atrazine residues in soil and groundwater. Proceedings of 47th New Zealand Plant Protection Conference. p 401-405.

JAMES, T.K. 1995: Development of analytical methods for determining bromacil and atrazine in soil and groundwater from field use in Waikato. Unpublished MSc thesis, University of Waikato. 147 p.

JAMES, T.K.; RAHMAN, A.; HOLLAND, P.T. 1999: Degradation and persistence studies with the sulfonylurea herbicide nicosulfuron. In Abstracts of the workshop on Environmental Aspects of Pesticide Use, November 1999, Hamilton.

LEHR, J.H. 1985: Nitrate: Unwarranted fear, unnecessary expense. Groundwater Monitoring Review 5(2): 4-5.

LEVY, J.; CHESTERS, G. 1995: Simulation of atrazine and metabolite transport and fate in a sandy-till aquifer. Journal of Contaminant Hydrology, 20: 67-88.

LINCOLN ENVIRONMENTAL 1997a: Nitrogen Inputs at Land Surfaces and Groundwater Quality. A bibliography of New Zealand publications. Report to Canterbury Regional Council and MAF Policy, Report No. 2776/2, 14 p.

LINCOLN ENVIRONMENTAL 1997b: Nitrogen Inputs at Land Surfaces and Groundwater Quality. Review of science, policy and management: international and New Zealand. Report to Canterbury Regional Council and MAF Policy, Report No. 2776/1, 106 p.

LINCOLN ENVIRONMENTAL 1998: A survey of nitrate contamination of NZ aquifers. Report to Ministry of Agriculture and Forestry, Draft Report No. 4309/1, 8 p.

MADISON, R.J.; BRUNETT, J.O. 1985: Overview of the occurrence of nitrate in ground water of the United States. *In* National Water Summary 1984—Hydrologic events, selected water-quality trends, and ground water resources. U.S. Geological Survey Water-Supply Paper 2275, p. 93-105.

MALBERG, J.W.; SAVAGE, E.P.; OSTERYOUNG, J. 1978: Nitrates in drinking water and the early onset of hypertension. Environmental Pollution, 15: 155-160.

MCBRIDE, G.; HOLLAND, P.; WILSON, K. 1998: Investigation of contaminated sheep dipping sites in the Waikato. Waikato Pesticides Awareness Committee (WaiPAC) unpublished report.

MCKNIGHT, G.M.; DUNCAN, C.W.; LEIFERT, C.; GOLDEN, M.H. 1999: Dietary nitrate in man: friend or foe?. British Journal of Nutrition 81: 349-358.

MCLARIN, W.; BEKESI, G.; BROWN, L.; MCCONCHIE, J. 1999: Nitrate contamination of the unconfined aquifer, Manakau, Horowhenua, New Zealand. Journal of Hydrology (NZ), 38: 211-235.

MCNAUGHTON, D.E.; HOLLAND, P.T.; CLOTHIER, B.; JAMES, T.K. 1999: Parameters for environmental persistence of pesticides in horticultural soils. In Abstracts of the workshop on Environmental Aspects of Pesticide Use, November 1999, Hamilton.

MINISTRY OF HEALTH 2000: Drinking-Water Standards for New Zealand 2000. Ministry of Health. 130p.

MUELLER, D.K.; HAMILTON, P.A.; HELSEL, D.R.; HITT, K.J.; RUDDY, B.C. 1995: Nutrients in ground water and surface water of the United States - an analysis of data through 1992. Water-Resources Investigations Report 95-4031. 74 p.

O'DEA, T.F. 1980: Wairarapa groundwater study report by Scientific Advisory Group. Wairarapa Catchment Board.

OTTLEY, C.J.; DAVISON, W., EDMUNDS, W.M. 1997: Chemical catalysis of nitrate reduction by iron(II). Geochimica et Cosmochimica Acta 61: 1819-1828.

PANG, L.; CLOSE, M.E. 1999: Attenuation and transport of atrazine and picloram in an alluvial gravel aquifer : a tracer test and batch study. New Zealand Journal of Marine and Freshwater Research 33: 279-291.

PANG, L.; CLOSE, M.E.; WATT, J.P.C.; VINCENT, K.W. 2000: Simulation of picloram, atrazine, and simazine leaching through two New Zealand soils and into groundwater using HYDRUS-2D. Journal of Contaminant Hydrology 44(1): 19-46.

PARSLOW, R.C.; MCKINNEY, P.A.; LAW, G.R.; STAINES, A.; WILLIAMS, R.; BODANSKY, H.J. 1997: Incidence of childhood diabetes mellitus in Yorkshire, northern England, is associated with nitrate in drinking water: an ecological analysis. Diabetologia 40: 550-556.

POSTMA, D.; BOESEN, C.; KRISTIANSEN, H.; LARSON, F. 1991: Nitrate reduction in an unconfined sandy aquifer: water chemistry, reduction processes and geochemical modelling. Water Resources Research 27: 2027-2045.

POTHULURI, J.V.; MOORMAN, T.B.; OBENHUBER, D.C.; WAUCHOPE, R.D. 1990: Aerobic and anaerobic degradation of alachlor in samples from a surface-to-groundwater profile. J. Environ. Qual., 19: 525-530.

QUIN, B.F.; BURDEN, R.J. 1979: The effects of land use and hydrology on groundwater quality in Mid-Canterbury, New Zealand. Prog. Wat. Tech. 11 (6): p433-448.

RAHMAN, A.; HOLLAND, P.T. 1985: Persistence and mobility of simazine in some New Zealand soils. New Zealand Journal of Experimental Agriculture: 13: 59-65.

RAHMAN, T.K.; JAMES, T.K.; MARTIN, P.; FULLERTON, D.K. 1991: Persistence of metsulfuron in different soils. Proc. 44th NZ Weed and Pest Control Conference. p 99-104.

RAHMAN, A.; HOLLAND, P.T.; MA, Q.L.; JAMES, T.K.; MCNAUGHTON, D.E. 1999: Test of the Root Zone Water Quality Model (RZWQM) under New Zealand conditions. In Abstracts of the workshop on Environmental Aspects of Pesticide Use, November 1999, Hamilton.

REDDY, K.R.; PATRICK, W.H. 1981: Nitrogen transformations and loss in flooded soils and sediments. CRC Critical Reviews in Environmental Control, 13: 273 - 303

ROBERTSON, W.D.; CHERRY, J.A. 1995: In situ denitrification of septic-system nitrate using reactive porous media barriers: field trials. Ground Water 33: 99-111.

RODRIGUEZ, C.J.; HARKIN, J.M. 1997: Degradation of Atrazine in Subsoils, and Groundwater Mixed with Aquifer Sediments. Bulletin of environmental contamination and toxicology 59(5): 728735.

ROSEN, M.R. 1996: Hydrogeology, water quality, and nitrate movement in the unconfined gravel aquifer beneath the Maraekakaho sheep feedlot, Hawke's Bay, New Zealand. Journal of Hydrology (NZ) 35: 29-49.

ROSEN, M.R. 1997: The national groundwater monitoring network (NGMP): Structure, implementation and preliminary results. Institute of Geological & Nuclear Sciences, Science Report 97/26, 47 p.

ROSEN, M.R. 1999: The importance of long-term, seasonal monitoring of groundwater wells in the New Zealand National Groundwater Monitoring Programme (NGMP). Journal of Hydrology (NZ) 38: 145-169.

ROSEN, M.R.; BRIGHT, J.; CARRAN, P.; STEWART, M.K.; REEVES, R. 1999: Estimating rainfall recharge and soil water residence times in Pukekohe, New Zealand, by combining geophysical, chemical and isotopic methods. Ground Water 37: 836-844.

ROSEN, M.R.; JONES, S. 1998: Controls on the groundwater composition of the Wanaka and Wakatipu basins, Central Otago, New Zealand. Hydrogeology Journal 6: 264-281.

ROSEN, M.R.; MCNEILL, W.J. 1996: Nitrate concentration and migration in groundwater beneath the Maraekakaho feedlot, Hawkes Bay. Institute of Geological and Nuclear Sciences, Science Report 96/2, 78 p.

ROSEN, M.R.; REEVES, R.; ESER, P.; CHAGUÉ-GOFF, C.; COSHELL, L. 1998: Comparison of groundwater quality from forested (Waimarino River), urban (Turangi), and natural wetland (South Taupo Wetlands) subcatchments at the southern end of Lake Taupo. Institute of Geological and Nuclear Sciences, Science Report 98/1, 59 p.

ROSEN, M.R.; SHEPPARD, D.; ROBERTS, K.; VILJEVAC, Z.; SMAILL, A.; REEVES, R. 2000a: Effects of storm water infiltration on groundwater quality in a fractured rock aquifer in Auckland. Proceedings of the New Zealand Water and Waste Association Stormwater Workshop, 12-14 April 2000, Auckland.

ROSEN, M.R.; CAMERON, S.; MURRAY, D. 2000b: Report on TDR and soil lysimeter results from TDC effluent irrigation site at Rakanui Road. Institute of Geological and Nuclear Sciences Client Report No. 2000/21, 24 p.

SAFFIGNA, P.G. 1977: Nitrate in Canterbury well water and streams. Proceedings of the conference: Environment '77, University of Canterbury, Christchurch, New Zealand, 54-57

SCHIPPER, L.A. 1998: Treatment walls: nitrate removal from ground water and other uses. Proceedings of the New Zealand Land Treatment Collective Technical session 18: Effects of land-treated wastes on groundwater, 1-7.

SCHIPPER, L.A.; VOJVODIĆ-VUKOVIĆ, M. 1998: Nitrate removal from groundwater using a denitrification wall amended with sawdust: Field trial. Journal of Environmental Quality 27: 664-668.

SCHIPPER, L.A.; VOJVODIĆ-VUKOVIĆ, M. 2000: Nitrate removal from groundwater and denitrification rates in a porous treatment wall amended with sawdust. Ecological Engineering 14: 269-278.

SELVARAJAH, N.; MAGGS, G.; CRUSH, J.R.; LEDGARD, S.F. 1994: Nitrate in groundwater in the Waikato Region. *In* L.D. Currie, P. Loganathan, (eds.) Recent developments in understanding chemical movements in soils: significance in relation to water quality and efficiency of fertilizer use, 160-185.

SINTON, L.W. 1982: A groundwater quality survey of an unsewered, semi-rural area. New Zealand Journal of Marine and Freshwater Research 16: 317-326.

SMITH, C.M.; WILCOCK, R.J.; VANT, W.N.; SMITH, D.G.; COOPER, A.B. 1993: Towards sustainable agriculture: freshwater quality in New Zealand and the influence of agriculture. MAF policy Technical Paper 93/10.

SMITH, V.R. 1993a: Groundwater contamination from activities at a fertilizer works. Canterbury Regional Council Report 93 (37), 28 p.

SMITH, V.R. 1993b: Groundwater contamination by triazine pesticides. Levels Plain, South Canterbury. Canterbury Regional Council Report 93 (36), 36 p.

SMITH, V.R. 1993c: Groundwater Quality in Canterbury. Results of the Summer 1992/1993 Survey. Report 93 (32), 16 p.

SMITH, V.R. 1993d: Groundwater contamination by organic chemicals in Canterbury. Canterbury Regional Council Report 93 (20).

SPALDING, R.F.; EXNER, M.E. 1993: Occurrence of Nitrate in Groundwater - A Review. J. Environ. Qual. 22: 392-402.

SPARLING, G.; DRAGTEN, R.; AISLABIE, J.; FRASER, R. 1998: Atrazine mineralization in New Zealand topsoils and subsoils: Influence of edaphic factors and numbers of atrazine-degrading microbes. Australian Journal of Soil Research 36: 557-70.

SPRUILL, T.B. 1983: Relationship of nitrate concentrations to distance of well screen openings below casing water levels. Water Resources Bulletin 19: 977-981.

STANTON, D.J.; MARTIN, J.L. 1975: Nitrate levels in subsurface waters of the Waimea Plains, Nelson. New Zealand Journal of Marine and Freshwater Research 9(3): 305-9.

TALBOT, J.P; WEEBER, J.H.; FREEMAN, M.C.; MASON, C.R.; WILSON, D. 1986: The Christchurch artesian aquifers. North Canterbury Catchment Board and Regional Water Board.

TARANAKI REGIONAL COUNCIL 1995: Report on an investigation of pesticides in shallow groundwater in Taranaki. 95-14, Taranaki Regional Council.

TATE, K.R.; GILTRAP, D.J.; CLAYDON, J.J.; NEWSOME, P.F.; ATKINSON, A.E.; TAYLOR, M.D.; LEE, R. 1997: Organic Carbon stocks in New Zealand's terrestrial ecosystems. Journal of the Royal Society of New Zealand. 27(3): 315-335.

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY 1992: Another Look: National Survey of Pesticides in Drinking Water Wells. Phase 2 Report. EPA 570/9-91-020.

WANG, F.; BRIGHT, J.; HADFIELD, J. 1998: Nitrate transport modelling and contaminant tracing in groundwater at the Waitahanui Wastewater Treatment Site. Proceedings of the New Zealand Land Treatment Collective Technical session 18: Effects of land-treated wastes on groundwater, 69-80.

WARD, M.H.; MARK, S.D.; CANTOR, K.P.; WEISENBURGER, D.D.; CORREA-VILLASENOR, A.; ZAHM, S.H. 1996: Drinking Water Nitrate and the Risk of Non-Hodgkin's Lymphoma. Epidemiology, Vol. 7, No. 5: 465-471.

WEBB, T.H.; LILBURNE, L.R. 1999: Use of the LEACHM model to map risk of groundwater contamination by pesticide leaching on a regional scale. In Abstracts of the workshop on Environmental Aspects of Pesticide Use, November 1999, Hamilton.

WEBER, J.B. 1994: Properties and behaviour of pesticides in soil. In: Mechanisms of pesticide movement into ground water. R.C. Honeycutt and D.J. Schabachker (Eds.) Lewis Publishers. 15 - 41.

WEIJNEN, P.H.C.; LINSKENS, W.M.A.; SNIJDERS, A.; VAN DER LINDEN, A.M.A. 1990: Behaviours of pesticides in aquifer materials: In situ experiments. 725502001, National Technical Information Services, US Department of Commercial, Brussels.

WEISENBURGER, D.D. 1991: Potential health consequences of ground-water contamination by nitrate in Nebraska. *In* I. Bogardi and R.D. Kuzelka (eds.) Nitrate contamination: Exposure, consequence, and control. NATO ASI Serial G: Ecological Sciences 30, Springer-Verlag, Berlin, 309-315.

WHITE, E. 1983: Chemicals and their importance to the Lake. NZDSIR Information Series No. 158, Chapter 6, Lake Taupo, Ecology of a New Zealand Lake: p 63-72.

WILCOCK, R.J. 1989: Patterns of pesticide use in New Zealand. Part 1, North Island 1985-1988. Water Quality Centre Publication No 15, DSIR.

WILCOCK, R.J.; CLOSE, M.E. 1990: Patterns of pesticide use in New Zealand. Part 2, South Island 1986-1989. Water Quality Centre Publication No 16, DSIR.

WORLD HEALTH ORGANIZATION 1993: Guidelines for drinking-water quality. 2nd edition. Vol.1. Recommendations. 188 p.

9

Microbial contamination of New Zealand's aquifers

LESTER W SINTON

THE HIDDEN CONTAMINATION

For thousands of years, people have used groundwater for both drinking and crop irrigation, generally assuming that it will be microbially pure and wholesome. This assumption holds in New Zealand where, although the country is well-endowed with surface waters, around half the population depends wholly or in part on groundwater for domestic supply (Ministry of Health, Water Information N. Z. electronic database – WINZ and Chapter 10).

According to WINZ, there are 1,080 bores in New Zealand feeding into community reticulation systems. The water from 80% of these bores, including those serving Napier and Hastings, Lower Hutt, and Christchurch, is not chlorinated before entering the reticulation system.

In spite of world-wide confidence that groundwater will be free of harmful micro-organisms, there is long-standing evidence that this is not always so. For example, there is a biblical reference (Second Kings; Chapter 2; Verse 21) to what was possibly microbial contamination of groundwater, when Elijah purified a contaminated spring with salt. However, probably the best known historical reference to groundwater pollution is the classic investigation in 1854 by Dr John Snow, who tracked the cause of a cholera epidemic in London to a particular well in Broad Street (Snow 1855). This bore was sunk into saturated alluvial gravels near the Thames River (which was then heavily polluted with sewage).

Three interesting points arise from the Broad Street well study: (1) Snow had no knowledge of what caused cholera; indeed it would be nearly 30 years before the microbial agent for this disease was isolated. (2) The incident draws to our attention the fundamental paradox of groundwater contamination – groundwater is to some extent protected from contamination by a mantle of soil and subsoil, but when contamination does occur, that same mantle hides it from our view. The faecal material floating in the Thames would have deterred the good citizens of Broad Street from drinking the river water, but any such evidence near the well was out of sight. (3) The solution to the Broad Street well problem was the same as it often is today – the London authorities simply closed the well, and went to another source of water for that district. Protecting the groundwater from contamination in the first place was not considered to be a valid option.

In this chapter, we'll briefly examine the sorts of microbes that cause waterborne disease, describe the approach we use to indicate their possible presence, suggest possibilities for identifying faecal sources in groundwater, discuss the susceptibility of New Zealand aquifers to microbial contamination, list the potential sources of this form of pollution, and outline some of the principles and processes involved in microbial movement and transport.

WATERBORNE DISEASES

Introduction

A wide variety of enteric pathogens can infect the human gastro-intestinal tract. Like all living things, these microbes face evolutionary imperatives to ensure their survival. They

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need to move on, enter the mouths of new hosts, and infect their gastro-intestinal tracts. There are three ways this can occur – through person-to-person contact, via food, and via water. Although some enteric pathogens can use all three routes (which frequently complicates epidemiological investigations), water is undoubtedly an effective way for rapid spread, and many pathogens have developed mechanisms for ensuring their survival (and thus their transport) in water.

This adaptation of many enteric microbes to water transport means that, despite advances in water and wastewater treatment, waterborne diseases pose a major world-wide threat to public health. It is estimated that waterborne pathogens infect around 250 million people each year, resulting in 10 to 20 million deaths (Anon. 1996). Although most of these infections occur in developing nations, it is worthwhile noting that the incidence of waterborne disease in the United States has been reported as actually increasing, with more waterborne outbreaks being reported between 1971 and 1985 than in any previous 15-year interval since 1920 (Craun 1988). Many of these outbreaks have been associated with contaminated groundwater. For example, 44% of the waterborne disease outbreaks in the US between 1981 and 1988 were associated with untreated or inadequately disinfected groundwater (Craun 1991).

Types of enteric pathogens

Four broad types of waterborne pathogens infect humans throughout the world. From the smallest to the largest, these are viruses, bacteria, protozoans and helminths. Only the first three are micro-organisms; the helminths are multicellular organisms. Most of these pathogens are enteric, and are transmitted by the "faecal-oral route"; that is, they grow in the gut, are excreted in faecal matter, contaminate the environment, including water, and then gain access to new hosts through being ingested.

Viruses

Viruses are the simplest living things, usually consisting only of a protein coat ("capsid"), surrounding a nucleic acid core. They don't respire or metabolise; they only reproduce, and need to do so in a living cell (i.e., they are "obligate intracellular parasites"). They are also the smallest living things, most being less than 100 nanometers (nm) in diameter. The structure of a typical virus is shown in Fig. 9.1.

A number of different waterborne viruses infect the human gastro-intestinal tract. They are important pathogens for several reasons: (1) They are generally resistant to water and wastewater treatment processes. (2) Infected individuals can excrete large numbers of viruses – up to 10^{10} particles per gram of faeces (Rao and Melnick 1986) – with a shedding period of up to 50 days. (3) The minimum infective dose is low – possibly as low as one virus unit for some types. This makes enteric viruses highly infectious. While most of the general population are susceptible to enteric virus illnesses, small children, the elderly, and those with compromised immune systems, are most at risk.

Because viruses are difficult to assay, the viral agents of many outbreaks are often either not identified or are regarded as "poorly-characterised" (Craun 1984). Nevertheless, in the United States, over half of waterborne disease outbreaks are probably caused by viruses (Rao and Melnick 1986), and around 44% of all outbreaks have been associated with groundwater (Craun 1984).

The New Zealand Ministry of Health lists the following known viruses as important in New Zealand drinking waters (Ministry of Health 1995a). All of these viruses are shed in the faeces of infected individuals.

Enteroviruses: Enteroviruses cause a range of diseases, including throat infections, cardiac symptoms and conjunctivitis. They can cause gastroenteritis, but not normally as a single infection. They tend to be consistently present in sewage (albeit at low levels) and are probably the easiest enteric viruses to culture. Thus, they tend to be used as an "indicator" group for other enteric viruses (Murray et al. 2000). Ironically, there is no reliable evidence that they are transmitted by water.

Adenoviruses: Two types of adenoviruses (40

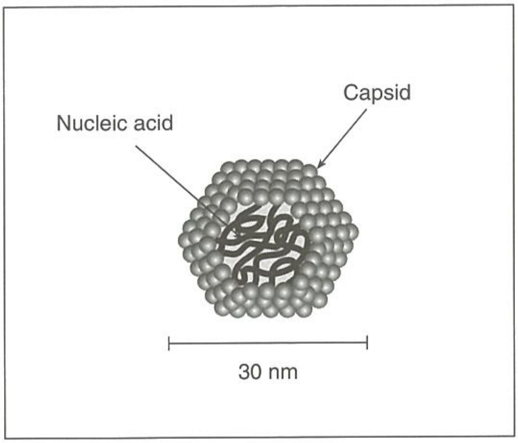

Figure 9.1 *Structure and size of a typical enteric virus, with one section of the icosahedral capsid removed to show the nucleic acid core.*

and 41) cause acute gastroenteritis, particularly among children. Others cause throat infections. Adenoviruses tend to be endemic, rather than epidemic, so are possible alternatives to enteroviruses as enteric virus indicators. However, the gastroenteritis adenoviruses are difficult to culture.

Norwalk virus: The Norwalk virus, and Norwalk-like agents, are part of a poorly-characterised group, which usually cause rapid, self-limiting epidemics of gastroenteritis. Outbreaks of Norwalk-like viruses associated with groundwater have been reported in the US (Craun 1984).

Reoviridae (rotaviruses and reoviruses): Reoviruses and rotaviruses are widespread in sewage and natural waters. According to the Ministry of Health (1995a), reoviruses have not been proven to cause human disease, but have been isolated from patients with gastroenteritis. Rotaviruses have been associated with waterborne outbreaks in Sweden and the US (Craun 1984), but do not appear to have been specifically associated with groundwater transmission.

Hepatitis viruses: Several viruses cause hepatitis. The two most important with respect to water and wastewater are hepatitis A and E. Three others – hepatitis B, C, and D – are spread only by contact with body fluids of infected individuals. Contaminated groundwater supplies have been responsible for Hepatitis A outbreaks in the US (Craun 1984), and Hepatitis E is probably also water transmissible (Gerba et al. 1985). Hepatitis A and E viruses cause liver infections, with symptoms such as jaundice.

Bacteria

Bacteria are unicellular microbes that are much larger than viruses, and have a far more complex structure. They come in various forms, with most enteric bacterial pathogens being rod- or tear-drop-shaped, about 6 μm long by 1.5 μm in diameter. Typically, they consist of a complex cell wall enclosing cytoplasm, at the centre of which is a circular DNA molecule.

A wide range of bacterial pathogens are found in faeces and wastewater. Because many normally non-pathogenic strains can become "opportunistic pathogens", given the right set of circumstances, the list in Table 9.1 is not exhaustive. Nevertheless, it gives the principal pathogens that have been, or theoretically could be, transmitted by groundwater.

Some of the bacteria in Table 9.1 are rarely encountered in New Zealand. The principal waterborne bacterial pathogens commonly transmitted by the faecal-oral route (i.e., excluding waterborne pathogens, such as *Legionella pneumophila* and *Leptospira*) considered by the Ministry of Health (1995a) to be important in New Zealand are discussed below.

Campylobacter jejuni: *C. jejuni* (Fig. 9.2) is one of a number of *Campylobacter* species that cause gastroenteritis. Although waterborne outbreaks have been reported in New Zealand (Ministry of Health 1995a), there is no reliable evidence that the unusually high incidence of *Campylobacter* infections in New Zealand is associated with water transmission. Animals, including ruminants, can harbour *C. jejuni* (Franco and Williams 1994), including serotypes that cause human infections (Jones et al. 1984), but this association has not been scientifically demonstrated in New Zealand.

Table 9.1 *Principal waterborne diseases caused by bacteria, and transmitted by the faecal-oral route.*

Bacterium	Major disease	Major reservoir	Principal site affected
Salmonella typhi	Typhoid fever	Human faeces	Gastrointestinal tract
Salmonella paratyphi	Paratyphoid fever	Human faeces	Gastrointestinal tract
Shigella	Bacillary dysentery	Human faeces	Lower intestine
Vibrio cholerae	Cholera	Human faeces	Gastrointestinal tract
Enteropathogenic *E. coli*	Gastroenteritis	Human faeces	Gastrointestinal tract
Yersinia enterocolitica	Gastroenteritis	Human/animal faeces	Gastrointestinal tract
Campylobacter jejuni	Gastroenteritis	Human/animal faeces	Gastrointestinal tract

Salmonella spp.: Salmonellae are generally regarded as pathogens of animals, which provide an important reservoir for infection of humans (Blackmore and Humble 1987). Most *Salmonella* infections cause acute but transient gastroenteritis, but some human-specific serovars (Typhi and Paratyphi) invade tissues and cause enteric fever. Groundwater-related outbreaks have been reported in the USA (Craun 1991). Although Salmonellae have been isolated from natural waters in New Zealand (Donnison and Ross 1999), waterborne transmission has not been demonstrated in this country.

Escherichia coli: Most strains of *E. coli* are harmless, but several can cause serious diseases. The best known is probably enterohaemorrhagic *E. coli* 0157:H7. Several cases of groundwater transmission of enteropathogenic *E. coli* have been reported, including an outbreak in Japan which infected over 900 people (Craun 1984).

Shigella spp.: Bacteria of the *Shigella* genus cause bacillary dysentery. Groundwater-associated outbreaks have been reported in the US (Craun 1984), but the incidence in New Zealand appears to be low (Ministry of Health 1995a).

Vibrio spp.: Various *Vibrio* species are found in water, but only one *Vibrio cholerae* strain causes classic cholera symptoms. Groundwater-associated cholera outbreaks are common in underdeveloped countries, and have also been reported in countries such as Portugal (Craun 1984). Cases of cholera are detected from time to time among people entering New Zealand, but the disease has not become established here.

Yersinia enterocolitica: *Y. enterocolitica* is another waterborne human enteric pathogen that is commonly found in animals (Blackmore and Humble 1987). Groundwater-related outbreaks overseas have included the infection of 1,900 people at a skifield in Montana (Craun 1984). The Ministry of Health (1995a) recognises a "growing awareness" of this organism as a cause of gastroenteritis in New Zealand, but the mechanism of transmission is poorly understood.

Protozoa

Protozoa are unicellular micro-organisms that are larger than bacteria, and tend to have more complex cell structures and life cycles. It

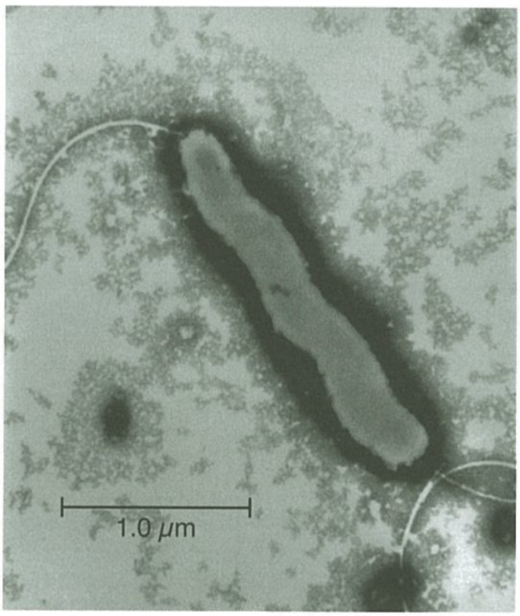

Figure 9.2 *An electron micrograph of the spiral-shaped, pathogenic bacterium,* Campylobacter jejuni. *The whip-like flagellae, one at each end, are used for locomotion.*

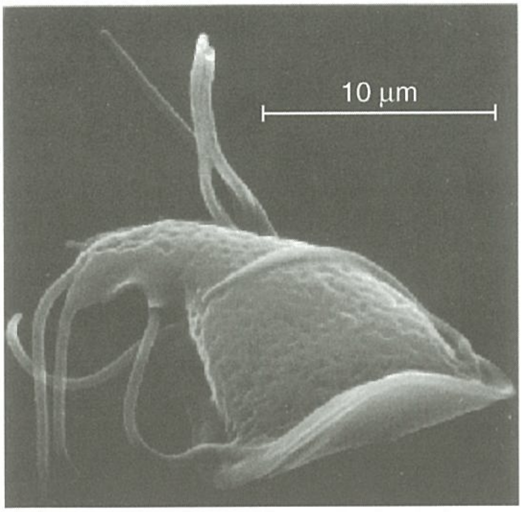

Figure 9.3 *A scanning electron micrograph of a trophozoite of the protozoan,* Giardia intestinalis.

is sometimes believed that protozoa are too large to be transported in groundwater, but there is no evidence to support this. At sizes ranging from around 5 μm in diameter to 20 μm long, they are theoretically small enough to be transported in alluvial gravels and coarse sands over similar distances to bacteria. Although there appears to be no reliable evidence for groundwater-associated protozoan outbreaks, this may be because of the difficulties associated with protozoan assay.

The Ministry of Health lists the following protozoans as important in New Zealand drinking waters (Ministry of Health 1995a). All of these are shed in the faeces of infected individuals.

Giardia intestinalis: *G. intestinalis* (formerly *G. lamblia*) (Fig. 9.3) has been found in waters throughout New Zealand (Brown et al. 1992). It has also been found in a wide range of domestic and wild animals (Marino et al. 1991; Tonks et al. 1991), although it has not been demonstrated that these are human strains (Brown 1993).

Cryptosporidium parvum: *Cryptosporidium* sp. has also been found in a wide range of natural waters in New Zealand (Ionas et al. 1998), and instances of cryptosporidiosis have been reported (Carter 1984). Animals are generally regarded as important reservoirs for this organism (Carrington and Smith 1995). Infection in humans can be life-threatening (Smith 1993), but in most animals it is usually asymptomatic.

Entamoeba histolytica: *E. histolytica* causes amoebiasis or amoebic dysentery. It is not endemic in New Zealand, but cases of amoebiasis occur among returning travelers (Ministry of Health 1995a).

Helminths

A number of faecal-oral helminth pathogens, particularly *Enterobius vermicularis* (a pinworm) and *Toxicara canis* (a roundworm) are very common in New Zealand. Others such as *Ascaris lumbricoides* (a roundworm) and *Trichuris trichiura* (a whipworm) are occasionally encountered but are probably not endemic (G. Paltridge, Canterbury Health, pers. comm.). None of the helminths in New Zealand is considered to be water transmissible, with the possible exception of the zoonotic *Fasciola hepatica* (a liver fluke), which completes part of its life cycle in an aquatic snail. This species appears to be on the increase in New Zealand (Mitchell 1995), and there is a remote possibility that it could be transmitted to humans via watercress (G. Paltridge, Canterbury Health, pers. comm.). Worldwide, there appear to be no reliable accounts of groundwater transmission of helminths.

INDICATORS OF FAECAL CONTAMINATION

The problem with pathogens

It is possible to detect pathogens in water samples, and since the 1980s, there have been significant advances in pathogen extraction and assay methods. These advances have included new methods for extracting viruses from natural waters (although overall recovery rates remain low), and the use of the polymerase chain reaction in pathogen assays (although this technique is currently non- or semi-quantitative, and does not reliably distinguish between viable and non-viable organisms).

Direct assay for pathogens has its place in water microbiology, for example, where a particular water supply needs to be confirmed as the source of an identified enteric disease outbreak. Advances in pathogen detection occasionally lead to calls for microbial water quality monitoring to be based on pathogens (e.g., Grimes 1999). There are, however, fundamental problems surrounding the presence of pathogens in water, and methods for their detection. The many different types of waterborne pathogens require very different (and often complex and costly) extraction and culture procedures. Thus, decisions are inevitably required as to which pathogens to look for. In addition, pathogens are usually present in water in low concentrations, which requires the processing of large volumes, thereby adding to the cost and time associated with their detection.

Even it were to become practically and economically possible to count all types of viable pathogens in a single water sample, the results of such a test could still be misleading. Many pathogens (such as the Norwalk virus) occur in outbreaks, so, even in quite heavily polluted water, their counts can quickly vary from occasional highs to functionally undetectable lows. Thus, a sewage-polluted groundwater supply being monitored only for pathogens could pass inspection on Tuesday morning and fail on Wednesday afternoon, even though the level of faecal pollution was largely unchanged between the two sampling events.

The problems associated with pathogen monitoring in water were recognised in the late 1800s, when it was decided that the most practical approach was to look for other micro-organisms that simply indicate the *presence* of faecal contamination and, thereby, the *possible presence* of pathogens. Thus, the valuable and enduring concept of the "indicator" organism was born.

Indicator organisms

The characteristics of an ideal indicator organism for faecal pollution have been described by a number of reviewers, including Bonde (1966) and Cabelli (1977). Briefly, an indicator should be:

- consistently present in faecal material,
- present in sufficient numbers to provide a reasonable estimate of the level of faecal contamination,
- approximately as resistant to treatment processes and environmental stresses as the most resistant pathogens likely to be present in the faecal source, and
- quantifiable by reasonably simple and straightforward methods.

Many different micro-organisms have been suggested as faecal indicators. Although no indicator is "ideal" for all situations, the following are either in widespread use, or are under investigation as indicator organisms.

Coliform bacteria

Coliform bacteria, including the subset group of "faecal" coliforms, are the most commonly used indicator organisms. Their use has been reviewed by many authors, most notably Geldriech (1966). They are rod-shaped bacteria that are found in large numbers in faeces. Some coliforms can be found in unpolluted water, although most faecal coliforms are of faecal origin. One faecal coliform species – *Escherichia coli* – is almost certainly from faeces. Either faecal coliforms, or *E. coli* are recommended for the monitoring of New Zealand fresh waters by the Ministry for the Environment and Ministry of Health (1998), although groundwaters are not specifically included in this recommendation. New Zealand drinking water standards used to be based on faecal coliforms (Ministry of Health 1995b). They are now based on a maximum allowable value (MAV) of less than one *E. coli* in 100 ml of sample, but (total) coliforms and faecal coliforms may also be used to monitor drinking water supplies (Ministry of Health 2000).

Enterococci

Enterococci are spherical enteric bacteria that exist in pairs or chains, and have been recommended as faecal indicators in New Zealand marine waters by the Ministry for the Environment and Ministry of Health (1998), based on epidemiological evidence from United States Environmental Protection Agency studies in the 1970s and 80s (Cabelli 1983). Although some New Zealand regional councils monitor groundwater for enterococci, there is no epidemiological basis for doing so. The literature on enterococci and other faecal streptococci as faecal indicators has been reviewed by Sinton et al. (1993a, b).

Faecal bacteriophages

Since the 1960s, there has been increasing interest in the use of enteric bacteriophages as both faecal and viral indicators. Bacteriophages (or "phages") are viruses that attack and replicate inside bacteria. Large numbers of enteric phages are excreted in faeces, along with their bacterial hosts. Two phages of *E. coli* – the somatic coliphages and F-RNA phages – have been extensively investigated as faecal indicators and viral models. Somatic coliphages are a heterogeneous group of phages (often with "tails" – see Fig. 9.4) that attach to the bacterial cell wall. F-RNA phages are small icosahedral phages (about the same size as many enteric viruses) that attach to the "F-pili" – filamentous structures on "male" bacterial strains. The use of faecal bacteriophages as indicators has been reviewed by the International Association on Water Pollution Research and Control (1991) and Havelaar et al. (1993).

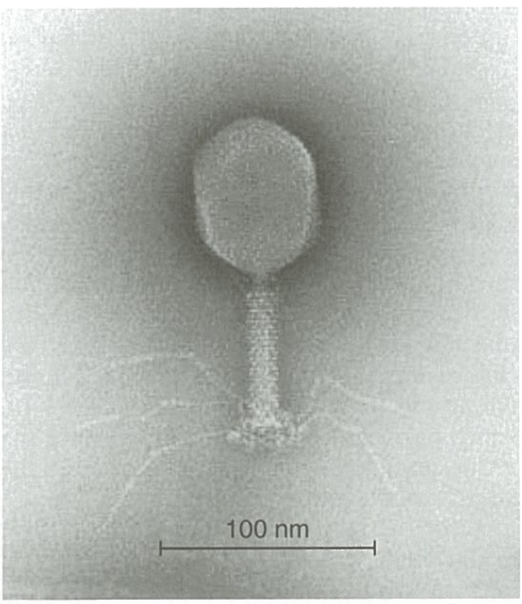

Figure 9.4 *An electron micrograph of the somatic coliphage T4. This phage has a polyhedral head, a tail, and tail fibres which help the phage attach to the cell wall of the host bacterium.*

IDENTIFICATION OF FAECAL SOURCES

General

Faecal indicator microbes show the presence of faecal material in water, but do not indicate its source – specifically, whether it is of human or animal origin. To groundwater resource managers, identification of faecal sources is of particular significance in unsewered, non-reticulated, semi-rural communities. In these areas, individual drinking water bores are often close to potential sources of faecal contamination such as septic tank systems and animal containment areas.

Methods for identifying faecal sources have been reviewed by Sinton et al. (1998a), and the principal approaches and problems are briefly outlined here. Source identification is of interest to water managers for two reasons. First, human faeces are generally perceived by the public as constituting a greater human health risk than animal faeces, although reliable epidemiological evidence in support of this view is lacking. Second, irrespective of the relative risks, the ability to identify sources through water assay would assist in the overall management of faecal pollution.

MICROBIAL METHODS

Many different faecal micro-organisms have been suggested as differentiating faecal sources but, on closer investigation, most have proved to be unsuitable. Among the more promising are:

Bifidobacteria - Some species are believed to be indicative of humans, whereas others indicate animals, but this has not yet been confirmed for environmental samples.

F-RNA phages - Different subgroups appear to be associated with human and animal faecal sources, although this has not been extensively investigated.

Rhodococcus coprophilus - This actinomycete is a potential indicator of grazing animals, because it grows primarily in the dung of herbivores. However, it is persistent in aquatic environments, and existing culturing techniques are time-consuming.

The development of DNA-based techniques, such as gene probes (for bifidobacteria) and polymerase chain reaction (for *R. coprophilus*), may assist in the assay of some microbial faecal source indicators.

Chemical methods

A wide variety of "anthropogenic" chemicals are associated with human activity, and are potential markers of human pollution sources (Eaganhouse 1997). Most promising from a groundwater perspective are washing powder constituents such as fluorescent whitening agents, sodium tripolyphosphate, and linear alkyl benzenes, because they may be found in septic tank effluent. In addition to anthropogenic chemicals, different isomers of a group of chemicals in the mammalian gut called faecal sterols offer the possibility of distinguishing between human and animal sources, and even between different animals (Sinton et al. 1998a).

The only published study of faecal source identification in New Zealand groundwaters appears to be that of Close et al. (1989), who measured fluorescent whitening agents and sodium tripolyphosphate levels in 67 individual household bores at Yaldhurst, west of Christchurch. Septic tank systems were implicated as the source of contamination in 17% of the samples, which exhibited detectable levels of whitening agents and/or sodium tripolyphosphate. Sodium tripolyphosphate levels were significantly correlated with faecal coliform concentrations. With improved detection limits, these chemicals may become useful tools for identifying septic tank effluent contamination in unsewered areas (Close, pers. comm.).

MICROBIAL GROUNDWATER TRACERS

Enteric micro-organisms indicate the presence of faecal contamination in water, and in future it may also be possible to distinguish between human and animal faecal pollution in groundwater quality surveys. However, other tools are needed for experiments involving the marking of microbial contamination sources, and tracing the rate and extent of movement of faecal microbes. The best way to do this is through the use of specific microbial tracers.

A microbial tracer – the red-pigmented bacterium *Serratia marcescens* – was first used to demonstrate water movement between two wells by Ditthorn and Luerssen (1909). Since then, other bacteria, yeasts and bacteriophages have been used to trace groundwater movement. Microbial water tracing techniques are now widely used in groundwater research, and the approach has been reviewed by Sinton, (1980a, b), Keswick et al. (1982b), and Sinton and Ching (1987).

Microbial tracers were first used in New Zealand in 1977 in an array of experimental bores at Burnham in mid-Canterbury (Sinton 1979; 1980a), and at Heretaunga (Thorpe et al. 1982). At Burnham, a thermophillic bacterium, *Bacillus stearothermophilus*, and a hydrogen sulphide positive (H_2S^+) strain of *E. coli* were injected into bore 2 (Fig. 9.5), and their passage through bores 4 to 7 was recorded, indicating a velocity (based on first-arrival) of around 190 m day^{-1}. However, because of background counts in sewage, both of these tracers were found to be unsuitable for use in contaminated groundwater.

More successful were three antibiotic-resistant *E. coli* strains which were tested at the Burnham and Templeton sites (Sinton 1980b; Sinton and Close 1983), and were later applied to septic tank studies (Sinton 1986; see *Septic tank systems*). These strains are recovered on media containing antibiotic concentrations that suppresses most other bacteria, including those from sewage. Four safety factors were considered when selecting these tracers: the strains were confirmed as non-pathogenic serotypes, the antibiotics selected have little application in medicine, the resistance factors were not plasmid-borne (which greatly reduces the chance of transfer to other bacterial cells), and the strains were derivatives of *E. coli* K12, which has been laboratory-cultured since the 1930s, and has lost the ability to colonise the human gastro-intestinal tract.

In order to ascertain rates of viral transport in alluvial gravels, Noonan and McNabb (1979) injected two types of bacteriophage – ØX174 and T4 – into bore 2 at Burnham (Fig. 9.5). ØX174 was recovered from bore 4, and T4 from bores 4, 5 and 6, demonstrating transport times similar to those recorded previously for bacteria. However, neither phage was suitable for

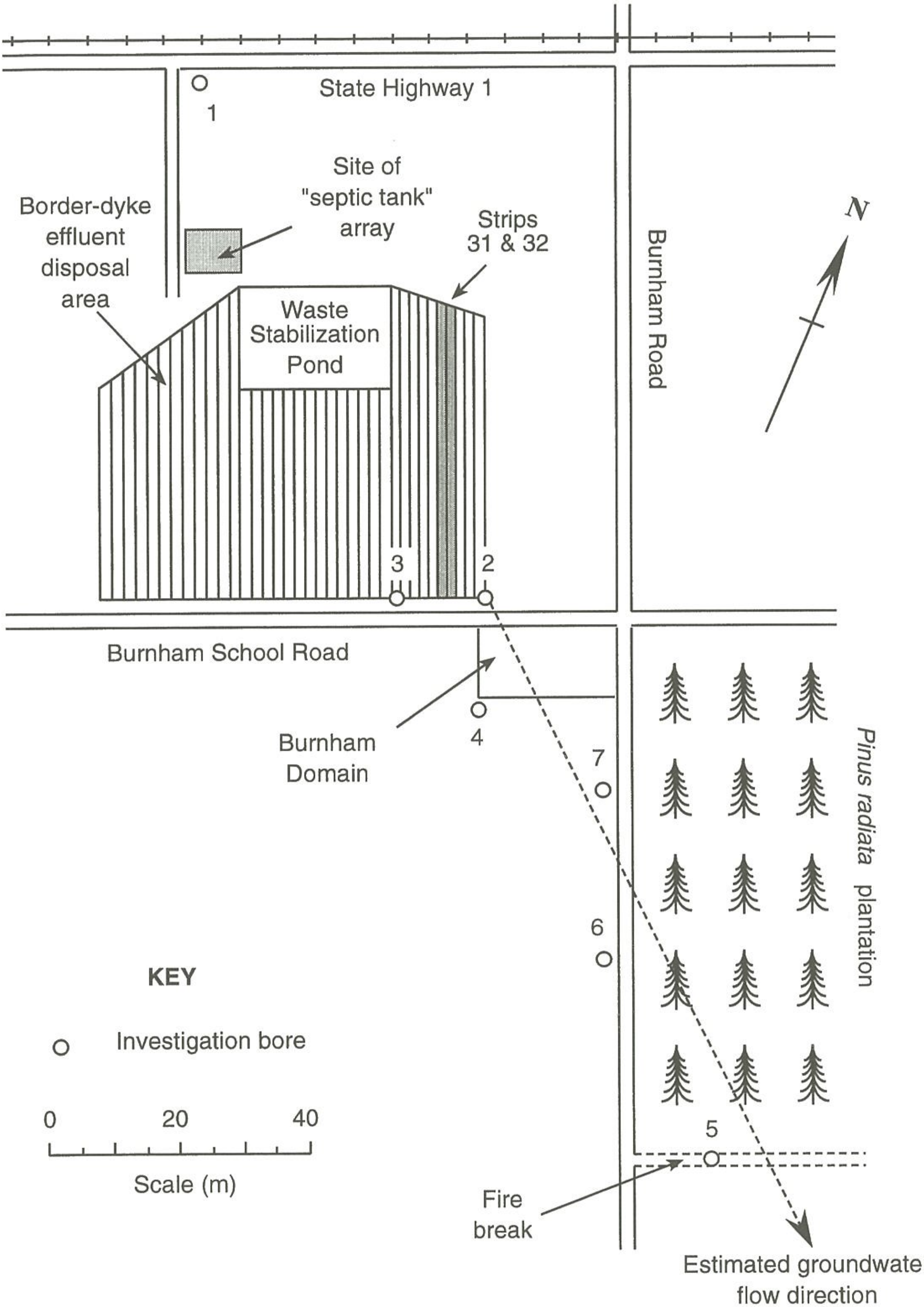

Figure 9.5 *Burnham wastewater treatment plant and associated array of experimental bores.*

use in sewage-polluted water, because their *E. coli* hosts also recover other sewage phages. The selection of phage tracers for sewage-polluted water is a more complex problem than for bacteria. A host must be found that is susceptible to the selected tracer, but resistant to other sewage phages. In the mid 1980s, Sinton and Ching (1987) evaluated two phage-host systems for use in sewage-polluted water. Two bacterial hosts – *E. coli* H_2S^+ from the earlier tracing experiments (Sinton 1980a) and a strain of *Staphylococcus aureus* – were found to give low background phage counts in sewage samples. A phage (named ØMWD1) of *E. coli* H_2S^+ and phage 80 of *S. aureus* were then used to trace the movement of waste stabilisation pond effluent 6 km down a river system (Sinton and Ching 1987). However, these tracers have not so far been used in groundwater research in New Zealand.

Two more recent studies have involved application of the bacterial tracer *E. coli* J6-2 and the bacteriophage MS2, These were used at experimental sites at Templeton (Sinton et al. 1997) and Burnham (Sinton et al. 2000; see Microbial transport and survival in groundwater). Overall, bacterial and viral tracers continue to be powerful tools in research into the transport of enteric micro-organisms into and through aquifer systems.

VULNERABLE AQUIFERS

There is no simple formula for assessing the vulnerability of New Zealand aquifers to microbial contamination. However, in general, susceptible aquifers are likely to be:

- of sufficient porosity to allow microbial penetration and transport.
- shallow, and unconfined.
- overlain by light soils and porous subsoil strata
- recharged by water with high susceptibility to microbial contamination, such as surface drainage or river recharge from intensively stocked or urbanised areas.

There is no national record of incidents or levels of microbiological contamination of aquifers in New Zealand. Indeed, *The State of New Zealand's Environment* report (Ministry for the Environment 1997) refers only to chemical contamination of groundwater. Information on microbial quality is collected and held by regional councils, and in some cases by health authorities. Almost all of this information is collected from private bores, where it is frequently difficult to ascertain whether the contamination originates in the groundwater, or from surface drainage through poorly constructed well heads.

The information below was obtained from all 15 regional and district councils by personal communication, from publications, internal regional council reports, and "state of the environment" reports. However, it is not intended to be a comprehensive record of incidents or levels of microbial contamination, or of aquifers prone to microbial contamination. The regional attention accorded to microbiological quality is, understandably, uneven and depends on the local importance of groundwater resources, and their degree of susceptibility to microbial contamination.

1. Northland: Groundwater supplies are found in shallow, unconfined marine sands in the Aupori Peninsula (Thorpe 1992). Although the susceptibility to microbial contamination in these sands is theoretically high, most drinking water supplies in this area are extracted from deeper strata. *Giardia intestinalis* has been found in some drinking waters supplied from springs, but it is unclear whether this contamination arose from the groundwater, or from surface run off into the supply intake. The Poroti Springs, in fractured volcanic strata, partly supplying Whangarei city, are theoretically susceptible to microbial contamination, but no problems have been encountered to date (Phipps, Northland Regional Council, pers. comm.). However, septic tank systems are suspected contributors to microbial contamination of groundwater beneath Russell, particularly of the shallow gravel aquifer in the central area of the township (Northland Catchment Commission 1987).
2. Auckland: Microbiological contamination of groundwater is not regarded as a major problem in the Auckland region. However, the area contains a large number of small coastal communities, many of which are

unsewered and draw water from shallow household bores. Some incidents of suspected septic tank effluent contamination of groundwater have been identified in island communities in the Hauraki Gulf (G. Crowcroft, Auckland Regional Council, pers. comm). In the Onehunga groundwater system, which is part of the larger Auckland aquifer system, bacterial counts in bores tend to rise after rainfall (H. Thorpe, University of Canterbury, pers. comm.).

3. Waikato: This region contains areas of shallow, unconfined, pumice sands, where there is a possibility of microbial contamination from activities such as intensive grazing and land application of dairy-shed effluent. The major aquifers in the Tokoroa region, which supply both the Kinleith pulp and paper mill and the Tokoroa township, are in extensively fractured ignimbrite, and there is extensive interaction between the surface and groundwaters. Thorpe (1992) notes the possibility of conflict between potable use of groundwater in the Tokoroa area and activities such as animal waste disposal. Although no widespread problems of microbiological contamination have been identified in the Waikato region, in some unsewered coastal towns, up to half the wells surveyed have been microbially contaminated (Environment Waikato 1998; J. Hadfield, Environment Waikato, pers. comm.).
4. Bay of Plenty: Microbial contamination in groundwater is not regarded as a significant problem in the Bay of Plenty region. Incidents of bore water contamination arise occasionally, but these are generally attributed to poor well head protection (J. Gibbons-Davies, Environment Bay of Plenty, pers. comm.). Contamination of shallow groundwater by septic tank effluent is a possibility in small communities on the shores of the Rotorua lakes (Ray et al., 2000).
5. Gisborne District: The Poverty Bay Flats overly a complex groundwater system, which includes the shallow, coastal, Te Hapara sands. No major microbiological contamination problems have been identified in the region. However, shallow, unconfined groundwater systems beneath unsewered, non-reticulated coastal communities are considered to be at risk of microbial contamination, particularly from grazing animals. A few cases of possible septic tank effluent contamination of bores have also been identified (A. Reid and P. Burrows, Gisborne District Council, pers. comm).
6. Hawke's Bay: The Heretaunga system is an important shallow alluvial gravel aquifer supplying Napier and Hastings. The aquifer is partly unconfined, and septic tank effluent contamination of groundwater in some areas has been strongly suspected (Barnett and Simons 1980; Liddell and Simons 1982). Rates of microbial movement in this aquifer system have been specifically investigated (Thorpe et al. 1982). In addition, suspected microbial pollution of household bores in sandy coastal areas has been reported (Hughes 1998).
7. Taranaki: The Taranaki-Wanganui region contains extensive but discontinuous shallow volcanic sands and ashes. No major microbial pollution problems have been reported for groundwaters in the Taranaki region. However, faecal indicators are occasionally recorded in individual bores, and a piezometer close to a septic tank system in Ohakura showed evidenced of faecal contamination from the disposal structure (J. Williams, Taranaki Regional Council, pers. comm.).
8. Manawatu-Wanganui: Microbial contamination of groundwater is not a major problem in the region. Faecal indicator bacteria have been recorded in bores in the Horowhenua and Tararua Districts, but poor bore development and well head protection are suspected as the sources of this contamination in many cases (G. Bekesi, Horizons Manawatu Wanganui, pers. comm.).
9. Wellington: This region includes several shallow, mostly unconfined, alluvial gravel aquifers in the Wairarapa area, as well as the important Hutt Valley aquifer. However, to date, there have been no major

microbial contamination problems recorded in these aquifers, or in the shallow coastal groundwater systems in the Pekapeka-Paraparaumu area. However, incidents of microbial contamination, where septic tank systems are the suspected source, have been recorded in beach communities at Riversdale and Te Horo beach (A. Jones, Wellington Regional Council, pers. comm.). There is intensive urban development over the unconfined region of the important Hutt Valley aquifer, so microbial contamination from sources such as fractured sewer mains is possible (H. Thorpe, University of Canterbury, pers. comm.).

10. Tasman District: Tasman Bay and Golden Bay both contain small, shallow alluvial aquifers in river valleys, which are theoretically susceptible to microbial contamination. However, the most important aquifer in the region is the Waimea Plains system. A recent bacteriological survey of wells in this area showed that 60% of shallow wells and 20% of deeper wells tested positive for faecal coliforms (Tasman District Council 2000). However, the shallow wells were excavated rather than drilled, so surface drainage may have contributed to these results.
11. Marlborough: Although the potential for microbial contamination of the Wairau Plains aquifer is recognised, no major microbial contamination problems have emerged in this region. A survey of bores down-gradient of the unsewered (but water-reticulated) community of Renwick showed no evidence of microbial contamination (P. Davidson, Marlborough District Council, pers. comm.).
12. Canterbury: This region contains the large, economically important Canterbury Plains alluvial gravel aquifer systems, which are extensively used for domestic supply, via both individual bores and reticulated systems. The depth to water table varies widely, from a few metres below ground level to >100 m away from the rivers and coast. The shallow aquifers, including those in the inter-montane basins, such as the Waiau Plains, are the most vulnerable to microbiological contamination.

    Microbiological surveys of wells in the Canterbury Plains area in 1994 showed that 15% contained faecal coliforms. A similar survey in 1995 showed that 8.8% tested positive for faecal coliforms (up to 200 100 ml^{-1}). In general, the contaminated bores were extracting groundwater from less than 30 m below ground level. In some areas, particularly in South Canterbury, the incidence of microbial contamination is higher. For example, a groundwater quality survey of 89 bores between the Waihao and Waitaki Rivers showed that 66% contained faecal coliforms. The higher incidence of faecal contamination has been attributed to the shallower groundwater in this area of the plains (Canterbury Regional Council 1997; Haywood 1999).

    Microbial contamination of groundwater in the Canterbury region has been attributed to poor well head protection, septic tank systems, and land application of animal effluents. In many small settlements in Canterbury, septic tank effluent disposal occurs in proximity to drinking water bores. Intensive investigations in a few of these communities has shown significant microbiological contamination of shallow groundwater near septic tank effluent disposal points (Smith 1994; Canterbury Regional Council 1997).

    Microbial contamination of aquifers in the Canterbury area has been the subject of specific research programmes. These have included the effects on groundwater of septic tank effluent (Ayrey and Noonan 1983; Sinton 1982; 1986; Close et al. 1989) and effluent irrigation schemes (Martin and Noonan 1977; Sinton et al. 1997). These studies are discussed under Sources of microbial contamination.
13. West Coast: No major issues problems of microbial pollution of groundwater have been identified in this region. However, a few incidents of domestic bore water contamination have been reported on alluvial river plains, and permissible levels of dairyshed effluent discharge to land (in terms

of the effects of nitrate-nitrogen concentrations in groundwater) suggest the need to also monitor faecal indicator levels (T. James, West Coast Regional Council, pers. comm.).

14. Otago: Microbial contamination has been noted in at least two shallow, unconfined aquifers in this region. High faecal coliform counts have been recorded throughout the Lower Waitaki Alluvium groundwater system. This is an area in which there are many dairy farms, which are irrigated by both spray and flood irrigation of fresh water, and spray irrigation of dairy-shed effluent. Individual septic tank systems may also contribute to the observed faecal coliform counts. Microbial contamination has also been recorded in the Wakitipu Basin sediments where the groundwater table is frequently less than 1 m below ground level. A variety of land uses, and septic tank systems, are possible contributors to microbial contamination in this rapidly-growing area (T. Heller, Otago Regional Council, pers. comm.).
15. Southland: This region contains extensive but discontinuous groundwater systems, including some shallow gravel aquifers. Although the groundwater is generally not used for municipal supplies, it is used by over half of Southland's farms, 90% of these for either stock watering or domestic supply (Hamill 1999). In 1997-98, the Southland Regional Council surveyed bores in unconfined aquifer areas. Around 40% of samples contained faecal coliforms. However, whereas nitrate nitrogen levels appeared to be related to proximity to septic tank systems, microbial contamination levels tended to reflect to the degree of well head protection (Hamill 1999).

SOURCES OF MICROBIAL CONTAMINATION

General

There are many potential sources of microbial contamination of New Zealand aquifers. The major sources are given below, but the list is not intended to be exhaustive. Nor are the sources necessarily ranked in order of importance.

Grazing animals

In June 1999 there were about 46 million sheep/lambs and 4.6 million beef/dairy cattle/calves in New Zealand (Meat and Wool Economic Service of New Zealand 2000). Based on conservative faecal excretion rates (R. McFarlane, Lincoln University pers. comm.), the annual deposition on New Zealand pastures is around 13 x 10^6 tonnes of sheep faeces and up to 12.5 x 10^6 tonnes of cattle faeces. Thus grazing animals form the largest potential source of microbial contamination of New Zealand aquifers, and the entry of even a small proportion of this material into groundwater would provide a significant source of zoonotic pathogens. However, ironically, the effects of scattered (i.e., non-point source) dung deposition on the microbial quality of groundwater has not been systematically investigated.

Grazing animals also give rise to three forms of point source contamination – offal pits, dairy-shed effluent, and animal containment areas. Offal pits are covered separately below. Dairy-shed effluent is frequently sprayed onto pasture, and the application of faecal material in liquid form theoretically confers greater mobility on the faecal micro-organisms. However, the effects of this activity on microbial groundwater quality are not well understood. Similarly, the effects of animal containment areas on the microbial quality of groundwater have not been investigated. However, in Hawke's Bay, a feedlot was found to be causing chemical contamination of down gradient groundwater (Rosen et al. 1995).

Septic tank systems

Most households in New Zealand are connected to reticulated sewerage systems. However, in many rural and semi-rural areas, a high proportion of households are on septic tank systems. For example, most of the properties in the Selwyn District, west of Christchurch, are served by individual septic tank systems. In 1992, this was around 6,000 systems (O'Boyle 1992), and the number of "lifestyle blocks" served by septic tank systems has increased significantly since then. Potentially, this represents a significant regional input of human effluent to groundwater.

The design and operation of New Zealand septic tank systems has been described by Fox (1984). A typical setup consists of a single-chambered tank in which the household effluent receives some degree of anaerobic treatment, before being discharged into a disposal structure. This structure is usually a shallow soakage trench or a deep soakage pit. More rarely, deep injection bores or evapo-transpiration mounds are used. The problems with soakage trenches are largely associated with side-wall sealing and the resulting seepage of effluent to the surface, particularly in fine soils with a high clay content. Soakage pits are used in these situations to connect with underlying porous strata. These pits are in common usage in Canterbury, where the porosity of the gravels is such that some soakage pits have been in continuous service for over 30 years.

Although deep soakage pits are effective disposal systems, the potential threat to groundwater quality from direct connection with porous gravels is obvious, and there is long-standing anecdotal evidence of groundwater contamination by septic tank effluent. However, the first systematic investigation of this form of contamination appears to have been carried out by Mulcock and Noonan (1973), who examined the effects of two boulder pits at Tai Tapu, near Christchurch, on surrounding soils and soil water. They found coliforms and faecal streptococci in a test bore 26 m away from one soakage pit, although it was not possible to conclusively demonstrate that the septic tank system was the source of the contamination.

Subsequently, groundwater quality surveys of unsewered areas in Hawke's Bay (Barnett and Simons 1980) and Canterbury (Sinton 1982; Ayrey and Noonan 1983) showed evidence of groundwater contamination by faecal indicator bacteria. The study by Sinton (1982) was conducted at Yaldhurst, west of Christchurch. One third of the 120 bores in a baseline survey contained coliform bacteria. Of 25 bores selected for fortnightly sampling for a further 8 months, 23 exhibited intermittent contamination by indicator bacteria. Although deep disposal structures were suspected as the source of some of the contamination in all these surveys, this relationship could only be inferred because of a lack of research information on both faecal source identification and mechanisms of microbial movement from deep disposal structures.

To better understand the effects on groundwater of deep disposal of septic tank effluent, an experimental site (for location, see Fig. 9.5) was set up at Burnham (Sinton 1986). The site consisted of a single-chambered septic tank, which could be connected to one of two disposal structures – a 5.5 m deep soakage pit and an 18-m-deep injection bore (the former is widely used in Canterbury; the latter is used in a few situations where thick impermeable clay layers preclude soakage pit construction). The movement of faecal coliforms and bacterial tracers was recorded over 9 m from the soakage pit into an unconfined aquifer, and 42 m from the injection bore into a confined aquifer. There was evidence of groundwater mounding beneath both disposal structures, and the consequent radial spread of leachate. In both the confined and unconfined aquifers, the most heavily contaminated bores exhibited marked diurnal fluctuations in response to periods of effluent discharge. Faecal coliform counts over a 3-day period in one of the shallow bores 4 m below and 3 m to the side of the soakage pit are presented in Fig. 9.6. This rapid response in microbial counts to periods of discharge, and even to individual discharge events, suggests that the overall microbiological quality of drinking water from household bores in alluvial gravel areas may only be ascertained by intensive monitoring.

The results from the deep injection into the confined aquifer suggested a conservative down-gradient safe separation distance of 200 m (to ensure no faecal coliforms in 100 ml). However, a report prepared for Environment Canterbury suggests that if a septic tank and disposal structure (other than an injection bore) are working properly, the contaminant plume length should be less than 50 m (Canterbury Regional Council 1999a). This suggests that the groundwater effects of a septic tank system could be confined within a 4-hectare lot size. However, simulations of a cluster of three disposal fields around a common corner suggested

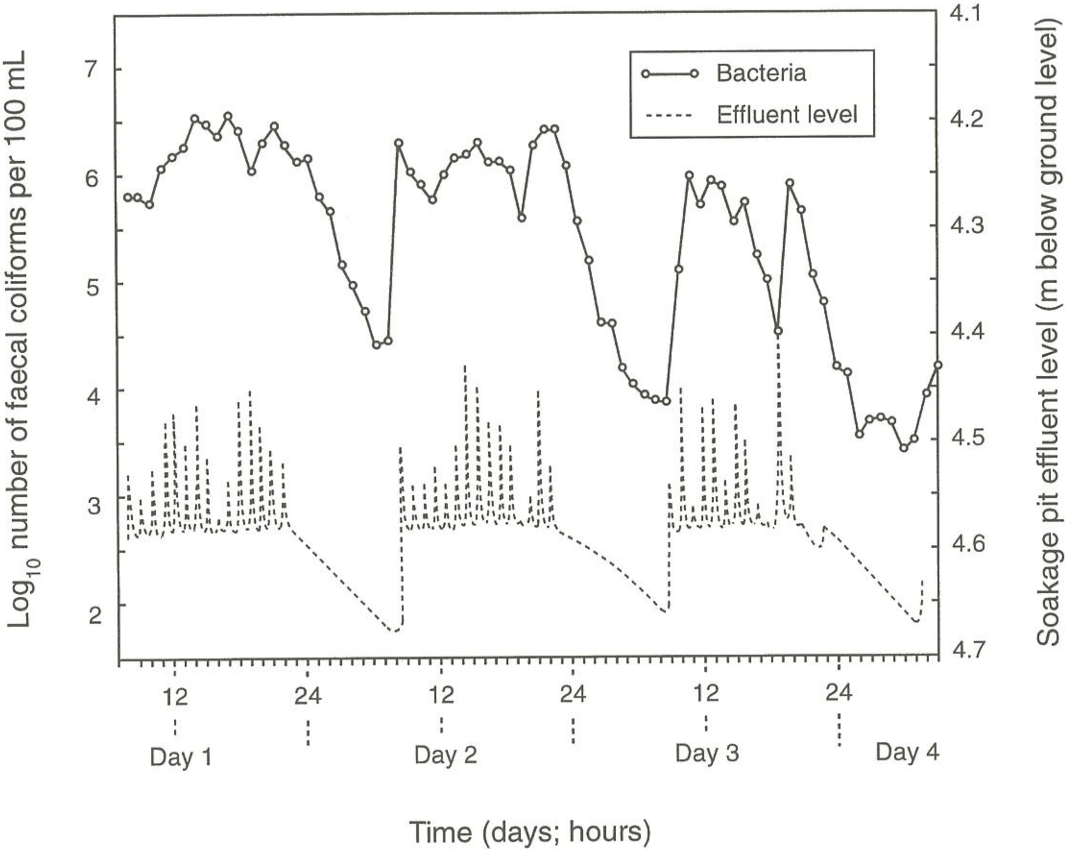

Figure 9.6 *Fluctuations in faecal coliform bacteria concentrations over a 3 day period in a bore 3.0 m from a septic tank soakage pit, compared to effluent level in the pit. The effluent level recorded the individual septic tank discharges to the pit. From Sinton (1986); reproduced with permission from Water, Air and Soil Pollution.*

that bacterial problems with contaminant plumes could extend out to 75 m. A second Environment Canterbury report notes that plume lengths of up to 180 m may apply to viruses in septic tank effluent, but that the uncertainties associated with viral transport in unsaturated and saturated strata are currently too great to allow meaningful recommendations to be made (Canterbury Regional Council 1999b).

Effluent irrigation

Effluent irrigation systems have been used in New Zealand since the 1880s (Wilcock 1984). Many different types of effluent are now applied to land in this country, with the most common being the discharge from waste stabilisation ("oxidation") ponds. According to the unpublished New Zealand Water and Waste Association's Wastewater Treatment Plant Database, 179 of the 266 wastewater treatment plants serving larger communities are waste stabilisation ponds. Of these, 30 are listed as discharging to the land. The oldest existing effluent irrigation scheme in the country serves the township of Templeton, near Christchurch (Quin 1984).

Although the potential for microbial contamination of groundwater by effluent irrigation schemes had long been recognised, systematic investigation of this issue in New Zealand appears to have begun with the study by Martin and Noonan (1977). To estimate the likely effects on groundwater of waste stabilisation pond effluent irrigation from the proposed town of Rolleston, two existing effluent irrigation schemes were selected for study – the Templeton plant, and the scheme serving the Burnham military camp. Both schemes consist of a waste stabilisation pond discharging to grazed pasture via border-dyked irrigation. Arrays of monitoring bores were installed down-gradient of each site, together with an upstream control bore. The Burnham site is shown in Fig. 9.5, and Templeton site in Fig. 9.8.

There were three principal findings from the study: (1) Faecal bacteria reached the groundwater table in sufficient concentrations to be detectable at least 900 m down gradient. Fig. 9.7 shows the counts of faecal coliform bacteria in the Burnham bore array following

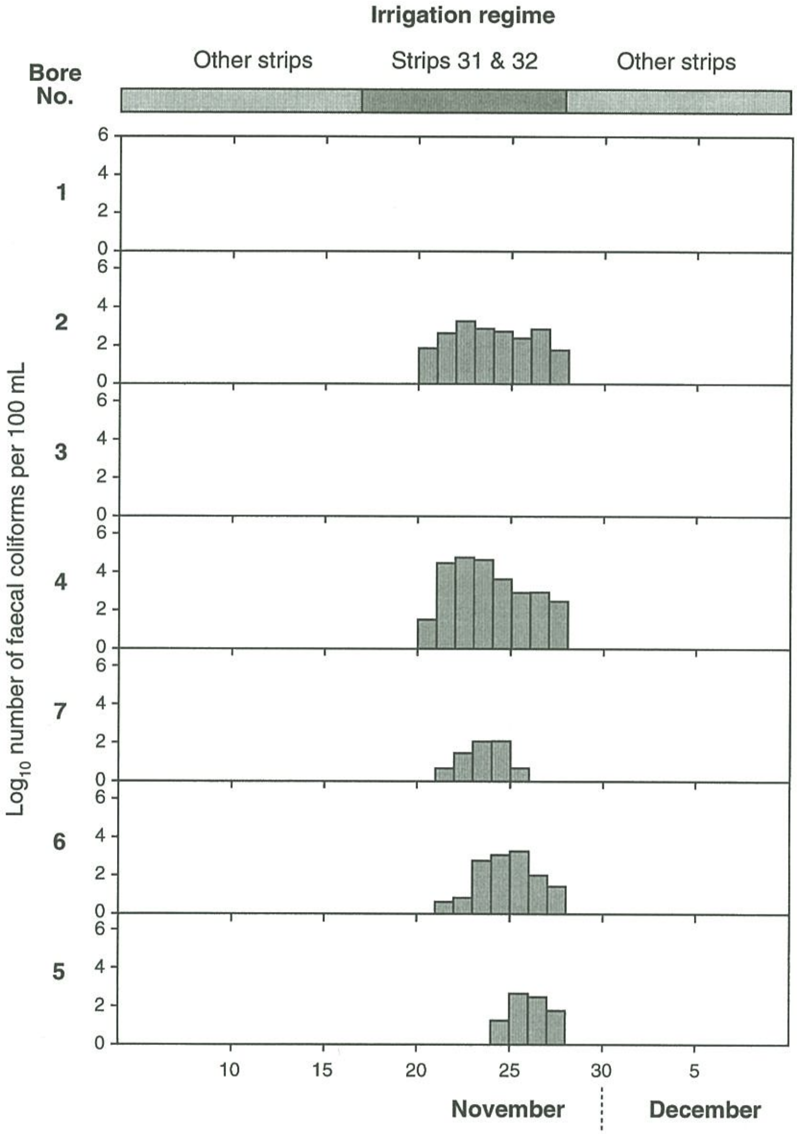

Figure 9.7 *Counts of faecal coliform bacteria in the Burnham bore array following effluent irrigation of strips 31 and 32 (Fig. 9.5). Modified from Martin and Noonan (1977).*

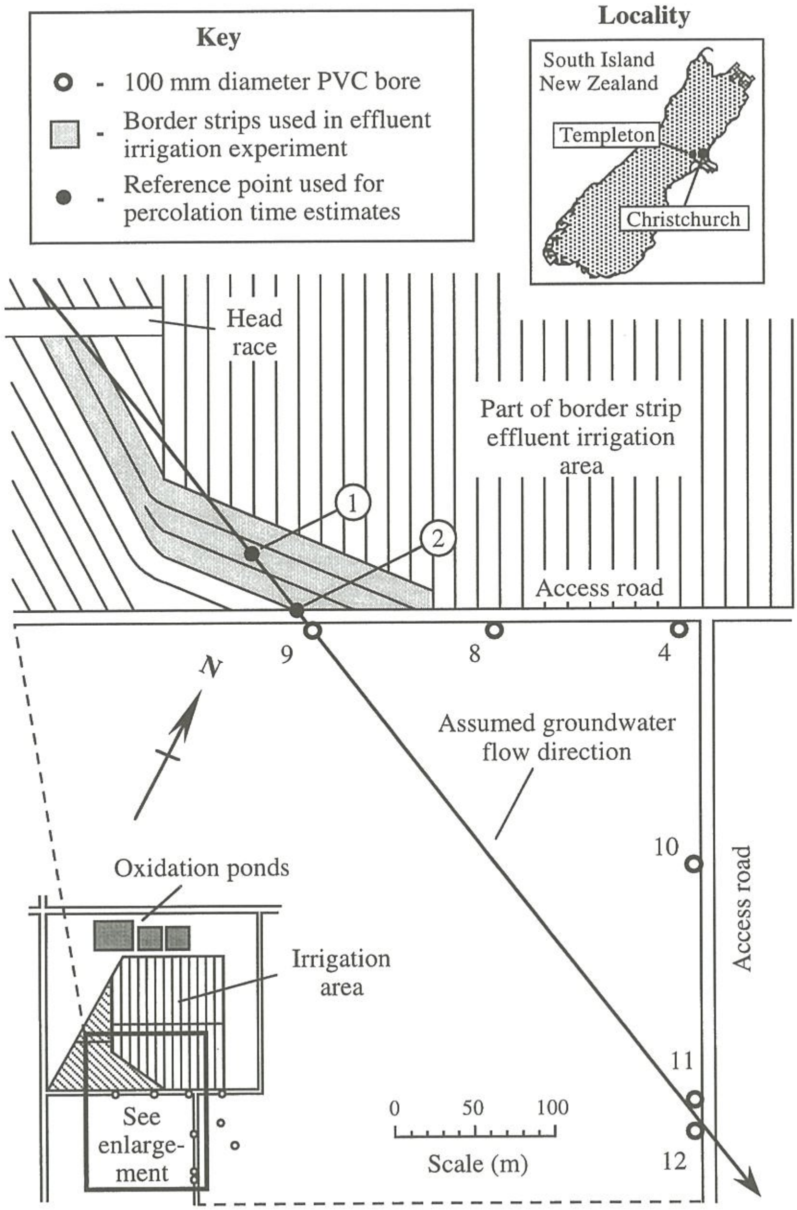

Figure 9.8 *The Templeton effluent irrigation area, showing the associated monitoring bores, and the set of strips used for viral contamination experiments. From Sinton et al, (1997); reproduced with permission from Water, Air and Soil Pollution.*

application of effluent to strips 31 and 32 (shaded in Fig 9.6). Similar results were obtained from Templeton. (2) The rate of transport of the bacteria in the groundwater was around 150 m day^{-1}. (3) Bacterial counts rose in the monitoring bores following rainfall.

The study by Martin and Noonan (1977) showed that faecal bacteria from waste stabilisation pond effluent could be transported through the soil and subsoil profile to groundwater. The bacteriophage tracing experiment by Noonan and McNabb (1979) also demonstrated that viruses injected into an alluvial gravel aquifer could be transported at a similar rate to bacteria (see Microbial tracers). However, it had not been demonstrated that viruses in waste stabilisation pond effluent applied directly to the land at these sites could reach the groundwater table, 10 - 15 m below.

Accordingly, a study was carried out at the Templeton site to gauge viral transport into and through the underlying aquifer (Sinton et al. 1997). Irrigation of two strips (Fig. 9.8) resulted in the contamination – by faecal coliform bacteria, somatic coliphages, and F-RNA phages – of bores 9 and 11, approximately 60 m and 445 m down-gradient of the centre of the strips. F-RNA phages showed the greatest attenuation between the soil surface and the first bore, and faecal coliforms the least (Fig. 9.9). Thus, it appears that enteric viruses in the percolating effluent can reach the groundwater table at schemes such as Templeton, although they are likely to be retained to a greater extent than bacteria by the soil/subsoil profile.

A simple model was set up to estimate the rate of percolation through the 13 m vadoze zone. Based on times to peak concentration in the groundwater, percolation times ranged from 1.6 to 10.5 hr, with travel times for the bacteriophages being 1.4 - 3.4 times longer than for the bacteria. This suggests much shorter percolation times to groundwater for

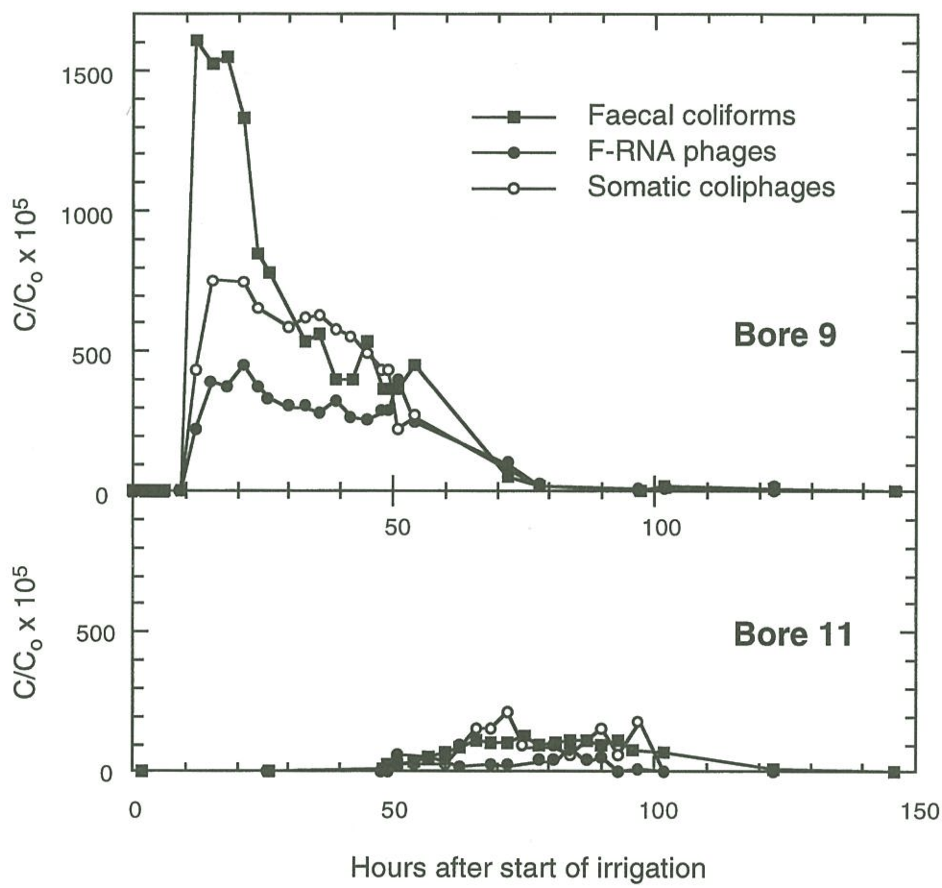

Figure 9.9 *Concentrations of faecal coliforms, F-RNA phage and somatic coliphages in Templeton bores 9 and 11 following effluent irrigation of strip set 32 (Fig. 9.8). From Sinton et al. (1997); reproduced with permission from Water, Air and Soil Pollution.*

the bulk of the micro-organisms than was reported in earlier studies (Quin 1984). Tracing experiments using injected waste stabilisation pond effluent, microbial tracers and fluorescent dye were also conducted in this study. These experiments are discussed in the section Microbial survival and transport in groundwater.

Land application of sludge

Several different types of sludges are produced in New Zealand (Fenton and McMahon 1992). However, domestic sewage sludges are the most likely to contain pathogens and are thus of greatest interest in terms of their potential impact on the microbial quality of groundwater. Furthermore, of the various types of disposal of sewage sludges, only the application of liquid sludges in agricultural and forestry situations is likely to be relevant to groundwater quality. Pathogens, particularly viruses, are known to accumulate in sludge (Bertucci et al. 1986). Cliver (1986) reported 2,400 to 15,000 pfu L^{-1} in primary sludge and 5,000 pfu L^{-1} in secondary sludge. Straub et al. (1993) found human enteric virus concentrations up to 1,000 L^{-1} of sludge, and reported slow inactivation of poliovirus in sludge-amended desert soils in cold winter conditions and rapid inactivation in hot, dry summers.

Most of the guidelines associated with land application of sludge focus on the problems with aerosols arising from spray irrigation, and on restricting access to the disposal areas by grazing animals and the public (USEPA 1989; Department of Health 1992). Microbiological impacts on groundwater of land-applied sludge have rarely been investigated. Liu (1982) found that over a period of 4 years of heavy sludge application to farmland, 92-98% of the bacteria were inactivated in the soil, and few indicator bacteria were found in the leachate. However, Jorgensen and Lund (1985) found enteroviruses in groundwater 3 m below a forest site used for sludge application.

In Europe and North America, the risk of microbial contamination of groundwater following sludge application has been suggested as minimal (Sommers and Barbarick 1986), and this is probably true for most situations in New Zealand. However, a more detailed assessment is required of the potential for microbial leaching from liquid sludge application, particularly to stony soils underlain by shallow alluvial gravels.

Landfills

Although landfills are recognised as a potential source of groundwater contamination by faecal micro-organisms, this form of contamination is poorly understood. As noted by Engelbrecht et al. (1974), the microbial hazard from landfills is a function of the density of pathogens arriving in the landfill, their survival, and rate of movement in leachate. In North America, disposable diapers are considered to be a significant source of faecal material in landfills (Scarpino et al. 1979), although their importance as a faecal source has not been investigated in New Zealand. Bacterial pathogens have been found in landfill leachate (Scarpino et al. 1979) and their survival rates have been studied (Donelly et al. (1982). There is also the possibility of "secondary" faecal inputs to landfills from birds and rodents, although this does not appear to have been scientifically investigated.

Offal pits

Disposal of offal and carcasses by burial in pits is widely practiced in New Zealand. Some of these pits are both deep and large, and carry the potential for disease transmission via groundwater to both domestic and stock water bores. In recognition of this potential, carcasses are normally burnt before burial in "foot and mouth" disease outbreak exercises. Overseas, above-ground composting, incineration, or rendering are more often the preferred options for carcass disposal, so information is scarce on the microbial characteristics of offal pits, and their potential for groundwater contamination.

Although a Ministry of Agriculture and Fisheries policy report raises concerns about groundwater quality down-gradient of offal pits (Ministry of Agriculture and Fisheries 1991), Ministry guidelines for their construction and operation only require that the pit bottom be more than 1 m above the groundwater table. The problems posed by offal pits in alluvial gravels are recognised in a report on the topic recently prepared for Environment Canterbury (Canterbury Regional Council 1999c). The report reviews the available literature, and recommends a distance of at least 3 m between the base of the pit and the groundwater table, and that the pit be located a minimum of 250 m up-gradient of any water supply well.

Sewer main leakage and fracture

Most sewers leak, with the degree of leakage being largely related to the age of the pipes. Although leaking or damaged sewers laid in porous strata such as alluvial gravels clearly pose a threat to groundwater, it is impossible to offer a meaningful assessment of the degree of risk involved. Sewer leakage is only likely to be a problem in reticulated urban areas overlying saturated (particularly unconfined) gravels. However, in most of these areas, such as Christchurch city, the water supplies are drawn from deep bores, beyond the immediate threat of contamination.

One (non-groundwater related) incident in New Zealand is worth noting. In 1983, in Queenstown, a fractured sewer main discharged into a stream, contaminating lake water near the water supply intake. This resulted in a gastroenteritis outbreak among 3,500 people in the town, most probably caused by an enteric virus (Thorstensen 1985). A similar fracture, say as a result of earthquake damage, could significantly impact microbial groundwater quality in an area underlain by shallow, saturated gravels.

MICROBIAL TRANSPORT TO GROUNDWATER

General

A wide range of complex factors determine the extent of microbial transport to groundwater. These factors are essentially those determining the survival and transport of microbes in unsaturated soils. For both bacteria and viruses, factors determining survival, and those determining transport obviously interact – the longer the microbes survive, the greater the possibility is that they will reach the groundwater table.

Bacteria

The topic of bacterial survival and penetration in soil has been reviewed by a number of authors, including Gerba and Bitton (1984), Peterson and Ward (1989), and Harvey and Garabedian (1991). Bacterial survival in soil is enhanced by higher soil moisture, greater penetration into the soil profile (desiccation and sunlight effects are greater at the soil surface), lower temperatures, lower pHs (in the range 3 – 5), higher organic matter, and low numbers of antagonistic soil microflora. Bacterial inactivation rates differ between species, but tend to decrease for all species if the bacterial cells are adsorbed to soil particles.

Bacterial transport through soils increases under saturated conditions. The principal factors acting to remove bacteria during transport are filtration and adsorption. Rates of removal by filtration tend to be greater in soils with low particle sizes. Accumulation of bacteria in soil pores can also act as a filtration mechanism, and bacterial filtration rates can be very high in the biological mats that develop around shallow septic tank effluent disposal structures (Ziebell et al. 1974; Tyler et al. 1977). Sedimentation in quiescent zones is also considered to be a factor in bacterial removal. The effects of cell morphology are less certain, but there is some evidence that larger cells are transported faster in saturated soils (Gerba and Bitton 1984; see *Pore size exclusion* below).

Adsorption is also a factor in the removal of bacteria by soils, and this is influenced by the surface area available for adsorption. Thus, clays, with their platy shapes and large surface area per given volume, play an important role in microbial removal. Cations, including Fe^{3+}, Cu^{2+}, and Zn^{2+}, at concentrations commonly found in soils, can reduce the repulsive forces between surfaces and thereby enhance bacterial adsorption. Low soil pH also enhances bacterial retention. Conversely, bacteria move further through soils in low ionic strength waters, and may thus penetrate further during rainfall. Soluble organics may also compete with bacteria for adsorption sites, thereby reducing bacterial adsorption.

Viruses

Reviews of viral survival and penetration in soil include those of Gerba and Bitton (1984), Vilker (1981), and Tim and Mostaghimi (1991). Some of the factors determining bacterial survival in soil also apply to viruses. Virus inactivation in soil is increased by higher temperatures, lower soil moisture, soil microbial activity and non-neutral pH values. The effects of adsorption on viral inactivation are less certain.

Many of the factors determining bacterial transport in soils also apply to viruses, with two exceptions – viruses are so small that the effects of filtration and sedimentation are considered to be negligible. However, as with bacteria, viral transport increases under saturated conditions. Virus removal during transport is considered to largely be a function of adsorption – adsorption rates tend to be higher at low pH values, at low flow rates, in fine-textured soils (particularly those with high clay contents), and in the presence of high cation concentrations. Adsorption is lower in the presence of dissolved organics, and desorption may occur in the presence of percolating rainwater. Adsorption varies with virus type, possibly due to their different isoelectric points.

Macropore flow

In some soils, a high proportion of the pore space is in the form of "macropores", including cracks and root holes. These fissures facilitate rapid microbial transport through soil ("macropore flow") compared to the slower movement ("matrix flow") through the surrounding (and more homogeneous) soil profile (Beven and Germann 1982). Micro-organisms being transported by macropore flow are less likely to be subjected to the above physicochemical processes. Corapcioglu and Haridas (1985) showed that application of matrix flow theory, based on the Darcy-Richards equation, produces maximum microbial penetration distances in unsaturated soils of around 0.2 m. This is much lower than observed penetration distances for both bacteria and viruses (as summarised by Gerba and Goyal 1985). Although the process is still poorly understood, approaches such as the application of kinematic wave theory have been used to quantify microbial transport in macropores (Germann et al. 1987).

Microbial survival and transport in New Zealand soils

There is surprisingly little reported information on microbial survival and transport in New Zealand soils. Childs et al. (1977) determined rates of coliform movement through several North Island soils. Guy and Small (1977) and Guy and Visser (1979) investigated the survival and adsorption rates of faecal coliforms. *E. coli*, and faecal streptococci in effluent-irrigated soils. The shortest survival times and highest adsorption rates appeared to occur in soils with low pH values and high clay contents.

Macropore flow in New Zealand soils is also not well understood. Quin (1984) suggested that the microbial contamination of groundwater by the Templeton effluent irrigation scheme observed by Martin and Noonan (1977) was substantially due to macropore flow. Sinton et al. (1997) reached similar conclusions for this site, but the relative proportions of micro-organisms transported by the macropore and matrix flow routes have not been established.

MICROBIAL SURVIVAL AND TRANSPORT IN GROUNDWATER

General

Many of the factors determining microbial transport in soils also apply to groundwater. The two basic differences between the environments are that: (1) groundwaters are, by definition, always in a saturated state, and (2) pore sizes tend to be larger, and flow rates higher, in true aquifer systems. The generally larger pore sizes and faster flow rates in most aquifers mean that attenuating mechanisms such as filtration, sedimentation and adsorption, will have less effect, and transport distances will be greater than in saturated soils.

In terms of inactivation rates, the most important difference between groundwater and surface water is that the former lacks the important inactivating mechanism of sunlight. Inactivation of both faecal bacteria and bacteriophages in sunlight-exposed surface waters is considerably more rapid than in groundwaters (Sinton et al. 1994; 1998b).

Bacteria

Reported survival rates of bacteria in groundwater are given in Table 9.2. However, in the Templeton investigation discussed above (Sinton et al. 1997), application of the AT123D contaminant transport model produced a removal rate (λ value) for the *E. coli* J6-2 tracer that was up to 2.7 times higher than those reported in the literature. This was attributed to the inclusion in the λ value of removal processes other than inactivation, whereas the reported inactivation rates are derived primarily from static microcosms, ranging in complexity from laboratory-stored flasks (Sinton 1980b) to in-well dialysis bags (Sinton 1980a) and membrane filter chambers (McFeters et al. 1974).

The principal removal processes at Templeton (apart from inactivation) were likely to have been filtration and sedimentation in the smaller pore spaces, irreversible adsorption, and losses due to antibacterial activity in the nutrient rich aquifer. Another possibility is loss of faecal bacteria due to grazing by the resident population of aquifer macroinvertebrates. In a study of these animals at the Templeton site, it was found that 10% contained coliform bacteria, apparently derived from grazing on sewage-derived material (Sinton 1984).

Viruses

Microcosm studies indicate that viruses survive longer in groundwater than bacteria. Reported survival rates for different viruses in groundwater are given in Table 9.2. In addition, Yates et al. (1985) reported a wide range of inactivation rates for phage MS2, ranging from 0.069 day^{-1} to 0.37 day^{-1} (giving a mean value of around 0.17 day^{-1}) in groundwater samples collected from 9 sites in the United States and held at 12 – 13°C. Although most of the factors affecting survival in soils discussed earlier also apply to groundwater, viral survival rates in groundwater have generally only been reliably correlated with temperature (Yates et al. 1985). Yates and Yates (1987) presented an equation for the adjustment of viral inactivation for temperature, based on the synthesis of data from 172 survival experiments. However, when this equation was applied to the groundwater temperature in the Templeton investigation discussed above (Sinton et al. 1997), it produced MS2 inactivation rates ranging from 8 to 11 times less than the total removal rates (λ values) calculated using the AT123D contaminant transport model. Of the various removal mechanisms (apart from inactivation) included in phage λ values, irreversible adsorption in the Templeton aquifer was considered to have been the most significant.

Pore size exclusion

In early tracing experiments at Burnham (Sinton and Close 1983), it was noted that times to peak concentrations were faster for microbial tracers compared to chemical tracers (Fig. 9.10). Similar differences have been observed in other laboratory and field studies (Wood and Ehrlich 1978; Thorpe et al. 1982; Wilson et al. 1984; Smith et al. 1985; Champ and Shroeter 1988; Bales et al. 1989). The explanation most commonly offered for this phenomenon is pore size exclusion: larger particles (such as bacteria) cannot pass through smaller pores available to dissolved chemicals, but can only travel through the larger pores, where groundwater velocity is higher. Thus, microbial transport in groundwater can be faster than the average groundwater velocity.

Although the above studies present evidence of pore size exclusion in terms of chemical and microbial tracers, it is less clear whether this phenomenon can also be demonstrated for different sized micro-organisms. In the study of phage transport in irrigated effluent described earlier (Sinton et al. 1997), two tracing experiments were conducted involving both bacteria and bacteriophages. In the first experiment, rhodamine WT dye and waste stabilisation pond effluent were injected into bore 9 (Fig. 9.8). The observed tracer curves, which were fitted with predicted curves using the contaminant transport model AT123D, are presented in Fig. 9.11, and show that the micro-organisms reached peak concentrations

Table 9.2: *Some reported survival rates of bacteria and viruses in groundwater*

Micro-organism	Die-offa rate (log10 day-1)	Reference
Bacteria		
Coliforms	0.42	McFeters et al. (1974)
Faecal coliforms	0.16	Martin and Noonan (1977)
	0.49	Sinton et al. (1997)[b]
Escherichia coli	0.16	Bitton et al. (1983)
	0.32	Keswick et al. (1982a)
	0.31 - 0.39	Sinton (1980b)
	0.43	Sinton et al. (1997)[b]
	0.36	McFeters and Stuart (1972)
	0.14 - 0.5	Thorpe et al. (1982)
Faecal Streptococci	0.03	Bitton et al. (1983)
	0.23	Keswick et al. (1982a)
Enterococci	0.33	McFeters et al. (1974)
	0.24	McFeters and Stuart (1972)
Salmonella typhimurium	0.23	Keswick et al. (1982a)
	0.24	McFeters and Stuart (1972)
Shigella dysenteriae	0.32	McFeters and Stuart (1972)
Vibrio cholerae	1.00	McFeters and Stuart (1972)
Viruses		
Poliovirus	0.035 - 0.138	Yates et al. (1985)
	0.21	Keswick et al. (1982a)
	0.77	O'Brien and Newman (1977)
Coxsackievirus	0.05 - 0.11	Dillon and Pavelic (1995)
Echovirus	0.05 - 0.11	Dillon and Pavelic (1995)
	0.051 - 0.186	Yates et al. (1985)
Rotavirus	0.36	Keswick et al. (1982a)
Coliphage f2	0.39	Keswick et al. (1982a)
Coliphage T7	0.15	Niemi (1976)
F-RNA phages	0.83	Sinton et al. (1997)[b]
Phage MS2	0.0114-0.162	Yates et al. (1985)
	0.62	Sinton et al. (1997)[b]

a As $\log_{10}(C_t/C_o)$, where C_t = concentration after 24 hours, and C_o = initial concentration.
b Reported as a "decay rate", incorporating other removal mechanisms, such as filtration and adsorption

before the dye. Pore size exclusion explains this result, but does not explain why the phage reached peak concentrations before the bacteria, because F-RNA phages (at 26 nm diameter) are considerably smaller than cells of faecal coliforms, such as *E. coli* (about 1.5 µm diameter, by up to 6 µm long). The second tracer experiment, involving the bacterial tracer *E. coli* J6-2, and the F-RNA phage MS2, produced a similar result. The most likely explanation is that the phages were more often adsorbed to particles in the effluent-polluted aquifer that were larger than bacteria and were therefore transported faster (by pore size exclusion). Bales et al. (1991) have also noted the possibility of phage adsorption to mobile particles.

A second set of tracing experiments was carried out in unpolluted groundwater at Burnham (Sinton et al. 2000), at the site of an expanded "septic tank array" (Figs. 9.5 and 9.12). Fig. 9.13 shows the tracer curves from two bores in one experiment, following injection of rhodamine WT dye, *E. coli* J6-2, and phage MS2 into bore 1. As in the Templeton experiments, predicted curves were fitted to the observed data using the AT123D model. Although the differences between the microbial tracers were not great, Fig. 9.13 shows that the times to peak concentration – *E. coli* < phage MS2 < rhodamine WT dye – were consistent with the concept of pore size exclusion. The differences between the Templeton and Burnham studies shows that further research is required into the different mechanisms governing bacterial and viral transport in groundwater.

THE FUTURE

New Zealand remains heavily dependent on groundwater for domestic water supply, and this dependence is likely to increase with an increasing population. For reticulated systems, there is likely to be continued resistance to chlorination of a microbially "pure" water supply. The New Zealand holiday home continues to be a popular recreational option, and there is a growing popularity of "lifestyle blocks". Problems of microbial contamination of groundwater arise with both types of dwelling, because they are frequently located in areas serviced by individual household bores and

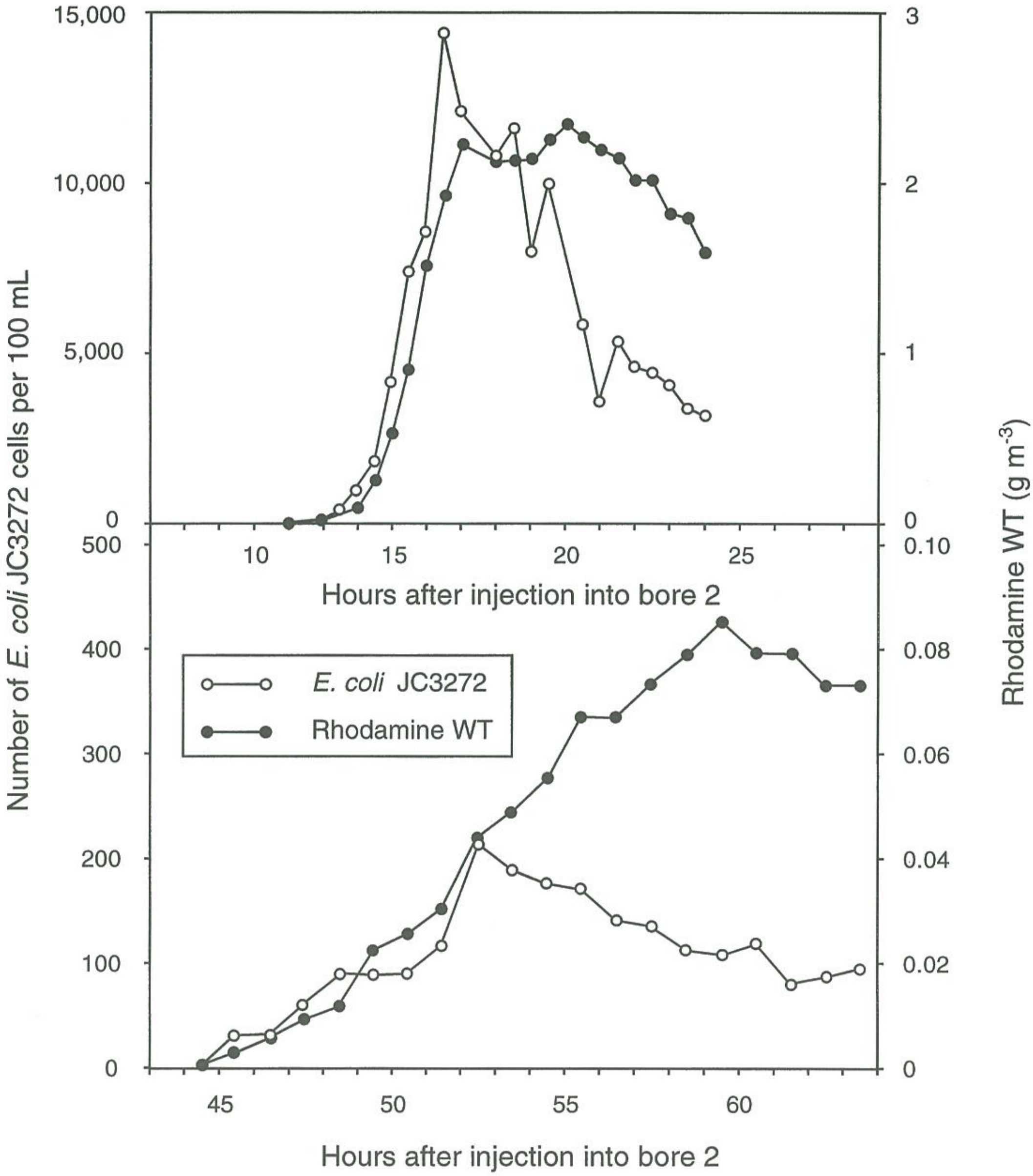

Figure 9.10 *Concentrations of* E. coli *JC3272 cells and rhodamine WT dye in Burnham bores 4 and 6, following injection into bore 2 (see Fig. 9.5). From Sinton and Close (1983).*

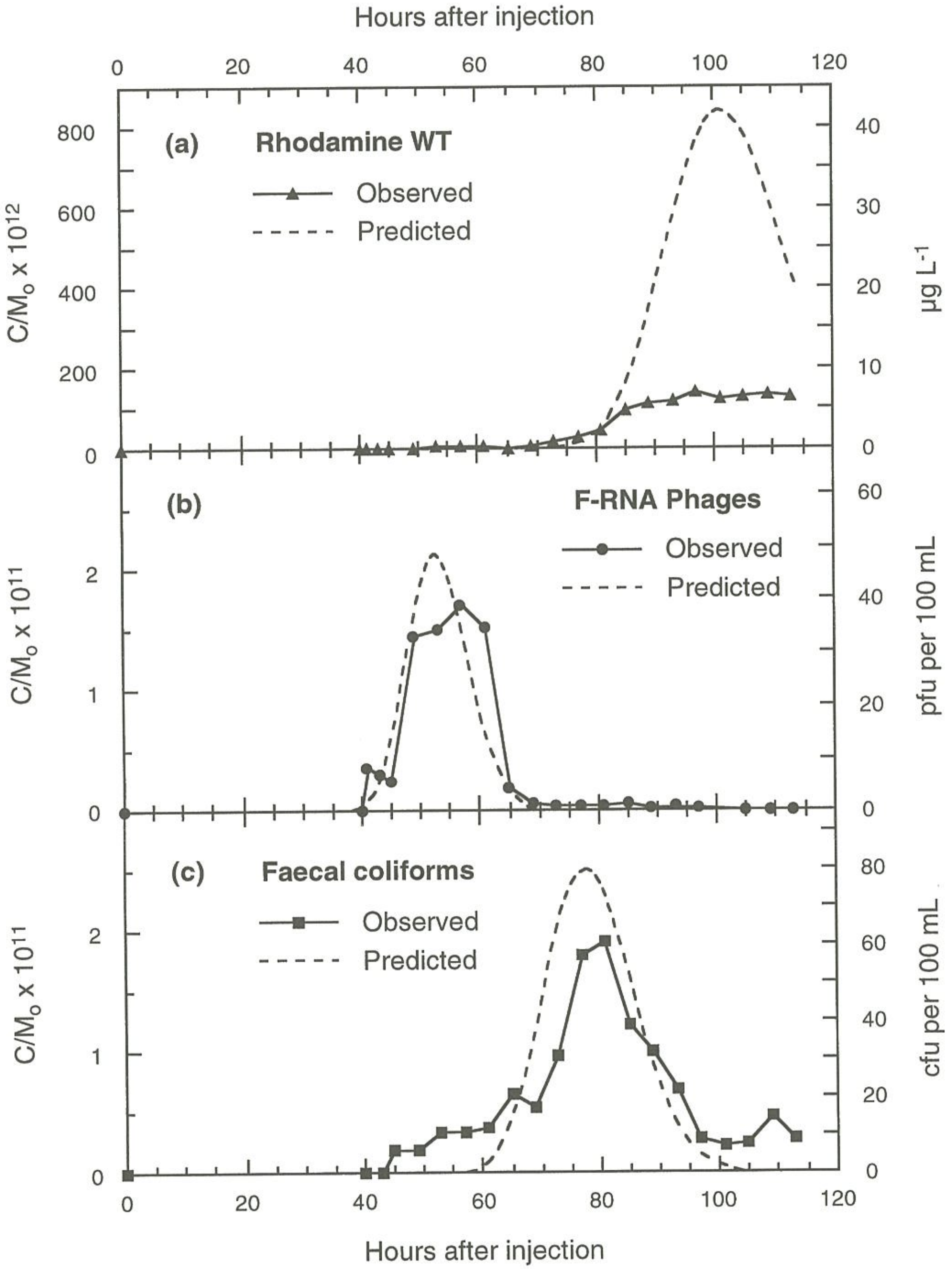

Figure 9.11 *Observed and simulated concentrations of rhodamine WT dye, F-RNA phages, and faecal coliforms in Templeton bore 11, following their injection (in 1000 L of oxidation pond effluent) into bore 9 (see Fig. 9.8). The data are presented both as a proportion of the total mass in the injection mixture (C/M_o), and as actual concentrations. Simulated concentrations were obtained using the contaminant transport model AT123D. From Sinton et al. (1997); reproduced with permission from Water, Air and Soil Pollution.*

septic tank systems. In addition, domestic bores on both lifestyle blocks and larger farms frequently draw water from groundwater beneath intensively grazed land.

The Ministry for the Environment's Draft National Agenda for Sustainable Water Management (Ministry for the Environment 1999) notes the importance of groundwater for both urban and rural water supplies. The Agenda also notes that more research effort is required on microbiological contamination issues. Since the mid 1970s, research data has been published on the movement of faecal micro-organisms into and through alluvial aquifers in New Zealand. This research has focussed primarily on transport from sources such as septic tank systems, and effluent irrigation schemes.

However, there are still significant gaps in our knowledge about aquifer susceptibility to microbial contamination, and the principal contributors to this form of pollution. There is still no reliable means of identifying the source of faecal micro-organisms in bore water, and in particular of determining whether they are of human or animal origin. The extent of viral transport and attenuation in saturated and unsaturated conditions is still poorly understood. There has also been little validation of existing models for predicting bacterial and viral transport in groundwater systems. And, in spite of high stock numbers in New Zealand, the contribution of grazing animals to the microbiological quality of shallow aquifers has not been systematically investigated. For example, in Canterbury, flood irrigation has substantially raised stocking rates in some areas, such as the Waiau plains, increasing both the faecal load and the potential for microbial leaching to shallow groundwaters. Also in Canterbury, spray irrigation from groundwater sources has meant that dairying is now carried out on shallower soils than were previously considered suitable for this activity. It is not known whether these changes in land use have any measurable effect on the microbial quality of groundwater.

Some of the issues above are being addressed by ongoing research in ESR, funded from the Public Good Science Fund (PGSF). One project is evaluating chemical and microbiological

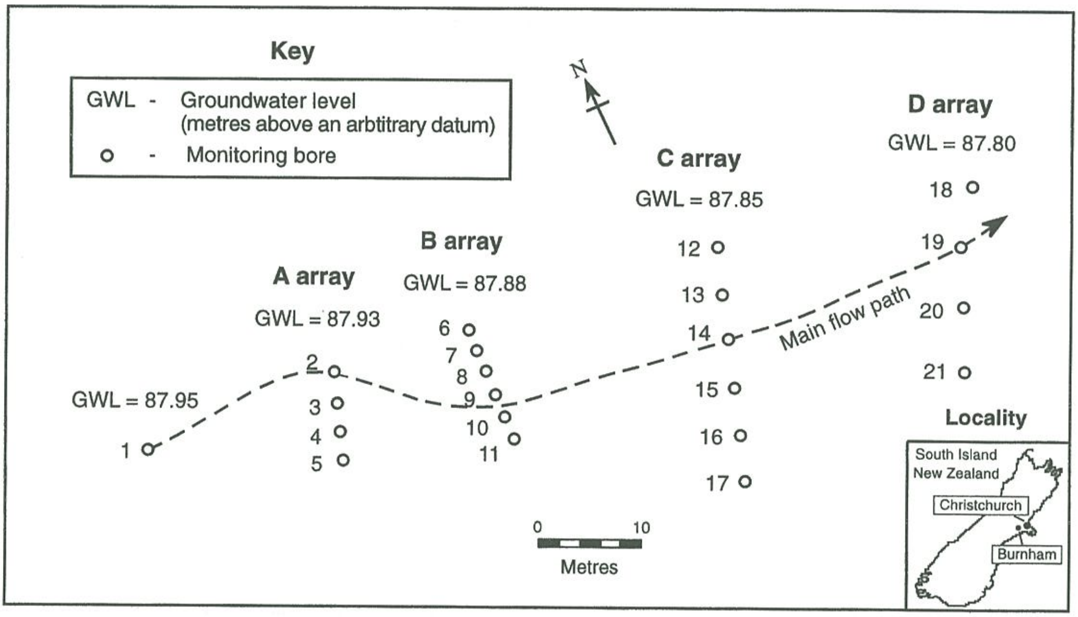

Figure 9.12 *The Burnham bore array used for the microbial tracing experiments presented in Fig. 9.13. From Sinton et al. (2000); reproduced with permission from the New Zealand Journal of Marine and Freshwater Research.*

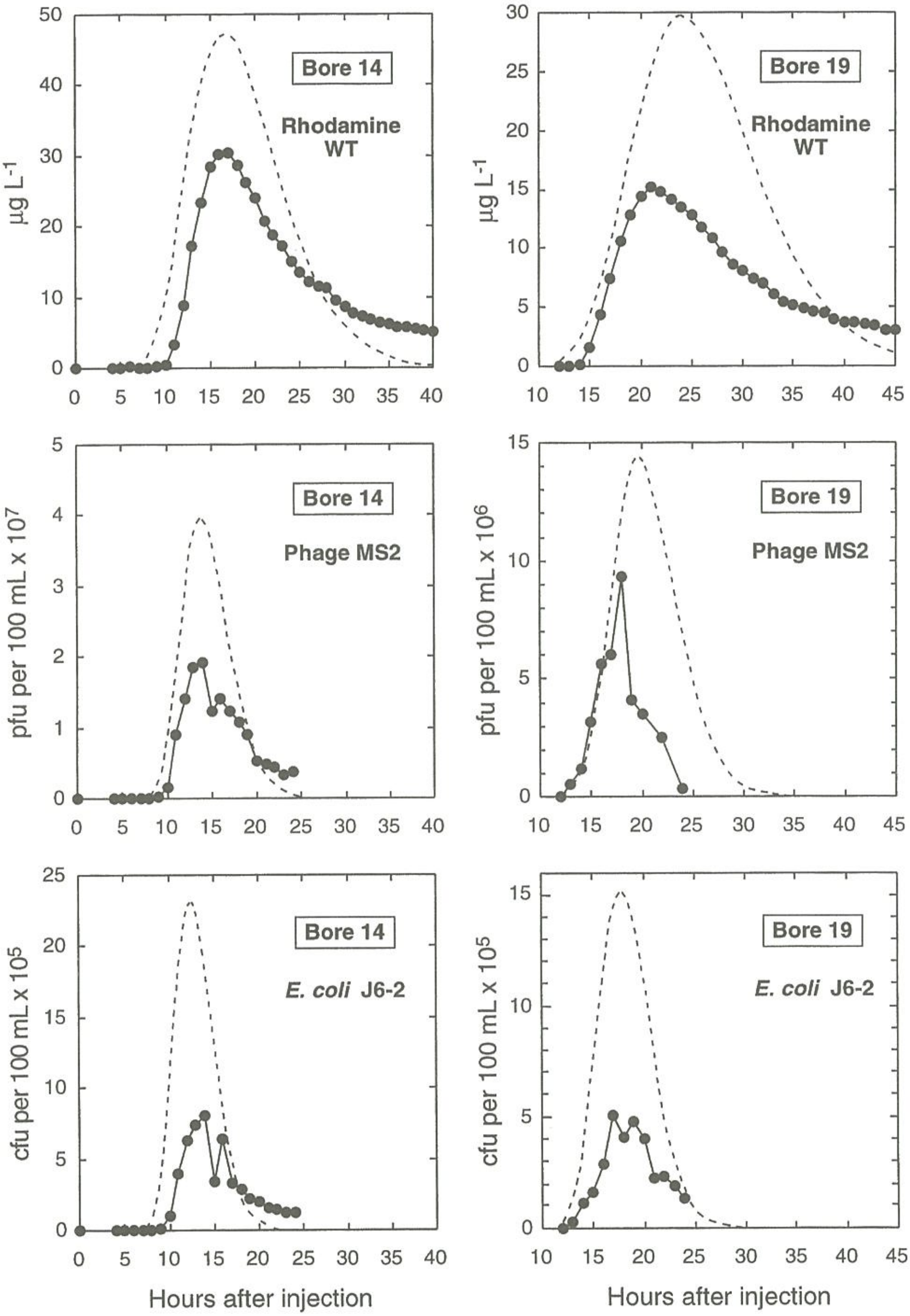

Figure 9.13 *Observed and simulated concentrations of rhodamine WT dye, phage MS2, and* E. coli *J6-2 in Burnham bores 14 and 19 (Fig. 9.12), following their injection into bore 1. Simulated concentrations were obtained using the contaminant transport model AT123D. From Sinton et al. (2000); reproduced with permission from the New Zealand Journal of Marine and Freshwater Research.*

methods for distinguishing between human and animal faecal sources (this topic is relevant to both surface and groundwater systems). Several other projects are based around groundwater research facilities in Central Canterbury, including arrays of experimental bores at Burnham and Templeton, and an 8 m groundwater column, established on the Lincoln University campus, in conjunction with Lincoln Environmental. The column is being used to develop and validate models for predicting rates of transport and attenuation of bacteria and viruses in a range of saturated materials. Further research is also underway on the percolation of faecal micro-organisms to groundwater from both effluent and freshwater irrigation schemes, including the proportion that are transported to groundwater by macropore flow.

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REFERENCES

Anon. 1996: Waterborne pathogens kill 10 M - 20 M people/year. World Water and Environmental Engineering, June 1996: 6.

Ayrey, R.B.; Noonan, M.J. 1983: The effect of land use on groundwater quality in Central Canterbury. In: Noonan, M.J. (Ed.). Microbiology and Water Quality, Proceedings, Joint Conference N. Z. Committee on Water Pollution Research and N. Z. Microbiological Society. Technical Publication No. 3, Department of Agricultural Microbiology, Lincoln College, Canterbury, New Zealand, 69-78.

Bales, R.C.; Gerba, C.P.; Grondin, G.H.; Jensen, S.L. 1989: Bacteriophage transport in sandy soil and fractured tuff. Applied and Environmental Microbiology 55: 2061-2067.

Bales, R.C.; Hinkle, S.R.; Kroeger, T.W.; Stocking, K. 1991: Bacteriophage adsorption during transport through porous media: Chemical perturbations and reversibility. Environmental Science and Technology 25: 2088-2095.

Barnett, B.G.; Simons, P.K. 1980: Septic Tank Discharges in Hawke's Bay. Internal Report, Hawke's Bay Catchment Board and Regional Water Board, Napier, New Zealand. 36 pp.

Bertucci, J.J.; Sedita, S.J.; Lye-Hing, C. 1986: Viral aspects of applying sludge to land. In: Rao, V.C.; Melnick, J.L. (Eds). Viruses in Sediments, Sludges and Soils. CRC Press.

Beven, K.; Germann, P. 1982: Macropores and water flow in soils. Water Resources Research 18: 1311-1325.

Bitton, G.; Farrah, S.R.; Ruskin, R.H.; Butner, J.; Chou, Y.G. 1983: Survival of pathogenic and indicator organisms in groundwater. Ground Water 21: 405-410.

Blackmore, D.K.; Humble, M.W. 1987: Zoonoses in New Zealand. Publication No. 112, Veterinary Continuing Education, Massey University, Palmerston North, New Zealand. 107 pp.

Bonde, G.J. 1966: Bacteriological methods for the estimation of water pollution. Health Laboratory Science 3: 124-143.

Brown, T.J. 1993: *Giardia* and Giardiasis in New Zealand. Report to the Ministry of Health June 1991 - September 1993. Massey University/New Zealand Ministry of Health Giardia Unit. 37 pp.

Brown, T.J.; Hastie, J.C.; Kelly P.J.; van Duivenboden R.; Ainge, J.; Jones, N.; Walker, N.K.; Till D.G.; Sillars H.; Lemmon, F. 1992: The presence and distribution of *Giardia* cysts in New Zealand waters. New Zealand Journal of Marine and Freshwater Research 26: 279-282.

Cabelli, V.J. 1977: Indicators of recreational water quality. In: Hoadley, A.W.; Dutka, B.J. (Ed.). Bacterial indicators: health hazards associated with water. ASTM STP 635: 222-238.

Cabelli, V.J. 1983. Health Effects Criteria for Marine Recreational Waters. EPA-600/1-80-031, U.S. Environmental Protection Agency, Cincinnati, Ohio.

Canterbury Regional Council 1997: Regional Environment Report 1995/96. Canterbury Regional Council Report 97(10): 47-60.

Canterbury Regional Council 1999a: Preliminary Modelling Results Regarding Septic Tank Discharges. Canterbury Regional Council Report No. U99/83. 17 pp.

Canterbury Regional Council 1999b: Groundwater Modelling of Viral and Bacterial Transport from On-Site Sewage Disposal. Canterbury Regional Council Report No. U99/86. 17 pp.

Canterbury Regional Council 1999c: Offal and Carcass Disposal by Burial and Associated Groundwater Quality Risks. Canterbury Regional Council Report No. U99/87. 22 pp.

Carrington, E.G.; Smith, H.V. 1995: The occurrence of *Cryptosporidium* spp. oocysts in surface waters and factors influencing their levels, with particular reference to the United Kingdom. In. Belts, W.B.; Casemore, D.; Fricker, C.; Smith, H.; Watkins, J. (Eds). Protozoans Parasites and Water. The Royal Society of Chemistry Special Publication No. 168, 57-62.

Carter, M.J. 1984: The detection of *Cryptosporidium* oocysts in faecal samples. New Zealand Journal of Medical Laboratory Technology 38: 122-123.

Champ, D.R.; Schroeter, J. 1988: Bacterial transport in fractured rock—a field scale tracer test at the chalk river nuclear laboratories. Water Science and Technology 20: 81-87.

CHILDS, C.W.; SEARLE, P.L.; WELLS, N. 1977: Infiltration through soil as a tertiary treatment of effluent. New Zealand Soil Bureau Scientific Report No. 29, Department of Scientific and Industrial Research, Wellington.

CLIVER, D.O. 1986: Fate of viruses during sludge processing. In: Rao, V.C.; Melnick, J.L. (Eds). Viruses in Sediments, Sludges and Soils. CRC Press.

CLOSE, M.E.; HODGSON, L.R.; TODD, G. 1989: Field evaluation of fluorescent whitening agents and sodium tripolyphosphate as indicators of septic tank contamination in domestic wells. New Zealand Journal of Marine and Freshwater Research 23: 563-568.

CORAPCIOGLU, M.Y.; HARIDAS, A. 1985: Microbial transport in soils and groundwater: A numerical model. Advances in Water Resources 8: 188-200.

CRAUN, G.F. 1984: Health aspects of groundwater pollution. In: Bitton, G.; Gerba, C.P. (Eds). Groundwater Pollution Microbiology. John Wiley and Sons, Inc., New York, 135-179.

CRAUN, G.F. 1988: Surface water supplies and health. Journal of the American Water and Wastewater Association 80: 40-52.

CRAUN, G.F. 1991: Causes of waterborne outbreaks in the United States. Water Science and Technology 24: 17-20.

DEPARTMENT OF HEALTH 1992: Public health guidelines for the safe use of sewage effluent and sewage sludge on land. Department of Health, Wellington. 66 pp.

DILLON, P.; PAVELIC, P. 1995: Draft guidelines on the quality of stormwater and treated wastewater for injection into aquifers for storage and reuse. Centre for Groundwater Studies Report No. 63. Centre for Groundwater Studies, Glen Osmond, SA 5064.

DITTHORN, F.; LUERSSEN, A. 1909: Experiments on the passage of bacteria through soil. Engineering Record 60: 642.

DONELLY, J.A.; SCARPINO, P.V.; BRUNNER, D. 1982: The survival of bacterial indicators in lysimeters and landfills. Water Science and Technology 14: 1558-1559.

DONNISON, A.M.; ROSS, C.M. 1999: Animal and human faecal pollution in New Zealand rivers. New Zealand Journal of Marine and Freshwater Research 33: 119-128.

EAGANHOUSE, R.P. 1997: Molecular Markers in Environmental Chemistry. ACS Symposium Series. American Chemical Society, Washington, DC. 426 pp.

ENGELBRECHT, R.S.; WEBER, M.J.; AMIRHOR, P.; FOSTER, D.H.; LAROSSA, D. 1974: Biological properties of sanitary landfill leachate. In: Milana, J.F. Jr.; Sagik, B.P. (Eds). Virus Survival in Water and Wastewater Systems. Water Resources Symposium No. 7. Centre for Research in Water Resources, University of Texas, Austin, Texas, 201-217.

ENVIRONMENT WAIKATO 1998: Taking the Pulse. Highlights from the Waikato State of the Environment Report 1998. Environment Waikato, Hamilton. 36 pp.

FENTON, J.A.; MCMAHON, S.D. 1992: Land Application of Sludge. Land Treatment Collective Technical Review No. 6. 40 pp.

FOX, E.G. 1984: Septic tanks: Their function and operation. In: Wilcock, R.J. (Ed.). Land Treatment of Wastes Part 1. Water and Soil Miscellaneous Publication No. 69. 193-202.

FRANCO, D.A.; WILLIAMS, C.E. 1994: *Campylobacter jejuni*. In: Hui, Y.H.; Gorham, J.R.; Murrell, K.D.; Cliver, D.O. (Eds). Food Borne Disease Handbook: Diseases Caused by Bacteria. New York Marcel Dekker, 71-96.

GELDREICH, E.E. 1966: Sanitary significance of fecal coliforms in the environment. Federal Water Pollution Control Federation, Water Pollution Control Research Series Publication No. WP-20-3. 122 pp.

GERBA, C.P.; BITTON, G. 1984: Microbial pollutants. Their survival and transport pattern to groundwater. In: Bitton, G.; Gerba, C.P. (Eds). Groundwater Pollution Microbiology. John Wiley and Sons, Inc., New York, 65-88.

GERBA, C.P.; GOYAL, S.M. 1985: Pathogen removal from wastewater during groundwater recharge. In: Asano, T. (Ed.). Artificial Recharge of Groundwater, Butterworth Publishers, 283-317.

GERBA, C.P., ROSE, J.B.; SINGH, S.N. 1985: Waterborne gastroenteritis and viral hepatitis. Critical Reviews in Environmental Control 15: 213-235.

GERMANN, P.F.; SMITH, M.S.; THOMAS, G.W. 1987: Kinematic wave approximation to the transport of *Escherichia coli* in the vadoze zone. Water Resources Research 23: 1281-1287.

GRIMES, J. 1999: Water we count on. New Scientist 161: 46.

GUY, E.M.; SMALL, J.A. 1977: Survival of streptococci and coliforms of bovine faecal origin in drainage water and soil store at different temperatures. New Zealand Journal of Agricultural Research 20: 13-18.

GUY, E.M.; VISSER, T.A. 1979: Adsorption and survival patterns of *Escherichia coli* and *Streptococcus bovis* in six New Zealand soils. New Zealand Journal of Agricultural Research 22: 341-348.

HAMILL, K. 1999: Nitrate in Southland's groundwater: Hot spots in your back yard. Water & Wastes in N. Z. 107: 30-32.

HARVEY, R.W.; GARABEDIAN, S.P. 1991: Use of colloid filtration theory in modeling movement of bacteria through a contaminated sandy aquifer. Environmental Science and Technology 25: 178-185.

HAVELAAR, A.H.; VAN OLPHEN, M.; DROST, Y. 1993. F-Specific RNA bacteriophages are adequate model organisms for enteric viruses in fresh water. Applied and Environmental Microbiology 59: 2956-2962.

HAYWOOD, S. 1999: Report on groundwater quality investigations south of Timaru. Project EMQ028400. Internal Report, Canterbury Regional Council. 6 pp.

HUGHES, G. 1998: Bay View Domestic Wastewater Treatment Systems. Summary Report, Prepared for Hawke's Bay Regional Council by Opus International Consultants Ltd. 26 pp.

INTERNATIONAL ASSOCIATION ON WATER POLLUTION RESEARCH AND CONTROL 1991: Review paper: Bacteriophages as model viruses in water quality control. Water Research 25: 529-545.

IONAS, G.; LEARMONTH, J.J.; KEYTS, E.A.; BROWN, T.J. 1998: Distribution of *Giardia* and *Cryptosporidium* in natural waters systems in New Zealand–A nationwide survey. Water Science and Technology 38: 57-60.

JONES, D.M.; ABBOTT, J.D.; PAINTER, M.J.; SUTCLIFFE, E.M. 1984: A comparison of biotypes and serotypes of

Campylobacter sp. isolated from animal and environmental sources. Journal of Infection 9: 51-58.

JORGENSEN, P.H.; LUND, E. 1985: Detection and stability of enteric viruses in sludge, soil and groundwater. Water Science and Technology 17: 185-195.

KESWICK, B.H.; GERBA, C.P.; SECOR, S.L.; SECH, I. 1982a: Survival of enteric viruses and indicator bacteria in groundwater. Journal of Environmental Science and Health A17: 903-912.

KESWICK, B.H.; WANG, D-S; GERBA, C.P. 1982b: The use of microorganisms as ground-water tracers: A review. Ground Water 20: 143-149.

LIDDELL, P.J.; SIMONS. P.K. 1982: Potential Point Sources of Groundwater Contamination of the Heretaunga Plains Unconfined Aquifer Including the Omahau Road Industrial Area. Hawke's Bay Catchment Board and Regional Water Board. 30 pp.

LIU, D. 1982: The effect of sewage sludge land disposal on the microbiological quality of groundwater. Water Research 16: 957-961.

MARINO, M.R.; BROWN. T.J.; WADDINGTON, D.C.; BROCKIE, R.E.; KELLY, P.J. 1991: *Giardia intestinalis* in North Island possums and ship rats. New Zealand Veterinary Journal 40: 24-27.

MARTIN, G.N.; NOONAN, M.J. 1977: Effects of Domestic Wastewater Disposal by Land Irrigation on Groundwater Quality of the Central Canterbury Plains. Water and Soil Technical Publication No. 7, Ministry of Works and Development, Wellington, New Zealand. 25 pp.

MCFETERS, G.A.; BISSONNETE, G.K.; JESEKI, J.J.; THOMSON, C.A.; STUART, D.G. 1974: Comparative survival of indicator bacteria and enteric pathogens in well water. Applied Microbiology 27: 823-829.

MCFETERS, G.A.; STUART, D.G. 1972: Survival of coliform bacteria in natural waters. Field and laboratory studies with MF chambers. Applied Microbiology 24: 805-811.

MEAT AND WOOL ECONOMIC SERVICE OF NEW ZEALAND 2000: Annual Review of the New Zealand Sheep and Beef Industry. Publication No. G2166, Meat and Wool Economic Service of New Zealand, Wellington. 48 pp.

MINISTRY FOR THE ENVIRONMENT 1997: The State of New Zealand's Environment 1997. Ministry for the Environment, Wellington. 653 pp.

MINISTRY FOR THE ENVIRONMENT 1999: Making Every Drop Count. The National Agenda for Sustainable Water Management Action Plan. Draft for Public Comment. Ministry for the Environment, Wellington. 44 pp.

MINISTRY FOR THE ENVIRONMENT AND MINISTRY OF HEALTH 1998: Bacteriological Water Quality Guidelines for Marine and Fresh Water. Ministry for the Environment/Ministry of Health. Published by the Ministry for the Environment, Wellington, New Zealand. 16 pp.

MINISTRY OF AGRICULTURE AND FISHERIES 1991: Management of Waste Products from Animal Based Industries. MAF Policy 108, Ministry of Agriculture and Fisheries, Wellington.

MINISTRY OF HEALTH 1995a: Guidelines for Drinking Water Quality Management for New Zealand. Chapter 7, Microbiological Quality. Ministry of Health, Wellington. 96 pp

MINISTRY OF HEALTH 1995b: Drinking Water Standards for New Zealand 1995. Ministry of Health, Wellington. 87 pp.

MINISTRY OF HEALTH 2000: Drinking Water Standards for New Zealand 2000. Ministry of Health, Wellington. 130 pp.

MITCHELL, M. 1995: The distribution and epidemiology of liver fluke in New Zealand. Surveillance 22: 22-25.

MULCOCK, A.P.; NOONAN, M.J. 1973: Soil Contamination by Septic Tank Effluent. Department of Agricultural Microbiology, Lincoln University. 39 pp.

MURRAY, S.; SINTON, L.; SAVILL, M. 2000: Enteroviruses–Indicators of viral pollution of water. Water and Wastes in N.Z. 114: 26-31.

NIEMI, M. 1976. Survival of *Escherichia* coliphage T7 in different water types. Water Research 10: 751-755.

NOONAN, M.J.; MCNABB, J.F. 1979: Contamination of Canterbury Groundwater by Viruses. In: Noonan, M.J. (Ed). Groundwater. The Quality and Movement of Groundwater in Alluvial Aquifers of New Zealand. Department of Agricultural Microbiology Technical Publication No. 2, Lincoln University, Canterbury, New Zealand, 195-201.

NORTHLAND CATCHMENT COMMISSION 1987: Russell Water Resources. Technical Publication No. 1987/3, Northland Catchment Commission. 93 pp.

O'BOYLE, K. 1992: Septage: The Selwyn Experience. Addendum to: Fenton, J.A.; McMahon, S.D. 1992: Land Application of Sludge. Land Treatment Collective Technical Review No. 6. 40 pp.

O'BRIEN, R.T.; NEWMAN, J.S. 1977: Inactivation of polioviruses and coxsackieviruses in surface water Applied Environmental Microbiology 33: 334-340.

PETERSON, T.C.; WARD, R.C. 1989: Development of a bacterial transport model for coarse soils. Water Resources Bulletin 25: 349-357.

QUIN, B.F. 1984: The Templeton Scheme: A review. In: Wilcock, R.J. (Ed.). Land Treatment of Wastes Part 1. Water and Soil Miscellaneous Publication No. 69. 29-46.

RAO, V.C.; MELNICK, J.L. 1986: Environmental Virology. American Society for Microbiology, Washington, D.C., USA. 88 pp.

RAY, D.E.; GIBBS, M.M.; TURNER, S. 2000: Assessing septic tank contamination of the Rotorua Lakes. New Zealand Water and Wastes Association 42 Annual Conference, 27-29 September 2000, Rotorua, N. Z. Paper WW47 on CD.

ROSEN, M.R.; WHITE, P.A.; REEVES, R.R. 1995: Hydrogeology and water quality of the unconfined gravel aquifer beneath the Maraekakaho feedlot, Hawke's Bay. Institute of Geological and Nuclear Sciences Report 95/1. IGNS, Lower Hutt, NZ. 66 pp.

SCARPINO, P.V.; DONNELLY, J.A.; BRUNNER, D. 1979: Pathogen content of landfill leachate. Municipal Solid Waste: Land Disposal. Proceedings of 5th Annual Research Symposium. EPA-600/9-97-023a, 138-167.

SINTON, L.W. 1979: The use of bacteria as tracers of groundwater movement. In: Noonan, M.J. (Ed.). Groundwater. The Quality and Movement of Groundwater in Alluvial Aquifers of New Zealand. Department of Agricultural Microbiology Technical Publication No. 2, Lincoln University, Canterbury, New Zealand, 93-103.

SINTON, L.W. 1980a: Investigations into the use of the bacterial species *Bacillus stearothermophilus* and *Escherichia coli* (H_2S positive) as tracers of groundwater movement. Water and Soil Technical Publication No. 17, Ministry of Works and Development, Wellington, New Zealand. 24 pp.

SINTON, L.W. 1980b: Two antibiotic resistant strains of *Escherichia coli* for tracing the movement of sewage in groundwater. Journal of Hydrology (NZ) 19: 119-130.

SINTON, L.W. 1982: A groundwater quality survey of an unsewered semi-rural area. New Zealand Journal of Marine and Freshwater Research 16: 317-326.

SINTON, L.W. 1984: The macroinvertebrates in a sewage-polluted aquifer. Hydrobiologia 119: 161-169.

SINTON, L.W. 1986: Microbial contamination of alluvial gravel aquifers by septic tank effluent. Water, Air and Soil Pollution 28: 407-425.

SINTON, L.W.; CLOSE, M.E. 1983: Groundwater Tracing Experiments. Publication No. 2 of the Hydrology Centre, Ministry of Works and Development, Christchurch, New Zealand. 38 pp.

SINTON, L.W.; CHING, S.B. 1987: An evaluation of two bacteriophages as sewage tracers. Water, Air and Soil Pollution 35: 347-356.

SINTON, L.W.; DAVIES-COLLEY, R.J.; BELL, R.G. 1994: Inactivation of enterococci and fecal coliforms from sewage and meatworks effluents in seawater chambers. Applied and Environmental Microbiology 60: 6, 2040-2048.

SINTON, L.W.; DONNISON, A.M.; HASTIE, C.M. 1993a: Faecal streptococci as faecal pollution indicators: A review. Part I: Taxonomy and enumeration. New Zealand Journal of Marine and Freshwater Research 27: 101-115.

SINTON, L.W.; DONNISON, A.M.; HASTIE, C.M. 1993b: Faecal streptococci as faecal pollution indicators: A review. Part II: Sanitary significance, survival and use. New Zealand Journal of Marine and Freshwater Research 27: 117-137.

SINTON, L.W., FINLAY, R.K.; HANNAH, D.J. 1998a: Distinguishing human from animal faecal contamination in water: A review. New Zealand Journal of Marine and Freshwater Research 32: 323-348.

SINTON, L.W.; FINLAY, R.K.; LYNCH, P.A. 1998b: Sunlight inactivation of fecal bacteriophages and bacteria in sewage-polluted seawater. Applied and Environmental Microbiology 65: 3605-3613.

SINTON, L.W.; FINLAY, R.K.; PANG, L.; SCOTT, D.M. 1997: The transport of bacteria and bacteriophages in irrigated effluent into and through an alluvial gravel aquifer. Water, Air, and Soil Pollution 98: 17-42.

SINTON, L.W.; NOONAN, M.J.; FINLAY, R.K.; PANG, L.; CLOSE, M.E. 2000: Transport and attenuation of bacteria and bacteriophages in an alluvial gravel aquifer. New Zealand Journal of Marine and Freshwater Research 34: 175-186.

SMITH, J.L. 1993: *Cryptosporidium* and *Giardia* as agents of foodborne disease. Journal of Food Protection 56: 451-461.

SMITH, M.S.; THOMAS, G.W.; WHITE, E.E.; RETONGA, D. 1985: Transport of *Escherichia coli* through intact and disturbed soil columns. Journal of Environmental Quality 14: 87-91.

SMITH, V.R. 1994: Groundwater Quality in the Unsewered Township of Southbridge. Technical Report 94 (8), Environmental Management Group, Canterbury Regional Council. 12 pp.

SNOW, J. 1855: On the mode of communication of cholera (2nd edition). London: J. Churchill. 162 pp. Reprinted in: Snow on cholera. New York: Hafner, 1965.

SOMMERS, L.E.; BARBARICK, K.A. 1986: Constraints to land application of sewage sludge. Utilization, Treatment, and Disposal of Waste on land. Soil Science Society of America, Madison, WI. USA, 193-243.

STRAUB, T.M.; PEPPER, I.L.; GERBA, C.P. 1993: Virus survival in sewage sludge amended soil. Water Science and Technology 27: 421-424.

TASMAN DISTRICT COUNCIL 2000: Environment Today! Tasman District Council. 98 pp.

THORPE, H. 1992: Groundwater–The Hidden Resource. In: Mosley, P.M. (Ed.). Waters of New Zealand. NZ Hydrological Society, Wellington, NZ, 167-186.

THORPE, H.R.; BURDEN, R.J.; SCOTT, D.M. 1982: Potential for Contamination of the Heretaunga Plains Aquifers. Water and Soil Technical Publication No. 24, Ministry of Works and Development, Wellington, New Zealand. 149 pp.

THORSTENSEN, A.L. 1985: What happened in Queenstown - an object lesson for water supply authorities. NZ Local Government, February 1985: p 455.

TIM, U.S.; MOSTAGHIMI, S. 1991: Model for predicting virus movement through soils. Groundwater 29: 251-259.

TONKS, M.C.; BROWN, T.J.; IONAS, G. 1991: Giardia infection in cats and dogs in New Zealand. New Zealand Veterinary Journal 39: 33-34.

TYLER, E.J.; LAAK, R.; MCCOY, E.; SANDHU, S.S. 1977: The soil as a treatment system. In: Home Sewage Disposal. American Society of Agricultural Engineering Publication. Proceedings 5-77 ASAE, St Joseph, Michigan, 22-37.

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY 1989: Environmental Regulations and Technology: Control of Pathogens in Municipal Wastewater Sludge for Land Application Under 40 CFR Part 257. US Environmental Protection Agency, Cincinnati, OH. EPA/625/10-89/006. 71 pp.

VILKER, V.L. 1981: Simulating virus movement in soils, In: Iskandar, I.K. (Ed.). Modelling Wastewater Renovation: Land Treatment. John Wiley and Sons, New York, 223-253.

WILCOCK, R.J. 1984: Land disposal of sewage effluent in New Zealand: A review. In: Wilcock, R.J. (Ed.). Land Treatment of Wastes Part 1. Water and Soil Miscellaneous Publication No. 69: 12-28.

WILSON, L.G.; GERBA, C.P.; BOLTON, M.W.; ROSE, J.B. 1984: Subsurface transport of urban runoff pollutants. In: Durham, N.N.; Redelfs, A.E. (Eds). Proceedings of the Second International Conference on Groundwater Quality Research, University Printing Services, Okalahoma State University, Stillwater, 158-160.

WOOD, W.W.; EHRLICH, G.G. 1978: Use of baker's yeast to trace microbial movement in ground water. Ground Water 16: 398-403.

YATES, M.V., GERBA, C.P.; KELLY, L.M. 1985: Virus persistence in groundwater. Applied and Environmental Microbiology 49: 778-781.

YATES, M.V.; YATES, S.R. 1987: A comparison of geostatistical methods for estimating virus inactivation rates in ground water. Water Research 21: 1119-1125.

ZIEBELL, W.A.; NERO, D.H.; DEININGOR, J.F.; MCCOY, E. 1974: In: Home Sewage Disposal. Proceedings of the National Home Sewage Disposal Symposium, American Society of Agricultural. Engineer, St. Joseph, MI, p.58.

10

Groundwater and Health

HELEN DAVIES

INTRODUCTION

How safe is New Zealand's groundwater to drink? This chapter focuses on the health effects of using groundwater for a drinking-water supply.

Ministry of Health records indicate that about 50% of New Zealand's population depends totally or partially on groundwater as a source for drinking water, with the rest of the population obtaining their drinking water from rivers, streams, lakes (man-made or natural) or rain captured by roof catchment systems (calculated from Ministry of Health 2000a). There is thus a need to understand the factors influencing groundwater quality, the sampling required for adequate information on quality as it relates to health, and methods to protect and to effectively treat groundwater.

Groundwater quality can be influenced by the quality of the water seeping into the ground, by the nature of the ground through which it passes, and by migration of mobile contaminants in the water.

Because groundwater contamination is much less conspicuous than surface water contamination, it can go unnoticed for a long time. As groundwater is relatively inaccessible, and the aquifer material to which contaminants may be adsorbed is even more so, remediation can be difficult and therefore prohibitively expensive. Moreover, contaminants can remain in the aquifer for a considerable time, affecting its use. For these reasons, protecting groundwater resources from contamination is very important.

In New Zealand, a number of organisations play a direct or indirect role in the health protection issues associated with the use of groundwater for water supply. This chapter reviews these health protection issues.

USE OF GROUNDWATER FOR DRINKING-WATER SUPPLY

Sources of water for drinking must be selected with their intended use in mind. Water required for drinking should have suitable microbiological, chemical and physical qualities or be suitable for treatment to an acceptable standard. Whether the water is acceptable for drinking without any treatment will depend upon the quality of the water abstracted and the degree to which this quality remains constant. The Ministry of Health considers that the only type of source water that can be used without any treatment to inactivate or remove microorganisms is groundwater that has been proven as 'secure'. Groundwater is considered to be secure (Fig. 10.1) when it is unlikely to be contaminated by pathogenic organisms because it is not directly affected by surface or climate influences and it is abstracted via a secure well-head or similarly proven structure.

Groundwater supplies are obtained from wells or springs. They tend to show far less variation in quality from season to season than surface waters. However, groundwater supplies may vary considerably in quality from one well location to another.

The selection of a source for a drinking-water supply involves a review of the available sources and their characteristics. The potential for these characteristics to alter with future changes in land use in the recharge zone is also important. Factors to consider include sustainable yield, water quality, collection requirements (well design etc.), treatment requirements, transmission and distribution requirements, and the economics of use (adapted from Hamann et al. 1990).

The cost of investigating a new groundwater supply is typically greater than investigating

Davies H. 2001: Groundwater and Health. *In* Groundwaters of New Zealand, M.R. Rosen and P.A. White *(eds)*. New Zealand Hydrological Society Inc., Wellington. p253-272.

Criteria for demonstrating the security of groundwater

Groundwater is considered to be secure when it can be demonstrated not to be likely to be contaminated by pathogenic organisms because it is:

- not directly affected by surface or climate influences, as is demonstrated by compliance with criteria a, b and c below
- abstracted via a secure well head or similarly proven structure.

a. *E. coli* is absent from the groundwater.

The groundwater shall initially be monitored at the frequency required for an unsecure groundwater over 12 consecutive months. If no *E. coli* are found during this 12-month period, and criteria b and c below are met, the groundwater is classed as secure and monitoring can then revert to that required for secure groundwater.

b. The well head is secure.

For a well head to be classed as secure, there must be a sealed pumping and piping system including backflow prevention devices and restrictions on any potentially contaminating land use or activity in the vicinity of the well head.

c. The groundwater is not directly affected by surface or climate influences.

The lack of surface or climate influences can be demonstrated by the residence time in the aquifer or by the lack of significant and rapid shifts in determinands that are linked to surface effects as shown by:

i. less than 0.005 percent of the water shall have been present in the aquifer for less than one year (demonstrated by the tritium and/or CFC methods) and/or
ii. variations in the groundwater characteristics shall not exceed a coefficient of variation of more than:

- 3.0 percent in conductivity
- 4.0 percent in chloride concentration
- 2.5 percent in nitrate concentration (standardised variance)

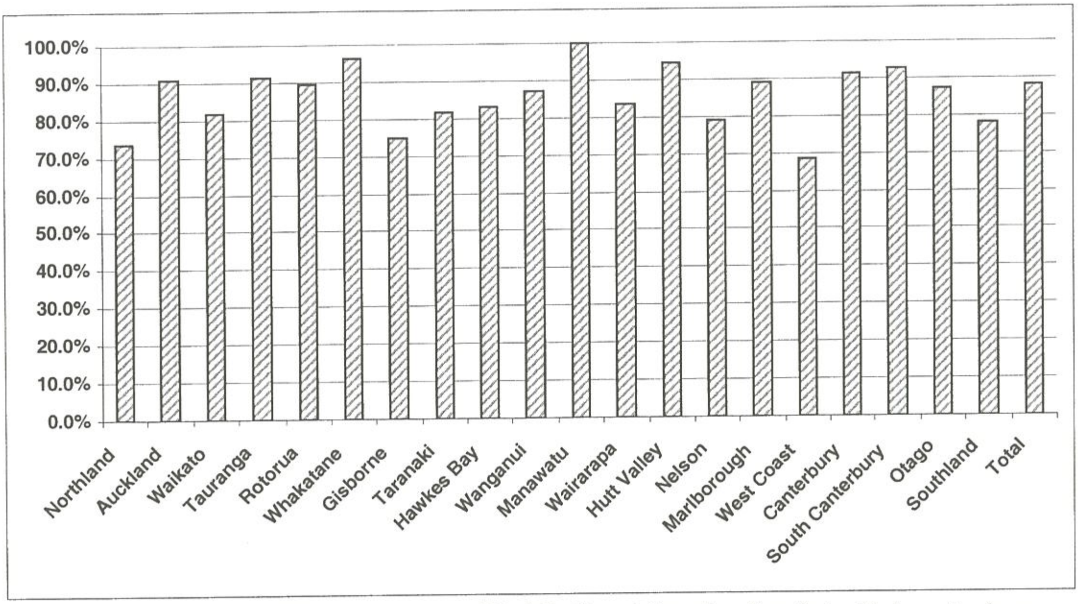
when measured at least:

- monthly for one year
- once every two months for two years
- three monthly for three years.

Reference: *Drinking-Water Standards for New Zealand, 2000* (Ministry of Health 2000b)

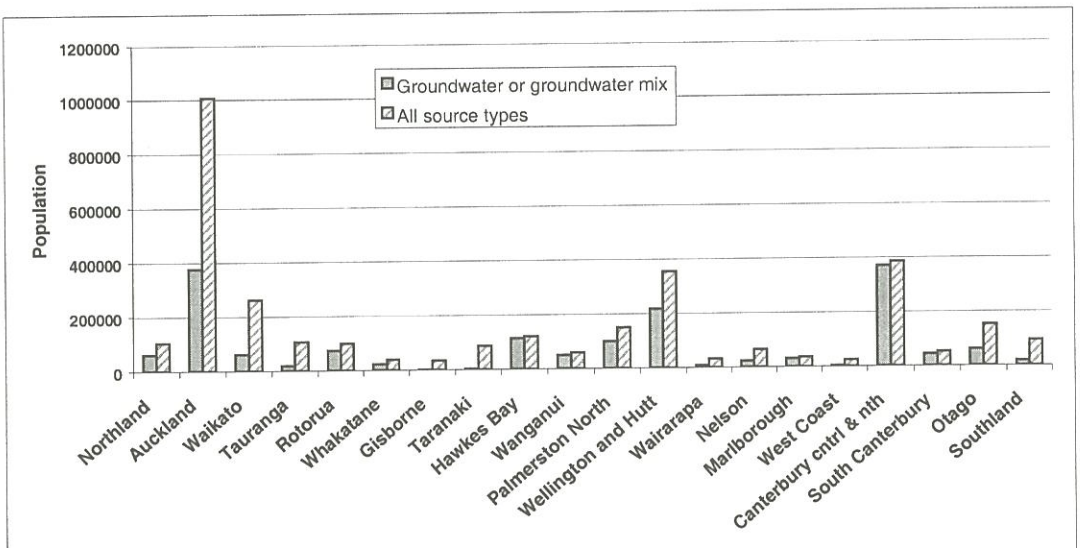
Figure 10.1. *Criteria for demonstrating the security of groundwater.*

a surface water supply. Several test wells may be required to determine aquifer yield and the quality of the groundwater supply. Furthermore, groundwater can be more expensive to provide than surface water because of the pumping requirements. Nevertheless, groundwater is a common source of water in New Zealand (Table 10.1). Groundwater is generally of higher, and less variable, quality than surface waters which often means that less treatment is required. Groundwater is often more readily available than surface water.



These data have been obtained from the Ministry of Health's Water Information New Zealand information base (WINZ), which contains the Register of Community Drinking-Water Supplies in New Zealand, September 2000. Population figures have been taken from the latest census (Department of Statistics 1996).

Figure 10.2. *Percentage of population obtaining drinking water from a Ministry of Health registered supply, by health district.*



These data have been obtained from the Ministry of Health's Water Information New Zealand information base (WINZ), which contains the Register of Community Drinking-Water Supplies in New Zealand.

Figure 10.3. *Use of groundwater for drinking-water purposes, by population (Ministry of Health registered supplies only).*

Bores frequently can be sunk where the water is needed, reducing the need for extensive pipe networks to transfer water from a source such as a river to the town where it is used.

The Ministry of Health's 'Register of Community Drinking-Water Supplies in New Zealand' (Ministry of Health 2000a) contains a summary of the components (i.e. sources, treatment plants and distribution zones) of known community drinking-water supplies. Community drinking-water supplies are defined as 'all drinking-water supplies serving more than 25 people for more than 60 days a year' (Ministry of Health 2000a).

Approximately 88% of New Zealand's population receive water from a registered drinking-water supply (Fig. 10.2). Registered supplies include some that are not used as a primary source of drinking water i.e. marae, schools and camping grounds. The actual percentage of the population receiving water from a registered supply will thus be lower than that shown, because of double counting. Groundwater is the sole source of drinking water for 26% (Table 10.1) of the population of New Zealand that use water from a registered supply. A further 25% of the population are supplied by a mixture of groundwater and water from another source such as rivers, streams, reservoirs, lakes, and rainwater. Groundwater is also an important water source on a regional basis (Fig. 10.3).

People that do not have access to a Ministry of Health registered drinking-water supply obtain water from their own domestic sources or from some other reticulated, but unregistered system. The registration of drinking-water supplies is very important because it allows supplies to be assessed using nationally consistent methods and information to be collated in a systematic fashion by a central body. It also permits analysis of national data to identify problems of national or regional concern.

GROUNDWATER QUALITY – GENERAL FEATURES

Introduction

Groundwater is usually superior to surface water with regards to its microbiological quality, turbidity and organic carbon concentrations. Water entering the ground is naturally filtered, and its passage is retarded as it passes through layers of soil, ground and aquifer material. The effectiveness of filtration and retardation in reducing contaminants depends upon the ground conditions (porosity, permeability, temperature, chemical and physical properties of the ground), and the intrinsic microbiological populations. A layer of low porosity and permeability materials, such as a confining layer, separating the groundwater from land-use activities, will provide protection against migration of contaminants into the groundwater.

Mineralisation

The mineral content of groundwater may be greater than surface water due to dissolution of minerals in the ground material into the water, and it may require treatment. Groundwater in low-rainfall regions is generally harder and more mineralised than water in high-rainfall regions. The degree of hardness and mineralisation will also depend upon the chemistry of the water, because water with certain chemical properties will dissolve solid material more readily.

Geothermal waters

Geothermally-influenced groundwater is common at many locations in New Zealand, and in some areas is used for drinking water. In these areas, the groundwater may contain elevated levels of chemicals (e.g. arsenic, boron and fluoride) at levels that may affect health. Arsenic, in particular, has been detected at potentially significant levels in thirty-five groundwater supplies in New Zealand serving a total of 122,634 people (Ritchie 2000).

Microbiological contaminants

The most common and widespread health risk associated with drinking water is contamination, either directly or indirectly, through human, animal and occasionally bird faeces containing disease-causing microorganisms. The contamination of groundwater by microbiological organisms that can infect humans and cause disease is a particular concern in New Zealand, due to our high numbers of livestock, and to the large numbers of domestic septic tanks and shallow wells.

Table 10.1. *Source water types used for drinking water, by population (Ministry of Health registered supplies only), by health district.*

Type of source water	Groundwater only	Groundwater plus other source	Surface water only	Surface water plus rainwater	Rain water only
Northland	11,760	50,020	34,309	2,280	5,816
Auckland	52,952	322,996	626,707	4	3,960
Waikato	39,891	21,695	200,043	0	444
Tauranga	6,418	12,700	87,423	0	76
Rotorua	73,234	0	25,994	50	200
Whakatane	17,910	4,000	16,310	0	0
Gisborne	825	1,068	31,160	25	1,437
Taranaki	4,222	0	81,017	0	1,266
Hawkes Bay	112,691	402	6,107	81	968
Wanganui	4,893	46,089	8,485	0	822
Palmerston North	27,606	71,544	47,835	165	2,488
Wellington and Hutt	67,255	149,810	138,425	105	50
Wairarapa	2,228	5,705	24,222	5	160
Nelson-Marlborough (Nelson Office)	12,565	10,575	41,255	0	485
Nelson-Marlborough (Blenheim Office)	26,680	4,404	5,162	0	15
West Coast	3,568	160	20,290	0	389
Canterbury cntrl & nth	342,601	28,605	14,974	0	443
South Canterbury	12,645	31,012	8,535	0	58
Otago	15,494	46,080	89,649	0	428
Southland	18,263	950	73,673	69	1,017
All of New Zealand	**853,701**	**807,815**	**1,581,575**	**2,784**	**20,522**
% population of NZ	**26%**	**25%**	**48%**	**0.1%**	**1%**

These data have been obtained from the Ministry of Health's Water Information New Zealand information base (WINZ) which contains the Register of Community Drinking-Water Supplies in New Zealand, September 2000.

The natural filtering action of aquifer media on percolating water, combined with the long residence time of water in an aquifer, are often sufficient to render water microbiologically safe. However, the groundwater may contain pathogenic organisms if water moves rapidly and there is a source of pollution close to the well, or if poor well construction allows the entry of contaminated surface water. The speed and maximum distance that microbiological contaminants can travel through an aquifer system depends on the characteristics of the aquifer and the type of microorganisms. The distance microbiological contaminants can travel in some New Zealand aquifers is greater than expected because (Sinton 1986): 1) they have relatively high rates of groundwater flow, and 2) larger particles, such as bacteria, may only be able to travel through larger pores (Sinton et al. 2000) in the aquifer material, where groundwater velocity is higher.

Coliform bacteria are frequently used to identify the extent of faecal contamination. The presence of faecal coliforms in a water sample means that pathogenic bacteria, viruses and protozoa may also be present. The coliform group of bacteria has been used internationally as an indicator of the bacteriological safety of water. These bacteria are always present in the intestinal tracts of humans and other warm-blooded animals and are expected in large numbers in faecal wastes. The presence of coliform organisms in water is an indicator of pollution (A. Kouzminov pers. comm.) because water is not a natural medium for these organisms. Many studies of microbial contamination in New Zealand groundwaters have used faecal coliform bacteria as indicators.

The potential for microbiological contamination (Chapter 9) of aquifer systems needs to be evaluated when well installation is proposed, to prevent human or livestock effluent from entering drinking-water resources. This is particularly necessary in view of the rising number of 'lifestyle blocks' that are being created in semi-rural areas of New Zealand. These are often serviced by their own domestic septic tank for disposal of waste water and by a well for drinking water, rather than being linked up to community services. The use of this land for intensive livestock farming, made attractive through the introduction of irrigation, places additional pressures on groundwater quality because of the increased faecal material from the livestock and enhanced contaminant migration caused by irrigation.

Chemical contaminants

Trace concentrations of chemicals may be introduced to groundwater by human activity, in particular nitrate from agricultural activities and organic chemicals such as pesticides, herbicides, petroleum hydrocarbons and industrial solvents. Fortunately, with the exception of one pesticide (dieldrin) identified at over half of its Maximum Acceptable Value (Ministry of Health 2000b) in one small rural supply to date, Ministry of Health programmes have not found organic chemicals at concentrations significant to health in any registered community drinking-water supplies using groundwater. However, very low concentrations of pesticides (that are not of potential health significance at the concentrations recorded) have been detected in five community drinking-water supplies that use groundwater. This indicates that contamination through land-use activities is occurring and therefore chemical contamination is an important consideration for long-term management of aquifers.

In national groundwater pesticides surveys conducted in 1990, 1994 and 1998/99 (Chapter 8; Close 1995, 1996; Close and Rosen in press), pesticides have been detected in a significant percentage of the wells sampled. Wells included in these surveys are not limited to those used for community drinking-water supply and were selected using a variety of criteria, such as the importance of each aquifer to the region, the vulnerability of the aquifer to pollution, area land uses, and the application or storage of pesticides in the area. The most recent survey (1998/99) detected pesticides in 29 of the 95 wells sampled (31%) (Close and Rosen in press).

Nitrate can be found in groundwaters as a result of agricultural activities and also from the use of domestic septic tanks in areas lacking reticulated sewage systems. Close (1989) found areas with rapid flow of effluent through highly permeable materials, with marked daily fluctuations of chemical concentrations in some nearby wells. Poorly constructed oxidation ponds can also allow seepage of nitrate into groundwater (Ministry for the Environment 1999b).

Consideration of the impact of on-site wastewater disposal, agricultural activity including pest management, the location of landfills and underground storage tanks, and above-ground activities that involve the use of soluble, mobile and persistent chemical contaminants should be part of an evaluation of the suitability of a groundwater source for drinking-water supply. Protection of groundwater quality is an aim of groundwater management because contamination can be extremely costly to remediate.

Radiological contaminants

Radioactivity in drinking water is derived from the leaching of radionuclides from rocks and soils or their deposition from the atmosphere. Naturally-occurring radionuclides from these two sources account almost entirely for the radioactivity present in New Zealand drinking water (Ministry of Health 1995a). A nationwide survey of radioactivity in drinking-water conducted by the National Radiation Laboratory in 1980 indicated that radioactivity levels in all drinking-water supplies serving population groups of 5000 or more were below 50 percent of the Maximum Acceptable Values for alpha- and beta- radioactivity and radon-222 (Ministry of Health 2000b). Radiological contaminants are not considered further in this chapter because there is no reason to believe that these low levels have altered since the 1980 survey.

SURVEILLANCE

Public health surveillance is the process of collection, analysis and interpretation of health information. Health information relates not only to knowledge about patterns of disease, but also to information about factors that affect the risk of disease occurring.

One of the most important demonstrations of the value of health surveillance was given by Dr John Snow in the 1850s, when he established the link between the occurrence of cholera and a hand pump in Broad Street, Soho, London by plotting each case of cholera on a map.

Surveillance information is collected on communicable disease occurrence and can be used to identify public health priorities. The *New Zealand Public Health Report*, produced by the Ministry of Health, provides reports on surveillance and on investigations of outbreaks. The disease surveillance data gives a monthly update of national surveillance data covering all notifiable diseases. Notification data are obtained from medical practitioners through the requirements of section 74 of the Health Act 1956. Thus the number of infections can be monitored. These notification rates underestimate the true incidence because many people do not seek medical attention and because the medical practitioner does not always pass notifiable disease information on to the Medical Officer of Health. A UK study found that notification rates varied with the type of disease. The ratio of cases in the community to cases reaching national surveillance was lower for bacterial pathogens (salmonella 3.2:1, campylobacter 7.6:1) than for viruses (rotavirus 35:1, small round structures viruses 1562:1) (Wheeler et al. 1999).

It can be difficult to establish a link between occurrences of a waterborne disease and a contaminated source of drinking water. The drinking water would be only one of several possible sources of infection. This limits the ability of disease surveillance data to be used to identify poor water quality as the cause. For example, although it has been noted that New Zealand leads the developed countries for incidence of campylobacteriosis (Ministry for the Environment 1999a), this disease can be spread by a number of means, not just by ingesting contaminated water. However, where rates of a communicable disease that can be spread by contaminated water are high, the quality of the water supply should be investigated as a possible cause. For this reason public health surveillance requires the collection of information relating to all the health risk areas associated with provision of drinking water including: the management of source water quality; treatment plant processes and management systems; and maintenance and adequacy of the distribution network.

Surveillance of drinking-water supplies is undertaken by Health Protection Officers. These officers have designated powers under the Health Act, 1956. The Ministry of Health has developed an information base—Water Information New Zealand (WINZ)—to support evidence-based public health decisions and actions at both the national and local level and to assist water suppliers and Health Protection Officers in their tasks of collecting and assessing water samples. The information base is used for calculating the compliance of supplies with the drinking-water standards (Ministry of Health 2000b). It contains records for all registered community drinking-water supplies, (community supplies are those that serve more than 25 people for more than 60 days a year), including ownership, information on specific risks for each source, treatment plant and distribution zones, and the monitoring requirements for compliance with the standards. Water suppliers input their monitoring data and any transgressions of the requirements in the standards are identified through the algorithims within WINZ. This information base is designed to simplify the task of surveillance and can be used to identify water systems that are at high risk of producing drinking water that is unsatisfactory in public health terms.

ASSESSMENT OF DRINKING WATER QUALITY FOR HEALTH SIGNIFICANCE

Safe drinking water that is available to everyone is a fundamental requirement for good public health (Ministry of Health 2000b). Aside from frequent references to concerns for the aesthetic properties of water, historical records indicate that standards for water quality as they relate to public health were notably absent up to and including much of the nineteenth century. With the realisation that various epidemics (e.g., cholera and typhoid) had been caused or spread by contaminated water, people saw that the quality of drinking water could not be accurately judged by taste and smell alone; more stringent criteria were required. This resulted in laws relating to minimum treatment of water, and then to the establishment of drinking-water standards (Cotruvo and Vogt 1990).

New Zealand's Ministry of Health has developed a number of tools for promoting safe drinking-water supplies. Although these tools are largely non-regulatory at present, they can be used together to bring about an improvement in the quality of drinking water. They provide the detail necessary to implement the basic legal requirements for provision of potable water defined in the building and health acts. The tools include:

- the drinking-water standards for New Zealand;
- the public health grading of community drinking-water supplies;
- the development of an information base—Water Information New Zealand (WINZ)—to assist water suppliers in managing their supplies and to assist Health Protection Officers to audit water supplies in their area;
- the register of community drinking-water supplies in New Zealand;
- the guidelines for drinking-water quality management in New Zealand; which include data sheets relating to all contaminants listed in the drinking-water standards for New Zealand;
- annual reports on the microbiological quality of drinking water in New Zealand.

The drinking-water standards for New Zealand (Ministry of Health 1995a, 2000b) use a prioritised system of monitoring, with four priority classes for contaminants in drinking water. Microbiological contaminants are given highest priority in the standards because effects of infection are potentially acute and widespread. Chemical contamination is given second priority as the effects are not usually acute.

The drinking-water standards for New Zealand are intended to (Ministry of Health 2000b):

- set out the compliance requirements;
- facilitate consistency of application throughout New Zealand;
- protect public health while minimising unnecessary monitoring;
- be appropriate for both large and small supplies of drinking water.

The standards list the maximum levels of microbiological, chemical and radiological contaminants in drinking water acceptable for public health as Maximum Acceptable Values (MAVs). The MAV of a contaminant is the maximum concentration of that contaminant which does not result in any significant risk to the health of a 70kg consumer over a lifetime of consumption of two litres of the water per day. They also specify, for community drinking-water supplies, the protocols for water sampling.

"Guideline values" (Ministry of Health 1995b) are used for contaminants that affect the taste, odour and appearance of water but are not, in themselves, a significant health risk. Guideline values (or ranges for some contaminants) are given because they tend to be subjective.

To demonstrate compliance with the standards only those relatively few contaminants that fall into the higher potential risk categories (Priorities 1 and 2) must be monitored. Monitoring of contaminants in the lower potential risk categories (Priorities 3 and 4) is not required to demonstrate compliance with the standards, which aim to minimise monitoring costs without compromising public health.

Priority 1 contaminants are microbiological and are the same for all registered community drinking-water supplies in New Zealand. Priority 2 contaminants are specific to each supply and are identified by Ministry of Health assessment of the characteristics of each source, treatment plant and distribution network.

All of the Ministry of Health programmes to implement drinking-water protection strategies relate to supplies that are registered as community drinking-water supplies. Water quality information held by the Ministry of Health is limited to registered supplies. However, unregistered supplies must still meet basic legislative requirements that cover the provision of a supply of potable water (s.64 Building Act 1991). This water must be adequate, convenient and wholesome (s.39 Health Act 1956). Moreover, the source of water supply must not be placed or constructed, or be in such a condition, as to render the water offensive, or liable to contamination, or likely to be injurious to health (s.29 Health Act 1956). The difference in the management requirements for unregistered supplies, therefore, relates to the collection of information that permits assessment of their 'potability' by way of analytical results, treatment and operations management.

MICROBIOLOGICAL QUALITY OF GROUNDWATER USED FOR DRINKING WATER SUPPLY

The provision of a water supply with a low risk of microbiological contamination is of the utmost importance to the health of any community. Microorganisms such as bacteria, viruses and protozoa can multiply in the body and cause acute illness. They may then spread from the infected person to the community by person-to-person contact, or faecal contamination of the water supply, causing disease epidemics.

The Ministry of Health's annual review of the microbiological quality of drinking water in New Zealand is used to inform the public about the microbiological quality of community drinking-water supplies. The annual review assesses national compliance of community drinking-water supplies with the microbiological criteria of the standards. The annual review helps to reduce the risk of waterborne disease by publicly identifying various deficiencies in microbiological water quality and in the monitoring of microbiological quality.

It is currently impractical to monitor water supplies for all potential human pathogens. Surrogates have to be used to indicate possible contamination of the water supply with human and animal waste. The microbiological acceptability of drinking water is presently demonstrated by monitoring that indicates an absence of *Escherichia coli* (*E. coli*) bacteria and protozoa (*Giardia* and *Cryptosporidium)*. *E. coli* is used to indicate possible contamination of water by faecal waste and thus the potential presence of pathogenic bacteria and viruses. Their absence is demonstrated through negative results from *E. coli* sampling, or may be partially replaced by monitoring to demonstrate satisfactory water treatment as measured by sufficient levels of free available chlorine. *E. coli* do not reliably indicate the presence of the protozoans *Giardia* and *Crytosporidium.* The likelihood of an absence of protozoa is demonstrated through checks on the level of water treatment.

While microbiological compliance criteria indicate a likelihood that there is no microbiological contamination, they are not a guarantee of its absence. For this reason, protection of source water quality is very important.

There were 1865 (Table 10.2) treatment plants registered in New Zealand when the last microbiological survey was undertaken. Of these, 136 treatment plants fully complied with the faecal coliform, *Giardia,* and *Cryptosporidium* compliance criteria in that year. This represents 7% of treatment plants, which supply 75% of the population. In terms of population served, compliance rates generally increased with increasing population size. The majority of treatment plants (76%, Table 10.2) complied with none of the microbiological criteria. These are mostly small supplies used by 10% of the population (Ministry of Health 2000c).

Table 10.2 presents the results for all registered 'treatment plants' in New Zealand. Many of these receive water from sources other than groundwater, and some treat the water to improve its quality. Only the faecal coliform results from treatment plants that do not treat their water in any way provide information on the quality of the raw groundwater. This information is of most use to those managing groundwater.

Of the registered drinking-water treatment plants (Ministry of Health 2000a), 472 use groundwater that is untreated (Table 10.3). Failures to meet the standards for faecal coliform bacteria are caused by (Table 10.3): positive faecal coliform results, a lack of monitoring, inadequate sampling, and the use of non-

Table 10.2. *Microbiological compliance with the standards in 1999 (Ministry of Health 2000c).*

Population band	Total No. treatment plants	Faecal Coliform compliance			Giardia compliance			Cryptosporidium compliance		
		No.	% TPs	%pop	No.	% TPs	%pop	No.	% TPs	%pop
<500	1484	53	4%	0.2%	183	12%	0.3%	175	12%	0.3%
500-999	103	19	18%	0.2%	18	17%	0.2%	14	14%	0.1%
1000-4999	155	55	35%	2%	50	32%	2%	41	26%	2%
5000-19,999	62	39	63%	6%	37	60%	5%	35	56%	5%
20,000-49,999	39	34	87%	19%	23	59%	14%	20	51%	13%
50,000-99,999	12	10	83%	11%	10	83%	11%	9	75%	10%
100,000+	10	10	100%	49%	9	90%	46%	9	90%	46%
Total	1865	220	12%	87%	330	18%	79%	303	16%	76%

Population band	Total No. treatment plants	No compliance			Fully compliant		
		No.	% TPs	%pop	No.	% TPs	%pop
<500	1484	1282	86%	2%	31	2%	0.1%
500-999	103	76	74%	0.8%	6	6%	0.1%
1000-4999	155	83	54%	3%	28	18%	1%
5000-19,999	62	20	32%	3%	34	55%	5%
20,000-49,999	39	3	8%	1%	19	49%	12%
50,000-99,999	12	1	8%	0.8%	9	75%	10%
100,000+	10	0	0%	0%	9	90%	46%
Total	1865	1465	79%	10%	136	7%	75%

Note: % TP refers to the percentage of the treatment plants in that population band.
% pop refers to the percentage of the population represented by all registered supplies

NB: The indicator for assessing bacteriological quality changed from faecal coliforms to *E.Coli* in 2000 (Ministry of Health 2000b)

Table 10.3. *Causes of failure to comply with standards for faecal coliform bacteria for supplies using untreated groundwater only.*

Population band	Total No. treatment plants	Faecal Coliform compliance	Faecal Coliform fail	Not monitored	Inadequate sampling or use of a non-registered laboratory*
		No.	No.	No.	No.
<500	370	15	15	291	49
500-999	24	5	1	8	10
1000-4999	34	11	2	6	15
5000-19,999	17	13	0	1	3
20,000-49,999	22	20	0	1	1
50,000-99,999	3	3	0	0	0
100,000+	2	2	0	0	0
Total	472	69	18	307	78

Source: A. Ball, ESR, Christchurch pers. comm. from raw data used to compile the Annual Review of the Microbiological Quality of Drinking-Water in New Zealand (Ministry of Health 2000c)

* Non-registered laboratories: The Ministry of Health has a register of laboratories that meet certain quality criteria, and have consequently been approved to conduct sample analysis as outlined in the standards. These laboratories must be used if the analytical results are to be accepted by the Ministry of Health.

registered laboratories. Unlike the faecal coliform compliance criteria, the *Giardia* and *Cryptosporidium* compliance criteria vary with the water source and treatment, and thus do not directly indicate source quality; they are therefore not discussed further.

The results show that, in the 1999 microbiological survey, drinking-water from 18 of the 472 treatment plants (3.8 per cent) using untreated groundwater recorded positive results for coliform bacteria, indicating that faecal contamination was present in the water. A minority of supplies (69 of 472 – 15%) met the compliance requirements because many suppliers failed to monitor the water correctly, if at all. The number of supplies that might test positive for faecal coliform bacteria could well be higher than 3.8 per cent, as almost two thirds were not monitored. These results suggest that the microbiological quality of some of New Zealand's groundwaters is sub-standard, which is of serious concern. Microbiological contamination of groundwaters is discussed in further detail in Chapter 9.

CHEMICAL QUALITY OF GROUNDWATER USED FOR DRINKING WATER SUPPLY

The standards list MAVs for over 130 chemical contaminants that can affect health. The chemical species that require on-going monitoring are determined by a programme that assesses all water supplies serving populations greater than 100 to identify all chemicals that should be classified as 'Priority 2'. Chemicals identified in supplies at greater than 50% of their MAV are classified as Priority 2 following assessment and sampling. All Priority 2 chemicals need to be monitored, as specified in the standards, to achieve chemical compliance. To date, the task of identifying Priority 2 chemicals has been completed for 859 supplies. The Priority 2 identification process will continue in some form when all supplies currently registered has been assessed so that newly registered supplies, or existing supplies that have changed, can be assessed. This will provide accurate information for monitoring of the chemical quality of drinking water.

A summary of results generated to date through Priority 2 identification is presented in Table 10.4 (Ritchie 2000). These results represent all chemicals identified in water supplies at greater than 50% of their MAVs.

Metals and disinfection by-products

Ministry of Health surveys of drinking-water quality generally sample water from consumers' taps to get samples representative of water being consumed by the public. This provides information on public exposure. The samples will have been affected by any treatment processes and by contact with the distribution system. Contact with the distribution pipes, individual plumbing and the consumers' taps has its most significant impact on the concentrations of: antimony, cadmium, chromium, copper, lead and nickel. Results have shown that elevated metal concentrations are frequently the result of corrosion of pipes and tap fittings, rather than contamination within the source water. Metals that could be sourced from corrosion are indicated in Table 10.4.

Similarly, disinfection by-products may occur in drinking water that has been disinfected, usually by chlorine. Disinfection by-products are therefore not contaminants within the source water, although they often indicate the presence of elevated concentrations of natural organic matter within it. This organic matter contains chemicals that are involved in a series of reactions with the disinfectant, leading to the production of disinfection by-products. Drinking-water supplies that use groundwater have far fewer disinfection by-products (Table 10.4) identified at concentrations potentially significant to health than surface water supplies. This is because groundwater generally contains lower concentrations of natural organic matter than surface water, and fewer drinking-water supplies that use groundwater are disinfected.

A distinction needs to be made between the number of supplies recommended for classification as Priority 2 (which require on-going monitoring), and the populations affected. Many of New Zealand's registered community water supplies serve small populations. In September 2000 there were 1104 registered drinking-water supplies serving up to 100 people, and 924 serving over 100, giving a total of 2024 registered supplies in New Zealand (Min-

Table 10.4. *Number of water supplies in which chemicals identified in water supplies at greater than 50% of their Maximum Acceptable Value (Priority 2 chemicals).*

Determinand	Groundwater		Surface water		Rain water		Mixed sources		Total	
	No.	Pop.	No.	Pop.	No.	Pop.	No.	Pop.	No.	Pop.
Antimony=	16	6,694	4	100,870	3	445	1	218	24	108,227
Arsenic	35	122,634	34	142,136	1	200	0	0	71	264,970
Barium	3	262	1	150	0	0	0	0	4	412
Boron#	7	3,342	1	30	0	0	0	0	8	3,372
Bromodichloro-methane *	0	0	4	7,560	0	0	0	0	4	7,560
Cadmium=	24	28,024	20	47,213	0	0	9	17,385	53	92,622
Chloral hydrate/ trichloroacetaldehyde *	4	4,990	64	148,514	0	0	10	73,930	78	227,434
Chloroform *	0	0	2	540	0	0	0	0	2	540
Chromium	1	150	0	0	0	0	0	0	1	150
Copper=	46	33,031	12	20,078	8	1,173	8	5,605	74	59,887
Dichloroacetic acid *	1	450	33	48,543	0	0	5	20,730	39	69,723
Dieldrin	1	150	0	0	1	210	0	0	2	360
Di(2-ethylhexyl)-phthalate	1	121	0	0	0	0	0	0	1	121
Fluoride	3	763	0	0	0	0	0	0	3	763
Lead=	149	177,872	120	307,710	26	3818	36	84,076	331	57,3,476
Manganese	17	3,924	1	600	2	276	3	5,210	23	10,010
Mercury	1	2	0	0	0	0	0	0	1	2
Nickel=	64	101,606	45	249,660	2	355	14	13,670	125	365,291
Nitrate	43	86,344	1	150	3	145	3	11,040	50	97,679
Selenium	2	502	0	0	0	0	0	0	2	502
Total HAA *	3	4,750	59	119,130	1	270	7	31,730	70	155,880
Total THM *	8	6,100	24	22,433	0	0	3	47,230	35	75,763
Trichloroacetic acid *	1	450	19	32,075	0	0	2	4,630	22	37,155
Totals	430	582,161	444	1,247,362	47	6,892	101	315,454	1,023	2,151,899

= Corrosion derived metal. *Disinfection by-product.
The MAV for boron increased from 0.3 mg/L in the 1995 standards to 1.4 mg/L in the 2000 standards.
These data are Priority 2 recommendations from the Ministry of Health's Priority 2 Chemical Identification Programme, October 2000 (Ritchie 2000). They do not include the Priority 2 recommendations made for fluoride intentionally added at treatment plants.

istry of Health WINZ database). Although it is important to protect all consumers, financial constraints means that the size of the populations affected by the chemical contaminants is taken into account.

Chemical contaminants (Table 10.5) can be present in groundwaters for many reasons; potential sources of the more important contaminants (listed in Table 10.5) include:

- Arsenic: The MAV for arsenic is 0.01 mg/L (Ministry of Health 2000b). Arsenic can enter water through weathering of minerals and rocks, run-off from soils, from geothermal fluids, or from atmospheric deposition. Mineralised zones of sulphitic ores probably contain the highest concentrations of arsenic, although high levels of arsenic also occur in some coals and peats. In New Zealand, arsenic occurs in greywacke, schists and in Tertiary volcanics. Geothermal fluids contain elevated concentrations of arsenic, so water bodies in New Zealand that include geothermal discharges, such as the Waikato River typically have high arsenic concentrations. Arsenic can also be released to the aquatic environment via the discharge of wastes from industries (Ministry of Health 1995b data sheets).
- Boron: The MAV for boron increased from 0.3 mg/L (Ministry of Health 1995a) to 1.4 mg/L (Ministry of Health 2000b) which removed the majority of Priority 2 classifications for boron.
- Nitrate: The MAV for nitrate is 50 mg/L expressed as nitrate (Ministry of Health 2000b).

Table 10.5. *'Key' Priority 2 chemicals and populations receiving drinking-water from a groundwater source.*

Chemical	Population with chemical identified in water supplies at greater than 50% of their maximum acceptable value (Priority 2 chemicals)
Arsenic Nitrate Boron* Manganese	122,634 86,344 3,342 3,924
Corrosion metals *(a product of the ability of the water to corrode pipework and plumbing)*	• Antimony: 6,694 • Cadmium: 28,024 • Copper: 33,031 • Lead: 177,872 • Nickel: 101,606
Disinfection by-products *(formed from organic matter in the water combining with the disinfectant used to treat the water)*	• Chloral hydrate/trichloroacetaldehyde: 4,990 • Dichloroacetic acid: 450 • Total haloacetic acids: 4,750 • Total trihalomethanes: 6,100 • Trichloroacetic acid: 450.
Others	• Barium: 262 • Dieldrin: 150 • Di(2-ethylhexyl)phthalate: 121 • Fluoride 2b: 763 • Selenium: 502

Priority 2 = Chemical has been identified in the supply at >50% of its MAV
MAV = Maximum Acceptable Value listed in the Drinking-Water Standards for New Zealand, 2000 (Ministry of Health 2000b)
Fluoride 2b: Fluoride derived from the source water rather than from intentional addition at the treatment plant for dental protection purposes. *The MAV for boron increased from 0.3 mg/L in the 1995 standards to 1.4 mg/L in the 2000 standards.

Nitrate and nitrite can enter water from the oxidation of reduced nitrogenous compounds (such as ammonia and organic nitrogen compounds from vegetable and animal debris and animal excrement); they can also enter water via agricultural, domestic and industrial discharges. Major sources of nitrate include municipal wastewaters, septic tanks, fertiliser and animal excreta (Ministry of Health 1995b, data sheets).

- Manganese: The MAV for manganese is 0.5 mg/L (Ministry of Health 2000b). The Ministry's results for manganese, however, have been obtained from samples taken from consumers' taps rather than from raw water. Manganese concentrations are lowered in many treatment plants through simple aeration/oxidation procedures. These results are therefore likely to be an underestimate of the pre-treatment concentrations in the source waters. Manganese can reach the aquatic environment from the weathering of rocks and minerals and runoff from soils. It can also enter source waters (usually anoxic) by chemical reduction or microbiological activity. Manganese is an essential trace element; people require an estimated daily intake of 30-50 mg per kilogram of body weight. Manganese absorption rates can vary with actual intake, its chemical form, and the presence of other metals such as iron and copper. Typically, only about 3-8% of ingested manganese is absorbed by the gastro-intestinal tract. Manganese is thus often regarded as one of the least toxic elements (Ministry of Health 1995b data sheets). Manganese can affect the appearance of water; it is deposited in water mains and causes water discolouration. For this reason an aesthetic guideline value of 0.05 mg/L is given.

- Corrosion-derived metals: The MAVs for six metals that have been found at levels potentially significant to health in New Zealand's drinking-water supplies are as follows: Antimony 0.003 mg/L; Cadmium 0.003 mg/L; Chromium 0.05 mg/L; Copper 2 mg/L; Lead 0.01 mg/L; Nickel 0.02 mg/L (Ministry of Health 2000b). These metals have been found in significant concentrations in tap water because of corrosion of pipes and plumbing fittings, rather than because of their presence in source waters. Concentrations of lead, cadmium, antimony and nickel can often be reduced to levels that are not a health hazard simply by flushing the tap before use, to remove stagnant water from the plumbing or tap fittings (Nokes 1999). Because of this simple removal procedure the Ministry of Health treats these metals differently from other Priority 2 chemicals. The water supply will be considered to comply with the standards for lead, cadmium, antimony or nickel, if the water supply owner provides a public warning to consumers at least twice a year, for example with each water supply bill or water rate demand, and also publishes a public notice that states that:
  - the water supplied in that district is mildly corrosive to plumbing fittings and may/will accumulate lead, cadmium, antimony or nickel if it lies for too long in the pipes;
  - at least 500 ml of water should be flushed from the tap and discarded to flush away corrosion products before using the water for food preparation or drinking (Ministry of Health 2000b).

APPROPRIATE SAMPLES

Some words of caution are required regarding methods of assessment of the quality of a groundwater. Variations in water quality due to geographical location, temperature, time of sampling or depth within the aquifer should be accounted for in any monitoring programme.

The standards specify sampling protocols, frequencies and the types of locations that should be used to obtain results that allow a statistically valid statement to be made about the water quality (Ministry of Health 2000b). The key factors in determining the frequency and number of samples for on-going monitoring of a supply are preventing monitoring from becoming prohibitively expensive whilst providing the necessary standard of information.

Whether monitoring is conducted to assess the characteristics of a new supply, or for quality control of an existing supply, appropriate collection techniques should be used. These include adequate purging of the well, use of correct equipment, cleanliness of equipment, appropriate storage and transfer of samples and so on. Guidelines for the collection of groundwater samples for chemical and isotopic analyses are provided by Rosen et al. (1999). The Ministry of Health list of laboratories approved for water analysis is detailed in the standards (Ministry of Health 2000b), and this provides some quality assurance with regards to analysis of the samples.

On-going monitoring over many years can allow changes in contamination levels to be identified, which is essential for reviewing management practises. Rosen (1999) has noted the importance of systematic collection of long-term information on groundwater quality. The New Zealand National Groundwater Monitoring Programme (NGMP) aims to assess the long-term trends in water quality in key areas of New Zealand, but it has been in operation for only a short time.

AESTHETIC PROPERTIES OF GROUNDWATER

The appearance, taste, and smell of water are very important to consumers because consumers link those properties with its safety. Drinking-water suppliers receive most complaints as a result of a problem with the aesthetic properties of water, not because of trace levels of contaminants significant to health. Water will most closely meet consumer expectations when it is clear, colourless, odourless and contains no unpleasant taste (Ministry of Health 1995b). However groundwater will always contain dissolved chemicals as well as particulate substances because water is such a good solvent. Many of these chemicals are beneficial in small amounts and may even contribute to the palatability of the water, and thus its aesthetic quality. However, at high concentrations they may affect taste or hardness, or they may cause other problems, such as the staining of laundry in the case of manganese and iron.

Finally, the corrosion of pipes, plumbing fittings and hot-water cylinders caused by some groundwater may have economic implications.

ADVERSE HEALTH EFFECTS ASSOCIATED WITH GROUNDWATER

Contaminants in groundwater that affect public health can be classified as causing either acute or chronic health effects. Acute effects occur within hours or days of the time that a person consumes a contaminant. Almost every chemical contaminant could have an acute effect if consumed at high enough concentrations in drinking water. However, the contaminants that most frequently cause acute effects in New Zealand are microbiological (bacteria, protozoa, viruses, and algae). Examples of acute effects range from mild stomach upsets to death. People who are weak, or have compromised immune systems are more likely to suffer severe effects.

Chronic effects can occur if people consume a contaminant at low levels over many years. The drinking water contaminants that can have chronic effects include chemicals such as solvents and pesticides, and radionuclides such as radium. The potentially chronic effects of drinking water contaminants include cancer, liver or kidney problems, and reproductive difficulties. The MAVs listed for chemicals and radionuclides in the standards (Ministry of Health 2000b) provide criteria which, if met, present insignificant chronic health effects from consumption of drinking-water over a lifetime. Water quality is important for those rearing livestock as well as for human health. Research in Canada indicates that livestock supplied with high-quality water have higher rates of production compared with stock given poor-quality water (Ministry for the Environment 1999a).

EXAMPLES OF ADVERSE HEALTH EFFECTS OF CONTAMINATED GROUNDWATER

Campylobacter

New Zealand leads the developed countries for incidence of campylobacteriosis (Ministry for the Environment 1999a), but this disease is spread in a number of ways, not just by contaminated groundwater. An outbreak of campylobacteriosis attributable to contaminated drinking water occurred recently in New Zealand at a school camp. The outbreak involved 67 cases (5 confirmed and 62 suspected) of campylobacteriosis at a school holiday camp near Christchurch in January 1997. A retrospective cohort study identified a contaminated water supply as the most likely source of infection (Bohmer 1997).

Arsenic

Arsenic is a natural part of the earth's crust in some parts of the world, and may be found in water that has flowed through arsenic-rich rocks. Adverse health effects, including skin cancer, dermal lesions, and peripheral vascular disease ("blackfoot disease"), have been observed in populations ingesting arsenic-contaminated drinking water (World Health Organisation 1996).

Perhaps the most widely reported cases of arsenic contamination are those in Bangladesh and West Bengal (India). Over the last two decades, untreated tube-well water was heavily promoted and developed as a safe alternative to microbe-contaminated untreated surface water. In the 1980s, evidence of arsenic contamination was found, but only very recently (mid-1990s) has public awareness of the crisis emerged. Recent investigations indicate that the arsenic is released to groundwater under naturally occurring reducing conditions in aquifers associated with specific sedimentary materials. Concentrations as much as seventy times the national drinking-water standard of 0.05 mg/L have been measured in both Bangladesh and India (World Health Organisation website). These concentrations greatly exceed any encountered in New Zealand: where arsenic has been identified in drinking-water supplies in New Zealand, it is rarely above 0.05 mg/L. However, arsenic above the New Zealand national drinking-water standard of 0.01 mg/L has been identified in a significant number of supplies.

Fluoride

Levels of daily exposure to fluoride depend on the geographical area (World Health Organisation 1996) India is one of a number of countries in which fluorosis is a health problem. Concentrations as high as 25 mg/L have been reported in drinking water, with a correspondingly high incidence of skeletal and dental fluorosis (Susheela 1984). High levels of fluoride intake due to high concentrations in drinking water, food and air also have been documented for some areas of China. The combustion of coal containing high levels of fluoride has contributed to this problem (World Health Organisation 1992).

Fluoride can appear in New Zealand waters as a result of the weathering of alkaline and siliceous igneous and sedimentary rocks, especially shales. Fluoride species are also found in volcanic and geothermal fluids (Ministry of Health 1995b). However, naturally occurring fluoride is rarely present in New Zealand's drinking-water supplies at levels potentially significant to health. The Ministry of Health's Priority 2 Chemical Identification Programme has identified three supplies with fluoride present at greater than 50% of its MAV to date, with one in which the fluoride concentration exceeded the MAV (Ritchie 2000).

In New Zealand, natural levels of fluoride are generally low, and many community drinking-water suppliers adjust the level of fluoride in their water before it is distributed as a protection against dental caries. These water suppliers are required to monitor their water (13 samples per calendar quarter) in order to ensure that the fluoride does not exceed its MAV of 1.5 mg/L, and is maintained within its recommended range of 0.7–1.0 mg/L (Ministry of Health 2000b). The MAV is set at a level to protect against mottling of teeth (dental fluorosis). In New Zealand there are no documented cases of adverse health effects from consumption of naturally present, or intentionally added, fluoride in drinking water.

Nitrate

Much attention has been given worldwide to the elevated concentrations of nitrate that can occur in ground and surface waters. Intake of excessive concentrations of nitrate is suspected to cause infantile methaemoglobinaemia, and the World Health Organisation drinking water guidelines (and New Zealand's MAV) are established to prevent methaemoglobinaemia. However, recent research and a review of historical cases offer a more complex picture of the causes of infantile methaemoglobinaemia, with gastrointestinal infection and inflammation and the ensuing overproduction of nitric oxide being the possible cause in many cases (see Chapter 8). If so, current limits on allowable levels of nitrate in drinking water may be unnecessarily strict (Avery 1999).

The environmental effects of nitrate pollution of surface waters are quite well known. Ammonia-N is highly toxic to fishes and other animals, and the eutrophication of waters leads to a loss of organisms due to lack of oxygen. Nationwide efforts to limit nitrate input into water resources are therefore valid for environmental as well as for human health reasons. Furthermore, elevated nitrate concentrations may indicate the presence in the groundwater of other contaminants such as pathogens and pesticides associated with agricultural activity, i.e. nitrate can indicate a general degradation of the quality of the groundwater.

Elevated nitrate concentrations are frequently recorded in New Zealand groundwater samples, particularly in areas where wells are shallow and draw water from unconfined aquifers. To date 53 community water supplies have had nitrate identified at concentrations greater than 50% of the MAV, and the concentration of nitrate in six registered community supplies using groundwater have exceeded the MAV. However, in many agricultural areas, non-registered domestic supplies are used, and we do not have Ministry of Health information relating to these.

Burden (1982) reported that 'To date, no cases of methaemoglobinaemia have been reported in New Zealand but this could, at least in part, result from the fact that methaemoglobinaemia is not classified as a 'notifiable' disease. However, Selvarajah (1996) noted that an infant death case in 1994 had been reported. Following a prescription the 6-month-old infant (who had vomiting and diarrhoea) received glucose and an electrolyte prepared using con-

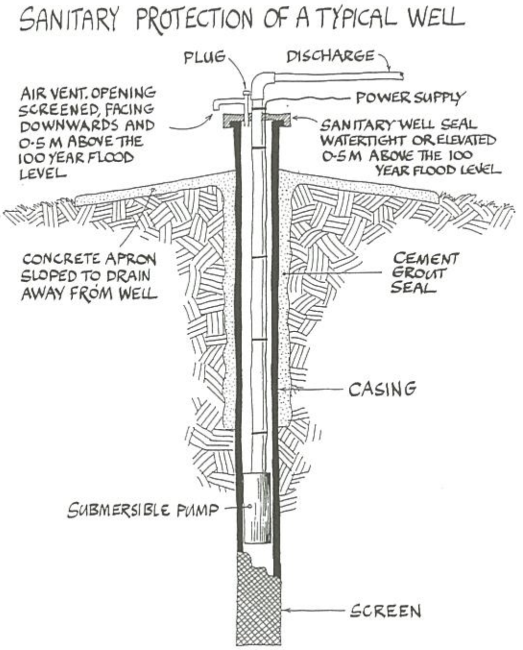


Figure 10.4 *Sanitary protection of a typical well (after Ministry of Health 1995b).*

taminated groundwater (27 mg/L nitrate- N) at her home in the Franklin area and died after developing symptoms related to methaemoglobinaemia.

APPROPRIATE WELL CONSTRUCTION

To ensure a high quality water supply, wells need to be constructed to reduce the potential for contamination. A major factor is the selection of a flood-free well site, far from potential pollution sources. The Ministry of Health has specified construction (Fig. 10.4) details for wells to be used for drinking-water supply (Ministry of Health 1995b). The construction design aims to prevent contaminants from entering the aquifer via preferential pathways created by the well. A New Zealand drilling standard is presently in preparation, and this will develop minimum standards for drilling, construction, development, testing and maintenance of bores (New Zealand Drilling Standard Development Project 2000).

In addition to the procedures used by the Ministry of Health to improve the quality of New Zealand's registered community water supplies, public education is necessary to improve the quality of the numerous existing wells. An example of public education is Environment Canterbury's well-head protection leaflet (Fig. 10.5).

TREATMENT OF GROUNDWATER

Microorganisms

The contamination of groundwater with pathogenic microorganisms is an important public health problem in New Zealand because of the large number of shallow groundwater supplies used for community and domestic drinking water. In some parts of Canterbury 60% of groundwater bores are contaminated with faecal material (Ministry for the Environment 1999a). Many of these contaminated

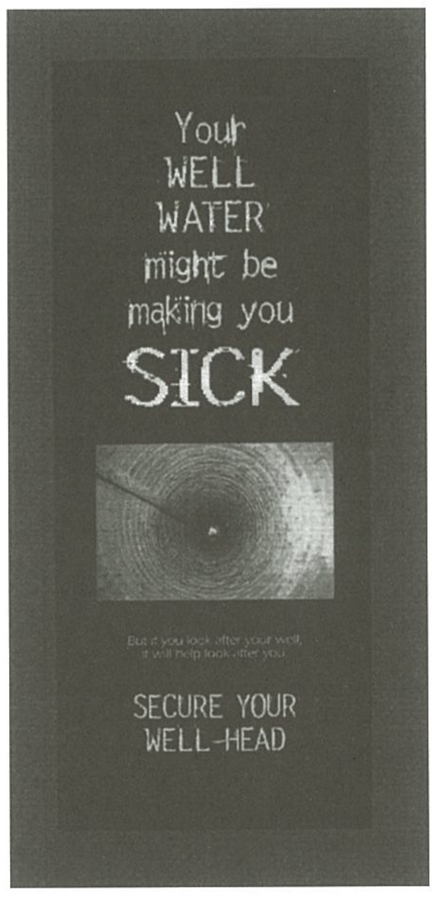


Figure 10.5. *Public education pamphlet to promote projection of water quality abstracted from domestic wells*

drinking-water supplies are untreated and therefore those who use them risk infection by disease-causing organisms. The public health risk associated with these water supplies often receives little public attention because the supplies frequently serve small populations. Also, it can be difficult to reliably demonstrate any higher incidence rates of communicable disease that could be attributable to the water quality. However, Ministry of Health results for registered community supplies that use groundwater show a significant occurrence of positive faecal coliform results (Ministry of Health 2000c), and treatment to remove or inactivate microorganisms is thus important. The Ministry of Health considers that groundwater verified as secure is the only type that does not require treatment to inactivate or remove microorganisms (Ministry of Health 2000b).

Water can be treated to remove or inactivate microorganisms using a number of chemical or physical processes. The majority of New Zealanders receive water from large water supplies that have been treated. In 1999, 73% of the population received chlorinated water, 20% received untreated water from secure groundwater (Fig. 10.1), 7% received untreated water from a non-secure groundwater and less than 1% received drinking water that was either ozonated or treated by UV, chlorine dioxide (ClO_2) or mixed oxidants (Ministry of Health 2000c).

Disinfectants vary in their ability to inactivate microorganisms, so requirements for effective pre-treatment of the water will vary with the disinfectant used. In all cases, correct treatment protocols are necessary, and initial selection of the most appropriate technology plus monitoring of management protocols at treatment plants is important for the provision of drinking water that is acceptable for public health.

Chemicals

If chemical contamination exists in a water supply it will be dependent upon specific conditions relating to each supply, so appropriate treatment options must be determined on an individual basis.

Treatment options for some common chemical contaminants are discussed below.

- *Arsenic:* Conventional coagulation treatment with iron or aluminium salts can effectively remove arsenic. The effectiveness depends on the oxidation state of the arsenic (trivalent arsenic should be converted to pentavalent arsenic by oxidation with chlorine or potassium permanganate), the pH at which the process is carried out, and whether iron or aluminium is used as the coagulant.

  Lime-softening, ion exchange resins, and activated alumina can also be used to remove arsenic. The removal of arsenic from water by ion exchange and alumina depends upon the arsenic being present as the negatively-charged arsenate ion, AsO_4^{3-}. This ion contains arsenic in the highest oxidation state (+5), and oxidation of any arsenic in the +3 oxidation state is required if it is to be removed by these two processes (Ministry of Health 1995b data sheets).
- *Nitrate:* Nitrate is not removed from water by classical methods of treatment. Ion exchange systems for removing nitrate have been developed, but commonly water is simply diluted with water of lower nitrate concentration from another source (Ministry of Health 1995b data sheets).
- *Manganese:* Manganese concentrations are lowered in many treatment plants through simple aeration/oxidation procedures.
- *Corrosion-derived metals:* Studies of lead and nickel in tap water have shown that flushing the tap is an effective way to significantly reduce the concentrations of these metals (Nokes 1999). However, water suppliers will often wish to reduce the ability of the water to corrode metal pipes for economic reasons.

Methods for reducing the capacity of water to corrode metal pipework vary with the chemistry (and microbiology) of the water, and physical factors such as flow velocity and temperature. The adjustment of pH is the most common method used to reduce corrosion.

CONCLUSIONS

New Zealand possesses significant groundwater resources, and these resources are used for the supply of drinking water to approximately 50% of the population.

According to census figures, approximately 88% of New Zealand's population receive water from a registered drinking-water supply. There is a lack of nationally consistent information on the quality (in terms of public health) of drinking-water supplies that serve the remaining 12% of the population. Of the registered drinking-water supplies using groundwater sources, information on microbiological quality is still inadequate due to a lack of any monitoring or insufficient monitoring.

Available information on the microbiological quality of untreated drinking-water supplies that use groundwater as a source indicates that faecal contamination is possible. Positive faecal coliform results were recorded from 3.8 per cent of untreated groundwater supplies in the latest Ministry of Health report on microbiological quality of drinking water. This perecentage is probably an under-estimate, as most untreated groundwater supplies are inadequately monitored, or not monitored at all, and this limits the availability of microbiological data.

The majority of New Zealanders live in large towns served by well-managed and treated water supplies. Poor microbiological quality is most frequently associated with supplies to small, scattered populations. This makes management of microbiological contamination and improvement of these groundwater supplies a major challenge nation-wide.

Available information on the chemical quality of registered community drinking water from groundwater sources suggests that it is generally good. Some chemicals have been found in groundwaters at concentrations potentially significant to health (greater than 50% of the Maximum Acceptable Value for a lifetime of exposure). These are (in order of the size of population affected) arsenic, nitrate, and manganese. Corrosion metals and disinfection by-products affect some populations, but are not present in the source waters. Of these chemicals, nitrate is the only one that is related to land use. This suggests that control of land-use activities that contribute nitrate to groundwater is important. Like microbiological contamination, poor chemical quality is often associated with supplies that serve small, scattered populations and this creates management problems.

Chemical contamination of groundwater resources by other land use activities is currently minimal and generally not a health hazard. Management strategies such as appropriate construction of wells, securing of existing well heads, the establishment of well-head protection programmes are important to protect groundwater supplies.

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REFERENCES

Avery, A. 1999: Infantile methaemoglobinemia: Re-examining the role of drinking water nitrates. Environmental Health Perspectives 107: 583-586.

Bohmer, P. 1997: Outbreak of campylobacteriosis at a school camp linked to water supply. In The New Zealand Public Health Report. Ministry of Health, Wellington. Vol 4 (8): 58-59.

Building Act 1991: Section 64: Buildings which are deemed to be dangerous or insanitary.

burden, R.J. 1982: Nitrate contamination in New Zealand aquifers: a review. New Zealand Journal of Science 25: 205-220.

Close, M.E. 1989: Effects of septic tank effluent on chemical quality of alluvial gravel aquifers. In: New Zealand Journal of Marine and Freshwater Research 23: 275-286.

Close, M.E. 1995: Pesticides in New Zealand's groundwater. Proceedings of the first AgResearch/Landcare Research pesticide residue workshop 1994. L. Boul and J Aislabie (eds.). Manaaki Whenua-Landcare Research: 47-52.

Close, M.E. 1996: Survey of pesticides in New Zealand groundwaters, 1994. New Zealand Journal of Marine and Freshwater Research 30: 455-461.

Close, M.E.; Rosen, M.R. (in press): National survey of pesticides in groundwater - summer 98/99. New Zealand Journal of Marine and Freshwater Research.

Cotruvo, J.A.; Vogt, C.D. 1990: Rationale for water quality standards and goals. Water Quality and Treatment. A handbook of community water supplies (Fourth edition), American Water Works Association. McGraw-Hill, Inc, 1194p.

Department of Statistics 1996: 1996 census, regional summary. Department of Statistics, Wellington, 345p.

Hamann, C.L.; McEwen, J.B.; Myers A.G. 1990: Guide to selection of water treatment processes. Water quality and treatment. A handbook of community water supplies (Fourth edition). American Water Works Association. McGraw-Hill, Inc, 1194p.

Health Act 1956: Section 29: Nuisances defined for purposes of this Act, and section 39: Requirements of dwelling houses as to supply of water and sanitary conveniences.

Ministry for the Environment 1999a: Making every drop count. The national agenda for sustainable water management - action plan. Draft for public comment, 44p.

ministry for the Environment 1999b: Resource Management Act practice and performance: Are desired environmental outcomes being achieved? A case study of farm dairy effluent management, 28p.

Ministry of Health 1995a: Drinking-water standards for New Zealand. Compiled by: national drinking-water standards review expert working group for the Ministry of Health, Wellington, 87p.

Ministry of Health 1995b: Guidelines for drinking-water quality management for New Zealand, 832p.

Ministry of Health 2000a: Register of community drinking-water supplies in New Zealand. 2000 Edition. Ministry of Health, Wellington, 370p

Ministry of Health 2000b: Drinking-water standards for New Zealand. Compiled by: National Drinking-Water Standards Review Expert Working Group for the Ministry of Health, Wellington, 130p.

Ministry of Health 2000c: Annual review of the microbiological quality of drinking-water in New Zealand, 1999, by Andrew Ball. Ministry of Health, Wellington, 159p

New Zealand Drilling Standard Development Project 2000 in press: New Zealand drilling standard development project, draft standard. Project leader: Gillian Crowcroft, Auckland Regional Council.

Nokes, C. 1999: Risk factors leading to the appearance of corrosion-derived metals in drinking-water. Prepared as part of a Ministry of Health contract for scientific services by ESR, Christchurch, 98p.

Price, M. 1985: Introducing groundwater. British Geological Survey, George Allen & Unwin, London, 195p

Ritchie, J. 2000: Additional recommendations for the identification of Priority 2 chemical determinands in New Zealand drinking-water supplies (1/7/00-1/10/00). Prepared as Part of a Ministry of Health contract by ESR, Christchurch, 61p.

Rosen, M. 1999: The importance of long-term, seasonal monitoring of groundwater wells in the New Zealand National Groundwater Monitoring Programme (NGMP). Journal of Hydrology (NZ) 38(1): 145-169.

Rosen, M.; Cameron, S.; Taylor, C.; Reeves, R. 1999: New Zealand guidelines for the collection of groundwater samples for chemical and isotopic analyses. Institute of Geological and Nuclear Sciences Science Report 99/9. IGNS, Lower Hutt, 81p.

Selvarajah, N. 1996: Sustainable nitrogen fertiliser use in the Waikato region. New Zealand Soil News 5: 183-189.

Sinton, L. 1986: Microbial contamination of alluvial gravel aquifers by septic tank effluent. In: Water, Air and Soil Pollution 28: 407-425.

Sinton, L. 2000: Transport and attenuation of bacteria and bacteriophages in an alluvial gravel aquifer. New Zealand Journal of Marine and Freshwater Research 34: 175-186.

Susheela, A. 1984: Epidemiology and control of fluorosis in India. NFI bulletin, Nutrition Foundation of India, 5.2.1984.

World Health Organisation 1992: Endemic fluorosis: a global health issue - a technical report within the WHO/UNEP human exposure assessment locations project. World Health Organisation/United Nations Environment Programme, 58p.

World Health Organisation 1996: Guidelines for drinking-water quality. Second edition, Volume 2. Health criteria and other supporting information. World Health Organisation, Geneva, Switzerland, 973p.

World Health Organisation Website: Sustainable development and healthy environments. Protection of the human environment.

Wheeler, J.; Sethi, D.; Cowden, J.; Wall, P.; Rodrigues, L.; Tompkins, D.; Hudson, M.; Roderick, P. 1999: Study of infectious intestinal disease in England: rates in the community presenting to general practice, and reported to national surveillance. British Medical Journal, 318: 1046-1050.

11

Groundwater management in New Zealand

ANDREW D. FENEMOR AND CHRISTINA A. ROBB

INTRODUCTION

Groundwater management is the informed control of activities that may affect aquifer systems. It is a combination of:

- understanding groundwater systems and predicting how they will respond to activities,
- establishing and reviewing objectives for managing a groundwater system;
- applying management tools to implement or control these activities; and
- monitoring to assess whether management actions have achieved the required objectives.

All connected parts of an aquifer system must be managed together, so other connected aquifers, overlying soils through which rainfall recharges the system, and any rivers, lakes, springs, wetlands or coast connected to the aquifer must be considered. If an aquifer is managed in isolation from its surroundings, important controls on its response to activities–such as abstraction inducing recharge of the aquifer from river flows–could be over-simplified or overlooked. Successful management of any system requires that the bounds and behaviour of the system be known or estimated.

Many activities can affect aquifer systems:

- abstraction of groundwater and surface water;
- irrigation or artificial recharge (increased recharge);
- changes in land use that alter the amount of rainfall recharge to groundwater;
- quarrying and gravel extraction that change drainage of groundwater to surface waters;
- landfills, contaminated sites, underground fuel storage tanks, septic tanks, land disposal of effluent from municipalities and industries, and activities causing possible contaminant spills (point source contamination); and
- infiltration of animal effluent, nutrients, pesticides, and other contaminants from agricultural, horticultural and urban land uses (non-point source contamination).

For this chapter, we have divided groundwater management into two categories–management of groundwater quantity and management of groundwater quality.

Groundwater quantity means the quantity of water stored and flowing through an aquifer. Only a portion of this quantity can be abstracted. The quantity available is affected by abstractions, changes in recharge and changing land use. The effects of any reductions in groundwater quality, however, depend on the type of contaminant, the uses to which the groundwater is put, and the values of any surface water bodies into which groundwater discharges. A major threat to New Zealand's groundwater quality is from diffuse or 'non-point' sources such as infiltration of animal effluent from grazed pasture or contamination of irrigation or rainfall recharge (Ministry for the Environment 1997a). An increasing trend toward land application of treated sewage effluent and industrial wastes is also a threat for future groundwater quality (Cameron et al. 1997). Deteriorating groundwater quality is a global problem that is proving difficult to stop and reverse (World Water Vision 2000)-the effects are unseen, the connections between cause and consequence are poorly understood, and there is a lack of acknowledgement of the problem by those contributing to it.

In practice, the influences on groundwater quality and quantity overlap. For example, abstraction of groundwater near the coast can cause the salt-water/fresh-water interface to move inland. Similarly, appropriate construction and maintenance of bores is important

Fenemor A.D. and Robb C.A. 2001: Groundwater management in New Zealand. *In* Groundwaters of New Zealand, M.R. Rosen and P.A. White *(eds)*. New Zealand Hydrological Society Inc., Wellington. p273-289.

for protecting aquifers from surface contamination.

This chapter begins with an outline of the legislative and institutional arrangements used in New Zealand to manage groundwater. It then summarises the methods and tools used to characterise, manage and monitor groundwater quantity and quality. The final section presents challenges for future research and groundwater management in New Zealand. More details on the management practices and specific issues faced by each region in New Zealand can be found in Chapters 12 to 26 of this book.

LEGISLATIVE BACKGROUND

Legislative history

Chapter 2 summarises the history of groundwater development in New Zealand, and the history of legislation. The 1967 Water and Soil Conservation Act (WSCA) was the first piece of legislation to provide a management framework for water resources. The 'water right' (now 'water permit'), which authorises the taking and use of water from natural sources, was first required by the WSCA. 'Natural water' included rivers, streams and underground water. The WSCA also required a 'water right to discharge' wastes (now a 'discharge permit') to natural waters by direct, normally piped, discharges. Non-point source groundwater pollution was poorly controlled by the original WSCA, however the 1983 amendment required water rights to be obtained for discharges onto or into land where contaminants could, through natural processes, enter natural water. This amendment controlled such discharges as landfill leachates and stormwater soakage.

Resource Management Act 1991

Groundwater management under the WSCA was superseded by the Resource Management Act (RMA) in 1991. The RMA is the dominant piece of environmental legislation in New Zealand, covering the coast, fresh and geothermal water, air, noise and land use. The focus changed from one of multiple use of water resources under the WSCA to the promotion of sustainable management of resources under the RMA. The law gives a mandate for sustainable use, development and protection of natural and physical resources, with a particular emphasis on protecting the life-supporting capacity of resources, safeguarding the foreseeable needs of future generations, and avoiding, remedying, or mitigating adverse effects on the environment. Rather than controlling activities such as water abstraction per se, the RMA emphasises avoiding or limiting the environmental effects of those activities.

There were few changes to groundwater management in the transition to the RMA. Under the RMA, councils are able to prepare regional plans under a statutory process, with binding effect once they are operative. This provision gave legal backing to the earlier process of preparing informal water management plans—including groundwater management plans—containing policies and rules for particular water bodies. The statutory submission and hearing process allows public involvement in preparing a groundwater management plan, providing certainty about the limits and controls on water use, land use and discharges. The RMA encourages integrated management of natural resources, so groundwater planning can be treated as part of the management of water bodies and land within a whole catchment or region. Groundwater is now considered under the RMA as eligible for protection or preservation under a water conservation order issued by the Minister for the Environment, although none has so far been issued for groundwater.

Under the RMA all or part of a water permit to take water within a catchment, aquifer or geothermal field can be transferred. Such transfers can be encouraged in regional plans, and were intended to promote the efficient use of water by creating a market for water. Transferability requires a fully allocated resource where demand exceeds supply, sufficient knowledge of resource availability and the effects of its use, a range of water uses with different values, enforceable permits, metered takes, and a system for allowing interested parties to negotiate (Fenemor 1991). Although provisions for site-to-site transfers of water permits have been included in some operative water plans (e.g. the Oroua Catchment Water Allocation and River Flows Regional Plan, Manawatu-Wanganui Regional Council 1995), very few transfers have occurred, other than those associated with land purchase or subdivision. Transferability—or the ability to purchase a water allocation—has often been opposed because of the perception that it amounts to a privatisation of a public resource.

Institutional arrangements

One of the underlying principles of the RMA is that decision-making is best left to those directly affected by the results of those decisions. Local authorities are responsible for implementing most of the RMA, and are divided into two tiers (regional and district/city councils) for this purpose. Under the RMA, district and city councils are responsible for the effects of land use (including hazardous substances and natural hazards), subdivision, noise, and the effects of activities on the surface of lakes and rivers. They are also responsible for community services, including local roads, sewerage and water supply.

Regional councils are responsible for controlling the taking, use, damming, and diversion of surface water, groundwater and geothermal water; maintaining and enhancing water quality and quantity; regulating the discharge of contaminants to land, air or water; controlling activities in the coastal area (together with the Minister of Conservation); controlling land use for soil conservation and other purposes, and regulating the introduction of plants into water bodies. Resource management decisions by a local authority can be appealed to the Environment Court.

There are 12 regional councils, 70 district or city councils (also referred to as territorial authorities) and 4 unitary authorities. The unitary authorities—Gisborne District, Nelson City, Tasman District and Marlborough District—have functions of both regional and territorial authorities.

Regional councils and unitary authorities (Fig. 11.1) have primary responsibility for water resource management. Water management in New Zealand has been addressed at regional level since 1968, when responsibility for wa-

Figure 11.1 *Regional and unitary councils of New Zealand.*

ter resources was given to Regional Water Boards under the WSCA. The duties and responsibilities of regional and unitary councils include preparing optional regional plans that contain policies, management methods and rules for water resources and their use, and in some cases controls to manage the effects of land use on water quality and quantity. Regional and unitary councils also make decisions on applications for resource consents that allow the taking, use, damming and diversion of water. This may involve public submissions, hearings and an appeal to the Environment Court. In recent years, these councils have also had an increasing role in the education of the public and resource users, and in monitoring and reporting on the state of the environment and on the effectiveness of their resource management plans.

The Minister for the Environment has an overview and monitoring role in the implementation of the RMA, with some direct areas of responsibility, for example: recommendations on issuing of national policy statements; national environmental standards; water conservation orders; and the 'call-in' of major resource consent applications. An important

Ministry role is to develop and disseminate to councils technical and planning information for good resource management, and to facilitate communication on good practice among councils.

Statutory regional water plans

Nearly all regional councils have opted to prepare regional plans that include the management of water quality and water allocation. Some councils have chosen a single plan to cover all land, air and water management within their region, and others a set of plans, one of which concerns, for example, water quality. Some plans address issues of water management within a single catchment.

A regional plan describes the significant management issues for a particular area or resource within the region. The plan will then set out objectives, policies and rules to address these issues, and also outline the environmental results that are anticipated from their implementation. Regional councils must ensure that their plans are not inconsistent with national or regional policy statements or other regional plans, and must also have regard to any planning documents prepared by *iwi* authorities.

By the end of 2000, four regions had operative plans relating to water for the whole region—Wellington, Hawke's Bay, Taranaki and Marlborough. Proposed plans for Northland, Waikato, Otago and Southland were going through formal consultation as outlined in Schedule 1 of the RMA. Environment Bay of Plenty and Environment Canterbury had released less formal discussion documents as part of preparing a plan. The only catchment-specific plans that cover groundwater management are in Tasman District, where water management is carried out for combined groundwater-surface water zones (e.g. Tasman District Council 1995). In 2001, Tasman District Council was in the process of combining these plans into the water chapter of its Tasman Resource Management Plan, which covers all district and regional planning issues throughout the region.

The detail, scope and contents of these plans vary considerably—some contain detailed provisions, for example, minimum water levels and allocation limits, whereas others set broad frameworks and become umbrella documents for plans addressing details for a specific aquifer or catchment. Water management plans under the RMA framework were a relatively new mechanism for groundwater management, with the first of the region-wide plans becoming operative in 1998. No doubt plan provisions will be further tested in the Environment Court.

Resource consents

Unless it is permitted under a rule in a regional plan, anyone taking groundwater—except for reasonable domestic, stock water or firefighting needs—needs to obtain a resource consent (water permit) to do so. Similarly, anyone wanting to discharge effluent to water, or to land in circumstances where the contaminant may enter water, must obtain a consent. Some councils still use non-statutory plans to guide consent decisions. Often these are plans that were prepared under the WSCA and have yet to be revised or replaced under the RMA.

Resource consents contain conditions outlining the circumstances when abstraction or discharge is to be restricted or cannot be exercised, other measures aimed at mitigating the effects of the activity, supply of information, financial contributions or bonds, self-monitoring, and performance standards. Ground-water consents can be issued for up to 35 years, but 5-15 years is the most common duration. Although the RMA makes no specific provisions for consents to be renewed once they expire, the practice in New Zealand has been to replace expired consents with a new consent with conditions similar to the original.

GROUNDWATER QUANTITY

Effects of changes in groundwater quantity

Changing the quantity of water in a groundwater system has many potential effects:

- decreased groundwater levels or pressures (including 'mining' of groundwater);
- increased water levels causing surface ponding and water-logging of land;

- reduced water levels in nearby wells due to localised drawdown effects of pumping;
- increased potential for seawater intrusion, or inflows from other low-quality water bodies;
- changes in flows in springs or spring-fed streams, or wetlands;
- changes in the flow rates between the aquifer and rivers, streams, or lakes;
- land subsidence; and
- reduced flow to the margins of the aquifer.

In the shallow alluvial aquifers common throughout New Zealand, pumping becomes excessive when wells on the margins of the aquifer lose yield to the extent that they run out of water. Even wells in the centre of such an aquifer can lose yield if there is a concentration of pumpage, the wells are shallow, or there are areas of low permeability and hence high drawdowns.

The effect of the use of groundwater on receiving waters, whether surface waters or aquifers, has often been overlooked (Beanland et al. 1994). The effects on receiving water are particularly pertinent to irrigation, because irrigation increases the drainage flow to groundwater and therefore the potential for leaching of nutrients and contaminants, as well as the volume of recharge.

Aquifer characterisation

Characterising the aquifer system and predicting how it will respond to stresses such as abstraction or reduced recharge is an important early step in managing groundwater quantity. The logical management unit for groundwater is each individual aquifer. However, when an aquifer is laterally extensive, it may need to be subdivided into discrete management zones, preferably defined along hydrogeological boundaries such as depositional edges, faults, or zones of broadly similar hydraulic characteristics.

Characterising an aquifer requires two types of information: the geological formations and properties of the aquifer, and the hydrodynamics of water moving through the aquifer. Information that helps to characterise aquifers includes:

- groundwater level or pressure records;
- aquifer boundaries, laterally and at depth (Chapter 3);
- hydraulic characteristics, primarily permeabilities and storage coefficient;
- estimation of rainfall recharge (Chapter 5);
- estimation of river recharge or loss to springs and rivers (Chapter 6);
- estimation of irrigation recharge;
- actual records of water use;
- allocated volumes;
- estimates of permitted takes; and
- isotope and hydrochemical analyses to determine the relative contribution of river recharge and rainfall recharge, and the geology of the groundwater source (Chapter 7).

Investigation and monitoring programmes by regional councils are complemented by bore log information and pump tests that are usually requested with new consent applications. Groundwater level or pressure is monitored in aquifers where there is significant abstraction, and assessed for any long-term trends. However, unlike surface water, this monitoring data does not directly indicate the amount of water in the resource. The water level in a well is an indirect indicator of the amount of water stored, but the quantitative relationship depends on the geological characteristics of the aquifer, the well depth, and the location of the well with respect to surface water boundaries.

Quantifying groundwater resources requires methods for relating data from monitoring bores to the availability of water and for predicting how an aquifer will respond to abstraction or reduced recharge. The most comprehensive method is the use of computer simulation models, which can be calibrated against monitoring data and used to predict environmental effects, such as the effects of abstraction on spring flows, seawater intrusion and stream flows (e.g. Fenemor 1988; Robb 1999). Simulation models require a high standard of field data and knowledge of the dynamics of the system to accurately predict the aquifer's response to different scenarios. Groundwater simulation models are available commercially, with most New Zealand applications using a model based on the United States Geological Survey's MODFLOW code. Considerable time

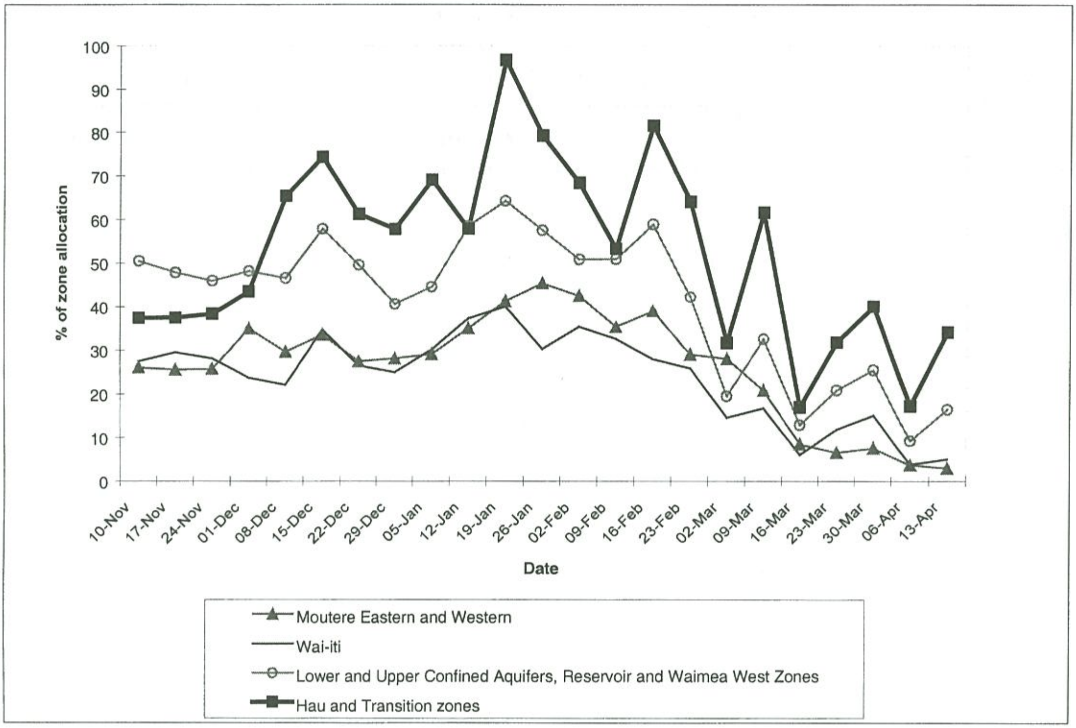


Figure 11.2 *Weekly metered abstraction for water management zones in Tasman District for the 1997/98 summer.*

and money are required to produce an adequately calibrated groundwater model, and it is estimated that only about 20% of allocated groundwater is from an aquifer for which there is a calibrated model (Robb 2000). Other alternatives to simulation models used by regional councils are annual water budgets based on predicted inflows and outflows to an aquifer, coupled with throughflow analysis based on aquifer parameters.

Calculating an annual water balance or developing a computer simulation model requires information on the volumes of water abstracted. This information is available only if water meters are fitted at the point where water is abstracted, and the information is collated by the regional council. Metering of irrigation pumpage in Tasman District, for example, has shown that cumulative weekly groundwater usage during a 10-year drought seldom exceeds 60% of total allocations (Fig. 11.2). The difference between allocation and use is most noticeable in irrigation and occurs because crops require water at different times of the summer, some irrigated land is fallow, and irrigation application rates vary among crops and soil types. In many regions of New Zealand water meter information is not available, and actual use is estimated from power usage, from surveys of abstractors, or is estimated from an assumed pumping time and the flow rate given on the resource consent.

Management objectives for groundwater quantity

Management of groundwater quantity (groundwater allocation) is the management of abstractions in a way that meets the aspirations of the community. This depends on the level of protection desired for the resource and its associated ecosystems, compared to the benefits that can be gained from use and development of the resource. Groundwater use is controlled in three main ways: preparation of regional plans, resource consent decisions, and education of users. The preparation of a management plan is the most comprehensive approach, as it allows community discussion and negotiation as to how an aquifer will be managed.

Good management requires the definition of the limits within which the aquifer is to be constrained. These limits should be stated as management objectives, for example:

- maintaining well yields at greater than 50% of their winter yield;
- preventing seawater intrusion more than 50 metres inland into the aquifer during any drought of less than 20-year return period;
- maintaining a minimum river flow in a river-aquifer system when flow losses induced by groundwater pumping would otherwise breach this flow limit; and
- limiting the total amount of water allocated so that abstractors can take up to 80% of their full allocation during a 1-in-10 year drought.

The management challenge is then to identify actions (rules) that will achieve the stated objectives. These actions could include limiting the volumes of groundwater pumped by users in sensitive zones, cutbacks in extraction at sensitive times, or remedial measures such as artificial recharge of the aquifer. The preparation of either formal RMA plans or informal strategies for an aquifer, river-aquifer system or part of an aquifer requires setting, prioritising and optimising management objectives. In our opinion, existing plans could be improved in the area of setting clear and quantifiable objectives for groundwater management. For example, very few councils limit total abstraction in order to provide a specified reliability of supply to users. Continued allocation of groundwater to increasing numbers of users will lead to restrictions becoming too frequent and compromising the viability of individual users' enterprises. If a management objective is to maintain a particular 'security of supply' to users, at some point limits must be placed on further groundwater allocation.

Another area of existing water plans that could be improved is monitoring the effectiveness of plans. The RMA requires that councils monitor the suitability and effectiveness of a plan for achieving its objectives and policies. Existing monitoring tends to concentrate on hydrological and water quality monitoring (i.e. state-of-resource monitoring) rather than monitoring the important values for which a resource is being managed. On its own, state-of-resource monitoring does not necessarily indicate that environmental outcomes were the result of management actions; the environmental state may change from other causes. Monitoring the effectiveness of plans is an aspect of water management that should be given increasing emphasis as councils move from plan preparation to implementation. Monitoring will feed into the plan review process, and allow for adapting management actions in response to monitoring results.

Existing water allocation systems are coming under increasing scrutiny as to whether they prevent or promote the most economic use of water (Memon 1997). In current practice, existing consent holders retain their water even if there are new users with more efficient technologies and the ability to obtain greater economic benefit from the water. Although the transfer of water permits could address this problem, few transfers have occurred, even though transfers have been permitted under the RMA since 1991. There is opportunity for less permanent transfers, but this requires administrative flexibility.

Tools for managing groundwater quantity

Regional councils commonly use a package of measures to achieve their management objectives for groundwater resources—allocation limits for the aquifer, rationing restrictions during critical periods and water usage limits that tailor the allocation to the proven need for that water. Limits on bore spacing for new bores, limits on individual and cumulative pumping rates from bores, and restrictions on pumping rates at critical times when pumpage is at a peak or aquifer recharge is low, can reduce drawdown on nearby wells. Measures to reduce the likelihood of seawater intrusion and effects on springs and other surface waters include limiting pumping near sensitive water bodies, such as during critical high tides, and avoiding further allocations from wells close to those bodies. Engineered responses such as recharging wastewater into wells, as is practised along the coast in Israel (Shelef 1977), are also feasible, although expensive. The most commonly used management tools are outlined below.

- Water allocation limits

As the total volume of water abstracted from an aquifer increases, water levels and pressures in the aquifer decline; this is in addition to the localised drawdown effect on nearby wells. At some point, lowering of water levels and pressures will have adverse environmental effects, such as reduced spring flows, or will prevent abstraction from some wells either due to water levels falling below the intake screen of a well, or because pumping depths exceed the level from which it is economic to pump. The greater the volume abstracted from an aquifer, the more frequently one or all of these events will occur. A balance must therefore be reached between the security of supply for individual users, and the number of users who have access to the resource.

The setting of a total allocation limit (a predetermined limit on the total amount of water that can be abstracted) is a method for minimising environmental effects caused by lowered water levels and protecting the reliability of the supply. In addition, setting a limit communicates the fact that the resource is finite, which encourages a community to accept the need for increased efficiency and better management of the available water. An allocation limit can be implemented by simply allocating groundwater through water permits until a pre-set limit is reached. An alternative, frequently used for surface water, is a system in which permits continue to be allocated, but those granted most recently (junior permits) are the first to be restricted during times of aquifer stress. This is the North American 'prior appropriations' system. Although the majority of regional councils set allocation limits for surface water, only four had formally set limits for groundwater by the end of 1999.

- Restrictions on pumping during water-short periods

A trigger or threshold level related to the degree of stress on an aquifer is needed when restrictions are to be placed on those pumping groundwater. The trigger will be related to the particular management objective being monitored. For example, a suitable trigger for excessive yield reduction could be a water level in a monitoring well in a sensitive part of the aquifer, which signals the need for the resource manager to cut back pumpage when the water table falls below a threshold value. The trigger for seawater intrusion could be a coastal well monitored for salinity, and for low river flows could be a flow gauging station sited in a critical river reach.

Security of supply may be addressed by setting an allocation limit for a defined frequency of drought. Figure 11.3 shows how a council might set levels of security of supply for various drought return periods (smooth line)—these might be implemented as water rationing steps

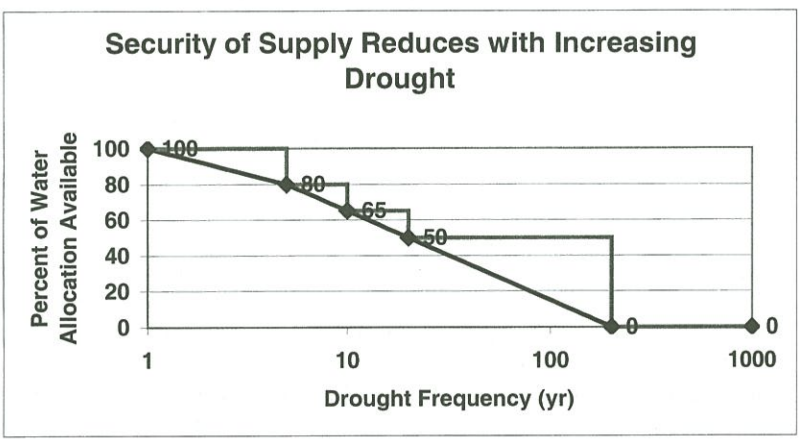


Figure 11.3 *Relationship between water availability and drought severity.*

as groundwater management triggers are reached during those droughts. In this example, extraction has ceased when a 200-year drought frequency was reached, which might occur for an aquifer system when the flow in a connected river had reached a set minimum, or where aquifer mining was occurring. However, for most aquifers, the objective should be to maintain some minimum security of supply no matter what the drought frequency, to give certainty for the water users' businesses. Assessing the financial consequences of reduced water availability becomes critical in determining an acceptable security of supply.

- Limits on rate of use

A further tool for groundwater quantity management is the specification of reasonable usage rates. Applications to take water will be assessed against these rates to determine if the quantity of water applied for is reasonable for its intended use. These limits are most commonly used for irrigation to assess a reasonable peak use rate (often expressed in mm/week or m^3/year) based on crop type, local climate conditions and soil type. However, it is also possible to set limits on rate of use for households (200 litres per person per day is commonly used for allocation in New Zealand - Robb 2000), and for industry, based on best practice. While many councils quantify groundwater resources using annual water budgets, only Auckland Regional Council includes in each consent an annual limit on the amount of water taken.

A frequently overlooked problem in water allocation is the potential for certain uses of water, particularly irrigation, to affect receiving water bodies. In most cases the receiving water is groundwater. The volume of drainage water can be significantly reduced by improvements in irrigation practice and by efficient irrigation (Lincoln Environmental 1996). Limiting the amount of water available on a seasonal basis is a key requirement of efficient irrigation, as the majority of potential water savings occur through irrigating less frequently rather than by reducing the take during peak demand (McIndoe 2000). Seasonal limits are most applicable for aquifers in which most of the pumpage is drawn from storage rather than from connected water bodies.

- Land-use controls

While groundwater extraction is the main reason for groundwater allocation, other human factors can affect groundwater availability. The rates of aquifer recharge and discharge can be changed, for example, by raising or lowering the levels of rivers intersecting the aquifer, by changing contributing river flows, or by changing the infiltration characteristics of rainfall recharge areas.

The effects of afforestation of pasture land on groundwater recharge have been addressed in the Tasman district for the deep Moutere aquifers by limiting both further afforestation in the recharge zone and further water allocation from those aquifers. The Environment Court agreed with irrigators, in a case against the Tasman District Council, that protection of existing groundwater allocations required that new afforestation must not exceed 20% of the area of any land title in this recharge area (Wratten vs Tasman District Council RMA 367/94). The Council's Moutere Water Management Plan now requires that a land-use consent be obtained for afforestation exceeding this 20% threshold.

GROUNDWATER QUALITY

Potential effects of altered groundwater quality

The potential effects of changes in groundwater quality depend very much on the toxicity and physical characteristics of the contaminant. Groundwater contaminants such as nitrates and faecal bacteria both originate from activities and discharges on the overlying land. Other contaminants include pesticides, microbes, heavy metals, organic chemicals and salt water. They can limit the use of groundwater for drinking, stock or irrigation water, and contaminate connected surface water systems and ecosystems.

In some aquifers, poor water quality is not caused by human activity but by hydrogeological factors, such as the minerals in the formation through which the water flows (see Chapter 4). Such waters may also breach standards for use and require treatment. Groundwater contaminated by iron and manganese, for example, can be treated simply by aeration to precipitate out the oxides of these metals.

Nitrate contamination of groundwater by agriculture (see Chapter 8) is arguably the most widespread and difficult problem to manage. Nitrate contamination derives from the use of nitrogenous fertilisers and from animal effluent. The agricultural stock of New Zealand generate a volume of faecal material equivalent to 150 million people (Ministry for the Environment 1997a).

Faecal material from animals and humans, from septic tanks and land application of community effluent, are sources of microbial and bacteriological contamination. Indicators of microbial contamination in current use, such as faecal coliforms, may be inadequate predictors of risks to human health in both surface water and groundwater, and the real risks may be more of a problem than is generally believed (Ministry for the Environment 1998). Chapter 9 outlines the risks and potential sources of microbial contamination in New Zealand's aquifers.

Disposal and careless handling of hazardous substances and hazardous wastes in the past has left New Zealand with a number of contaminated sites. Over 7,000 sites associated with landfills, service stations, sawmills, timber treatment plants, railway yards, engine works, metal industries and chemical manufacturing may be contaminated. Of these, approximately 1,500 are estimated to be a high risk to the environment and to health (Ministry for the Environment 1997a). Some of New Zealand's contaminated sites are polluted by persistent organochlorines. However, there are also sites used by businesses such as the oil industry and gasworks that are contaminated by hydrocarbons and other substances. Only one-third of existing landfills have systems in place for dealing with leachate (Ministry for the Environment 2000). The extent to which groundwater is adversely affected is unknown.

Characterising groundwater quality

All data and information used to characterise water quantity is also important in managing water quality. A good understanding of aquifer dynamics is vital, particularly the processes by which the aquifer is recharged, because it is usually the recharge water that is carrying the contaminants into the aquifer. This requires understanding of the links between the pollutant source and the aquifer as a sink. In addition to understanding water flows, data on the dilution and dispersion properties of an aquifer are needed to assess its capacity to assimilate contaminants. How a contaminant will behave once it reaches the water requires information on its adsorption, dispersion, dilution and decay properties.

Regional councils collect quite extensive data on groundwater quality. The types of chemical and microbiological data collected are usually determined by general requirements such as drinking water standards, or perceived risks in specific areas due to pesticides, hydrocarbons, heavy metals or sea-water intrusion.

The National Groundwater Monitoring Programme (NGMP) (Rosen 1999) is based on a subset of sites monitored by regional councils. Samples are collected to a consistent standard (Rosen et al. 1999) from over 100 sites throughout New Zealand on a quarterly basis, and typically analysed for major cations, anions, trace elements and nutrients, such as sodium, potassium, calcium, sulphate, alkalinity, nitrate, phosphate, fluoride, iron, and bromide. Occasionally, other constituents such as pesticides and heavy metals are also tested. The NGMP allows national comparison of aquifer chemistries because the samples are all analysed at one laboratory in a consistent manner and all samples undergo stringent quality control checks (see Chapter 4).

The Ministry of Health also collects data for those communities whose potable water is supplied wholly or in part by groundwater. Samples are measured for compliance with the Drinking Water Standards for New Zealand 2000, established by the Ministry of Health (Ministry of Health 2000). These standards include a system of classifying water sources. Aquifers that have been demonstrated to be secure from the 'direct influence of surface water' are classified as 'secure groundwater' and monitored monthly. Chapter 10 outlines the links between groundwater and health.

Data are important to track quality, but data alone do not allow predictions of how activities will affect groundwater quality. Simulations of groundwater flows combined with contaminant transport models are required. Further models are needed to simulate the movement of water and contaminants through soils and the unsaturated zone overlying the water table. In areas such as sites for the land application of effluent, it is also important to model the crop uptake of nutrients in order to predict nutrient flows to groundwater (Morton et al. 2000).

If the movement of contaminants from the land surface to groundwater is slow, the effect of a given activity on groundwater quality may not be evident for many years. Even if an activity is stopped immediately, adverse effects may continue for many years. The time delay between the activity and its effect is more often a problem with groundwater quality than quantity. There should be a more precautionary approach to managing activities that affect groundwater. Monitoring the amount of contaminant applied or the quality of leachate immediately below the land may be more appropriate than relying solely on groundwater quality monitoring.

Management objectives for groundwater quality

The management of groundwater quality involves meeting community aspirations for ecosystem health and water quality by controlling activities that cause either point or non-point contamination. Managing groundwater quality is often very closely associated with managing surface water quality. For example, regulating land uses above a groundwater system that flows into a lake may prevent high nitrate levels in the lake (see later section on non-point source discharges).

Knowing that the water quality of an aquifer is deteriorating is not enough. For many groundwater quality problems, the resource manager needs to set a threshold groundwater quality, beyond which the effects are considered unacceptable. This threshold depends on the present and future uses to which the groundwater may be put. Quality standards for potable water differ, for example, from the water quality thresholds for industrial or irrigation use. The Ministry for the Environment has encouraged or developed guidelines—as opposed to mandatory standards—for environmental quality. Examples include the ANZECC water quality guidelines (Australia and New Zealand Environmental and Conservation Council 2000), and guidelines for the application of sewage effluent to land (New Zealand Land Treatment Collective 2000). Guideline development is an important service that the Ministry can provide for regional and district councils, who must implement the Resource Management Act.

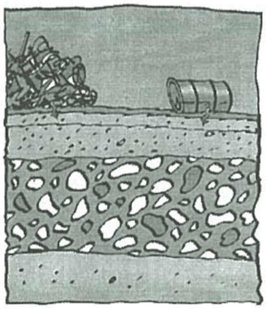
Groundwater quality objectives could include, for example:

- maintaining groundwater quality in the resource so that it is suitable for human consumption and irrigation without treatment;
- improving water quality in a spring-fed stream so that by 2010 it is suitable for primary contact recreation; and
- preventing any degradation in groundwater quality in productive aquifers.

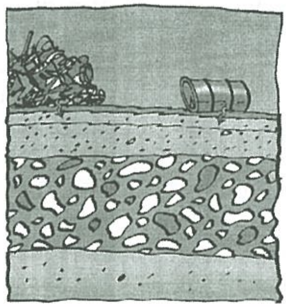
Setting management objectives is not just a technical issue—community preferences must be gauged. In 2000 Environment Canterbury asked all Christchurch City residents, via a pamphlet drop in mailboxes, which water quality option they preferred for the aquifers beneath the city—strong controls on land use to protect groundwater quality, or to accept some decline in groundwater quality with fewer controls (Fig. 11.4). Over 90% of the 5,500 replies received were in support of the first option.

Tools for groundwater quality management

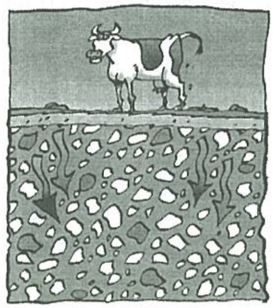
The same tools—plans, resource consent decisions and education of users—apply in management of both water quality and quantity. Management of point source pollution is similar to management of groundwater quantity, because it involves the direct control of activities that usually require resource consents. In comparison, non-point discharges are difficult to characterise and not easy to control with discharge permits. Non-point source contamination arises from practices associated with land use, many of which do not require consents. It is also often difficult to attribute



The Christchurch confined aquifers are protected from contamination by a thick layer of fine sediment, which acts like a seal. This limits household and agricultural fertilisers, pesticides, industrial wastes and other contaminants from seeping down into the groundwater supply



There are places where the system is not so well sealed. Where this occurs, pressure can decline as a result of over-pumping, allowing contaminants into the aquifers



There are some areas, particularly in western parts of the city and inland, where there is no protective overlying sealing layer. In these areas it is easier for contaminants to travel down into the groundwater and into aquifers underlying the city.

As Christchurch city grows and land use intensifies in the surrounding rural areas, the risk of contamination increases. This is a threat to our present high quality untreated drinking water.

Please indicate your preferred option by ticking one of the boxes below.

❑ OPTION 1:

Protect our high quality drinking water standards. Accept strong controls on urban growth/land use.

This would mean:

+ The city's image of having exceptionally high quality untreated drinking water is protected.
+ The least risk option is chosen; prevention is often less costly than clean-up.
– City growth and agricultural activities will be constrained by strong land use controls on the western fringe where there is little or no protective layer over the aquifers.
– Industries would require strong contaminant prevention measures, and high-risk type industries may be prohibited in some areas.
– Wells supplying the urban area may have to be sunk to deeper aquifers to prevent pressure loss and consequent contaminant leakage downward into the uppermost aquifer. Wells in the uppermost aquifer would be prohibited from locating in some areas, eg near old rubbish dumps or close to seawater areas. This will increase the costs of supplying water to households, industry and irrigators.

❑ OPTION 2:

Allow some low level of contamination provided our groundwater is still suitable for drinking without treatment. Less stringent controls on urban growth/ land use.

This would mean:

± The city's image of having untreated water is retained. However we can no longer say that we have exceptionally high quality water.

± City growth and agricultural activities are constrained, but less than for Option 1.

- An increased risk of contamination and cost of clean-up.
- Alternative solutions for urban growth pressures would still need to be found.
- Some industries and agricultural activities may still require strong controls, particularly on the western fringe of the city where there is little or no protective layer over the aquifers.
- Industry requiring exceptionally high quality water will incur the cost of treatment, or relocate to deeper, higher quality aquifers, or they may go elsewhere.
- A one-way road – costly and difficult to return to Option 1 water quality.

Figure 11.4 *Survey of preferences on groundwater quality and land-use controls (courtesy of Environment Canterbury).*

non-point source pollution to a specific land use or property.

One obvious way to control non-point source contamination is to control land use. The RMA gives regional councils the ability to control land uses to maintain and enhance the quality of water in water bodies. Land use is also a responsibility of territorial authorities. This jurisdictional overlap can create problems in managing non-point pollution sources, but also opportunities for synthesis between regional and district plans.

Many councils use a combination of groundwater quality classification standards and controls on activity to protect water quality, because of the difficulties of relating cause and effect for groundwater quality management. Recharge zones for aquifers are vulnerable to polluting activities and can be designated as special groundwater protection zones where high standards of waste treatment are required or highly polluting activities may be limited. For example, the Canterbury Regional Policy Statement contains a policy that "hazardous substances shall not be located above unconfined aquifers or in aquifer recharge zones unless adequate precautionary measures are put in place". Tasman District Council has zoned Special Domestic Wastewater Disposal Areas in its Tasman Resource Management Plan, covering vulnerable areas where higher standards than a conventional septic tank system are required for disposal of domestic effluent. Similarly, wells supplying potable water may have designated wellhead protection zones around them, within which discharges or certain land uses are limited. For example, the Regional Freshwater Plan for Taranaki designates the discharge of farm dairy effluent onto or into land as a controlled activity subject to a set of conditions, one of which is that "the discharge shall not occur within 50 m of a bore, well or spring used for water supply purposes".

When groundwaters have already become contaminated, the difficulties and time required to improve them often mean that the cheapest option is to find an alternative water source of better quality, or to treat the water. Some innovative and inexpensive treatment methods are being developed, among them the treatment wall for filtering organic contaminants such as septic tank effluent using a carbon source such as sawdust (Schipper and Vojvodic-Vukovic 1998). However, the occurrence and overall costs of groundwater contamination are escalating, as population pressure increases worldwide (World Water Council 2000). The precautionary principle demands that we act carefully to prevent deterioration of groundwater quality.

Management of point source discharges

Where discharges to groundwaters can be controlled via the conditions on a discharge permit, those conditions need to be based on the expected 'worst case' groundwater quality resulting from the discharge. The assessment needs to account for dilution and dispersion of the contaminant within the aquifer under the full range of applied loads and groundwater levels. It must also incorporate the cumulative effects of existing discharges to ensure that the combined effects do not breach standards for downstream use, particularly by existing water users. A useful basis for the assessment is to start at the receiving body of water, then knowing the processes that will disperse and dilute the contaminant, work backwards to set limits on the rates and method of discharge from the contaminant source. The RMA allows consent authorities to specify a mixing zone that is effectively a zone of non-compliance, beyond which standards set in the consent or in a regional plan must be met.

Sometimes environmental standards dictate a higher standard of contaminant treatment, especially if the discharge is over or into a sensitive aquifer. For example, package sewage treatment plants with evapotranspiration disposal beds are more benign than a septic tank with a soakage field. The siting and design of modern landfills requires much higher technical standards, especially for leachate control and monitoring, than in the past. Aquifer vulnerability assessments such as DRASTIC (Allure et al. 1987) are useful regional tools that councils can use to identify the sensitivity of aquifers to such discharges.

When contamination has already happened, cleaning up the environment invariably has a greater cost than prevention would have cost. Procedures are available for identifying, assessing and managing contaminated sites (for example, the National Rapid Hazard Assessment System for Potentially Contaminated Sites, Ministry for the Environment 1992). When it is established that groundwater is being contaminated, the key issues are where the contamination is going, what risks it poses to downstream users, and how the risks should be managed. Methods for addressing these issues are not yet well developed. Indicators of remediation performance would normally be specific to a given site and developed as part of risk management planning.

The Ministry for the Environment has published guidelines for site assessment and management in the timber treatment, gasworks and petroleum industries (Ministry for the Environment 1997b, 1997c, 1999). Developing national environmental standards for dioxins and PCBs that will apply to industrial sites, and emissions and wastes involving organochlorines, is now the main focus of the Organochlorines Programme led by Ministry for the Environment. The Ministry also provides advice on liability, clean-up methods and management of these sites. Sometimes remediation costs fall on parties other than the polluter. The Ministry operates the Orphan Sites Remediation Fund, which provides a Government financial contribution towards the costs of cleaning up contaminated sites where either no one can be fixed with legal liability for the site or the liable party cannot pay. This fund is similar to the Superfund operated by the US Environmental Protection Agency.

Management of non-point source discharges

Many potential sources of groundwater contamination can be addressed by adjustments in day-to-day practices by land users: for example, using nutrient budgeting to determine fertiliser needs, nutrient and soil moisture budgeting to programme the spraying of dairy farm effluent, and soil moisture monitoring to schedule irrigation to avoid leaching of nutrients to groundwater. It is not practical for regional councils to enforce day-to-day actions by land users, so codes of practice or best management approaches, together with user education, are preferred. Examples include the Code of Practice for Management of Agrichemicals (NZS 8049 1995), which now has a formal accreditation programme (GROWSAFE®), and the Code of Practice for Fertiliser Use (New Zealand Fertiliser Manufacturers Research Association 1998). The success of such approaches is difficult to quantify.

Halting the decline in groundwater quality may also require the setting of some bottom-line regulatory controls, particularly if the problem requires urgent action. An example is Environment Waikato's initiative to stop further decline in the water quality of Lake Taupo, an internationally recognised trout fishery (Environment Waikato 2000). Groundwater draining into the lake, either directly or via streams, accounts only for about 5% of the hydrologic budget of the lake (Schouten 1980). The amount of nitrogen in the groundwater, however, is often orders of magnitude higher than in surface water inputs (Rosen et al. 1998), accounting for up to 30% of the mass of nitrogen entering the lake (M R Rosen, unpublished data). The nitrogen stimulates the growth of aquatic plants in the lake, reducing its clarity (White 1983). In addition, it is estimated that the lag in impact at the lake from groundwater transport may be some 2-40 years. Because groundwater is often substantially elevated in nitrogen from stock farming or other land uses e.g. sewage discharge, Environment Waikato considers some controls on nitrogen inputs necessary.

Environment Waikato considered a range of options, from 'do nothing' (Option 4, Figure 11.5) to the other extreme (Option 1), in which stock numbers are reduced and pasture is replaced with trees, and nutrient-stripping treatment processes are implemented for sewage, stormwater and industrial discharges. Management to maintain current lake water clarity and quality is the preferred option. Options requiring intervention would be implemented through controls on land use and resource consent requirements. Even those would take decades to have an effect on lake water clarity. If no action is taken now, Environment Waikato

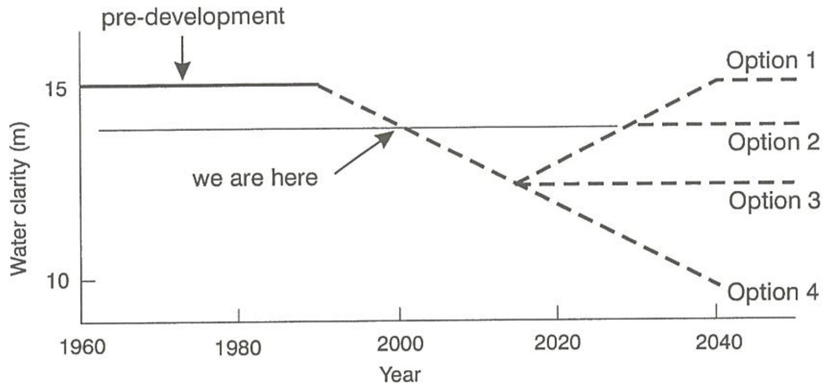


Figure 11.5 *Projected water clarity in Lake Taupo for four land management options (Environment Waikato 2000).*

predicts that nitrogen discharge to the lake could increase by 50%, which would result in a 35% decline in water clarity.

CHALLENGES FOR FUTURE GROUNDWATER MANAGEMENT

Groundwater is by definition unseen until it is removed from the ground or comes to the surface naturally. Groundwater flow and contamination processes are complex and difficult to understand. It is not surprising that groundwater tends to be forgotten until an environmental disaster brings it to our attention, as, for example, contaminated groundwater in drinking water causing health problems, as portrayed in the film 'Erin Brockovitch'. The challenge for water managers is to address these potential problems through water management plans, land management, and the raising of community awareness about groundwater resources.

As our rivers become fully allocated, groundwater is being increasingly exploited for irrigation and urban water supplies. In general, the quality of groundwater is higher and more consistent than that of surface water, and there is increasing economic and population pressure on groundwater resources. Although groundwater represents 29.5% of water currently allocated in New Zealand, half of the water allocated since 1990 has been allocated from groundwater (Robb 2000). Of all groundwater allocated under resource consents as of June 1999, 77% was for irrigation, and projections indicate that only half of New Zealand's irrigable land is currently irrigated. To ensure sustainable allocation of groundwater resources in the face of increasing demand, New Zealand will need to invest in groundwater resource investigations, assessments of sustainable yields and resource planning.

While issues and priorities can vary from region to region, many tools are in common use by water managers. There is therefore considerable potential to be gained from national research, development of new and improved water allocation tools, and the provision of a national overview of resource sustainability.

To ensure that nationally-funded research meets the needs of water management, the Regional Groundwater Forum (a group of regional council staff involved in groundwater management) has provided the Foundation for Research, Science and Technology with a list of "Priority Research and Information Needs", including:

- bore construction and maintenance;
- abstraction and allocation of groundwater;
- groundwater modelling;
- groundwater sampling;
- effluent disposal into or onto land;
- natural attenuation of contaminants;
- nitrogen management;
- groundwater quality indicators; and
- effects of afforestation on groundwater recharge.

Two themes emerging internationally in water resource management are the need to manage natural systems holistically, and to harness the more powerful systems models now being developed. The holistic approach involves integrated catchment management (e.g. Calder 1999). It is not just a case of different natural resources such as land and rivers being managed together, but building understanding between scientists and managers trained in different disciplines, and involving the community in research and resource management. Decision-support systems and models that integrate biological, physical, social and economic factors to answer the vexed question of what is sustainable use of each resource (e.g. Chapter 3) can assist these objectives.

Groundwater management is a complex issue that requires decisions in the face of uncertain scientific information and conflicting interests. A major obstacle is the lack of adequate time and resources to carry out both technical investigations and analysis, and the public consultation and education required to present management choices in a manner that clearly states the social and political tradeoffs that must be made. However, the implications of delaying or avoiding such decisions should not be overlooked. Individuals, and council and national politicians must be convinced of the need to invest in investigations and control activities before signs of aquifer stress appear. It is much more difficult to rescind users' groundwater allocations than to set sustainable limits before the aquifers are over-exploited. It is also hard to halt declining groundwater quality, because of poor knowledge linking the sources and the consequences. The costs of remediating contaminated groundwater greatly exceed those of preventing or managing the sources of the problem. The lesson must surely be to educate our communities to be aware of the importance of groundwater and of the risks if we do not manage the resource sustainably.

ACKNOWLEDGEMENTS

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REFERENCES

ALLURE, L.; BENNETT, T.; LEER, J.H.; PETTY, R.; HACKETT, G. 1987: DRASTIC: A standardized system for evaluating groundwater pollution potential using hydrogeologic settings: Robert S. Kerr Environmental Research Laboratory, U.S.Environmental Protection Agency Report EPA/600/2-87/ 035. 622 p.

AUSTRALIA AND NEW ZEALAND ENVIRONMENT AND CONSERVATION COUNCIL 2000: Australia and New Zealand Guidelines for Fresh and Marine Water Quality (5 volumes). Environment Australia.

BEANLAND, R; DRAVID, C; WATT, J. 1994: Irrigation Water Allocation - An Issue for Planners. Planning Quarterly, Journal of the New Zealand Planning Institute 114: 6-8.

CALDER, I.R. 1999: The Blue Revolution, Earthscan Publications, UK. 192 p.

CAMERON, K.C.; DI, H.J.; MCLAREN, R.G. 1997: Is soil an appropriate dumping ground for our wastes? Australian Journal of Soil Research 35: 995-1035.

ENVIRONMENT CANTERBURY 2001: How Precious is Our Water? Living Here January 2001, Special Christchurch-West Melton Edition.

ENVIRONMENT WAIKATO 2000: Issues and Options for Managing Water Quality in Lake Taupo. Discussion paper for landowners. Waikato Regional Council. 23 p.

FENEMOR, A.D. 1988: A Three-Dimensional Model for Management of the Waimea Plains Aquifers, Nelson. DSIR Hydrology Centre Publication 18, Christchurch. 133 p.

FENEMOR, A.D. 1991: A Case for Tradeable Water Permits to Take Water. Proc. Regional Resource Futures conference, Hamilton, August 1991: 229-238.

LINCOLN ENVIRONMENTAL 1996: Sustainable Irrigated Agriculture Project. Sustainable Management Fund Report. Barrhill/Lower Rakaia Irrigation Associations and the Ministry for the Environment. 68 p.

MANAWATU-WANGANUI REGIONAL COUNCIL 1995: Oroua Catchment Water Allocation and River Flows Regional Plan. 83 p.

MCINDOE, M. 2000: Testing of Irrigation Best Management Guidelines 1998-1999, Ministry of Agriculture and Forestry, Wellington. 36 p.

MEMON, A. 1997: Freshwater management policies in New Zealand. Aquatic Conserv: Marine and Freshwater Ecosystems 7: 305-322.

MINISTRY FOR THE ENVIRONMENT 1992: National Rapid Hazard Assessment System for Potentially Contaminated Sites, Ministry for the Environment Wellington. 71 p.

MINISTRY FOR THE ENVIRONMENT 1997a: The State of New Zealand's Environment 1997. Wellington. 650 p.

MINISTRY FOR THE ENVIRONMENT 1997b: Guidelines for Assessing and Managing Contaminated Gasworks Sites in New Zealand. Wellington. 244 p.

MINISTRY FOR THE ENVIRONMENT 1997c: Health and Environmental Guidelines for Selected Timber Treatment Chemicals. Wellington. 240 p.

MINISTRY FOR THE ENVIRONMENT 1998: Freshwater Microbiological Research Programme. Overview of the Programme. Fact Sheet, September 1998.

MINISTRY FOR THE ENVIRONMENT 1999: Guidelines for Assessing and Managing Petroleum Hydrocarbon Contaminated Sites in New Zealand. Wellington. 245 p.

MINISTRY FOR THE ENVIRONMENT 2000: The 1998/99 Landfill Census Report. Wellington. 88 p

MINISTRY OF HEALTH 2000: Drinking-water standards for New Zealand, 2000. National Drinking-Water Standards Review Expert Working Group, Ministry of Health, 130 p.

MORTON, J; O'CONNOR, M; CARNUS, J-M; WANG, H. 2000: Crop Selection and Management. Chapter Six in New Zealand Guidelines for Utilisation of Sewage Effluent on Land Part 2: Issues for Design and Management. Joint Publication of the New Zealand Land Treatment Collective and Forest Research, Rotorua: 105-119.

NEW ZEALAND FERTILISER MANUFACTURERS RESEARCH ASSOCIATION 1998: Code of Practice for Fertiliser Use, NZFMRA.

NEW ZEALAND LAND TREATMENT COLLECTIVE 2000: New Zealand Guidelines for the Utilisation of Sewage Effluent onto Land. Part 1: The Design Process. Part 2: Issues for Design and Management. L.J. Whitehouse, H. Wang and M. Tomer (eds.), Joint publication of the New Zealand Land Treatment Collective and Forest Research Institute. Rotorua New Zealand. Part 1: 36 p, Part 2: 180 p.

NZS 8409 1995: GROWSAFE - Agrichemical Users' Code of Practice. New Zealand Agrichemical Education Trust. Standards New Zealand.

ROBB, C.A. 1999: Groundwater Model of the Motueka/Riwaka Plains Aquifer System. Lincoln Environmental Report 2325. Tasman District Council. 70 p.

ROBB, C.A. 2000: Information on Water Allocation in New Zealand. Lincoln Environmental Report 4375. Ministry for the Environment. 180 p.

ROSEN, M.R. 1999: The importance of long-term, seasonal monitoring of groundwater wells in the New Zealand National Groundwater Monitoring Programme (NGMP). Journal of Hydrology (NZ) 38: 145-169.

ROSEN, M.R.; CAMERON, S.G.; TAYLOR, C.B.; REEVES, R. 1999: New Zealand guidelines for the collection of groundwater samples for chemical and isotopic analyses. Institute of Geological & Nuclear Sciences Science Report 99/9. 81 p.

ROSEN, M.R.; REEVES, R.R.; ESER, P.; CHAGUÉ-GOFF, C.; COSHELL, L. 1998: Comparison of groundwater quality from forested (Waimarino River), urban (Turangi), and natural wetland (South Taup Wetlands) subcatchments at the southern end of Lake Taupo. Institute of Geological & Nuclear Sciences Science Report 98/1, 59 p.

SCHIPPER, L.A.; VOJVODIC-VUKOVIC, M. 1998: Nitrate removal from groundwater using a denitrification wall amended with sawdust: field trial. Journal of Environ. Qual. 27: 664-668.

SCHOUTEN, C.J. 1980: Budget of water and its constituents for Lake Taupo. Hamilton Science Centre Internal Report No 80/53, 41 p.

SHELEF, G. 1977: Water Reuse in Israel. In Water Renovation and Re-Use. Shuval, H. (ed.), Water Pollution Series, Academic Press, New York. 463 p.

TASMAN DISTRICT COUNCIL 1995: Motueka/Riwaka Plains Water Management Plan. Made operative on 16 January 1995. 39 p.

WHITE, E. 1983: Chapter 6: Chemicals and their importance to the lake. In Lake Taupo: Ecology of a New Zealand Lake, Ruscoe, Q.W. (ed.): 63-72.

WORLD WATER COUNCIL 2000: World Water Vision - Making Water Everybody's Business. W.J. Cosgrove and F.R. Rijsberman (eds.). Earthscan Publications, London.

12

Northland

STEWART CAMERON, SUSIE OSBALDISTON, GEORGE SKUSE AND CALUM REVFEM

INTRODUCTION

Groundwater is an important source of water in the Northland region for horticulture and orchard irrigation, for industry and for public, household, and farm water supply. An increased demand on groundwater resources has resulted from changes from traditional farming to orcharding and market gardening during the last two decades, coupled with a steady increase in tourism. Prior to 1980 groundwater water abstraction in Northland was relatively minor, as water was predominantly obtained from surface supplies.

Geothermal water occurs at Ngawha and is used for electrical power production. Groundwater above the geothermal field is monitored to identify contamination, changes in temperature, and/or change in groundwater levels as a result of the geothermal water abstraction.

LOCATION AND DESCRIPTION OF PRIMARY AQUIFERS

The geological composition of Northland's aquifers can be broadly grouped into four categories: Jurassic greywacke, Cretaceous sandstone, Cenozoic basalt, and Quaternary sand, shell, and/or gravel. The volcanics are intruded into or overlie the sandstone deposits. The groundwater-bearing Quaternary sand and gravel deposits are generally located in the coastal areas of Northland.

Seventeen principal basalt, sand, and geothermal aquifers in Northland are shown in Figure 12.1. The three most utilised groundwater areas are the Aupouri Aquifer (Northland Regional Council 1991; Hydrogeo Solutions 2000), the Kaikohe Basalt Aquifer (Northland Regional Council 1992) and the Whangarei basalt aquifers. The basalt aquifers in the Whangarei area (Matarau, Glenbervie, Maunu, Maungatapere, Whatitiri, Maungakaramea, and Three Mile Bush) (Northland Regional Council 1983; Northland Regional Council 1989) are hydrologically separate groundwater systems but are referred to collectively as the Whangarei basalt aquifers. In addition, there are over 28 small, shallow, sand and gravel coastal aquifers (e.g. Russell, Matapouri and Taipa), and less-productive greywacke aquifers situated throughout the region that are not shown on Figure 12.1

Twelve aquifers in Northland have been recognised as important due to current groundwater demand from the aquifers, and their sensitivity to potential contamination. The geological composition of these aquifers is summarised in Table 12.1.

In general the basalt aquifers are semi-confined, and the small coastal sand aquifers are unconfined (Table 12.1). Aquifer pumping tests undertaken in ten of the main aquifer systems provide information on their transmissivity and storativity.

Aquifer recharge and discharge

Rainfall is the main source of recharge for the aquifers in the region. Lake water loss is a minor source of groundwater recharge in some areas of Northland (e.g. Pakaraka, Aupouri). No investigations have been undertaken on river flow loss to groundwater. Groundwater recharge tends to occur in winter months due to higher seasonal rainfall and decreased evapotranspiration. Generally dry summer conditions have a minimal effect on groundwater levels, but lower-than-normal winter rainfall results in reduced groundwater recharge and low groundwater levels at the start of the following summer.

Cameron S.; Osbaldiston S.; Skuse G. and Revfem C. 2001: Northland. *In* Groundwaters of New Zealand, M.R. Rosen and P.A. White *(eds)*. New Zealand Hydrological Society Inc., Wellington. p291-302.

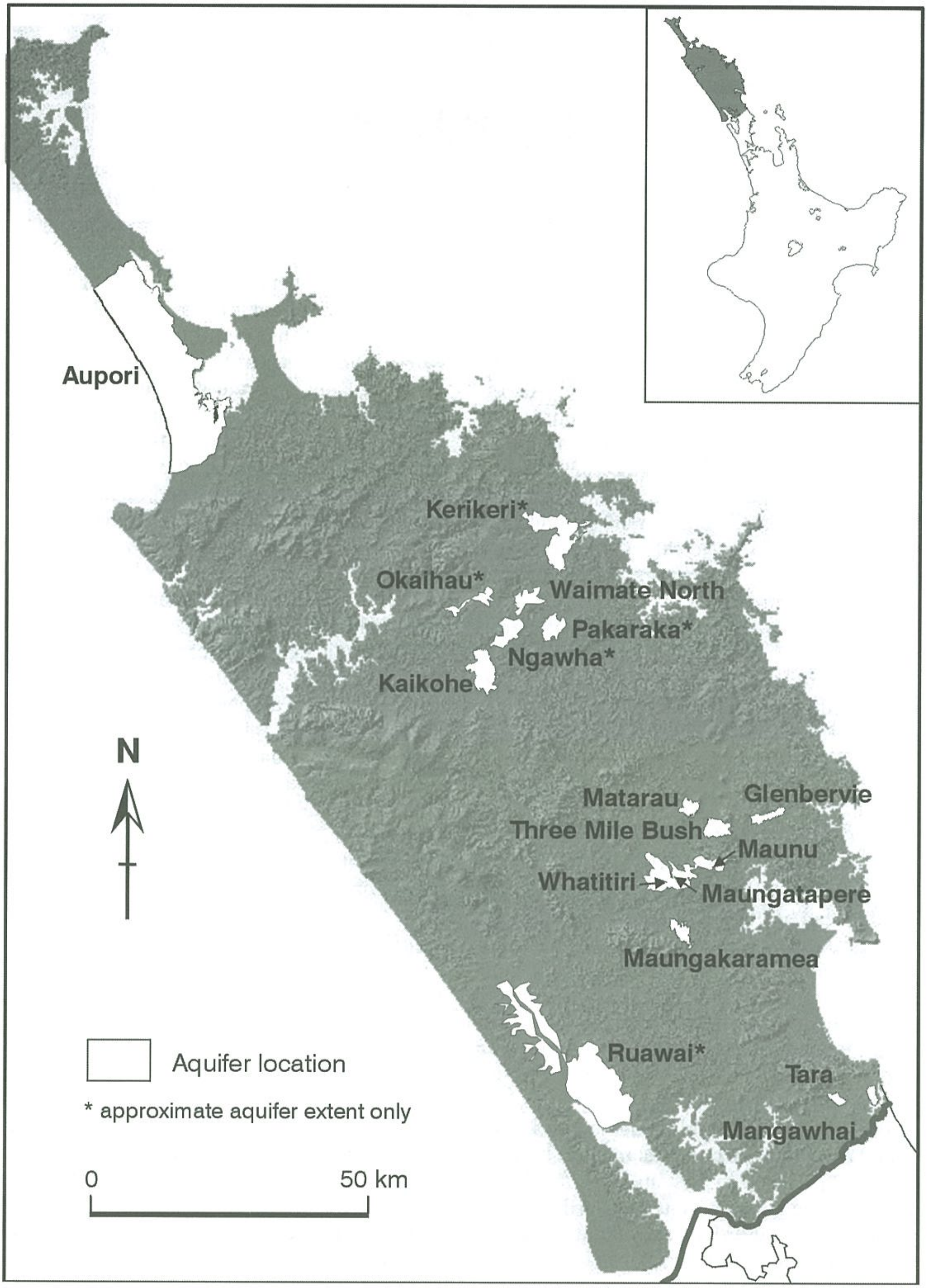


Figure 12.1 *Principle groundwater aquifers in Northland.*

Table 12.1 *Stratigraphy and hydraulic properties of aquifer units.*

Aquifer	Aquifer unit or zone	Broad lithologic description	Status e.g. confined/ semi-confined or unconfined	Saturated thickness in metres	Transmissivity in m^2/day	Storativity
Aupouri	Lower Aupouri Peninsula	Predominantly quartz and feldspar sands overlying limestone/ sandstone/mudstone	Semi-unconfined to confined	12-90	12-850	0.07-0.00002
Kaikohe		Basalt overlying Cretaceous siltstone	Semi-confined	50	70-170	0.020-0.072
Whangarei	Matarau	Basalt flows, cones and dikes overlying sandstone/mudstone	Semi-unconfined	8-20	108-3660	
Whangarei	Glenbervie	Taheke Basalt overlying greywacke/ interbeded sandstone and mudstone	Semi-confined	20-83	1 -36	0.002
Whangarei	Maunu	Taheke Basalt overlying sandstone/ mudstone	Semi-unconfined	8-58	30 - 89	0.002-0.0006
Whangarei	Maungatapere	Basalt with scoria overlying sandstone/ mudstone	Semi-confined	11-58	25-45	
Whangarei	Whatitiri	Taheke basalt overlying sandstone	Confined	4-30	25-4000	0.00004-0.0003
Whangarei	Maungakaramea	Basalt overlying micacaceous sandstone	Semi-unconfined	45-55	3-400	0.03
Whangarei	Three Mile Bush	Basalt with scoria overlying sandstone/ mudstone	Semi-unconfined	8-55	3-80	0.04
Mangawhai		Consolidated unweathered sands with quarts alluvial mud and gravel	Unconfined	8-50	5-440	0.00015-0.08
Taipa		Sand with some quartz	Unconfined	6 to 7	90 - 150	0.085-0.2
Tara		Basalt flow with underlying sedimentary rocks	Semi-unconfined	4-20	38-66	
Other shallow coastal aquifers		Predominantly sands/ alluvial mud and gravel.	Unconfined			

Northland's varying geology has a major influence on surface water flow and on the degree of groundwater recharge in areas. In permeable unconfined sand aquifers, a high percentage of rainfall infiltrates quickly to recharge the groundwater. In these areas there is minimal rainfall runoff contributing to stream flow. On the Aupouri Peninsula, the sand aquifer contributes little to stream baseflow, as the groundwater level is typically below the stream bed. The sand aquifers discharge predominantly at or near the coast.

The basalt aquifers have relatively rapid infiltration due to the fractured nature of the bedrock, and the existence of scoria cones. Discharge from the basalt aquifers is largely by spring flow at the edge of the basalt fields. These aquifers have considerable storage and the flow from springs generally continues during dry periods. Spring flow is a major contribution to stream baseflow in the basalt areas.

Catchments with significant areas of relatively low permeability greywacke sediment allow less infiltration of rainfall and have relatively low aquifer storage volumes. Stream flows in these catchments tend to recede quickly during dry summer periods.

Aquifer reporting and monitoring

Groundwater level monitoring has been undertaken in the Northland region since the mid-1970s. Since that time the network has been developed as groundwater issues have been identified.

Groundwater level monitoring is currently undertaken in all 12 of the focal aquifer systems in the Northland area (Table 12.1). Levels are monitored at six wells by automatic recorders and at 40 wells at monthly intervals (Northland Regional Council 1999). The monitoring wells have been selected to provide regional coverage and answer specific environmental concerns. The Northland Regional Council (NRC) is currently increasing the groundwater monitoring network to obtain more comprehensive information on regional groundwater quality and quantity.

Piezometric surveys have been undertaken in five aquifer systems (Table 12.2), providing information on groundwater flow directions and recharge areas. For example, the modelled steady-state piezometric map of the Aupouri Aquifer indicates groundwater flow is from the land towards the coast, or towards major water ways or low-lying topographic areas (Fig 12.2). On a local scale, groundwater flow direction is modified by local topography.

A groundwater flow model was developed in 2000 for the Aupouri Aquifer following a noticeable decline in groundwater level since 1990 at NRC monitoring wells in this aquifer. The model was developed to assess sustainable yields from the aquifer. Results of the modelling indicate that the aquifer is not over-allocated. The decline in groundwater level was considered to be caused by periods of below-average rainfall. The planting of *Pinus radiata* forest may also have reduced groundwater recharge over some of the modelled area.

Table 12.2 *Specific monitoring and reporting on major aquifer basins. Y= to a reasonable detail or frequency/spatially, L= limited information, blank = not measured or known.*

Aquifer Basin	Aquifer unit or zone	Wells survey	Piezometric data	GW level contours	Hydraulics testing	Water quality	Geology review	Reports compiled	Other
Aupouri	Sand and shell bed	12 Y	Y		Y	Y	Y	Y	
Kaikohe	Kaikohe Basalt	5 Y	Y		Y	L	Y	Y	
Whangarei	Matarau				Y		Y		
Whangarei	Glenbervie	7 L			L	L	Y		
Whangarei	Maunu	2 L	Y		L		Y	Y	
Whangarei	Maungatapere	1 L	Y		L		Y	Y	
Whangarei	Whatitiri	5 L	Y		Y	L	Y	Y	
Whangarei	Maunga-karamea	1 L			L		Y		
Whangarei	Three Mile Bush	3 L			Y		Y		
Mangawhai	Sand and sandstone	6 Y			Y	L	Y	Y	
Ngawha	Ngawha geothermal field	Y	Y	Y	Y	Y	Y	Y	well temp & pressure profiles
Tara		1 L			Y	L		Y	
Other shallow coastal aquifers		5 +		L			L	L	

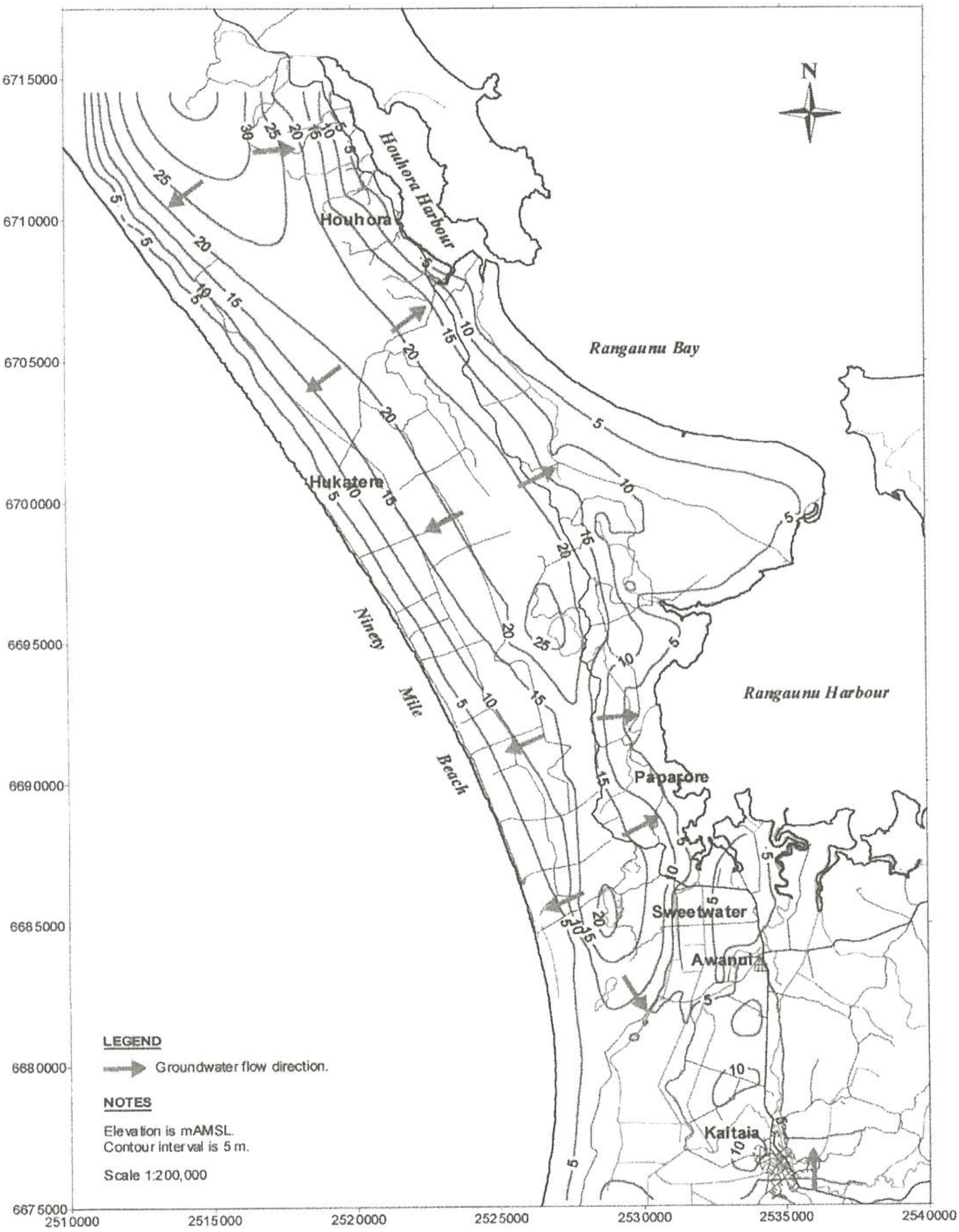


Figure 12.2 *Aupouri Aquifer contour map showing height of water table above mean sea level and directions of groundwater flow. (From Hydrogeo Solutions 2000).*

Table 12.3 *Water use and water balance information from reported aquifers.*

Aquifer/ Basin	Principal Water uses	Estimated annual average recharge (m^3)	Recharge sources	Major natural outflows	Estimated storage potential (m^3)
Aupouri Lower Aupouri Peninsula	Irrigation, dairy shed, stock water, domestic	6×10^7	Rainfall infiltration and surface water leakage	Coast	
Kaikohe	Irrigation, dairy shed, stock water, domestic, community supply	1 to 5×10^6	Rainfall infiltration	Springs	1 to 5×10^7
Whangarei Matarau	Irrigation, dairy shed, stock water, domestic		Rainfall infiltration	Springs	
Whangarei Glenbervie	Irrigation, domestic		Rainfall infiltration	Springs	
Whangarei Maunu	Irrigation, dairy shed, stock water, domestic,		Rainfall infiltration	Springs	
Whangarei Maungatapere	Irrigation, dairy shed, stock water, domestic,		Rainfall infiltration	Springs	
Whangarei Whatitiri	Irrigation, dairy shed, stock water, domestic, community water supply	2.6×10^7	Rainfall infiltration	Springs	4×10^8
Whangarei Maungakaramea	Irrigation, dairy shed, stock water, domestic,		Rainfall infiltration	Springs	
Whangarei Three Mile Bush	Irrigation, dairy shed, stock water, domestic		Rainfall infiltration	Springs	
Taipa	Irrigation, domestic	2.6 to 4.3×10^5	Rainfall infiltration	Coast and Taipa River	6.9×10^5 to 1.6×10^6
Mangawhai	Domestic, community supply		Rainfall infiltration	Coast and Mangawhai Estuary	
Tara	Irrigation, domestic	2.4×10^5	Rainfall infiltration	Spring	
Other shallow coastal aquifers	Domestic		Rainfall infiltration		

GROUNDWATER USE AND RESOURCE CONSENT SUMMARY

Groundwater in the Northland region is used for irrigation, public water supply, farm water supply, and household use (Table 12.3). Reticulated public water supplies typically use surface water augmented by groundwater where available e.g. Whangarei, Kaikohe, Okaihau and Ruawai. In areas where groundwater is available, rural households typically use it to supplement rainfall water supplies during periods of low rainfall.

An electronic bore construction and driller's log database was established by NRC in 1997. There are currently 2801 bores registered on the bore log database (Table 12.4). Results of recent bore surveys show there are a large number of bores in the Northland region that are not registered with the Council.

Information on new bores, and any newly, identified existing bores, is registered on the database when the Council receives it. The majority of bores that are located in aquifers other than the 12 main delineated aquifers (Table 12.4) are predominantly used to supplement household rainfall water supplies during dry periods and for stock requirements.

There are currently 223 resource consents to abstract groundwater in Northland region. The maximum daily volume for an individual consent ranges from 5 m^3 to 1500 m^3. The allocated

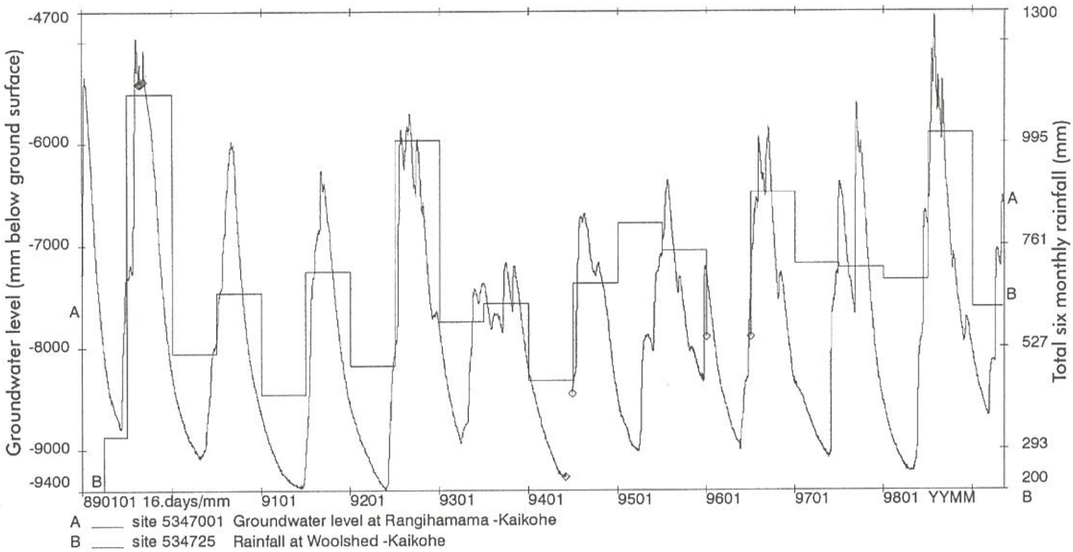


Figure 12.3 *Groundwater Level and Rainfall at Kaikohe Basalt Aquifer.*

total daily groundwater abstraction volume is currently 36,782 m^3 for the Northland region.

GROUNDWATER LEVEL OR WATER PRESSURE

Kaikohe Basalt Aquifer

The Kaikohe Basalt Aquifer has a seasonal pattern of lower groundwater levels in the late summer to early autumn, and higher groundwater levels in the winter and early spring (Fig 12.3). The seasonal fluctuation in groundwater level ranges from approximately 1.75 m to 4.5 m. The amount of seasonal fluctuation has steadily increased since 1993. This is likely due to an increase in winter rain during this period, rather than an increase in summer groundwater abstraction. Dry summers result in lower- than-normal seasonal groundwater level minima. The winter recovery of groundwater level depends on the volume of late autumn and winter rainfall. There is no apparent long-term decline in ground-water level.

Mangawhai Aquifer

The Mangawhai Aquifer also has seasonal low groundwater levels in the late summer and early autumn, and higher groundwater water levels in the winter and early spring (Fig12.4). The seasonal fluctuation in groundwater level ranges from 0.4 m to 2.5 m. Lower-than-normal groundwater levels occurred from 1990 to 1995 due to below-average rainfall. Groundwater levels recovered from 1995 to 1999 due to an increase in rainfall during this period. The amount of winter groundwater level recovery depends on late autumn and

Table 12.4 *Consents and wells survey information held by the Northland Regional Council for each aquifer.*

Aquifer/ Basin	Consents to take groundwater	Number of wells or bores registered with the NRC
Aupouri	42	362
Kaikohe	21	33
Whangarei Glenbervie	15	76
Whangarei Matarau	2	45
Whangarei Maungakaramea	6	30
Whangarei Maunu	28	149
Whangarei Three Mile Bush	15	93
Mangawhai	10	46
Tara	4	10
Other aquifers (mainly coastal)	80	1960

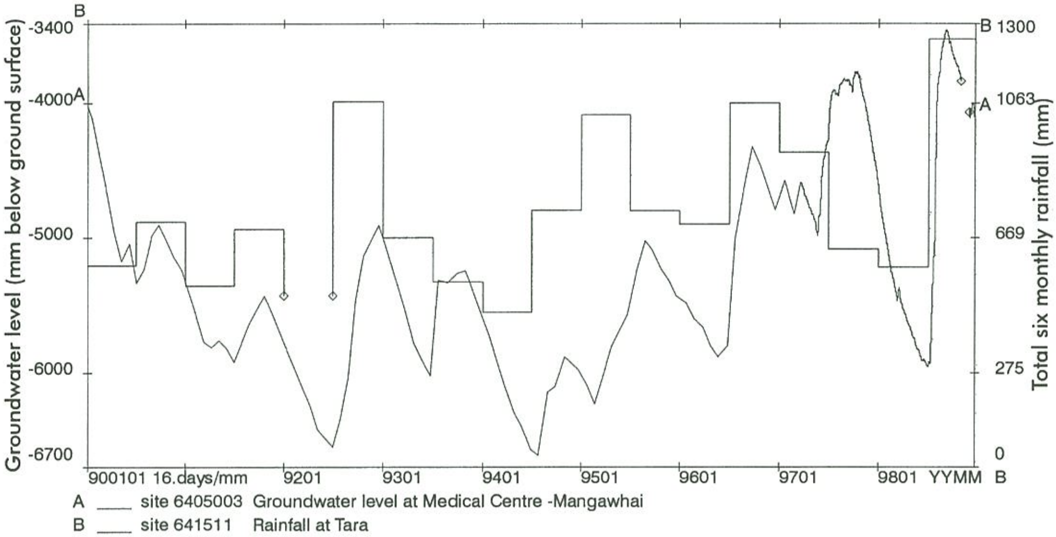


Figure 12.4 *Groundwater Level and Rainfall, Mangawhai Aquifer, Whangarei.*

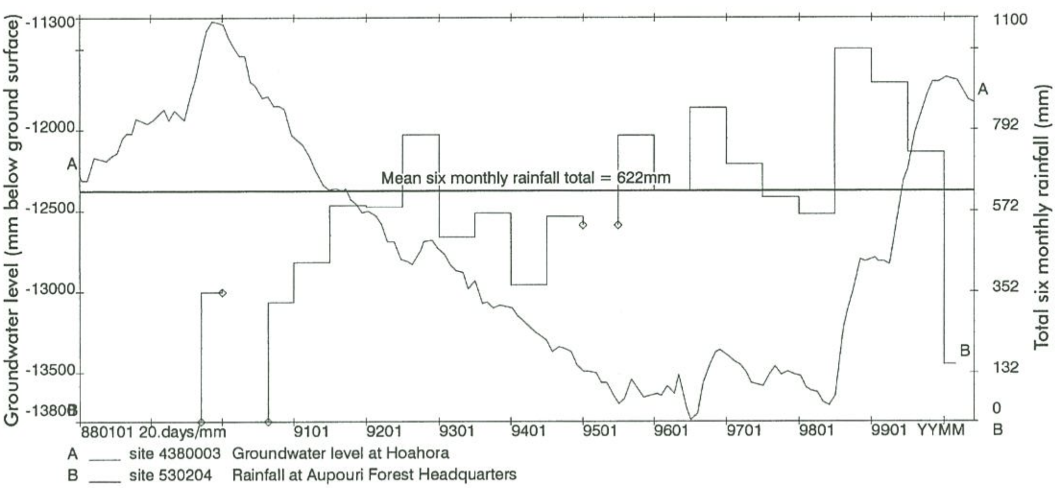


Figure 12.5 *Groundwater Level and Rainfall, Aupouri Aquifer.*

winter rainfall. There is no apparent long-term decline in groundwater level.

Aupouri Aquifer

Seasonal groundwater level fluctuations in the Aupouri Aquifer at Aupouri Forest Head quarters (Fig 12.5) were minimal during the period 1987 to 1998. This is due to the relatively even distribution of rainfall throughout the year during this period, and the depth of the aquifer measured at this site. Groundwater levels declined from 1990 to 1996 due to below-average rainfall. The period 1991 to 1994 was a period of intense El Niño weather conditions that caused dry weather conditions for much of the Northland region. Groundwater levels recovered during 1998 and 1999 as result of above-average rainfall.

Groundwater quality

The NRC monitors seven groundwater sites at three-monthly intervals for major anions and cations. Groundwater quality at all monitored sites meets New Zealand Drinking Water Guidelines and does not require treatment for potable water supply. The hydrochemistry of Northland's groundwater is variable and reflects the geology of the aquifer from which the water is drawn.

The Aupouri Aquifer has higher sodium and chloride concentrations than the inland basalt aquifers, reflecting its nearness to the coast and the leaching of these elements from the marine sediments. There is potential for seawater contamination of coastal aquifers (e.g. Taipa, Ngunguru, and Russell) during summer, when groundwater levels decline due to increased groundwater abstraction or to decreased groundwater recharge caused by below-average rainfall.

Groundwater levels, chloride concentrations and electrical conductivity are measured in coastal bores in the Taipa Sand Aquifer to monitor for seawater intrusion. Electrical conductivity levels are higher in the Taipa Sand Aquifer than in the inland basalt aquifers due to the seawater influence (Fig 12.6). In addition to the saltwater intrusion, a number of small unconfined coastal aquifers (e.g. Russell, Matapouri) are also at risk of bacterial contamination from septic tank and effluent disposal fields.

Nitrate-nitrogen concentrations in all Northland aquifers monitored are below New Zealand Drinking Water guidelines (11.3 mg/L) (Table 12.6). Nitrate-nitrogen measured in the Kaikohe Basalt Aquifer range between approximately 3 and 4 mg/L and are low (< 0.05 mg/L) in the Aupouri Aquifer (Fig 12.7). Concentrations are higher during winter when higher seasonal rainfall causes leaching of nitrogen to the water table. A primary source of nitrogen is probably the discharge of dairy effluent on land. Another potential nitrogen source in small communities is from septic tank discharges.

GROUNDWATER MANAGEMENT

The Revised Proposed Regional Soil and Water Plan for Northland details the objectives, policies and rules associated with groundwater management in the region.

One of the main objectives of the Plan is the sustainable use and development of Northland's groundwater resources, while avoiding, remedying or mitigating adverse effects on groundwater quantity and quality. The Plan recognises 36 basalt and coastal aquifers and a geothermal aquifer as being potentially 'at risk' due to land use, surface water interaction, proximity to seawater and septic tank discharges (Table 12.5).

The rules in the Plan restrict groundwater takes, use, diversions and drilling activities, depending on the potential effects of the activities. The rules permit groundwater takes for reasonable stock and domestic requirements provided specific criteria are met. The criteria, amongst other things, limit the daily permitted groundwater take, depending on the location and the potential for adverse effects as a result of the take. For example, smaller volumes are permitted to be taken from 'at risk' aquifers. In the event the permit criteria can not be met, then a resource consent to take groundwater is required from the Regional Council.

Drilling activities are also permitted in Northland, provided the activity is outside the 'at risk' aquifers identified in the Plan, and specific drilling standards and criteria are met. In the event that a drilling activity is within an 'at risk' aquifer or bore construction standards and criteria can not be met, then a re-

Table 12.5 *Potential water quality limitations in reported aquifers*

Aquifer/ Basin	Potential Water Quality Problem	Source of problem	Mitigation Measures
Shallow coastal aquifers	Salt water intrusion, bacterial contamination.	Proximity to coast and increased abstraction, old septic tanks	Regulated abstraction, effluent discharge, and maintenance of effluent disposal systems
Other Northland aquifers	Nitrate leaching	Dairy effluent application to land	Regulated application

Table 12.6 *Summary statistics for aquifer water quality.*
(Aupouri, Kaikohe & Whangarei data supplied by Institute of Geological and Nuclear Sciences).

Aquifer zone or basin	STAT	NO_3-N mg/L	NH_4-N µg/L	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	Cl mg/L	PO_4 µg/L	SO_4 mg/L	ALKT mg/L ($CaCO_3$)	F µg/L	Br µg/L	COND µS/m	SiO_2 mg/L
Aupouri															
@Colville	count	13	13	13	13	13	13	13	4	13	13	9	11	10	13
	mean	0.058	9.8	5.8	3.71	29.7	1.38	29.2	32.5	9.21	55	68.9	359	202	41.4
Well no. 4890	median	0.025	5.0	5.8	3.70	30.0	1.40	29.0	32.5	9.20	55	70.0	350	200	41.7
	variance	0.016	0.1	0.1	0.02	1.4	0.02	2.3	0.4	0.18	9	0.2	1	0	2.2
	sd	0.127	7.7	0.4	0.13	1.2	0.15	1.5	20.2	0.43	3	12.7	34	6	1.5
	min	0.002	5.0	5.0	3.50	28.0	1.20	26.7	15.0	8.46	50	50.0	320	190	38.6
	max	0.480	30.0	6.5	3.90	31.0	1.70	32.0	50.0	9.95	59	90.0	440	210	43.2
Kaikohe															
@Kaikohe Hill	count	13	13	13	13	13	13	13	4	13	13	7	11	10	-
	mean	3.5	10.1	10.1	4.89	13.8	1.58	12.1	103	2.16	54	31.4	48.6	162	-
Well no. 1922	median	3.5	5.0	10.4	5.00	14.1	1.60	12.2	115	2.20	56	25.0	50.0	160	-
	variance	0.12	0.1	2.1	0.37	1.9	0.06	1.0	1	0.02	73	0.4	0.1	1	-
	sd	0.34	7.7	1.5	0.61	1.4	0.24	1.0	36	0.15	9	21.0	9.5	24	-
	min	2.8	5.0	5.4	2.94	9.6	0.99	9.1	50	1.82	27	10.0	25.0	110	-
	max	4	30.0	11.1	5.30	15.0	1.90	13.6	130	2.42	62	70.0	60.0	210	-
Whangarei															
@Green's	count	12	12	12	12	12	12	12	4	12	12	7	10	9	-
	mean	1.59	8.67	38.9	6.0	17.8	1.39	14.7	42.5	9.76	142	57.9	59.5	293	-
Well no. 5916	median	0.89	5.00	41.9	6.0	18.2	1.50	14.6	45.0	9.62	158	60.0	60.0	320	-
	variance	4.19	0.03	144.0	0.2	5.5	0.14	1.1	0.1	2.95	2408	0.3	0.3	3	-
	sd	2.05	5.52	12.0	0.5	2.4	0.37	1.1	9.6	1.72	49	16.3	16.1	56	-
	min	0.22	5.00	12.2	5.1	13.2	0.60	13.3	30.0	6.10	38	25.0	25.0	190	-
	max	6.10	20.00	48.0	6.6	21.0	1.80	17.7	50.0	13.30	186	70.0	90.0	340	-
Taipa	count	25	-	29	29	27	-	28	-	-	7	-	-	76	-
@Taipa Sands	mean	1.9	-	77.3	7.76	26.4	-	48.7	-	-	249	-	-	56	-
Motel	median	0.2	-	78.4	7.86	26.8	-	49.4	-	-	260	-	-	54	-
Well no. 2332	Variance	73.3	-	35.5	0.15	2.0	-	27.8	-	-	448	-	-	244	-
	sd	8.6	-	6.0	0.39	1.4	-	5.3	-	-	21	-	-	16	-
	min	0.0	-	52.1	6.91	23.9	-	40.0	-	-	220	-	-	44	-
	max	43.0	-	84.0	8.45	28.5	-	58.3	-	-	270	-	-	188	-

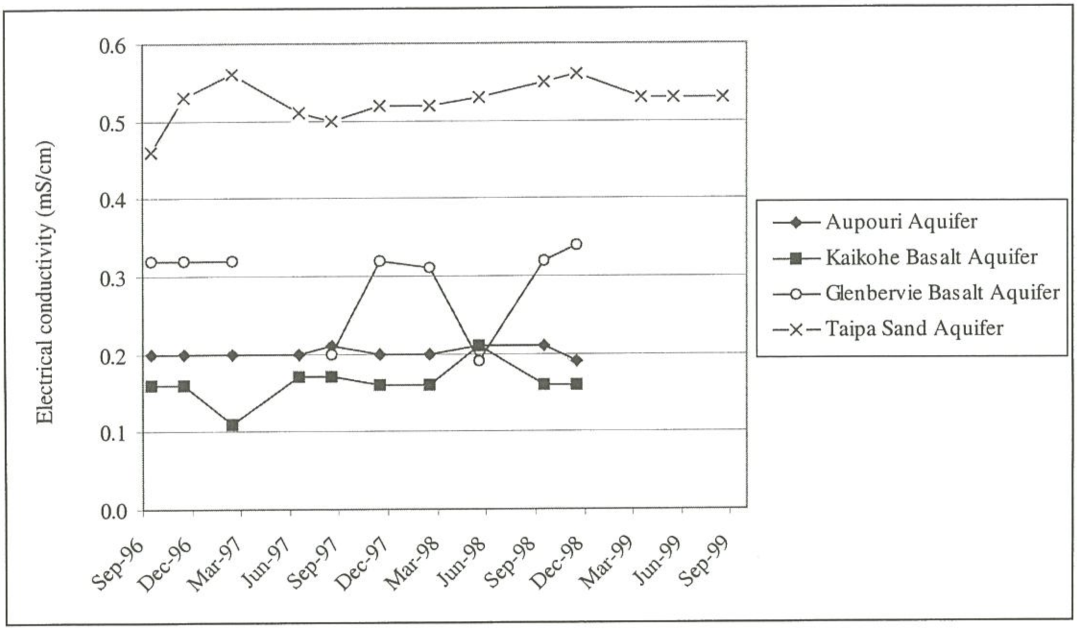


Figure 12.6 *Electrical conductivity in Northland aquifers.*

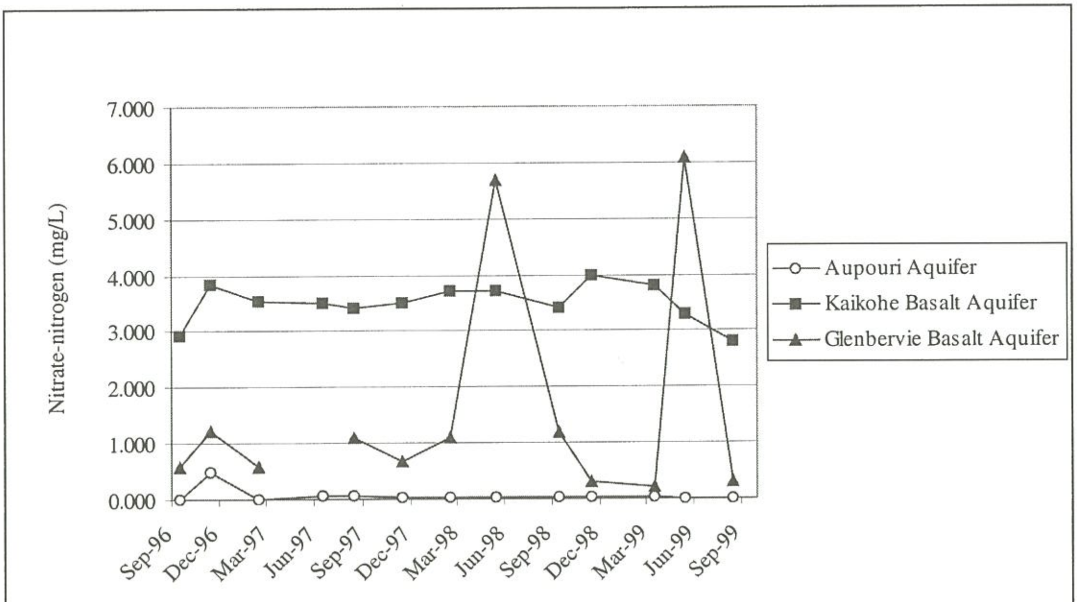


Figure 12.7 *Nitrate-nitrogen concentrations in Northland aquifers,*

source consent is required to drill the bore. All bore construction and drilling information associated with any drilling activity in Northland must be forwarded to the Council.

Resource consents to take groundwater, and drill a bore are subject to specific conditions imposed to avoid or minimise potential adverse effects. Monitoring the exercise of resource consents is carried out to ensure that the conditions are complied with and the bore construction activities do not adversely affect the environment.

The general state of the groundwater resources in Northland is also monitored. The State of Environment (SoE) groundwater monitoring is used:

- to obtain baseline information on water quantity and quality of different aquifers,
- to determine changes in groundwater quantity and quality over time as a result of climate variation, land use and groundwater abstraction, and
- to ensure the management of the groundwater resources in Northland is sustainable and consistent with the objectives and policies of the Northland Regional Plans.

The results of monitoring resource consents and the general state of groundwater resources can provide information on which to base future management decisions.

REFERENCES

NORTHLAND REGIONAL COUNCIL 1983: Groundwater Resources on the Maunu, Maungatapere and Whatitiri Area. 1983/2.

NORTHLAND REGIONAL COUNCIL 1989: Assessment of Mangawhai Hydrogeology.

NORTHLAND REGIONAL COUNCIL 1991: Aupouri Peninsula Water Resources Assessment.

NORTHLAND REGIONAL COUNCIL 1992: Kaikohe Water Resources Assessment.

NORTHLAND REGIONAL COUNCIL 1999: Annual Environmental Monitoring Report 98-99.

HYDROGEO SOLUTIONS 2000: Aupouri Aquifer Sustainable Yield Groundwater Modelling Study. Report commissioned by Northland Regional Council.

13

Auckland

GILLIAN CROWCROFT AND ALASTAIR SMAILL

INTRODUCTION

The Auckland region (Fig 13.1) has the smallest land area (2% of New Zealand) of the 15 regions that use groundwater, but has the largest and fastest growing population. Thirty-one percent of New Zealand's population lives in the Auckland region. As a result, the pressure on the region's natural resources is more intense than in other parts of the country. The Auckland region is generally short of fresh water. Because of its geography and geology (Fig 13.2), surface water stream catchments and groundwater resources are generally small (Auckland Regional Council 1999). The annual average rainfall is c. 1250 mm, although local variation in rainfall is marked (800 – 1800 mm).

Aquifers in the Auckland region are low-yielding compared with other parts of New Zealand. In its infancy Auckland obtained its water supply from springs discharging from the Auckland volcanic cones and basalt. The combination of low aquifer yields and pressure from a growing population stressed groundwater resources, and polluted water supplies became a problem in some areas. Large surface water supply dams in the Hunua and Waitakere Ranges now supply 90% of the metropolitan water demand. However, projected water needs for the region exceed existing yields and water from the Waikato region will be used in the near future. Most groundwater in the region is abstracted from the Franklin and Bombay basalts, Waitemata sandstones, Auckland basalts, Pleistocene sands and Kaawa shell beds. The region also has two well-developed geothermal fields, at Waiwera and Parakai. The primary aquifers that have been developed and used in the Auckland region are discussed in the following sections. Where known, aquifer parameters and availability figures have been provided. While Auckland's aquifers are considered to be low-yielding, they are still an important source of water in many rural areas and for some industry within the municipal water supply area. Approximately 200 new bores, mostly for water supply, are drilled each year.

WAITEMATA AQUIFERS

Aquifer distribution and description

The Waitemata Group sediments comprise mainly flysh sequences (alternating sandstone and mudstone). Apart from in a few locations,

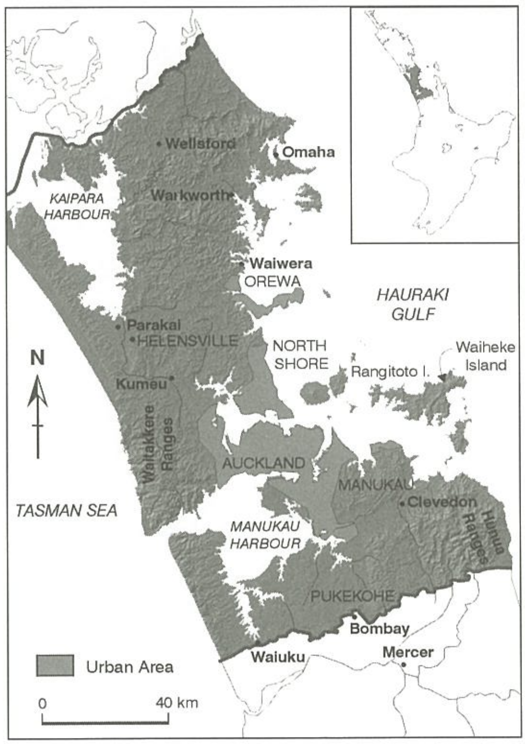


Figure 13.1 *Location map for the Auckland region.*

Crowcroft G. and Smaill A. 2001: Auckland. *In* Groundwaters of New Zealand, M.R. Rosen and P.A. White *(eds)*. New Zealand Hydrological Society Inc., Wellington. p303-313.

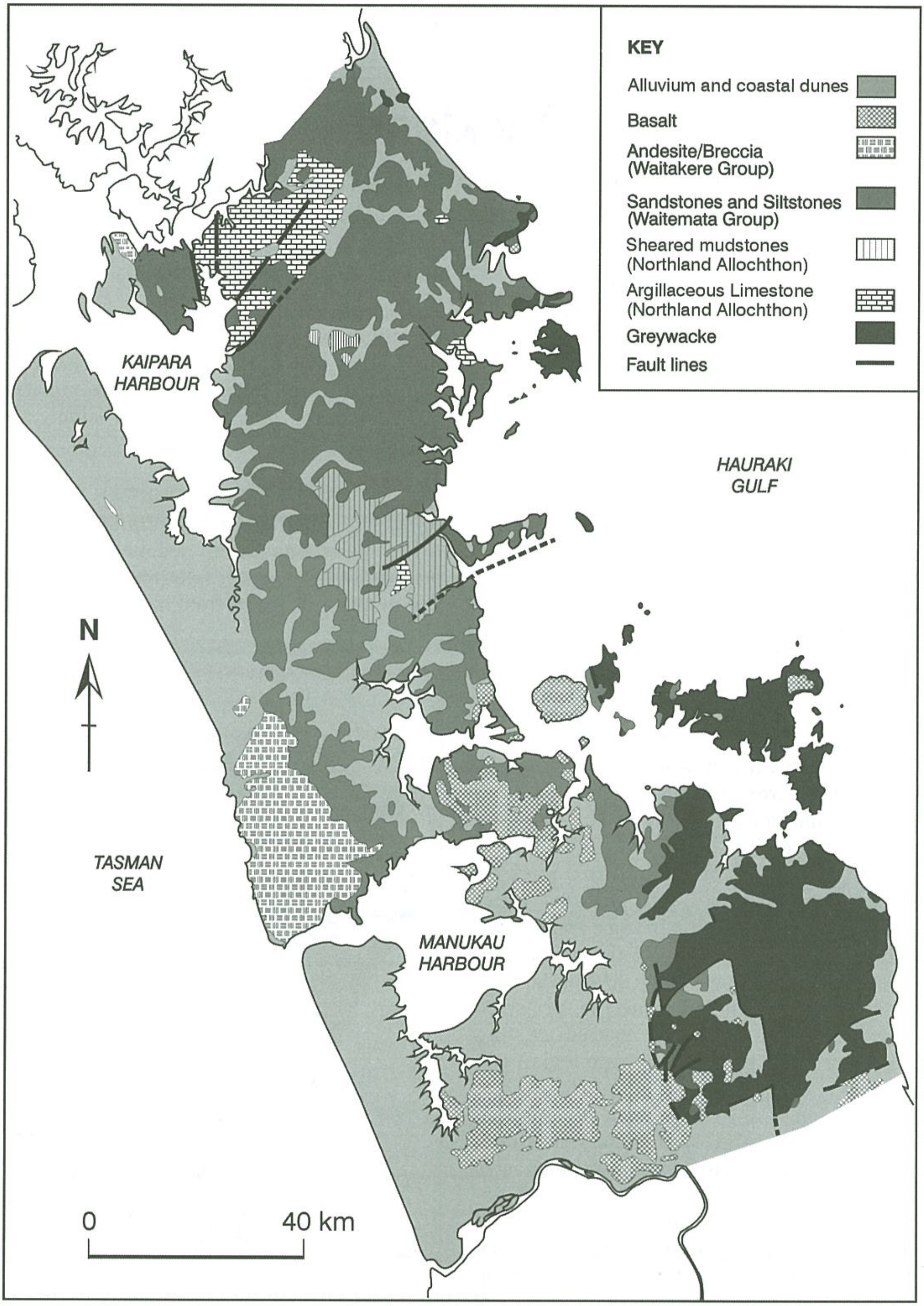


Figure 13.2 *Simplified geology of the Auckland region. Note. Great Barrier Island is not shown.*

such as the Hunua Ranges, some Hauraki Gulf Islands and areas of Onerahi rocks in the north of the Auckland region, Waitemata Group rocks form the local basement (Ballance 1976). Waitemata Group rocks vary across the Auckland Region, particularly in the thickness of sandstone beds and the amount of jointing and fracturing. Their total thickness varies from several metres to greater than 1000 m.

Hydraulic parameters of the Waitemata aquifer vary across the region, resulting in intensive aquifer development in some areas and little development in other areas. Transmissivities are in the range 1-250 m^2/day, but are generally less than 100 m^2/day. Storativities show that the aquifer is generally confined and in the range 0.001–0.00001. The aquifer is generally low-yielding. Bores are generally drilled to depths of 200–400 m and cased with 100 mm or 150 mm diameter casing to 100–200 m depth. Bore yields range from a few cubic meters per day to over 1000 m^3/day. Typical yields for a 100 mm diameter bore are 30–300 m^3/day.

The chemical composition of groundwater in the Waitemata aquifers can be broadly classified into two types, based on total hardness/total alkalinity ratio (TH/TA), pH, silica and total iron concentrations. Shallow groundwaters (<200 m depth) commonly have a high TH/TA ratio, and are hard calcium carbonate waters with near-neutral pH, high total iron (>1.0 g/m^3), and silica concentrations greater than 40 g/m^3. Deeper groundwaters commonly have a low TH/TA ratio, and are soft sodium bicarbonate waters with pH >8.5, low total iron (<0.2 g/m^3) and silica concentrations of less than 40 g/m^3.

Groundwater availability, management and use

The Waitemata aquifers are divided into smaller areas for management. Groundwater availability has been calculated for Waitemata aquifers based on annual recharge rates equivalent to 3%-10% of annual rainfall. The most recent availability figures for key groundwater management areas are shown in Table 13.1.

Water allocation figures represent the total volume of groundwater allocated to resource consent holders in 1999. No allowance is made for users of groundwater that do not require a resource consent. As all consent holders are required to fit and read a water meter, the total authorised use for the 12 months ending May 1999 has also been calculated.

Groundwater levels in the Waitemata aquifers respond to seasonal fluctuations in rainfall and, to a lesser extent, to seasonal pumping (Fig 13.3). Most aquifer recharge occurs during autumn and winter, resulting in aquifer recovery by September-October. Apart from in geothermal areas, most groundwater abstraction is during summer and autumn. A network of 42 water level monitoring bores are measured monthly to ensure that groundwater abstraction does not exceed aquifer recharge.

In the Kumeu and Manukau aquifer management areas groundwater demand is greater than the safe yield of the aquifer. No groundwater has been allocated above the level set to sustain the aquifers Omaha groundwater abstraction is monitored very closely to ensure that water levels in the coastal aquifer do not fall to levels that will allow salt-water intrusion. While land in this area has been used for horticulture over the last 20 years, many properties are being subdivided for lifestyle and holiday home blocks. New groundwater management problems are likely to arise as a result, such as septic tank contamination and reduced recharge. The Orewa-Whangaparaoa aquifer has been undergoing a period of water level recovery since the cessation of pumping

Table 13.1: *Water availability, allocation and use for Waitemata aquifers.*

Management Area	Water availability m^3/y	Water Allocation m^3/y	Water Use m^3/y
Omaha	105,000	70,000	53,000
Kumeu	1.56 million	833,000	392,000
Whangaparaoa/Orewa	1.39 million	97,000	41,000
Manukau	790,000	708,000	501,000
Clevedon	1.34 million	685,000	511,000
Karaka-Waiau Pa	2.7 million	1.02 million	582,000

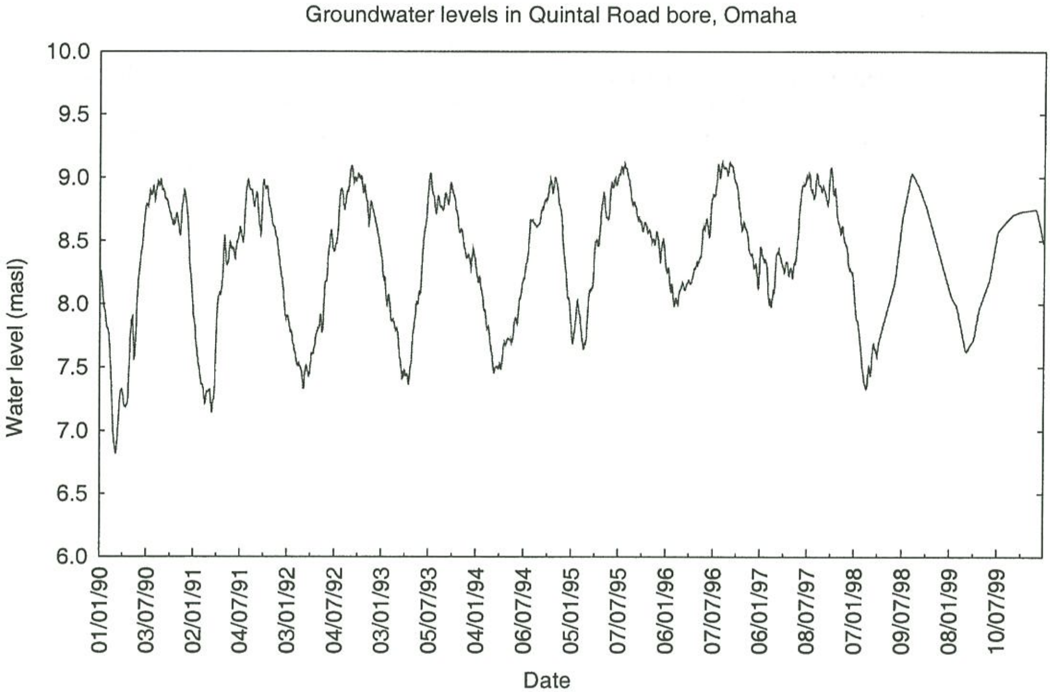


Figure 13.3 *Typical Waitemata aquifer hydrograph for the period 1990–1999.*

for municipal supplies by Rodney District Council in 1996. Prior to 1996 the aquifer was fully allocated and demand was increasing. Water demand is now met through the municipal water supply company, Water Care Services Ltd.

AUCKLAND VOLCANICS

Aquifer distribution and description

The Auckland City landscape is dotted with numerous basaltic cones and their associated flow deposits and tuff rings. Volcanism started in the central Auckland area about 150,000 years ago (Homer et al. 2000). While it is relatively easy to recognise the remaining cones e.g. Mt Eden and One Tree Hill, other features are less visible, being obscured by urban development. The main interest in the Auckland volcanics has been the value of the rock resource and as a result many cones and flows have been quarried to provide aggregate.

Pyroclastic material from the volcanic centres has coalesced, resulting in hydraulic connections between the basalt flows. The main basaltic aquifers in the Auckland region are Onehunga/Mt Wellington, Western Springs (Mt. Eden/Three Kings/Mt. Albert), Mt Richmond and, to a lesser extent, Mt Eden/Epsom and Auckland Domain.

Groundwater movement is dominantly by fracture flow. As the volcanic materials are anisotropic, aquifer properties vary considerably over short distances, both horizontally and vertically. Transmissivities and aquifer thicknesses and contributing volcanic centres for the main volcanic aquifers are presented in Table 13.2.

Well yields may vary considerably depending on the nature of the aquifer materials. Scoriaceous and heavily fractured zones produce more groundwater than the tuffaceous and dense, less fractured zones. The direction of groundwater flow is strongly controlled by the paleotopography of the underlying low-permeability Waitemata Group rocks. Groundwater flows down paleovalleys infilled by basaltic lava flows. Groundwater levels in the volcanic aquifers respond rapidly to rainfall events (within 20 minutes in some moni-

Table 13.2: *Auckland volcanic aquifers' origin, transmissivity and thickness. Origin, transmissivities and thicknesses of Auckland aquifers.*

Aquifer Name	Contributing Volcanic centres	Transmissivity (m^2/day)	Aquifer thickness
Onehunga/ Mt Wellington	One Tree Hill, Mt Smart, Mt Wellington	108 -260	< 60m
Western Springs	One Tree Hill, Three Kings, Mt Albert	28-7700	< 50m
Mt Richmond	Mt Richmond	260 (tuff)-800 (basalt rock)	< 45m

toring bores). Groundwater hydrographs for automatically monitored bores show many sharp peaks imposed on the underlying seasonal water levels (Fig 13.4).

Groundwater in the basalt aquifers is generally low in dissolved constituents, as shown by conductivities below 30 mS/m, and is some of the highest quality groundwater in the region. Contamination from stormwater may show up as elevated concentrations of sulphate, potassium, bicarbonate and total hardness. Elevated nitrate, in the order of 2-4 g/m^3, is a result of leaky sewers and stormwater input.

Groundwater availability, management and use

Groundwater availability has been calculated on the basis of rainfall infiltration in areas with different land uses, including artificial recharge by stormwater. The present recharge is considerably greater (by as much as 3 times) than it was before urban development, due to the input of stormwater runoff from impervious surfaces directly into the aquifer. Additional recharge occurs from water main and sewer leakage.

Most groundwater demand is for municipal supply and industry. Despite the vulnerability

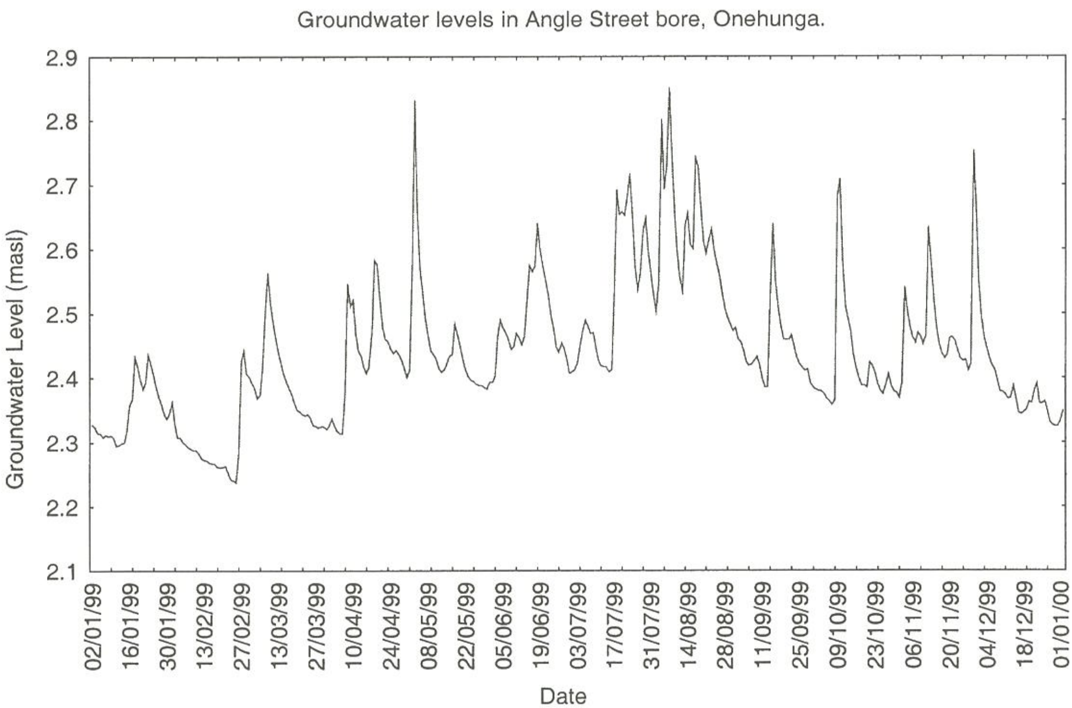


Figure 13.4 *Groundwater levels in a typical Auckland volcanic aquifer bore, showing the rapid response to recharge events.*

Table 13.3 *Volumes of Auckland volcanic aquifer groundwaters available, allocated, and used in 1999.*

Management Area	Water availability m3/y	Water Allocation m^3/y	Water Use m^3/y
Onehunga/Mt Wellington	13.2 million	9.8 million	Approx. 4.5 million
Western Springs	9.6 million	2.84 million	1.12 million
Mt Richmond	880,000	480,000	340,000

of the Auckland volcanic aquifers to urban contamination, the groundwater quality is suitable for most uses. The area of highest use is Onehunga/Mt Wellington, where numerous industries use groundwater for processing.

Automatic water level recorders are installed in six groundwater monitoring bores, and 33 bores are monitored monthly. Groundwater levels respond rapidly to rainfall events, as would be expected in aquifers with such high transmissivities. The response is enhanced due to the additional injection of stormwater.

SOUTH AUCKLAND VOLCANICS

Aquifer distribution and description

The South Auckland Volcanic Field extends from Papakura to Pukekawa and west across the Manukau lowlands to Waiuku. The field consists predominantly of lava flows, scoria cones and tuff rings formed through phreatomagmatic activity from at least 97 centres (Briggs et al. 1994). While the 0.51 million - 1.59 million-year-old field has been separated into Bombay basalt (older and to the east) and Franklin basalt (to the west), they cannot be clearly separated on the basis of their hydrogeology. In low-lying areas of South Auckland e.g. around Drury, the volcanics are mantled with Pleistocene sediments.

Much of the flanks of Pukekohe Hill and Bombay Hill have been developed for growing greens, potatoes and onions, and water to irrigate these generally comes from shallow (30-60 m deep) bores drilled into the fractured basalt. As a result of pumping, low summer groundwater levels have restricted yields from some shallow bores and reduced spring flows, which form an important baseflow to local streams. Deeper bores, fully penetrating the lower volcanic aquifer, are now more commonly installed than shallow bores.

Transmissivities in the South Auckland Volcanics vary from 7 m^2/day to as much as 5600 m^2/day, although more typically transmissivities are in the order of 10–500 m^2/day. Storativities vary from 7×10^{-5} to 4.2×10^{-2}. Groundwater levels respond quickly to rainfall events.

Groundwater chemistry in the South Auckland Volcanics are broadly separated based on depth within the aquifer. Water from shallow bores (30-60 m) has a comparatively low pH and low alkalinity compared with water from deeper bores (>60 m). This is not surprising, as shallower water has less contact time with the aquifer matrix and less time to dissolve minerals. Water from shallow volcanic aquifers also tends to have higher nitrate levels, which are related to land use practises.

Groundwater availability, management and use

Groundwater resources in the Manukau lowlands have been developed since the late 1800s. Since the horticultural boom in the early 1980s demand for groundwater resources in South Auckland has increased to the point where new applications for water permits have been declined in some areas, including the Pukekohe basalt aquifer. People wanting reliable water supplies in areas overlying restricted aquifers have had to drill more expensive bores into deeper aquifers, such as the Kaawa shell aquifer and the Waitemata aquifer.

Groundwater availability for the Pukekohe Groundwater Management area is 1 million m^3/year. Ninety-nine percent of this has been allocated to groundwater users. In 1999 consent holders used 633,000 m^3 of groundwater.

Three groundwater monitoring bores in the volcanic aquifer are monitored automatically and another three bores are monitored monthly. Groundwater levels respond rapidly to rainfall events, as would be expected in aquifers with such high transmissivities.

Water quality has not been a problem for most people wanting to extract groundwater in the Pukekohe area. The water chemistry makes it useful for almost all applications. However, elevated nitrates in some bores, to levels above the NZ drinking water standard (currently 11.3 mg/L NO_3-N), has meant abstracted water is not suitable for human consumption without dilution.

KAAWA FORMATION

Aquifer distribution and description

The Kaawa shellbed(s) is an important aquifer in the Manukau lowlands, around Waiuku, Glenbrook and, more recently, south towards Pukekohe and Puni. Corresponding shell beds have been found in the Auckland Airport area, north to the Mangere lagoon and in the Middlemore area, underlying the Auckland and Grange Golf Club Courses. The lack of deep drilling in the Mangere area means that the relationship between these latter two shell beds is uncertain.

Kaawa shellbed is a locally-used name that refers to the shelly beds (0.5–6 m thick) within the Kaawa Formation (Kaihu Group). The Kaihu Group comprises mainly coastal marine sediments and dune sands. The Kaawa Formation rests unconformably on the Waitemata Group and comprises pumiceous shell and sandy shell beds, fine to medium sandstone with scattered pebbles, and some gravels (Auckland Regional Water Board 1989).

Bores constructed in the Kaawa aquifer are generally screened across coarse shell and/or sand beds. Typical well yields (for 100-150 mm-diameter bores) are in the range 800-1200 m^3/d. Transmissivities range from 30 to 500 m^2/day and storativities from 10^{-2} to 10^{-5}.

The chemistry of Kaawa aquifer groundwater is very similar to that of shallow Waitemata aquifer water, although calcium maybe slightly elevated by comparison. Kaawa shellbed groundwater has a wide composition range. The typical composition is characterised by a moderate pH of 8 due to moderate (4g/m^3) carbon dioxide, moderate total alkalinity (130 g/m^3), moderate silica (50 g/m^3) and low total iron (0.5 g/m^3). The water composition is not unique to the aquifer but typical of other deep sedimentary and volcanic aquifers elsewhere in the region.

Groundwater availability, management and use

Extensive investigations of the Kaawa aquifer in South Auckland were undertaken in the late 1980s as a result of a horticultural boom. A total groundwater availability of 17,500 m^3/day (6.4 million m^3/year) was determined for the Kaawa aquifer from flow net analysis. This figure includes the Glenbrook Volcanics and the overlying sand aquifers in the Glenbrook/Waiuku area.

The present Kaawa groundwater allocation of 6.2 million m^3/year has been allocated to 160 resource consent holders. Collectively, consent holders use approximately 75% of the total regional groundwater allocation. The largest groundwater user is the Franklin District Council, which supplies water to Pukekohe and Waiuku townships.

A network of 14 water level monitoring bores are used to measure seasonal recharge fluctuations and, to a lesser extent, seasonal abstraction in South Auckland. In other parts of the Auckland Region the Kaawa aquifer is used by only a small number of users. Water availability figures have only been developed locally, as part of resource consent application assessments of effects.

GEOTHERMAL GROUNDWATER

Distribution and description of Auckland's geothermal aquifers

Auckland's geothermal waters are low-temperature fracture-related systems. The most well known and developed resources are at Parakai, in the Kaipara District and Waiwera, north of Orewa. Other geothermal waters have been encountered during drilling at Whitford and East Tamaki and emerge as springs on Great Barrier Island.

Both Waiwera and Parakai geothermal waters rise along faults from greywacke rocks and are stored in Waitemata Group rocks. Maximum bore production temperature at the centre of the Waiwera field is 53°C and at Parakai is 65 °C.

Groundwater pressures in the Waiwera field stand below the water table in the overlying cold sand aquifer (Crane 1999). At Parakai the gradients are reversed, with geothermal pressures greater than the water table aquifer. Over the last few years rising geothermal pressures in the Parakai field have resulted in numerous bores requiring remedial works to contain the geothermal water. In many cases this has been achieved by adding up to 2 m of extra casing to the top of the bore.

Geothermal water is characterised by concentrations of boron, lithium and fluoride significantly greater than for non-geothermal fresh groundwater. The "thermal constituents are derived from reaction of rock-forming minerals with groundwater at depths where temperatures are sufficient to bring these elements into solution" (Auckland Regional Water Board 1986). Parakai and Waiwera geothermal groundwaters also have naturally high sodium and chloride, while East Tamaki and Whitford geothermal waters more closely resemble non-geothermal water.

Groundwater availability, management and use

Demand for Auckland's geothermal groundwaters is high in both Waiwera and Parakai, and the management of the geothermal fields is closely monitored. Underdeveloped fields at Whitford, Great Barrier Island and East Tamaki are not as closely managed. Geothermal resources are managed not only in terms of total groundwater abstraction but also for thermal efficiency. Pools are required to have covers, when not in use, to minimise heat loss and no water can be taken for home heating.

Forty-four consent holders are collectively allocated 465,000 m^3/year (1277 m^3/day) of geothermal groundwater from the Waiwera aquifer. Most consent holders take 1–2 m^3/day for spa pool use; the few larger users take water for commercial enterprises such as thermal pools and accommodation. The calculated groundwater availability for the thermal aquifer is an average of 1300 m^3/day or 475,000 m^3/year.

A total of 254,000 m^3/year geothermal groundwater is allocated to 26 consent holders at Parakai. In 1999 consent holders used a total of 181,000 m^3 of geothermal groundwater. Geothermal groundwater is used in motels, hotels and pool complexes and by householders for spa pool heating.

OTHER GROUNDWATER RESOURCES

Quaternary sediments

Low-lying parts of the Auckland region are mantled with generally less than 60 m of Quaternary sediments of the Tauranga Group. These sediments occur throughout the low-lying areas of the Manukau lowlands and have been an important source of minor water supplies for farm holdings and rural domestic use. Water bores drilled into these sediments are comparatively low yielding and the water is of poor quality due to elevated iron levels. The bores are also prone to contamination by septic tanks and salt water.

Greywacke

Auckland's greywacke rocks, which form much of the southeastern part of the region, including the Hunua Ranges and some Hauraki Gulf Islands, would not in general be considered particularly good aquifers. On Waiheke Island, where there is no municipal water reticulation and surface water supplies are limited, bores in greywacke may be the only alternative water supply. The primary porosity of greywacke in Auckland is very low and most groundwater movement is through fractures or along the contact with overlying material.

REGIONAL GROUNDWATER QUALITY

The Auckland Regional Council undertakes a regional baseline-monitoring programme for groundwater quality and contributes to the National Groundwater Monitoring Programme (NGMP). Twenty-three sites, representative of the aquifers across the region, are sampled at least annually for the regional baseline programme.

Groundwater across the region is of variable but generally good quality. Some shallow groundwaters have naturally high iron. Groundwater from some deep Waitemata sandstone bores and greywacke bores may contain boron at levels above the NZ drinking water standard and above tolerance levels for some crops.

As the Auckland region has a considerable length of coastline and high water demand in coastal settlements so there is potential for saltwater contamination of coastal aquifers. Groundwater in coastal areas is often drawn from shallow, thin, aquifers that are also susceptible to contamination from septic tank seepage.

The most significant groundwater contamination problems in the Auckland region at present are nitrate and stormwater.

Nitrate

Elevated nitrates occur in shallow volcanic aquifers in South Auckland and on the Auckland Isthmus. Elevated nitrate, with some groundwater above the standard for drinking water in New Zealand (Ministry of Health 1995), in South Auckland groundwater is from soil leaching and is a result of land-use practices. The heightened awareness of nitrate in groundwater amongst the community has led to initiatives from rural land users and the regional council to improve land practices to minimise nitrate leaching. On the Auckland Isthmus, nitrate in groundwater is the result of leakage from an ageing sewage reticulation system. Nitrate levels are below the standard for drinking water in New Zealand. The Auckland City Council continues to upgrade the sewer network.

Stormwater

On the Auckland Isthmus stormwater is disposed of in the basalt aquifers. This results in a large percentage of rainfall recharging the aquifer. However, the aquifers are susceptible to contamination. This includes both particulate matter in suspension as well as chemical pollutants. Groundwater quality has been compromised in some parts of the isthmus, in particular in the Penrose industrial area (Rosen et al. 2000). Stormwater from road run-off is thought to contribute the greatest load of contaminants to the aquifer. The present stormwater management practice is to continue with ground soakage as a disposal option, with pre-treatment of the stormwater. This should see a reduction in the volume of sediment, usually containing bound pollutants, entering aquifers.

REGIONAL GROUNDWATER USE

At present 1178 resource consents are issued to take up to 27,764,000 m^3 of groundwater per annum in the Auckland region. Most groundwater is used for irrigation, industry and municipal supply. Over 7000 bores have been drilled in the region to meet water demand and for site investigations.

Groundwater in Auckland is used for a wide variety of purposes including horticulture, industry, and recreation. Early European settlers in inner Auckland City were highly dependent on groundwater for municipal supply. While surface water supplies were developed for municipal areas, groundwater was used predominantly in rural areas, for farming, market gardening, orchards, and viticulture. The 1980s kiwifruit boom saw large-scale conversion of farms to kiwifruit orchards, and with it a marked increase in groundwater demand, especially in the Kumeu area and parts of South Auckland. Large water allocations were granted, only to be surrendered as the kiwifruit market declined.

The last 10 years have seen increased horticultural development, particularly in indoor greens, fruit and flowers. The latest trend in horticulture is large, more intensive glasshouse developments (c. 5 ha), with consequently higher water demands. Poultry farms have become a more significant user of water in the region. Golf clubs (approx. 34 clubs in the region) are now irrigating fairways, as well as the traditionally irrigated areas of tees and greens. Pasture irrigation has developed at a steady rate, with the primary limit on development being the huge capital requirements, with limited water resources a close second.

GROUNDWATER MANAGEMENT IN AUCKLAND

In administering the Resource Management Act Auckland, the Auckland Regional Council manages the region's groundwater resources. The primary management tools are the Auckland Regional Policy Statement (ARPS) (Auckland Regional Council 2000), regional plans, non-statutory plans and the resource consent process. The ARPS covers the use, development and protection of natural and physical resources of the Auckland region. It contains a description of issues, objectives, policies and methods for ground-water management. The ARPS includes a policy framework for the preparation of regional plans, for resource consent processing, and the preparation of non-statutory plans.

Currently the Auckland Transitional Regional Plan governs groundwater use in the region. This plan permits the taking of small quantities of groundwater and allows some discharges to ground. Some dairy-shed effluent discharges on to land are permitted in the Auckland Regional Plan: Farm Dairy Discharges (Auckland Regional Council 1999). The Auckland Regional Council is presently preparing an air, land and water regional plan, which will be notified in 2001 (Auckland Regional Council, in prep). This plan will be one of the primary tools for water resource management.

In areas of intensive groundwater resource development, non-statutory plans provide guidance for aquifer management. These plans (a total of 15) provide details of hydrogeology, aquifer recharge, water availability, water allocation guidelines, and details of management issues for the aquifer. Non-statutory plans (called Water Resource Allocation Reports) will still have a significant role in aquifer management within the framework of the new regional plan.

The Auckland Regional Council undertakes a groundwater monitoring programme that includes monitoring both the state-of-the-resource and resource consent compliance. Groundwater levels are monitored at 107 sites throughout the region. Some of these sites are monitored to assist aquifer management; 20 sites are designated for long-term baseline water level monitoring. Twenty-three sites are part of the groundwater quality long-term baseline monitoring programme. Of the approximately 1230 issued consents to take groundwater, 1187 are on the water use self-monitoring programme. As part of this programme consent holders are required to read their meters at specified intervals and submit the returns to the council quarterly. The remainder either are not currently exercising their consent or have yet to fit a water meter.

SUMMARY

Auckland has comparatively low-yielding aquifers, many of which are recharged by rainfall. Groundwater quality is good across the region, although a few aquifers have high iron and boron, which limits the use of extracted groundwater.

Groundwater is used to supply a small part of the Auckland metropolitan area, with most municipal supply coming from surface water supplies in the Hunua and Waitakere Ranges. Groundwater is also used for municipal supply in small rural townships such as Pukekohe, and by industries and horticulturalists. Groundwater supplies baseflow to surface water bodies such as the streams draining Pukekohe Hill.

Although Auckland's aquifers are relatively low-yielding, demand for water is high; in some areas demand exceeds availability and close management by the Auckland Regional Council and local water users is required. High demand aquifers include Onehunga/Mt Wellington volcanics and Manukau sandstone, both used dominantly for industrial supply, and the Kumeu-Hobsonville, Pukekohe and Omaha sandstone aquifers, which are used primarily for horticultural supply.

The current problems facing aquifer management in Auckland are deterioration of groundwater quality from certain land-use practices, stormwater discharges and saline intrusion of coastal aquifers.

REFERENCES

Auckland Regional Council 2000: Auckland Regional Policy Statement. Ch9: 1-9.

Auckland Regional Council 1999: Auckland Regional Plan: farm dairy discharges: 7-8.

Auckland Regional Council in prep: Regional Plan: Air, Land and Water.

Auckland Regional Water Board 1986: Investigation of factors controlling boron concentrations in groundwater in the Auckland Region TP34: 3-7.

Auckland Regional Water Board 1989: Kaawa formation aquifer system in the Manukau lowlands TP85: 70-74.

Balance, P.F. 1976: Stratigraphy and Bibliography of the Waitemata Group of Auckland. New Zealand Journal of Geology and Geophysics 19: 897-932.

Briggs, R.M.; Okada, T.; Itaya, T.; Shibuya, H.; Smith, I.E.M. 1994: K-AR ages, paleomagnetism, and geochemistry of the South Auckland volcanic field, North Island, N.Z., New Zealand Journal of Geology and Geophysics 37: 143-153.

Crane, S.G. 1999: He Kaupapa Tiaki i nga Wai Puia : draft Waiwera geothermal groundwater water resource assessment report. Auckland Regional Council TP115: 13-17.

HOMER, L.; MOORE, P.; KERMODE, L. 2000: Lava and Strata. A guide to the volcanoes and rock formations of the Auckland Region. Institute of Geological and Nuclear Science, Wellington, New Zealand. Pp3-7.

ROSEN, M.R.; HONG, Y.-S.; SHEPPARD, D.; ROBERTS, K.; VILJEVAC, Z.; SMAILL, A.; REEVES, R. 2000: Final report for the IAEA Urban aquifers RCA: determining the effects of storm water infiltration on groundwater quality in an urban fractured basalt aquifer, Auckland, New Zealand. Institute of Geological & Nuclear Sciences Limited science report 2000/20. 54 p.

14

Waikato

JOHN HADFIELD

INTRODUCTION

Groundwater in the Waikato region is a valuable resource used extensively for agriculture, water supply and industry. About 400 wells are drilled annually. The simplified geological map of the region showing the distribution of wells drilled (Fig 14.1) indicates that groundwater resources are developed mainly in the alluvial lowlands where land use is most intense.

Aquifers in the region are varied and include fractured rock in the Tokoroa and Pukekohe areas, small coastal sand aquifers in the Coromandel Peninsula, and the larger highly variable alluvial systems of the Hamilton Basin and Hauraki Plains.

Groundwater makes up about 90 percent of the region's fresh water resources. However, it supplies only a third of all consented consumptive water use (~250,000 $m^3 d^{-1}$ in 1997). Consented groundwater use increased by 43% from 1987 to 1997. A similar quantity of groundwater is taken as a permitted activity (no consent is required to take up to 15 $m^3 d^{-1}$). Up to 230,500 $m^3 d^{-1}$ of geothermal groundwater is also used in the Taupo area.

Groundwater is most intensively used in Pukekohe, Tokoroa, and some parts of the Coromandel, and to a lesser extent in the Hamilton Basin and the southern Hauraki Plains. Potential problems associated with taking groundwater include depletion of the resource, interference between users, reductions in stream flow, subsidence, and saltwater intrusion into coastal aquifers. Groundwater interacts with surface waters, sustaining stream flow during drought and influencing water quality. Integrated management is thus required to ensure sustainability. Groundwater resources of the Waikato are generally not stressed by current water use, as the climate reliably provides sufficient recharge. Average annual rainfall is 1,250 mm, varying from 1,100 mm in the Hauraki Plains to 3,500 mm in the Coromandel ranges, and over 5,000 mm at Mt Ruapehu.

This chapter describes Waikato groundwater resources, based primarily on investigations undertaken by Environment Waikato of selected aquifer systems, and also discusses important water quality issues.

SOUTH AUCKLAND AQUIFERS

The Pukekohe and Pukekawa areas in the north of the Waikato region are hydrogeologically complex. The generally low-angle topography is strongly influenced by Pleistocene basaltic volcanism, with numerous volcanic cones and tuff rings. The basalt aquifers vary substantially in their hydraulic properties depending upon their degree of fracturing, with measured transmissivities ranging from 7 $m^2 d^{-1}$ to 5,600 $m^2 d^{-1}$.

Alluvial Tauranga Group sediments separate shallow basalt aquifers from deeper Kaawa Formation, which is the other major local aquifer. Fine silty sediments at the base of the Tauranga Group form an effective but discontinuous aquitard (Figure 14.2).

The Pliocene, sometimes shelly, marine sand/sandstone Kaawa Formation can reach 300 m in thickness and typically has a local permeability of about 1 m d^{-1}.

The Kaawa Formation is limited southward and eastward by uplift on the Waikato and Drury faults respectively. It is underlain by the Miocene Waitemata Formation. These sandstone and siltstone flysch sediments are generally regarded as hydrogeologic basement but can yield small groundwater supplies.

Hadfield J. 2001: Waikato. *In* Groundwaters of New Zealand, M.R. Rosen and P.A. White *(eds)*. New Zealand Hydrological Society Inc., Wellington. p315-326.

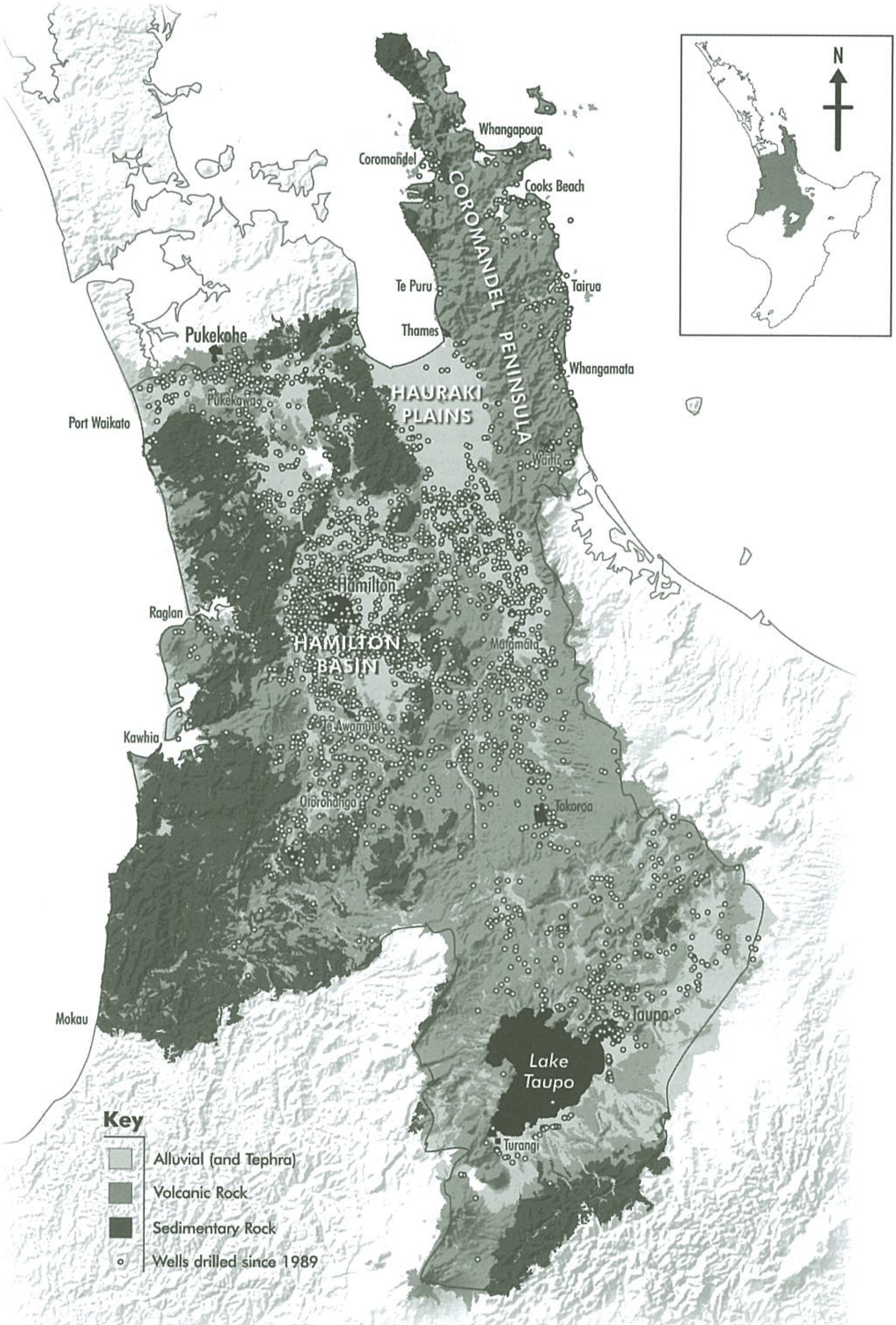


Figure 14.1 *Waikato region geology and wells drilled since 1989.*

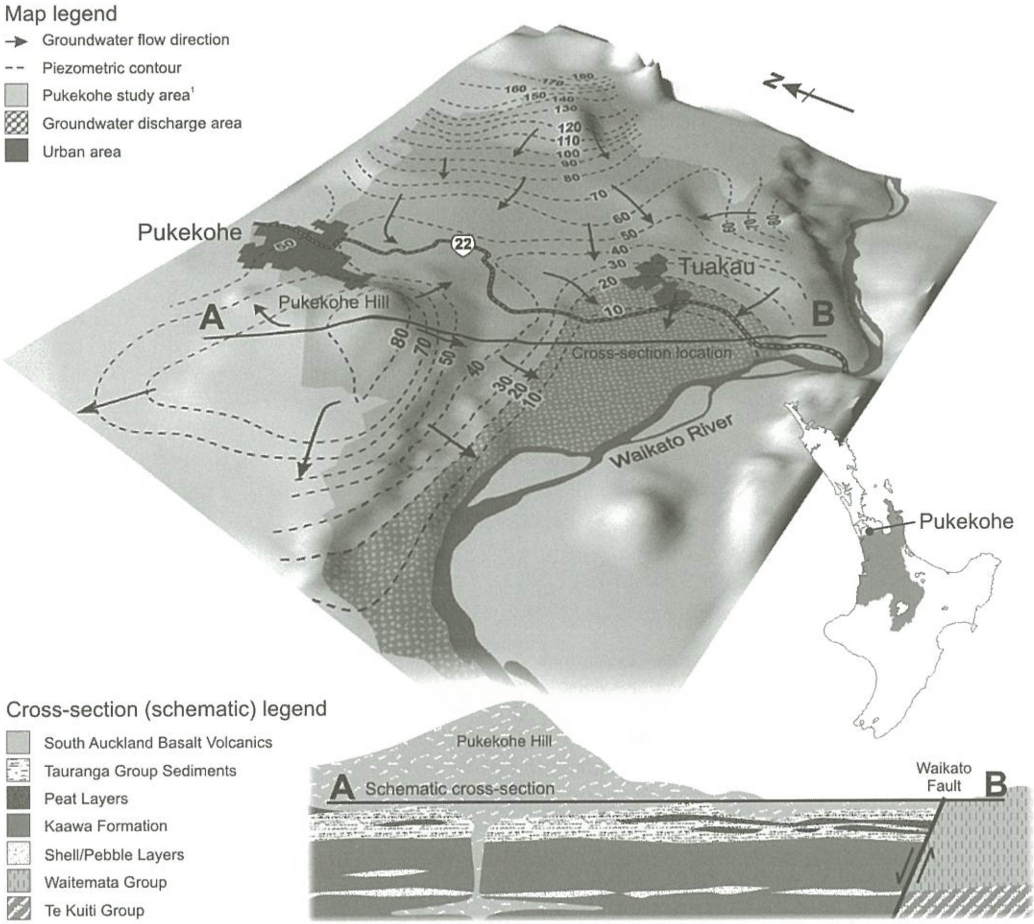


Figure 14.2 *Piezometric surface for shallow aquifers in the Pukekohe area and geological section. (after Petch et al. 1991).*

Piezometric contours for shallow aquifers in the Pukekohe area reflect the topography (Fig 14.2). The largely confined Kaawa Formation is recharged via vertical leakage over much of the area, particularly under Pukekohe Hill. Leakage across the overlying aquitard is estimated to range up to 100 mm and average 50 mm annually. Negative head gradients across the aquitard, however, indicate a discharge regime occurs generally below the 20 m topographic contour.

Water resources are intensively used in the Pukekohe and Pukekawa areas, particularly for market gardening during the summer months. Streams are sustained by groundwater during periods of drought. The five-year recurrent daily low-flow specific discharge is about 2.8 L s^{-1} km^{-2}. Stream-flow responds promptly to variation in shallow aquifer storage, indicating a close interaction (Petch et al. 1991).

Water available in Pukekohe streams for consumptive use is fully allocated and in some cases over-allocated during periods of low stream flow. Careful management is needed to balance the use of both shallow groundwater and stream water.

In 1987, 6,431 m^3 d^{-1} (2.3 x 10^6 m^3 annually) of groundwater was allocated in Pukekohe (59% of all water used in this area). This has more than doubled to 13,944 m^3 d^{-1} in 1997 (just under 10% of effective rainfall). Groundwater use

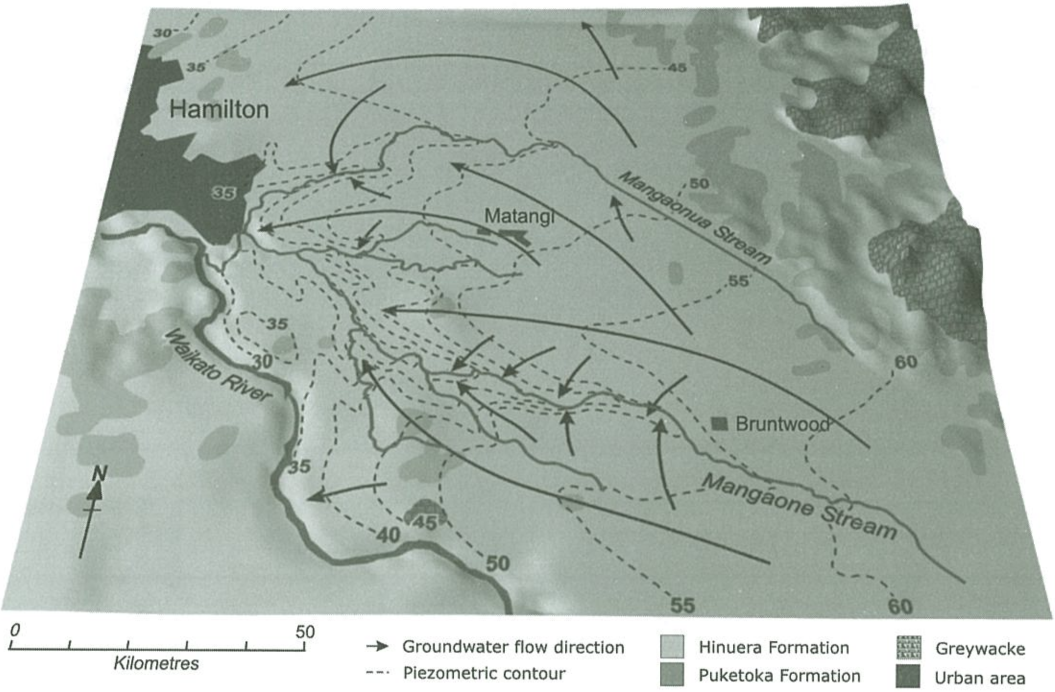


Figure 14.3 *Piezometric contours, groundwater flow directions and geology of the Mangaone and Mangaonua catchments, Hamilton Basin.*

has been directed, by Environment Waikato, to the deeper Kaawa aquifer, thereby minimising the effect on streams and shallow groundwater. The proportion of consented groundwater takes (greater than 15 $m^3 d^{-1}$) from the deeper Kaawa aquifer has increased from 20% of the total take in 1987 to 78% in 1997.

In the ten years to 1997 allocated groundwater use in Pukekawa has increased from 2,507 $m^3 d^{-1}$ (36% of all water use) to 6,937 $m^3 d^{-1}$. Shallow basalt aquifers provide more than 90% of the groundwater used (the Kaawa Formation is absent). As at Pukekohe, the basalt aquifers sustain stream flow, requiring integrated management (Bell et al. 1991).

Groundwater quality in the basalt aquifers is naturally very high, but the shallow aquifers are becoming increasingly degraded from intensive land use e.g. nitrate and pesticide contamination. The Kaawa Formation is less vulnerable to contamination and continues to have high water quality.

HAMILTON BASIN

The Hamilton Basin is a large graben flanked by greywacke ranges (Pakaroa and Hakarimata) and infilled with a thick sequence of largely alluvial Tauranga Group sediments distributed by the ancestral Waikato River (Kear and Schofield 1978).

The most productive aquifers in the basin are lenses of well-sorted sand and gravel. The highly variable and commonly pumiceous, Tauranga Group includes finer silts and clays, as well as common peat layers. Aquifer transmissivities estimated from Tauranga Group supplies tested range from about 10 $m^2 d^{-1}$ to 1000 $m^2 d^{-1}$, but are usually less than 100 $m^2 d^{-1}$ (Marshall and Petch 1985). Groundwater velocities for typical pumiceous sands of the Hinuera Formation have been measured at about 0.2 to 1 m d^{-1} (e.g. Hadfield et al. 1999).

Groundwater is recharged from rainfall and discharges predominantly by effluent flow to incised streams. Isotopic analyses suggest that the groundwater flux is predominantly in shallow aquifers (<5 years old) and groundwater in deeper aquifers is considerably older (thousands of years; Marshall and Petch 1985).

Groundwater contributes up to 85% of the base flow of local streams draining the basin. Only about three percent of the total available water is used in the Hamilton Basin. Three quarters of this is from ground water. There is no evidence of piezometric decline.

Detailed estimates of available water resources were made for the Mangaone and Mangaonua representative catchments (Fig 14.3). Maximum sustainable yield was estimated to be 360 mm y^{-1}, whereas the annual abstractive water use was about 10 mm y^{-1} in 1985. Annual low flow specific discharge varies from 1 to 4 L s^{-1} km^{-2}.

Groundwater quality in the Hamilton Basin is highly variable. Excessive nitrate concentrations are common in shallow, unconfined, aquifers and high iron concentrations are common in deeper and peaty sediments (Marshall 1986).

HAURAKI PLAINS

The Hauraki Plains form part of a young continental rift structure bounded by major normal faults. A large thickness of predominantly Tauranga Group sediments deposited by ancient Waikato River channels infills this major elongated depression structure to a depth of some 3 km (Hochstein and Nixon 1979). The plains are bounded to the west by poorly permeable greywacke of the Hapuakohe and Pakaroa Ranges, and to the east by the Kaimai Ranges (Fig 14.4) which consist predominantly of andesitic and rhyolitic rock.

Alluvial sediments beneath the plains may be described as a large leaky hydraulic system comprising numerous lensoidal aquifers. Groundwater flows northward along the Hauraki Plains toward the Firth of Thames (Fig 14.4). Recharge is from rainfall predominantly in the southern Hauraki Plains. Groundwater in the lower-lying northern plains discharges through artesian upwelling and leakage to streams and swamps. Sediment size and topographic gradient generally decrease toward the north. Substantial peat deposition is common north of Te Aroha.

Groundwater yields, typically less than 200 m^3 d^{-1}, generally increase toward the south, with the most productive well producing about 10,000 m^3 d^{-1}. The highly variable nature of the sediments is reflected in a large range of transmissivities ranging from less than 5 m^2 d^{-1} to about 25,000 m^2 d^{-1}.

Total water use in the Hauraki Plains is a small proportion (about 6 mm y^{-1}) of the total water available each year (effective rainfall is about 420 mm). Long-term monitoring shows the lack of stress on the aquifer system, with

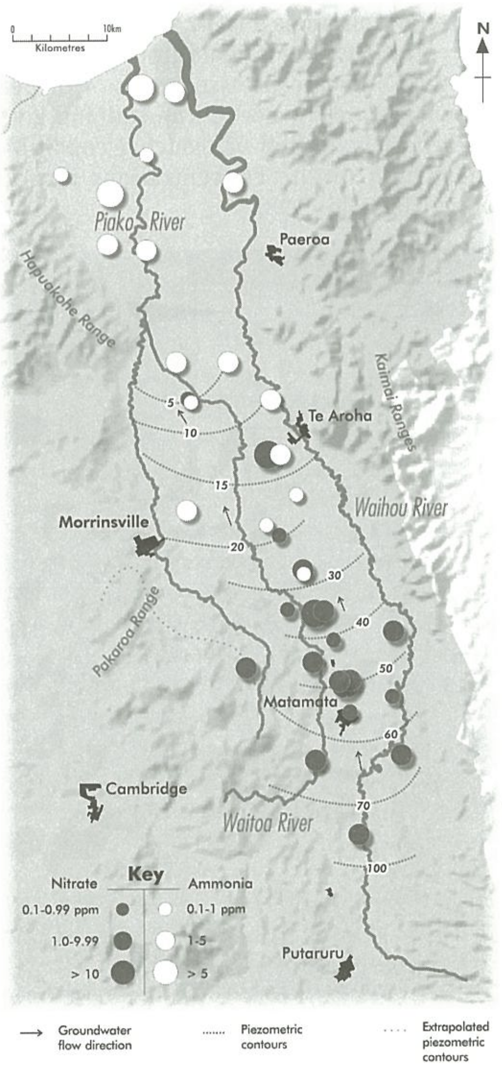


Figure 14.4 *Piezometric contours and nitrogen distribution in the Hauraki Plains.*

no evidence of declining water levels. Over the short term, piezometric levels in a confined aquifer near Matamata were found by Bardsley and Campbell (1994) to respond rapidly to rainfall loading, and the variations provide an estimate of water balance change.

Although the highly variable nature of the Hauraki aquifers is reflected in substantial variations in groundwater quality, there are strong spatial trends along the plains. A progressive change toward more reducing conditions toward the north is indicated by reduced nitrate and dissolved oxygen, and increased ammonium concentrations (Fig 14.4). Excessive iron concentrations, which limit groundwater use, generally increase in association with peat content toward the north. Iron staining gives a practical indication of reducing conditions where high nitrate concentrations are not found (Hadfield 1993).

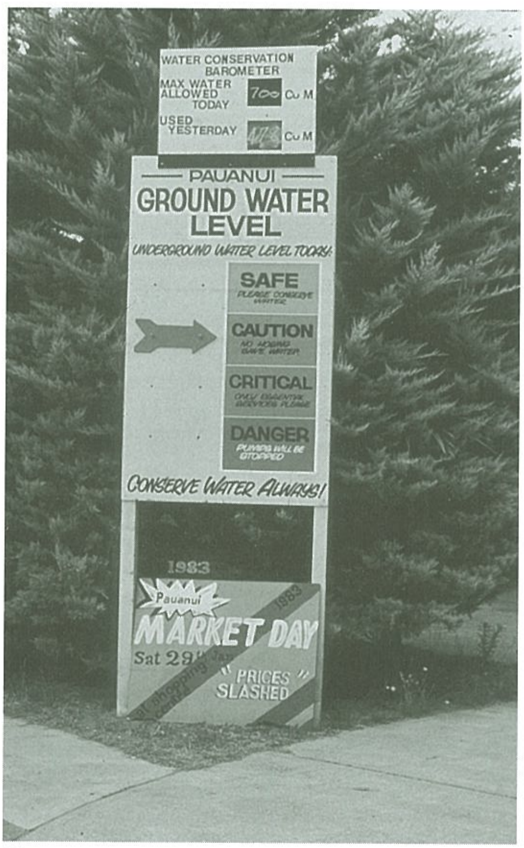


Figure 14.5 *Sign at Pauanui showing groundwater use and availability.*

COROMANDEL PENINSULA

Volcanic rocks (andesite and rhyolite) dominate the geology of the Coromandel Peninsula. These rocks are poorly fractured and generally yield only small volumes of groundwater. Nevertheless, some Coromandel settlements, including Whangamata, Hahei and Onemana, rely on water from fractured rock aquifers. Other settlements, such as Pauanui, Cooks Beach, Matarangi, Whiritoa and Whangapoua are situated on small, coastal sand aquifers from which they derive their water supplies.

Community interest in the sustainable management of these vulnerable aquifers is high (Fig 14.5).

The fractured rock aquifers used for water supply are poorly transmissive, with 13 $m^2\,d^{-1}$ reported for Hahei (Hadfield and Robertson 1991) and 12 $m^2\,d^{-1}$ for Whangamata (Pattle Delamore Partners Ltd 1997). The coastal sand aquifers are more transmissive, with a mean hydraulic conductivity of 15 $m\,d^{-1}$ reported at Pauanui by Woodard Clyde (1991) and about 20 $m\,d^{-1}$ estimated at Matarangi (Simon Carryer & Associates 1984).

Careful management of the coastal aquifers is required to avoid saltwater intrusion. Groundwater demand in these areas is highly seasonal and is increasing. Table 14.1 shows estimated groundwater use and aquifer recharge for those aquifers that have been investigated.

Groundwater quality in the Coromandel Peninsula is generally high. Localised microbial and nitrate contamination has, however, been reported in areas without reticulated wastewater systems.

Table 14.1 *Annual recharge estimates and groundwater use ($m^3\,d^{-1}$) for selected aquifers of the Coromandel Peninsula.*

Aquifer	Recharge	Average use	Summer use
Pauanui	3,650	300 (8%)	900 (25%)
Matarangi	2,300	130 (6%)	390 (17%)
Whangapoua	800	50 (6%)	270 (34%)
Cooks Beach	2,500	250 (10%)	900 (36%)

TOKOROA

Groundwater in the Tokoroa area is derived from a series of ignimbrite sheet aquifers. The Waiotapu and Whakamaru ignimbrites are the most important of these aquifers, providing most of the water for local industry, communities and agriculture. The Waiotapu aquifer in the Tokoroa area is typically 20-50 m thick and underlies 20-30 m of Whakamaru ignimbrite (Bird 1987).

Over 40,000 m^3 of groundwater is abstracted daily from the Waiotapu aquifer, predominantly for use by the Kinleith pulp and paper mill but also for the Tokoroa water supply. Groundwater use is about 20 to 40% of the Waiotapu aquifer throughflow, but there is no indication of overuse. Rapid gains and losses in local stream flow indicate strong interaction between groundwater and surface waters. Over 90% of runoff in the Pokaiwhenua catchment is derived from groundwater outflow.

Transmissivities of the highly fractured and confined Waiotapu aquifer were found by Tracy (1986) to range between 340 and 2,500 $m^2\,d^{-1}$, which is about ten times higher than for the overlying Whakamaru aquifer. Groundwater velocity in the Waiotapu aquifer was estimated to be between 5 $m\,d^{-1}$ and 16 $m\,d^{-1}$ near Kinleith, based on wastewater discharge and groundwater quality records.

Groundwater quality of the ignimbrite aquifers is naturally very high. A large contaminant plume, however, extends northward from the Kinleith pulp and paper mill. Although resin acids are detectable for 4 kms and elevated chloride for 12 kms (Fig 14.6), drinking water guidelines are not exceeded at any neighbouring water supply wells (Carter Holt Harvey 1997).

TAUPO

Groundwater in the Taupo area is taken predominantly from a series of pyroclastic (e.g. ignimbrite) and lesser alluvial aquifers. A major impact on groundwater in this area is geothermal fluid abstraction for power generation (providing 80% of New Zealand's geothermal energy). The geothermal use of up to 230,500 $m^3\,d^{-1}$ compares with about 500,000 $m^3\,d^{-1}$ for all other groundwater abstractions in the region.

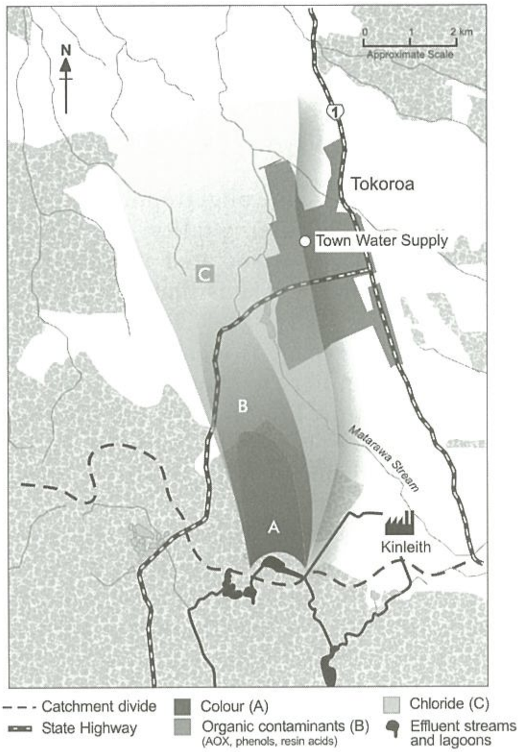


Figure 14.6 *Map of the plume of contaminated groundwater from the Kinleith pulp and paper mill.*

Geothermal extraction for electricity production at Wairakei and Ohaaki/ Broadlands has reduced pressure and temperature, leading to ground subsidence. Changes have also been experienced in heat flow, geothermal features, and flora and fauna in both geothermal systems. There is also evidence at both fields of inflow of cold ground water, especially at Wairakei, where until recently most geothermal waste-water was not re-injected (Department of Scientific and Industrial Research 1988).

The productivity of aquifers in the Taupo basin reflects physical characteristics and mode of transport. Permeability tends to be highest in coarse airfall deposits and well-sorted alluvial sediments. Transmissivity of alluvial sands at Waitahanui, about 10 km south of Taupo, ranges from 900 $m^2\,d^{-1}$ to 2,500 $m^2\,d^{-1}$ ($k \sim 50$ $m\,d^{-1}$). Tracer testing indicated groundwater velocity at this location to be about 0.9 $m\,d^{-1}$

(Hadfield 1995). In contrast, a less permeable rhyolite formation investigated at Waimarino (about 6 kms east of Turangi) using slug and pumping tests indicated a very low mean transmissivity of 0.2 $m^2 d^{-1}$ (Rosen and Coshell 1998).

Lake Taupo is a large oligotrophic lake with extremely high water quality. Growth of phytoplanton and associated reduction in water clarity in the lake is limited by nitrogen levels (Vant and Huser 2000). Groundwater seepage is identified by Rae et al. (2000) as an important source of nutrient enrichment in the littoral zone. Proliferation of nuisance periphyton can generally be ascribed to enrichment of groundwater from human settlements.

Many streams in the Lake Taupo catchment are spring-fed. Direct groundwater seepage to the lake was estimated by Schouten et al. (1981) at about 5% of total inflow. The relative addition of nitrogen to the lake from groundwater would however be substantially greater due the higher nitrogen concentrations in the groundwater. White and Downes (1977) found the inorganic nitrogen concentration of shallow groundwater sampled to average 1.4 ppm, compared to 0.1 ppm for surface waters. It is important to limit nitrogen enrichment of groundwater from land use (e.g. dairy farming) to protect lake water quality.

WESTERN REGION

Groundwater resources in the western region from northern Taranaki to Port Waikato are not substantially developed. Intensive land use is limited to the alluvial lowlands and yields from much of the greywacke and Tertiary limestone, sandstone, and siltstone are poor. Dissolution of limestone by underground water has led to notable karst development in the Waitomo area (Williams 1992).

GROUNDWATER QUALITY

Increases in activities affecting groundwater quality in the Waikato region means careful management is needed to avoid further degradation. The total consented volume of wastewater discharged to land in the Waikato Region has steadily increased during the last ten years to about 540,000 $m^3 d^{-1}$. Manufacturing industry discharge has increased from 12,900 $m^3 d^{-1}$ in 1988 to 81,770 $m^3 d^{-1}$ in 1997.

For community groundwater supplies, the most common groundwater quality parameters that approach or exceed drinking water guidelines are nitrate, arsenic, boron and metals produced by the corrosion of pipes by acid waters (e.g. zinc and copper). Elevated arsenic and boron concentrations in geothermal areas (mainly Taupo) are natural occurrences, whereas nitrate contamination reflects the effects of land use. Localised contamination of groundwater is also evident at numerous contaminated sites, including gasworks, landfills and timber treatment sites. The three main groundwater quality problems considered here are nitrate, pesticide and microbial contamination.

NITRATE CONTAMINATION

Nitrate contamination of groundwater is a major human health and environmental concern (Selvarajah et al. 1994; Chapter 8). High nitrate concentrations have been linked to a blood disorder in bottle-fed babies, known as methaemoglobinaemia or 'blue baby' syndrome (Weisenburger 1991). Groundwater contribution of nitrogen to surface waters also affects their ecology and can lead to eutrophication.

Excessive nitrate concentrations in groundwater are related to land-use activities, including pastoral farming, market gardening, application of nitrogenous fertilisers and industrial and sewage effluent disposal e.g. septic tanks. Nitrogen inputs to surface waters are strongly related to dairy cow stocking rates in most catchments of the Waikato region (Vant and Huser 2000).

Substantial variations in nitrate concentration have been reported during groundwater investigations across the region (Fig 14.7). Levels most commonly exceed the drinking water guideline of 50 ppm (Ministry of Health 1995) in the intensively dairy-farmed Hamilton-Mangaonua area (Marshal 1986) and in Pukekohe, where the predominant land use is market gardening (Ringham et al. 1990). In the Hauraki Plains (Fig 14.4) nitrate concentrations tend to decrease northward, with progressive

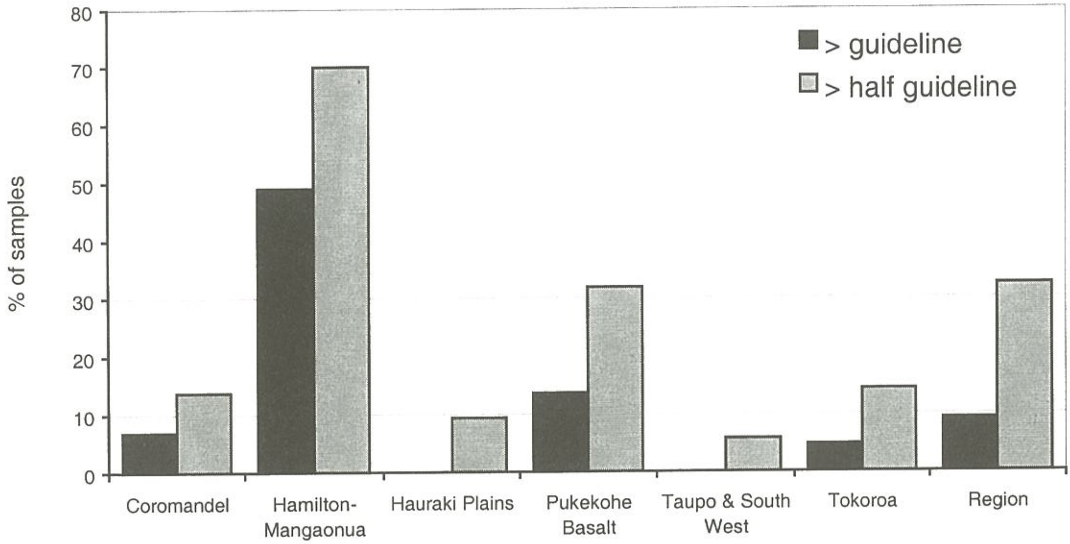


Figure 14.7 *Percentage of samples in sub-regional studies and regional investigations exceeding half guideline and guideline values for nitrates in drinking water.*

changes to lower-lying, finer and more peaty sediments. The decrease is associated with a change from recharge to discharge flow regimes and to reducing redox conditions (Hadfield 1993).

The results of regional groundwater nitrate monitoring at 108 sites throughout the region are shown in Figure 14.7. These sites are mainly shallow aquifers with low iron concentrations. Nitrate concentrations exceed drinking water guidelines at 9.3% of sites, while a third have concentrations over half this value (mean of 21.1 ppm and standard deviation of 25.5). A significantly higher mean nitrate concentration, of 41.8 ppm, was found at market garden sites. Nitrate concentrations are generally highest in shallow, vulnerable aquifers.

A total of 90 schools in the Waikato region use groundwater supplies. Analyses during 2000 showed that one of these supplies had nitrate concentrations exceeding drinking water guidelines and eight had concentrations above half the guideline value. Mean nitrate concentration was 6.94 ppm and the standard deviation was 11.42 (Hadfield and Nicole 2000).

There are few records available to indicate long-term nitrate trends. Monitoring data from school supplies, however, indicate a steady increase at several supplies since the 1950s (Fig 14.8). Nitrate levels above drinking water guidelines are a common and continuing problem in shallow, vulnerable aquifers.

An example of nitrate contamination of groundwater from land discharge is provided by a dairy factory near Cambridge. Land treatment of nitrogen wastewater began in 1968, in preference to direct discharge to the adjacent stream. Monitoring of shallow groundwater showed nitrate contamination from wastewater irrigation peaked at about 70 ppm in the early 1990s (Selvarajah et al. 1994). The management response of reducing the nitrogen load by spraying wastewater over a larger area and ceasing the use of nitric acid for cleaning at the factory has reduced nitrate concentrations to date by half. Denitrification trenches are also being tested at the site, using a sawdust mixture as the medium for passive bio-remediation of the shallow groundwater (Schipper and Vojvodić-Vuković 1997).

PESTICIDE CONTAMINATION

Pesticide contamination of groundwater was investigated in high use areas of the Waikato region. Aquifers considered to be particularly vulnerable to contamination were targeted.

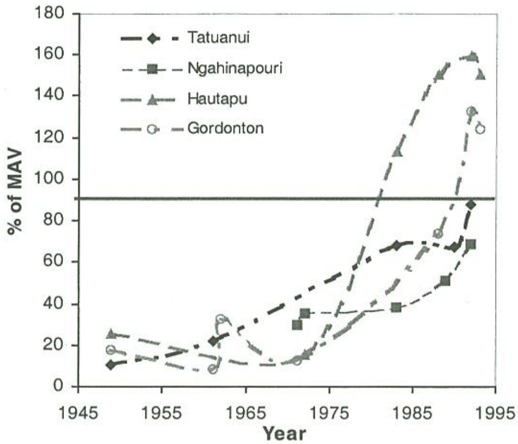


Figure 14.8 *Nitrate concentrations relative to maximum acceptable values (MAV) for drinking water at four selected school sites in dairy farming areas.*

Initially, groundwater samples were collected from 35 sites in the Pukekohe, and Hamilton Basin and southern Hauraki Plains areas (Hadfield and Smith 1997).

Up to 74% of the wells sampled contained detectable pesticide residues. A total of 20 different, mostly persistent and mobile, pesticide active ingredients were identified (Table 14.2).

Atrazine, alachlor, diuron, simazine, terbuthylazine and procymidone were most commonly detected. The concentrations of pesticides detected were generally well below the maximum acceptable values (MAV) for drinking water. Notable exceptions were two sites where dieldrin above the MAV (from nearby former sheep-dips) was detected.

Subsequent quarterly monitoring of 20 of the sites, undertaken over three years, indicated considerable variation in pesticide concentration and occurrence over time. A close relationship between pesticides detected in groundwater and those used at the site was apparent in five cases in the Hamilton Basin. The majority of pesticides in use, however, were not detected. Direct entry of pesticides into wells (e.g. during mixing) was indicated at some sites by the relatively high concentrations and rapid response.

There were also instances where detected pesticides were the result of historical use. Pesticides detected at several sites (at least five) apparently relate to chemical use at a neighbouring property.

Table 14.2 *Pesticides detected.*

Pesticide	No. of Sites	Concentration Range (ppb)	[1]MAV (ppb)
Alachlor	6	0.02-3.67	20
Atrazine	9	0.02-0.38	2
Bromacil	4	0.02-6.37	300 [3]
Dieldrin	2	0.01-0.18	0.03
Diuron	9	0.03-9.5	20 [2]
Hexazinone	2	0.04-0.24	300 [3]
Metolachlor	1	4.5	10
Metribuzine	3	0.02-0.28	50 [3]
Oryzalin	1	0.19	300 [3]
Oxadiazon	1	0.21	n.a[4]
Picloram	3	0.02-2.8	300 [3]
Pirimphosmethyl	1	0.01	100
Procymidone	5	0.01-3.04	700
Pirimisulfuron	1	2.7	n.a[4]
Propazine	1	0.28	50 [3]
Simazine	7	0.01-0.14	2
Terbacil	3	0.08-6.05	30 [3]
Terbuthylazine	7	0.01-0.15	20
Triclopyr	1	0.02	100
2,4-D	1	0.09	30

(1) Maximum acceptable values (MAV) specified in the New Zealand drinking water guidelines. (Ministry of Health 1995)
(2) Provisional MAV
(3) Health value from the Australian drinking water guidelines
(4) No guideline found but toxicity indicated to be quite low.

A potable water-supply well near Hamilton is one of two in which dieldrin was detected, at concentrations (up to 0.18 ppb) in excess of the MAV (0.03 ppb). Detailed investigation at this site showed the well penetrates a plume of contaminated groundwater from the site of a former sheep dip, 14 metres away. Soil around the dip location is heavily contaminated with dieldrin, which persists nearly 40 years after the use of this chemical ceased at the site. Modelling of dieldrin transport indicates that normal (non-preferential) leaching to groundwater is still increasing.

Much of the pesticide contamination detected is a legacy of past use or poor management practices. Careful management and selection of chemicals are needed to avoid adverse effects (Hadfield and Smith 1999).

MICROBIAL CONTAMINATION

The most common health risk associated with drinking water is contamination with micro-organisms that can cause disease, including bacteria, viruses and protozoa. Contamination may occur via poorly constructed wells, and from sources such as septic tanks, animal wastes and offal holes.

Investigations of microbial contamination of groundwater in the Waikato region have focused on areas without sewage reticulation. Studies of seaside settlements in the Coromandel Peninsula (Fig 14.1), found faecal coliforms in about 10% (Whangapoua; Hadfield 1997) to 53% (Te Puru; Tonkin and Taylor 1997) of the shallow wells sampled.

There are reported instances of microbial contamination of community groundwater supplies, however those monitored are generally free of faecal contamination (Institute of Environmental Science 1997). Although there is little information on the extent of individual rural groundwater supplies, an investigation of 40 wells in the Matangi area just east of Hamilton indicates that about 12% were contaminated with faecal coliforms (Tonkin and Taylor 1998).

GROUNDWATER MANAGEMENT

Careful management is required to avoid further degradation of groundwater quality. Environment Waikato maintains a groundwater quality and level monitoring network and investigates baseline character and trends. Point-source discharges and significant use are regulated through conditions for consents and regional rules to ensure sustainable resource management. Environment Waikato collaborates in producing codes of practice for managing non-point sources and is committed to environmental education as a means for managing groundwater quality. A web site has been developed to improve information provision and may be accessed at www.ew.govt.nz.

ACKNOWLEDGEMENTS

Wayne Russell, URS (NZ) Ltd and Dr Earl Bardsley, University of Waikato, provided useful review comments.

REFERENCES

Bardsley, W.E.; Campbell, D.I. 1994: A new method for measuring near-surface moisture budgets in hydrological systems. Journal of Hydrology 154: 245-254.

Bell, A.R.; Cochrane, P.R.; Depledge, D.; Maggs, G.R. 1991: Pukekawa-Onewhero area water resources. Waikato Regional Council Technical Report 1991/29. 90p.

Bird, G.A. 1987: A study of the groundwater resources of the Tokoroa region. Waikato Valley Authority Technical Publication no. 47. 156p.

Carter Holt Harvey 1997: Discharges to groundwater from Kinleith pulp and paper mill wastewater treatment system: Assessment of environmental effects. 68p.

Department of Scientific and Industrial Research 1988: Assessment of development impacts and reservoir response of Tauhara geothermal field. Report for the Waikato Valley Authority. 172p.

Hadfield, J.C. 1993: Groundwater chemistry of the Piako catchment, Hauraki Plains. Waikato Regional Council Technical Report 1993/7. 66p.

Hadfield, J.C. 1995: A groundwater contaminant tracer study at Waitahanui, Taupo. Unpublished University of Waikato MPhil thesis. 289p.

Hadfield, J.C. 1997: Groundwater quality at Whangapoua, Coromandel Peninsula. Environment Waikato Technical Report 1997/8. 30p.

Hadfield, J.C.; Nicole, D.A. 2000: Community groundwater supply protection. Environment Waikato Technical Report 2000/10. 50p.

Hadfield, J.C.; Nicole, D.A.; Thompson, M.A. 1999: A summary of groundwater investigations at the Rukuhia pesticide research site. Environment Waikato Internal Series Report No. 99/03. 33p.

Hadfield J.C.; Robertson, E.D. 1991: Hahei groundwater supply investigation. Waikato Regional Council Resource Consent Report 1991/1. 50p.

Hadfield, J.C.; Smith, D.J. 1997: Pesticide contamination of groundwater: An investigation in the Waikato Region, New Zealand. In: Proceedings of the 24th Hydrology and Water Resources Symposium, 1997: 246-251.

Hadfield, J.C.; Smith, D.J. 1999: Pesticide contamination of groundwater in the Waikato Region. Environment Waikato Technical Report 1999/9. 52p.

Hochstein, M.P.; Nixon, I.M. 1979: Geophysical study of the Hauraki depression, North Island New Zealand. New Zealand Journal of Geology and Geophysics 22: 1-19.

Institute of Environmental Science 1997: Annual report on the microbiological quality of drinking water in New Zealand 1996. Institute of Environmental Science, Christchurch. 141p.

Kear, D; Schofield, J.C. 1978: Geology of the Ngaruawahia Subdivision. New Zealand Geological Survey Bulletin 88. Department of Scientific and Industrial Research, New Zealand. 167p.

Marshall, T.W. 1986: Groundwater chemistry characteristics of the Mangaonua-Mangaone catchments. Waikato Valley Authority Technical Report 86/2. Hamilton. 23p.

Marshall, T.W; Petch, R.A. 1985: A study of the groundwater and surface water resources of the Hamilton Basin. Waikato Valley Authority Technical Publication no. 30. 190p.

MINISTRY OF HEALTH 1995: Drinking water standards for New Zealand. Ministry of Health, Wellington.

NATIONAL HEALTH AND MEDICAL RESEARCH COUNCIL 1996: Australian drinking water guidelines. 252p.

PATTLE DELAMORE PARTNERS LTD 1997: Whangamata water supply: Environmental effects assessment for proposed water supply at Insha Alah subdivision. 32p.

PETCH, R.A.; BELL, A.R.; DEPLEDGE, D.; HADFIELD, J.C.; MAGGS, G.R.; RINGHAM, K.L. 1991: An assessment of ground and surface water resources in the Pukekohe/Tuakau area. Waikato Regional Council Technical Report 1991/12. 141p.

RAE, R.; HAWES, I.; CHAGUÉ-GOFF, C.; GIBBS, M. 2000: Nuisance plant growths in the shallow littoral zone of Lake Taupo. NIWA report for Environment Waikato. 35p.

RINGHAM, K.L.; COCHRANE, P.R.; PETCH, R.A. 1990: Groundwater chemistry of the Northern Waikato district. Waikato Regional Council Technical Report 1990/5. Waikato Regional Council, Hamilton. 73p.

ROSEN, M.R.; COSHELL, L. 1998: Influence of eruptive volcanic lithologies on surface and ground water chemical compositions, Lake Taupo, New Zealand. In Arehart G,B. and Hulston, J.R., (Eds*)* Water Rock Interaction 9: 181-184.

SCHIPPER, L.A.; VOJVODIĆ-VUKOVIĆ, M. 1997: Nitrate removal from groundwater using a denitrification wall amended with sawdust: Field trial. Journal of Environmental Quality 27: 664-668.

SCHOUTEN, C.J.; TERZAGHI, W.; GORDON, Y. 1981: Summaries of water quality and mass transport data for Lake Taupo catchment, New Zealand. Water and Soil miscellaneous Publication 24, Ministry of Works and Development, Wellington. 167p.

SELVARAJAH, N.; MAGGS, G.R; CRUSH, J.R. 1994: Nitrate in groundwater in the Waikato Region. In Currie, L.D. and Loganathan, P. (Eds.) The efficient use of fertilisers in a changing environment: Reconciling productivity with sustainability. Occasional Report 7. Fertiliser and Lime Research Centre, Massey University, Palmerston North. 160-185.

SIMON CARRYER & ASSOCIATES 1984: Report on the groundwater resources of Omaru Spit Matarangi. 24p

TONKIN AND TAYLOR LTD 1997: Te Puru groundwater quality monitoring. 21 p.

TONKIN AND TAYLOR LTD 1998: Nitrate and microbial contamination in the Matangi- Tamahere area. Report for Environment Waikato. 23p.

TRACEY, B.K. 1986: Geohydrological investigations in the Kinleith-Tokoroa region. Unpublished University of Waikato MSc thesis. 183p.

VANT, B.; HUSER, B. 2000: Effects of intensifying land-use on the water quality of Lake Taupo. Proceedings of the New Zealand Society of Animal Production 60: 261-264.

WEISENBURGER, D.D. 1991: Potential health consequences of ground-water contamination by nitrates in Nebraska. In Bogardi, I. and Kuzelka, R.D. (Eds.) Nitrate contamination. *NATO* ASI Series. Vol G30, Springer-Verlag, Berlin. 309-315.

WHITE, E.; DOWNES, M.T. 1977: Preliminary assessment of nutrient loads on Lake Taupo, N.Z. Journal of Marine and Freshwater Research 11(2): 501-507.

WILLIAMS, P.W. 1992: Karst hydrology, In Mosley, M.P Ed. Waters of New Zealand. New Zealand Hydrological Society. 429 p.

WOODWARD CLYDE 1991: Review of Pauanui water supply. Report for Thames Coromandel District Council. 48p.

15

Bay of Plenty

DOUGALL GORDON

INTRODUCTION

The Bay of Plenty region is located on the east coast of the North Island. The region extends from Waihi Beach in the northeast to Cape Runaway to the southwest and includes the catchments that flow into the Bay of Plenty (Fig. 15.1). The land area of the region is 12 247 km^2, with a population of 243 078 (2001 census, provisional results) and the third-fastest regional growth in New Zealand. Just over 60 % of the region's population live within the cities of Tauranga and Rotorua.

Groundwater in the Bay of Plenty is used for urban drinking water supplies, industry, agriculture and horticulture. Groundwater resource assessment began during the 1980s, a time of high demand for water resources for irrigation and frost protection because of the

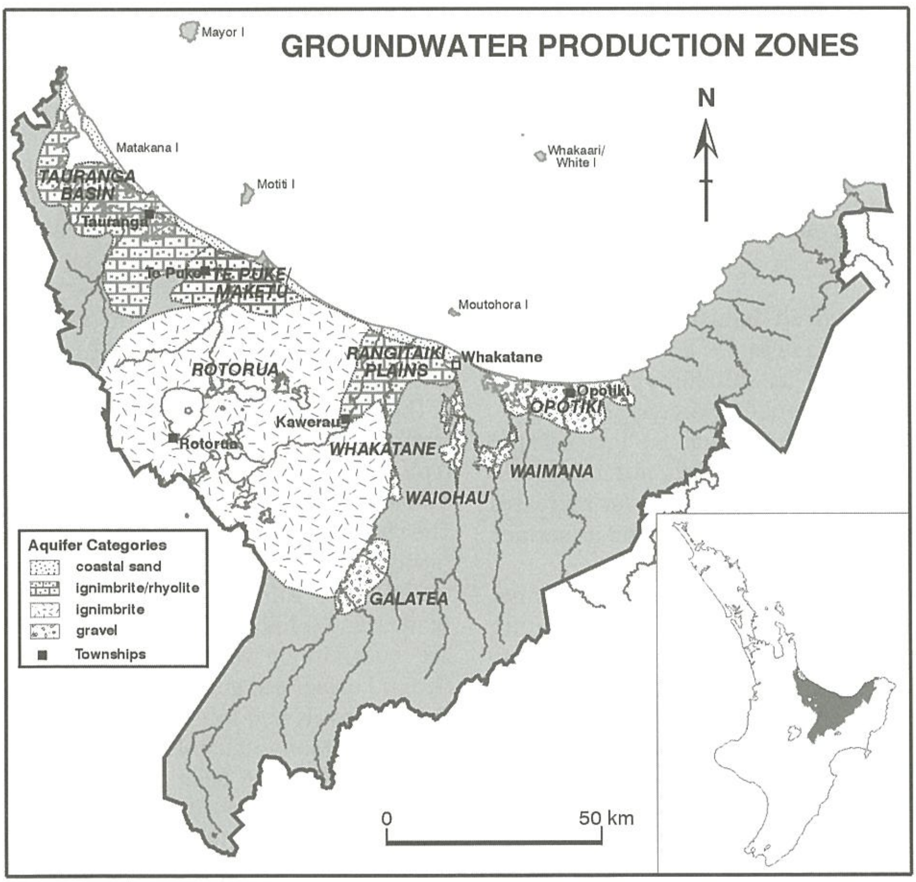


Figure 15.1 *Groundwater production zones in the Bay of Plenty region.*

Gordon D. 2001: Bay of Plenty. *In* Groundwaters of New Zealand, M.R. Rosen and P.A. White *(eds)*. New Zealand Hydrological Society Inc., Wellington. p327-354.

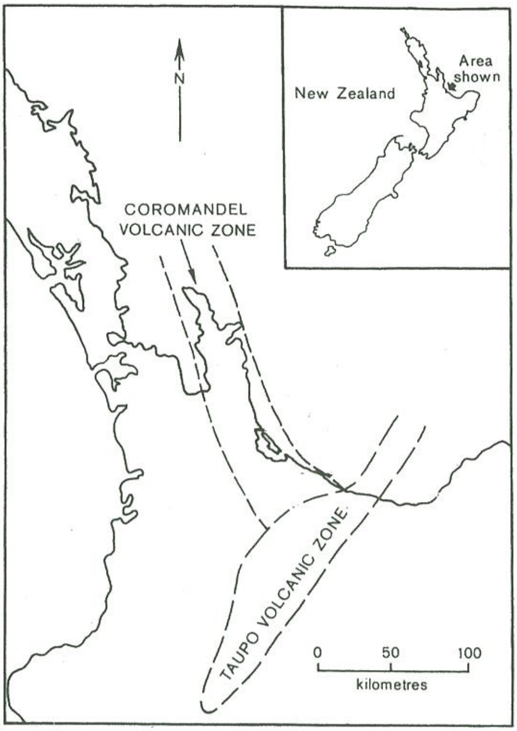


Figure 15.2 *Location of the Quaternary Taupo Volcanic Zone and Miocene Coromandel Volcanic Zone (from Simpson and Stewart 1987).*

expanding kiwifruit industry. Investigations were needed to determine the availability of groundwater and its suitability for kiwifruit irrigation and for public water supplies.

Groundwater is becoming an increasingly important resource, especially for irrigation, as demand for water in the region increases with regional economic growth and as surface resources become fully allocated.

The Bay of Plenty region has a large number of geothermal systems, both low-temperature tectonic and high-temperature volcanic systems. Geothermal fields provide a cheap source of energy for industry, and surface features such as hot springs have been used for recreation since humans arrived.

GROUNDWATER RESOURCES

Groundwater resources are predominantly found in the rhyolite, ignimbrite deposits and volcanoclastic sediments in the Western Bay of Plenty, Tauranga and Rotorua areas. Highly productive ignimbrite aquifers are found on the Rangitaiki Plains in the Eastern Bay of Plenty. The source of these lithologies is the Taupo Volcanic and Coromandel Volcanic zones (Fig. 15.2).

Groundwater resources in the Eastern Bay of Plenty are mostly found in shallow alluvial gravel and pumiceous sand aquifers in the flood plains and river terraces of the Rangitaiki, Galatea, and Opotiki river catchments. There are also numerous shallow sand aquifers within paleo-dune systems along the coastal margins of the region.

The groundwater resources of the region are identified on the basis of production zones where bores have encountered groundwater in the volcanic or alluvial formations. In general aquifers are found within seven production zones (Fig. 15.1): Tauranga basin, Te Puke–Maketu, Opotiki plain, Galatea plain, Coastal plain, Rangitaiki plain, and Rotorua.

TAURANGA BASIN

The two main geomorphic features of the Tauranga area are the Kaimai Range and Tauranga basin. The Kaimai Range is a product of andesitic volcanism and consists of alternating lavas and breccias that define the western margin of the Quaternary Tauranga basin (Fig. 15.3). The andesitic lavas dip eastwards, with possible down-faulting (Simpson and Stewart 1987).

The Tauranga basin has volcanic rhyolite lavas and dacitic to ryholitic ignimbrites and tephras derived from the southern Coromandel Volcanic Zone and the Taupo Volcanic Zone. The stratigraphic sequence consists of andesitic lavas overlain by dacitic and rhylitic ignimbrites known as the Aongatete and Waiteariki ignimbrite formations. These in turn are overlain by the sedimentary Tauranga Group Formation, consisting of series of silts, sands, gravels and intercalated rhyolitic ashes (Fig 15.3). Many volcanic units are the source of debris that has been reworked by fluvial processes and redeposited in sequences interbedded with the volcanic formations (Briggs et al. 1996). The landscape is dotted with a number of rhyolitic lava domes that have been

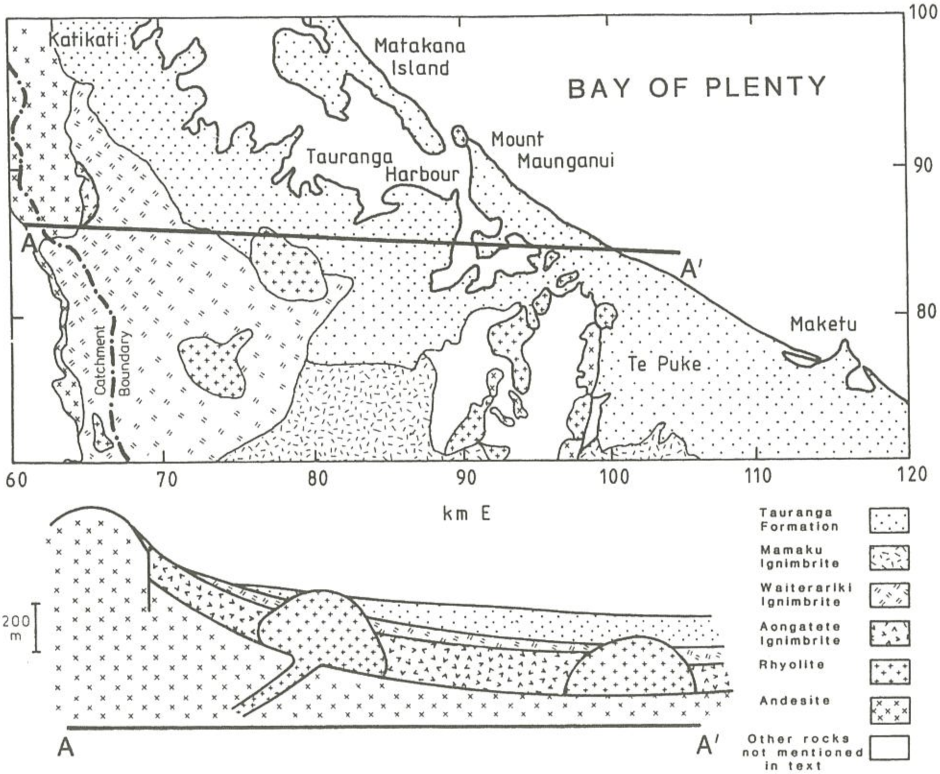


Figure 15.3 *Surface geology of the Tauranga basin and cross section with the stratigraphic relationships (from Simpson and Stewart 1987).*

extruded through the andesitic basement and are now exposed e.g. Mount Maunganui. Many buried rhyolitic lavas domes have been encountered during drilling.

Four general aquifer types are found in the Tauranga basin: ignimbrite aquifers, fractured rhyolite aquifers, sand and pumice aquifers, and gravel aquifers. The hydraulic head is provided by the higher elevation groundwater levels in the Kaimai Range.

Isotopic and geochemical studies have indicated that the Tauranga basin aquifers are recharged by rainfall from higher elevations, albeit very slowly (Simpson and Stewart 1987), but additional recharge occurs between aquifers as a result of leakage from adjoining formations. Yields of 5 to15 L/s are available in most of the Tauranga basin aquifers from correctly designed and constructed bores (Groundwater Consultants New Zealand Limited 1985a).

Low-transmissivity zones occur in the aquifer, within zones of unwelded ignimbrite, and can create flow boundaries and result in large drawdowns (Groundwater Consultants New Zealand Limited 1985a, 1985b). Fractured rhyolite aquifers have been found to produce yields of up to 75 L/s, but the limited extent of these aquifers often restricts their use at higher pumping rates (Groundwater Consultants New Zealand Limited 1989; Woodward Clyde 1991).

Aongatete Ignimbrite aquifer

The Aongatete Ignimbrite aquifer is the main source of cold water and of low-temperature geothermal waters beneath the Tauranga basin. This predominately unwelded ignimbrite formation underlies much of the local basement over most of the Tauranga basin and is overlain by the welded Waiteariki Ignimbrite Formation and the Tauranga Formation (Skinner 1986; Houton and Cuthbertson 1989). The

Aongatete aquifer is most likely confined by the lower-permeability Tauranga Formation sediments. The aquifer extends over an area of approximately 800 km^2, at depths from 200-600 m with an aquifer thickness ranging from 290 m to 490 m, eastward into the Tauranga basin (Skinner 1986). Many of the deep bores drilled into this unit contain warm water, with temperatures between 30°C and 55°C.

The aquifer has a transmissivity of 10-100 m^2/day and storativities of 2.5 x 10^{-4} to 4.5 x 10^{-4} (Groundwater Consultants New Zealand Limited 1985b). Bores generally have large drawdowns over short periods of time at low pumping rates. The aquifer has a relatively high storage coefficient that indicates that it is receiving leakage from underlying or overlying units.

Waiteariki Ignimbrite aquifer

The Waiteariki Ignimbrite aquifer is found within welded dacitic Waiteariki Ignimbrite Formation exposed in the eastern foothills of the Kaimai Range. The formation dips eastward toward Tauranga Harbour and unconformably overlies the Aongatete Ignimbrite aquifer; the top of the formation is non-welded and has been modified by erosion. The aquifer is at least 220 m thick, covering approximately 700 km^2 in the central Tauranga basin. Transmissivities typically range from 10 m^2/day to100 m^2/day. Pump tests indicate that leakage occurs into and out of the Aongatete Ignimbrite aquifer. The aquifer is probably confined by the overlying low-permeability Tauranga Formation sediments.

Minden Rhyolite aquifers

Numerous rhyolitic lava domes have been extruded through the andesitic basement within the Tauranga basin. Bores drilled into these rhyolite domes produce useful quantities of cold and warm groundwater as result of confined fracture flow through the domes. Cold groundwater is used for irrigation. In the Tauranga City area a rhyolite aquifer supplies warm water with temperatures ranging from 30°C to 55°C for heating and swimming pools. The cold and warm rhyolite aquifers are at a reasonably shallow depth (120 m) and are of limited aerial extent (60 km^2).

The long-term sustainable yield of the ryholite aquifer systems is uncertain because the recharge is currently unknown. Typically yields up to 75 L/s are possible, but pump-testing suggests that safe yields of 20 L/s-50 L/s are reasonable (Groundwater Consultants New Zealand Limited 1989; Woodward Clyde 1991). Transmissivities of 500 m^2/day to 1,400 m^2/day and storativities of 2 x 10^{-4} to 7 x 10^{-4} have been estimated for the ryholite aquifers in the Waihi–Anthenree area (Groundwater Consultants New Zealand Limited 1989; Woodward Clyde 1991).

Western Bay sand and gravel aquifers

Gravel and sand deposits found within the Tauranga Group sediments can contain water-bearing formations at depths of 30-150 m. Gravels are reasonably extensive in the foothills of the Katikati–Kauri Point area, but they do not appear to form extensive high-yielding aquifers. The gravels are often poorly sorted and contain a silt matrix, limiting permeability. A number of boreholes have encountered free-flowing conditions in these units, with sufficient yields (5 to 10 L/s) for useful domestic supplies (Groundwater Consultants New Zealand Limited 1985b).

TE PUKE–MAKETU

Groundwater in the Te Puke–Maketu production zone is found within a fault-bounded basin that has been infilled with volcanic rhyolite lavas, dacitic to ryholitic ignimbrites and tephras (Fig. 15.4) from the Coromandel and Taupo Volcanic zones. Many of the volcanic units have been the source of debris and alluvium that have been reworked by fluvial processes and redeposited in sequences that are often interbedded with the volcanic formations (Environment Bay of Plenty 1990).

The aquifers in the Te Puke–Maketu groundwater production zone include shallow gravel, sands, pumiceous sands, pumice, hard fractured ignimbrites, and rhyolites. Shallow bores from 0-40 m depth generally intercept reworked alluvial gravel, sands, and pumiceous sands. Bores drilled to 60-140 m depth generally intercept ignimbrites and rhyolite and at greater than 140 m generally encounter warm groundwater. The fine-grained volcanogenic

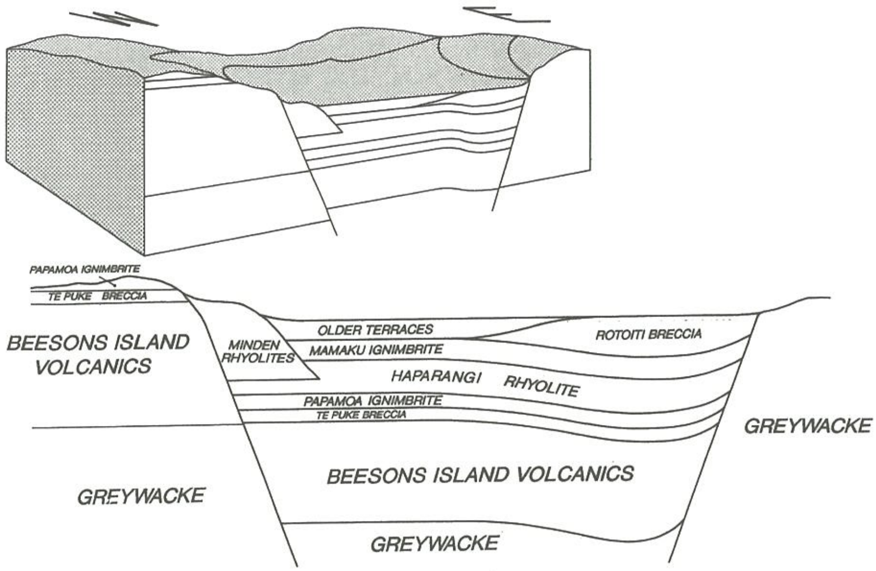


Figure 15.4 *Geological structure and stratigraphic relationships of the Te Puke–Maketu basin (from Environment BOP 1990).*

debris/alluvium appears to confine the shallow pumiceous sand aquifers and the deeper fractured ignimbrite aquifer. To date no correlation has been made between stratigraphic formations and the aquifers, but it is thought that moderately to highly transmissive aquifers occur in the foothills of the Te Puke–Pongakawa area. There a major spring discharge zone correlates with the top of the Mamaku Ignimbrite Formation (Environment Bay of Plenty 1990). Water levels are found approximately 70 m below ground surface in inland areas. At the coast water levels are found at shallower depths, with some flowing artesian bores in the Maketu area.

Recharge is from direct rainfall infiltration inland at the head of the basin, from the Mamaku Plateau and Rotoehu Forest areas. West of Pongakawa, in the Rotoehu Forest, there are a number of blind valleys and streams in which all stream flow is captured, directly recharging groundwater through fractures in the ignimbrite.

Yields of 2 to12 L/s have been found from aquifers in the Te Puke–Maketu basin and yields of up to 100 L/s are encountered in some deep bores. Higher yields tend to be from properly constructed bores in the deeper ignimbrite aquifer at depths of around 90-120 m. Transmissivity values in the deeper ignimbrite aquifers are between 350 m^2/day and 800 m^2/day and storativity values range from 2.5×10^{-3} to 7.5×10^{-4}, which is characteristic of fracture flow. Transmissivity values of up to 700 m^2/day have been measured in the shallow sands and pumice aquifers between 20 m and 32 m depth (Environment Bay of Plenty 1990).

OPOTIKI PLAIN

Groundwater occurs in the lower river alluvial terraces of the Otara and Waioeka river valleys and is found within greywacke river gravel formations. Groundwater is used for municipal supplies, dairy sheds, stock water, and domestic supplies. This area has relatively high rainfall (1400 mm mean annual rainfall), so the demand for groundwater for irrigation is low, however groundwater is used for kiwifruit and other horticultural crops during dry periods. Bore yields of up to 35 L/s have been encountered in adequately constructed bores drilled between 10 m and 70 m deep. Most bores have yields between 2 L/s and 10 L/s.

GALATEA PLAIN

Groundwater is known to occur within gravel fan deposits on the Galatea Plain. The steep streams and rivers of the Ikawhenua Range have transported eroded greywacke gravels and silts that have been deposited on Galatea Plain along with alluvial volcanic pumiceous sand from the Taupo volcanic zone.

Most bores that have been drilled on the Galatea Plain are between 10 m and 40 m deep with generally low yields of 0.3 to 2.5 L/s, and occasional yields of up to 5 L/s. Several bores drilled to 60-80 m have encountered permeable water-bearing gravels with yields of up to 20 L/s. Water-level monitoring indicates that water levels vary from 6 m to 14 m below ground level, and shallower water levels generally occur near surface waterways.

Pump testing has shown that the gravel aquifers are unconfined, with a transmissivity of 1400 m^2/day and a storage coefficient of 0.2 (Carryer & Associates Ltd 1997). These higher permeability gravel deposits are extremely variable and therefore there is some risk in drilling to greater depths to find high-yielding deposits. Zones of shallow higher-permeability gravel are often associated with stream beds. The flow of some streams is completely captured by the permeable gravels, and often emerges in the stream bed downstream as springs.

The yields that have been reported from pump testing are in the range of 0.3 to 2.5 L/s and borelogs indicate that the gravels on the Galatea Plain have a high silt content that limits permeability. This is consistent with resistivity surveys that indicate low-permeability strata (Ministry of Works 1985). It is likely that the gravel plain is too small and too close to the Ikawhenua Range source catchments for streams to create well-sorted permeable gravels (Pattle Delamore Partners 1996).

Groundwater is generally used for dairy sheds, stock water and domestic supplies, but there has been increasing demand for groundwater as a result of an intensification of dairying and demand for pasture irrigation to increase production during dry periods. However the groundwater resource is unproven for irrigation supplies and drilling to find high yields is speculative.

COASTAL PLAIN

Groundwater is found at Waihi Beach, Matakana Island, Mount Maunganui–Papamoa, Pukehina, and Ohope Spit in the paleo-dune systems. The sand aquifers are usually shallow and unconfined and are suitable only for local domestic supplies because of their limited extent and the threat of saline intrusion.

Many shallow groundwater bores are used for residential lawn and garden irrigation in coastal communities such as Mount Maunganui–Papamoa and Ohope. Most bores drilled in the sand aquifers along the coast are less than 10 m deep and have yields of 0.5 to 2.0 L/s. Water levels are generally 3 to 4 m below ground level. The sand aquifers are recharged by rainfall and often have poor water quality as a result of high iron and chloride. These aquifers are subject to contamination from land-use activities because they are generally unconfined.

RANGITAIKI PLAIN

The Rangitaiki Plain is an alluvial coastal plain of over 300 km^2 of alluvial and marine sediments and paleo-dune systems (Environment Bay of Plenty 1991). The Tarawera, Rangitaiki and Whakatane rivers flow northwards over the plain. The elevation of the plain ranges from 30 m asl in the south to below sea level in larges areas of the north. The northern area is cut off from the coast by a large dune system. Large areas of the northern plain are at, or slightly below, sea level and require substantial artificial drainage. This is controlled by a number of pumping schemes discharging groundwater to a network of canals.

The Rangitaiki Plain occupies the Whakatane Graben, an actively subsiding fault-bounded depression with a long-term subsidence rate of greater than 1.9 mm/year (Nairn and Beanland 1989). It is flanked to the east by the greywacke (Fig. 15.5) rocks of the Raungaehe Ranges and to the west by the volcanic Kaharoa Plateau.

Greywacke basement outcrops to the east and volcanic deposits of the Taupo Volcanic Zone outcrop to the south and west. Greywacke basement lies at depths of 1-2 km within the Whakatane Graben, which is infilled with alluvial sediments and volcanic deposits (Figs. 15.6a, 15.6b).

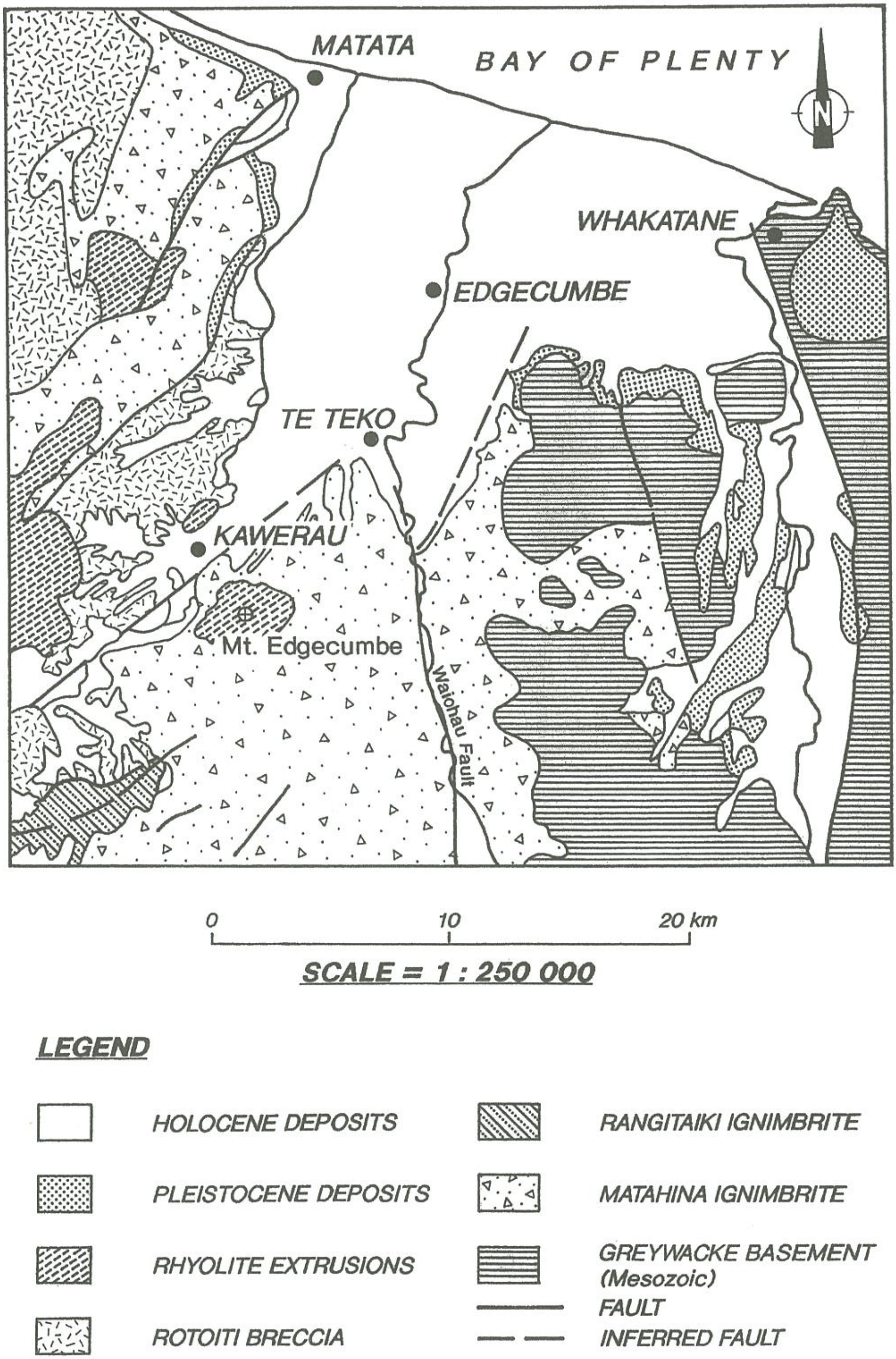


Figure 15.5 *Geology of the Rangitaiki Plains, Eastern Bay of Plenty (from Environment BOP 1991).*

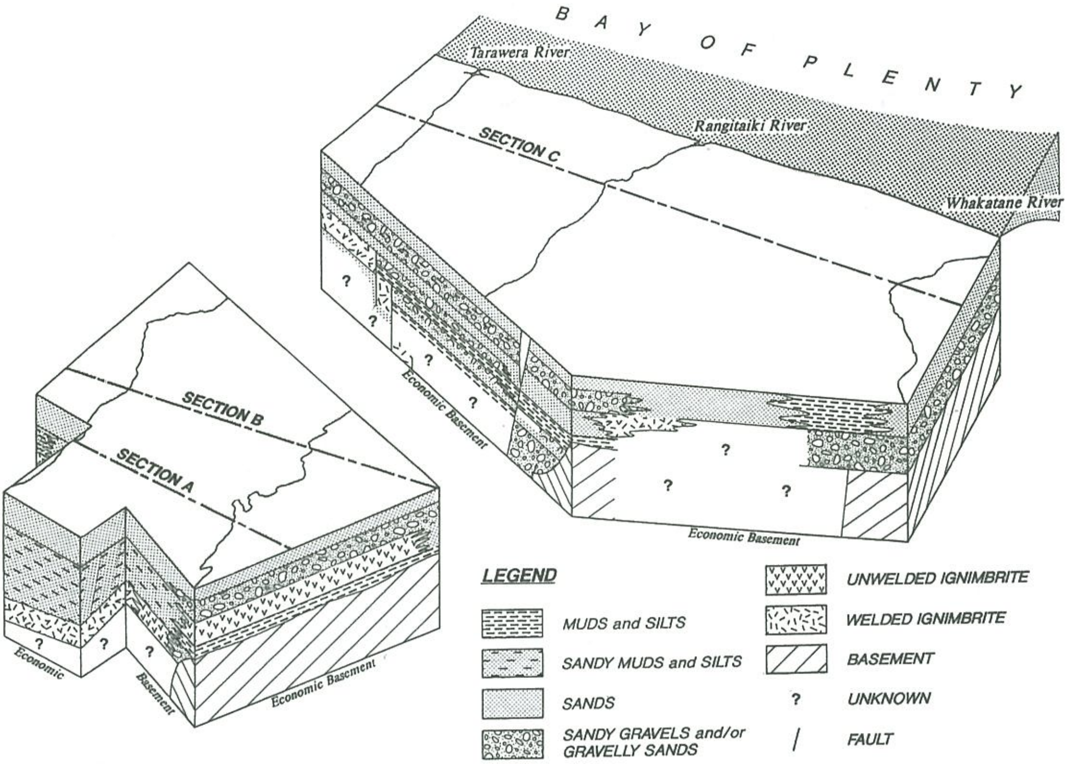


Figure 15.6a *Block diagram of the geology of the Rangitaiki Plains (from Environment BOP 1991).*

The Matahina Ignimbrite and the older Rangitaiki Ignimbrite have been identified beneath the Rangitaiki plains; these units are the product of major volcanic events within the Taupo Volcanic Zone. The likely source of the Matahina Ignimbrite is the Okataina volcanic centre, while the Rangitaiki Ignimbrite is thought to be derived from the Maroa volcanic centre, north of Taupo (Nairn 1999).

The shallow stratigraphy of the plain is dominated by unconsolidated alluvial sediments with alternating sequences of clay, peat, sand/ pumice, and gravel (Fig. 15.7). In the eastern plains the shallowest 10-15 m of sediment consists of alternating dune sands with peat. Elsewhere on the plains the shallowest 30 m of sediment is an alternating sequence of peat/ silt and pumice from the meandering river systems.

The groundwater systems of the plain are divided into a shallow system that is largely unconfined and is defined as extending up to 70 m deep, and a deeper groundwater system that extends below the shallow system to 400 m. The deep groundwater system becomes progressively confined with depth. The 400 m depth is considered to be the maximum that is economically feasible for obtaining potable groundwater (Environment Bay of Plenty 1991).

Shallow aquifer system

The shallow groundwater system is mostly in alluvial material. Shallow aquifers are found across most of the plains, but it is difficult to differentiate between aquifer systems because of the variable geology and limited understanding of the geohydrology. The shallow aquifers on the plain are generally unconfined or semi-confined by layers of peat, clay and silt.

The water yields of the unconsolidated system vary considerably. The highest yields are from the cleaner sand and gravel horizons, with poor yields from silty sand, silt, clay and ash

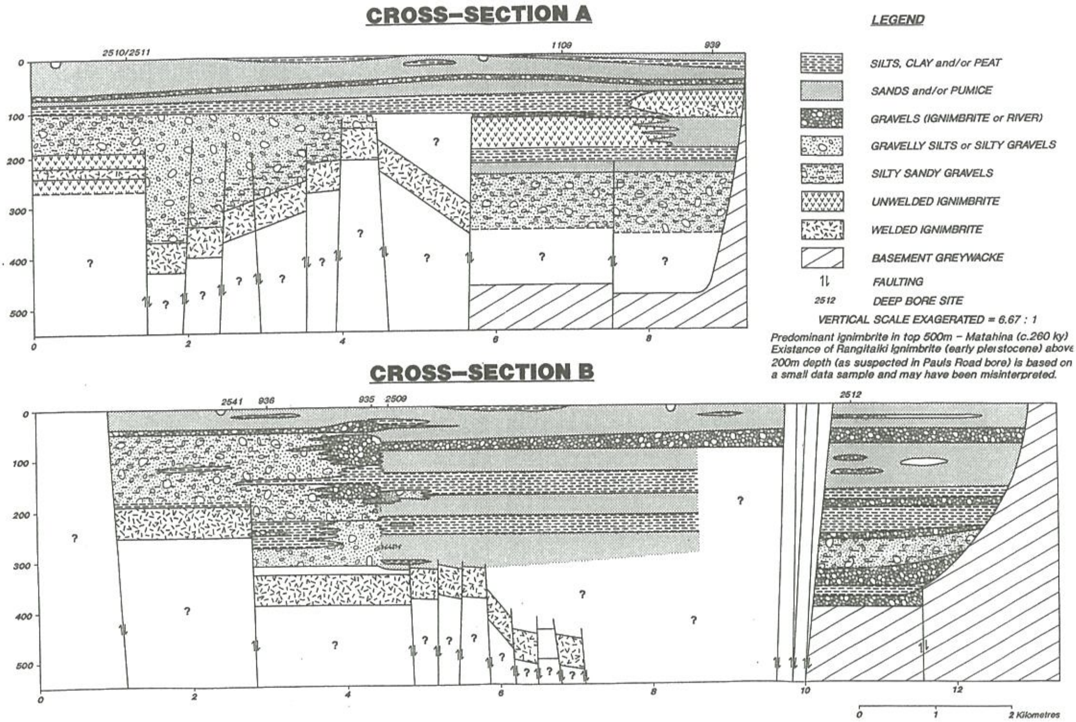


Figure 15.6b *Stratigraphic cross-sections showing the geology of the Rangitaiki Plains, complied from seismic profiles (Woodward 1988; O'Connor 1990) and borelog stratigraphy (from Environment BOP 1991).*

horizons. The average transmissivity is 445 m^2/day, but transmissivity values of between 200 and 500 m^2/day are considered to be representative of most of the shallow system (Environment Bay of Plenty 1991).

Sources of recharge to the shallow aquifer systems include rainfall from the surface drainage system, rivers, seepage from higher areas above the plains, and vertical leakage from the deeper aquifer systems. River gauging investigations have not shown any significant recharge of the shallow groundwater by rivers and surface drainage on the plain. Water-level monitoring shows that the shallow aquifer system responds to rainfall events. It has been estimated that between 15% and 30% of rainfall contributes to the shallow groundwater recharge on the plains (Environment Bay of Plenty 1991).

Shallow groundwater levels generally closely follow the topographic contours. Groundwater levels between Edgecumbe township and the coast are, to a significant extent, artificially controlled by a complex drainage system of pumping stations, floodgates and stopbanks. Numerous schemes pump water from the water table aquifer into canal systems, which then discharge to the major rivers. The groundwater level near coastal pump stations can fall to as much as 3 m below mean sea level from dewatering.

Water levels range from below mean sea level near the coast to between 11 and 13 m below ground surface at the head of the Tarawera and Rangitaiki River valleys, with annual changes typically ranging from 0.5 to 1.5 m. There are major springs located on the periphery of the Rangitaiki Plain, with Braemar and Jennings springs located on the western plain. Holland and Pumphouse springs are located on the southern Rangitaiki Plain near Kawerau. Braemar and Jennings springs supply the town of Edgecumbe and rural communities in the Whakatane District, and the

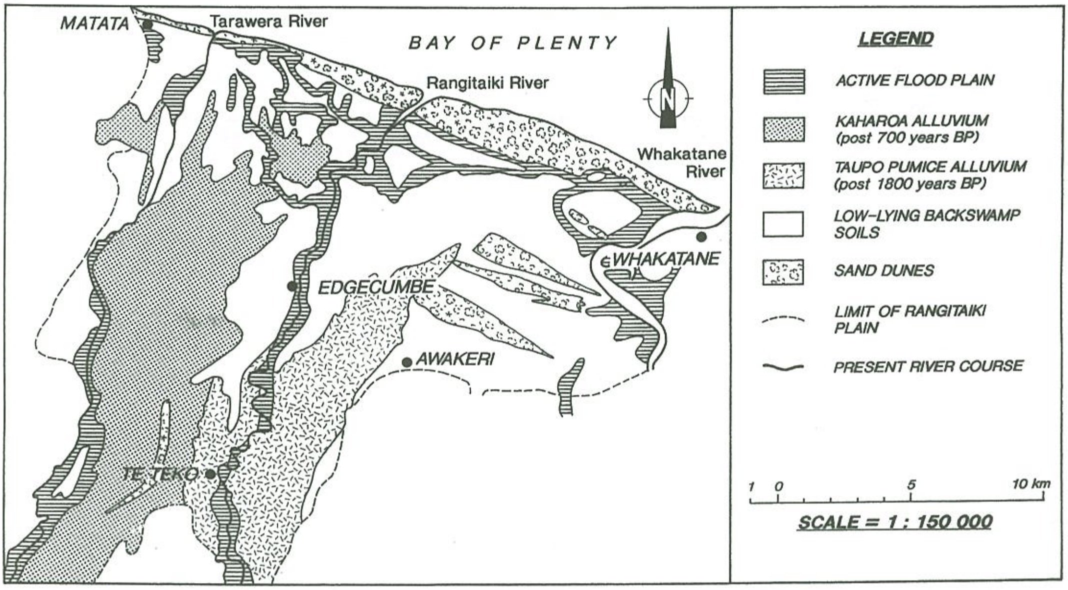


Figure 15.7 *Surface geology of the Rangitaiki Plains is dominated by alluvial material—peats, silt, pumice, sands, gravels and dune sand deposits (from Environment BOP 1991).*

Holland and Pumphouse springs supply communities of the Kawerau District. Pang (Environment Bay of Plenty 1994b) suggest that the recharge for the springs is from the adjacent upland hill catchments.

Deep aquifer system

The deep aquifer system, down to the economic basement of 400 m, is largely composed of unconsolidated alluvium, including gravel, sand, pumice, ash/silt/peat horizons and consolidated hard rock of volcanic ignimbrites. The ignimbrites tend to occur in the southwestern plain at Otakiri, although ignimbrite has been identified in the boreholes in the northern plain.

Geohydrological data on the deep aquifer systems is incomplete because of the limited number of drill holes, and it is not possible to correlate aquifers across the plain. A number of deep bores penetrate aquifer systems that contain unconsolidated volcanoclastic sediment. In the northeastern plain, and central and western plain, silt-sized material is associated with low-yielding aquifers. In the southeastern plain pumiceous and greywacke gravels and sands form higher-producing aquifer systems (Environment Bay of Plenty 1991).

In the southwestern plain near Otakiri, pumiceous sands and gravels form part of a pressurised artesian system at depths greater than 100 m. The lower parts of this unconsolidated system may be the upper unwelded portion of the Matahina Ignimbrite Formation. About 100 km^2 of the Matahina Ignimbrite is downfaulted within the Whakatane Graben to between 120-300 m depth (Woodward 1988), which makes the Matahina Ignimbrite a significant aquifer resource on the Rangitaiki Plain. The primary porosity is low, resulting in low yields, but yields are higher in the deeper, welded zones where water is stored and transmitted through fractures, cavities and joints (Environment Bay of Plenty 1991).

Transmissivity values for the deeper aquifers range from 18 to 6000 m^2/day. Transmissivities in the unconsolidated pumiceous sand and gravel aquifers range from 200-900 m^2/day with an average of around 400 m^2/day. In the southeastern plains, values of 1500 m^2/day are found. Transmissivities in the range 6000 to 12000 m²/day are found in fractured ignimbrite near Otakiri in the southwestern plains. Large volumes of water are available in the fractured ignimbrite units. The deep fractured aquifer systems are generally artesian, with water levels up to 20 m above ground level on the western plain margin (Environment Bay of Plenty 1991).

Most wells show no seasonal fluctuation in water level. The presence of low permeability horizons and increasing heads with depth suggests that the recharge source is beyond the plains. Deep recharge is likely to be occurring from volcanic formations in the west and south and also from transmission at depth from the upper river catchment alluvium. Oxygen-18 isotope results indicate a widespread rainfall source at an altitude of 100 m. Tritium and oxygen isotope analysis of samples from deep bores at Otakiri and Braemar Springs indicate that the mean residence time of the deep groundwater is about 50-100 years. From the tritium results the total storage volume of the Braemar Springs is around 6.3 million m^3, at least 50 times the annual discharge (Environment Bay of Plenty 1991).

Recharge of the deep groundwater in the eastern plain is probably from seepage through transmissive materials underlying the upper Rangitaiki River valley. Considerable uncertainty exists as to the discharge mechanism for the deep groundwater. No bores greater than 100 m exist along the coast, but the horizontally stratified nature of the sediments and a projection of the gradient of the deep Otakiri system suggest a discharge point off the coast (Environment Bay of Plenty 1991).

ROTORUA

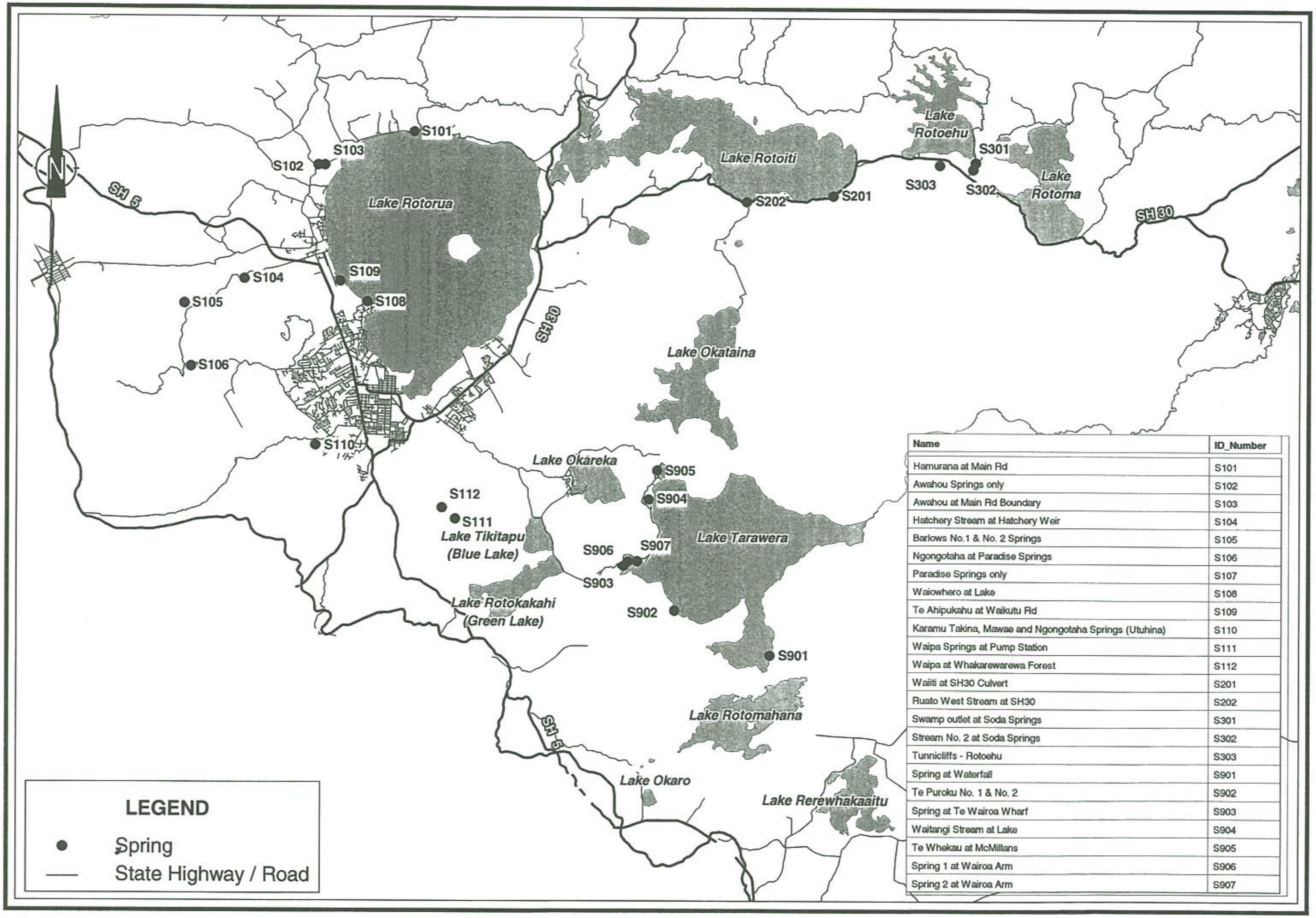
The Mamaku Ignimbrite is the most significant geological formation containing groundwater resources in the Rotorua area. The ignimbrite was erupted from the centre of present Lake Rotorua, approximately 220 000-230 000 years BP. The lake now occupies a large part of the caldera that resulted from the subsidence following the ignimbrite eruption (Houghton et al. 1995). The ignimbrite extends over an area of 100 km^2, is 120 m thick and contains two units. The lower unit is strongly welded and highly fractured. The upper zones of the Mamaku Ignimbrite are increasingly friable towards the top, with associated increases in porosity, and perhaps permeability, as result of vapour phase alteration by hot gas streaming through the sheet soon after emplacement (Rosen et al. 1998). Numerous rhyolitic lavas and domes were extruded through this ignimbrite. Later eruptions (late Quaternary) deposited loosely compacted pyroclastic pumice, breccias and tephras of varying thickness (up to 30 m), some of which have been reworked by fluvial processes.

Most bores in the Rotorua area are drilled 40-80 m into ignimbrite and rhyolite aquifers. Bores on the Mamaku Plateau are drilled to 100 m depth into ignimbrite aquifers. The extensively fractured rhyolite and ignimbrite aquifers have low to moderate bore yields but are the source of numerous highly productive springs (Pang et al. 1996).

Six of the identified springs (Fig. 15.8) are used for public water supply by the Rotorua District Council. Almost all the identified springs have flow rates greater than 20 L/s, with the highest producing springs in the Mamaku Ignimbrite (Rotorua District Council 1993).

The upland plateaus are the recharges areas for the ignimbrite and ryholite aquifers, and the lakes and rivers are discharge areas. The top unwelded zone of the Mamaku Ignimbrite contains uncompacted friable pumice that is very permeable and allows movement of water downward into joints within the ignimbrite formation. Surface water can enter large depressions or holes that can be 10-30 m deep and 3 m across. Surface water recharge to the aquifers through these depressions and holes occurs during storms. At depth the joints form permeable flow paths for horizontal groundwater flow, with the unwelded zone and the welded zones often functioning as preferential flows paths. Water can perch on welded zones and flow down the dip direction of the ignimbrite to emerge from springs (Rosen et al. 1998).

The large lakes such as Rotorua and Tarawera



Name	ID_Number
Hamurana at Main Rd	S101
Awahou Springs only	S102
Awahou at Main Rd Boundary	S103
Hatchery Stream at Hatchery Weir	S104
Barlows No.1 & No. 2 Springs	S105
Ngongotaha at Paradise Springs	S106
Paradise Springs only	S107
Waiowhero at Lake	S108
Te Ahipukahu at Waikutu Rd	S109
Karamu Takina, Mawae and Ngongotaha Springs (Utuhina)	S110
Waipa Springs at Pump Station	S111
Waipa at Whakarewarewa Forest	S112
Waiiti at SH30 Culvert	S201
Ruato West Stream at SH30	S202
Swamp outlet at Soda Springs	S301
Stream No. 2 at Soda Springs	S302
Tunnicliffs - Rotoehu	S303
Spring at Waterfall	S901
Te Puroku No. 1 & No. 2	S902
Spring at Te Wairoa Wharf	S903
Waitangi Stream at Lake	S904
Te Whekau at McMillans	S905
Spring 1 at Wairoa Arm	S906
Spring 2 at Wairoa Arm	S907

Figure 15.8 *Cold water springs of the Rotorua groundwater production zone (adapted from Pang et al. 1996).*

are the main discharge area for groundwater in the Rotorua area. Small lakes such as Rotoma, Okareka and Rotokakahi are discharge areas for local groundwater and also act as recharging lakes, through part or all of the lake bed, to other lakes in the area (Pang et al. 1996). Lakes such as Rotoehu, Okataina, Tikitapu and Rerewhaaitu have no surface outlets and therefore are likely to recharge the regional groundwater.

GROUNDWATER QUALITY

The water quality of Bay of Plenty groundwater is generally very good, but many bores have elevated levels of iron, manganese, arsenic, boron, nitrate and bacteria. A survey of arsenic levels in municipal supplies showed elevated levels of arsenic in groundwater supplies at Waihi beach, Rotorua, and Rangitaiki Plains. The high arsenic is likely to be derived from geothermal activity.

Bay of Plenty groundwaters are dominated by bicarbonate anions; high iron and manganese levels are found in the region's shallow aquifers and can also occur in the deeper aquifers. High silica content is also common in Bay of Plenty groundwaters because of the relatively high abundance of silicate minerals in the volcanic rhyolitic pumice and ignimbrite aquifers. The high silica content is likely to be the source of high alkalinity values. Waters from the ignimbrite aquifers are generally aggressive, with pH values between 6 and 6.5.

The Tauranga basin ignimbrite and rhyolite aquifers have good water quality, apart from moderate iron concentrations, and the water is generally suitable for horticultural irrigation and domestic uses. Water in the Te Puke–Maketu basin is moderately corrosive, with some bores having elevated iron levels, especially at Paengaroa. Groundwater is generally suitable for horticultural irrigation and stockwater. Some bores near Maketu and other coastal areas area have elevated chloride as a result of seawater trapped in the sediments.

Shallow groundwater on the Rangitaiki Plain generally contains higher concentrations of iron than deep groundwaters. The shallow groundwater of the plains is dominated by sodium and bicarbonate water types (Environment Bay of Plenty 1991) typical of what would be expected in a shallow unconfined system. The shallow groundwater aquifers generally have variable water quality because of high levels of iron and boron, but there are no geochemistry indicators that would suggest a geothermal input for the boron. The source of the high iron and boron is probably layers of peat and organic material in the aquifer sediments. This has been confirmed by high concentrations of boron found in peat deposits, particularly where peat has formed in saline or estuarine conditions (Kear and Ross 1961). The areas with the highest concentrations of iron (Fig. 15.9) and boron (Fig. 15.10) coincide with the largest peat deposits found in the central and northern plains, between the towns of Edgecumbe and Thornton.

Shallow groundwater aquifers in the central plain do not meet iron and boron guidelines for potable, irrigation, and boiler-feed water. High iron and manganese cause staining of plumbing fixtures and laundry and can accumulate in pipe work. High iron causes blockages to irrigation lines and boron is harmful to some sensitive crops such as kiwifruit. The low alkalinity, pH and total dissolved solids of the groundwater also make it unsuitable for boiler-feed water.

Nitrate is elevated in the shallow groundwater, but for most bores it is generally below drinking water guidelines. The elevated nitrates are from intensive agriculture and horticultural activity on the plains.

The Kawerau geothermal field influences the groundwater quality in the southern plains. High arsenic levels (11-16 μg/L) are typically found in groundwater that provides a municipal water supply to Kawerau township; the arsenic is probably from the nearby Kawerau geothermal field.

The water quality of the Rangitaiki Plain deep ignimbrite aquifers is generally very good and the water is widely used for irrigation and potable supplies. Deep groundwater is used for public water supplies because of its generally high quality. The recharge area for the deep

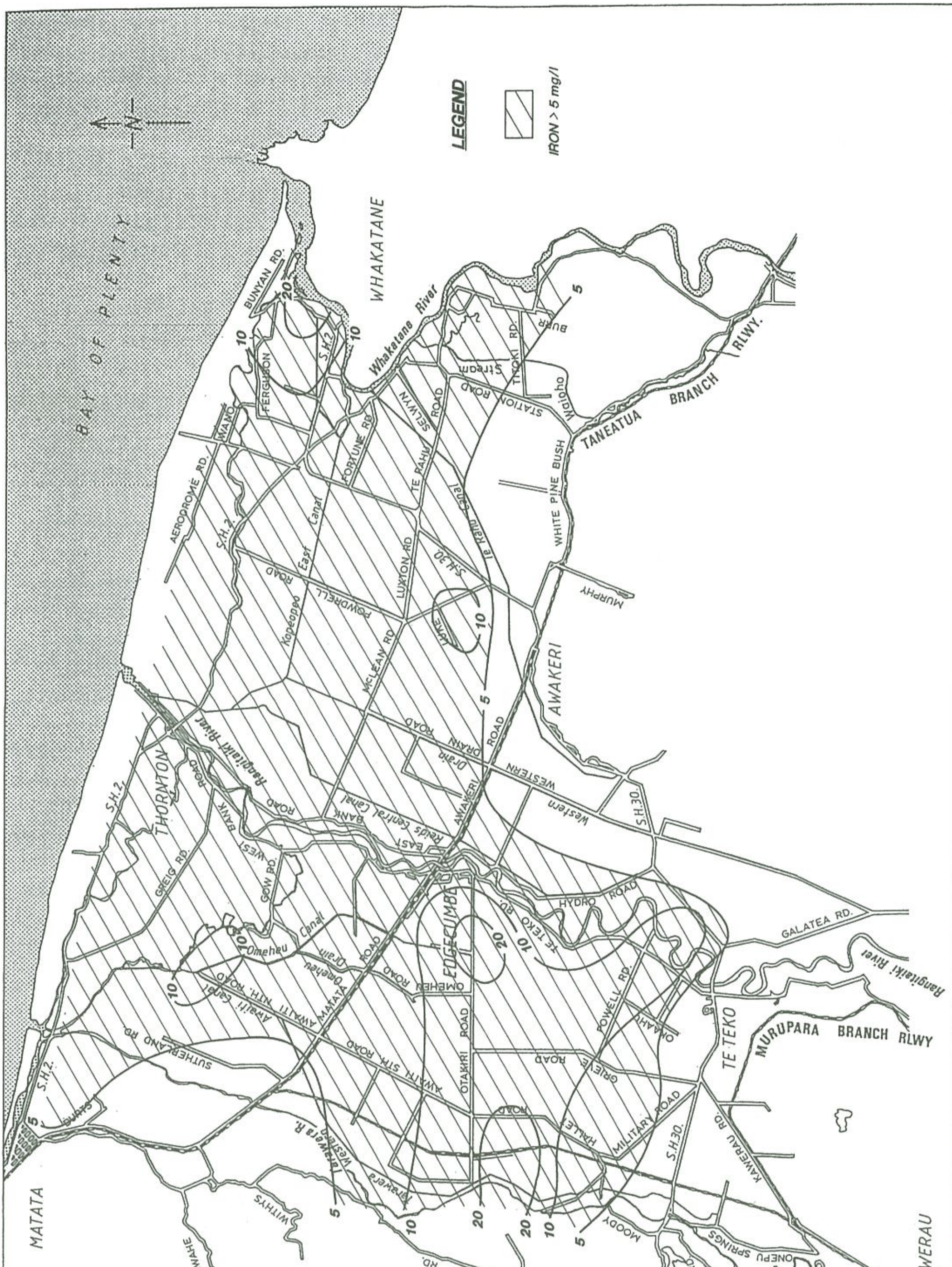


Figure 15.9 Contour map of iron concentrations in the shallow groundwater aquifers of the Rangitaiki Plains (from Environment BOP 1991).

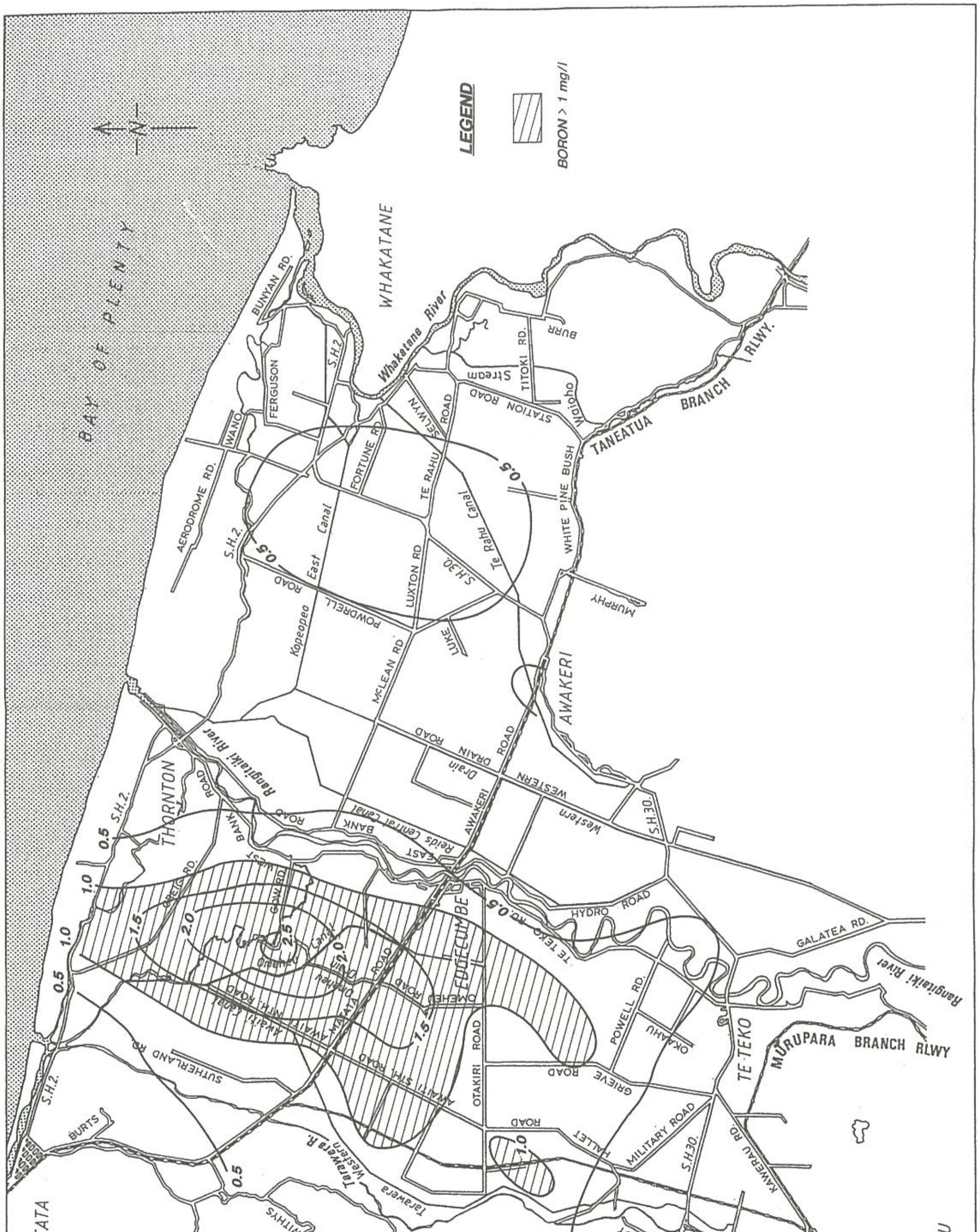


Figure 15.10 Contour map of boron concentrations in the shallow groundwater aquifers of the Rangitaiki Plains (from Environment BOP 1991).

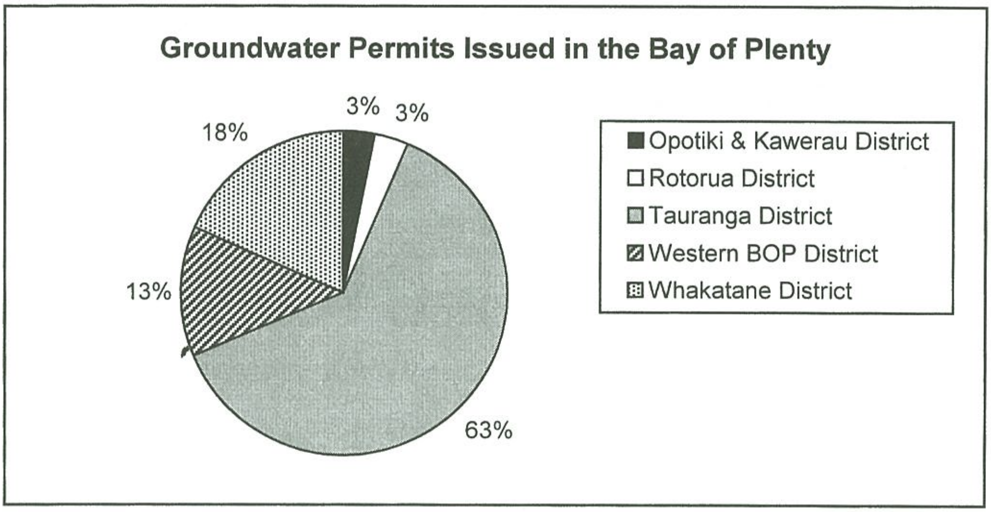


Figure 15.11 *Percentage of groundwater permits by district in the Bay of Plenty region.*

groundwater area is likely to be beyond the plains, away from the effects of intensive horticulture and agriculture.

Deep groundwater is very soft (low total dissolved solids) and is slightly acidic. The water from the deep system is thus corrosive to metallic pipe work or reticulation, and corrosion-resistant materials for bore construction are desirable. The deep groundwater also has a moderate to high silica content, which can cause scale problems in hot water or boiler systems. High iron concentrations occur in some deep bores that penetrate alluvial aquifers. High arsenic levels (8 μg/L) have been found in deep municipal water supply bores that penetrate the ignimbrite aquifers at Otakiri (Davies et al. 1994). High arsenic levels have also been found in the Braemar and Pumphouse springs, which are municipal water supplies, but drinking water guidelines for arsenic are exceeded only in the Braemar Spring waters (Davies et al. 1994).

The water quality of ignimbrite and rhyolite aquifers in Rotorua is good and generally complies with potable water quality guidelines. However water from the ignimbrite aquifers is characteristically very soft (low total dissolved solids) and is slightly acidic, which makes the water moderately aggressive and corrosive to metallic pipe work or reticulation. Groundwater that is used for public water supplies is usually treated to reduce the aggressive and corrosive effects.

GROUNDWATER USE AND MANAGEMENT

Environment Bay of Plenty requires water permits for any groundwater abstractions of over 15 m^3/day. Over 75% of permits issued by Environment Bay of Plenty are within the Tauranga and Western Bay of Plenty districts (Fig. 15.11), and over 83% of all permits are for horticultural irrigation (Fig. 15.12).

Groundwater in the Tauranga Basin is extensively used for horticultural irrigation and also for domestic and stock water supplies. The warm groundwater found in the Tauranga Basin is used for private spas and public swimming pools, and heating homes and greenhouses.

The shallow aquifer resources on the Rangitaiki Plain are extensively used for domestic and stock water. The deep groundwater is mostly used for horticultural irrigation and municipal water supplies. Groundwater-fed springs supply the city of Rotorua and the small communities around Lake Rotorua. Springs also supply the rural towns and communities on the Rangitaiki Plain. The Holland and Pumphouse springs supply communities in the Kawerau District and the Braemar and Jennings springs supply the town of Edgecumbe and rural communities in the Whakatane District.

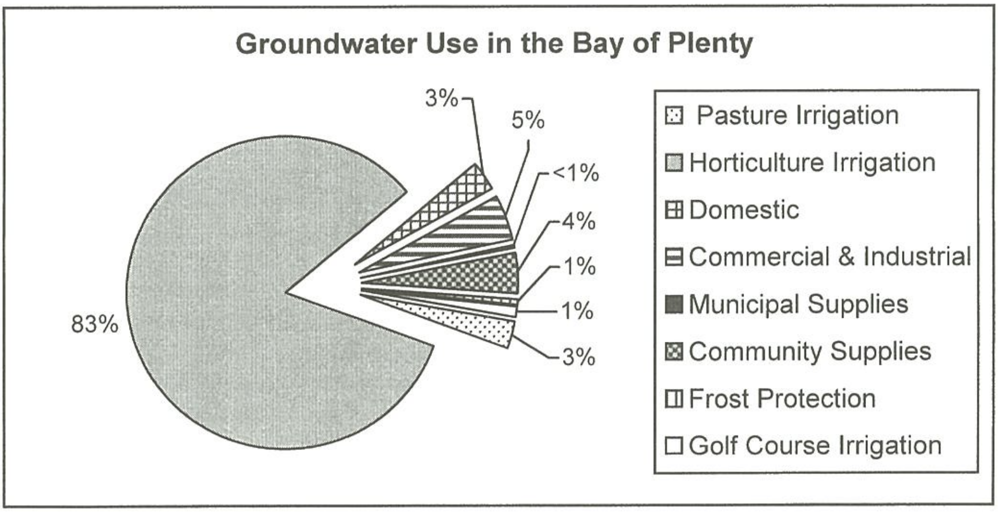


Figure 15.12 *Groundwater use in the Bay of Plenty region as of December 2000.*

Groundwater in the Te Puke–Maketu area is used for irrigation, dairy shed and stock water, and provides potable water supplies to small rural communities.

The large increase in allocations (Fig. 15.13) in the early to mid-1980s reflected the water requirements for irrigation and frost protection for the large number of kiwifruit orchards planted at that time. Water demand peaked at 275 000 m^3/day in 1988, with subsequent reduction in the number of permits until the mid 1990s, when allocation stabilised at 220 000 m^3/day.

Since 1998 there has been an increasing demand for groundwater for pasture and horticultural irrigation, with increased returns from dairy farming making it more economic to irrigate pasture during summer periods, and with increased returns from new varieties of kiwifruit. New orchards have been planted in the Western Bay of Plenty, particularly in the Te Puke–Maketu area. It is expected that demand for groundwater in some areas will increase as surface water streams become fully allocated.

Groundwater use in the Bay of Plenty is currently allocated on a "first-come-first-served" basis and assessed case-by-case. At present, permit holders in the region are allocated a maximum quantity per day. Environment Bay of Plenty is currently working on a regional plan that will include policy, methods, and rules for the management of groundwater resources, and will provide for the allocation of groundwater at sustainable yields to ensure quality and quantity are maintained. Environment Bay of Plenty monitors water quality and water level to ensure aquifers are being managed sustainably.

GEOTHERMAL RESOURCES

The Bay of Plenty region has a large number of geothermal systems (Fig. 15.14), with low-temperature tectonic systems and high-temperature volcanic systems (Chapter 3).

Low-temperature tectonic geothermal systems

Warm groundwater in the western part of the Tauranga–Maketu geothermal system around Tauranga Harbour is found within Aongatete Ignimbrite and Minden Rhyolite domes. Warm water production is mainly from fractures and joints in the rhyolite and ignimbrites. Bores that penetrate the resource have water temperatures in the range 20°C to 55°C from 200 m to 600 m deep bores. Production rates of 2.5 L/s can usually be expected from 100 mm bores (Environment Bay of Plenty 1994). The Mamaku Ignimbrite is the main source rock in the Papamoa–Maketu area (Simpson and Stewart 1987). At Maketu, there are natural springs and relatively shallow (40 m to 50 m) artesian bores

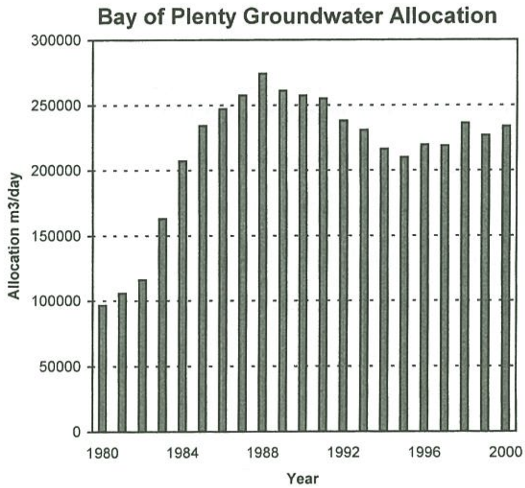


Figure 15.13 *Allocation of groundwater in the Bay of Plenty region to December 2000.*

that produce water at 40-45°C. This suggests very high vertical permeability. Bores in the Te Puke area encounter the warm water at depths greater than 300 m. Simpson (1987) suggested that the heat flow for the system is a result of convective and conductive heat transfer associated with deep circulation of waters. Geochemistry, isotopic ratios and dating of groundwater (Simpson and Stewart 1987) indicate that the age of the groundwater is hundreds of years, with younger water to the west. This suggests that recharge is from high elevations and the water is circulating at depth within the rhyolite and ignimbrites and then rising through faults and joints at the coast. The water geochemistry is predominantly bicarbonate and weakly mineralised, but bores near the coast (particularly on the Mount Maunganui Penin-

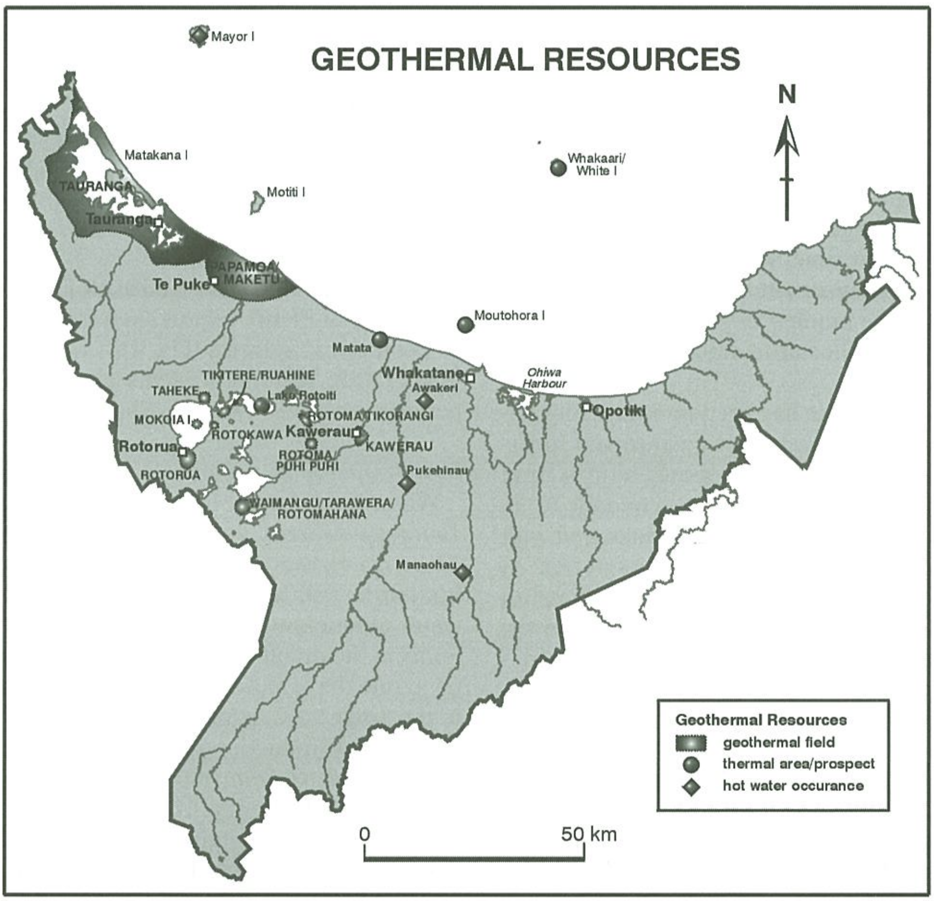


Figure 15.14 *Geothermal resources of the Bay of Plenty region as of December 2000.*

sula) have a seawater signature, indicating seawater intrusion.

Warm groundwater is generally used as a direct heat source for glasshouse heating, swimming pools, and private spas. A number of commercial operators use the warm groundwater for hot pools and swimming baths, for example, Sapphire Springs hot pools near Katikati, Fernland Spa hot pools, Welcome Bay hot pools and Mount Maunganui hot pools. Warm groundwater is also used for horticultural irrigation and frost protection. There are many private bores throughout the Tauranga area that use warm groundwater for spas, swimming pools, and home heating.

At Awakeri there are three hot springs, which are also known as the Pukaahu hots springs. Two of the springs are natural and one was created by excavation. The temperature of the springs ranges from 58°C to 70°C and the heat output from the two original springs is approximately 0.4 MW. The hot water is neutral chloride bicarbonate and weakly mineralised. Six production bores drilled to 98 m depth have an artesian flow of approximately 50 L/s. The springs and bores supply hot mineralised water for swimming baths, but the discharge from the original springs has declined since the production wells have been in use (Mongillo and Clelland 1984).

The Resource Management Act differentiates geothermal water from groundwater on the basis of temperature. At present all abstractions of warm groundwater over 30°C in the Bay of Plenty region require a resource consent. Recently there has been an increased demand for warm water from the Tauranga field. In 1996 there were approximately 50 warm water groundwater bores with current consents, and as of November 1999 this had increased to 134 consented bores.

High-temperature volcanic geothermal systems

There are 13 known volcanic geothermal systems in the Bay of Plenty region, of which eight are high-temperature fields—Kawerau, Rotorua, Rotokawa/Mokoia Island, Rotoma/Tikorangi, Rotoma/Puhipuhi, Taheke, Tikitere, and Waimungu/Rotomahana.

The level of information on individual geothermal systems varies greatly. The greatest amount of information is available for the geothermal fields of Kawerau and Rotorua, including operational computer models, reflecting the high commercial value of these fields. Other sites are have limited information and are recognised on the basis of surface activity (e.g. hot springs) and resistivity anomalies.

Most of the volcanic geothermal fields in the Bay of Plenty region have unique surface features such geysers, hot springs, hot pools, bubbling mud pools, deposits of silica sinter and sulphur, steaming ground, and a varied and unique ecology. The extent of some of the major volcanic geothermal fields in the Bay of Plenty region has been established from geophysical and geochemistry exploration (Cave et al. 1993; Keewood 1991; Allis et al. 1993).

Kawerau geothermal field

The Kawerau geothermal field is the most heavily utilised field in the region. The field is located on the banks of the Tarawera River, 4 km north of Kawerau township (Fig.15.15). Natural thermal activity consisted of hot springs, altered or steaming ground, steam and gas discharges from fumaroles, sinter, and hydrothermal eruption vents and deposits, but most of these thermal features are in a state of decline. Spring outflow decreased, from more 16 L/s in 1904 to 9 L/s in 1951 (Healy 1974). Seepages occur along the Tarawera River and most of the thermal activity is concentrated in a 2 km^2 area (Fig. 15.15). The field was developed in the 1950s to supply energy to the Tasman Pulp & Paper Mill, which was constructed at the site because of the presence of the geothermal field. Most of the geothermal surface features have declined as a consequence of the intense use of the field, or were damaged or destroyed during construction of effluent ponds, so little activity now remains.

The heat source of the Kawerau geothermal field is believed to be a local magmatic source under Mt Edgecumbe and the deep outflow in the vicinity of Mt Tarawera. The primary geothermal fluids (300-325°C) rise into the field along fissures in the basement greywacke. The geothermal fluids then spread laterally, where mixing occurs with cool groundwater recharge entering the field through shallow volcanic

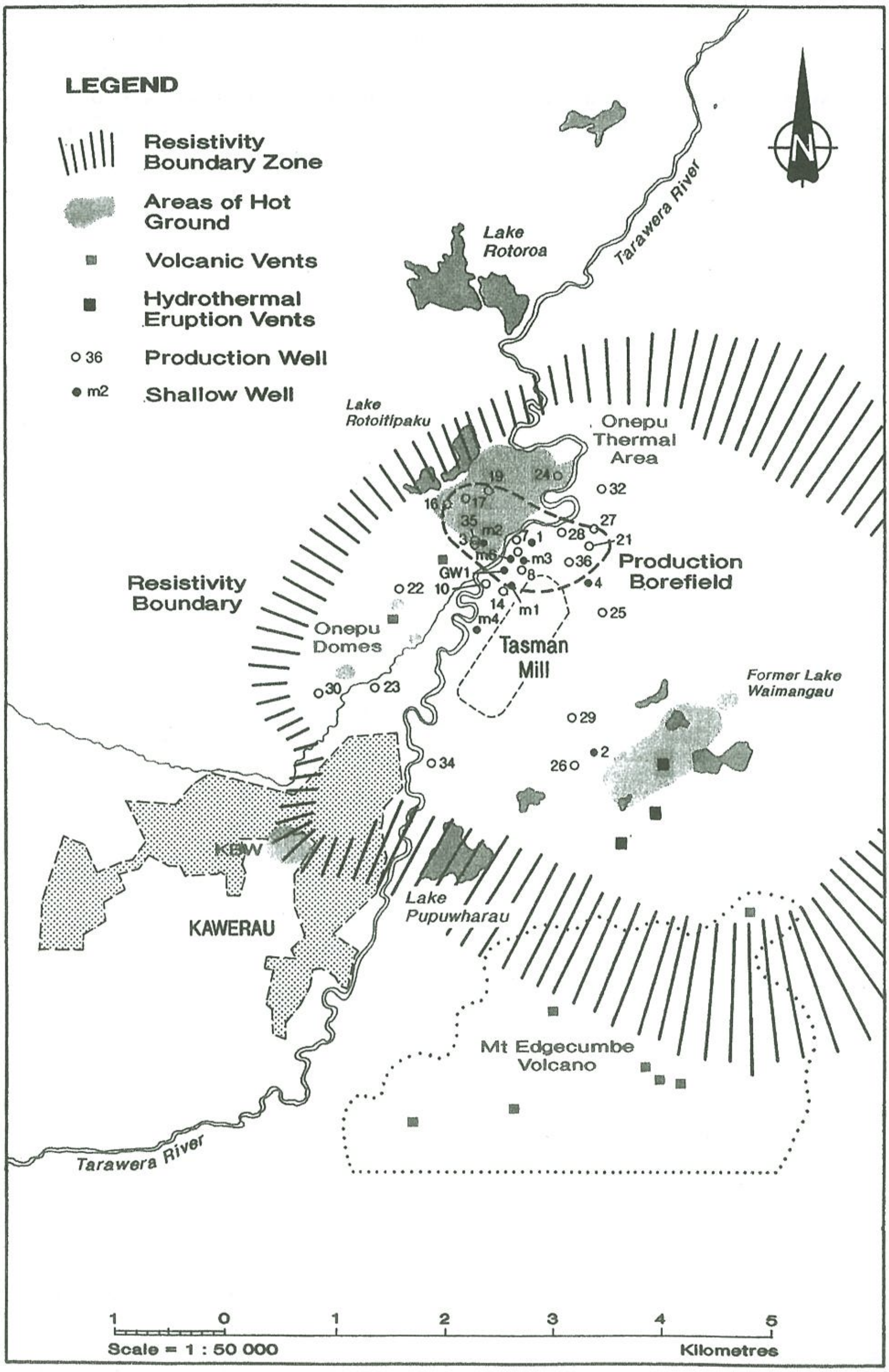


Figure 15.15 *Location and boundary of the Kawerau geothermal field and thermal areas, based on resistivity contours at 500 m depth (from Wigley 1993).*

sediments (Nairn 1981). The mass recharge into the geothermal reservoir is estimated to be 6000 to 7200 m^3/day (Bixley 1991). Temperature, pressure, and chloride measurements indicate that the outflow from the field is to the north (Allis et al. 1993).

Over 32 wells have been drilled at Kawerau, with seven now operating as production bores. The depth range of the wells is 433 m to 1617 m, with a temperature range of 120°C to 310°C. Bores in the Kawerau field tend to decline in output because of mineral scaling and cold water inflow. These problems have been overcome by regular cleaning of the bores and deepening bores to levels with a more reliable permeability (Cave et al. 1993). As of 1997, over 33% of the separated geothermal fluid is re-injected. The remainder is discharged into the Tarawera River (O'Shaughnessey 1997), resulting in heat, and a small amount of contaminant (arsenic, ammonium nitrogen, boron, hydrogen sulphide lithium, silica), pollution. This has been reduced by re-injection and by the construction of cooling ponds to reduce the heat load to the river.

Rotorua geothermal field

The Rotorua geothermal field is located at Rotorua City and underlies much of the city and the southern margin of Lake Rotorua. The Rotorua field is unique in that it contains New Zealand's last remaining area of major geyser activity, at Whakarewarewa (Allis and Lumb 1992).

Whakarewarewa and the heat from the Rotorua geothermal field are inextricably linked to the history, existence and identity of Rotorua City. Thermal activity has a special place in Maori culture, being used by the local Arawa people as a source of heat for cooking, bathing, food drying, processing flax fibres and medicinal purposes (Ministry of Energy 1985). Since European settlement in the early 1800s, the geysers have gained world renown. Rotorua is also know for its spas, and bores have been drilled to provide hot water for private homes, motels and other commercial and industrial uses.

Electrical resistivity and heat flow surveys suggest that the area of the geothermal field extends northwards into Lake Rotorua and south of Whakarewarewa (Allis and Lumb 1992; Whitford 1992) (Fig. 15.20).

The field is located in the southern part of the Rotorua caldera, which collapsed after the eruption of the Mamaku Ignimbrite some 140 000 years ago (Wood 1992). This ignimbrite forms the base of the shallow aquifer systems. The flow of geothermal fluids in the Rotorua field is largely controlled by the geological and geomorphic structure of the area. Hot alkali-chloride fluids appear to ascend from depth in the south part of the field to enter via the Ngapuna and Roto-a-Tamaheke faults. Hot alkali-chloride fluids also enter the rhyolite domes from the ignimbrite in the east and in the north near Kuirau Park (Wood 1992). Isotopic geothermometry indicates that the deep upflow has temperatures of the order of 350°C at depths of 3-5 km beneath the field (Allis and Lumb 1992).

The thermal activity at Whakarewarewa–Arikikapakapa consists of numerous alkaline-chloride hot springs, hot and boiling pools, hot acid-sulphate springs, mud cones and pools, lakelets, hydrothermal eruption craters, steaming and altered ground and extensive deposits of silica sinter, sinter aprons and terraces. Over 800 thermal features have been identified at Whakarewarewa (Cody 2000). The main geyser activity is concentrated at Geyser Flat, a 6000 m^2 tract of sinter-encrusted hot ground. Some of the named geysers are Pohutu, Te Horu, Prince of Wales Feathers, Mahanga, Waikorihihi, Kereru, and Wairoa. The largest and most spectacular, Pohutu Geyser, can erupt to an average height of 18 m (Cody and Lumb 1992).

During the 1950s and 1960s geothermal energy was considered a cheap and convenient energy source, resulting in an increase in well drilling into the geothermal field. Most bores were less than 200 m deep. Population growth and an energy crisis in the 1970s contributed to a significant increase in the well drilling and at the peak there were 406 bores in use. Much use of the geothermal energy was inefficient, resulting in wastage of the geothermal heat (Ministry of Energy 1985). By the late 1970s there was a significant decline in activ-

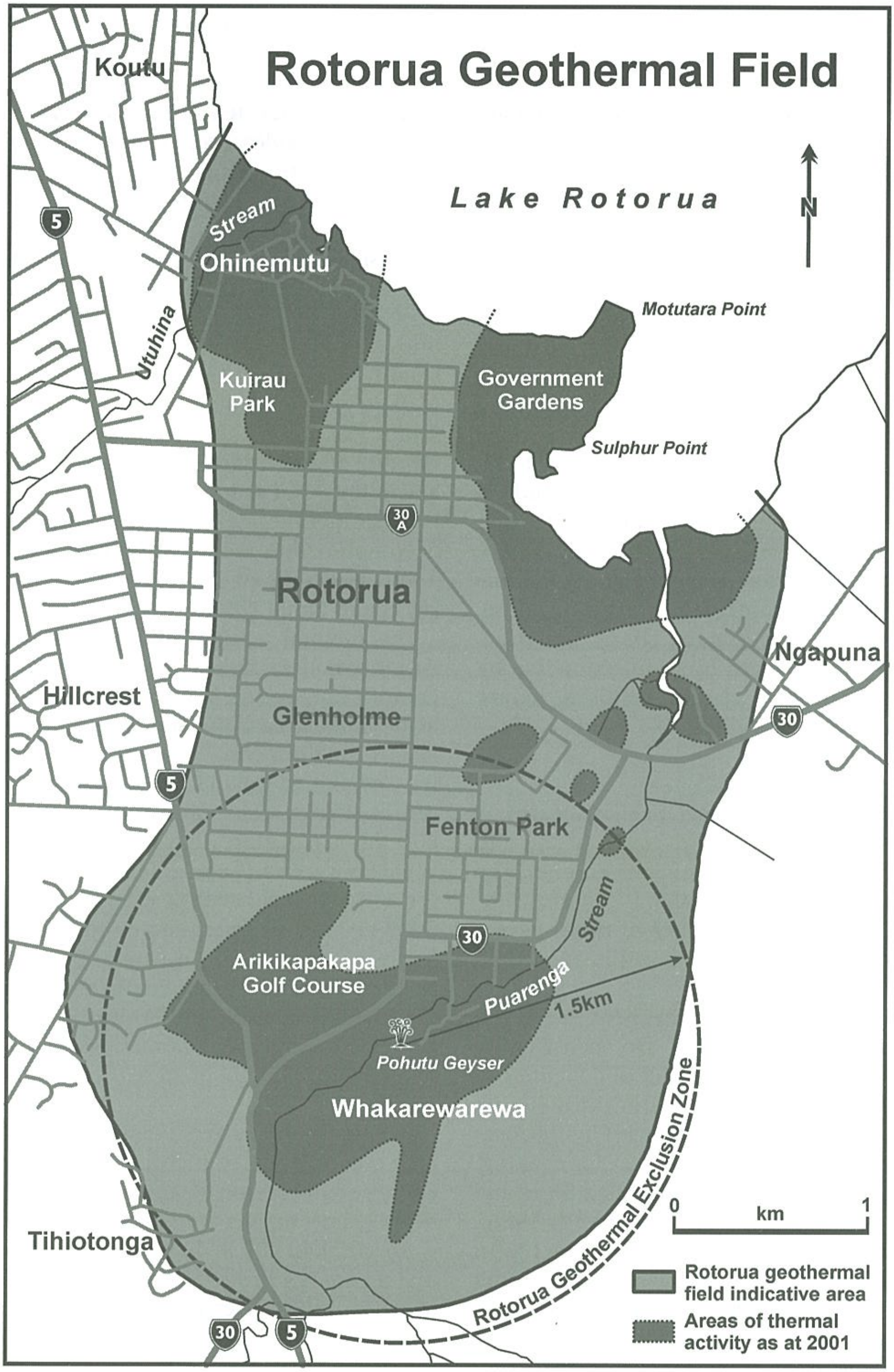


Figure 15.16 *Location and boundary of the Rotorua geothermal field and main geothermal areas, based up on resistivity contours at 500 m in depth (from Environment BOP 1999).*

ity at Whakarewarewa and other surface features across the field. For instance, in 1979 two major springs, Papakura and Korotiotio, failed (Grant-Taylor and O'Shaughnessy 1992). This decline was considered to be the result of withdrawal of geothermal fluid from the system by wells.

Public concern was expressed about the possible damaging effects on the activity of geothermal features at Whakarewarewa. The Minister of Energy and Rotorua District Council announced, in 1980, guidelines for dealing with drilling and use of geothermal energy in Rotorua. Amongst these was a ban on drilling anything other than replacement wells within a 1.5 km radius of Pohutu Geyser (Fig. 15.16).

A monitoring programme that began in 1982 found that a large fraction of geothermal energy abstracted from the field was wasted through inefficient use. As a result, the Rotorua Geothermal Taskforce was formed in 1983 to establish the extent of draw-off of geothermal fluid from the field and to investigate methods of reducing it (Ministry of Energy 1985).

Increasing concern over the effect of geothermal fluid withdrawal on the geysers at Whakarewarewa, and the apparent lack of action by local authorities, led the government to take emergency measures in 1986 by invoking its statutory authority. The government ordered the closure of all bores within a radius of 1.5 km of Pohutu Geyser and closure of all government department wells in Rotorua. The government also introduced a royalty regime for extracting fluid, which brought about a reduction in bore numbers from 406 to 141 by 1992 (Grant-Taylor and O'Shaughnessy 1992).

The total withdrawal from the field in 1985 was 31 000 tonnes/day, representing 40% of the natural up-flow; this was reduced to less than 9 500 tonnes/day by 1992 (O'Shaughnessy 1997). Following bore closure there was a marked increase in water level, or pressure head, across the field, starting in 1986 (Fig. 15.17). On average the water level, or pressure, in monitoring bores rose by 1 to 2 metres for the period from 1986 to 1988. Water levels have remained relatively stable until 1993, but since then there has been a gradual increase in water level in monitoring bores totalling 2.5 m. This rise is thought to be due to increases in injection (O'Shaughnessy 2000) as the field continues to adjust to a new equilibrium.

The increase in outflow at Whakarewarewa was estimated to be between 950 and 2 750 tonnes/day (Grant Taylor et al. 1992). Many of the geothermal features at Whakarewarewa responded quickly to field pressure recovery, with increased activity from geysers and resumption of flow from springs to levels similar to historic levels. For example, Pohutu geyser produced higher-energy eruptions (Cody and Lumb 1992).

The recovery of these natural features demonstrated that the preservation of aquifer pressure is important in maintaining surface features. Increases in thermal activity across the field have continued, with unprecedented eruption activity from Pohutu geyser and the resumption of flow of springs. In 1998 the Tarewa springs in Kuirau Park thermal area reactivated, resulting in damage to property. A hot spring began flowing under the garage floor of home units at Tarewa Road, with associated geyser activity from adjacent springs, resulting in the need for demolition and removal of the dwelling concerned. Investigation showed that the dwelling had knowingly been built on a geothermal feature (Cody 1998). This highlights the problem of an increased risk of damage to property as the field recovers.

Other geothermal fields

The major thermal features of the Rotoma–Tikorangi fields are warm springs (22-50°C)—Waitangi Springs and warm seepages along the southeastern shore of Lake Rotoehu, and Otei Springs on the southern shore of Lake Rotoma. These springs discharge large flows (up to 53 L/s) of warm dilute sodium bicarbonate chloride waters (Nairn 1981). The main Waitangi hot spring discharges weakly acid chloride-bicarbonate water at 50°C, with a heat flow of 8 MW (Nairn 1999). Solfataric activity (sulphur pans), hydrothermally altered ground, fumaroles (>90°C) and patches of steaming ground occur in a small confined area known as the Tokorangi thermal area (Nairn 1981, 1999). The area to the south, known as Te

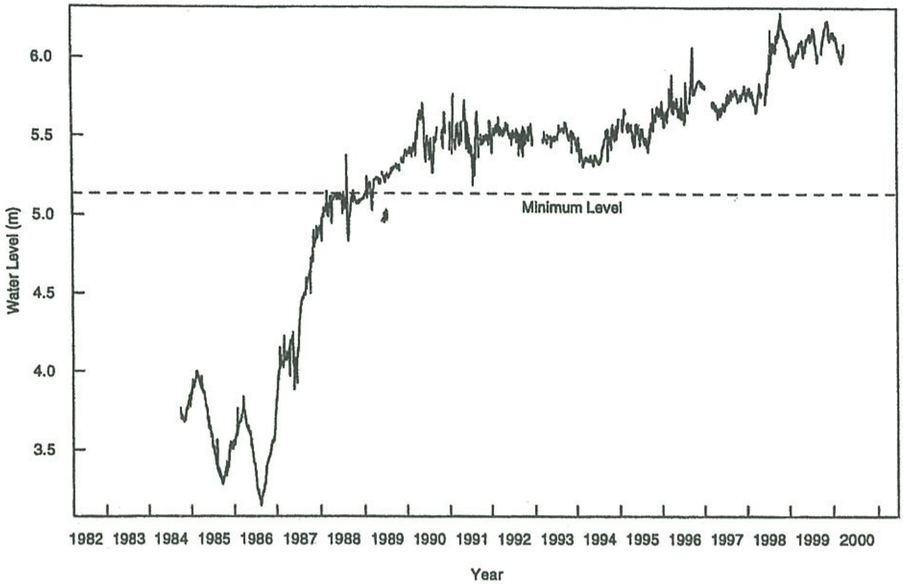


Figure 15.17 *Changes in water level (pressure) in the Rotorua geothermal field as reflected in Environment Bay of Plenty monitoring bore M16 (from Kissling 2000).*

Haehaenga basin, contains weakly mineralised warm springs (Nairn 1981), and areas of warm swampy ground occur along the Tarawera River (Bromley et al. 1988). The springs' deep geothermal chloride water is highly diluted because of mixing with large quantities of shallow groundwater (Nairn 1981, 1999).

Puhipuhi geothermal field is located 8 km east of Lake Tarawera and Haroharo Caldera. The field was identified by geophysical surveys during investigations for prospective geothermal resources by Fletcher Challenge in the late 1980s. Few present-day natural features are found there, but there is some hydrothermal alteration on the Puhipuhi hills and warm springs at Waiaute, west of the Puhipuhi hills. The springs range in temperature from 16°C to 23°C and have a chloride content of 20 to 81 mg/L.

The Taheke geothermal field, located 20 km north of Rotorua City, is a relatively small field and available data suggest that the field has a limited heat output. It may be connected with the Tikitere geothermal field to the north (Espanola 1974). The main reservoir for the field lies between about 400 m and 2 km depth and is inferred to be a two-phase (steam and water) system (Bromley 1994). The natural features consist of fumaroles, small springs and pools with temperatures of 57-97°C and hydrothermally altered ground.

The Tikitere geothermal field, located about 16 km northeast of Rotorua City, includes the well-known "Hells Gate" tourist thermal area and the Ruahine Springs 2.5 kilometres to the northeast (MacDonald 1974; Cave et al. 1993). The natural features are boiling springs and hot pools, seepages, steaming and hydrothermally altered ground, fumaroles, sulphur deposits and gas discharges. The hot pools are commonly turbid and usually boiling, with temperatures between 38°C to 100°C. Several shallow bores (70 m to 120 m) near Hells Gate discharge steam and hot chloride water.

The Waimangu/Rotomahana geothermal field is located 22 km southeast of Rotorua and has the most prominent geothermal features in the Okataina Volcanic Centre (Simmons et al. 1994). Surface activity at the Waimangu geothermal field occurs near the intersection of the caldera structure and is within the 17-km-long line of volcanic craters that formed across Mt Tarawera and through the Rotomahana geothermal area during the Tarawera basaltic rift eruption on 10 June 1886

(Wood 1994). The Waimangu Valley is a well-known tourist spot for viewing thermal activity and is renowned for its diversity of thermal features.

The thermal activity in the Waimangu Valleys consists of numerous alkaline-chloride hot springs, hot and boiling pools, hot acid-sulphate lakes, hydrothermal eruption craters, steaming and altered ground and minor silica deposits and sinter terraces. The near-boiling temperatures of many hot springs suggest that thermal water boils as it rises beneath the Waimangu Valley and Steaming Cliffs and that there is mixing with groundwater at shallow depths. Springs that show the most pronounced effects of mixing and dilution occur at higher elevations in the upper Waimangu Valley, as a result of topography and steep hydraulic gradients promoting penetration of groundwaters (steam heated or cold) in shallow fluid conduits (Simmons et al. 1994).

Rotokawa geothermal field is located 8 km northeast of Rotorua City and lies within the Rotorua caldera. Hot springs discharge into the nearby Lake Rotokawa and warm springs discharge into Lake Rotorua near the present airport. The hot springs that discharge into Lake Rotokawa are slightly acidic (pH 5.5) with moderate chloride and have a temperature of 45-52°C (Glover 1974). A number of wells from 45 m to 99 m in depth have been drilled and the water is used for pools, space heating, greenhouses and hotel developments. Discharge temperatures from the bores range from 29°C to 99°C, with the majority of the deeper bores flowing artesian. Geochemical evidence suggests that the deep reservoir is 160°C chloride water (Glover 1974).

The Lake Rotoiti geothermal area is located 19 km northeast of Rotorua City and is thought to be structurally related to the Tikitere graben and Haroharo caldera (Nairn 1974, 1999). The geothermal area underlies Lake Rotoiti. The highest heat flow occurs in the floor of the centre basin, which occupies about 2 km^2 and coincides with the deepest part of the lake (70 to 120 m in depth). Temperatures of up to 130°C have been measured in the lake sediments by Calhaem (1973), and a thermal gradient of 63°C/m was calculated.

No natural thermal features have been identified at Matata, but a low-resistivity anomaly has been identified. A bore drilled on behalf of the Ministry of Energy in 1986 failed to find high temperatures (Cave et al.1993).

Motuhora Island (Whale Island) is located 8 km offshore from the Bay of Plenty coast and is an eroded Quaternary andesite-dacite stratovolcano, consisting of a central cone and an intruded lava dome. A range of thermal features occur on the island—hydrothermally altered ground, steaming ground, fumaroles, sulphur deposits, silica sinter, and hot water springs. Temperatures of 98.5°C have been recorded in hot water flows and temperatures above 100°C were recorded in fumaroles (Lloyd 1974).

Whakaari (White Island) is an active composite andesitic volcano located about 50 km offshore from Whakatane. It consists of two overlapping cones, cut by a large breached crater on the eastern side of the island (Clarke and Cole 1986). Thermal activity is found within the crater complex and consists of numerous high-temperature fumaroles depositing sulphur, ephemeral mud pools and springs, and thermally altered ground (Mongillo and Clelland 1984). Springs and pools on the crater floors contain high quantities of free acids and sometimes boil vigorously. The temperature of fumarole activity ranges from 100°C to 350°C, with gas discharges of mostly carbon dioxide and sulphur dioxide, and sulphur deposition.

MANAGEMENT OF GEOTHERMAL RESOURCES

Environment Bay of Plenty is responsible for the sustainable management of all geothermal resources of the region, so that their potential, quality and attributes are retained and protected. Some of the geothermal resources in the region are protected from extractive use, while others are available for use and development, within the constraints of providing for the protection of significant features and avoiding any adverse effects. To guide resource users and to assist with the development of regional plans and the assessment of resource consent applications, all known geothermal resources in the region have been classified according to their values and uses, resulting in four different Geothermal Protection Levels (Environment Bay of Plenty 1999b, 2000):

- GPL 1 - Complete preservation of the natural, intrinsic, scenic, cultural, heritage and ecological values, for example, Whakaari (White Island);
- GPL 2 - Preservation and restoration of the natural, intrinsic, scenic, cultural, and heritage values by increasing the geothermal field pressures and the appropriate conservation and management of surface features, for example, Rotorua;
- GPL 3 - The use (including abstraction) of geothermal water and heat energy where the adverse effects can be avoided, remedied or mitigated, for example, Taheke; and
- GPL 4 - The use (including abstraction) of geothermal resources where the adverse effects of taking and discharging geothermal resources on the environment are avoided, remedied or mitigated, for example, Awakeri.

Environment Bay of Plenty is developing a regional plan that will include policy, method, and rules for managing the geothermal resources of the region. The Rotorua geothermal field, however, is managed under a separate plan.

The former Bay of Plenty Catchment Commission developed the Rotorua Geothermal Field Management Plan in late 1988, but it could not be implemented effectively because as it was a non-statutory plan. Environment Bay of Plenty (Bay of Plenty Regional Council) was formed in 1989 and inherited management responsibility for the field. With the imminent introduction of the Resource Management Act in October 1991, research was initiated and Environment Bay of Plenty began developing the Rotorua Geothermal Regional Plan. Unlike the preceding plan, this regional plan was a statutory document that would allow Environment Bay of Plenty to develop aims, objectives, policies and methods for managing the field, in consultation with the community. Due to the past history of bore closure, there was still much scepticism surrounding regulatory controls on the field. Section 32 of the Resource Management Act 1991 required Environment Bay of Plenty to have robust scientific information to support policy initiatives for a resource management plan for the geothermal field. It is conservatively estimated that, between 1982 and 1999, \$3.75 million has been spent on research and management of the field (Envirionment Bay of Plenty 1999b).

The Rotorua Geothermal Plan was proposed in December 1993, but the plan was appealed to the Environment Court in 1998. After the settling of appeals by the Environment Court, the plan became operative in July 1999. The aims of the Operative Rotorua Geothermal Regional Plan are to ensure that the Rotorua geothermal resource retains its value and potentials while protecting geothermal surface features; protecting *tikanga Maori*; identifying and, as practical, enhancing available geothermal resources; providing for the allocation of that resource for present and future efficient use; and managing and controlling all adverse effects on the field (Environment Bay of Plenty 1999b). Some of the key polices of the plan are:

- retention of the 1.5-km radius zone around Pohutu Geyser prohibiting mass abstraction, to protect the outstanding geothermal features at Whakarewarewa;
- no net increase in abstraction from the field;
- reinjection of all fluid where practicable;
- setting of a strategic level in the geothermal aquifer to sustain geothermal surface features and protect the resources into the future; and
- protection of surface features from physical destruction and restoration of outflows and avoidance of mitigation of natural geothermal hazards.

The plan is due for a full review commencing July 2004 (Environment Bay of Plenty 1999b).

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REFERENCES

ALLIS, R.G.; LUMB, J.T. 1992: The Rotorua Geothermal Field, New Zealand: Its physical setting, hydrology and response to exploitation. Geothermics Special Issue 21 No.1/2: 7-24.

ALLIS, R.G.; CHRISTENSON, B.W.; NAIRN, I.A.; RISK, G.F.; WHITE, S.P. 1993: Proceedings of the 15th New Zealand Geothermal Workshop.

BIXLEY, P.F. 1991: Hearing evidence to Environment Bay of Plenty's Regulation and Monitoring Committee, August 1991. Environment Bay of Plenty, File Reference 1370 02 2443.

BRIGGS, R.M.; HALL, J.G.; HARMSWORTH, G.R., HOLLIS, A.G.; HOUGHTON, B.F.; HUGHES, G.R.; MORGAN, M.D.; WHITEBREAD-EDWARDS, A.R. 1996: Geology of the Tauranga Area, Sheet U14 1:50 000, Occasional Report No. 22 Department of Earth Sciences, University of Waikato, Hamilton, New Zealand. 56 p

BROMLEY, C.J.; BOTTOMLEY J.J.; PEARSON C.F. 1988: Geophysical exploration for prospective geothermal resources in the Tarawera Forest. Proceedings of the 10th New Zealand Geothermal Workshop. 123-128.

BROMLEY, C. 1994: Taheke geothermal field scientific resource assessment. Unpublished report for consent application hearing. Environment Bay of Plenty File No. 1370 4142. 14 p.

CALHAEM, I.A. 1973: Heat flow measurements under some lakes in the North Island, New Zealand. PhD thesis, Victoria University Library, Wellington. 191 p.

CARRYER AND ASSOCIATES LTD 1997: Report on a pumping test carried out at Troutbeck Road, Galatea. Unpublished report prepared for Winstone Aggregates Ltd. 8 p.

CAVE, M.P.; LUMB, J.T.; CLELLAND, L. 1993: Geothermal Resources of New Zealand. Resource Information Report 8, Energy and Resources Division, Ministry of Commerce, New Zealand. 39 p.

CLARKE, R.H.; COLE, J.W. 1986: White Island. In: Smith, I.E.M. (ed.), Late Cenozoic Volcanism in New Zealand. Royal Society of New Zealand Bulletin 23: 169-178.

CODY, A.D. 1998: No. 20 Tarewa Road conditions report. Unpublished report to G.A.B. Robins N.Z. Ltd. 13 p.

CODY, A.D.; LUMB, J.T. 1992: Changes in thermal activity in Rotorua geothermal field. Geothermics 21 No.1/2: 215-230.

DAVIES, J.E.; AHLERS, W.W.; DEELY, J. 1994: Arsenic in drinking water: investigation of at risk supplies. Report prepared for the Ministry of Health, Institute of Environmental Science and Research Report CSC 96/1. 62 p.

ENVIRONMENT BAY OF PLENTY 1990: Te Puke-Maketu groundwater resource evaluation. Unpublished Technical Publication No.1, prepared by W. Russell and C. O'Brian. 60 p.

ENVIRONMENT BAY OF PLENTY 1991: Rangitaiki Plains groundwater resource evaluation. Unpublished Technical Publication No.2 prepared by S. Hodges, C. O'Brian, B. O'Shaughnessy, and A. Wilson. 140 p.

ENVIRONMENT BAY OF PLENTY 1994A: Geothermal groundwater resource of the Western Bay of Plenty. Unpublished Environmental Report No. 94/22, prepared by Sean Hodges. 37p.

ENVIRONMENT BAY OF PLENTY 1994b: Groundwater resources of the Lower Tarawera Catchment, Environment BOP, Environment Report 94/3, prepared by L. Pang, 149 p.

ENVIRONMENT BAY OF PLENTY 1999a: Operative Bay of Plenty Regional Policy Statement. Environment Bay of Plenty, Whakatane. 220 p.

ENVIRONMENT BAY OF PLENTY 1999b: Operative Rotorua Geothermal Plan: Environment B·O·P, Whakatane.142 p.

ENVIRONMENT BAY OF PLENTY 2000: Draft Water and Land Plan, Environment B·O·P, Whakatane. 334 p.

ESPANOLA, O.S. 1974: Geology and hot springs of Tikitere and Taheke hydrothermal fields, Rotorua, New Zealand. New Zealand Geological Survey Report No. 68, Department of Scientific and Industrial Research, New Zealand. 76 p.

GLOVER, R.B. 1974: Geochemistry of the Rotorua geothermal district. In: Geothermal Resources Survey - Rotorua Geothermal District, Department of Scientific and Industrial Research Geothermal Report No. 6, Department of Scientific and industrial Research Wellington. 108-110.

GRANT-TAYLOR, D.F.; O'SHAUGHNESSY, B.W. 1992: Rotorua geothermal field: response of field since closure (1987-1992). Technical Publication No.7, Environment B·O·P, Whakatane. 57 p.

GROUNDWATER CONSULTANTS (NZ) LTD 1985a: Western Bay of Plenty groundwater resource evaluation: Stage 2 exploratory drilling programme Katikati-Kauri Point region final report. 28 p.

GROUNDWATER CONSULTANTS (NZ) LTD 1985b: Investigation towards improvement of the town water supply at Athenree, Bay of Plenty. Unpublished report to Tauranga County Council. 15 p.

GROUNDWATER CONSULTANTS (NZ) LTD 1989: Construction and evaluation of test production well for a community water supply - Waihi Beach. Unpublished Report for the Ohinemuri County Council. 21 p.

HEALY, J. 1974: Kawerau geothermal field. In: Staff of New Zealand Geological Survey, Minerals of New Zealand (Part D: geothermal). New Zealand Geological Survey report 38D.

HOUGHTON, B.F.; CUTHBERTSON, A.S. 1989: Sheet T14 BD - Kaimai. Geological Map of New Zealand, 1: 50 000. Map (1 Sheet) and notes. Department of Scientific and Industrial Research, Wellington, New Zealand. 35 p.

HOUGHTON, B.F.; WILSON, C. J.N.; MCWILLIAMS, M.O.; LAMPHERE, M.A.; WEAVER, S.D; BRIGGS, R.M.; PRINGLE, M.S. 1995: Chronology and dynamics of a large silicic magmatic system: central Taupo Volcanic Zone, New Zealand. Geology 23: 13-16.

HUNT, T.M.; TOSHA, T. 1994: Precise gravity measurements at Inferno Crater Waimungu, New Zealand. Geothermics Special Issue 23 No. 5/6: 573-582.

KEAR, D.; ROSS, J.B. 1961: Boron in New Zealand coal ashes. New Zealand Journal of Science 4: 360-380.

KEEWOOD, M. 1991: The geology of the Waimangu field. Unpublished MSc Thesis, University of Auckland. 148 p.

KISSLING, W.M. 2000: Rotorua geothermal monitoring programme – summary of data for the period January 1998 to April 2000. Unpublished Industrial Research Report No. 994 to Environment Bay of Plenty. Applied Mathematics Group, Industrial Research Limited, Lower Hutt. 58 p.

LLOYD, E.F. 1974: Whale Island geothermal field. In Minerals of New Zealand, A summary of resources and prospects, Part D, Geothermal Resources, by staff of the New Zealand Geological Survey, N.Z. Geological Survey Report 38D, Rotorua. 5 p.

MACDONALD, W.J.P. 1974: Geothermal Resources Survey – Rotorua Geothermal District. Department of Scientific and Industrial Research Geothermal Report No. 6. Department of Scientific and Industrial Research, Wellington. 68 p.

MINISTRY OF ENERGY 1985: The Rotorua geothermal field. A report of the Geothermal Monitoring Programme and Task Force 1982-1985. Oil and Gas division, Ministry of Energy, Wellington. New Zealand. 493 p.

MINISTRY OF HEALTH 1995: Drinking-Water Standards for New Zealand 1995. 87p.

MINISTRY OF WORKS AND DEVELOPMENT 1985: Galatea pastoral irrigation scheme prefeasibility study report, prepared by R.A. Burnett and F.O. Campbell. 72 p.

MONGILLO, M.A.; CLELLAND, L. 1984: Concise listing of information on thermal areas and thermal springs of New Zealand. Department of Scientific and Industrial Research. Geothermal Report Number 9. 228 p.

NAIRN, I.A. 1974: 3.5 Lake Rotoiti Geothermal Field. In: Minerals of New Zealand. A summary of resources and prospects, Part D, Geothermal Resources, by staff of the N.Z Geological Survey, N.Z. Geological Survey Report 38D, Rotorua. 5 p.

NAIRN, I.A. 1981: Geothermal resources of the Okataina volcanic centre. New Zealand Geological Survey, Rotorua, New Zealand. 41 p.

NAIRN, I.A. 1999: Geology of the Okataina Volcanic Centre – An explanation to accompany the Environment Bay of Plenty GIS data set. Institute of Geological & Nuclear Sciences Limited, Lower Hutt. 148 p.

NAIRN, I.A.; BEANLAND, S. 1989: Geological setting of the 1987 Edgecumbe earthquake, New Zealand. New Zealand journal of geology and geophysics 32: 1-13.

O'SHAUGHNESSY, B.W. 1997: Compliance report – Crown Geothermal Consents for the Kawerau Geothermal Field. Environment Bay of Plenty Report 97/14. 26 p.

O'SHAUGHNESSY, B.W. 2000: Use of economic instruments in management of Rotorua geothermal field, New Zealand. Geothermics 29 No.4/5: 529-555.

PANG, L.; CLOSE, M.; SINTON, L. 1996: Protection zones of the major water supply springs in the Rotorua District for the Rotorua District Council. Unpublished Institute of Environmental Science and Research Report CSC 96/1. 77 p.

PATTLE DELAMORE PARTNERS LTD 1996: Preliminary water allocation strategy for the Galatea Basin. Unpublished report prepared for Environment Bay of Plenty. 35 p.

ROSEN, M.R.; MILNER, D.; WOOD, C.P.; GRAHAM, D.; REEVES, R. 1998: Hydrogeological investigation of groundwater flow in the Taniwha Springs area. Unpublished Geological and Nuclear Sciences report prepared for the Rotorua District Council. 25 p.

ROTORUA DISTRICT COUNCIL 1993: Report on rural land use practices in the Rotorua District, prepared by Sigma Consultants. 200 p.

SIMMONS, S.F.; STEWART, M.K.; ROBINSON, B.W.; GLOVER, R.B. 1994: The chemical and isopotic compositions of thermal waters at Waimangu, New Zealand. Geothermics Special Issue 23 No. 5/6: 539-554.

SIMPSON, M.P. 1987: Heat flow measurements on the Bay of Plenty coast, New Zealand. Journal of Volcanology and Geothermal Research 34: 25-33.

SIMPSON, B.; STEWART, M.K. 1987: Geochemical and isotope identification of warm groundwaters in coastal basins near Tauranga, New Zealand. Chemical Geology 64: 67-77.

SKINNER, D.N.B. 1986: Neogene volcanism of the Hauraki Volcanic Region. *In* Smith I.E.M. (ed.) Late Cenozoic volcanism in New Zealand. Royal Society of New Zealand Bulletin 23: 21-47.

WHITFORD, P.C. 1992: Heat flow in the sediments of Lake Rotorua. Geothermics 21 No.1/2: 75-88.

WIGLEY, D.M. 1993: Kawerau Geothermal Field Management Strategy – Draft May 1993, prepared for Bay of Plenty Regional Council. Works Geothermal, Wairakei, Taupo. 65 p.

WOOD, C.P. 1992: Geology of Rotorua geothermal system. Modelling mass, energy and chloride flows in the Rotorua geothermal system. Geothermics 21 No.1/2: 25-42.

WOOD, C.P. 1994: Aspects of the geology of Waimanagu, Waiotapu, Waikite and Reporoa geothermal systems, New Zealand: Background and History. Geothermics Special Issue 23 No. 5/6: 401-524.

WOODWARD, D. 1988: Seismic reflection survey on the Rangitaiki Plains, Eastern Bay of Plenty, New Zealand. Geophysics Division, Department of Scientific and Industrial Research Report 218. 12 p.

WOODWARD-CLYDE (NZ) LTD 1991: Assessment of yields – Athenree Quarry wells. Unpublished report to the Western Bay of Plenty District Council. 16 p.

16

Gisborne

DOUGALL GORDON

INTRODUCTION

The Gisborne region is located on the central and northern east coast of the North Island (Fig. 16.1). The region has a land area of 8265 km^2 and a population of 44 355 (2001 census, provisional results). The largest town is Gisborne (population about 30 000); outlying townships include Ruatoria, Tokomaru Bay, Tolaga Bay and Te Karaka, with populations of approximately 900, 550, 750 and 580, respectively.

The region consists mainly of steep hill country, with small areas of rolling hills and strips of terrace and river flats in the valleys. The dominant topographical features of the region are the Huiarau and Raukumara ranges, which divide the catchments of the East Cape peninsula from the Bay of Plenty region to the west. The Gisborne region is susceptible to meteorological drought because it is sheltered from the prevailing westerly winds by the Huiarau and Raukumara ranges. Rivers and streams of the region all typically have low flows in summer. Groundwater is therefore important for the economy of the Gisborne region and is used for the irrigation of vineyards, orchards, and market gardens, for stock water, and for providing vital backup potable water supplies when other sources are unavailable. The Gisborne District Council, which is a unitary authority having the functions of a regional and district council, administers the region (Gisborne District Council 1995).

Almost all the known groundwater aquifers in the region are located on the Poverty Bay flats, the coastal floodplain of the Waipaoa River (Fig. 16.2). Shallow unconfined sand aquifers occur at Tolaga Bay and Tokomaru Bay and shallow alluvial aquifers are associated with the river flats and terraces of the Waiapu River at Ruatoria and Tikitiki (Gordon 1997).

GROUNDWATER RESOURCES - POVERTY BAY FLATS

The Poverty Bay flats cover an area of about 18 000 hectares of the Waipaoa River valley and have a climate suited to arable farming, market gardening, horticulture and viticulture (Gisborne District Council 1995). The flats include sandy beaches at the foreshore, backed by dunes and sand ridges . Behind the coastal foreland the alluvial plain extends inland for over 20 km to an altitude of 30 m asl at Te Karaka. The Waipaoa River meanders across the plain, flowing into Poverty Bay near the city of Gisborne (Fig. 16.2).

Gisborne has an average annual rainfall of 1034 mm, with a range between 650mm and 1640 mm (Hessell 1980) and often experiences meteorological drought conditions due to the rain shadow effects of the eastern ranges. Droughts are most frequent during prolonged periods of westerly winds. Droughts usually reach a maximum intensity in early mid-summer when the water demand for irrigation is high. The average annual water deficit on the flats is estimated to be 400 mm (Hessell 1980).

Groundwater is important for irrigation on the flats, as surface water resources are limited to the Waipaoa River, which often has low flows during the summer months. The Waipaoa River also has a high suspended-sediment load, because the Tertiary mudstones and siltstones of its catchment are easily eroded. There is no major water distribution network for irrigators to use, so most water abstraction from the Waipaoa is generally by landowners adjoining the river.

Gordon D. 2001: Gisborne. *In* Groundwaters of New Zealand, M.R. Rosen and P.A. White *(eds)*. New Zealand Hydrological Society Inc., Wellington. p355-366.

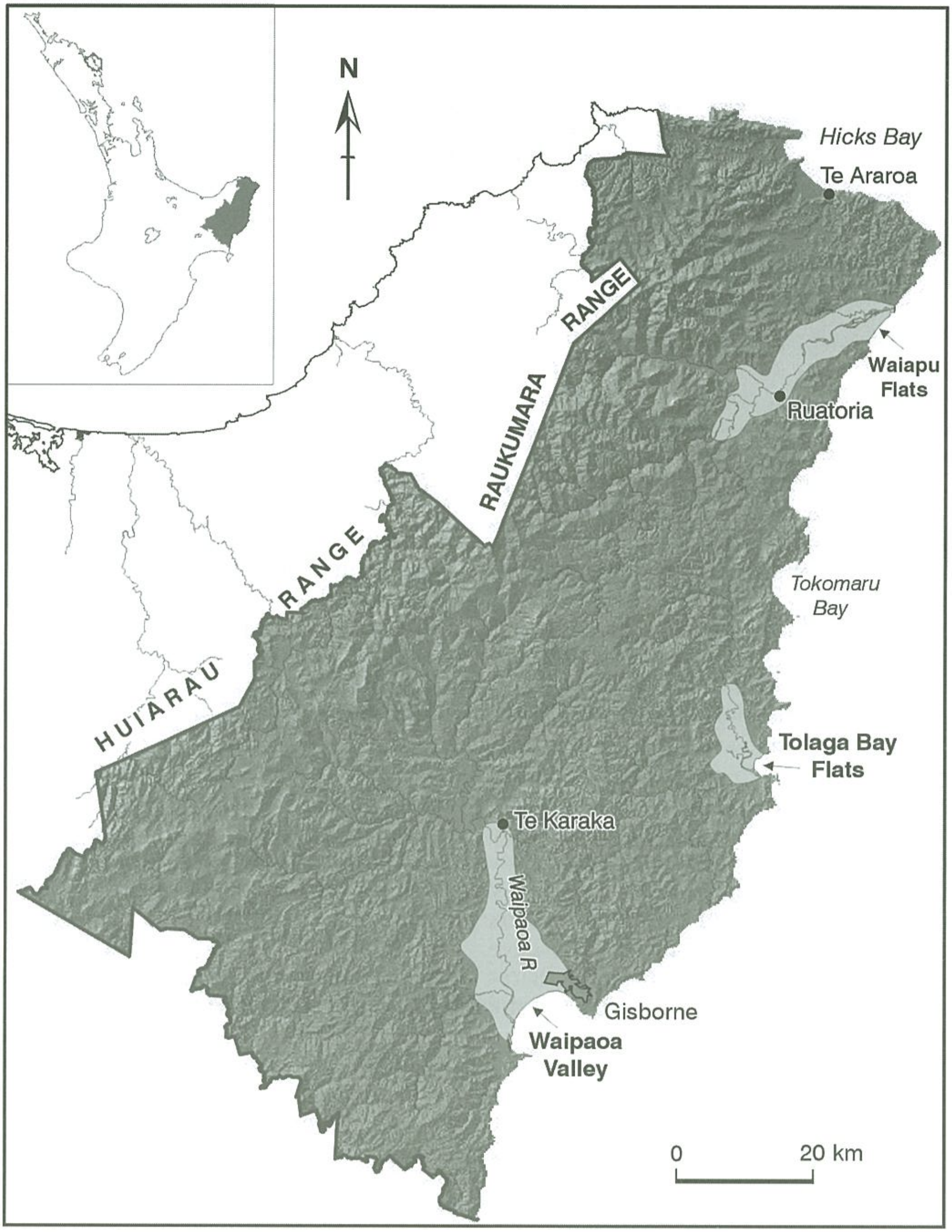

Figure 16.1 *Location of the Giborne region and groundwater areas of the Gisborne district.*

Major groundwater investigations on the Poverty Bay flats began in 1980 by the East Coast Catchment Board (now Gisborne District Council), with the assistance of the Department of Scientific and Industrial Research. These investigations were to determine the extent of aquifers on the Poverty Bays flats and the quantity and quality of groundwater present (Brown 1984). The investigations included geological assessments of existing drill hole data,

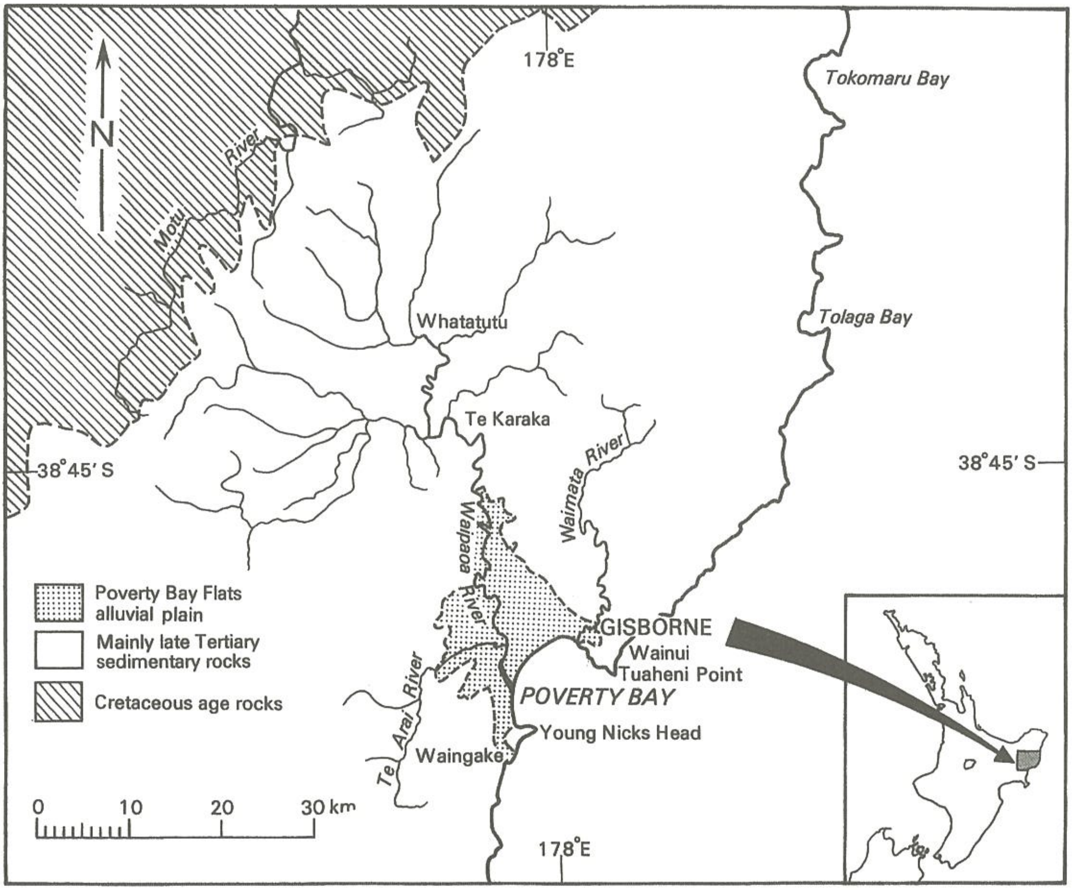

Figure 16.2 *Location of the Poverty Bay flats alluvial plain and surrounding geology. The Poverty Bay flats have been infilled with sediment eroded from the surrounding sedimentary Tertiary mudstone and sandstone and Cretaceous age rock (from Brown and Elmsly 1987).*

exploratory drilling, resistivity surveys, seismic surveys, aquifer pump tests and water quality analysis.

Geological setting

The Poverty Bay flats are within a basin structure that has been infilled with Quaternary terrestrial and marine sediments, including gravels and sands that form aquifers beneath the flats. Tertiary sandstone and mudstone form the basement rock; they are found at the surface of the Waipaoa River catchment and at depths between 50 and 200 m below the flats (Fig. 16.2).

Quaternary terrestrial and marine sediments were deposited in the valley on the flood plain of the Waipaoa River during episodes of sea level fluctuations in response to climate changes. During the last glacial period (Otira glaciation, 70 000-14 000 years B.P.) sea levels were approximately 120 m lower than at present. Terrestrial gravels derived from the Cretaceous-age greywacke rocks in the north-western headwaters (Fig. 16.2) were deposited on the Waipaoa valley flood plain, along with sand and silt eroded from the soft Tertiary sandstone and mudstone (Brown and Elmsly 1987).

At the end of the last glacial period the sea began to transgress and tectonic uplift occurred, causing changes in the length of the river profile. This resulted in down-cutting and reworking of the alluvium of the flood plain. By about 10 000 B.P. the sea had trans-

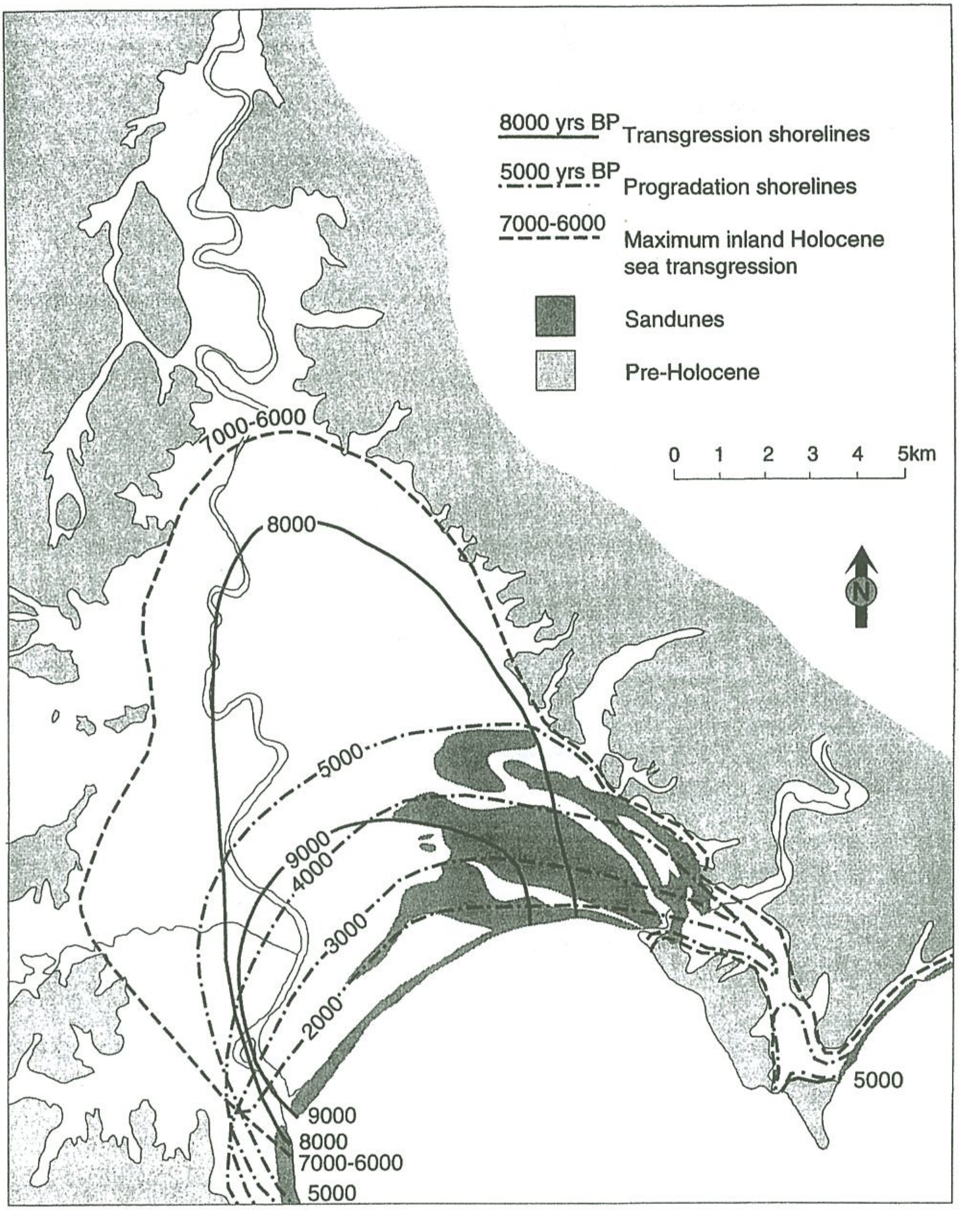

Figure 16.3 *Poverty Bay flats, Holocene marine transgression and progradation shorelines (from Brown 1995).*

gressed to approximately the present position of the Poverty Bay coast. At this time the Waipaoa River began building a delta to adjust to the changes in its river bed profile, with silt deposition and reworking of gravel deposits (Brown and Emsley 1987). By 8000 B.P. the sea transgressed further inland, resulting in deposition of swamp, estuarine, and lagoonal beach deposits over the top of reworked terrestrial glacial deposits. From 6500 B.P. to the present sea level has been stable at approximately the present level, but considerable coastal progradation has occurred as the meandering rivers filled the swamps and

Table 16.1 *Aquifers on the Poverty Bay flats.*

	Aquifer				
Name	Te Hapara Sand	Shallow Fluvial	Waipaoa Gravel	Makauri Gravel	Matokitoki Gravel
Depth range(m)	0-20	0-20	10-30	30-130	34-135
Type	Unconfined to confined	Unconfined to confined	Unconfined to confined	Confined	Confined

estuaries behind the coastal sand dunes (Brown 1995; Fig. 16.3). Volcanic ash derived from the Taupo Volcanic Zone has been concentrated by the river into thick deposits of pumiceous sand, interbedded with fluvial silt deposits.

Geohydrology

Water-bearing formations of sand and gravel make up a small part of the strata of the Poverty Bays flats. Five aquifer units are identified (Table 16.1).

The vertical and horizontal extent of the aquifers was assessed from interpretation of geological logs. A schematic cross-section of the inland flats from Kaitaratahi to the coast (Fig.16.4) indicates the main aquifer units, intervening silt aquitards, and aquifer interconnections.

Te Hapara Sand aquifer

Beach sands and dune sand deposits of this aquifer extend inland for about 5 km from the present-day coast. The aquifer is often confined by river silts and is possibly interconnected with the Waipaoa Gravel aquifer and shallow fluvial deposits. The permeability of the aquifer decreases to the southwest owing

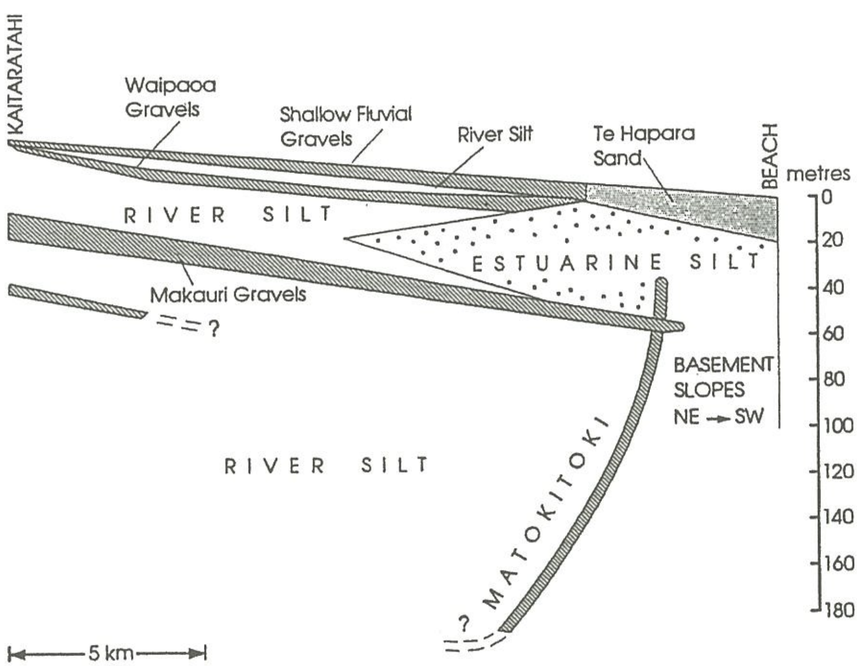

Figure 16.4 *Summary cross-section along the centre of the Poverty Bay flats from Kaitaratahi to the coast, showing the Poverty Bay aquifer system and stratigraphy—note the interconnecting aquifers and intervening silt aquitards. The Matokitoki gravel dips steeply to the north of Gisborne City (from Taylor 1993).*

to its increasing silt content towards the Waipaoa River (Brown and Elmsly 1987).

Pump tests conducted on the aquifer for durations of up to three days have shown that the aquifer is confined and leaky confined in places. Silt deposited by the Waipaoa River over the top of the sandy sediments forms a confining layer. The transmissivity of the aquifer averages 145 m^2/day. Storage coefficients vary, depending on the degree of confinement, and range from 2×10^{-5} in confined zones to 4×10^{-2} in leaky zones (Barber 1993).

Shallow Fluvial aquifers

The fluvial material forming these water-bearing layers is generally pumice and sand that has been derived from volcanic ash showers originating in the Taupo Volcanic Zone. These layers are interbedded with fluvial silt that often forms aquitards. Cut-off meanders, once occupied by the Waipaoa River, often contain water-bearing gravel and coarse sand. These aquifers can be located in depressions in the present-day topography (Brown and Elmsly 1987).

Shallow fluvial deposits extend from Kaitaratahi down the valley, and abut against sand dunes of the Te Hapara Sand aquifer and lagoonal-estuarine silt deposits inland from the present coast. The shallow fluvial deposits are generally centred on the present-day Waipaoa River and cover a wide area. The deposits can be up to 10 m thick and generally form a water-table aquifer that can be confined by river silts. The highest yielding wells are located in the paleo-river cut-off channels, penetrating gravel and course sand, with well yields generally sufficient for irrigation (Brown and Elmsly 1987).

Bores within the coarse sandy sediments have transmissivities from 250-500 m^2/day and storage coefficients ranging from 2×10^{-3} to 4×10^{-4}. Bores within the gravels have transmissivities up to 1100 m^2/day and storage coefficients of approximately 5×10^{-3} (Barber 1993). The aquifer is recharged by rainfall infiltration, with leakage from underlying aquifers. Some of the paleo-river cut-off channels are hydraulically connected to the present day Waipaoa River channel (Brown and Elmsly 1987; Gordon 1996).

Waipaoa Gravel aquifer

This aquifer is centred around the present river course and was formed from infilling of a relatively wide meandering channel that was cut into sediments when sea level was lower than at present. The Waipaoa River gravels were deposited by rivers that were adjusting to tectonic uplift and post-glacial sea level rise, from 7000-4000 B.P. (Brown 1995). The aquifer interfingers with the sand dunes (Te Hapara Sand aquifer) and lagoonal-estuarine silt deposits inland from the present coast (Brown and Elmsly 1987).

Pump testing shows this aquifer is confined and has a decreasing transmissivity down valley and away from the Waipaoa River. Bores close to the river have transmissivities ranging from 500-900 m^2/day, with a storage coefficient of 1×10^{-3}. Bores close to the river often have a strong hydraulic connection to the Waipaoa River, and water levels in the aquifer also respond quickly to changes in the river level (Barber 1993).

Makauri Gravel aquifer

The Makauri Gravel aquifer is the most extensive gravel deposit beneath the Poverty Bay flats and is thought to have been deposited by the Waipaoa River in the early post-glacial period. Radiocarbon dating of sediments above and below the aquifer has confirmed that the Makauri Gravels were laid down between 9000 and 7000 B.P. (Brown 1984, 1995). The aquifer consists of zones or layers of gravels interbedded with silt and sand deposits from 40 to 80 m deep, with deeper layers occurring at 100 to 130 m depth (Barber 1993).

Tectonic activity has given the aquifer a dip from the northeast to the southwest of the valley, with gravels encountered at 30-40 m in depth on the eastern side of the valley and 60-80 m in depth on the southwestern side of the Waipaoa River (Taylor 1994). The aquifer varies in thickness from 3-15 m. At Kaitaratahi the aquifer is approximately 7 m thick, and it is 12 m thick in the Makauri area. Exploratory drill holes and geophysical investigations have not found any evidence that the Makauri gravel continues beyond the present coast, which suggests that the aquifer is 'blind', with no outlet to the sea (Brown 1984).

The Makauri Gravel aquifer is the main groundwater source for the flats. Pump tests show that the aquifer is confined, with transmissivities ranging from 1000 to 2500 m^2/day and storage coefficients ranging from 1×10^{-4} to 2×10^{-4}. Transmissivity increases from the northern extent of the aquifer to the south and also towards the centre longitudinal axis of the aquifer (Barber 1993). Drillhole interpretations show the aquifer is made of alternating silt and gravel layers. Pump tests indicate that the layers are interconnected and behave as one unit.

Recharge to the aquifer appears to come from three sources: the hills to the northeast of the flats, from leakage from the bed of the Waipaoa River during the summer months, and from leakage from the Waipaoa and Matokitoki Gravel aquifers.

Matokitoki Gravel aquifer

The Matokitoki Gravel aquifer is a confined gravel aquifer. It is the deepest aquifer in the Quaternary sediments on the flats, and so relatively few wells have been drilled into it. The Matokitoki Gravel overlies the Tertiary siltstone and sandstone basement and is considered to be a remnant of early Quaternary sediments that survived erosion and were subsequently buried beneath younger sediments.

The aquifer lies in a narrow channel and extends from the eastern side of Gisborne City to Kings Road. It generally occupies structural or erosional channels in the Tertiary siltstone and sandstone basement. Brown and Elmsly (1987) suggest that the aquifer extends further to the north to Ormond and interfingers with the Makauri and Waipaoa Gravel aquifer, however there is considerable uncertainty as to its true extent to the northwest.

The width of the aquifer is probably no more than 2 km at its widest point. The thickness of the aquifer ranges from 4 m near the outskirts of Gisborne City to 28 m at Kings Road on the Poverty Bay flats (Barber 1993). The depth to the top of the gravel is around 34 m near the outskirts of Gisborne City to around 135 m at Kings Road. The aquifer is thought to have no outlet to the sea (Brown and Elmsly 1987).

Near Gisborne City the Matokitoki Gravel aquifer is a free-flowing artesian aquifer, and pump tests confirm the geological interpretation that the aquifer is confined. Pump tests and water level observations indicate that the Matokitoki Gravel aquifer and the Makauri Gravel aquifer react sympathetically with each other. During heavy pumping (>5000 m^3/day) significant leakage occurs into the aquifer from the Makauri Gravel aquifer above (Barber 1993). The average transmissivity is 380 m^2/day and storage coefficients range from 2×10^{-4} to 8×10^{-5}. Bore log samples taken from within the aquifer indicate that the gravels are 'pea size', up to a maximum of 20 mm in diameter (Barber 1993).

Recharge is derived mainly from the Waipaoa River, but the water has been isotopically dated at around 4300 years old (Taylor 1994), indicating a very slow flow through the aquifer. It is likely that the aquifer discharges water upwards into the overlying silts and sands to recharge streams, rivers and drains (Barber 1993).

GROUNDWATER QUALITY

Groundwater in the Poverty Bay flats gravel aquifers tends to be high in dissolved solids (hardness) and in iron, with the high dissolved iron (5-10mg/L) in the deeper Makauri and Matokitoki aquifers. The high iron and hardness in the Makauri and Matokitoki aquifers are a result of the dissolution of salt and minerals contained within the aquifer sediments. The shallower aquifer systems tend to have better water quality, but they are susceptible to contamination from land use because they tend to be unconfined.

Te Hapara Sand aquifer

Groundwater quality in this aquifer is variable (Table 16.2). Salinity levels are generally low, but near the coast higher levels occur because of residual salinity in the aquifer sediments. However in general salinity levels in the aquifer do not preclude domestic and irrigation use of the water. Alkalinity and hardness levels are high as result of the dissolution of biogenic material within the sands. The high alkalinity precludes water use in boilers, and if used for domestic purposes scale is likely to

Table 16.2 *Groundwater quality of Poverty Bay flats aquifers.*

Parameter	Te Hapara	Shallow Fluvial	Waipaoa Gravel	Makauri Gravel	Matokitoki Gravel
	Indicative Range	Indicative Range	Indicative Range	Indicative Range	Indicative Range
Total dissolved solids	300-500	200-400	200-400	300-1800	500-600
Chloride	25-80	20-80	10-50	10-750	50-100
Conductivity (mS/m)	87-116	50-70	50-96	95-300	80-120
Total iron	0-7	0.3-2.0	0-2.0	2-18	1-5
Total hardness (as $CaCo_3$)	400-800	300-750	250-900	300-1000	300-400
Sulphate	25-63	20-35	10-58	0-20	0.1-2.0
Phosphorus	0-0.15	0-0.2	0-0.2	0-0.2	0.05-0.2
Nitrate nitrogen	0-0.3	0-0.2	0-0.1	0-0.2	<0.05
pH	7.2-7.9	7.0-7.2	7.0-7.2	7.0-7.2	7.0-7.2
Carbon dioxide	15-100	25-60	30-100	60-250	50-80
Total Alkalinity (as $CaCO_3$)	300-500	250-350	250-500	250-700	500-700

All concentrations are in milligrams per litre (mg/L) unless indicated otherwise stated.

form in kettles and hot water tanks. Iron levels are low enough for domestic and irrigation use without treatment, but levels vary across the aquifer, depending on the amount of seepage from the gravel aquifers below.

The Te Hapara Sand aquifer is susceptible to chemical and bacteriological pollution as it is shallow, generally unconfined and is recharged from rainfall infiltration. However, nutrients such as phosphate and nitrate-nitrogen are generally within potable water quality guidelines (Ministry of Health 1995). Over-pumping of the aquifer has caused saline intrusion in some bores within a kilometre of the coast. Typically the conductivity of the affected groundwater rises from 900 mS/m to 2000 mS/m between October and April. The effect is more apparent during meteorological drought conditions over the summer months when there little recharge and pumping demand is higher (Barber 1993).

Shallow Fluvial aquifers

The water quality of the Shallow Fluvial aquifers generally decreases towards the coast, except near the paleo-river channels. Higher salinity levels, hardness, and alkalinity are found nearer the coast because of the dissolution of biogenic material and connate water, which is marine in origin, within the aquifer sediments (Brown and Elmsly 1987). Iron levels are moderately high (Table 16.2) but the water can be used for domestic purposes and irrigation. Nutrient levels are generally low, but the aquifer is susceptible to contamination by chemicals and pathogens from surrounding land use.

Waipaoa Gravel aquifer

Water quality in the Waipaoa Gravel aquifer is similar to that of the Waipaoa River, as the aquifer is directly recharged from the river (Barber 1993). Water quality reduces to the southwest because of increasing chloride salinity, alkalinity, hardness and iron (Gordon 1997). Water from this aquifer (Table 16.2) is generally acceptable for domestic use and irrigation, but may require treatment in some areas. Nutrients (phosphate nitrate) and pathogen levels are generally low, as the aquifer is generally protected from land-use contamination by confining layers and the aquifer is directly recharged from the river (Barber 1993).

Makauri Gravel aquifer

Water quality in the Makauri Gravel aquifer is generally poor because of high iron and hardness (Table 16.2), the result of mineral salts or connate water held within the aquifer sediments (Brown and Elmsly 1987). Isotopic dating of Makauri Gravel aquifer water indicates that it is 30–100 years old (Taylor 1994), allowing sufficient residence time for minerals to dissolve.

There is generally an increase in iron concentrations, hardness and salinity to the south, with high levels at the 'blind' toe of the aquifer near the coast and within the deeper gravel layers to the southwest (Brown and Elmsly 1987). Water to the south and in the deeper gravels layers of the aquifer is generally not suitable for domestic use or irrigation without treatment. The highest water quality within this aquifer is found to the north, in the vicinity of Makauri (Barber 1993).

Water quality declines during the summer pumping season, especially in bores used for irrigation at the southern toe of the aquifer. Iron staining of vegetation and blockage of irrigation jets have been attributed to lower quality water being drawn in from the blind toe of the aquifer, the deeper stagnant gravel layers, and the stagnant edges of the aquifer. Water quality usually improves again after winter recharge (Barber 1993).

Matokitoki Gravel aquifer

The water in this aquifer is not suitable for domestic or industrial use without treatment for hardness, iron, manganese and ammoniacal nitrogen (Barber 1993). The poor water quality may result from the long residence times of groundwater in the aquifer. Isotopic dating of water in the Matokitoki aquifer by Taylor (1994) suggests that the groundwater is around 4300 years old.

Elevated levels of chloride were encountered after prolonged heavy pumping (two months at a rate of 4320 m^3/day). When this water was chlorinated, the high levels of ammonical nitrogen caused the formation of chloramines, requiring an addition of a large quantity of chlorine to achieve adequate free chorine for treatment in the reticulation system (Barber 1993). Groundwater from this aquifer can be used for irrigation without treatment for iron.

Pesticides

A nationwide desktop assessment of pesticide contamination examined a worst-case scenario of pesticide usage, mobility, degradation and vulnerability to pollution (Close 1993a). The Gisborne–Poverty Bay area was one of the three highest ranked areas and was therefore selected for groundwater sampling for pesticides.

Pesticide analyses were made on water samples collected from eighteen bores in shallow aquifers on the Poverty Bay flats. Of the eighteen bores sampled, two bores contained detectable levels of the herbicide atrazine–bore GPF 032 in the Shallow Fluvial aquifer and bore GPG 052 in the Waipaoa Gravel aquifer (Close 1993a). Very high concentrations (37 mg m^{-3}) of the herbicide atrazine were found in bore GPF 032. This bore was located adjacent to a maize field where atrazine had been applied to the field. Bore GPF 032 is not normally used as a drinking water supply.

Further sampling for pesticide analysis was carried out on eight bores as part of a nationwide programme to assess pesticide contamination of New Zealand groundwaters in 1994 (Close 1996). Three of eight bores sampled had low-level contamination by the herbicides alachlor, atrazine and metolachlor (Table 16.3). No bores were found to have pesticide levels above the maximum acceptable value (MAV) as set out in the New Zealand drinking water guidelines (Ministry of Health 1995).

A further national survey of pesticides in groundwater took place in 1998/99 (Close and Rosen 2001). Six bores were sampled in the

Table 16.3 *Bores with detectable pesticide residues in 1993 (Close 1996).*

Bore No.	Bore depth (metres)	Aquifer	Bore use	Pesticide concentration
GPE 015	8.0	Shallow Fluvial	Domestic	0.05 mg m^{-3} atrazine
GPF 032	5.5	Shallow Fluvial	Domestic	0.1 alachlor, 0.9 atrazine, 0.1 metolachlor
GPM007	4.6	Te Harpara Sand	Agricultural Spraying	0.09 atrazine

Ministry of Health – Drinking-Water Standards 1995:
MAV for alachlor is 20 mg m^{-3}
MAV for atrazine is 2 mg m^{-3}
MAV for metolachor is 10 mg m^{-3}

Gisborne area. Two of these wells showed low levels of pesticides—Bore GPF 032 had 0.04 mg m^{-3} atrazine and bore GPM 007 had 0.02 mg m^{-3} atrazine, 0.02 mg m^{-3} alachlor, and 0.03 mg m^{-3} desethyl atrazine. Desethyl atrazine is a breakdown produce of atrazine.

Bores GPF 032 and GPE 015 consistently showed detectable levels of atrazine; both are located in the Shallow Fluvial aquifer. Detectable levels of atrazine were consistently found in bores within the Te Hapara Sand aquifer. However the results from all the surveys suggests that there are isolated hot spots of herbicide contamination that have persisted through time, but in general the shallow groundwater aquifers are generally free of pesticide contamination.

GROUNDWATER USE

Development and use of groundwater resources in the Gisborne region over the last 25 years has centred on the Poverty Bay flats. Land use in this area has intensified and diversified from agriculture to horticulture and market gardening, placing increasing demand on groundwater resources. The availability of groundwater (e.g. Fig 16.5) is therefore important to the economy of the Gisborne District.

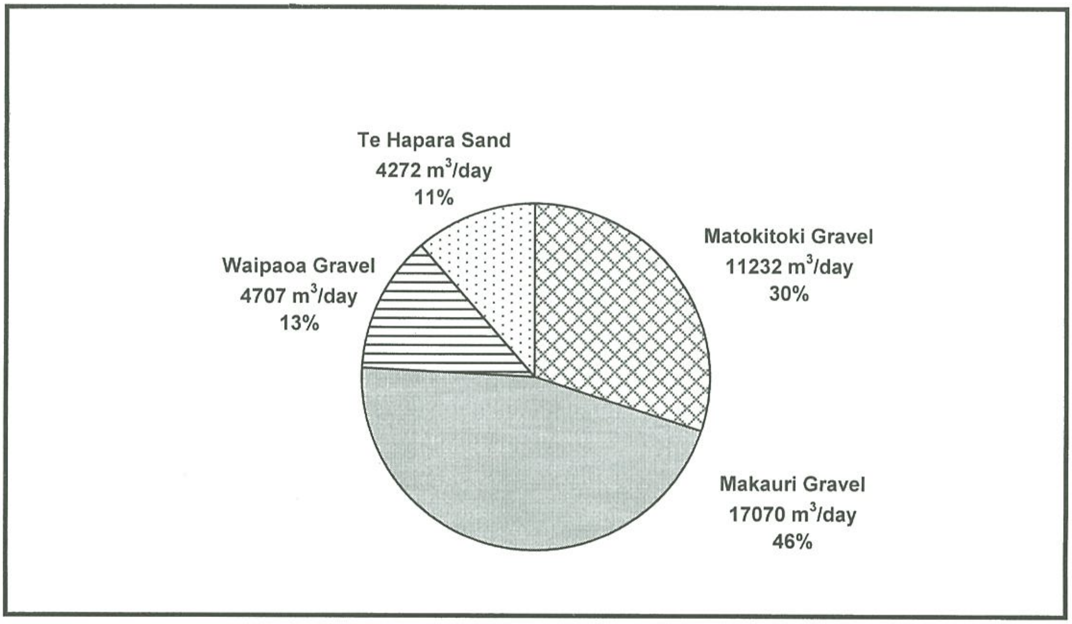

Figure 16.5 *Consented groundwater allocation for Poverty Bay aquifers as of 1997 (from Gordon 1997).*

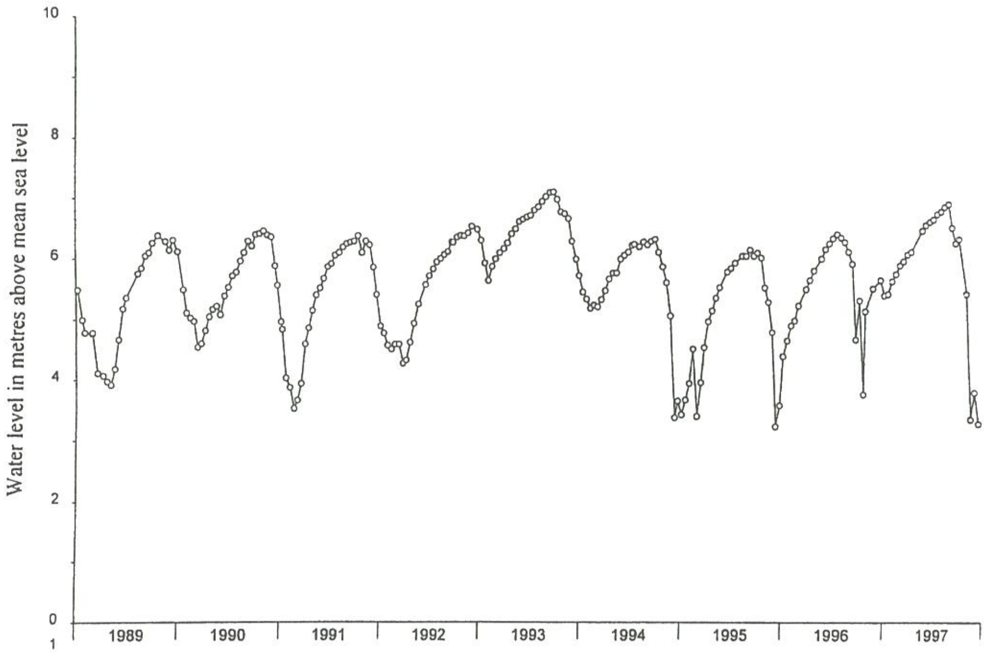

Figure 16.6 *Water level measurements from 1989-1997 in the deep bore in the Makauri Gravel aquifer near the coast, showing the seasonal change in water level of approximately 2 m (from Gordon 1997).*

In drought years groundwater resources are particularly valuable. Currently over 60% of the groundwater allocated (Gordon 1997) from Poverty Bay aquifers is used for irrigation, with the balance used for industrial and community supplies.

Groundwater supplies water to the town of Te Karaka on the northern flats and is also used for numerous small private community supplies. Two large wells that can provide Gisborne with an emergency water supply are drilled into the Matokitoki Gravel aquifer on the western boundary of Gisborne City. These bores have been used on several occasions. In February 1988 the Gisborne water supply was cut when a pipeline from the embankment dams in the Te Arai Valley broke. The bore was temporarily connected to the city water supply main and pumped to provide emergency water for two days until repairs were completed. Groundwater was used to supply Gisborne City for 21 days after Cyclone Bola in 1988 (Barber 1993).

Most of the rural households on the Poverty Bay flats use rainwater as a potable supply of water. Domestic groundwater bores are often used to supplement domestic supplies during the summer months of the year.

GROUNDWATER MONITORING AND MANAGEMENT

Gisborne District Council is responsible for the management and monitoring of groundwater resources in the Gisborne district. The council has developed programmes to monitor and manage groundwater resources in a sustainable manner as required by the Resource Management Act (1991).

A programme of monitoring water levels in aquifers on the Poverty Bay flats was started in 1986 by the East Cape Catchment Board; approximately 40 bores are monitored. The

Gisborne District Council operates a network of 90 groundwater-level monitoring bores, with measurements made fortnightly.

Seasonal water fluctuations can be observed in a long-term groundwater level plot for the Makauri Gravel aquifer (Fig. 16.6). The water level recovers completely each winter, which indicates no overall decline of water level in the aquifer.

Groundwater quality was monitored on an *ad hoc* basis for selected bores from 1983 to 1990. A groundwater quality programme was initiated in 1990 and now includes 87 monitoring sites that are sampled quarterly and analysed for the major anions and cations. Nutrient and bacterial analyses are also carried out on the shallow aquifers.

The council is currently managing groundwater under the transitional region plan through the resource management consent process. Resource management consents are currently issued for five years for abstractions over 10 cubic metres per day. Consents for large groundwater abstractions have conditions that limit the amount of abstraction according to the water level in the aquifer. Water meters are required on all consented abstractions; these are used to provide water use information and to enforce allocation compliance.

The council is currently reviewing the transitional regional plan to develop a regional plan for water management: it will include policy, methods and rules for the management of groundwater resources.

ACKNOWLEDGEMENTS

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REFERENCES

Barber, J.L. 1993: Groundwater of the Poverty Bay flats – A brief synopsis. Environment and Planning Department, Gisborne District Council. 55 p.

Brown, L.J. 1984: Makuri Gravel – A blind aquifer underlying Poverty Bay Flats, Gisborne. New Zealand Geological Survey Record 3: 69-77.

Brown, L.J. 1995: Holocene deposition in an area of late Quaternary subsidence on the northeast coast of North Island of New Zealand. Quaternary International 26: 21-33.

Brown, L.J.; Elmsly, T.A. 1987: Poverty Bay Flats' Groundwater Chemistry. New Zealand Geological Survey Record 5: 1-40.

Close, M.E. 1993a: Assessment of pesticide contamination of groundwater in New Zealand. 1. Ranking of regions for potential contamination. New Zealand Journal of Marine and Freshwater Research 27: 257-266.

Close, M.E. 1993b: Assessment of pesticide contamination of groundwater in New Zealand. 2. Results of groundwater sampling. New Zealand Journal of Marine and Freshwater Research 27: 267-273.

Close, M.E. 1996: Survey of pesticides in New Zealand groundwaters, 1994. New Zealand Journal of Marine and Freshwater Research 30: 455-461.

Close, M.E.; Rosen, M.R. 2001: 1998/99 National survey of pesticides in groundwater using GCMS and ELISA New Zealand Journal of Marine and Freshwater Research 35(2): 205-219.

East Coast Catchment Board 1985: Waipaoa water and soil resources development project, "Findings report" No. 4. 67 p.

Gisborne District Council 1995: Proposed Regional Policy Statement. Notified 5 March 1994.

Gordon, D.A. 1997: Groundwater in the state of our environment. Conservation Division, Gisborne District Council. 42-49.

Hessell, J.W.D. 1980: The climate and weather of the Gisborne Region. New Zealand Meterological Service.

Ministry of Health 1995: Drinking-Water Standards for New Zealand 1995. 87 p.

Taylor, C.B. 1994: Hydrology of the Poverty Bay flats aquifers, New Zealand: recharge mechanisms, evolution of the isotopic composition of the dissolved inorganic carbon, and groundwater-ages. Journal of Hydrology 158: 151-185.

17

Hawke's Bay

LARRY D LUBA

INTRODUCTION

Groundwater is relied on as a dependable and safe source of domestic, irrigation and industrial water supply throughout the Hawke's Bay region. Demand for good quality water is increasing steadily and groundwater is the main source of water for most of the region's urban centers.

The Hawke's Bay Regional Council is responsible for the management of the region's groundwater resources. The Council's proposed Regional Plan sets the framework for protection, management and, where appropriate, development of groundwater resources. As of June 1999 the Council had granted 2500 consents to abstract a total of some 10 million m^3/week of groundwater for various uses.

Three main groundwater systems have been identified within the tectonically active Hawke's Bay region (Fig 17.1). The largest and best known of these is the Heretaunga Plains aquifer system, which provides domestic water for a population of 143,000, and is used by large horticultural, agricultural, and food processing industries.

Also of importance is the Ruataniwha Plains aquifer system, which is being increasingly used for horticultural and pastoral development.

The third system, known as the Northern Coastal aquifer system, is located in the area between the Wairoa River and the Mahia Peninsula.

Other groundwater resources are used to a lesser extent. These include:

- the Poukawa Basin aquifer system,
- the Esk aquifer system, and
- the Papanui Stream Valley aquifer system.

HERETAUNGA PLAINS

The groundwater systems of the Heretaunga Plains have been described in detail by Dravid and Brown (1997). Information from Dravid and Brown's three-volume report forms the basis of the following description of the Heretaunga Plains groundwater systems.

Hydrogeology

The Heretaunga Plains comprise an area of about 300,000 hectares near Napier and Hastings on the east coast of the North Island (Fig 17.1). The plains are underlain by inter-leaved and inter-fingered river channel, overbank flood, estuarine and marine Quaternary sediments. These sediments have accumulated in the actively subsiding Heretaunga tectonic depression during a period of fluctuating sea levels. These Quaternary sediments, more than 250 m thick in parts of the depression, probably unconformably overlie early Pleistocene and late Pliocene marine sediments beneath the basin. The principal aquifers within the Quaternary sediments are predominantly river channel and shore-line gravels transported by the Tutaekuri, Ngaruroro and Tukituki rivers and their predecessors, and by long-shore drift. The aquifer gravels include some sand and silt. The aquifers are separated by relatively impermeable sediments comprising estuarine and marine muds, clays, silts, and poorly sorted sediments. Volcanic ash, pumice, and peat layers also occur. A general transition from river channel sediments to inter-bedded river, estuarine, and marine layers occur from west to east beneath the plain. Associated with this is a transition from unconfined to confined aquifers. Details of individual aquifers are complex, reflecting the effects of tectonic distortion of the region, migrating and meandering river channels, and changing sea levels.

Several aquifer systems are recognised within and around the Heretaunga Plains (Fig 17.2).

Luba L.D. 2001: Hawke's Bay. *In* Groundwaters of New Zealand, M.R. Rosen and P.A. White *(eds)*. New Zealand Hydrological Society Inc., Wellington. p367-380.

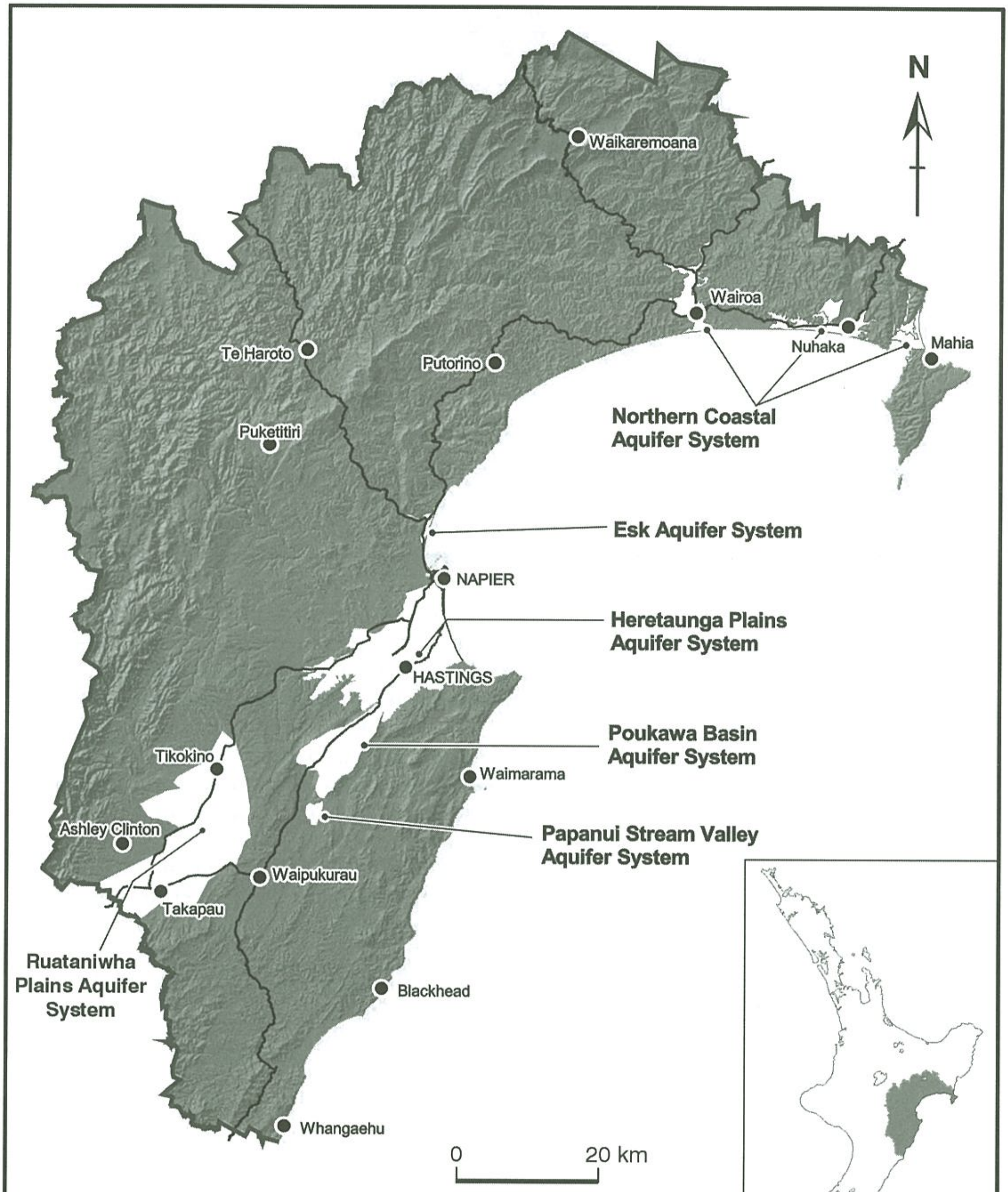

Fig 17.1 *Aquifers of the Hawke's Bay region.*

The Esk aquifer system consists of river and beach sediments on the coastal boundary between Whirinaki and Bayview.

The Ngaruroro-Tutaekuri (main) aquifer system underlies most of the Heretaunga Plains and extends to more than 250 metres depth. The limestone system on the periphery of the Heretaunga Plains occurs in the hills and beneath the margins of the plains. It consists of permeable units within Pliocene and Pleistocene

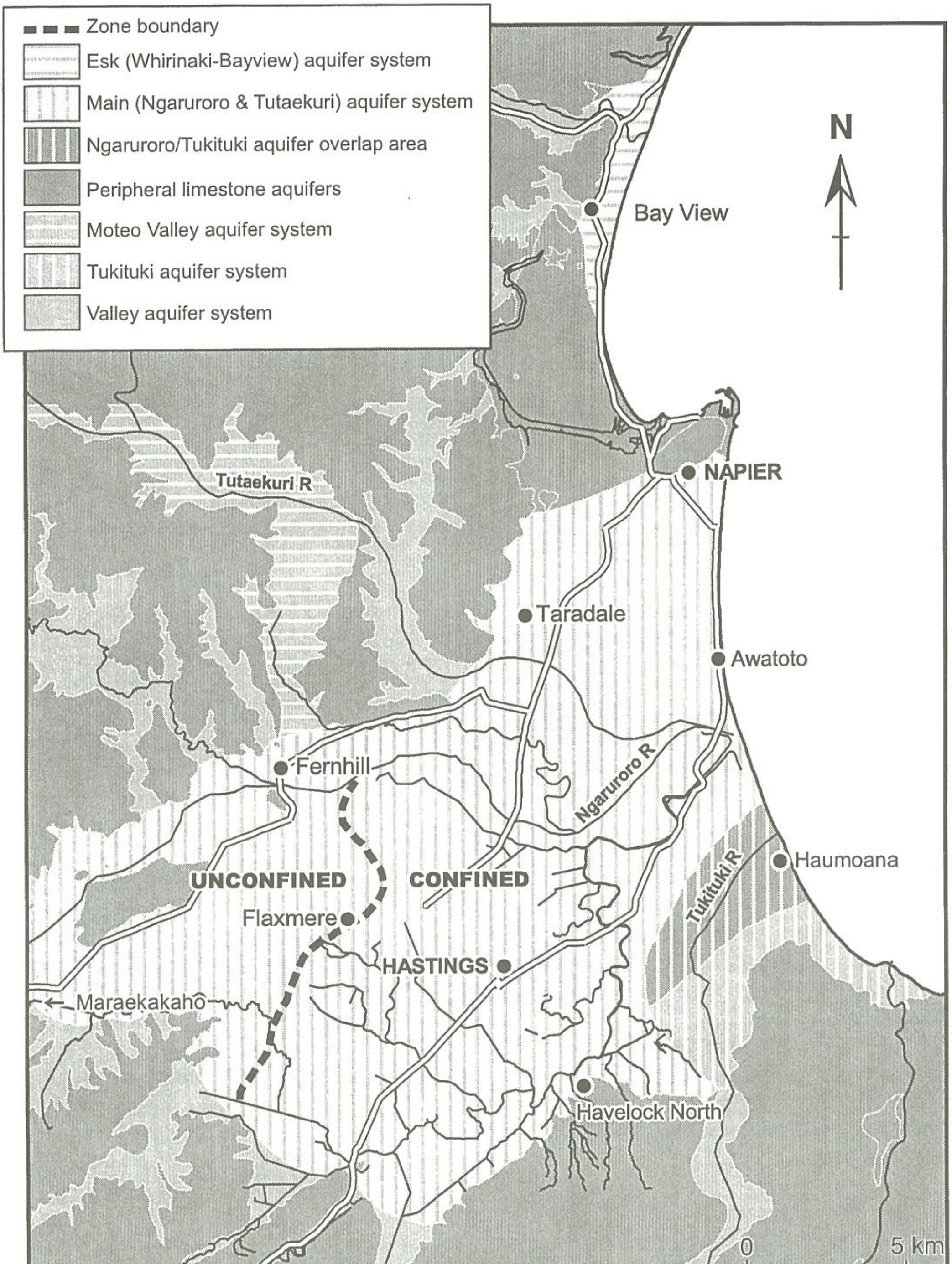

Figure 17.2 *The Heretaunga Plains aquifer system.*

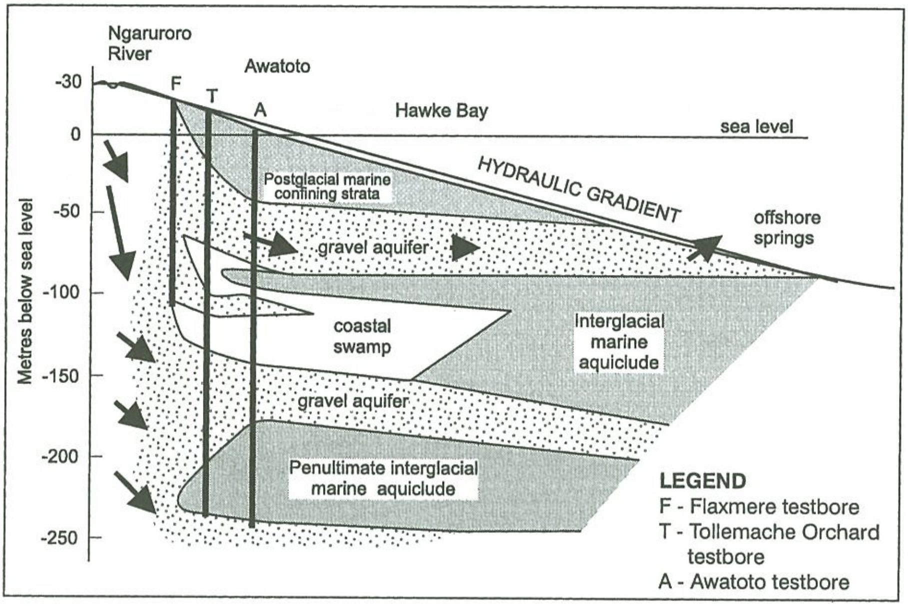

Figure 17.3 *Generalised cross section of the Heretaunga Plains and the offshore area showing deep exploratory bores,*

rocks. The average total thickness of the system has been estimated to be about 25 m to the west and about 10 m to the south of the plains.

The Moteo Valley Aquifer system occupies a former course of the Tutaekuri River and contains Quaternary gravels that form unconfined and confined aquifers. The thickness of gravels in the valley is unlikely to exceed 30 m.

The Tukituki Aquifer system, in the southeastern corner of the plains, mainly comprises shallow Quaternary gravels. This system overlies and is connected with part of the main system.

Shallow thin gravel aquifers also occur in valleys adjacent to the plains.

Figure 17.3 shows a simplified cross section of the Ngaruroro-Tutaekuri system beneath the Heretaunga Plains.

Groundwater flow and storage

Results from the most recent extensive piezometric survey of groundwater levels on and adjacent to the Heretaunga Plains, which was carried out in February 1995 during a period of very high abstractions, are shown in Figure 17.4. The illustrated piezometric contours, river gaugings, and other evidence show that the Ngaruroro River is the principal source of recharge for the Ngaruroro-Tutaekuri aquifer system. Groundwater from the river (at the western edge of the plain) flows downward, eastward, and southeastwards towards Flaxmere and Hastings, before flowing eastward and northeastward towards the coast, Taradale and Napier. The steeper piezometric horizontal gradients in the west are over an area where exploited aquifers are unconfined (Fig 17.2). The lower gradients, east of Flaxmere, are where confined aquifers and artesian wells occur.

Infiltration from the Ngaruroro River between Maraekakaho and Fernhill recharges the main Ngaruroro-Tutaekuri aquifer system at a rate of about 160 million m^3/year, equivalent to a rate of approximately 5 m^3/s. Infiltration from the Tutaekuri River supplies about 25 million m^3/year. These account for 84% and 13% respectively of total annual recharge to the aquifer system (Fig 17.5). A further natural source of recharge is rainfall, estimated to be 3% of total annual recharge (Fig 17.5). Rainfall recharge is most significant over the unconfined portion of the aquifer system and

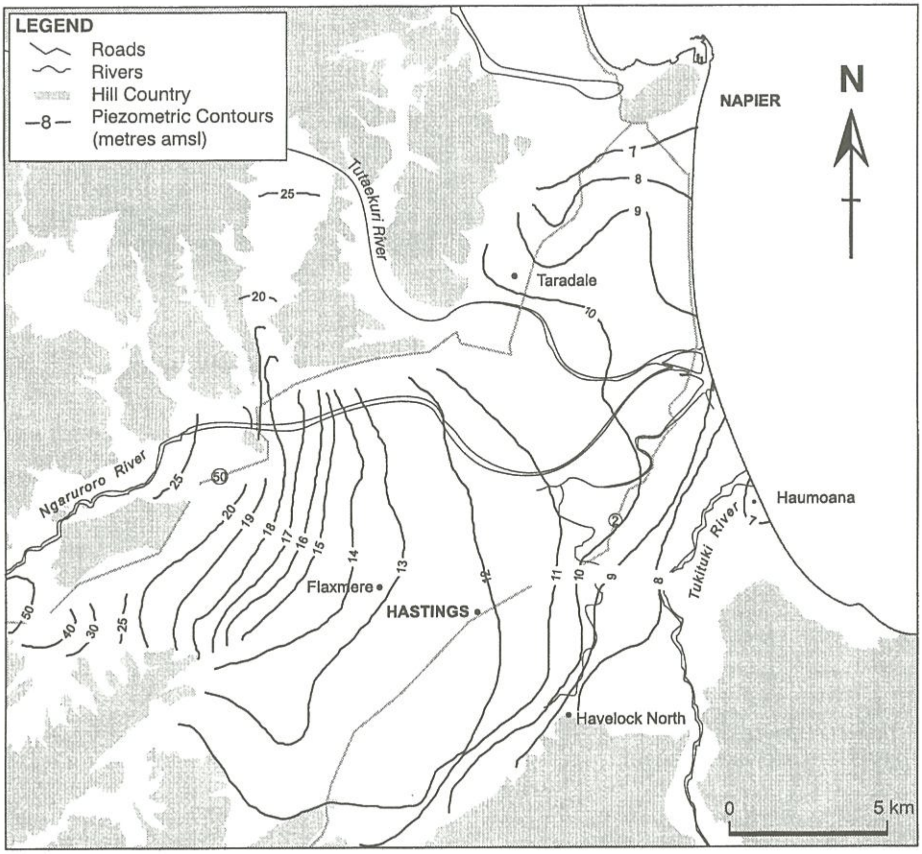

Figure 17.4 *Heretaunga Plains groundwater levels.*

individual rainfall events have been observed to increase local groundwater levels.

Radiological and stable isotopic analyses show that the velocity of groundwater flow tends to decrease with increasing aquifer depth and from the unconfined to the confined part of the system. Water taken from the shallowest confined aquifer beneath Clive, near the coast northeast of Hastings, has been deduced to take about 7 years to reach there from where it entered the aquifer system near Fernhill. Water flowing in deeper parts of the system takes much longer to reach the coast.

Outflows from the main aquifer system include seepages and springs within the plains amounting to some 120 million m^3 /year, and well abstractions accounting for approximately 66 million m^3/year. Some of the discharge from the springs occurs in submarine springs offshore in Hawke Bay (Fig 17.3). Figure 17.5 shows the percentage of outflows from the Ngaruroro-Tutaekuri aquifer system.

About 9000 wells have been drilled on the Heretaunga Plain, but many are no longer in use. The wells are mainly for public and private water supply, irrigation, and processing and manufacturing industries. Of the total water abstracted from the aquifer (66 million m^3) in 1994/95, 46 million m^3 was abstracted from the confined aquifer and some 20 million m^3 is estimated to have been abstracted from the unconfined parts of the aquifer system.

Storage in the Heretaunga Plains aquifer systems, has been estimated to be:

- 990 million m^3 in the unconfined area of the main system,
- 60 million m^3 in the confined part of the main system,

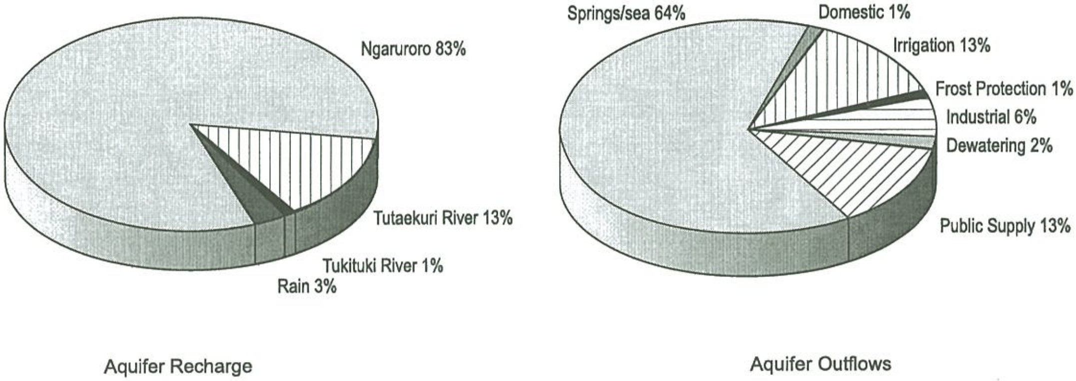

Figure 17.5 *Heretaunga Plains aquifer water balance.*

- 2 million m^3 in the Moteo valley,
- 6 million m^3 in the Tukituki system, and
- 27 million m^3 in the peripheral limestone system.

Available data do not suggest a significant change in long-term groundwater storage from the most heavily used confined areas of the Ngaruroro-Tutaekuri aquifer system. Groundwater levels naturally fluctuate by up to 1–2 metres in the middle of the plains and by as much as 5 metres on the margins between summer and winter. Levels fall during the summer and rise during the winter. Short-term falls are largely responses to increases in irrigation and domestic demand.

Long-term records of groundwater levels within the unconfined portion of the Ngaruroro-Tutaekuri aquifer however suggests a fall in annual average groundwater levels by about 1.5 metres over the last 30 years.

Groundwater quality

The quality of groundwater within the unconfined and confined aquifers of the Heretaunga Plains has been studied in detail. At depths of less than 80 metres, the water quality is very good, being very similar to that of the Ngaruroro River. At depths exceeding about 100 metres the groundwater is characterised by increases in iron and manganese concentrations and in hardness. The groundwater quality is inferior near the southwestern and southeastern boundaries of the plains, and near the hills just to the west of Napier, due in part to elevated hardness and mineral enrichment by water from the adjacent hills.

Studies have shown that the shallow unconfined aquifers are the most susceptible to contamination. A number of current land uses affect the quality of groundwater, particularly within the unconfined portion of the Ngaruroro-Tutaekuri aquifer.

For instance septic tanks have a localised effect on the quality of groundwater. The Hastings District Council has estimated that more than 500 septic tanks are located in the plains. Similarly, some samples of spring water collected on the Heretaunga Plains have contained pesticides and elevated nitrate concentrations, although none have been above maximum allowable limits or exceeded other water quality standards.

In terms of groundwater management, potential high-risk sources of contamination of the groundwater have been identified and include:

- domestic wastewater discharges,
- industrial discharges into or onto land,
- stormwater discharges,
- leachate discharges especially from closed landfills,
- septic tank and industrial effluent discharges,
- storage, use and spillage of hazardous substances (including pesticides),
- changes in land use from pasture to viticulture,
- over-use and leaching of fertilisers,
- backflows into wells,

- the puncturing of seals between aquifers as the result of poor well construction and maintenance.

The quality of groundwater across the Heretaunga Plains is very good. Careful monitoring and management plans for those areas of the plains most vulnerable to groundwater degradation are being developed.

Groundwater use

The Heretaunga Plains groundwater is vital to the economy of the Hawke's Bay Region. Groundwater provides about 85% of the domestic, agricultural and industrial water requirements of the 143,000 people living within the Heretaunga Plains and adjacent areas. Groundwater use during the 1994/95 year amounted to some 6.6 million m^3 (Fig 17.5), and included:

- irrigation and frost protection, 26 million m^3;
- public water supply, 24 million m^3;
- industrial processing using own supply, 11 million m^3; and
- rural domestic supply, 2 million m^3.

Groundwater use has increased strongly in recent years, particularly for irrigation and public water supply.

Three million cubic metres per year of groundwater are extracted to deliberately lower water table levels and thus permit desired land uses. These extractions are from shallow depth and mainly from the lower plains.

Groundwater management

Meeting the increasing demand for groundwater poses problems mainly in areas on the margins of the Heretaunga Plains.

A number of groundwater management strategies have been devised for the Heretaunga Plains area. These strategies include:

- developing a comprehensive monitoring program to measure the quality of surface waters and groundwater; water supply, irrigation and industrial withdrawals; spring-fed discharges; pumped dewatering withdrawals; and the levels of rivers and groundwater,
- investigating factors responsible for the shortage of groundwater on the southern margins of the Heretaunga Plains,
- developing policies for specific aquifers and/or land uses, and best management practices to minimise the potential risk of contamination of groundwater,
- developing policies to minimise the drainage of irrigation water to groundwater and surface waters, and
- promoting effective public awareness programs about potential water resource degradation.

RUATANIWHA PLAINS

Hydrogeology

The Ruataniwha Plains (Fig 17.1) comprise a tectonically active area of 26,000 hectares located in a fault-bounded basin between the Ruahine Ranges in the west and the Raukawa Range in the east. The basin has been tilted south-eastwards. Four major rivers flow from the Jurassic rocks of the Ruahine onto the plains. Two rivers, the Tukituki and Waipawa, flow from the plains through gaps in the Pliocene and early Pleistocene rocks of the Raukawa Range. These gaps are about 5 km apart. The hydrogeological environment beneath the plains is complex (Pattle Delamore Partners 1999) and includes a heterogeneous multi-layered system of discontinuous Quaternary alluvial sand and gravel aquifers. The alluvial aquifer system extends to depths of over 150 metres in some areas. The full thickness of the system across the plains is unknown.

Figure 17.6 shows a geological section across the centre of the plains in a direction parallel to the ranges (NNE-SSW). Several unconfined and confined aquifer systems occur beneath the plains. The recent terrace aquifer group of sediments includes the central plains unconfined aquifer, the Tukipo aquitard, and other recent terrace deposits. The unconfined aquifer is situated in the east of the plain, with extensive outcrops in the vicinity of Ongaonga and Tikokino.

This aquifer consists of clean loose sands and gravel with minor silt or silt-bound layers. It occurs between ground level and 25 metres depth and is tapped by about 25% of all bores located within the Ruataniwha Plains. Individual yields of the bores are generally less

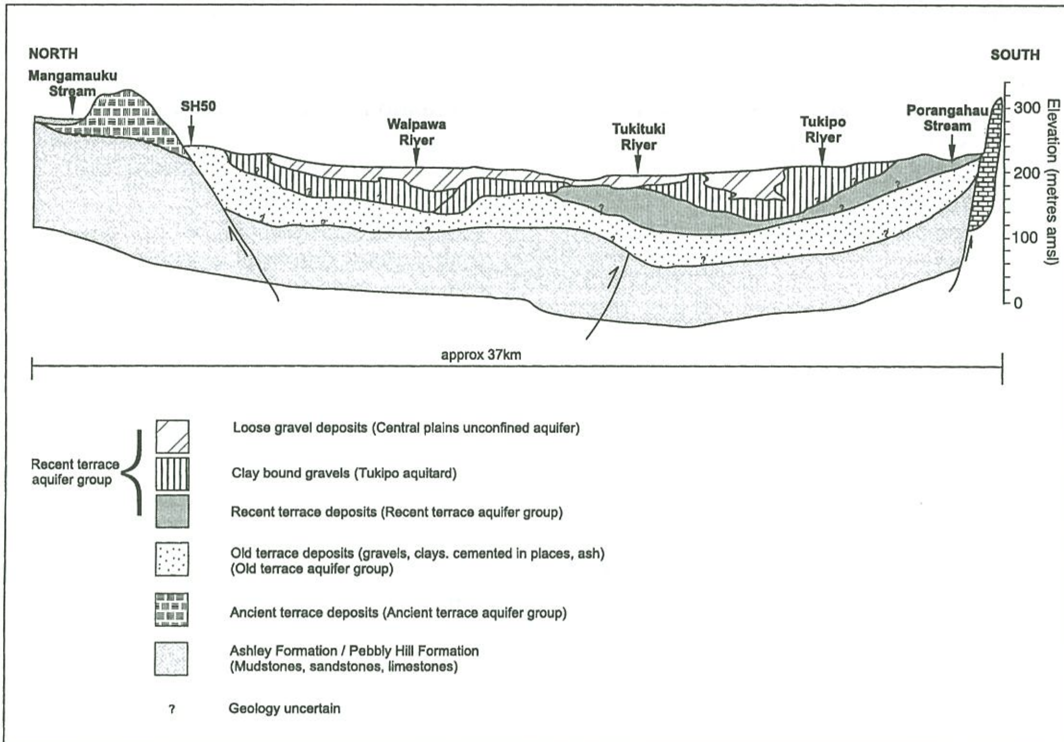

Figure 17.6 *Ruataniwha Plains – aquifer system cross-section.*

than 300 m^3/day, but some yields are in excess of 2000 m^3/day.

The central plains unconfined aquifer is underlain in places by the Tukipo aquitard, which outcrops south of Ongaonga. This aquitard consists of clay-bound gravel and extends to depths of about 80 metres in places. The other recent terrace deposits outcrop in the southeastern half of the plains and underlie parts of the central plains unconfined aquifer, and parts of the Tukipo aquitard.

The old terrace aquifer group outcrops in the northwestern half of the plains and underlies the recent terrace aquifer group in the eastern half. The old terrace aquifer group occurs at depths up to 120 metres. It consists of compact (and sometimes cemented) sands and gravel within which occur clay, silt-rich ash and pumice layers. Many bores are screened in the old terrace aquifer group.

The ancient terrace aquifer group also outcrops in the northwestern half of the plains, but at a higher elevation than the old terrace aquifer group. It outcrops within the Ruahine foothills and its sediments are similar to those of the old terrace aquifer group, except that they are more compact and cemented. Very few bores have penetrated the ancient terrace aquifer group.

Data from oil exploration bores and observations of outcrops around the plains suggest that important artesian aquifers may occur around and beneath the plains in limestone. However in some localities thick mudstones or sandstones may overlie this limestone.

Groundwater flow

Groundwater levels recorded in wells, classified into three groups according to their depth, have been used to compile a composite piezometric map (Fig 17.7) which shows that horizontal components of groundwater flow are toward the east and southeast of the Ruataniwha Plains. The horizontal direction of groundwater flow is similar to that of surface water drainage.

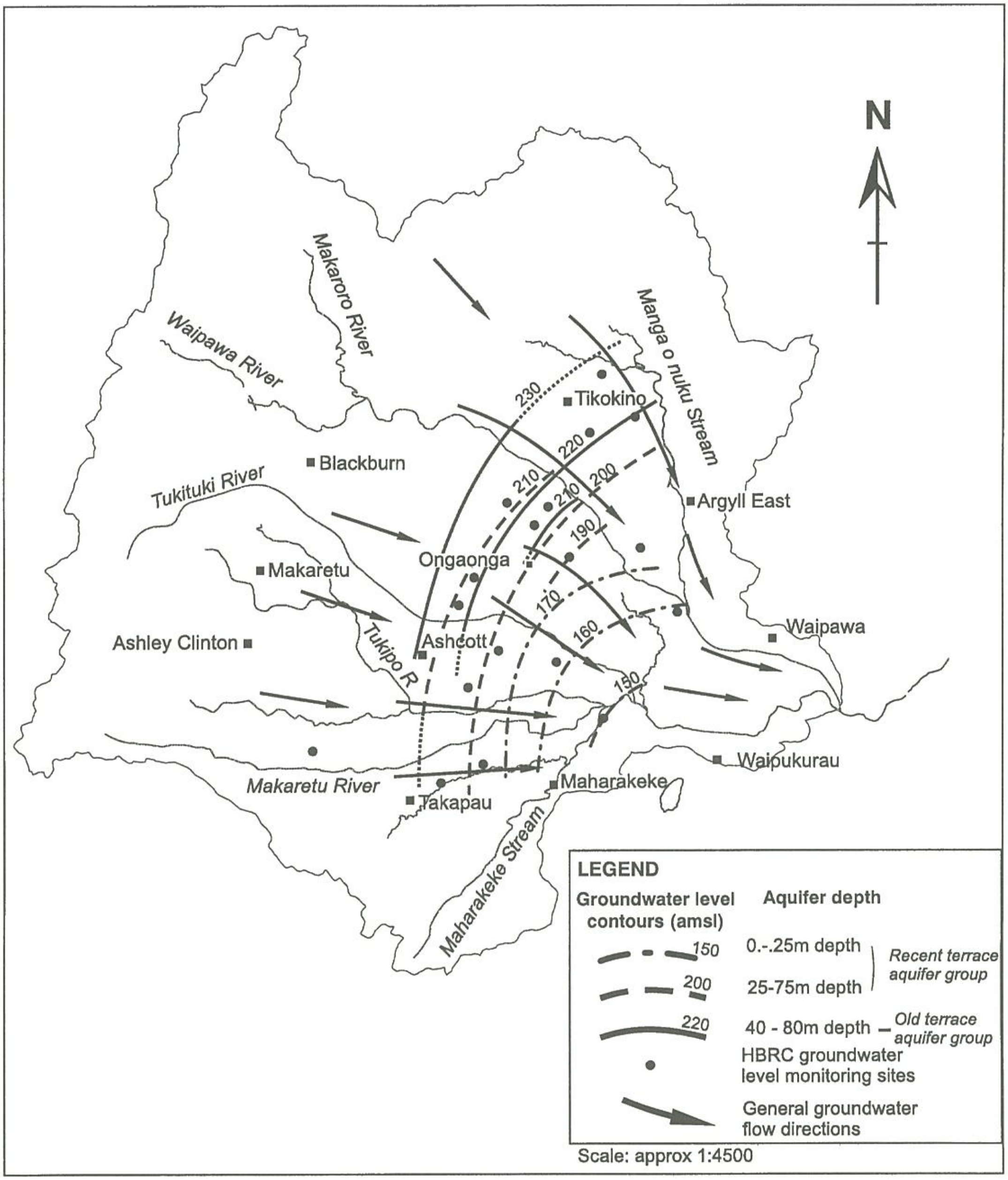

Figure 17.7 *Ruataniwha Plains – piezometric levels and the direction of groundwater flow.*

The piezometric data also show that piezometric surface levels increase with increasing depth in the eastern half of the basin, showing that water is likely to be leaking upwards in this area.

The shallow alluvial aquifers are recharged by infiltrating precipitation on the plains, infiltration from rivers and streams, subflow from adjacent strata, and excess irrigation. Chemical analyses indicate that some water seeps upwards into the deep alluvial aquifers from the underlying limestone and sandstone units.

Annual recharge by infiltrating precipitation in the plains and catchments draining into the plains has been estimated at about 180 million m^3/year, and recharge by infiltration from watercourses at about 150 million m^3.

River gauging and hydraulic head recording show that groundwater is discharging from the alluvial aquifers in the south and eastern portions of the Ruataniwha Plains. Discharges occur as springs along the eastern margin of the plain, as seepages into watercourses, as subflow into the lower Tukituki catchment, as well as by abstractions.

The total annual discharge into the rivers and the subflow have been estimated at about 290 million m^3 and 6 million m^3 respectively. Well abstractions have been estimated as 30 million m^3/year.

To date it has not been possible to determine whether the alluvial aquifer system is in a state of equilibrium or under stress.

Groundwater levels have been recorded within various alluvial aquifer units at over 25 monitoring wells. The longest record is some 12 years. Hydrographs indicate an overall lowering of groundwater levels over the last several years in a number of locations; the most pronounced is in the Te Papa No. 2 (Tideda site 884001) monitoring bore, which shows a 2 m decline in water levels over 12 years. The observed fall in levels is probably related to a number of factors, including the length of monitoring records available, increased irrigation withdrawals and below-normal rainfall over this period.

Groundwater quality

The groundwater within some areas of the Ruataniwha Plains is vulnerable to contamination due to inappropriate land use. Nearly all land in the Ruataniwha Plains is developed for agricultural production. The Ruahine foothills area supports sheep and cattle farming, whereas the lower plains support intensive horticulture, dairying, and process cropping. Over recent years there has been a trend towards more intensive land use and increased dairying. Principle sources of potential contamination are related to agrichemicals, fertilisers, dairy effluent discharge, and septic sewage disposal. Potentially the highest risk areas include the unconfined Central Plains aquifer and areas underlying river loss zones.

A key indicator of groundwater quality is the maximum nitrate levels found in water. Background levels across the plains are generally less than 1 mg/L nitrate-nitrogen, however on occasions, during compliance monitoring of consented activities, nitrate-nitrogen levels exceeding the New Zealand drinking water standards have been detected.

Groundwater use

There are about 230 bores in the plains, of which at least 100 are active wells. Approximately 75% of all bores take groundwater from within the upper 60 metres of alluvial sediments. Three zones of high groundwater use occur on the Ruataniwha Plains. Two of the zones, located between Ongaonga and Tikokino, draw water from the Central Plains unconfined aquifer. The third, a few kilometres east of Takapau, draws water from the recent terrace aquifer group.

Bores within the Central Plains unconfined aquifer zone are typically between about 50 and 60 metres deep whereas those in the zone east of Takapau are up to about 70 metres deep.

Groundwater accounts for about 70% of total water used for irrigation, industry and potable water supply on the plains. During the last 10 years, groundwater use has increased in all sectors, with permitted irrigation withdrawals increasing by over 400%. Available information indicates that between 1980 and 1995 the land covered by consents to irrigate increased from 260 ha to 2200 ha.

Between 1980 and 1995 the allocated maximum weekly groundwater take increased from 87,000 m^3 to 500,000 m^3. It is anticipated that the demand for groundwater will continue to increase with a continued expansion of dairying.

Groundwater management

The future management of water resources in the Ruataniwha Plains will involve the development of a plan for monitoring groundwater and surface water. The groundwater monitoring system will be continually updated to reflect an improved understanding of water resources within the plains, and to quantify volumes of groundwater extracted from the various alluvial aquifers. There will need to be special emphasis on areas where groundwater levels are falling.

To effectively manage the groundwater resource it will be necessary to more fully understand groundwater-surface water interactions; the quantity, quality and dynamics of water in deep aquifers and the sustainable yields of the various groundwater sub-catchments.

NORTHERN COASTAL AREA

Hydrogeology

The Northern Coastal area of Hawke's Bay encompasses a region between Wairoa and the Mahia Peninsula (Fig 17.1). Data on aquifers in the area have been summarised in a report by Cameron (1999).

Six aquifer systems have been defined within this area, based on lithology, geology, groundwater quality and location.

The systems include the Wairoa Valley aquifer system (c. 5,230 hectares), the Nuhaka coastal aquifer system (4,110 hectares), the Nuhaka limestone aquifer (>1,050 hectares), the Mahia sand aquifer system (1,571 hectares), the Mahia alluvium aquifer system (970 hectares), and the Mahia Peninsula Tertiary aquifer.

The Wairoa Valley aquifer sediments consist of late Quaternary fluvial gravels, which are inter-bedded with alluvial and marine silt and clay. Two confined aquifers occur in the lower valley, where the shallower is about 10 to 12 metres thick and the deeper is up to 5 metres thick. Depths to the aquifers are 12 to 22 metres and 26 to 54 metres, respectively.

The Nuhaka coastal system includes the unconfined Nuhaka River Valley aquifer, the confined paleo-beach gravel Nuhaka township aquifer, and the Nuhaka coastal sand and alluvium aquifer. The unconfined Mahia sand aquifer is on the tombola between the Mahia Peninsula and the mainland. The Mahia Peninsula tertiary aquifer consists of sandstones, siltstones, and mudstones within which are fractured zones.

Groundwater flow and storage

Piezometric surface maps for the aquifer systems have not yet been prepared due to a lack of data. As the topography within the northern coastal area is rolling to hilly, the horizontal component of groundwater flow is likely to be similar to that of the surface water.

Recharge and discharge areas for each aquifer system have not yet been determined. However it is assumed that each of the aquifer systems is recharged primarily by rainfall and that the aquifers discharge at locations near the coast.

Annual recharges from precipitation and river losses have not been estimated for any of the Northern Coastal aquifer areas. Based on resource management consents, the total annual groundwater abstracted from the six aquifer systems has been estimated to be nearly 3 million cubic metres. Slightly more than half of the abstraction is from the Nuhaka Coastal Aquifer System.

Most of the Northern Coastal aquifers are located within valleys or are adjacent to the coast. Most bores are within narrow areas where groundwater is generally found at depths of less than 30 metres.

Records of groundwater level have been collected since about 1996 for the Wairoa Valley aquifer, Nuhaka coastal aquifer, Mahia sand aquifer, Mahia alluvium aquifer and the Mahia tertiary aquifer systems. Existing data indicate relatively stable average groundwater levels for all aquifers except the Mahia sand and Mahia alluvium aquifers.

Hydrographs for the Mahia sand and Mahia alluvium aquifers show seasonal increases and decreases in groundwater level. The fall in levels during summer is probably a consequence of the seasonal increase in population of the Mahia seaside resort.

Groundwater quality

The Northern Coastal area has a low population density, limited industry and sparsely developed agriculture. Most of the hilly land in and near the northern coastal area is used for livestock grazing. However, relative to the New Zealand drinking water standards, the groundwater from most of the northern coastal area is poor to moderate in quality. Groundwater is seldom used for drinking water due to undesirable iron levels and hardness, and the availability of a better water supply from rivers or rainwater.

Groundwater sampling generally indicates low concentrations of nitrate-nitrogen in relation to the New Zealand drinking water standards. However at a few sites nitrate-nitrogen levels, on occasion, exceed the drinking water standards. One such site is located on the Mahia sand aquifer, down-gradient of a landfill.

Relatively little groundwater contamination from agricultural or industrial sources other than landfills is anticipated in this area.

Groundwater use

Groundwater accounts for only about 16% (about 3 million m^3/year) of all water permitted to be taken within the northern coastal area. About 55% of the permitted groundwater extraction is from the Nuhaka area and about 70% of this is for irrigation and industrial use.

Groundwater management

Aquifers that appear to offer the greatest potential for future water supply include the Nuhaka limestone aquifer, the Nuhaka coastal sand and alluvial aquifer, the Mahia sand aquifer and the Wairoa Valley shallow aquifer. Amongst these the unconfined and fractured Nuhaka limestone aquifer may offer the best potential for future use.

Further investigations should help characterise the hydraulic properties of these aquifers and determine whether the quality of groundwater would be suitable for irrigation and/or industrial water supply.

Future investigations of possible groundwater contamination need to be targeted at areas downstream of landfills, and at assessing risks to human and environmental health.

OTHER GROUNDWATER RESOURCES

Esk aquifer system

Information on the Esk aquifer system has been summarised by Dravid (1997).

The Esk aquifer system is located in an area extending from Napier Hill and Park Island north to Bay View and across the Esk River, and including the Whirinaki area (Fig 17.1). The system consists of river and beach gravel sediments adjacent to the coast, along with mixed silt and sand beneath the Esk River floodplain.

In the Bay View area the coastal gravels and an underlying limestone unit form a connected unconfined-confined aquifer system.

The unconfined aquifer is usually within 10 metres of the ground surface. Inland a multilayered confined aquifer system has been penetrated to explored depths of about 40 metres.

Near Park Island (Lagoon Farm area) the limestone aquifer is semi-confined to confined. Hydraulic heads are above ground surface and well yields are poor to moderate. The limestone is 15 to 25 metres below ground surface.

A piezometric surface map of groundwater levels has been compiled using data recorded in 1995 for 15 wells near the coast between Bay View and the Whirinaki area. Groundwater flow is from the Esk Valley toward the coast. Groundwater movement will likely occur mainly within old buried river channels. The extent of groundwater recharge by the Esk River is unknown but it is likely that the river recharges the aquifer system.

Groundwater levels within parts of the unconfined aquifers of the Esk system are influenced by rainfall and ocean tides. In general static groundwater levels range between 4 and 6 metres below ground surface, with fluctuations of about 2 metres between summer and winter levels.

Groundwater within the Esk aquifer is characterized by local elevated electrical conductivities, increasing sodium and chloride concentrations toward the coast, and low total dissolved solids. The shallow coastal groundwater may be affected by salt-water intrusion, particularly in the northern part of the aquifer system. The low total dissolved solids concentration suggests that the aquifer system is recharged by infiltrating rainwater and seepage from the Esk River.

The unconfined aquifer may be at risk of contamination as a result of irrigation and septic tank discharges. Localised elevated concentrations of nitrate-nitrogen have been observed in a number of coastal wells in the Bay View–Whirinaki area. These most likely result from septic tank discharges.

The unconfined coastal aquifer is highly susceptible to contamination, and specific groundwater management policies may have to be developed in order to maintain the quality of groundwater at an acceptable level for domestic consumption.

Poukawa Basin aquifer system

The Poukawa Basin is about 15 kilometres south of Hastings (Fig 17.1). The 4 by 8 kilometre basin is a northeast-southwest-trending tectonic depression. The catchment is effectively a closed system, with low hills at the northern and southern ends and the Raukawa and Kaokaoroa Ranges to the west and east, respectively.

The basin is infilled with Quaternary sediments that are more than 234 metres thick. Lake Poukawa occupies the centre of the basin.

Three aquifer systems have been identified within the basin at depths of less than 108 metres. The aquifers have been found within late Quaternary sediments and in the Pliocene and early Pleistocene sediments that underlie the Poukawa Basin and outcrop on the surrounding hills.

Within the basin an unconfined aquifer, at between 2 and 15 metres depth, consists of shallow fluvial and lake sediments. Lake Poukawa is linked to this aquifer. A confined aquifer of late Quaternary fluvial sediments, including sand and silty sand, occurs below about 38.5 metres in depth. Pressure heads of up to 9 metres above ground surface have been recorded within this confined aquifer.

Limestone, siltstone and sandstone form the adjacent hills. The structure of the Poukawa Basin suggests that the limestone (and associated aquifers) may underlie the entire Poukawa Basin and that sandstones and siltstones may underlie the limestone aquifers. An isopach map suggests that the limestone is about 150 metres thick between Lake Poukawa and the Kaokaoroa Range.

Chemical, stable and radiogenic isotopes, pressure, and other available data suggests that the deep aquifers are recharged by rainfall in the surrounding hills. There is evidence supporting upward leakage into shallower basin sediments and into Lake Poukawa. Flowing artesian wells occur within the lower portion of the Poukawa basin.

Soils within the Poukawa Basin are naturally fertile. Groundwater will be an increasingly important source of irrigation water for crop production.

The Poukawa Basin is an area of high demand for water, but its groundwater resources are poorly understood. Improvement of understanding of the groundwater resources will require:

- the identification and quantification of system inputs and outputs,
- assessment of vertical and horizontal groundwater flows,
- assessment of aquifer (hydraulic) properties,
- development of a groundwater mass balance and
- development of a comprehensive long-term groundwater monitoring programme.

Papanui Stream Valley aquifer system

The Papanui Stream Valley aquifer system is located between 50 and 55 kilometres southwest of Napier (Fig 17.1) and is poorly understood. It includes a number of shallow aquifers (depths up to about 9 metres), and deeper confined aquifers between about 20 and 26 metres and between about 30 and 39 metres depth within the Papanui Stream Valley. The shallow confined aquifer system consists of blue and red gravel with shale, whereas the deeper confined aquifer system consists of loose red gravel.

The valley is a previous watercourse for the Waipawa River. It is therefore likely that both confined aquifer systems extend over a sizeable area within the old channel of the Waipawa River.

Limited tests indicate the deeper confined aquifer system has a reasonably high transmissivity (about 2,500 m^2/day) and storativity (about 0.00018).

Based on topographic elevation, it is inferred that the horizontal component of groundwater flow is from the Waipawa River toward the north.

Potential sources of recharge water include the Waipawa River and rainfall. Rainfall within the Papanui River Valley averages about 900 mm per year, with most rainfall occurring during the winter. However about 25% of the time summer rainfall is less than 30 mm per month, and flow in the Papanui Stream is very low or non-existent. Observed groundwater levels at bores within the confined aquifers suggest that groundwater levels are responsive to rainfall events. Potential recharge from the Waipawa River is not yet understood.

The quality of the shallow groundwater is consistent with water derived predominantly from the Waipawa River. Shallow bore water is characteristically low in salinity, low in iron and manganese concentrations and low in most other major ions. Appreciable nitrate-nitrogen concentrations have been found in some bores at the north end of the old Waipawa River Valley and in bores located away from the main river channel. These suggest the infiltration of rainfall into the shallow groundwater.

The deep groundwater is of medium salinity and very hard, with moderately elevated iron and manganese. Some relatively high nitrate-nitrogen concentrations also occur.

Other than intensive livestock operations at the headwaters of the Papanui Stream, no other concentrated sources of groundwater contamination are known within the valley.

The central catchment area has a high potential for increased cropping and horticulture, provided a water supply is available. A number of irrigation schemes using groundwater have recently been developed within the Papanui Stream Valley. Groundwater resources adjacent to the major river channels and the Papanui Stream may be developed further. However, since groundwater levels may be drawn down during periods of high demand, careful monitoring and observation of groundwater levels will be required to manage the groundwater resource.

The Papanui Stream Valley lies within a water-short area. A better understanding of this groundwater resource is needed—the requirements to bring this about are similar to those listed for the Poukawa Basin aquifer system.

ACKNOWLEDGEMENTS

The figures were adapted for this chapter by Stu Davey. The text has been edited by Bob McIntyre and Michael Broadbent.

REFERENCES

Cameron, S.G. 1999: Northern Hawke's Bay Coastal Groundwater Study. Report EMT 99/2, Hawke's Bay Regional Council.

Dravid, P.N. (David) 1997: Brief review of current knowledge of the Esk Aquifer System. Hawke's Bay Regional Council.

Dravid, P.N. (David); Brown, L.J. 1997: Heretaunga Plains Groundwater Study. Hawke's Bay Regional Council and Institute of Geological and Nuclear Sciences Ltd.

Pattle Delamore Partners 1999: Ruataniwha Plains Conceptual Hydrogeological Model. Report EMT 99/3, Hawke's Bay Regional Council.

18

Taranaki

GLENN STEVENS

INTRODUCTION

The Taranaki region is located in the west of the North Island (Fig 18.1). The dominant features of the landscape are the andesitic cone of Mt Taranaki/Egmont (2,518 m) and its surrounding volcanic ring plain. The region also includes dissected hill country to the east, and marine terrace formations to the south and, to a lesser extent, the north.

The north-south trending Taranaki Boundary Fault Zone marks the boundary between the Taranaki basin to the west and up-thrown Tertiary sediments, which form the dissected hill country, to the east. To the west the down-thrown Tertiary formations are of wide extent and stratigraphically similar to the sequences of the eastern hill country. They are unconformably overlain by Quaternary volcanic deposits of the Egmont Volcano and earlier volcanic centres, and the surrounding ring plain.

A number of geologic formations are recognised within the Tertiary sediments, principally the Urenui, Matemateaonga, Tangahoe, and Whenuakura formations (Fig 18.1). The Urenui and Tangahoe formations are dominantly impermeable siltstones and mudstones and form extensive aquitards.

Usable aquifers occur in Taranaki volcanics, coastal marine terraces, Whenuakura Formation and Matemateaonga Formation. The Mount Messenger Formation, whilst outcropping in the far north of the region, generally lies too deep beneath much of the region to be a practical source of groundwater.

TARANAKI VOLCANIC AQUIFERS

The Taranaki volcanic deposits are from a group of four Quaternary volcanoes: Paritutu is the oldest (~1.7million years), followed by Kaitake, Pouakai and Egmont (Taranaki Regional Council 1996). The Taranaki volcanic deposits include the present ring plain surrounding Mt Taranaki/Egmont and that of the earlier volcanic centres. These deposits comprise lava, pyroclastic (air fall material including ash) and lahar deposits. Thicknesses of up to 170 m have been encountered near Stratford. However, in general the formation thins concentrically away from the volcanic source. The formation extends to the coast in the west of the region. To the east, the volcanic deposits thin and give way to the older Tertiary deposits of the Taranaki Basin. To the north and south they are disrupted by the Quaternary marine terrace deposits.

The Taranaki volcanic deposits contain both coarse material (sands, breccia, agglomerates) and fine material (clay, tuff and ash), resulting in irregular lithologies and anisotropic hydrogeologic conditions (Taylor and Evans 1999). This results in a complex groundwater system of multiple perched aquifer systems and partially confined aquifers. Typically the water table on the ring plain lies 1 to 10 m below ground level. The water table generally follows the topography, although it is much more subdued. The Taranaki Ring Plain Survey (Taranaki Catchment Commission 1984) found that shallow wells are generally low-yielding, with flow rates up to 4 L s^{-1} being typical, although yields of 13 L s^{-1} have been recorded.

The observed values of hydraulic conductivity of $9.3x10^{-6}$ to $1.7x10^{-5}$ m s^{-1} are consistent with tuffaceous, silt and fine sand lithologies.

The Taranaki Volcanic aquifers are primarily recharged by rainfall infiltration.

MARINE TERRACE AQUIFERS

The Marine Terrace deposits occur on coastal areas south of Hawera and, to a lesser extent, the coastal areas north of New Plymouth. The

Stevens G. 2001: Taranaki. *In* Groundwaters of New Zealand, M.R. Rosen and P.A. White *(eds)*. New Zealand Hydrological Society Inc., Wellington. p381-386.

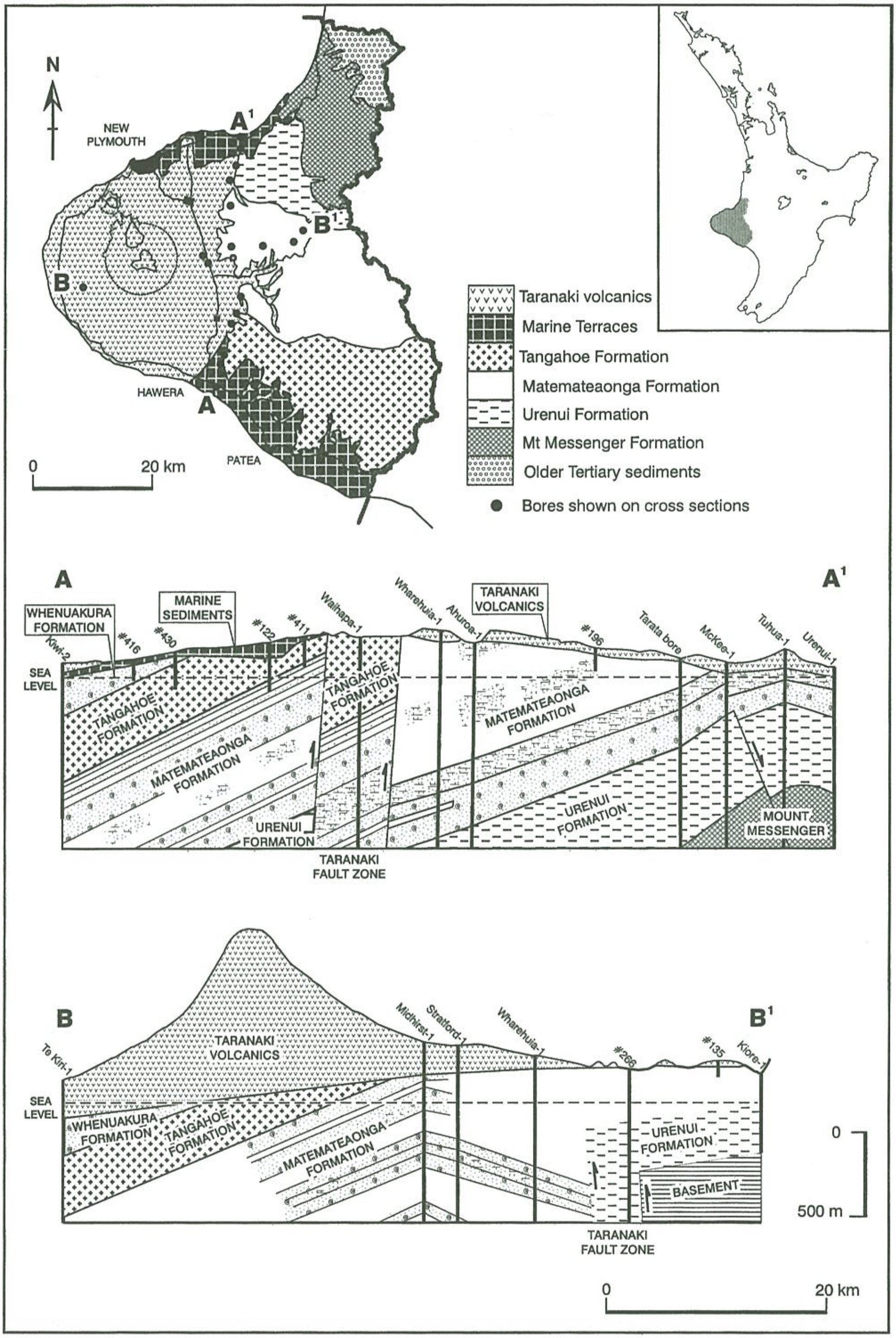

Figure 18.1 *Schematic geological map and cross-sections of the Taranaki region (adapted from Taranaki Regional Council 1996).*

cutting of marine terraces and the deposition of Plio-Pleistocene shelf sediments are attributed to eustatic fluctuations in sea level, progressive uplift of south Taranaki, and subsidence of the south Wanganui Basin (Taranaki Geological Society 1993).

In South Taranaki the Marine Terrace deposits overly the Whenuakura Formation on a wave-cut platform which represents an erosional unconformity. Basal units are typically marine sands, often with conglomerate or shell layers. These sediments grade up to terrestrial sediments. The marine terrace sediments range up to about 40 m in thickness and include multiple unconfined aquifers (Taranaki Regional Council 1996).

The average observed bore yield is 1.3 L s^{-1}, with yields up to 3.8 L s^{-1} being recorded. The highest yields occur from the coarser grained units such as the basal sands and conglomerates. The observed yield, however, depends on the size, construction and individual conditions of a bore, and does not necessarily reflect the theoretical yield from the aquifer itself.

The water table in the marine terraces generally lies 1 to 15 m below ground level, and typically follows the topography, although it is much more subdued.

The Marine Terrace Aquifers are primarily recharged by rainfall infiltration.

WHENUAKURA FORMATION AQUIFER

The Whenuakura Formation comprises Tertiary concretionary shelly blue-grey siltstones, mudstones and sandstones. It includes bedded pebbly sands, siltstone, mudstone, limestone and shellbeds (Taranaki Regional Council 1996). It is overlain by the Taranaki volcanic deposits north of Hawera and the marine terrace deposits to the south. It is underlain by the impermeable Tangahoe Formation. The Whenuakura Formation is not exposed at the surface, except in some incised river valleys in the south (Taylor and Evans 1999).

Groundwater is abstracted from the sandstone and shelly limestone layers and several relatively extensive aquifers have been identified within the formation. Bores abstracting water from the Whenuakura Formation typically display yields of up to 9.5 L s^{-1}. Hydraulic conductivities have been measured at $1.3x10^{-5}$ to $5.8x10^{-5}$ m s^{-1}.

Recharge to these aquifers is not well understood. Some recharge may occur via the overlying Taranaki volcanic deposits in the north and marine terrace deposits in the south. Some recharge may also occur where the formation is exposed in incised river valleys.

MATEMATEAONGA FORMATION AQUIFER

The Matemateaonga Formation comprises alternating Tertiary sandstone, conglomeratic shell and mudstone beds. The formation extends across almost the entire region, except north of Urenui (Taylor and Evans 1999) and contains multiple aquifers. In a hydrocarbon exploration bore near Stratford, the formation is encountered from 170 to 1,086 m below ground level. It is exposed throughout large areas of the eastern hill country in central and south Taranaki (Fig 18.1). The formation contains a greater proportion of sands towards the south, and is finer-grained in the north (Taranaki Regional Council 1996).

In North Taranaki the Upper Matemateaonga Formation Aquifer is largely unconfined. Elsewhere in the region the aquifer is either confined or partially confined. Flowing artesian conditions exist at a number of localities, particularly in a band of incised hill country bordering the ring plain from Toko south to Ohangai (Taranaki Regional Council 1996).

Yields of up to 15 L s^{-1} have been observed from aquifers within the Matemateaonga Formation. Hydraulic conductivities of $1.4x10^{-5}$ to $3.0x10^{-4}$ m s^{-1}, and storativities of $1.1x10^{-5}$ to $2.3x10^{-4}$, are measured.

Potentiometric contours for the Upper Matemateaonga Formation Aquifer (Fig 18.2) imply radial groundwater flow away from Mt Taranaki/Egmont and south-westerly flow from the eastern hill country, where the formation is exposed at the surface. The contours indicate that there is probably significant recharge to the aquifer from surface infiltration in the unconfined areas of the east and north, and leakage from the overlying volcanic deposits of Mt Taranaki/Egmont and the surrounding ring plain.

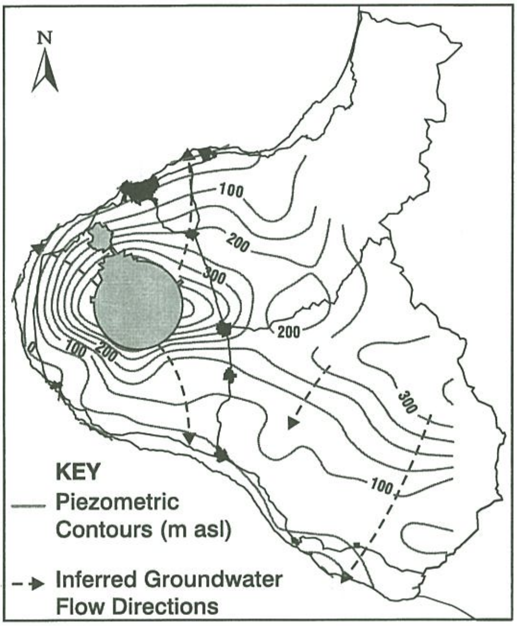

Figure 18.2 *Upper Matemateaonga Formation aquifer potentiometric map (Taranaki Regional Council 1996).*

GROUNDWATER QUALITY

The lithology of the aquifer and the residence time of the groundwater in the subsurface determine the quality of a particular groundwater. For the principal aquifers in Taranaki, total dissolved solids generally increase with increasing depth through the Taranaki volcanics, Whenuakura Formation aquifers and Matemateaonga Formation aquifers.

At depths greater than around 800 m below ground level, fresh groundwater gives way to groundwaters that are typically very saline (up to 22,000 g m^{-3} as NaCl). Water from such depths, however, is encountered only during hydrocarbon exploration activities.

Groundwater from the Taranaki Volcanic deposits typically has elevated free carbon dioxide, iron and manganese concentrations. The free carbon dioxide is a result of decomposition of organic matter buried when existing vegetation was overwhelmed during volcanic eruptions (Taranaki Catchment Commission 1984). This has resulted in the formation of relatively acidic groundwaters that can cause corrosion of pipe work and metallic fittings.

The iron and manganese concentrations reflect the relatively abundant iron and manganese oxides and minerals in the andesitic rock material of the Taranaki volcanic deposits. The distribution of elevated iron concentrations in aquifers is widespread, but variable, throughout the Taranaki Volcanic aquifers. The iron can cause staining of fixtures, clogging of pipes and encrustation of well screens. Iron bacteria are present in some wells, particularly those intercepting strata associated with old swamp and marsh deposits.

The groundwater quality of the underlying Tertiary aquifers is generally much better than that of the overlying volcanic aquifers, although it has a higher hardness.

Because of intensive dairy farming in the region, the shallow unconfined aquifers, particularly the volcanics and marine terrace aquifers, are susceptible to nitrate-nitrogen contamination. Measurements of almost 200 samples of shallow groundwater in Taranaki have revealed elevated nitrate-nitrogen concentrations in some areas of intensive dairy farming, particularly in South Taranaki where stocking rates are generally high. The excessive use of nitrogen-rich fertiliser to increase pasture production also contributes to nitrate-nitrogen contamination.

Presently there is relatively little intensive horticulture in Taranaki, so elevated nitrate-nitrogen concentrations associated with such activities are not readily quantifiable.

An investigation of potential pesticide contamination of shallow groundwater at 32 sites (Taranaki Regional Council 1995) found traces of pesticides at only two sites. These sites are tree nursery operations and concentrations were well below those of environmental concern. No pesticide residues were found in any of the sample sites on dairying land. The use of pesticides by the dairy industry, Taranaki's predominant agricultural activity, is relatively low.

Sea water intrusion has been recorded at coastal bores at the now disused Waitara and Patea freezing works in north and south Taranaki respectively. Some coastal municipal groundwater supply bores for the Patea township have also encountered problems with sea water intrusion in the past, but these bores are no longer in use. Elsewhere in the region, most groundwater is used for stock and domestic supplies, and abstraction rates are typically so low that sea water intrusion is not a problem. However, it should be assumed that any coastal groundwater supply is vulnerable if over-pumped.

BASEFLOW OF SURFACE STREAMS

Groundwater discharge contributes to the baseflow of many of the region's surface waterways, particularly the ring plain streams emanating from the slopes of Mt Taranaki/ Egmont. Discharge of groundwater on the mountain, particularly above 1,100 m above sea level, occurs via zones of springs that feed many of the radial streams that flow from the mountain. For example, approximately 60% of the low flow in the Kapuni Stream is derived from spring zones at 1,067 m and 610 m asl (Taranaki Regional Council 1996).

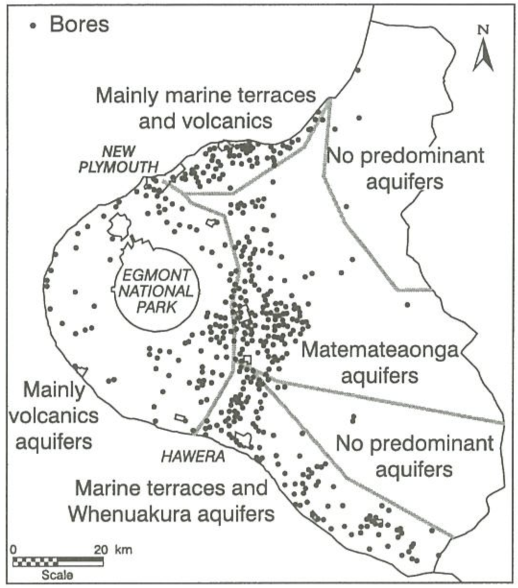

Figure 18.3 *Bore locations in the Taranaki region (Taranaki Regional Council 1996)*

GROUNDWATER USE AND MANAGEMENT

Although yields from the aquifers in the Taranaki region are relatively low, groundwater is still a valuable resource for the region. Groundwater is abstracted for domestic and farm water supplies throughout the region and it is utilised for community water supplies by several settlements in the south of the region.

The groundwater resources of the ring plain were first described in The Taranaki Ring Plain Water Resources Survey (Taranaki Catchment Commission 1984). This survey found that approximately 13% of all water used was from groundwater, mostly for stock and domestic supplies. Most of the groundwater (85%) was abstracted from shallow wells and bores in the Taranaki Volcanic aquifers. Often these wells were hand dug and unlined. The major exceptions to this were the municipal water supplies of the Patea and Waverly townships in the south of the region, which are from the Whenuakura Formation Aquifer.

The greater proportion of bores drilled are on the ring plain to the east of Mt Taranaki, in areas not covered by rural water schemes using surface water supplies, and on the marine terraces in the south of the region (Fig 18.3).

In recent times there has been an increasing use of the deeper Tertiary aquifers (i.e. the Whenuakura Formation and Matemateaonga Formation aquifers) for stock and domestic water supplies. This is mainly due to the better security of supply and higher water quality. Bores to depths in excess of 150 m are not uncommon. Often bores abstracting water from the Tertiary aquifers were completed by grouting a well casing through the overlying volcanic or marine terrace strata and leaving an open hole in the underlying Tertiary formation. However, the installation of well screens is becoming increasingly common.

The Proposed Regional Fresh Water Plan for Taranaki permits abstractions of up to 50 m^3 day^{-1}, provided that certain conditions are met. The total groundwater abstracted in the Taranaki region as a permitted activity has been estimated to be in the order of 7,700 m^3 day^{-1} (Taranaki Regional Council 1996) and is primarily used for domestic and farm water supplies.

There are currently 26 resource consents for the abstraction and use of groundwater in the Taranaki region, with a total allocation of 13,183 m^3 day^{-1} (153 L s^{-1}). About 39% (60 L s^{-1})

of the allocated abstraction is for a single resource consent for the de-watering of the Motunui methanol plant site to reduce the seismic risk. Some of this groundwater is used for the Tikorangi community water supply. In the south of the region approximately 20% (30 L s^{-1}) is allocated, via a number of resource consents, for community water supplies for the Patea and Waverley townships.

New Plymouth District Council has completed some exploratory drilling in the north of the region to assess the potential for municipal water supply, but did not find groundwater in sufficient quantity.

The groundwater system is also used for the disposal of water produced from hydrocarbon exploration and recovery operations. A significant quantity of deep connate groundwater is brought to the surface with the hydrocarbons. This water is typically very saline and cannot be discharged to surface waterways without substantial treatment. Consequently this water is returned to the groundwater system by deep well injection. The deep aquifers that receive this water are themselves saline. Significant aquitards separate these aquifers from the shallower aquifers used for water supplies.

The Taranaki Regional Council undertakes "State of the Environment" monitoring of groundwater resources in the Taranaki region. Groundwater level and groundwater quality data, appropriate to the level of use encountered in Taranaki, are collected and reported on every five years. The Taranaki Regional Council also maintains a database of wells and bores in the region and such data are available upon request.

The groundwater resources of Taranaki continue to be important to the regional economy. However, the surface water resources are expected to meet the foreseeable demand in most areas. As a consequence, whilst continued development of the groundwater resources will occur, there is unlikely to be significant pressure on the groundwater resources in the future.

ACKNOWLEDGEMENTS

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REFERENCES

Taranaki Geological Society 1993: Field Guide to Taranaki Geology, Taranaki Branch of the Geological Society of New Zealand. Geological Society of New Zealand Misc. Series Publication No. 64.

Taylor C.B.; Evans C.M. 1999: Isotopic indicators for groundwater hydrology in Taranaki, New Zealand. Journal of Hydrology (NZ) 38(2): 237-270.

Taranaki Catchment Commission 1984: Groundwater Hydrology-Taranaki Ring Plain Water Resources Survey.

Taranaki Regional Council 1995: Report on an Investigation of Pesticides in Shallow Groundwater in Taranaki, Technical Report 95-14.

Taranaki Regional Council 1996: Groundwater Resources of The Taranaki Region.

19

Manawatu-Wanganui

GABOR BEKESI

INTRODUCTION

The Manawatu-Wanganui region has a considerable variety of geographical and geological environments (horizons.mw 1999). The region stretches from the Horowhenua District in the south to near Lake Taupo in the north, and from the Tasman Sea coast in the west to the Pacific coast in the east. Groundwater use, however, is concentrated in the South Wanganui Basin and in the eastern river valleys in the Tararua District (Fig 19.1). These areas are separated by the axial Tararua and Ruahine mountain ranges. These greywacke ranges receive high rainfall and are the main groundwater recharge areas. Away from these ranges, towards the Tasman Sea coast, deep groundwater becomes confined and groundwater is abstracted from many artesian bores, particularly in river valleys.

SOUTH WANGANUI BASIN

The South Wanganui Basin extends from Wanganui to the Horowhenua District. West of the axial ranges, the greywacke rock that forms the basement deepens steeply westward and is estimated to be several kilometres deep offshore, south of Wanganui. Tertiary and/or Quaternary sediments overlie the greywacke basement. Most bores tap these unconsolidated gravels and sands in the southern and central parts of the basin. In the north, near Wanganui, older Tertiary limestone also yields groundwater.

Most groundwater is recharged by the infiltration of rainfall over the Tararua and Ruahine ranges, although some local recharge also occurs over anticlines described by Te Punga (1957). The rainfall shows a strong orographic pattern, increasing with altitude. Figure 19.2 shows groundwater levels in the region. Recharge areas include the axial ranges and the steep hill country of the upper Wanganui and Rangitikei river catchments. Groundwater flows towards the nearest coastline in most of the basin: towards the northwest in the Horowhenua area, west in the Manawatu and southwest in the Rangitikei area. The regional groundwater flow pattern approximates the surface water drainage patterns of the main rivers. In Wanganui, groundwater flow is towards the southwest and toward the Wanganui River.

The degree of sorting of aquifer materials generally increases with increasing distance from the axial ranges. This suggests increasing hydraulic conductivity towards the coast, an inference consistent with the increasing distances between the contour lines towards the coastline, particularly in the Manawatu area (Fig 19.2). Vertical changes are indicated in Figure 19.2 by complex contour patterns or local anomalies in the Manawatu River valley, near Palmerston North, and in Wanganui. Strong upward vertical groundwater gradients have been observed in both areas. Near Palmerston North, vertical hydraulic gradients can be as high as 1:3 (0.33).

TARARUA DISTRICT

The hydrogeology of the Tararua District differs from that of the Manawatu and Horowhenua areas. Here thin Quaternary alluvium covers thick Tertiary mudstone and sandstone. Aquifers are restricted to within 30 metres of the surface and to river valleys, often bounded by faults on both sides. East of the Tararua and Ruahine ranges, almost all bores tap unconsolidated gravel and sand resting on Tertiary mudstone. This mudstone transmits little water and is therefore of little value as a groundwater source. Although little is known about the groundwater recharge areas, it is likely

Bekesi G. 2001: Manawatu-Wanganui. *In* Groundwaters of New Zealand, M.R. Rosen and P.A. White *(eds)*. New Zealand Hydrological Society Inc., Wellington. p387-396.

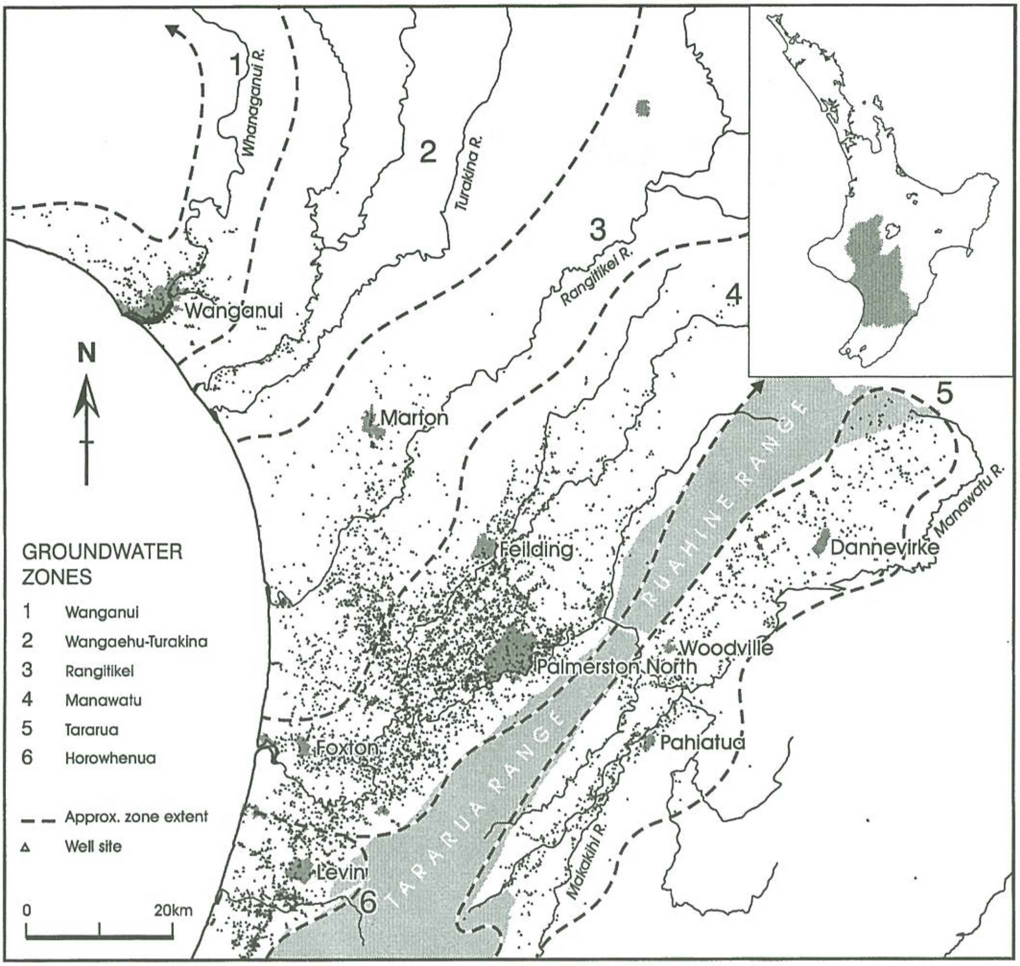

Figure 19.1 *The location of bores in the Manawatu-Wanganui Region. The Tararua and Ruahine ranges separate the South Wanganui Basin (west of the ranges) and the Tararua District. Each small marker represents one of the region's 8000 documented bores. The total number of bores is estimated as 12000.*

that groundwater is recharged via rainfall infiltration over the axial ranges and over the Puketoi Range in the east. Efforts to obtain deep groundwater in the Tararua District have been unsuccessful: deep test bores recovered small quantities of brackish groundwater. These deep brackish waters may have risen from considerable depth in tectonic areas.

AQUIFERS IN THE REGION

Little is known about aquifer boundaries in the region, so the aquifers are simply classified by geographic location (Table 19.1).

Wanganui

Artesian bores have been drilled for nearly 100 years in Wanganui, but the poor quality of the drilling records prevents any detailed study of the aquifers. The hill country to the north is the prospective recharge area for Wanganui groundwater. Groundwater flow is towards the Wanganui River and the coastline. Vertical flow is strongly upwards.

Mark-Brown (1979) and Wells (1983) described the relation between the Wanganui Series sediments and aquifers. They considered the Nukumaru Group (approximately 1.5-1.1 mil-

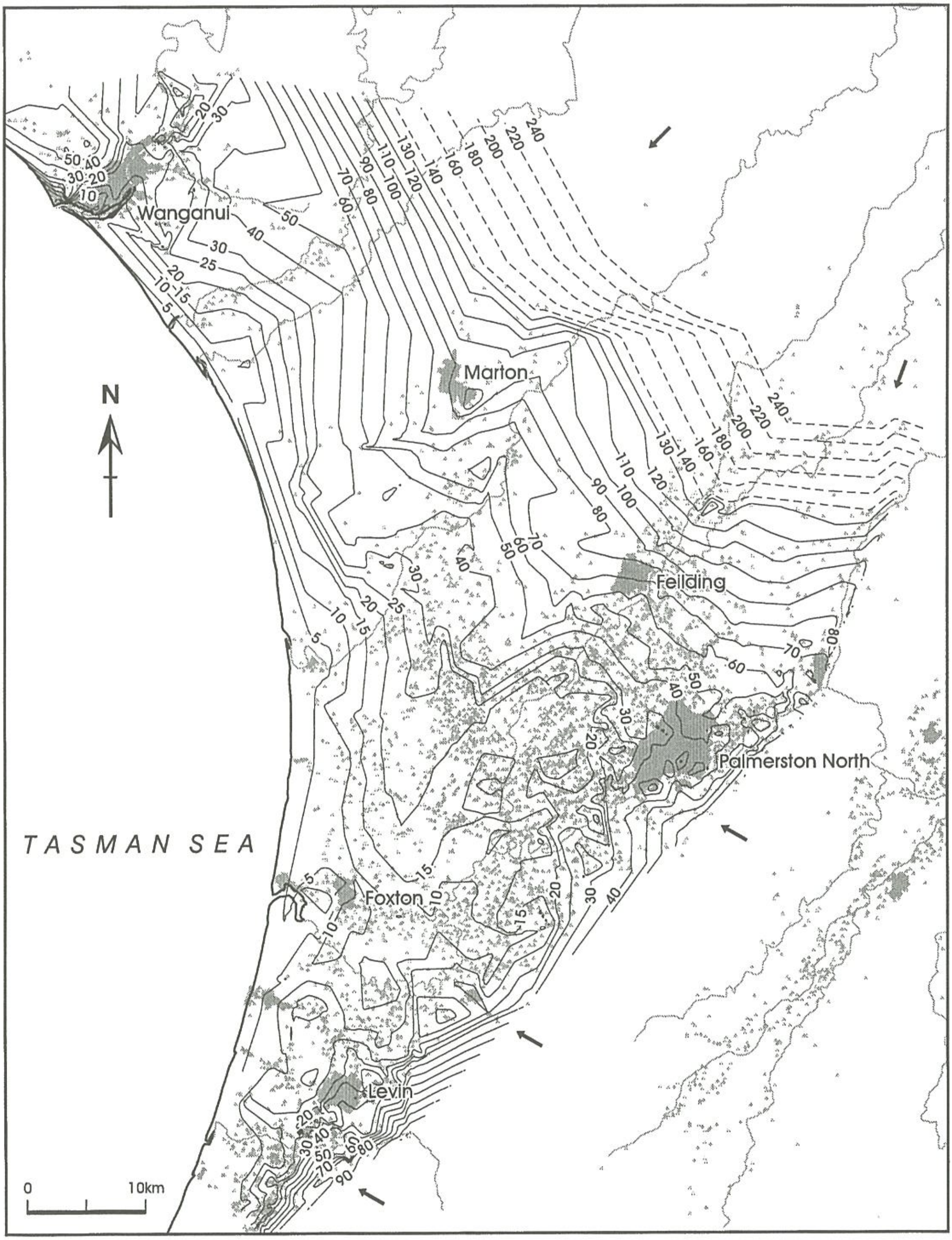

Figure 19.2 *Groundwater levels in the South Wanganui Basin. Contours are in metres above mean sea level. Contours above 130 m are based on only a few observations. Groundwater levels are based on regional scale mapping and are not suitable for detailed field scale studies. Small dots represent observation sites; arrows indicate regional groundwater recharge.*

lion years old), consisting of interbedded sands and limestone, was the most important potential aquifer because of its high transmissivity. The present water supply bores for Wanganui City tap this aquifer. Mark-Brown (1979) lists transmissivities for non-Nukumaruan aquifers as less than 50 m^2/day and storativities for confined aquifers in the lower 10^{-4} to upper 10^{-5} range. Wells (1983) also recognised the importance of faults as possible conduits for vertical groundwater flow. Fowles (1987) described Wanganui groundwater quality and classified the water, on the basis of major ion concentrations, as belonging to five major aquifers. Groundwater quality is controlled by the northeast-oriented Upokongaroa fault that divides Wanganui into two distinct hydrogeologic zones. East of the fault, deep groundwater is sodium-bicarbonate type, while west of the fault it is calcium/magnesium-bicarbonate type.

Wangaehu-Turakina

Information is restricted as to the location, approximate depth, and sometimes static water levels, of bores. Deep confined bores yield good quality groundwater in large enough quantities for domestic and stock use and irrigation. These deep bores have large artesian heads.

Rangitikei

Groundwater in this area is recharged, possibly from rainfall, in the hill country of the upper Rangitikei catchment. The quality and quantity of groundwater available appear to be controlled by proximity to surface water. The use of shallow groundwater is restricted to areas near the Rangitikei River and surface watercourses. Elsewhere, the shallow groundwater is high in iron, making it unpleasant. Groundwater levels (Fig 19.2) indicate a horizontal groundwater flow towards the west and southwest; vertical hydraulic gradients appear to be insignificant. The deep groundwater is generally hard and contains excessive quantities of iron and manganese.

Manawatu

About half of the region's estimated 12,000 bores are situated in the Manawatu area. Groundwater use includes municipal water supply (Palmerston North, Feilding, and Ashhurst), institutional supply (Massey University), industrial and dairy farm supply, market gardening and horticultural irrigation, heat exchange, stock water and domestic use. Most of the water used is from confined aquifers, although unconfined groundwater is used, particularly near surface water courses and in recharge areas. Petricevich (1970) and Voss (1979) studied Manawatu groundwater. Russell (1989) created the first conceptual groundwater model for the Manawatu. Confined Manawatu groundwater is recharged from both the Tararua Range, and the Pohangina Anticline (Te Punga 1957) and the Ruahine Range (Fig 19.3). Groundwater flows westward and is discharged in the coastal area.

Recharge areas, where vertical groundwater flow is downwards, include the axial ranges, the Pohangina, Feilding, Mount Stewart, and Himatangi anticlines and the Tararua foothills. Figure 19.3 shows the approximate position of recharge and discharge areas in the Manawatu. Groundwater levels are deep, and

Table 19.1 *Manawatu-Wanganui aquifers.*

Aquifer	Density of bores	Description	Main use
Wanganui	High	Mainly deep confined	Municipal, industrial, domestic
Whangaehu, Turakina	Low	Deep confined in the river valleys	Stock, domestic, irrigation
Rangitikei	Moderate	Unconfined and confined	Stock, domestic, irrigation
Manawatu	Very high	Mainly confined	Domestic, municipal, irrigation, stock, domestic
Horowhenua	Very high	Mainly unconfined	Domestic, stock, irrigation
Tararua	High	Solely unconfined	Domestic, stock
Coastal	Moderate	Shallow	Domestic in coastal settlements Various elsewhere

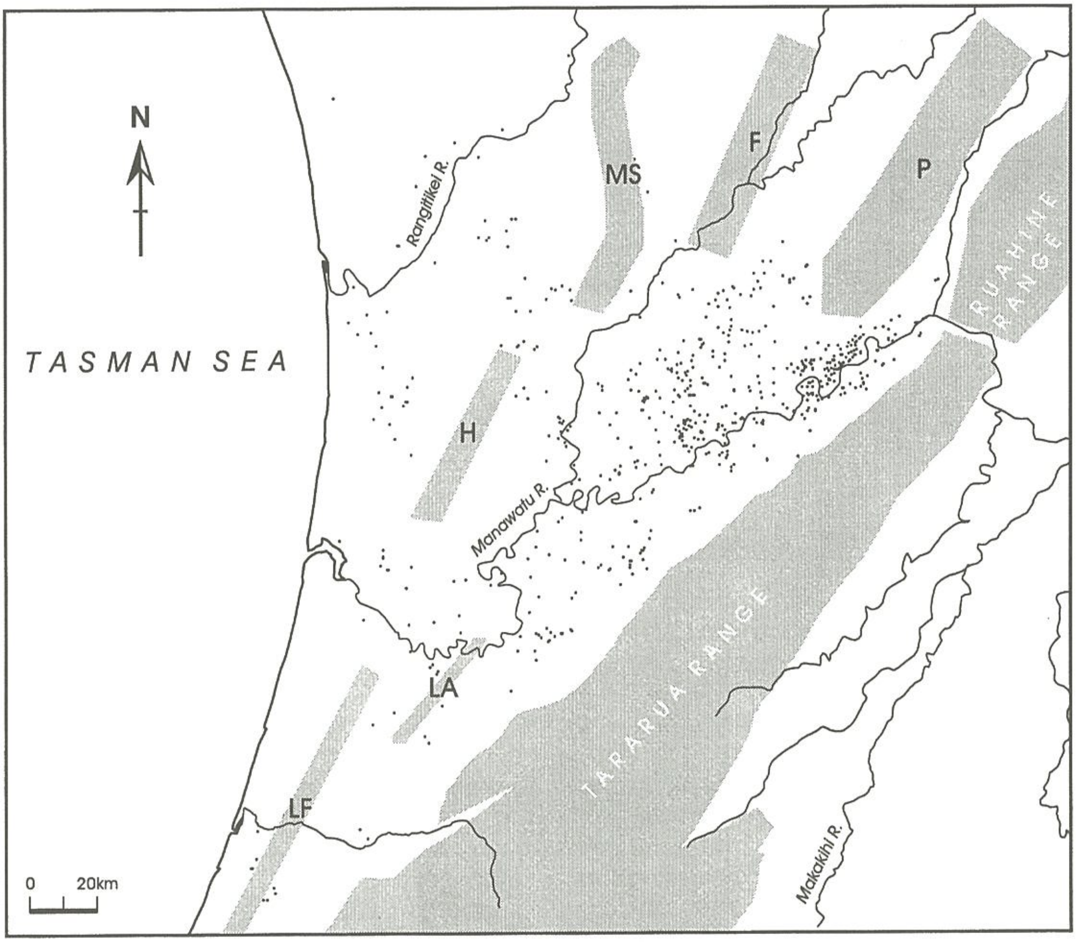

Figure 19.3 *Groundwater recharge areas (shaded) in the Manawatu and Horowhenua areas. Small circles represent bores with static water level above ground level, representing discharge areas. P - Pohangina anticline, F - Feilding anticline, MS - Mount Stewart anticline, H - Himatangi anticline, LA - Levin anticline (Te Punga 1957); LF - Levin fault (Bekesi 1989).*

hydraulic conductivities low, in the recharge areas. In discharge areas the phreatic surface is very close to ground level, with increasing artesian head with increasing bore depth, and higher hydraulic conductivities. The transition between recharge and discharge areas in Manawatu is not very well understood. A single aquifer in the recharge area may split into several thin branches of gravels or sands in the discharge areas. These branches are not easy identified as they are quite thin and may have leaky vertical hydraulic connections with each other. Deep groundwater, with high static head above ground level, is estimated to be hundreds to tens of thousands of years old, based on tritium and carbon isotope dating (Fox et al. 1996).

Whakarongo, a market gardening area east of Palmerston North, is such a discharge area. At least four confined aquifers (Bekesi 1991) form a complex, three-dimensional, and in places leaky, system. Gravel "aquifers", some only 5 m thick, at different depths exhibit different potentiometric levels. Vertical hydraulic gradients are as high as 1:3 (0.33). Figure 19.4 shows groundwater levels at the Te Matai

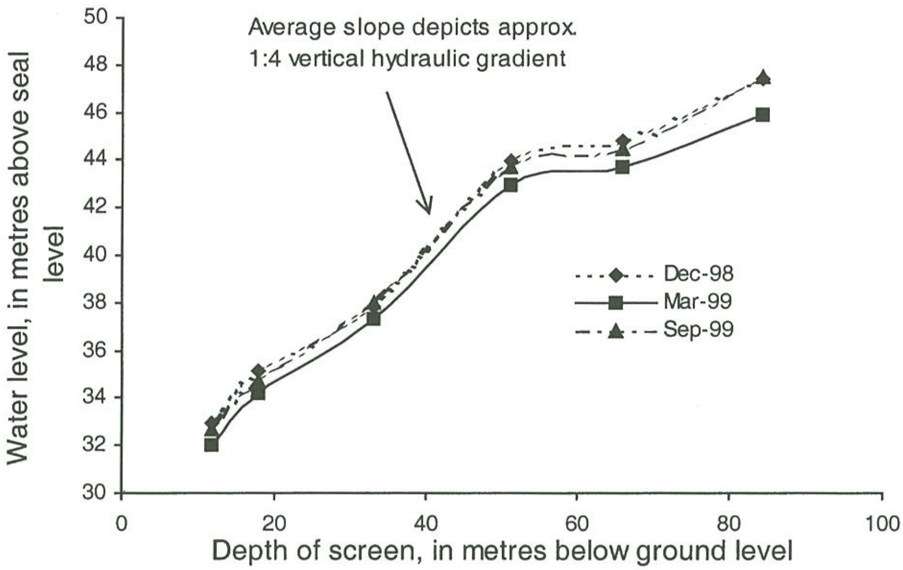

Figure 19.4 *Groundwater level as a function of screen depth at the Te Matai road automated site, Whakarongo.*

Road automated groundwater site for six piezometers, as a function of screen depth. The strong upward gradient is shown by the positive, approximately 1:4 (0.25) vertical gradient at this site.

Transmissivities for the confined aquifers vary between 200 and 2000 m^2/day; storativity decreases with depth (confinement increases) and is between $5x10^{-5}$ and $3x10^{-3}$. About 100 bores (bore density is 3.3/km^2, and median bore depth is 50 m) abstract up to 40,000 m^3/day of groundwater in Whakarongo. The high demand for water caused the groundwater level in the "medium confined aquifer" to decline through the 1970s (Bekesi 1991). Groundwater levels have since stabilised at a new, lower level.

Horowhenua

The Horowhenua area represents the southwestern margin of the South Wanganui Basin: the distance between the Tararua Range, the recharge area, and the coast is of the order of 10 km. The main difference between the Manawatu and Horowhenua areas is the depth to basement. In Manawatu, the basement is deeper and the sedimentary sequence is thicker. The aquifers of interest are found at the top of the sedimentary sequence. In Horowhenua, sediments on the western side of the Levin fault are as thin as 15 metres (Fig 19.5). Basement relief has a more direct effect on the hydrogeology in Horowhenua, where upfaulted greywacke rock forms a barrier to horizontal groundwater flow. Most groundwater is recharged from rainfall infiltration over the Tararua Range. Groundwater flow is towards the west-northwest and approximates the surface water drainage patterns of the Ohau and Manawatu Rivers. There are lateral zones (Fig 19.5), each with a specific hydrogeological character.

Recharge zone: The outcropping greywacke rocks of the Tararua Range and the alluvial/colluvial fans that flank the range form the main recharge area for most Horowhenua aquifers.

There are no bores in the Tararua Range. Immediately west of the ranges, in the foothills area, the aquifer material is poorly sorted. As a result, bores that tap these poorly sorted materials (sand and gravel with fine material) yield limited amounts of water (less than 100 L/min). The top, fractured part of the greywacke can yield some water, although deeper

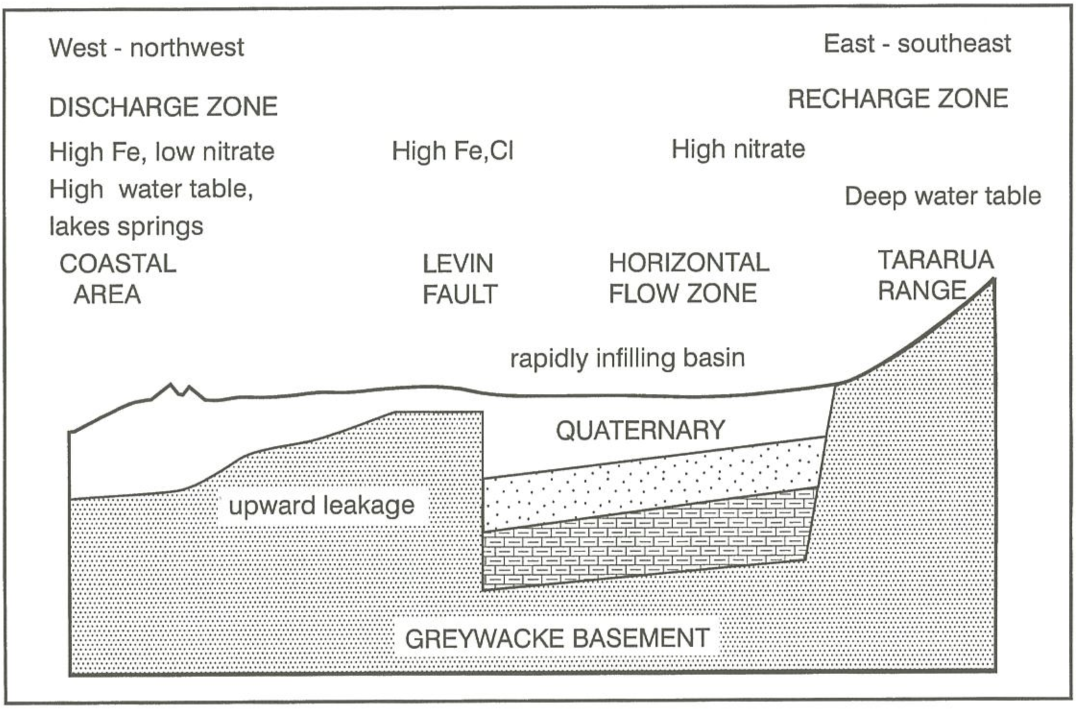

Figure 19.5 *Simplified hydrogeological section, Horowhenua (Bekesi 1996)*

groundwater in this zone is commonly brackish (containing high chloride levels). Static water levels are deep, generally more than 20 metres below ground level.

Horizontal flow zone: the basin: The greywacke basement is covered by up to 1000 metres of sediments within the basin. Most Horowhenua bores are located in this zone, between the Levin Fault and the foothills. Bores are shallower than 100 metres and tap various sand and gravel aquifers. Groundwater quality changes with bore depth. Shallow groundwater is normally low in iron and high in nitrate-nitrogen, while deeper bores have a higher iron and manganese content. In addition, shallow groundwater is corrosive and is known to react with copper or brass fittings. Static water levels are between 3 and 10 metres below ground level in most places in this zone.

Levin Fault zone: West of Levin, a north-east-oriented fault, the Levin fault, displaces the basement greywacke rock so that it is only 15 metres below ground level over the fault zone (Bekesi 1989). Groundwater in the Levin fault zone is directed upwards because of the combination of low hydraulic conductivity (of the greywacke rock) and upward-rising deep groundwater. Above the fault static water levels are very high and the deep brackish water rises above ground level.

Coastal discharge zone: The hydrogeology of the Horowhenua coastal discharge zone is essentially the same as elsewhere along the west (Tasman Sea) coast in the region. Therefore the "coastal aquifers" of Table 19.1 are also discussed in this section.

Characteristics of the coastal discharge area include springs, a high water table, free-flowing artesian bores and surface water drainage problems. The phreatic surface in this zone is within 3 metres of the ground surface, and during seasonal high levels can reach the ground level. Horizontal groundwater flow is towards the coast. There is a strong interaction between groundwater and surface water. This is most apparent in the series of coastal lakes between the Horowhenua and Wanganui areas. Upward-moving groundwater maintains lake levels in the sand coastal country.

Groundwater is the main source of water in rural Horowhenua, and more than 600 bores abstract groundwater, mainly for human and stock drinking water. Land use has been intensive, particularly above the horizontal flow zone, and this has resulted in nitrate contamination of Horowhenua groundwater.

The focus of groundwater management in the Manawatu-Wanganui region has shifted in the 1990s from groundwater allocation to groundwater quality, particularly in areas where shallow groundwater is the main source of drinking water e.g. the Horowhenua and Tararua Districts. In addition, the discharge of domestic, agricultural, and industrial effluent onto, and into, the ground has also increased because of the high cost of alternative disposal systems. Land-based "treatment" of contaminants is actively encouraged by horizons.mw. In many areas, this is often without regard to the hydrogeology and the resulting possibility of contamination (Bekesi 1998b).

Nitrate concentrations of groundwater exceed the maximum acceptable value in many bores in Horowhenua and in some bores in the Tararua District (Fig 19.6). Groundwater is also contaminated by bacteria in some parts of the Horowhenua and Tararua Districts. While poor bore development remains the main reason for bacterial contamination, land use and associated diffuse sources are the most likely causes for the nitrate contamination of Horowhenua groundwater.

Nitrate-nitrogen in Horowhenua groundwater

Nitrate-nitrogen is considered a broad indicator of contamination of groundwater from a variety of sources, including fertilisers, and agricultural and human wastes. Nitrate is considered toxic in water in excessive concentrations. The most significant health implication of excessive nitrate in water is a condition known as blue baby syndrome in bottle-fed infants. (see Chapter 8). Nitrosamines may also arise as products from consumption of nitrates. High levels in water and diet have been linked to some type of cancers.

The New Zealand upper limit for nitrate in drinking water is 11.3 mg/L as NO_3-N. Nitrate levels exceed the NZ drinking water standard in more than 20% of Horowhenua bores (Bekesi 1996). Nitrate contamination is a major problem in the Horowhenua because shallow groundwater is the principal source of drinking water for most rural Horowhenua residents and for stock. In some areas, shallow groundwater is the only available source of drinking water.

Statistical and spatial simulations (Bekesi 1996) indicate that if all inland Horowhenua bores were sampled, about 20% of shallow bores would exceed the drinking standard nitrate levels. More than one-third of all bores are predicted to have nitrate levels above 7 mg/L, and two-third of all shallow inland Horowhenua bores are predicted to have levels above 3 mg/L. In addition, there has been a significant increase in nitrate over the last ten or twenty years in some bores that originally had low levels of nitrate (Bekesi 1998a,b). For example, nitrate levels have increased from 0.6 to above 4 mg/L in a bore situated east of Levin. Nitrate concentrations are high in the Manakau, Ohau, and Lake Horowhenua-Koputaroa areas and in some beach settlements (Fig 19.6). The wide spread of contaminated bores and the slowly increasing trend of contamination in some bores indicate diffuse sources, associated with land use, in addition to on-site sewage disposal (septic systems). There is thus a potential for further degradation of groundwater quality in Horowhenua.

GROUNDWATER ALLOCATION

Groundwater allocation problems in the region are often dismissed on the erroneous theory that groundwater recharge exceeds demand over the entire region. A widespread misconception is that, as long as groundwater use is less than natural recharge, there are no problems and the groundwater yield is "safe". As Bredehoeft (1997) points out, the "safe yield" of an aquifer depends on both discharge and recharge to and from the groundwater system, and discharge is often the crucial factor. As the amount of coastal discharge is not known or calculated, the "safe yield" is therefore not known for most the region's groundwater sys-

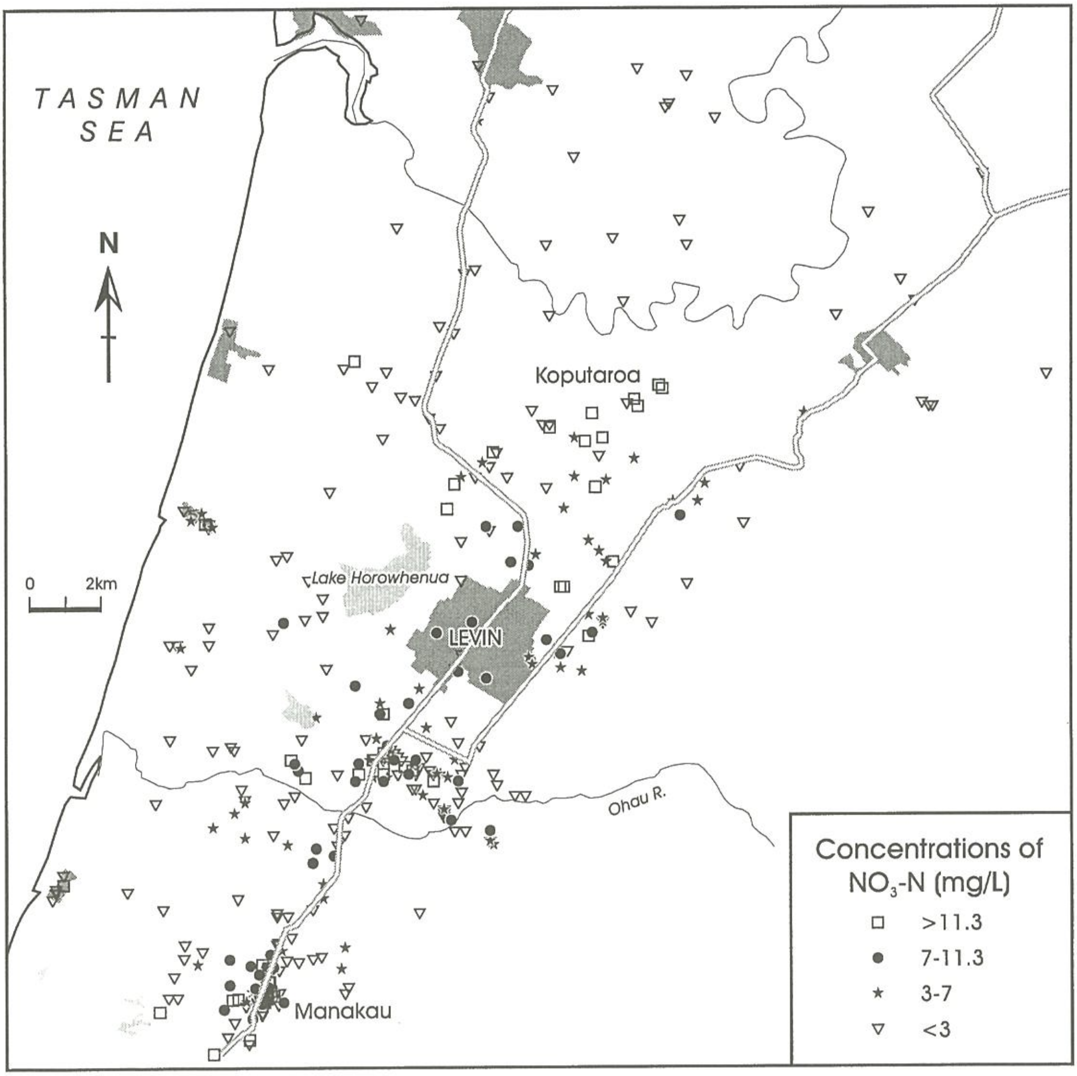

Figure 19.6 *Nitrate-nitrogen concentration in Horowhenua groundwater.*

tems. In the absence of safe yields, declining groundwater levels are considered as an indication that the current groundwater regime is not sustainable. Most groundwater use in the South Wanganui Basin is from confined aquifers with very low storage. The water levels of highly confined aquifers are very sensitive to changes in aquifer recharge and discharge and therefore are more vulnerable than unconfined waters. The low storage and moderate transmissivity (between 200 and 2000 m^2/day) of confined aquifers causes interference between bores situated as far as several kilometres apart. Many bores have been drilled, particularly in the Wanganui and Manawatu areas, to these confined aquifers and large abstraction rates have stressed aquifers locally and seasonally. To avoid interference between bores, new water supply developments often target deeper aquifers. Groundwater levels in the "medium confined aquifer" in Whakarongo declined in the 1970s because of the high demand and abstraction from that aquifer. Since 1991 any new bore in Whakarongo is directed by horizons.mw to target particular aquifers, to minimise interference and to evenly stress the aquifers. Although this "rule" is not included in a formal allocation plan, it has been very successful. Groundwater levels have stabilised and water permit applications have attracted less concerns or submissions than through the 1970s and 1980s.

In the 1990s confined groundwater levels have declined south of Feilding (horizons.mw 1999) and continue to decline at present. This decline cannot be explained by a decrease in rainfall up in the recharge area, therefore an increase in surface and groundwater use appears to be the most likely cause of the decline. In the future groundwater levels south of Feilding will either stabilise on a new and lower level, or continue to decline. In the latter case ground and surface water use may have to be limited locally.

REFERENCES

BEKESI, G. 1989: Geophysical studies over the North Horowhenua Sedimentary Basin. Unpublished MSc Thesis, Victoria University of Wellington.

BEKESI, G. 1991: Underground water in the lower Manawatu Valley. Manawatu-Wanganui Regional Council internal report No.17.

BEKESI, G. 1996: Nitrate-Nitrogen in Horowhenua Groundwater. Manawatu-Wanganui Regional Council Report No. 96/EXT/243, 27 pp.

BEKESI, G. 1998a: Nitrate-nitrogen in Horowhenua Groundwater, Monitoring results. Int. report No. 98/INT/129, Manawatu-Wanganui Regional Council.

BEKESI, G. 1998b: The development of an aquifer vulnerability assessment methodology with application to the Manawatu area of New Zealand. Unpublished PhD dissertation, Victoria University of Wellington.

BREDEHOEFT, J. 1997: Safe yield and the water budget myth. Editorial, Ground Water 35(6):929.

FOWLES, C.R. 1987: Aspects of the water quality of underground water in the Wanganui region. Rangitikei-Wanganui Catchment Board, 55p.

FOX, V.J.; BROWN, L.J.; TAYLOR, C.B.; BEKESI, G. 1996: Environmental isotopes applied in a study of the groundwater hydrology of the Manawatu aquifers, North Island, New Zealand. Proceedings of 1996 Western Pacific Geophysical Meeting, American Geophysical Union, July 23-27, 1996, Brisbane, Australia.

HORIZONS.MW 1999: Measures of a changing landscape State of the Environment Report, Manawatu Wanganui Region 1999. horizons.mw report No. 99/Ext/371.

MARK-BROWN, N.V. 1979: A report on groundwater in the lower Wanganui catchment. A report on investigations carried out by the Rangitikei-Wanganui Catchment Board from 1977-1979. Rangitikei-Wanganui Catchment Board, 29p.

PETRICEVICH, M. 1970: Preliminary report on the water resources in the Manawatu region. Manawatu Catchment Board report.

RUSSELL, W. 1989: Groundwater -Manawatu Plains. A report prepared by GCNZ Consultants for the Central Districts Catchment Boards.

TE PUNGA, M.T. 1957: Live anticlines in western Wellington. NZ Journal of Science and Technology 38(5): 433-446.

VOSS, D. 1979: A summary of groundwater investigations in the Manawatu area over the period October 1977 to April 1979. Manawatu Catchment Board report.

WELLS, P.C. 1983: The underground water resources in relation to the geology of the Wanganui area. Rangitikei-Wanganui Catchment Board report, 15p.

20

Wellington

MATTHEW MORGAN AND BRYDON HUGHES

INTRODUCTION

Significant groundwater resources exist in three river floodplain and coastal plain areas in the Wellington region: the Hutt Valley, the Kapiti Coast and the Wairarapa Valley (Fig 20.1). Besides these fluvial gravel aquifer systems, groundwater also occurs in coastal marine gravel and sand, in fractured limestone in the Wairarapa, and in jointed and fractured greywacke.

Groundwater is an important resource in the Wellington region. The Hutt Valley aquifers supply up to 35% of the municipal water for the greater Wellington urban area. Otaki on the Kapiti Coast and the Wairarapa towns of Martinborough and Carterton also rely on groundwater. In rural areas of the Kapiti Coast and Wairarapa Valley, groundwater is an important source for domestic use, stock watering and irrigation.

The groundwater resources of the region are under-utilised in many areas. Groundwater aquifers have the potential to sustainably provide more of the region's water requirements.

Management framework

The Wellington Regional Council manages groundwater under the framework of the Regional Freshwater Plan, which became operative in December 1999 (Wellington Regional Council 1999).

The three main groundwater areas have been divided into zones for management purposes (Fig 20.1). Each groundwater management zone encompasses an area that exhibits similar hydrogeological characteristics, based on bore log information, pump test data, hydrograph analysis, water quality and piezometric surveys.

HUTT VALLEY

History of groundwater use

The first artesian bore recorded in the Hutt Valley was drilled in 1883. The quality and reliability of the artesian water improved on that previously derived from local streams and shallow hand-dug wells. By the late 1880s a majority of residents in the lower valley used private wells for water supply. Large industries utilising groundwater were also being established.

The first municipal supply bore was installed at Williams Grove, Lower Hutt by the Hutt Borough Council in 1908. By the 1920s several other small bores had been drilled for a relatively limited municipal supply. During 1933-34, the first large-scale artesian pumping station (capable of supplying 22,750 m^3/day) was developed at Gear Island, near the mouth of the Hutt River. This pumping station supplemented the water for Wellington City supplied from the Wainuiomata River Scheme. The standard practice for industry and municipal supplies was to group wells close together for convenience for pumping and reticulation (Roche 1915).

During the 1940s and 1950s more industries reliant on groundwater were established in the Seaview and Gracefield areas of Lower Hutt. In 1959 the Hutt Valley Underground Water Authority was formed and assumed responsibility for "*controlling the tapping, use, and pollution of underground water*" under the Underground Water Act 1953. While the Authority had no responsibility for water supply, it undertook extensive hydrogeological investigations in both the Upper Hutt and Lower Hutt basins during the 1960s. These investigations included drilling test bores to the greywacke basement at Petone, Seaview and Somes Is-

Morgan M. and Hughes B. 2001: Wellington. *In* Groundwaters of New Zealand, M.R. Rosen and P.A. White *(eds)*. New Zealand Hydrological Society Inc., Wellington. p397-410.

land, and at Upper Hutt (Trentham Memorial Park). As a result of concern over increasing demand and falling artesian levels during the 1970s, the Authority controlled the allocation of groundwater and embarked on an extensive programme of sealing unused or leaking artesian bores.

In August 1974, the Lower Hutt Valley aquifer was tested to determine how much water could be abstracted without saltwater intruding into the aquifer through the springs in Wellington Harbour (Donaldson and Campbell 1977). The results showed that the arrangement of abstraction wells at that time (almost all in the Petone-Seaview foreshore area) limited sustainable groundwater withdrawal during summer.

In 1981, the Wellington Regional Council, which assumed the functions of the Hutt Valley Underground Water Authority and Wellington Regional Water Board, rationalised the municipal supply system in the Hutt Valley and established the Waterloo Wellfield in the central Lower Hutt area, as recommended by Donaldson and Campbell (1977). This wellfield, which has a capacity of up to 150,000 m³/day, is the major abstraction point in the Hutt Valley.

Apart from limited industrial use in the Upper Hutt area, little development of groundwater resources has occurred elsewhere in the Hutt catchment.

Geological setting

The Hutt catchment is a series of basins formed as a result of tectonic deformation associated with fault movement during the mid to late Pleistocene Period (last 1 million years). The largest of these basins, the Lower Hutt – Port Nicholson basin, extends over 100 km² in area, and encompasses the Lower Hutt Valley

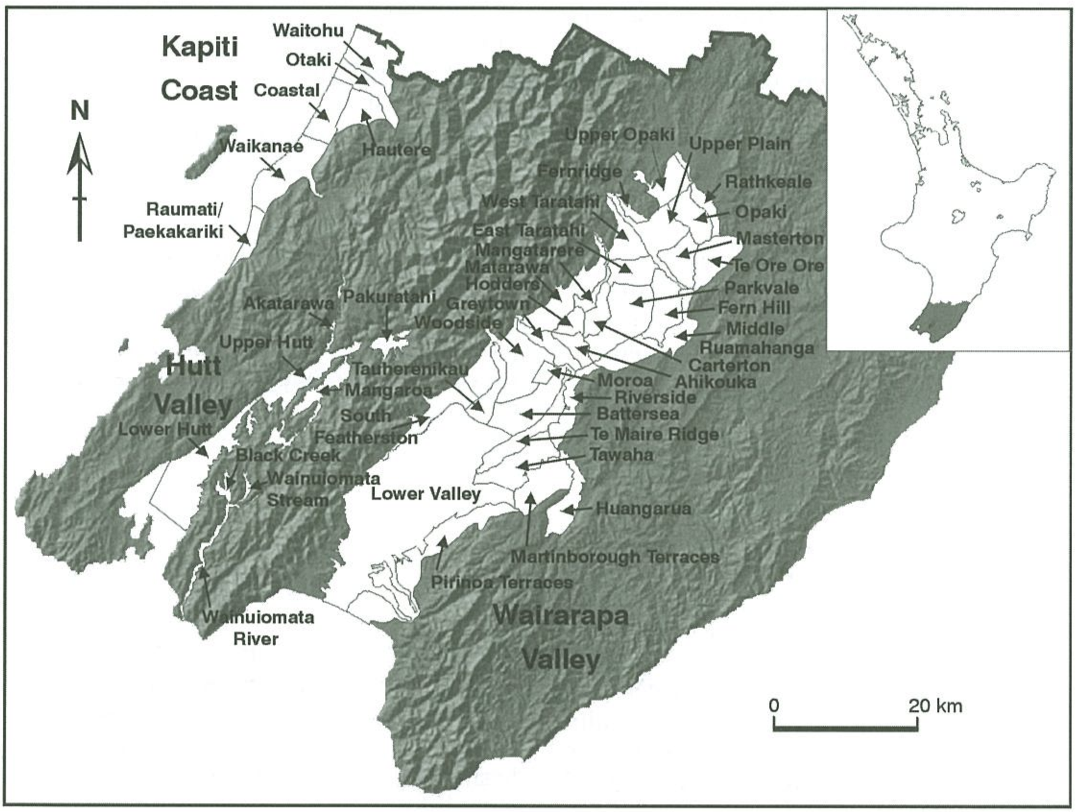

Figure 20.1 *Main groundwater management zones of the Wellington region.*

and Wellington Harbour. Other similar structures form the Upper Hutt, Pakuratahi and Mangaroa (which includes Whiteman's Valley) basins.

The Lower Hutt – Port Nicholson basin is bounded in the west by the Wellington Fault and the greywacke ridges of the western hills and in the east by the eastern hills. Upthrust basement greywacke fault blocks surface in Wellington Harbour to form Somes and Ward Islands. Geophysical investigations indicate that the sedimentary sequence extends to a depth of over 600 metres adjacent to the Wellington Fault at Kaiwharawhara (Wood and Davy 1992).

Because the Lower Hutt-Port Nicholson Basin is subsiding, subsurface deposits consist of layers of fluvial deposits of predominantly gravel, separated by interglacial finer, grained marine sediments. These are a result of Quaternary (last 2 million years) climate fluctuations and the resultant variation in relative sea level.

During the cold glacial periods, erosion of the southern Tararua Range produced large volumes of sediment that were transported and deposited in a Hutt River delta extending toward the present harbour entrance. As the climate warmed during interglacial phases, the sediment supply to the Hutt River reduced and much of the previously deposited fluvioglacial material was reworked as the Hutt River entrenched into the older sediments. During the interglacial phases the rising sea level inundated much of the Lower Hutt Valley, depositing fine-grained marine and marginal marine sediments over the reworked gravel deposits.

Further inland, the Pakuratahi, Mangaroa and Upper Hutt basins are each infilled with relatively thick sequences of poorly sorted, locally derived alluvial material.

Hydrogeology

The pattern of alternating deposits of alluvial material separated by thin deposits of fine-

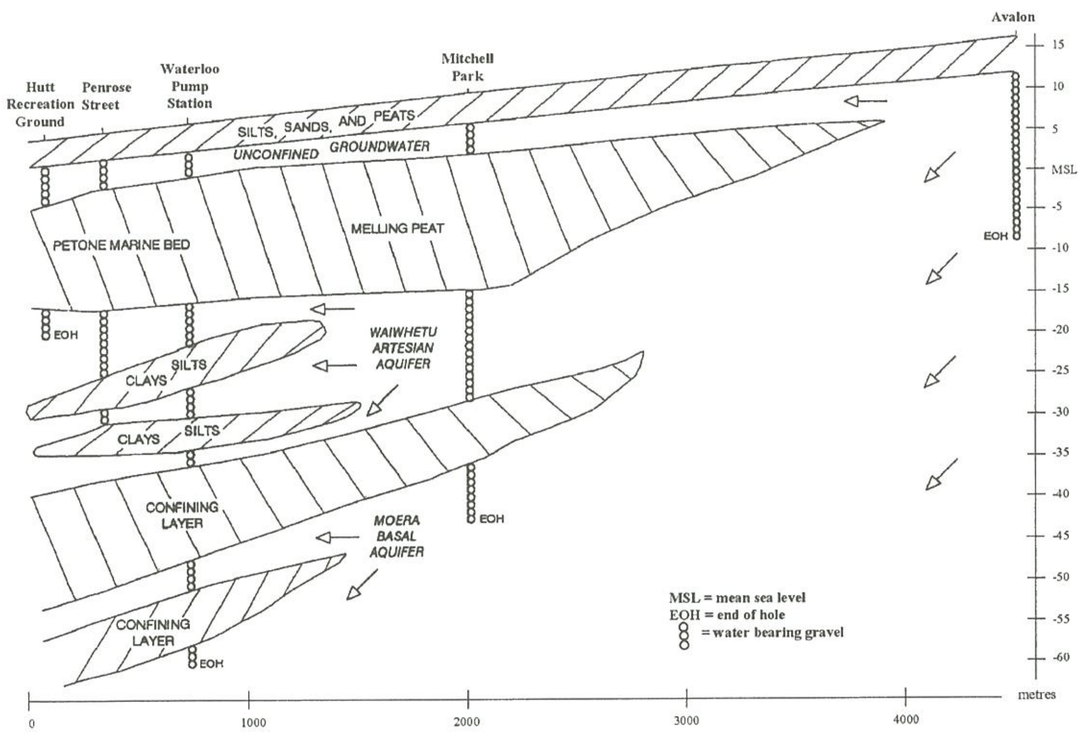

Figure 20.2 *Long Section of the Lower Hutt aquifer system from Avalon to Hutt Recreation Ground (Reynolds, 1993).*

grained marine sediments forms the basic stratigraphy of the Lower Hutt-Port Nicholson Basin. Stevens (1956) defined formal stratigraphic units for the Quaternary deposits penetrated by wells in the Lower Hutt Valley. The Hutt Valley Underground Water Authority test bores provided information about the deeper strata overlying the greywacke basement. A depositional sequence of four glacial and three interglacial formations spanning the last 500,000 years was identified (Mildenhall 1995; Begg and Mazengarb 1996).

The layers of fine-grained marine sediments that cap the two confined aquifers in the Lower Hutt Valley extend to an irregular margin approximately 5 km inland from the present coast (Fig 20.2). North of this margin, the aquifer system is unconfined and is recharged by the Hutt River and incident rainfall. To the south, both the Waiwhetu and underlying Moera aquifers are subartesian or flowing artesian and extend under Wellington Harbour toward the harbour entrance.

Groundwater flows south from the recharge area through the confined aquifer system toward Wellington Harbour, following the natural topographic gradient. Numerous springs distributed across the harbour floor provide natural outlets. Concurrent gaugings of the Hutt River across the unconfined recharge area indicate a flow loss of approximately 140,000 m^3/day under average flow conditions, reducing to 50,000 m^3/day during summer low flows. Depending on groundwater level, approximately 75 percent of this recharge flows into the confined aquifer system, the balance discharging to the lower reaches of the Hutt River. Rainfall recharge is estimated to provide less than 5 percent of the overall water budget (Wellington Regional Council 1995).

The high permeability of the alluvial gravel sediments is shown by average transmissivity values of the order of 35,000 m^2/day for the Waiwhetu Aquifer. As a result the aquifer yields are extremely high. In contrast, the permeability of the underlying Moera Aquifer is about two orders of magnitude lower, due to the poorer sorting and increased weathering of the deeper sediments (Hughes 1998).

Analyses of the environmental isotope tritium indicate a groundwater residence time of approximately 14 months at the Waterloo wellfield, increasing to a minimum age of approximately six years at the foreshore. The analyses indicate that the bulk of groundwater movement occurs by piston flow through more permeable deposits in the upper 20 metres of the Waiwhetu Aquifer.

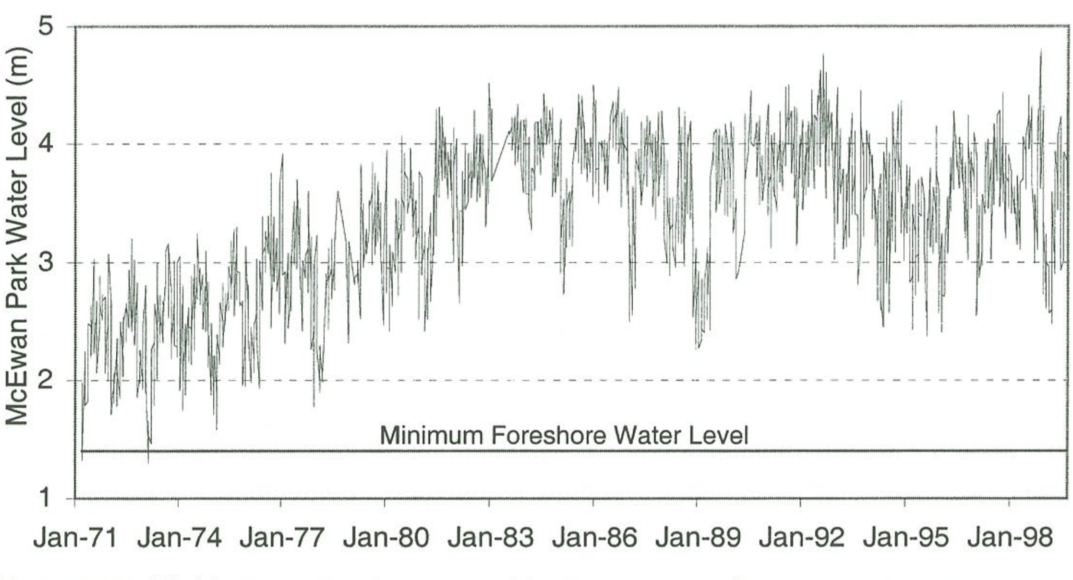

Figure 20.3 *Weekly average artesian pressure (above mean sea level) at the Petone foreshore.*

A series of tritium analyses of groundwater samples from the Waiwhetu Gravel and the Moera Gravel in the Hutt Valley Underground Water Authority test bores at Petone and Seaview show considerable variation in groundwater age with depth within the aquifers. In the Waiwhetu Aquifer at the foreshore, the age range is 6 to 40 years, while for the Moera Gravel the age range is 5 to >70 years (Morgenstern pers. com. 1999). This is as a result of variation of flow rate and flow paths within the aquifers. Groundwater chemistry also varies with depth.

Groundwater levels

Hutt Valley groundwater levels have been recorded at a network of monitoring sites established by the Hutt Valley Underground Water Authority since the late 1960s. Figure 20.3 shows a plot of weekly average artesian pressure recorded at the Petone foreshore over this period. The plot shows a steady recovery in piezometric levels from the mid-1970s through to the mid-1980s, in response to the relocation of the major municipal supply wellfield inland to Waterloo and a decline in the number of large industrial users near the foreshore.

Groundwater quality

Groundwater quality is very good throughout the Hutt Valley. This is generally due to the relatively rapid rate of throughflow, limiting the time available for groundwater to become mineralised.

The spatial distribution of groundwater quality in the Lower Hutt Valley reflects a typical sequence of geochemical change from chemically oxidising conditions in the recharge zone to reducing conditions in the harbour area.

Groundwater in the Waterloo wellfield contains relatively low concentrations of major ionic constituents (Fig 20.4) and is suitable for municipal supply without treatment; only lime is added for pH correction. As a result of the high subsoil permeability, shallow water table and rapid rate of groundwater throughflow, the Waiwhetu Aquifer is vulnerable to contamination originating in the unconfined recharge area. This area is covered by extensive urban development. The vulnerability to contamination was highlighted in 1988 when approximately 70,000 litres of petrol was lost in the recharge area from a leaking underground storage tank. Fortuitously, no resulting contamination was detected in the Waterloo wellfield, approximately 3.5 kilometres down-gradient. The dispersion and dilution associated with groundwater recharge derived predominantly from the Hutt River and the high transmissivity of the Waiwhetu Gravel aquifer probably reduced the impact of contamination.

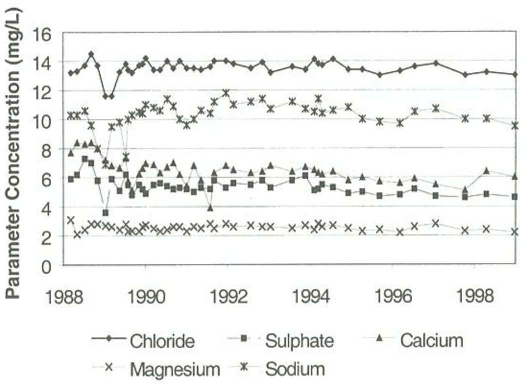

Figure 20.4 *Long-term trends in groundwater quality at the Colin Grove municipal supply well, Waterloo wellfield, Lower Hutt.*

Groundwater management

The major factor limiting the abstraction of groundwater in the Lower Hutt Valley is the potential for seawater intrusion into the Waiwhetu Aquifer. Springs distributed across the harbour floor provide a natural outlet for groundwater flow, but also provide a potential point for sea water to enter the aquifer system should outflow be sufficiently reduced because of low piezometric levels. In order to prevent this a minimum head of 1.4 metres above mean sea level at the Petone foreshore has been set as the minimum operating level for the Waiwhetu Aquifer.

The Wellington Regional Council developed a finite difference groundwater model for the Waiwhetu Aquifer in 1993 (Reynolds 1993). The model is used as a predictive tool for groundwater management. An extensive constant-rate (570 L/s) pump test over 4.5 days was completed on the Waterloo wellfield in November 1995 (Butcher 1996a). Aquifer parameter values were verified and data was gathered for transient calibration of the model.

For the current abstraction pattern, an annual allocation limit of 32.85 million cubic metres has been set, with a maximum daily take of 120,000 m^3. Measured abstraction from the Waiwhetu Aquifer varies from around 50,000 m^3/day during winter to a peak of around 110,000 m^3/day during late summer. Current abstraction averages around 65,000 m^3/day.

KAPITI COAST

Geological setting

The Kapiti Coast extends from Otaki to Paraparaumu, occupying a relatively narrow coastal plain flanking the western side of the Tararua Range. It is at the south-eastern margin of the South Wanganui Basin (Anderton 1981) a broad half-graben structure extending from Taranaki to Cook Strait.

The present-day landforms and subsurface depositional sequence of the Kapiti Coast have formed as a result of geological processes associated with climatic fluctuations during the Quaternary Period. The major phases of deposition that built up the present day coastal plain occurred as a result of accelerated erosion in the Tararua Range during glacial periods. The accumulation of thick sequences of poorly sorted alluvial material was aided by subsidence of the underlying greywacke basement due to ongoing tectonic deformation.

As sea levels rose during warmer interglacial and postglacial periods, layers of fine marine sediments were deposited along the seaward margin of the coastal plain, and the major river systems entrenched into the underlying alluvial deposits. The maximum extent of the postglacial sea level transgression is marked by a prominent marine terrace up to 4 kilometres inland that can be traced the length of the coastal plain. As the coastline has prograded over the subsequent 6500 years, deposits of marine and aeolian sands up to 50 metres thick formed along the coastal margin.

Hydrogeology

Fleming (1972) defined formal stratigraphic units for the Quaternary deposits of the Kapiti Coast. These include: Foxton Dunesand (postglacial dune sand – aquifer); Kenakena Formation (postglacial marine – confining strata); Parata Gravel (last glaciation fluvial – semi confined to confined aquifer); Otaki Formation (last interglacial dune and beach sand – aquitard, semi-confined, confined aquifer).

The Te Horo test bore provided information about deeper aquifers. In total, three glacial and two interglacial formations spanning the last 300,000 years were recognised within the 180 metre-deep deposit and sequence (Kampman and Caldwell 1985).

Based on their depositional environment, the aquifer systems of the Kapiti Coast can be grouped into three categories: glacial and interglacial deposits, postglacial coastal marine sand deposits, and recent river gravels.

The glacial and interglacial gravel deposits form a thick, poorly stratified aquifer system that extends throughout the Kapiti Coast and underlies aquifers formed by postglacial geological processes. The three recognised aquifers have moderate yields (T=500 to 1000 m^2/day) and become increasingly well confined along the coastal margin.

The postglacial sand deposits form an unconfined aquifer up to 50 metres thick near the present coastline. Bores screened in these deposits are generally low yielding (T <100 m^2/day) and are used for domestic supply.

Deposits of reworked river channel gravels form high-yielding (T=5,000 to 30,000 m^2/day) aquifers adjacent to the present course of the Waikanae and Otaki rivers and Waitohu Stream.

The Kapiti aquifers are recharged from rainfall on the coastal plain and from infiltration through the large alluvial fans that flank the foothills of the Tararua Range. Exceptions are the unconfined alluvial gravel aquifers adjacent to the major rivers, which have hydraulic connections with the surface water.

Groundwater levels

Groundwater levels are currently monitored at 6 automatic recorder sites and approximately 30 manual dipping sites on the Kapiti Coast. Water levels on the coastal plain fluctuate with seasonal variations in rain. The magnitude of fluctuations in levels varies from 8-9 metres close to the Tararua foothills to less than 1 metre in coastal areas (Wellington Regional Council 1994).

Groundwater quality

Groundwater quality is variable in the Kapiti Coast aquifers. It is generally very good in the shallow alluvial gravel aquifers recharged by river infiltration, reflecting the relatively high rate of groundwater throughflow. In contrast groundwater contained in the deeper semi-confined and confined aquifers on the coastal plain is mineralised, with levels of iron and manganese significantly higher than drinking water standards. In the Hautere groundwater management zone, wells tapping the penultimate glaciation aquifer (Pukehou formation) yield groundwater with boron levels of 2-15 mg/L (Kampman and Caldwell 1985). Boron levels over 3 mg/L are toxic to some horticultural crops such as kiwifruit. Boron in the groundwater is probably derived from the greywacke basement.

Land use on the coastal plain has led to localised contamination of shallow unconfined aquifers. A significant number of bores on the coastal plain have elevated nitrate levels, apparently from both point and non-point sources (Hughes 1997). Figure 20.5 shows the temporal variation in nitrate-nitrogen concentration in monitoring bores in the Waitohu and Hautere groundwater management zones.

Groundwater management

Table 20.1 contains details of the water balance, sustainable allocation limit and level of allocation for each of the Kapiti groundwater management zones. Each zone may contain

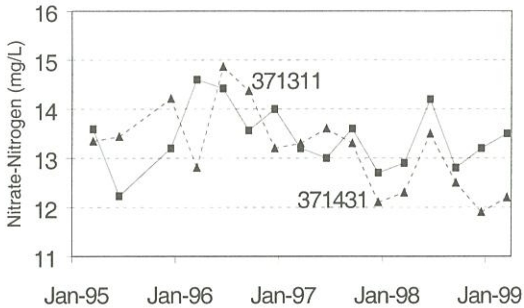

Figure 20.5 *Temporal variations in nitrate-nitrogen levels in the Waitohu (371311) and Hautere (371431) groundwater management zones.*

multiple aquifers that are hydraulically connected via common recharge zones or vertical leakage. A sustainable allocation limit is defined for each aquifer based on a simple water budget estimated for the entire zone.

Groundwater on the Kapiti Coast is used for domestic and municipal water supply and horticultural irrigation. Currently the groundwater allocation on the Kapiti Coast totals approximately 15 million cubic metres per year (40,000 m^3/day).

In the past decade the Kapiti Coast has experienced a major increase in the urban and rural population. This has resulted in the increasing use of groundwater for municipal supply. However, groundwater use in the Waikanae and Paraparaumu areas is constrained by the elevated iron and manganese concentrations in the confined aquifers. There has also been a significant increase in the number of shallow bores used for domestic supply as a result of rural-residential development across the Kapiti Coast.

Table 20.1 *Water balance and allocation limits for the Kapiti Coast groundwater zones.*

Groundwater Zone	Rainfall recharge (million m^3/year)	River recharge (million m^3/year)	Sustainable allocation limit (million m^3/year)	Current allocation (million m^3/year)	Percentage of resource allocated
Waitohu	4.9	1.5	6.41	1.80	28
Otaki	3.7	7.8	11.50	7.96	71
Hautere	8.7	0.0	6.67	0.70	10
Coastal	6.5	0.0	6.92	0.86	13
Waikanae	9.3	7.9	10.71	2.43	23
Raumati	4.9	0.0	4.77	0.41	9

WAIRARAPA VALLEY

History of groundwater use

Initially groundwater use in the Wairarapa Valley was limited to rural domestic and stock water supplies. Due to pressure on surface water resources in the 1970s and an increasing demand for further agricultural development, the Wairarapa Catchment Board carried out an extensive ground water study between 1981 and 1986. The study included drilling exploratory bores, establishing automatic and manual ground water level recording sites, piezometric surveys; spring flow monitoring, simultaneous stream flow gaugings, pump testing, chemical and isotope analysis, geophysical logging of bores, electrical resistivity surveys, and seismic surveys (Wairarapa Catchment Board and Regional Water Board 1989).

Consents for groundwater use in the Wairarapa Valley were minimal in the 1970s. By 1989, 25 million m^3/year was allocated and in 1999 this has increased to 48 million m^3/year involving 250 groundwater consents.

In recent groundwater development much of the water is abstracted from shallow unconfined or semi-confined aquifers at depths of less than 80 metres.

Geological setting

The geology of the Wairarapa is complex. The Wairarapa Valley is a structural depression 110 km long, with a maximum width of 15 km, running NE-SW into Palliser Bay. The valley is bounded by the Mesozoic greywacke sandstone and argillite ranges: the Tararua and Rimutaka ranges to the north and west; the Aorangi Range to the south. To the east of the valley is Tertiary hill country with thick bands of limestone, sandstone, siltstone and mudstone. The depth to the greywacke basement under the Wairarapa Valley may be up to 3 kilometres in places (Hicks and Woodward 1978). The valley is infilled with Late Tertiary and Quarternary marine and alluvial deposits (Capes et al. 1990).

During glacial periods, increased erosion of the Tararua Ranges resulted in the deposition of coalescing alluvial fans bordering the ranges. These fans were composed principally of poorly sorted sands and gravels. Deposition of the alluvial fans forced the Ruamahanga River eastward towards its present-day position. In the lower Wairarapa valley, erosion predominated as sea levels fell. During interglacial periods the western tributaries of the Ruamahanga River entrenched into the alluvial fans, with the reworked alluvial sediments being deposited further east and in the lower valley. As sea levels rose during interglacial periods and the valley subsided, fine-grained material or estuarine sediments were deposited in the lower valley. The pattern of alternating deposits of alluvial and fine-grained marine or estuarine sediments is similar to that observed in the Lower Hutt basin, although the layers of alluvial sediments in the lower Wairarapa valley are generally thinner. The thin sand and gravel aquifers of the lower valley are likely to have been deposited during the onset of interglacial periods. Since the end of the last glaciation, when sea level may have been as much as 240 metres lower (Stevens 1974), there have been at least six warmer periods. This indicates that a number of sand and gravel layers probably exist to depths of at least 240 metres, or to considerably greater depths if subsidence occurred throughout the Pleistocene. The area has also been extensively faulted and folded by earth movements that have left blocks of greywacke and older alluvial sediments, such as Te Maire Ridge and Lansdowne Hill, protruding above it. The plains area is about 1200 square kilometres. Average annual rainfall is up to 7000 mm in parts of the Tararua Ranges, decreasing to around 1600 mm on the western side of the Wairarapa Plains and 800 mm on the eastern side.

Hydrogeology

To a large degree the area's hydrogeology is governed by its depositional history. In the lower Wairarapa Valley, generally thin sand and gravel aquifers are separated by significant thicknesses of fine-grained sediment, principally clay. Aquifer transmissivities are reasonably high as the aquifers are comprised of reworked sands and gravels. The alluvial fan aquifers in the western portion of the valley are composed of poorly sorted sands and gravels and typically have low transmissivities. Shallow aquifers composed of recent gravels adjacent to the Ruamahanga River and its western tributaries generally have high transmissivities. Confined flowing artesian aquifers exist throughout the lower valley and in some other areas. Many of the Wairarapa's aquifers tend to be heterogeneous, containing thin bands with significantly higher hydraulic conductivity.

Groundwater quality, environmental isotopes, groundwater hydrographs and concurrent river flow data has been used to define groundwater recharge mechanisms (Gunn et al. 1987). The low-yielding aquifers in alluvial fans remote from the main rivers are recharged solely by rainfall infiltration. River infiltration forms a significant proportion of recharge to the shallow aquifers adjacent to the main rivers.

Groundwater levels

The Wellington Regional Council monitors groundwater levels at 18 automatic recorder sites and measures 36 manual dipping sites monthly in the Wairarapa Valley. The monitoring programme was reviewed in 1997; now more intensive monitoring occurs in high-use aquifers and little or no monitoring in low-use aquifers.

Figure 20.6 shows the seasonal variation of groundwater levels in aquifer 2 at Parkvale, which is predominantly recharged by rainfall. The effects of high demand and lower recharge during the 1997/98 drought can be clearly seen, together with its continuing effects into 1999.

Groundwater Quality

Water quality is highly variable within the Wairarapa Valley. Levels of iron and manganese are above drinking water guidelines in many aquifers, with the highest levels in the deeper aquifers of the lower Valley (Fe ~ 15 mg/L, Mn ~ 1 mg/L). Elevated levels of nitrates occur in shallow unconfined aquifers higher up the valley (Fig 20.7), with the Opaki, Upper Plain, Te Ore Ore, West Taratahi, East Taratahi, Carterton and Moroa zones (Fig 20.1) all having areas that exceed 6 mg/L NO_3-N. Some individual bores in these areas can exceed the drinking water standard of 11.3 mg/L NO_3-N. Elevated levels of bacteria occur in many of the shallow aquifers. Generally such contamination is not widespread, but more an indication of poor land-use practices adjacent to bores.

An extensive review of historical monitoring of groundwater quality and the development of a baseline monitoring programme occurred in 1997 (Butcher 1997a).

During the operation of the Waingawa Freezing Works, very high ammonia and nitrate-nitrogen levels were recorded down-gradient of the effluent treatment and disposal area. Extensive monitoring and investigations of groundwater quality have occurred in the area since 1985. Although both ammonia and nitrate-nitrogen concentrations have generally declined following the closure of the works in 1989, a large area

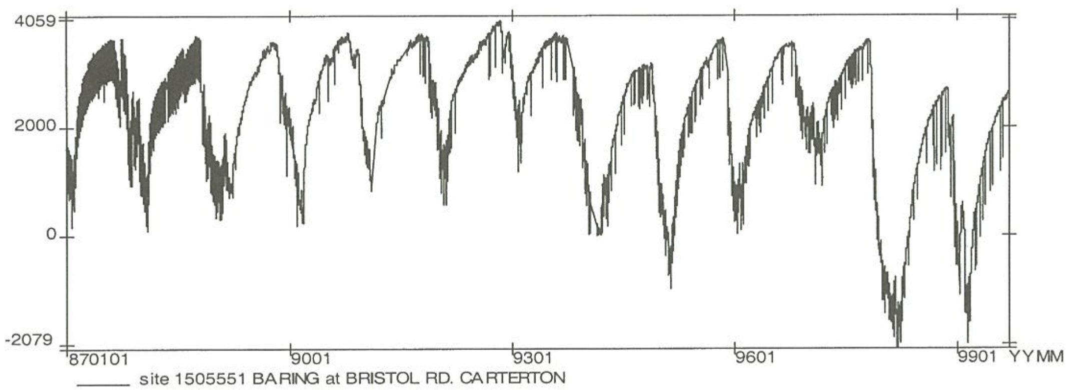

Figure 20.6 *Groundwater levels (1987-1999) in the Parkvale zone, aquifer 2(mm above top of casing).*

Table 20.2 *Water balance, safe yield and consented water use from Wairarapa aquifers.*

Ground water Zone	Identified Aquifers (approximate depths in metres)	Average Trans-missivity (million m^3/year)	Estimated rainfall recharge (million m^3/year)	Estimated river recharge (million m^3/year)	Estimated aquifer through-flow (million m^3/year)	Estimated aquifer safe yield (million m^3/year)	Existing consented groundwater use (million m^3/year)	Existing consented groundwater use (m^3/day)	Percent of aquifer safe yield allocated
Fernridge	To 5 - 15	50	2.7	0.0	0.2	1.5	0.00	0	0
Upper Plain	To 15	1200	13.0	4.7	17.0	$17.0^{\#+}$	1.91	8372	11
	35 to 50	40			0.5		0.00	0	
Upper Opaki	To 10+	75	7.6	0.0	1.4	$4.5^{\#+}$	0.00	0	0
Opaki	To 8 – 17	90	3.2	0.0	0.5	2.3	0.14	715	6
	12 – 23 to 28	130			0.7				
	48 to 52	25			0.1		0.00	0	
Masterton	To 35+	100	5.4	Minor	0.9	3.2	0.27	1468	8
	15 to 30	250			2.3	2.3	0.04	173	2
West Taratahi	To 25+	140	8.2	0.0	2.3	$5.3^{\#}$	0.00	0	0
East Taratahi	To 10 – 15	800	5.2	0.0	7.3	$6.8^{\#+}$	0.23	1165	3
	30 – 35+	120			1.1		0.00	0	
Parkvale	To 10 – 15	300	7.6	0.0	1.3	$4.5^{\#+}$	0.64	3513	14
	18 to 30	790	4.1		3.5	4.1	2.46	12245	60
	35 to 50	630			1.7				
Fern Hill	To 25	75	8.0	0.0	1.3	4.7	0.01	160	0
Rathkeale	To 6+	3300	3.9	Ungauged	4.5	4.5	1.47	6729	33
Te Ore Ore	To 12 – 14	880	8.0	6.3	3.5	$10.6^{\#+}$	2.82	12815	27
	To 50+	990			2.9				
	40 to 50	425			0.4		0.00	0	
Middle	To 10 – 12	4000	9.1	Ungauged	7.3	7.3^{+}	4.78	23805	65
Ruamahanga	15 to 30	1200			2.2	2.2	1.18	5911	54
Riverside	To 10 – 15	3100	5.0	Ungauged	2.8	3.9^{+}	0.81	4570	21
Tawaha	To 15 – 30	4500	3.4	3.4	7.2	11.0	8.41	39623	76
Matarawa	To 15+	100	15.0	0.0	5.5	10.0	0.67	2920	7
Mangatarere	To 5 – 15	2100	2.4	Ungauged	7.6	$7.6^{\#+}$	1.75	7678	23
Hodders	To 8 – 10	100	3.2	0.0	0.6	4.0^{+}	0.49	2507	12
	To 12+	780			4.3				

Table 20.2 *Water balance, safe yield and consented water use from Wairarapa aquifers (continued).*

Ground water Zone	Identified Aquifers (approximate depths in metres)	Average Trans-missivity (million m^3/year)	Estimated rainfall recharge (million m^3/year)	Estimated river recharge (million m^3/year)	Estimated aquifer through-flow (million m^3/year)	Estimated aquifer safe yield (million m^3/year)	Existing consented groundwater use (million m^3/year)	Existing consented groundwater use (m^3/day)	Percent of aquifer safe yield allocated
Carterton	To 8 – 12	230	3.6	0.0	1.7	3.9^{+}	1.08	6287	28
	15 to 30	340			2.5				
Greytown	To 8 – 15	4800	6.2	17.0	17.0	20.0$^{\#}$	1.37	7513	7
Ahikouka	To 10	1000	3.6	Minor	3.0	3.3$^{\#+}$	1.76	9926	53
Tauherenikau	To 15	4300	9.9	13.0	15.8	20.0$^{\#}$	1.71	8856	9
Sth Featherston	To 12	340	4.1	Minor	3.0	5.3^{+}	0.48	2318	9
	60 to 70	390			3.4				
Battersea	To 10 – 20	240	7.6	0.0	2.2	5.3$^{\#+}$	1.92	10279	36
	30 to 40	70			0.6		0.00	0	
	90 – 100	25			0.2		0.00	0	
Moroa	To 5 – 10	860	1.6	0.0	2.1	0.8	0.49	2803	61
Woodside	To 35+	50	22.0	0.0	1.5	16.0	0.25	1182	2
	50 to 60	290			8.6				
Lower Valley	Turanganui 1	200	28.0	Minor	1.1	1.1	0.47	2270	43
	Tauanui 1	220		Minor	0.8	0.8	0.01	29	1
	Whangaehu 1	130		Minor	0.5	0.5	0.18	864	36
	Kahutara 1	250		0.0	0.9	0.9	0.00	0	0
	Aquifer 2	270 to 8000		Minor	13.5	13.5	6.28	32055	47
	Aquifer 3	300 to 2700		Minor	7.7	7.7	2.74	10890	36
Martinborough	10 to 25	170	7.9	0.0	2.5	7.8	0.36	1972	5
Terraces	30 to 55	260			5.1				
Pirinoa Terraces	15 to 25	Unknown	18.1	0.0		18.1	0.38	2093	2
Huangarua	To 10	1100	2.8	Ungauged	2.0	2.0$^{\#+}$	0.04	275	2
	15 to 30	500			1.0	1.0	0.51	2700	51
Total						245.3	48.11	236681	20

$^{\#}$ Unacceptable reduction in stream flows could occur before this safe yield is reached
$^{+}$ Unacceptable interference drawdowns between bores could occur before this safe yield figure is reached

continues to show average nitrate levels above the drinking water standard. Sludge from the old effluent ponds was removed and spread on adjacent land in 1995, possibly increasing down-gradient nitrate levels (Butcher 1999).

In August 1981 approximately 500 litres of 60% concentrate copper, chromium, arsenic (CCA) preservative solution were spilled at a timber treatment plant at the south end of Masterton. This spill contaminated the shallow gravel aquifer adjacent to the Waingawa River. It was only discovered a few days after the spill, when a downstream groundwater user noted their water supply had a yellow tinge and their dog was sick. Water had to be trucked in to groundwater users for many months. A comprehensive monitoring programme was undertaken for the following 12 months to determine the extent of the contamination (Wellington Regional Council files). Arsenic and Chromium levels of 9.3 mg/L and 37 mg/L respectively were measured in groundwater from the timber plant's bore about two weeks after the spillage. Levels of chromium above drinking water standard were detected 1000 metres down-gradient 3-6 months after the spillage and the chemical was detected in bores up to 2.5 kilometres away. Further spillages of large volumes of more dilute CCA occurred in February and March 1986 and led to further contamination of the shallow aquifer. The timber company was prosecuted by the Wairarapa Catchment Board. Follow-up sampling between 1992 and 1994 showed levels of CCA in on-site soil samples were generally above MfE Timber Treatment site guidelines. However, with the exception of one

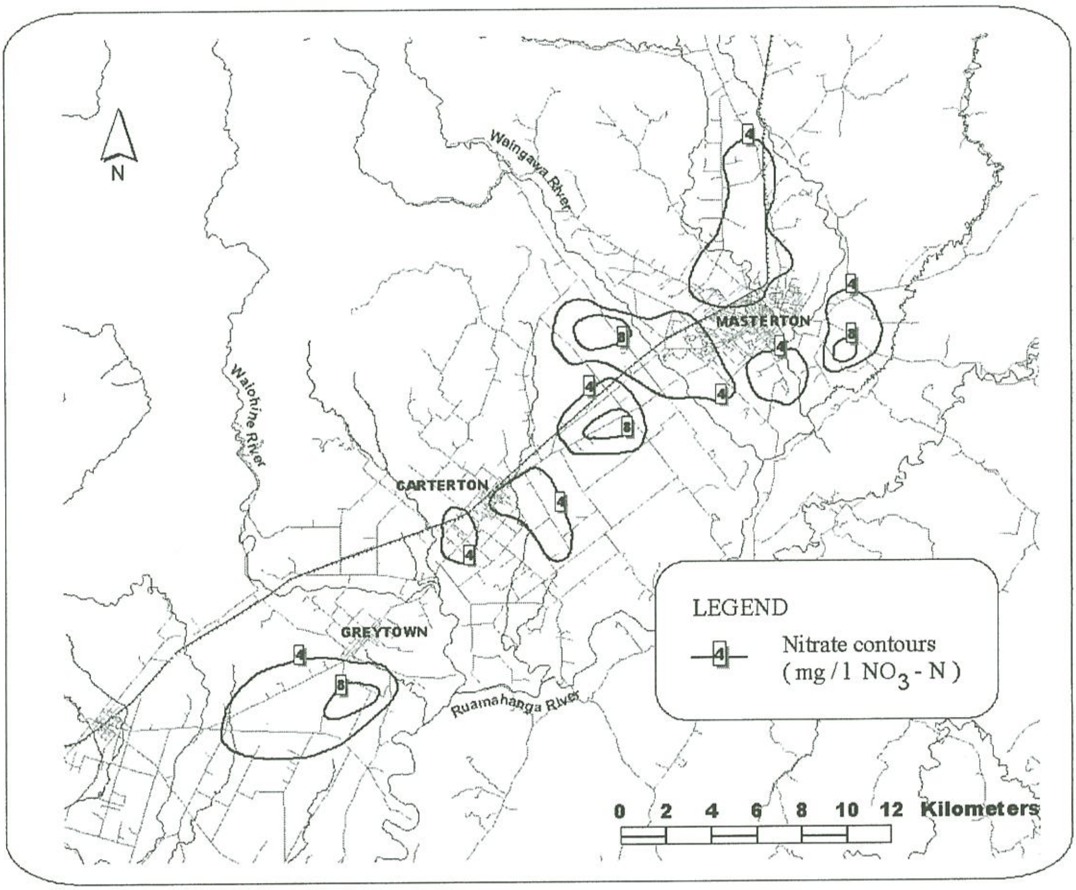

Figure 20.7 *Main areas in the Wairarapa with elevated nitrate levels.*

groundwater sample, the down-gradient groundwater quality met NZ Ministry of Health criteria for drinking water.

Groundwater management

Butcher (1996b) divided the Wairarapa Valley into 29 groundwater management zones. Aquifer characteristics can vary considerably within each zone. The water balance, safe yield and allocated water use of identified aquifers in each groundwater management zone is summarised in Table 20.2.

Detailed groundwater resource reports have been written for four groundwater management zones with significant water allocation demands: the Lower Valley, Tawaha, Parkvale, and Te Ore Ore zones (Butcher 1996c,d,e; 1997b).

Groundwater discharge via springs and surface seepage is a major source of flow in a large number of Wairarapa streams. Groundwater pumping, mainly from shallow aquifers, may significantly decrease spring flows. Additionally, pumping of shallow bores and wells adjacent to rivers has the potential to reduce flows.

Early groundwater development in the lower Wairarapa Valley involved the drilling of bores to obtain flowing artesian water, often with many bores drilled on individual farms. The water simply flowed freely to troughs and tanks for stock, and to a lesser extent, domestic water supplies. A seasonal reduction in artesian head resulted from a major increase in the use of these flowing artesian aquifers for irrigation in the 1980s. As a consequence, pumps had to be installed on a number of bores and reticulated farm water supplies developed.

Land use changes have seen an increase in demand for water for pasture irrigation for dairying and for vineyard irrigation.

ACKNOWLEDGEMENTS

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REFERENCES

Anderton, P.W. 1981: Structure and Evolution of the South Wanganui Basin, New Zealand. New Zealand Journal of Geology and Geophysics 24(1): 39-63.

Begg, J.G; Mazengarb, C. 1996: Geology of the Wellington area, scale 1: 50,000. Institute of Geological and Nuclear Sciences geological map 22. 1 sheet + 128p.

Butcher, G.M. 1996a: Report of the pump testing carried out on the Waterloo wellfield, Lower Hutt. November 1995. Report prepared for Wellington Regional Council. 25p + apps.

Butcher, G.M. 1996b: Safe yield estimates for identified aquifers in the Wairarapa Valley. Report prepared for Wellington Regional Council. 74p.

Butcher, G.M. 1996c: Ground water resources of the Lower Wairarapa Valley. Report prepared for Wellington Regional Council. 69p + 10 apps.

Butcher, G.M.. 1996d: Ground water resources of the Ruamahanga River floodplain, Martinborough to Pukeo. Report prepared for Wellington Regional Council. 54p + 8 apps.

Butcher, G.M. 1996e: Ground water resources of the Parkvale/Waihakeke area, Carterton. Report prepared for Wellington Regional Council. 44p + 5 apps.

Butcher, G.M. 1997a: Wairarapa Valley ground water quality programme. Brief review of existing information and proposal for baseline ground water quality monitoring programme 1997 – 2000. Report prepared for Wellington Regional Council. 21p + 7 apps.

Butcher, G.M. 1997b: Te Ore Ore ground water study. Report prepared for Wellington Regional Council. 69p + 6 apps.

Butcher, G.M. 1999: Monitoring Review, Discharge to Land Consent – Affco NZ Ltd. Report prepared for Consents and Compliance Section, Wairarapa Division, Wellington Regional Council. 23p + 1 app.

Capes C.D.; Lamb S.H.; Vella P.; Wells P.E.; Woodward D.J. 1990: Geological structure of Wairarapa Valley, New Zealand from seismic reflection profiling. Journal of the Royal Society of New Zealand 20(1): 85-105.

Donaldson, I.G; Campbell, D.G; 1977: Groundwaters of the Hutt Valley-Port Nicholson Basin. DSIR Information Series No. 124. 78p.

Fleming, C.A. 1972: The contribution of C14 dates to the Quaternary geology of the "Golden Coast", western Wellington. Tuatara 19(2): 61-69.

Gunn, I.; Butcher, G.; Stewart, M.K. 1987: Groundwater studies on the Wairarapa Plains using isotopic and chemical data. In: Smith D.K. (Comp.) Proceedings of the Groundwater Chemistry Workshop. Technical Publication 41, A.R.W.B., Auckland. Pp 139-155.

hicks, S.R.; Woodward D.J. 1978: Gravity models of the Wairarapa region, New Zealand. New Zealand Journal of Geology and Geophysics 21(5): 539-544.

Hughes, B.N. 1997: Nitrate Contamination of Groundwater on the Kapiti Coast, December 1996. Wellington Regional Council Technical Publication No. WRC/RINV-T-97/26. 40p + 1 apps.

Hughes, B.N. 1998: Moera Aquifer Investigation. Wellington Regional Council Technical Publication No. WRC/RINV-T-98/13. 29p + 2 apps.

Kampman, I.; Caldwell, K.J. 1985: Groundwater resources of the Waitohu, Otaki and Mangaone. Manawatu Catchment Board. 56p + 3 apps.

Mildenhall, D.C. 1995: Pleistocene palynology of the Petone and Seaview drillholes, Petone, Lower Hutt Valley, North Island, New Zealand. Journal of the Royal Society of New Zealand 25(2): 207-262.

Reynolds, T.I. 1993: Computer modelling of groundwater and evaluation of scenarios for pumping from the Waiwhetu Aquifer, Lower Hutt Basin. Wellington Regional Council Publication No. WRC/CI-G-93/45. Vols 1 to 3, 142p + 4 apps.

Roche, W.J. 1915: Raising of water from artesian wells, with special reference to the water supply of the Lower Hutt Borough. Proceedings of the New Zealand Society of Civil Engineers, vol. 1, 92-107.

Stevens, G.R. 1956: Stratigraphy of the Hutt Valley, New Zealand. New Zealand Journal of Science and Technology B38: 201-235.

Stevens, G.R. 1974: Rugged Landscape. The Geology of Central New Zealand. A.H. & A.W. Reed Ltd. 286p

Wairarapa Catchment Board and Regional Water Board 1989: Wairarapa Ground Water Study. Publicity Report. 44p.

Wellington Regional Council 1994: Hydrology of the Kapiti Coast. Publication No. WRC/CI-T/G-94/13. 215p + 17 apps.

Wellington Regional Council 1995: Hydrology of the Hutt Catchment, Volume II Groundwater Hydrology. Publication No. WRC/CI-T-95/38. 260p + 9 apps.

Wellington Regional Council 1999: Regional Freshwater Plan for the Wellington Region. Publication No. WRC/RP-G-99/31. 181p + 11 apps.

Wood, R.A.; Davy, B.W. 1992: Interpretation of geophysical data collected in Wellington Harbour. Institute of Geological and Nuclear Sciences client report no. 1992/78. 18p + figs.

21

Tasman

JOSEPH THOMAS

INTRODUCTION

The Tasman District covers an area of approximately 9,652 km^2 (Fig 21.1) and has a population of about 40,000 people. Nelson City, which lies northeast of Richmond (Fig 21.1), covers an area of approximately 42 km^2 and has a population of 41,000 people. Groundwater is an important source of water in the Tasman District for irrigation, industry, town drinking supplies, domestic water supplies and stockwater. Of the total of 1,262 water permits in the Tasman District (as of year 2000), 65% are for groundwater abstraction and 35% for surface water. The total groundwater use by volume is 62.5% of a total 6500 L/s of water allocated for consumptive use. On the other hand, groundwater is only a very minor source of water for Nelson City (D Ballagh pers. comm.). There are only two water permits to take groundwater (total of 1.1 L/s) within the Nelson City boundary. All the City's water supplies are from surface water sources.

Economic quantities of groundwater occur primarily in the alluvial flood plains of the Tasman District, including the Waimea Plains, the Motueka/Riwaka Plains, the Takaka Valley and the Aorere Valley (Fig 21.2). Groundwater also occurs in the inland alluvial river terraces of the Motueka and the Buller Rivers. Groundwater is also found in the Moutere Valley but is at much greater depths, with the deepest groundwater extraction bore being 540 m deep. The Moutere Gravel, which covers the Moutere Valley and underlies the Waimea Plains, consists of terrestrial gravels that were deposited in the Pliocene-Pleistocene periods.

Within the Nelson City area groundwater is very limited due to the lack of alluvial valleys or floodplains with significant thicknesses of water-bearing gravels. Most of the valleys are narrow, with only a limited thickness of gravels overlying low-permeability bedrock. Wells or bores that do tap groundwater are normally adjacent to streams and their principal source of water is infiltration from the streams.

For water-management the Tasman District is divided into catchments (Fig 21.2), each with its own hydrological and hydrogeological characteristics. Many of the management catchments are further subdivided into water management zones.

WAIMEA PLAINS GROUNDWATER RESOURCES

The Waimea Plains covers an area of 75 km^2 and is located at the coastal margin of the Waimea catchment, adjacent to the town of Richmond. The Waimea Plains are formed of late Quaternary terrestrial terrace and floodplain gravels deposited by the Waimea River and its major tributaries, the Wairoa River to the east and the smaller Wai-iti River to the south (Dicker et al. 1992). The soils of the Waimea Plains are highly productive, with the principal source of water for irrigation, domestic, industrial and urban supply being groundwater from the various aquifers that underlie the area.

Three major aquifers (Fig 21.3) have been delineated under the Waimea Plains: the Lower Confined Aquifer, Upper Confined Aquifer and the Appleby Gravel Unconfined Aquifer. There are also minor aquifers called the Hope Minor Confined and Unconfined Aquifers. Figure 21.4 shows the three-dimensional hydrogeology of the Waimea Plains.

Appleby Gravel Unconfined Aquifer

The Appleby Gravel Unconfined Aquifer underlies the floodplains of the Wai-iti, Wairoa and Waimea Rivers and the delta of the Waimea River. This aquifer is up to 15 m thick, with a water-table depth averaging 2

Thomas J. 2001: Tasman. *In* Groundwaters of New Zealand, M.R. Rosen and P.A. White *(eds)*. New Zealand Hydrological Society Inc., Wellington. p411-425.

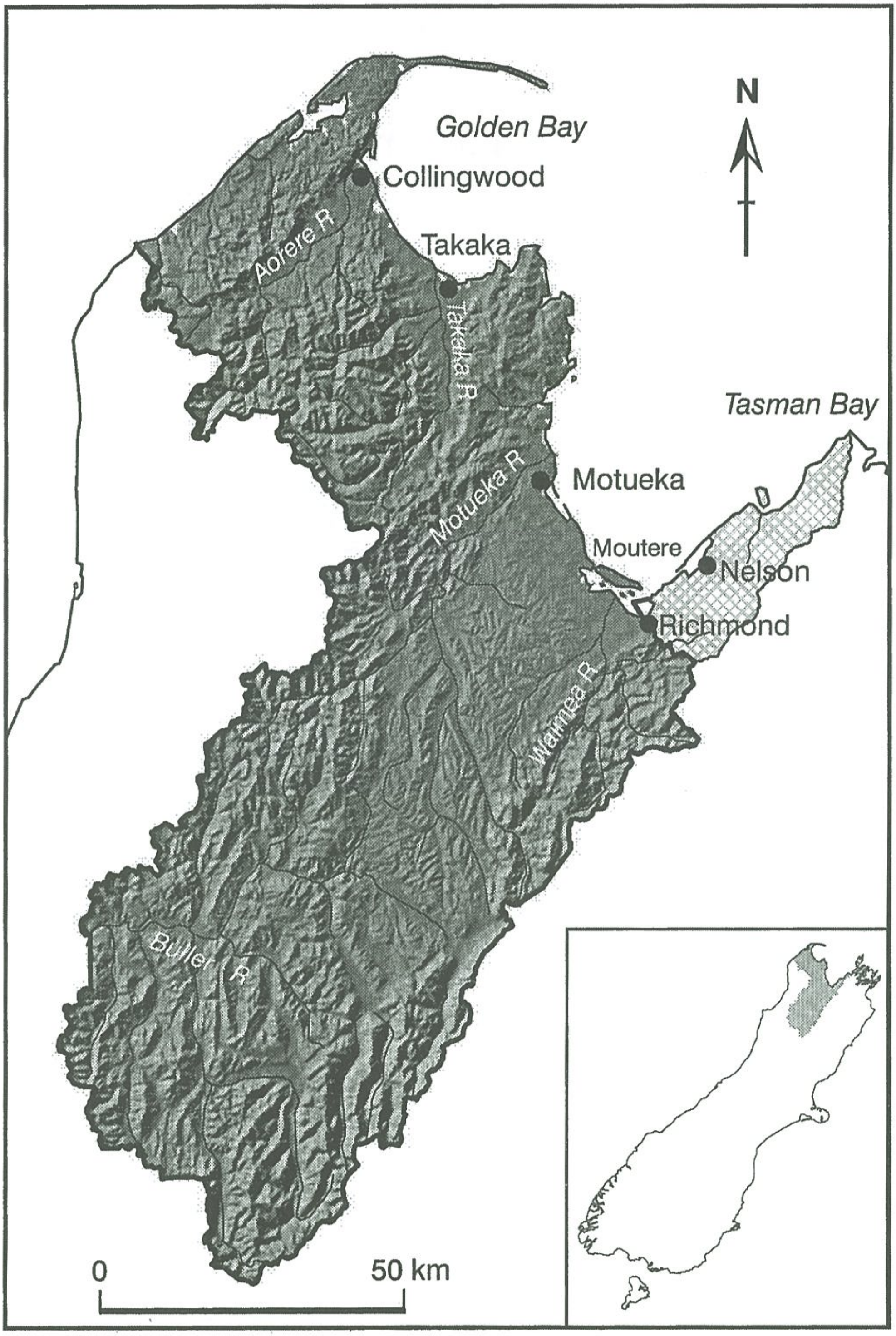


Figure 21.1 *Map of the Tasman District and Nelson City.*

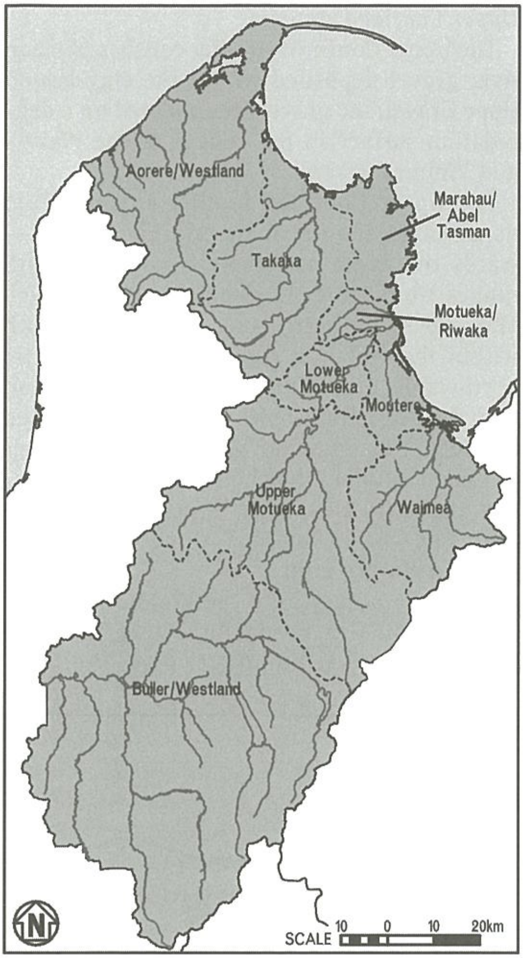


Figure 21.2 *Tasman District water management catchments.*

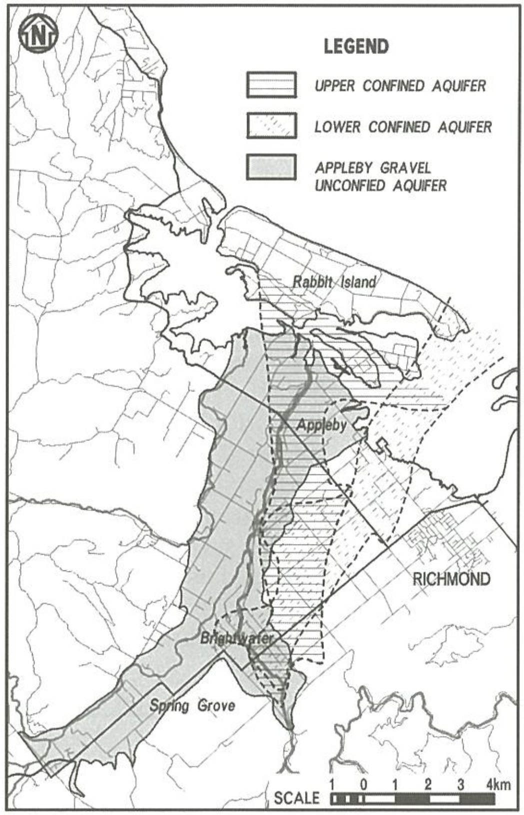


Figure 21.3 *Waimea Plains – major aquifers.*

to 3 m below ground level. The aquifer is underlain by the clay-bound Hope Gravel. The contact with the Hope Gravel is less distinct in the Wai-iti Valley, where the Appleby Gravel aquifer is less permeable than in other areas of the Waimea Plains. Transmissivity values in the Wai-iti area range from 2,000-3,500 m^2/day. The most permeable area in the Appleby Gravel Unconfined Aquifer is the youngest gravel adjacent the Wairoa and Waimea Rivers. Transmissivity values of 20,000 m^2/day have been measured adjacent the Waimea River and in the delta part of the plains. The Appleby Gravel Unconfined Aquifer is in contact with the Upper Confined Aquifer, and in lateral contact with marine gravel and sand in the Waimea delta region. The Appleby Gravel aquifer is recharged from the rivers and from rainfall and irrigation drainage. The main river recharge zones are between the Wairoa Gorge and Brightwater township, upstream of the State Highway 60 Bridge near Appleby and downstream of Spring Grove on the Wai-iti River.

Groundwater quality in the Appleby Gravel Unconfined Aquifer is generally good, with low quantities of dissolved solids. The Tasman District Council's nitrate (NO_3^-) survey in the summer of 1999/2000 shows the nitrate levels to be low, with most parts of the aquifer having values between 10-30 mg/L. Areas of higher nitrate levels have been found near the margins of the aquifer i.e. near the boundary between the Upper Confined Aquifer and Appleby Gravel Unconfined Aquifer near Appleby.

Hope Minor Confined and Unconfined Aquifers

East of the Appleby Gravel, minor water-bearing lenses occur in gravel fans in the Hope Gravel, derived from the eastern hills. These minor unconfined and confined aquifers are seldom more than 0.5 m thick and rarely occur below a depth of about 15 m. Laterally they are discontinuous, so pumping drawdowns are high.

Recharge is only from rainfall and associated run-off because the aquifers are above the level of any river. The Hope aquifers have elevated nitrate levels (NO_3^-) and levels of up to 75 mg/L were measured in a nitrate survey carried out by the Tasman District in the summer of 1999/2000. The mean nitrate level from the Hope aquifers for the survey was 49 mg/L. Pumpage from these aquifers is primarily for domestic use and small-scale irrigation. Water levels and yields decline markedly in these aquifers in summer.

Upper Confined Aquifer

The Upper Confined Aquifer consists of clean river gravel deposited within the clay-bound Hope Gravel; the gravel accumulated on a degradation surface in the valleys of the Wairoa and Waimea Rivers.

The Upper Confined Aquifer extends from its recharge zone near the Wairoa Gorge towards the coast at Rabbit Island. Its depth ranges from 18 to 32 m below ground level. The upper confining layer is disrupted both within the recharge zone and from Appleby northwards, providing a hydraulic connection with the overlying Appleby Gravel unconfined aquifer. Transmissivity values for the Upper Confined Aquifer range between 600-1,300 m²/day. Highest yields in the Upper Confined Aquifer have been obtained along the western edges of Burkes Bank.

Recharge occurs from the Wairoa River via the Appleby Gravel and in winter from the Hope aquifers via the gravel fans. The latter

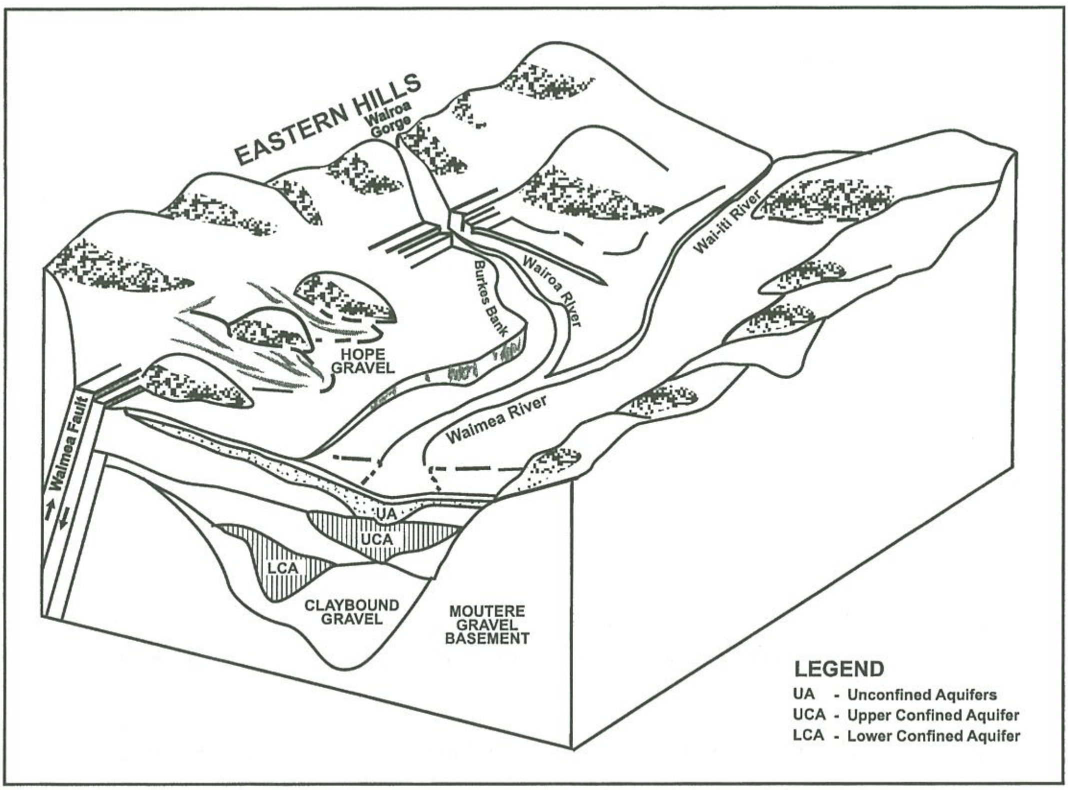


Figure 21.4 *Three-dimensional hydrogeology of the Waimea Plains.*

source is confirmed by the high nitrate levels measured in the Upper Confined Aquifer and by the flow directions derived from winter piezometric survey. Nitrate (NO_3^-) levels of up to 132 mg/L were measured in this aquifer in the 1999/2000 nitrate survey. The mean nitrate level for the aquifer from the 1999/2000 survey was 54 mg/L.

Lower Confined Aquifer

The Lower Confined Aquifer is lithologically similar to the Upper Confined Aquifer. It extends from the Wairoa Gorge in a more easterly direction, to beyond the entrance to the Waimea Inlet east of Rabbit Island. It ranges from 30-50 m deep and is recharged near the Wairoa Gorge and in winter from the gravel fans from the eastern hills, which also recharge the Upper Confined Aquifer. Seawater intrusion in this aquifer is a potential concern due to the large pumpage from wells near the coast. The aquifer extends under the Waimea inlet and the nature of the seaward contact of the aquifer is unclear. Pump testing shows a transmissivity range of between 200–1,600 m^2/day. Nitrate (NO_3^-) levels are generally elevated in this aquifer. A nitrate survey carried out in the summer of 1999/2000 shows a mean nitrate value for the aquifer of 42 mg/L; the highest value measured was 70 mg/L.

Groundwater model – Waimea Plains aquifer system

Computer modelling of the Waimea groundwater system in the 1980s (Fenemor 1988) provided information on the sustainable yields of each aquifer, based on the pattern and levels of pumpage occurring during the March 1983 drought, which was about a 1-in-34 year drought in terms of river flows (up to May 1992). Figure 21.5 shows the inflows and outflows predicted by the model for March 1983; this 'water balance' figure is the basis for some of the allocation limits set in the 1991 Waimea Water Management Plan. The Tasman District is currently updating the previous groundwater flow model, incorporating new hydrological, hydrogeological and water-use data, as well as improving the river-aquifer interaction module. Data from the updated model will be used to review the allocation limits and triggers, as set in the 1991 Waimea Water Management Plan.

MOUTERE VALLEY GROUNDWATER RESOURCES

The Moutere catchment covers an area of about 205 km^2 and is located south of Motueka (Fig 21.1). Much of the Moutere catchment is covered by the Moutere Gravel Formation, with materials reworked from the Moutere Gravel forming the valley floors. An exception is part of the Powley Creek catchment, which is derived from Separation Point Granite.

Moutere shallow groundwater resources

Shallow domestic or stock wells (<20 m) on the valley floors penetrate the valley fill. The yields of these wells are low and supplies are localised and unreliable in drought periods (Thomas 1989a). Shallow wells on the Moutere hills also tend to have low yields and unreliable supplies. There is also a minor source of groundwater in shallow coastal sand/gravel from south of Ruby Bay to Mapua. The principal recharge for the shallow Moutere groundwater is rainfall and, to a variable extent, adjacent streams. An additional concern for the shallow groundwater resource at Mapua is the risk of seawater intrusion.

Deep Moutere groundwater resource

Significant groundwater resources are found in the Deep Moutere Aquifers. Groundwater investigations show the Moutere area to have a northeast-trending basin structure, with the Moutere Gravel being about 600 m thick in the deepest part. Three aquifers are found in vertical succession: the Shallow Moutere Aquifer, Middle Moutere Aquifer, and Deep Moutere Aquifer (Thomas 1989b).

A major fault identified by seismic survey compartmentalises the groundwater system into two zones—the Western Zone and Eastern Zone, with the fault itself being a barrier boundary (Thomas 1991a). Figure 21.6 shows the Western and Eastern groundwater zones. Figure 21.7 shows a schematic three-dimensional model of the Moutere Valley. Groundwater of the Moutere aquifers is recharged by direct rainfall infiltration through unconfined sections of the aquifer in the south-

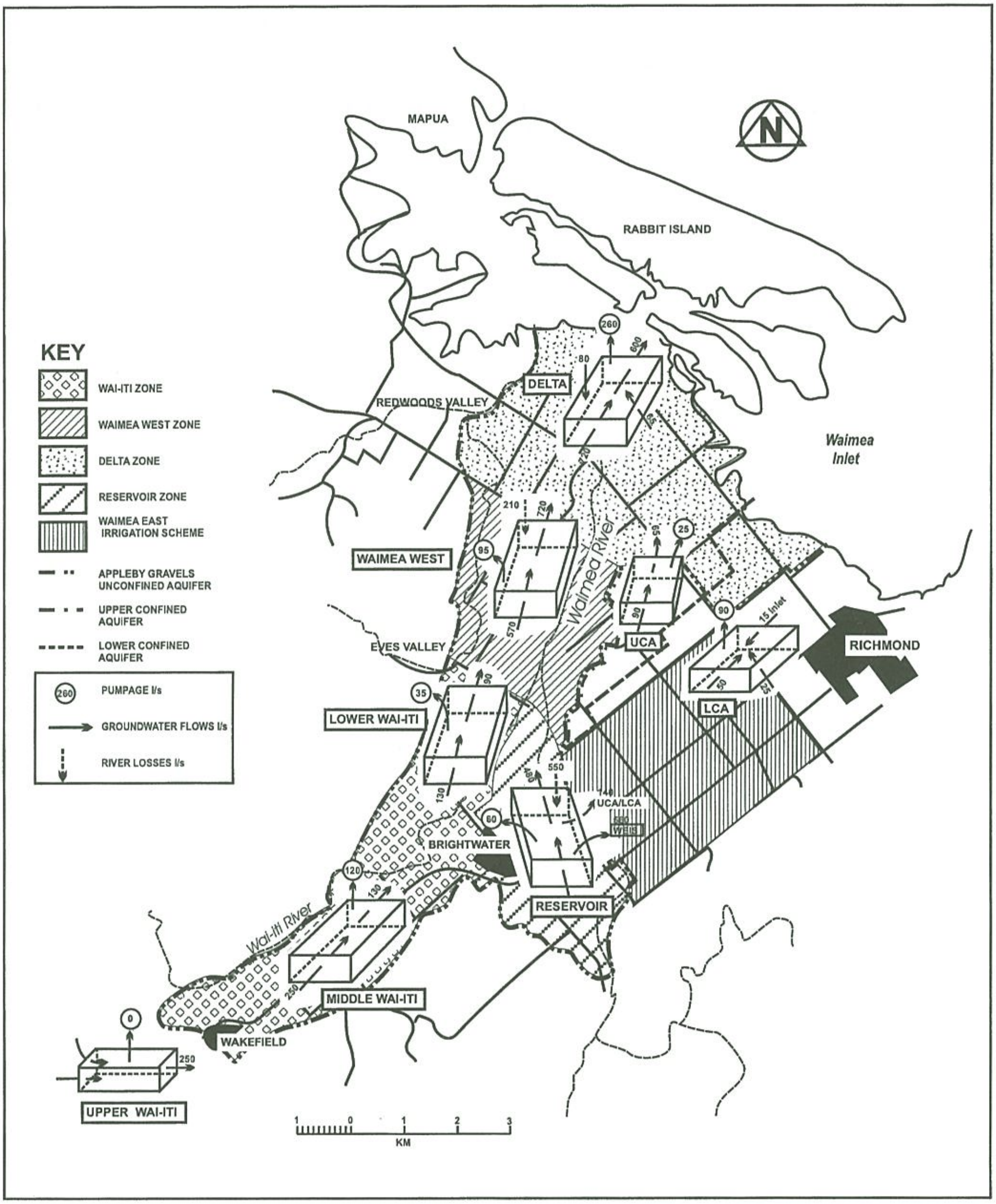


Figure 21.5 *Waimea Plains water budget, March 1983 drought, from groundwater modelling.*

west sector of the catchment (Fig 21.6). Figure 21.8 shows a schematic recharge model for the Moutere aquifers.

Groundwater yields improve significantly with depth and are influenced strongly by basement topography. Many deep bores (>50 m) have artesian heads. The aquifer system is a leaky one, with higher heads at depth.

The aquifers have low permeabilities, thus interference effects due to pumping are noticeable at distances of hundreds of metres. Well casing is required to protect shallow wells from pumping interference.

The transmissivity of the Shallow Moutere Aquifer is less than 15 m^2/day, while the Middle Moutere Aquifer ranges from 25-40 m^2/day,

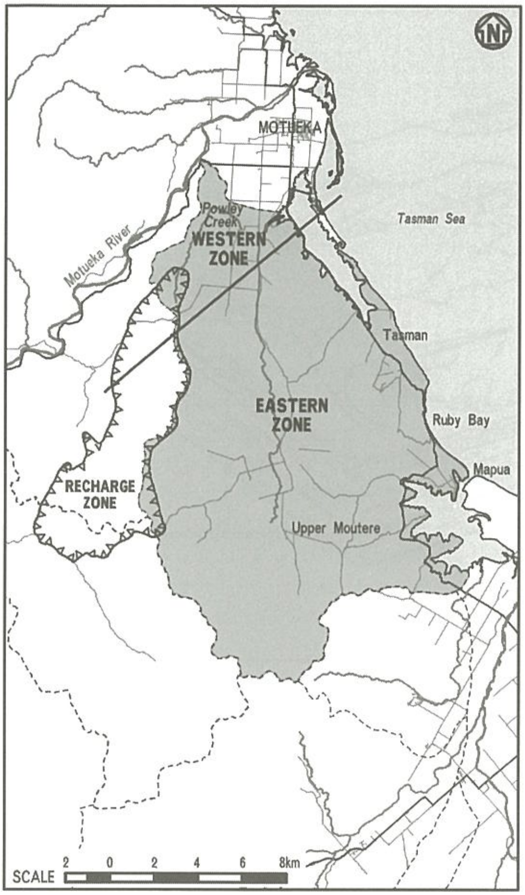


Figure 21.6 *Moutere groundwater zones.*

and the Deep Moutere Aquifer is greater than 50 m²/day (Thomas 1991a). Groundwater from the Deep Moutere Aquifers (with the exception of certain parameters) is of good quality. The parameters that exceed guideline values are pH, which is low, and levels of iron and manganese, which are high.

These parameters are a reflection of the depth the water is coming from, as well as the residence time of the water in the gravels.

MOTUEKA/RIWAKA PLAINS GROUNDWATER RESOURCES

Alluvial gravels washed into Tasman Bay from the Motueka and Riwaka Rivers have formed an area of coastal plains covering approximately 40 km^2 (Fig 21.9).

The main township of Motueka (population 7,000) is located centrally near the coast; the plains support intensive horticulture. The Motueka Gravels form an aquifer system that is underlain in the west and north by a faulted granite block and in the south by the older Moutere Gravel. The Motueka/Riwaka Plains aquifer system is the principal source of water for irrigation, industrial and domestic use on the plains. In 1998 a new water supply for Kaiteriteri, a popular seaside holiday area which lies north of Motueka, was abstracted from the Motueka/Riwaka Plains groundwater system.

Motueka/Riwaka Plains aquifers

The lithology and thickness of the Motueka Gravels vary over the plains, with the thinnest gravels at the margins of the plains (Fig 21.10). The gravels are about 6 m deep at Lower Moutere, thickening to about 30 m in the Central Plains area (Thomas 1994). To the south the Motueka Gravels have mixed with material flushed out of the Moutere Valley and have a high content of fine sands, silts and clays. In the Central Plains, the gravels are cleaner and consist of well-rounded clasts, predominantly of granite, sandstone, siltstone and basic igneous rocks, in a granite-derived sand mix. The land adjoining the Riwaka River is underlain by gravels flushed from the Riwaka River mixed with colluvial granitic outwash.

Three high-yielding aquifers occur in the central parts of the plains (Thomas 1991b). The shallowest aquifer lies 1-10 m below ground level. Transmissivities calculated from pumped well tests exceed 2,000 m^2/day. The middle aquifer is the most widely exploited and lies 10-16 m below ground level, with measured transmissivities exceeding 4,000 m^2/day. The deepest aquifer is the least exploited and lies below 16 m, with measured transmissivities exceeding 2,500 m^2/day.

The aquifer system is recharged by rainfall on the plains and by outflows from the Motueka and Riwaka Rivers. Water exits the groundwater system either into Tasman Bay, into springs near the coast, or back into the river, or is pumped from wells.

Groundwater quality

Groundwater from the Motueka Gravel Aqui-

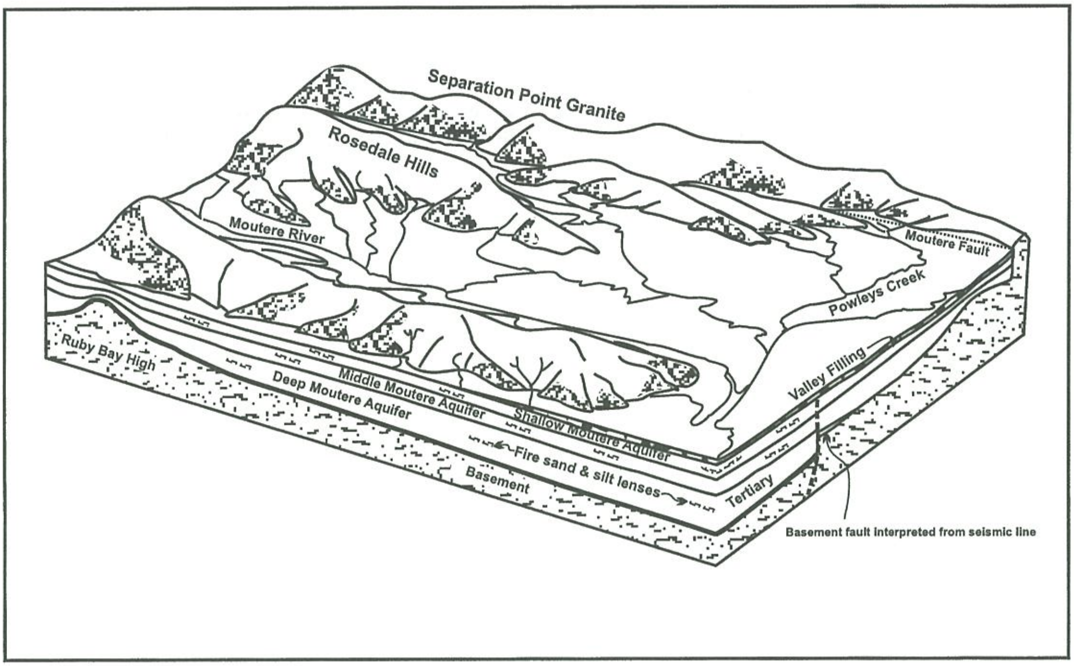


Figure 21.7 *Three-dimensional hydrogeology of the Moutere Valley.*

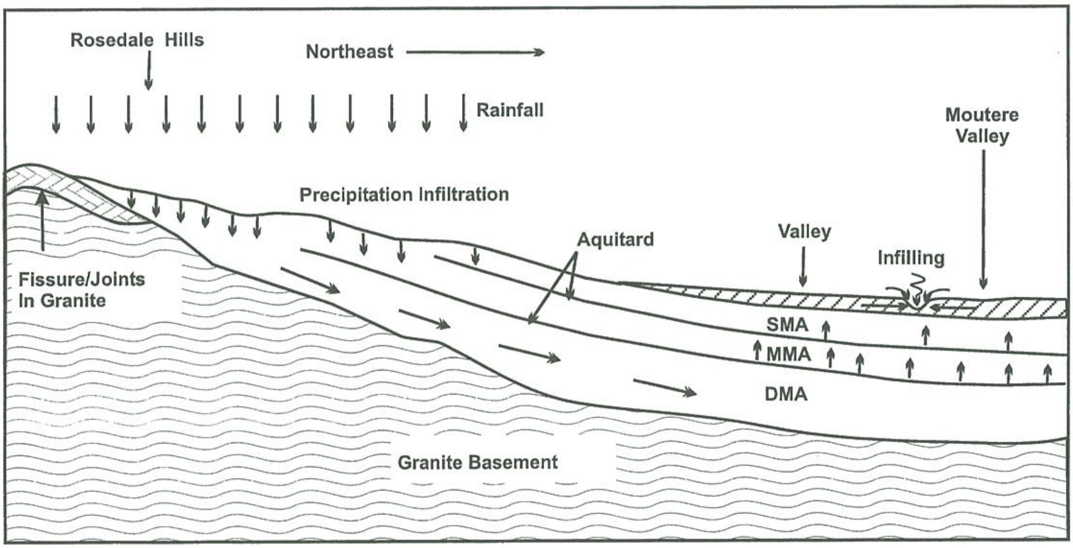


Figure 21.8 *Schematic recharge model for the Moutere aquifers.*

fer is of high quality, with low quantities of dissolved solids. Water quality deteriorates towards the south and west of Riwaka towards the foothills (Thomas 1994). Elevated nitrate (NO_3^-) levels occur to the south of the plains in the Lower Moutere area, where levels of up to 48 mg/L have been measured. The high nitrate levels are a result of leaching of fertilisers and animal waste, linked with the lower permeability of the aquifer here. Groundwater to the west towards the foothills of Riwaka has generally elevated iron, manganese and sulphate

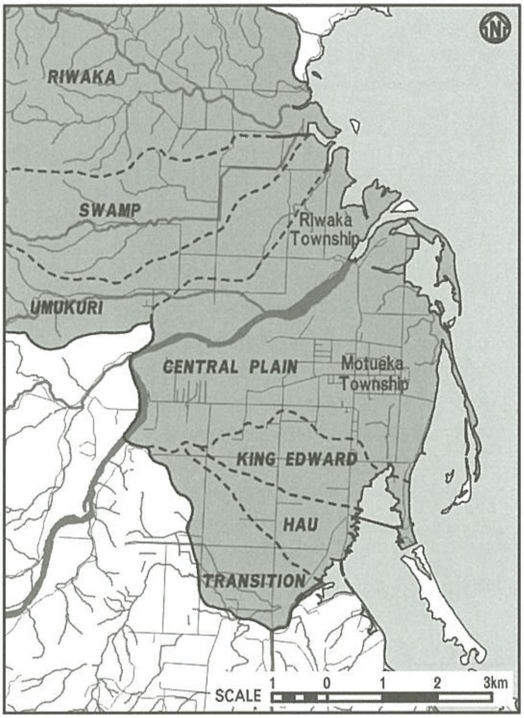


Figure 21.9 *Water management zones of the Motueka/Riwaka Plains.*

levels, which is reflective of the swampy and peaty environment. Groundwater adjacent the Riwaka River is generally hard because of the high amount of dissolved carbonate in the river water from its karst source.

Groundwater model – Motueka/Riwaka Plains aquifer system

The computer model of the Motueka/Riwaka Plains groundwater resource (Robb 1999) was developed to help determine levels of water use that are sustainable in terms of their effects on seawater intrusion, and river and spring flows, and to determine the broad-scale effects of pumping on other bore users. The model takes into account the physical and hydraulic features of the system, including aquifer properties, well locations and pumping rates (domestic; irrigation; industrial), soil types, irrigation methods, crop types, river flow, and rainfall and irrigation rates. Daily irrigation water usage was calculated taking into account climatic conditions, crop type, crop water needs and soil type. The predicted use was recalibrated to water meter records.

The model can be used to determine zone water budgets and hence total allocations for given management scenarios. For example, Figure 21.11a shows the January-March Zone Water Budgets for a 20-year drought, with existing irrigation, the Kaiteriteri Water Supply, plus irrigation in the King Edward and Central Plains zones increased to allow for all available land to be irrigated (~350 hectares more).

Figure 21.11b shows the flow figures for a 20-year drought with no irrigation. The model is to be used to set allocation limits for each of the water management zones (Fig 21.9) based

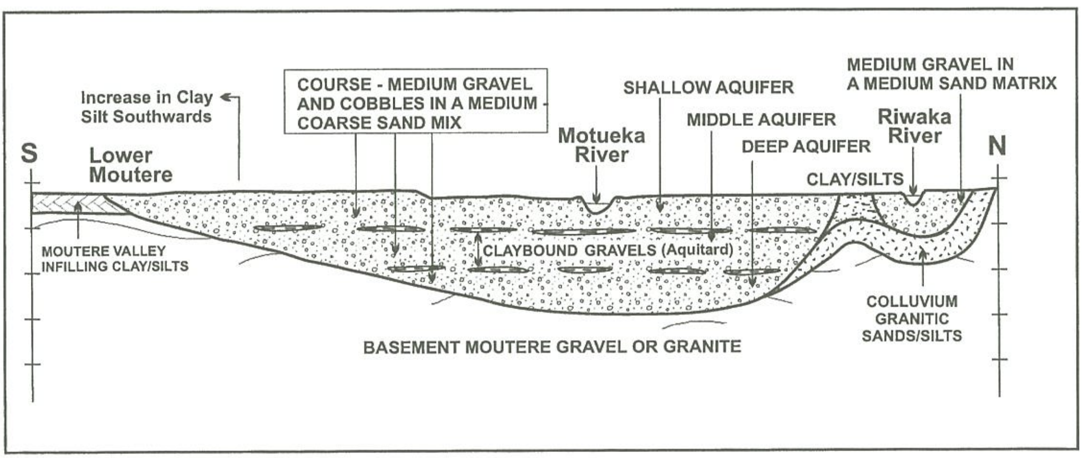
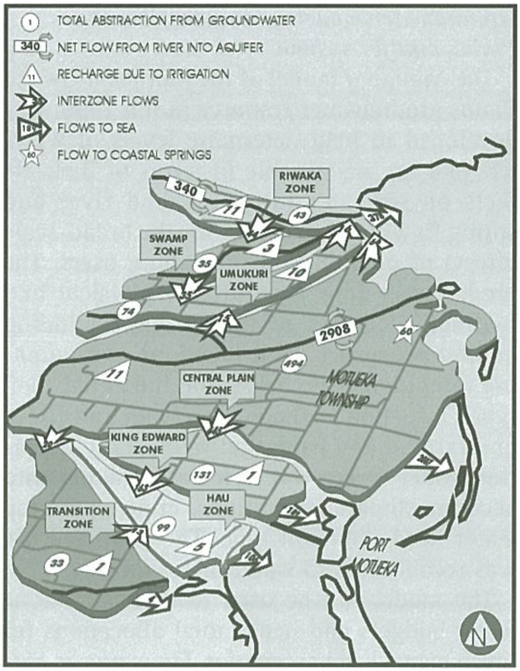
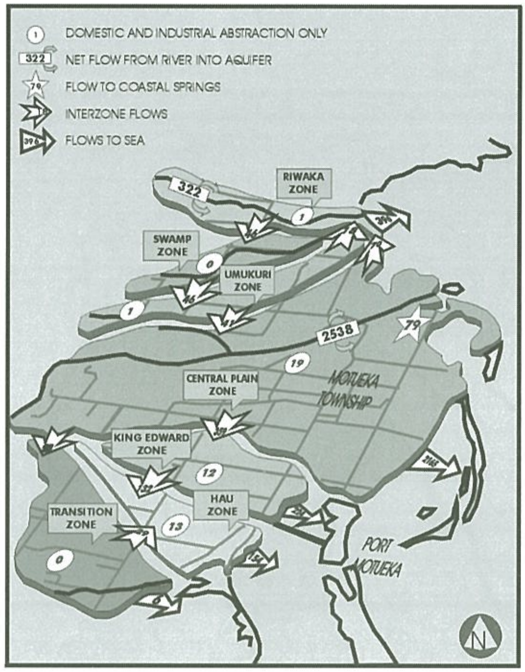


Figure 21.10 *Schematic north-south cross-section through the central part of the Motueka/Riwaka Plains.*



All existing abstraction including the Kaiteriteri water supply, plus an increase in the area irrigated in Central Plains and King Edward Zones, is included. Flows are average flows (litres/second) over the period 1 January to 31 March.

Figure 21.11a *Groundwater flows for a planning scenario in a 20-year drought.*



The only abstractions are for domestic and industrial water. Flows are average flows (litres/second) over the period 1 January to 31 March.

Figure 21.11b *Groundwater flows for no irrigation scenario in a 20-year drought.*

on management planning objectives defined for the area.

GROUNDWATER RESOURCES OF THE TAKAKA VALLEY

The geographical catchment area for the Takaka Valley lies south of Takaka, and is 928 km^2 in area (Fig 21.12a). It includes subcatchments of the Waingaro, Anatoki, Motupipi and Waikoropupu Rivers. There are three main water-bearing units in the area and these are directly related to the lithology and geology. The three main aquifers are called the Arthur Marble Aquifer, Takaka Limestone Aquifer and the Takaka Valley Unconfined Gravel Aquifer

Arthur Marble Aquifer

The Arthur Marble Aquifer is the principal karstic aquifer that occurs in the Takaka Valley area; it is in the Ordovician Arthur Marble. In the Takaka catchment Arthur Marble is found beneath the Takaka Valley floor from Upper Takaka to the Golden Bay coast, and in the mountain ranges parallel to this valley section. The Marble covers an area of about 180 km^2 in the central and lower Takaka subcatchments. Under the central Takaka Valley floor the marble is covered by tens of metres of alluvial gravel (45 km^2) and in the lower Takaka catchment it is additionally covered (45 km^2) by impervious Tertiary formations–the Motupipi Coal Measures and Tarakohe Mudstone.

Solution of the marble has caused the formation of a striking surface karst landscape, with features such as karren, dolines and swallow holes, strong serrated relief and a significant subterranean aquifer system.

The Arthur Marble Aquifer is unconfined from Upper Takaka to about Hamama (Edgar 1998). In the unconfined area Arthur Marble is overlain by cavernous Takaka Limestone and/or permeable alluvial gravels. The

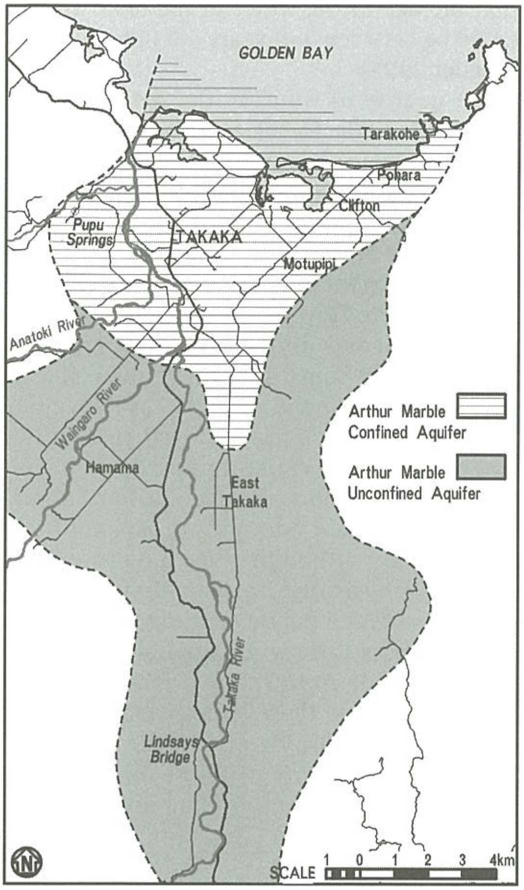


Figure 21.12a *Arthur Marble Aquifer–Takaka Valley*

lithological boundary between marble and limestone has no distinguishable influence on groundwater flows in these unconfined areas. North of Hamama the Arthur Marble Aquifer becomes confined by the impervious Motupipi Coal Measures that overlie the Arthur Marble. Figure 21.12a shows the extent of the Arthur Marble Aquifer and its unconfined and confined areas.

Figure 21.12b shows a cross-section from Lindsay's Bridge to Waikoropupu Springs and out to sea. The aquifer surface in the unconfined area is defined by the water table, which may lie above the surface of the marble body within the overlying Takaka Limestone or Quaternary Gravels. In the confined area the surface of the aquifer is determined by the presence and elevation of impervious Motupipi Coal Measures.

Aquifer depth is controlled by the thickness of the marble and the depth to which solution penetrates. In East Takaka, as well as upstream of the Waikoropupu Springs area, deep bores reveal karstification to depths of more than 100 m. Geological data indicate that the marble extends several hundred metres below the valley floor and karstification could occur to these depths, although the exact depth of karst development in the marble is unknown.

Aquifer recharge occurs in areas where Arthur Marble outcrops, or from the unconfined aquifer in the central Takaka Valley. The aquifer is recharged both by rainfall and through flow loss from the Takaka and Waingaro Rivers, and from the creeks drain-

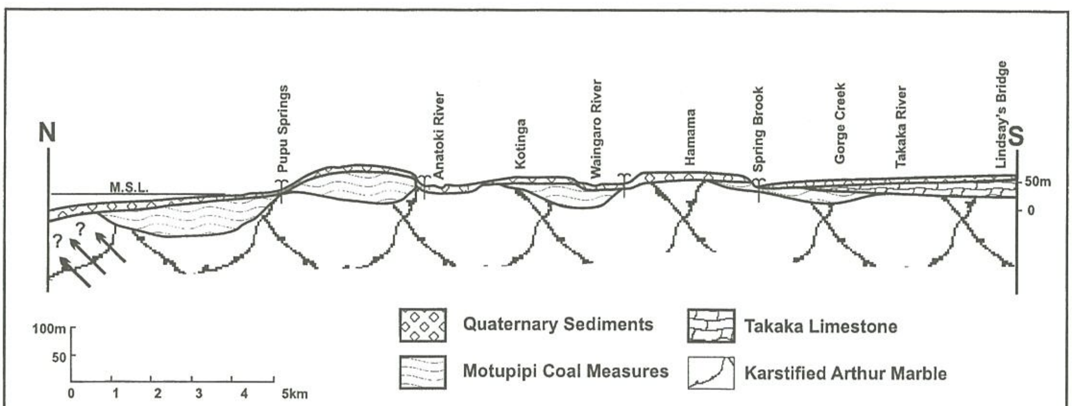


Figure 21.12b *Cross-section Lindsay's Bridge to coast (adapted from Muller, 1987).*

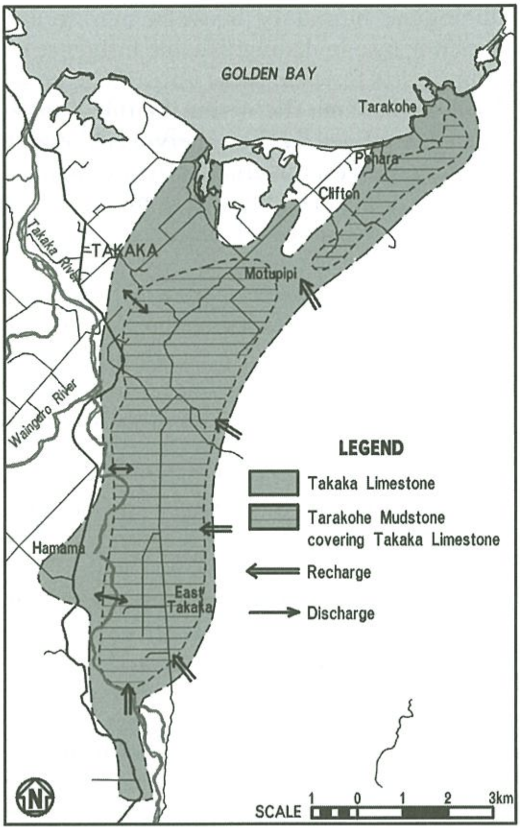


Figure 21.13 *Takaka Limestone Aquifer.*

ing into the Takaka Valley from both the east and west. Many of the creeks flow on the surface in their upper reaches, but go underground into the aquifer upon reaching the marble country. The Takaka River on average loses 8 m³/sec through the gravel of the riverbed into the karst aquifer system below Lindsay's Bridge. On days when the river flow at Upper Takaka is less than 9.4 m³/sec, stretches of the Takaka River below Lindsay's Bridge are dry.

The Waikoropupu Springs emerge from the Arthur Marble Aquifer. The Waikoropupu Springs are the largest springs in New Zealand, with a mean flow of 13.2 m³/sec. Hydrological monitoring shows the springs respond to rainfall in the marble catchment, as well as to river flows, especially the Takaka River. The springs water is a mixture of waters that have spent varying amounts of time within the aquifer. Isotopic data and chemical data indicate that the age of the water in the main springs could be between 3–8 years old (adapted from Mueller 1992).

The quality of water in the Arthur Marble Aquifer is high. In the confined part of the aquifer, e.g. at Waikoropupu Springs, the nitrate (NO_3^-) levels are low, averaging about 1.2 mg/L. The water is hard due to the karst source. The Waikoropupu Springs also has a seawater content of about 0.5–0.7 % (Mueller 1992). As the flow at the springs increases, so does the concentration of seawater, which may indicate some sort of venturi mixing with water from the deepest cave levels of the aquifer, which are believed to be filled by seawater. The Waikoropupu Springs may not be the end point of the aquifer. Submarine springs are thought to exist out in Golden Bay, although they have not been detected physically. Tasman District Council's recent water balance estimates, however, show there is little water available from the Arthur Marble Aquifer for offshore springs, so the flow from these springs may be intermittent at best (Doyle and Edgar 1998). Alternatively, there are could be other sources of water to the aquifer that are currently unknown.

Takaka Limestone Aquifer

The Takaka Limestone Aquifer occurs between East Takaka and Tarakohe (Fig 21.13) and is a result of karstification of the Oligocene Takaka Limestone. The Takaka Limestone Aquifer in the northern half of the Valley (north of Hamama and East Takaka) is underlain by an aquiclude (i.e. Motupipi Coal Measures). To the south of Hamama and East Takaka the aquiclude is absent and the Arthur Marble and Takaka Limestone Aquifers are indistinguishable. The Takaka Limestone is gently folded into a series of low-amplitude synclines and anticlines. Only small amounts of groundwater are abstracted from this aquifer. Several bores tap into the aquifer in East Takaka, where the depth to limestone ranges from 60 to 120 m. In the Motupipi area bores have encountered the aquifer at depths of about 20 to 60 m below ground level. The aquifer thickness varies between 30 and 60 m.

The total aquifer volume of the Takaka Limestone Aquifer is about 7.5 x 10^7 cubic metres (Mueller 1987). The aquifer is recharged mainly by rainfall and by seepage from creeks draining the eastern boundary. Recharge is also thought to occur at the southern end of the aquifer from river flow seeping into the underlying gravel and into limestone, as well as the underlying marble. Groundwater quality is generally good, although it is hard water, indicating its karst source.

Takaka Valley Unconfined Gravel Aquifer

Quaternary gravel and sand deposits cover most of the Takaka Valley from Upper Takaka to the sea. The major water-bearing gravels underlie the lowest river terraces of the Takaka Valley, and Takaka township (Fig 21.14). The thickness of the gravels varies down the valley. Around Lindsay's Bridge the gravels are about 10 m thick, whilst recent drilling upstream of East Takaka revealed a gravel thickness of 57 m. The gravel is generally between 5-12 m thick in East Takaka. In the central part of Takaka township the gravels are estimated to be about 30–40 m thick. The whole of Takaka township uses private individual domestic bores that are 6–8 m deep. The water level is only 2–3 m below ground level throughout the year. The groundwater quality in this aquifer is high, with low concentrations of dissolved minerals and nutrients.

GROUNDWATER RESOURCES OF THE MOTUEKA CATCHMENT

The Motueka catchment includes the areas of the Lower Motueka and Upper Motueka (Fig 21.2). Appreciable quantities of groundwater are found in the lower river alluvial terraces within the Motueka catchment (Fig 21.15); less water is available in the higher river terraces. The location of wells affects the extent to which groundwater extraction reduces river flows. There is, as yet, little technical information available. While good flow data is available for the rivers in the catchment, knowledge of the effect of groundwater on the river is critical in managing the water resources.

The aquifers are unconfined, with the primary source of recharge for the groundwater system being the adjacent river system and, to some extent, rainfall. Several factors influence the relationship between the river and the groundwater, including lithology, riverbed elevation, gravel permeability, thickness of gravel (6–12 m), connectivity with and distance from the river, and riverbed conductance. A three-year investigation programme started in July 1999 by the Tasman District Council is proposed to answer some of the questions about river and groundwater linkages and the size and availability of the groundwater resource.

GROUNDWATER RESOURCES OF THE AORERE/WESTLAND AREA

Not much is known about the groundwater resources in this area—because of the high rainfall here (>2000 mm) there is limited demand for groundwater. Groundwater is known to

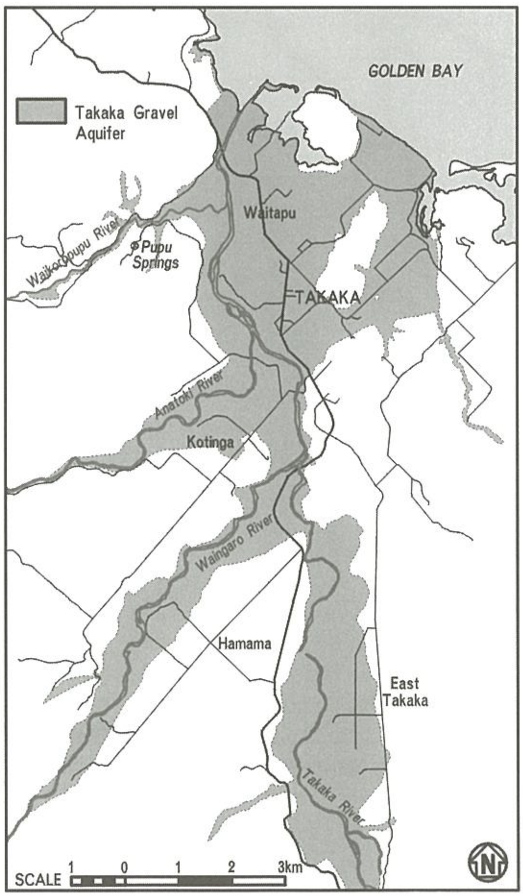


Figure 21.14 *Takaka gravel aquifer.*

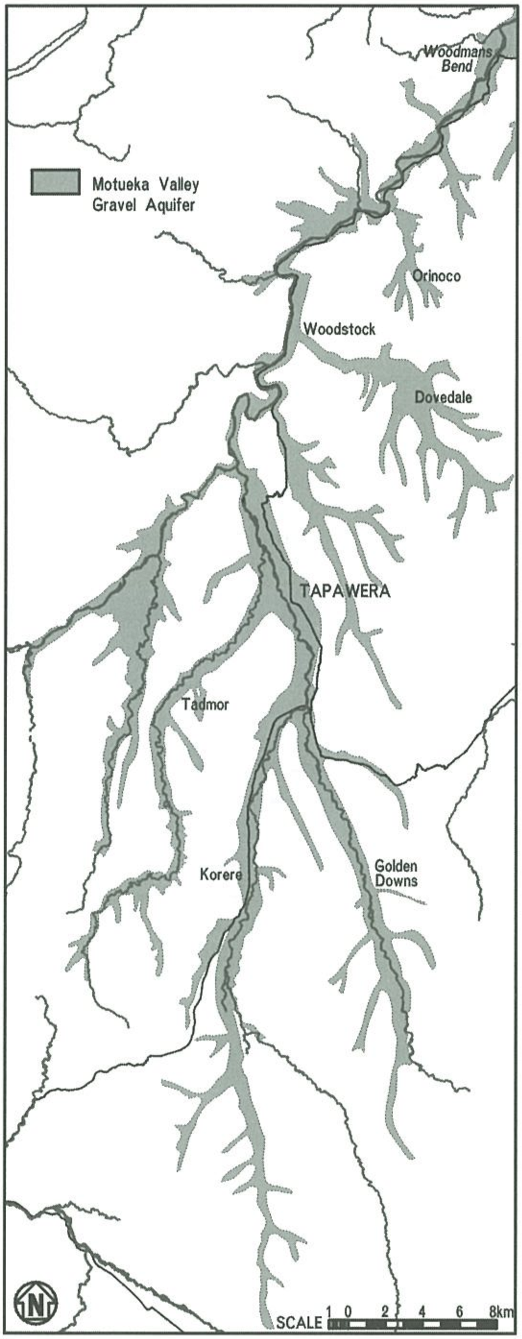


Figure 21.15 *Motueka Valley gravel aquifer*

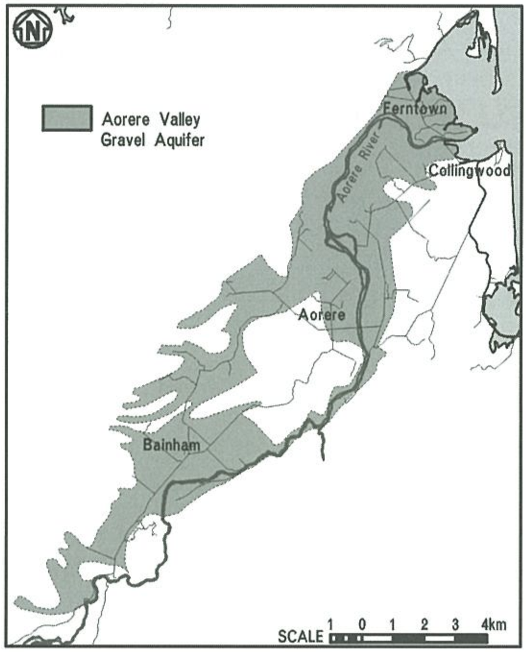


Figure 21.16 *Aorere Valley gravel aquifer*

exist in the lower river alluvial terraces of the Aorere River (Fig 21.16). Groundwater is extracted mainly from wells and a limited number of bores, and is used mainly for domestic drinking water and in dairy sheds. The limited borelog data shows the water-bearing gravels to be between 6-20 m deep and the aquifer itself to be unconfined. The limited data on groundwater quality also shows that, at least in the delta end of the Aorere, the water is corrosive, with a low pH and high iron levels. This is attributed to the swampy environment of the gravels at the delta area.

GROUNDWATER RESOURCES OF THE BULLER/WESTLAND AREA

Not much is known about the groundwater resources in this area, as there is little demand for groundwater and hence few groundwater investigations have been carried out here. Groundwater exists in the lower river terraces of the Buller River and its tributaries. The township of Murchison has a reticulated water supply from two bores (5.6 and 8.2 m deep) located on the lowest terrace of the Matakitaki River. The yields from these bores are high and the water quality is good, with low levels of dissolved minerals and nutrients. The principal recharge to these aquifers would be seepage from the adjacent river and rainfall.

GROUNDWATER RESOURCES OF THE MARAHAU/ABEL TASMAN AREA

Not much is known about groundwater resources in this area, as a substantial part of the area lies within Abel Tasman National Park. Available data indicates that, due to the topography and geology of the area, the groundwater resources are very limited. Known groundwater resources occur in the valley floors of the Marahau River, a catchment at the southern end of the area. The aquifer here is unconfined and about 12–18 m thick (Stevens 1996). The quality of groundwater from the aquifer adjacent the river is better than its quality at the margins: water here has elevated concentrations of iron and manganese, and some shallow wells show bacterial contamination. The bacterial contamination is attributed to the area being unserviced by any sewerage system, with all residents depending on septic tank disposal systems.

REFERENCES

DICKER, M.J.I.; FENEMOR, A.D.; JOHNSTON, M.R. 1992: Geology and Groundwater Resources of the Waimea Plains, Nelson, New Zealand Geological Survey Bulletin 106, DSIR Geology & Geophysics, Lower Hutt, New Zealand, 59 p.

DOYLE, M.; EDGAR, J. 1998: There are no springs in the water balance. Meteorological Society of New Zealand and New Zealand Hydrological Society Joint Conference - Abstracts. University of Otago, Dunedin, New Zealand, p 27.

EDGAR, J.E. 1998: Hydrogeology of the Takaka Valley. Unpublished MSc thesis, University of Canterbury, Christchurch, New Zealand.

FENEMOR, A.D. 1988: A Three-Dimensional Model, for the Management of the Waimea Plains Aquifers, Nelson. Publication No.18 of the Hydrology Centre, Dept of Scientific & Industrial Research, Christchurch, New Zealand, 133 pp.

MUELLER, M. 1987: Takaka Valley Hydrogeology (Preliminary Assessment) - Unpublished Report Prepared for the Nelson Catchment and Regional Water Board, Nelson, New Zealand, 70 pp.

MUELLER, M. 1992: Geohydrology of the Takaka Valley. Unpublished report prepared for the Nelson-Marlborough Regional Council, Nelson, New Zealand, 32 pp.

ROBB, C.A. 1999: Groundwater Model of the Motueka/Riwaka Plains Aquifer System. Report prepared for the Tasman District Council. Report No 2325/1 Lincoln Environmental, Lincoln, Canterbury, New Zealand, 53 p.

STEVENS, G.J. 1996: The Water Resources of the Marahau Catchment, Tasman, New Zealand. Unpublished MAppSc thesis, Lincoln University, Canterbury, New Zealand.

THOMAS, J.T. 1989a: Hydrogeology of the Moutere Valley, Nelson, New Zealand. Unpublished MSc thesis, University of Canterbury, Christchurch, New Zealand. 342 p.

THOMAS, J.T. 1989b: Groundwater Investigations in the Moutere Catchment. Proceedings of the New Zealand Association of Soil and Water Conservation, Nelson, New Zealand. pp 19-26.

THOMAS, J.T. 1991a: Water Resources of the Moutere Catchment. Unpublished Nelson-Marlborough Regional Council Internal Report, Nelson, New Zealand, 8 pp.

THOMAS, J.T. 1991b: Water Resources of the Motueka/Riwaka Plains. Unpublished Nelson-Marlborough Regional Council Internal Report, Nelson, New Zealand, 15 pp.

THOMAS, J.T. 1994: Management of a Shallow Aquifer System in New Zealand - The Motueka/Riwaka Plains Case Study. The Institution of Engineers Australia & International Association of Hydrogeologist - Water Down Under 94. Adelaide, Australia, Vol 2, Part B: 627-633.

22

Marlborough

PETER DAVIDSON

INTRODUCTION

The Marlborough District is characterised by a diverse range of landforms from snow-capped mountains bounding the main divide to beaches clad in native bush in the Marlborough Sounds, and to broad alluvial river valleys on the dry east coast.

Maori and European settlement largely centred on the fertile alluvial plains and river valleys of the Wairau, Awatere, Rai/Pelorus, Kaituna, and Tuamarina rivers. The Wairau Plain is the largest, with a total area of some 20,000 hectares, but with an average annual rainfall of less than 800 millimetres is relatively dry. This contrasts with the Marlborough Sounds catchments, which can receive up to 2000 millimetres of rainfall per year (Fig 22.1).

All the main population centres of Marlborough are totally or partially dependent on groundwater. The main centre of Blenheim, with a population of around 20,000, is situated on the Wairau Plain. Picton and Havelock are also dependent on groundwater.

Irrigation is needed to offset high evapotranspiration in the summer months. Sources of irrigation water on the dry east coast are scarce over summer, as all but the Wairau, Awatere and Waihopai rivers are ephemeral. By contrast much of the Wairau Plain is underlain by an easily accessible and high-yielding alluvial aquifer that has been recognised and used since the nineteenth century.

In modern times nothing symbolises Marlborough more than the burgeoning wine industry, which has established an international reputation for producing quality wine. Mixed farming was the predominant land use in the Lower Waihopai, Awatere and southwest Wairau Plain in the 1970s. By the late 1990s, vineyards had replaced pasture as the principal land use in parts of these areas. These areas are frequently short of water.

The southwest Wairau Plain area is almost totally reliant on groundwater. The search for groundwater to irrigate vineyards has, since the early 1980s, contributed significantly to knowledge about the aquifer system. As many wells were drilled between 1985 and 2000 as in the whole period before 1985.

Today, the Wairau Plain aquifers supply all of the municipal requirements for Blenheim and the towns of Renwick and Woodbourne, together with most of the irrigation water. Many rural residents rely on individual wells for drinking and stock water. Groundwater is also used to augment summer municipal supplies for Havelock and Picton, and was their primary supply during the height of the 1997/98 drought.

Natural groundwater quality is generally high, with only isolated instances of pesticide or nitrate contamination and elevated levels of iron. For example, Blenheim's municipal drinking water is currently pumped direct from the aquifer into homes. In addition many of the important spring flows around Blenheim, including Spring Creek, are serviced from groundwater.

The primary focus of this chapter is the Wairau Plain where agriculture, industry and the human population are almost totally dependent on groundwater. The aquifers in the Wairau Plain will be described and their water quantity and water quality characteristics will be discussed. The known characteristics of aquifers in the Tuamarina, Rai, Pelorus, Kaituna, Upper Wairau, and Lower Awatere valleys will be summarised.

Davidson P. 2001: Marlborough. *In* Groundwaters of New Zealand, M.R. Rosen and P.A. White *(eds)*. New Zealand Hydrological Society Inc., Wellington. p427-440.

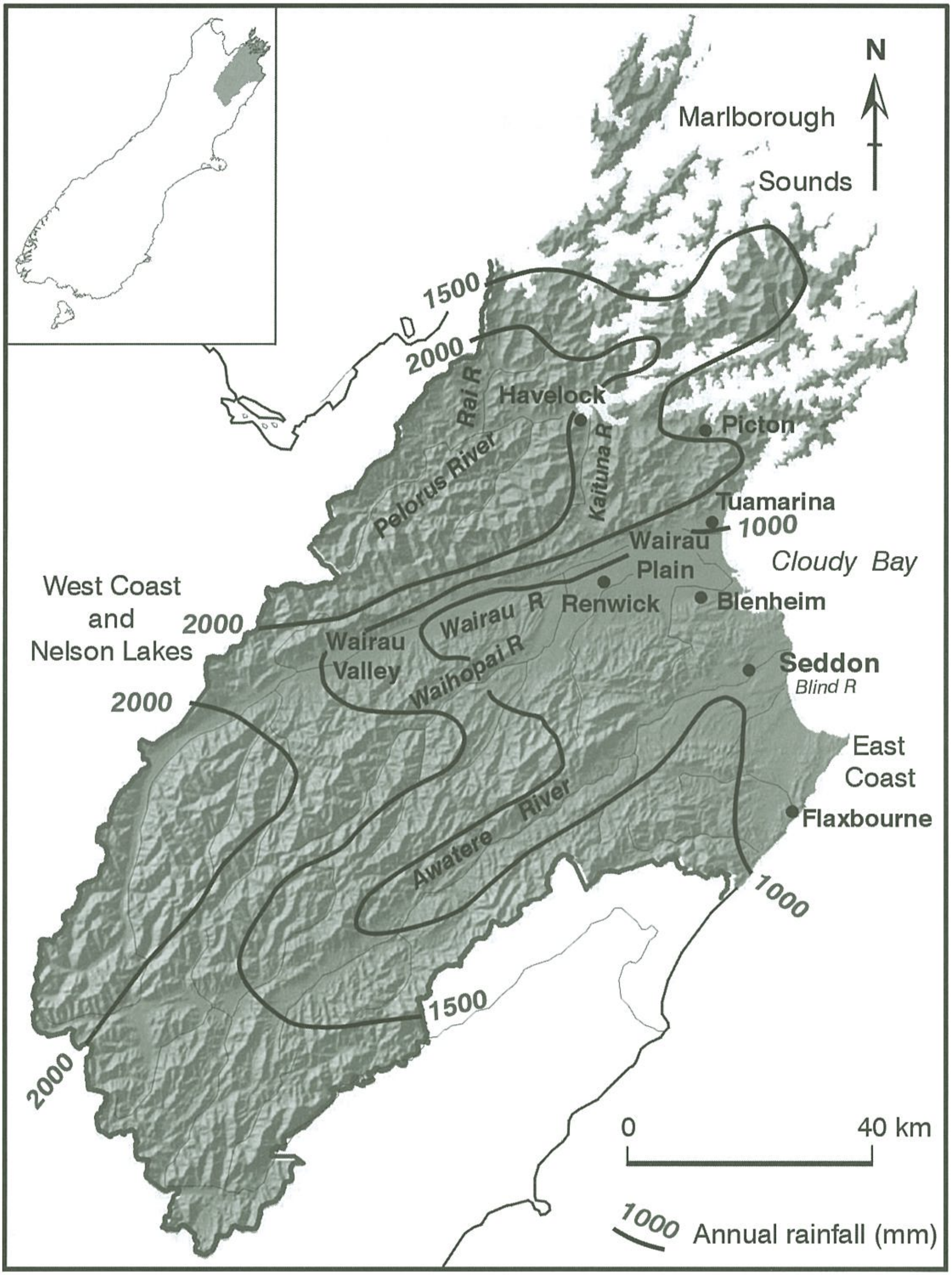


Figure 22.1 *Marlborough District - rainfall and regional setting.*

GEOLOGICAL SETTING

Marlborough is dissected by a series of major structural rifts, which have created fault angle depressions that have been in-filled with sediments and tilted to the north.

Successive glaciations in the Pleistocene period deposited the alluvial Wairau Plain. Glacial periods resulted in aggradation of unsorted outwash gravels by the Wairau River, while this material was re-worked and re-deposited further down-valley during warmer interglacial periods. Sea-level rise inundated the coastal area and deposited marine clays that act as aquifer capping layers. Brown (1981) recognised a series of five alluvial formations and correlated these with the stratigraphic units defined by Suggate (1965).

WAIRAU PLAIN AQUIFERS

The diverse group of aquifers underlying the Wairau Plain are important to the local communities and the major Wairau Aquifer is of national significance due to its high yield and size.

The Wairau plain can be divided into a relatively high-yielding northern sector and a relatively low-yielding zone south of Woodbourne. The northern zone is considered to be a single interconnected aquifer referred to as the Wairau Aquifer (Fig 22.2). The southern area is more complex and consists of a group of aquifers known collectively as the Southern Valleys aquifers (Fig 22.2). Other aquifer systems are the Deep Wairau Aquifer and Rarangi Shallow Aquifer.

The Wairau Plain aquifers support the largest water demands, and therefore are the focus of groundwater management. A network of seventeen automated monitoring wells provide continuous aquifer pressure records that are used as the primary barometer of aquifer health.

WAIRAU AQUIFER

Introduction

Most of the northern Wairau Plain area of around 15,000 hectares is underlain by the Wairau Aquifer (Fig 22.2). There are currently few limitations on water use for residents or irrigators living over the Wairau Aquifer. The physical and chemical characteristics of the aquifer are reasonably well known because of a long history of use and a relatively simple structure (Marlborough Catchment and Regional Water Board 1988).

Hydrogeology

A combination of highly permeable alluvial sediments, and the presence of the perennially flowing Wairau River, result in a large natural reservoir with a large water storage.

While there are periods of extreme low flow, such as in March 1973 when the Wairau River flow at Tuamarina fell to 3 m^3/second, catchment areas near the western boundary of the Marlborough region ensure reasonably reliable flows. The permeable sediments hosting the aquifer exist by virtue of the Wairau River reworking and re-depositing older glacial outwash material (Brown 1981).

The behaviour of wells close to the Wairau River channel is largely governed by river flow, and their response to recharge events is similar to that of a river hydrograph. For example, most of the increases in groundwater level at Well 398 located 1000 m south of the river channel are associated with increases in river level of the Wairau River (Fig 22.3).

Flow gaugings show that northwest of Renwick (Fig 22.2) the channel consistently loses around 7 m^3/second of water to the underlying aquifer. Discharge of the Wairau River to groundwater is implied by piezometric contours (Fig 22.4). However, much of this flow does not reside permanently in the aquifer. As much as 4.5 m^3/second flows out to sea via a belt of springs that rise east of Woodbourne and include Spring Creek (Taylor et al. 1992).

The aquifer is generally unconfined west of Woodbourne (Fig 22.5) and is fully confined seaward of Blenheim by Pleistocene marine sediments. The series of aquifers underlying Christchurch does not appear to the same extent under the Wairau Plain. Brown (1999) suggested that the Wairau River had eroded most of the earlier part of the sequence, leaving a remnant along the southeastern edge of the Wairau Plain.

Aquifer levels are, year round, commonly artesian in the confined coastal area. The

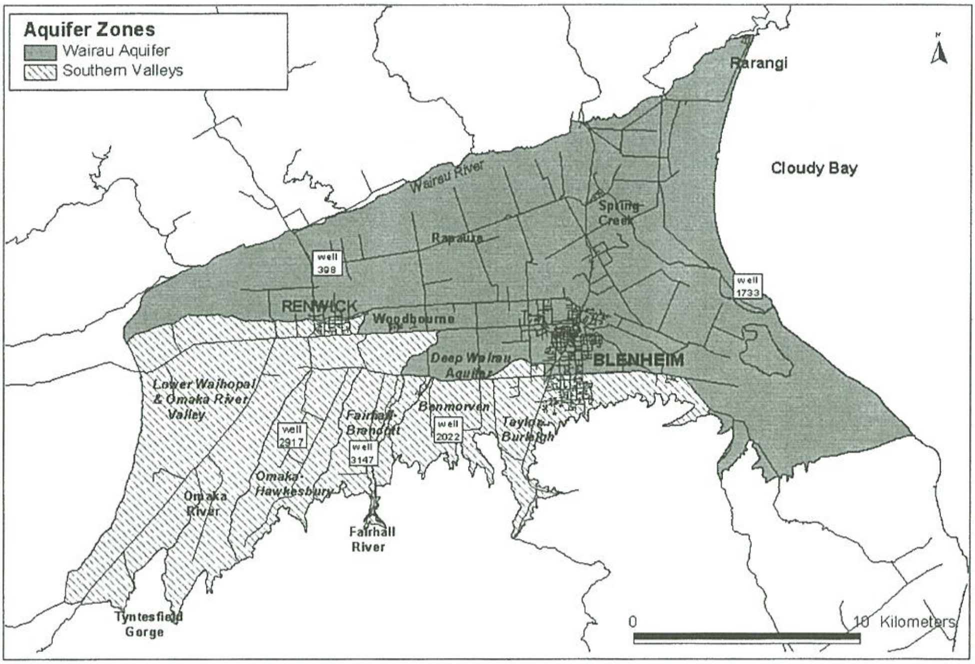


Figure 22.2 *Wairau Plain aquifers.*

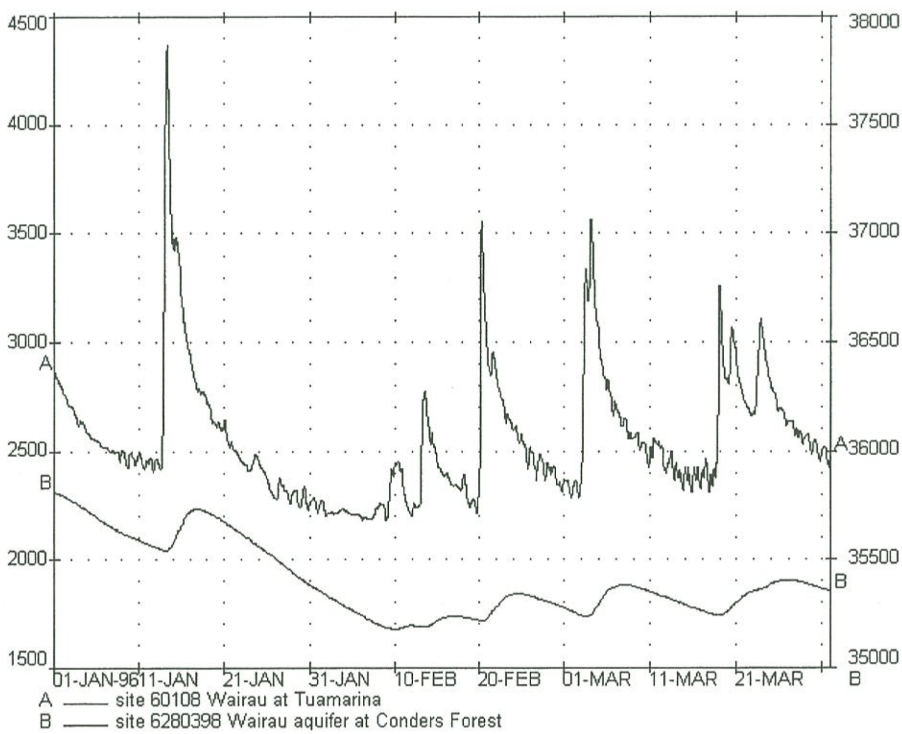


Figure 22.3 *Groundwater level in Well 398.*

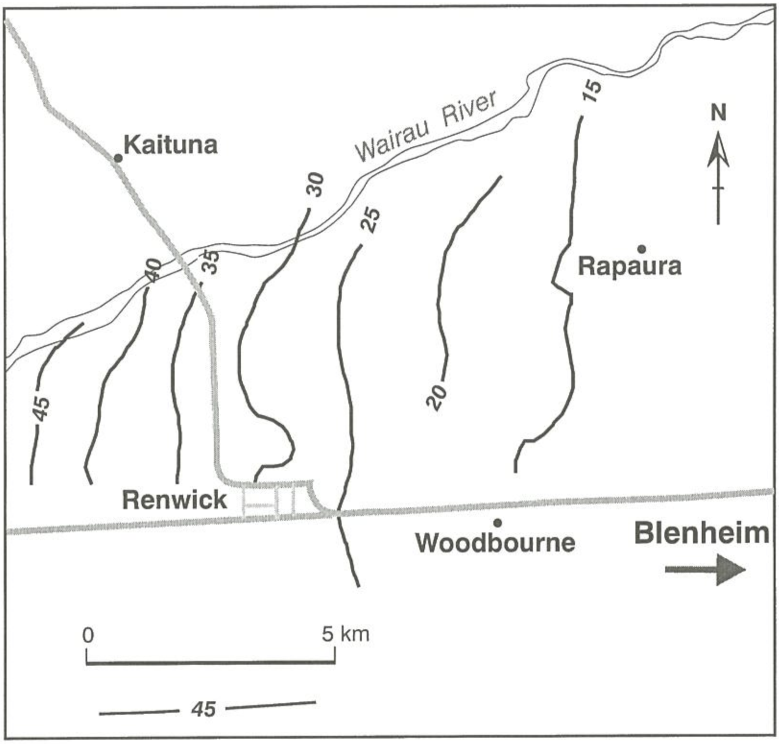


Figure 22.4 *Piezometric levels in the Wairau Aquifer, May 1988.Figure 22.5 Structure of the Wairau Aquifer.*

greatest summer decline in groundwater level occurs at Woodbourne where levels drop by 15 m between winter and summer. A net decline of 0.5 to 1.5 metres due to pumping and associated land-use changes is suggested by groundwater level measurements since the early 1970s. This is supported by anecdotal evidence of reduced spring flow, and a shift to submersible-type pumps in the Rapaura area since the 1940s. Aquifer transmissivities vary from low to very high, depending on seasonal conditions and proximity to the Wairau River, with values of 500 to 10,000 m^2/day.

The southern extremity of the Wairau Aquifer is defined by the recharge influence of the Wairau River. This varies seasonally, depending on the relative contribution of the Wairau River, as compared with sources of recharge to the south such as the Fairhall and Omaka Rivers.

Wells tend to be about 15 metres deep in the unconfined zone, but up to 50 metres deep in the coastal confined zone, with individual yields of around 15 m^3/hour or greater.

Water quality

Given the high rate of Wairau Aquifer through-flow, it is not surprising that its groundwater chemistry is very similar to that of Wairau River water. Even near the coast in the centre of the valley, where groundwater may be several decades old, the composition of water has not evolved far from its dilute Wairau River state (Close 1999). Groundwater on the northeastern and southeastern peripheries of the Wairau Plain shows the effects of stagnant flow, with a transition to sodium-chloride-bicarbonate type water.

The Durov plot (Fig 22.6) shows a range of Wairau Plain groundwater compositions, with the younger Wairau Aquifer water being characterised as calcium-bicarbonate type (Close 1999). Samples from the unconfined, semi-confined and confined zones form a tight clus-

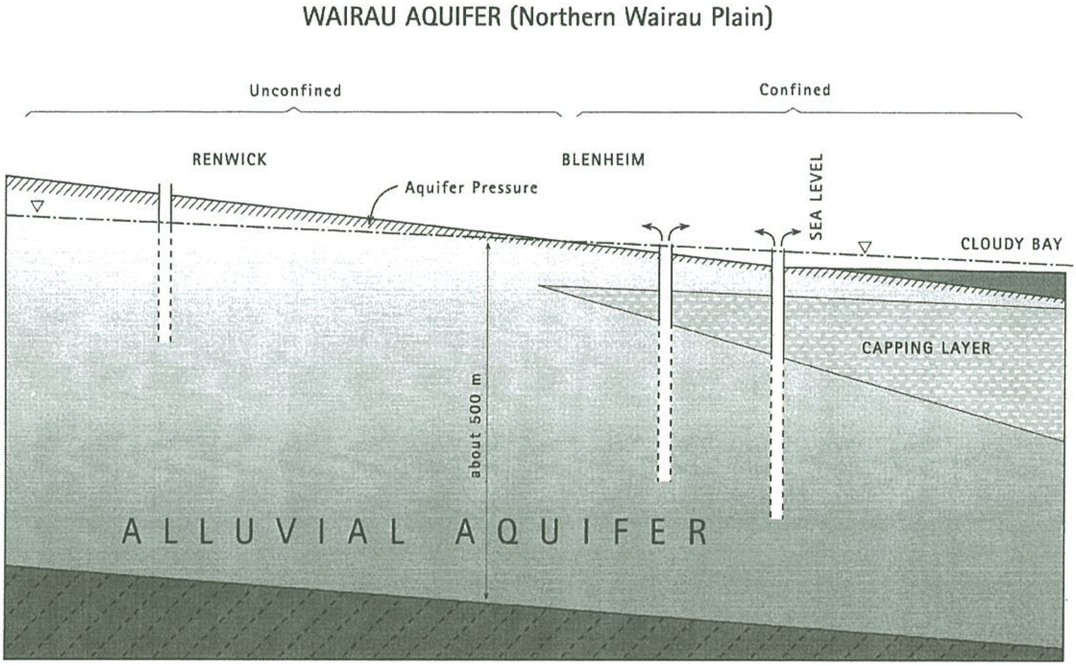


Figure 22.5 *Structure of the Wairau Aquifer.*

ter on the conductivity plot. Nitrates and pesticides are low in concentration which probably reflects the high rate of aquifer flow. High flow rates will tend to flush out any surface contaminants.

SOUTHERN VALLEYS AQUIFERS

Introduction

The southwest Wairau Plain, with its khaki-coloured hills and dry river beds, is short of irrigation water in summer but has recently attracted intensive grape plantings. Groundwater is the only reliable source of summer irrigation water and it was under pressure during the 1997/98 drought. Aquifers in the Southern Valleys include the Brancott, Fairhall River Gravels, Omaka River Valley, Omaka-Hawkesbury, Benmorven, Taylor–Burleigh, and Deep Wairau (Fig 22.2). Groundwater is sufficient for domestic and stock water supplies. Relatively low well yields mean that multiple wells are often required for a vineyard irrigation.

The area is no stranger to controversy, because of water shortages, with a history of water management problems and hearings. Knowledge of the local aquifers has been, until recently, inadequate to define sustainable limits. All major groundwater abstractions are now metered.

Hydrogeology

The Southern Valley aquifers lack the permeable formations and perennial sources of recharge. Up until the late 1980s, the well depth generally quoted for an irrigation supply was 35 metres below ground level. A demand for greater reliability has resulted in a search for deeper sources, with most new production wells being at least 60 metres in depth, while several have exceeded 200 metres.

Static water levels in the deeper wells tend to increase with increasing depth and provide the basis for separating the gravel sequence into four aquifer layers (Fig 22.7). The shallow layers are relatively well defined but little is known about the deeper layers.

Aquifer yield is low, with measured transmissivity values generally less than 30 m^2/day. A spaghetti-like geometry of the paleo-channels results in aquifers which exhibit multiple boundaries during testing. A

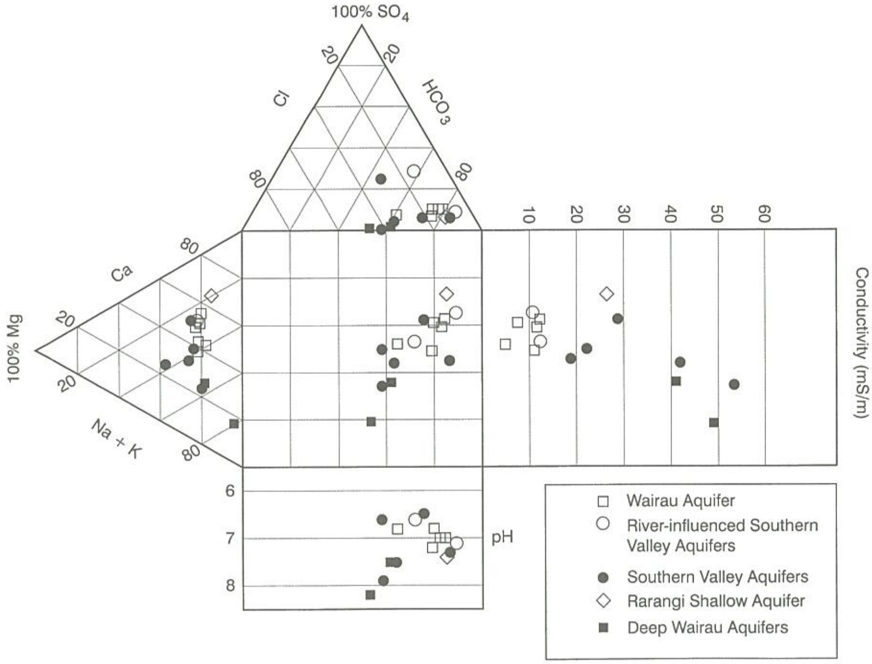


Figure 22.6 *Durov plot of Wairau Plain groundwaters.*

recent review of aquifer results suggests a degree of anisotropy with a bias from west to east or southwest to northeast (Russell 1999b).

Most aquifers are semi-confined or confined with the Benmorven Aquifer exhibiting the greatest degree of confinement. Storativity values, between $4x10^{-3}$ to $5x10^{-5}$, reflects this.

Environmental isotope results suggest that recharge originates from local runoff and rainfall. Taylor et al. (1992) showed that flow between individual valleys such as the Omaka-Hawkesbury and Fairhall-Brancott was likely. Discharge from the aquifers flows into the Wairau Aquifer or escapes to the surface as spring flow.

The southern boundary of the Southern Valley aquifers is marked by outcropping greywacke. However, the northern boundary is less obvious where it coalesces with the Wairau Aquifer. A 3-dimensional representation through the Wairau Plain (Fig 22.8) shows the Southern Valleys aquifers fan deposits extending from the southern ranges and interfingering with the Wairau Plains aquifers.

Historically the Southern Valleys aquifers

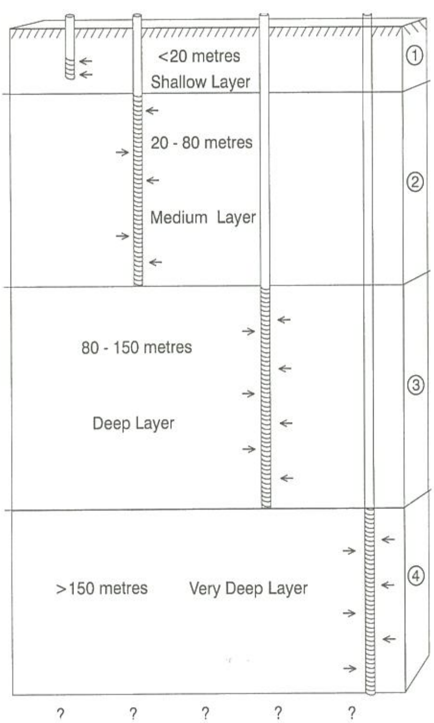


Figure 22.7 *Vertical aquifer layers - Southern Valleys aquifers.*

have been separated into a series of individual aquifers whose boundaries have been defined in terms of surface features. Today an aquifer classification based on well yield is used (Fig 22.9) which more fairly reflects aquifer behaviour. The areas of highest yield are closest to the Wairau River.

Water quality

The water quality of the Southern Valleys aquifers is poorer than that of the Wairau Aquifer, with higher levels of chemicals. This is thought to reflect relatively sluggish flow and the occurrence of marine deposits at Benmorven. The groundwater has higher sodium, chloride and alkalinity levels than water from the Wairau Aquifer, and often has elevated levels of iron or manganese. Groundwater quality reflects the local geology and is more variable than that of the Wairau Aquifer.

A Durov plot (Fig 22.6) shows a range of Southern Valleys aquifers' groundwater compositions; they are classified as sodium-calcium-bicarbonate type (Close 1999).

Brancott Aquifer and Fairhall River Gravels Aquifer

The predominant landuse in the Fairhall-Brancott Valley is vineyards. The two aquifer systems underlying the area are the Brancott Aquifer and the Fairhall River Gravels Aquifer. Static aquifer pressures generally decline with depth below ground level at the southern end of the valley and the northern section has artesian flows.

Little was known about the extent or potential yield of the Brancott Aquifer. Average well depths were commonly less than 50 metres below ground level before the late 1980s, but today wells are often drilled to depths of 120 metres. The large Montana Wines Brancott Estate vineyard set a new trend in the early 1980s by transporting water into the area via a pipeline from the Wairau Aquifer, rather than relying on local resources.

The Fairhall River Gravels Aquifer is a shallow unconfined system within the thin veneer of permeable gravels surrounding the Fairhall River. The key to this water resource is the Fairhall River. Sufficient water exists for all users when the Fairhall River is flowing. However, the water storage in the gravel is quite limited and can sustain irrigators for only short periods. The groundwater is fully allocated and was hit by the 1997/98 summer drought, when it disappeared and some locals resorted to trucking water.

Drainage of the gravels (Fig 22.10) during the height of drought conditions, for example over the 1997/98 summer for monitoring well 3147 (Fig 22.2), causes declines in groundwater levels.

Omaka River Valley Aquifer

This alluvial system underlies an irrigable area of some 1500 hectares, extending from Tyntesfield Gorge to Woodbourne (Fig 22.2). It is essentially a larger version of the Fairhall River Gravels system with a wider floodplain and greater groundwater storage.

An unconfined aquifer extends to a depth of around 10 metres. The boundaries of a deeper layer are uncertain. Drilling in this area has discovered low-yielding aquifers at 267 metres below ground level, although these may not be directly linked to the Omaka River.

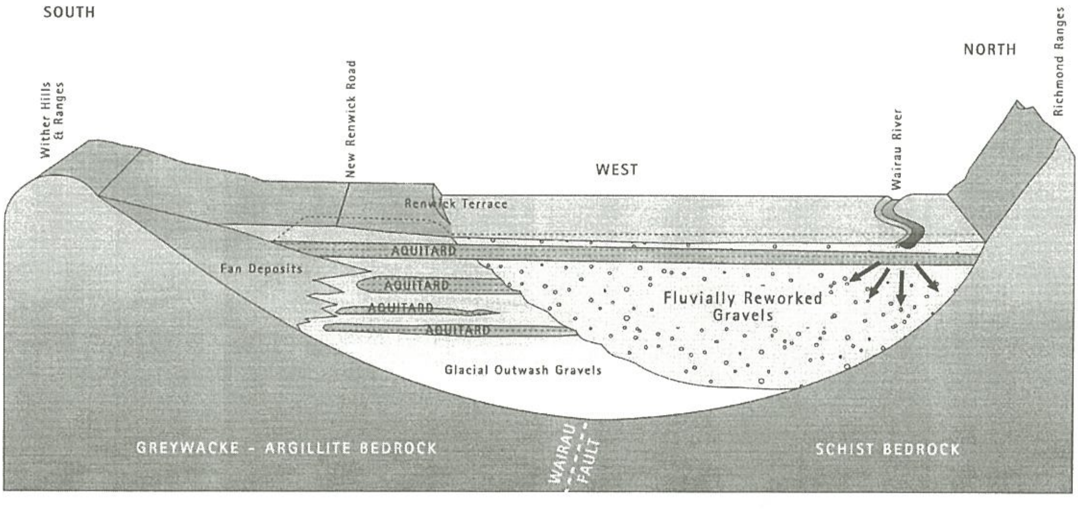
Recharge to the deeper layers occurs only when Omaka River flow is greater than about 500 L/s at Tyntesfield Gorge. Groundwater levels are sensitive to drought conditions, for example a voluntary reduction in irrigation water use occurred during the 1997/98 drought.

A numerical model of the aquifer assessed the volume of water stored in the gravels (Callander 1994). An interim allocation limit of 170 L/s was approved by Marlborough District Council in 1994, based on the estimated 5-year, 7-day low flow of around 130 L/s and the water storage in the aquifer.

Omaka-Hawkesbury Aquifer

The Omaka-Hawkesbury Aquifer area underlies the 1000 hectare Omaka-Hawkesbury Valley southwest of Renwick.

The district's deepest exploratory well (2917, Fig 22.2), was drilled in this area by Marlborough District Council to determine if economic aquifers exist at depth. This well was



COASTAL ZONE OF WAIRAU PLAIN

Figure 22.8 *Section across the Wairau Plain near the coast.*

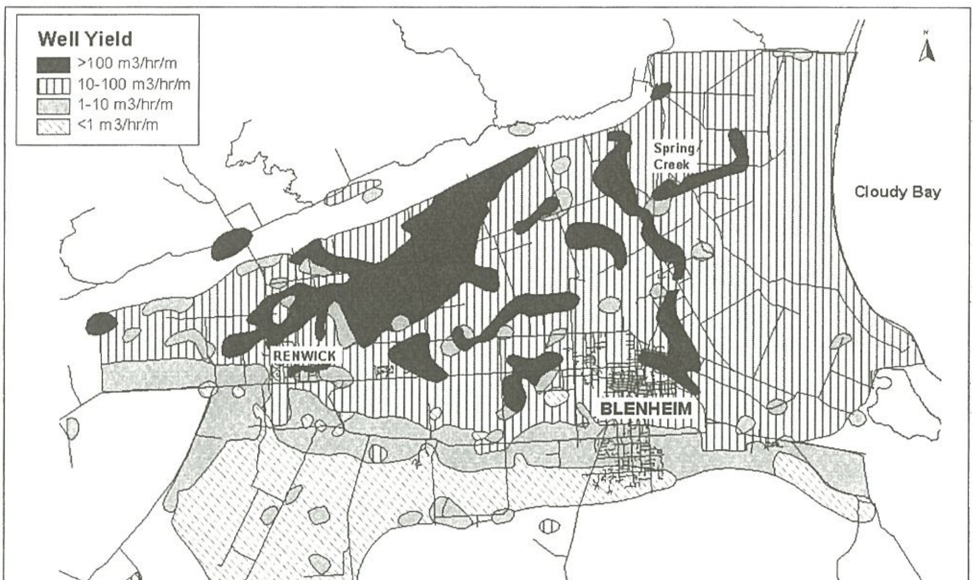


Figure 22.9 *Well yields – Wairau Plain.*

drilled to a depth of 400 metres below ground level but intersected no new irrigation sources.

Piezometric maps derived from 1995 aquifer pressure surveys of this area showed the Southern Valleys aquifers consist of multiple layers. Significant declines in water levels result from pumping this aquifer. However, groundwater levels do recover to their pre-irrigation season values each spring which suggests present abstraction rates are in balance with recharge.

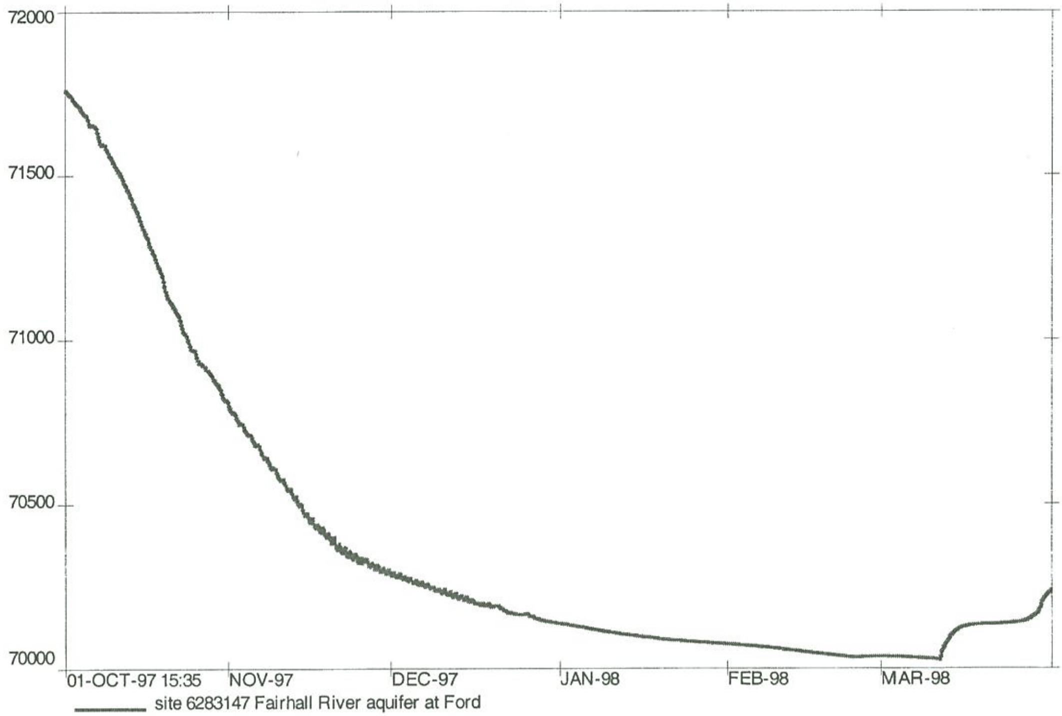


Figure 22.10 *Declining groundwater levels in the Fairhall River Gravels Aquifer caused by drainage of gravels.*

Benmorven Aquifer and Taylor-Burleigh Aquifer

The Benmorven Aquifer is unusual among the Southern Valleys aquifers, as it has a much higher degree of confinement and at least three separate zones, each with distinctive properties. For example, the range in groundwater conductivity and chloride across the Benmorven area is as great as for the entire Southern Valleys aquifers.

Water quality is poor which is a concern for residents, but less of a concern for crop irrigation. The first aquifer used for irrigation is the aquifer at a depth of 30 metres. Groundwater at successively lower levels, down to current depths of over 100 metres were exploited as groundwater became scarcer. Each aquifer is associated with a confining layer. Groundwater levels increase with increasing depth (Marlborough District Council 1998) in the area.

Artesian pressures of up to 15 metres above ground level occur, although these typically decline over time with pumping. Aquifer pressures appear to have fallen by around 5 metres in the most southern area since the first wells were drilled in the early 1970s.

The decline in aquifer pressure since 1997 (Fig 22.11) has been attributed to a series of dry years from 1997 to 1998 and the establishment of a new equilibrium as the various aquifer layers interact.

The Taylor-Burleigh aquifer is of little economic importance as the urbanised eastern zone is largely serviced by the Blenheim municipal supply, while groundwater in the western sector is limited and only sufficient to service domestic water supplies.

DEEP WAIRAU AQUIFER

A consequence of the 1997/98 drought was the failure of many wells and a search for more reliable sources of irrigation water. In many instances there was no alternative but to drill to greater depths, and at Fairhall a new series of aquifers was discovered at depths of 150 to 300 metres. A consequence of this deep drilling was a major advance in knowledge and a corresponding leap in water demand. Some saw the Deep Wairau Aquifer as the panacea for the water problems of the southwest Wairau Plain, given its apparent isolation and yield, but subsequent testing showed a link with shallower aquifers. Uncertainty as to whether an active source of recharge exists or whether the aquifer is blind has resulted in a cautious approach to its development.

Environmental isotope analyses showed the aquifer water was recharged around 20,000 years before present and originated from high altitude catchments feeding either the Wairau or Waihopai Rivers (Taylor 1999). The aquifer water has a distinctive chemistry, with higher sodium, alkalinity and chloride than the Southern Valleys Aquifer suite and a pH that is generally greater than 8. These properties, in conjunction with low nitrate levels, are consistent with older water that has had time to evolve and undergo chemical processes such as ion exchange and dissolution (Close 1999). Downhole flow measurements show the majority of the water enters the wells at depths generally greater than 150 metres, which supports the concept of a separate deep source of recharge (Russell 1999a).

Confining layers of marine sediments result in artesian pressures of up to 15 metres above ground level in the Fairhall area. The aquifer is unconfined or semi-confined to the west and aquifer testing shows interconnection between the unconfined, semi-confined, and confined aquifer.

RARANGI SHALLOW AQUIFER

Rarangi (Fig 22.2) is a small settlement in the northeast corner of the Wairau Plain that relies almost exclusively on the Rarangi Shallow Aquifer for its drinking water supplies, although it is partially underlain by the Wairau Aquifer to the south. The Rarangi aquifer is unconfined and permeable, and is thus susceptible to surface contamination, while overpumping could potentially lead to seawater intrusion.

Water quality is generally good, although there are pockets where naturally high levels of iron or manganese cause a problem. The Rarangi Shallow Aquifer is used for drinking water and for irrigation of the local golf course while the Wairau Aquifer is used to irrigate crops.

OTHER AQUIFER SYSTEMS

Tuamarina Valley

The high rainfall Tuamarina Valley (Fig 22.1) is a tributary of the Wairau River which flows south from near Picton and is predominantly a dairying area. Groundwater is commonly used for milking shed, stock and drinking water purposes, and as a supplementary supply for the township of Picton. Local groundwater systems can be divided into a shallow aquifer layer associated with the Tuamarina River, which occurs everywhere (Brown et al. 1985), and a deeper confined aquifer underlying the northern part of the valley.

The shallow layer is high yielding, although it is susceptible to surface contamination due to a high water table and local agricultural land use. The deeper aquifer, which commonly exhibits artesian pressures, contains older water that is generally of poorer quality.

Rai, Pelorus and Kaituna Valleys

Water demand in the Rai, Pelorus and Kaituna valleys (Fig 22.1) is relatively low because of the relatively high rainfall. Groundwater and surface water provide for the water needs in these areas. Supplementary irrigation is needed in times of severe drought when local rivers are generally used.

The Havelock Aquifer in the Kaituna Valley is used as a backup for the local municipal supply and provides water to the mussel processing industry. This aquifer is being closely monitored as it is poorly understood, is commercially pumped, and could be prone to salt water intrusion.

Several wells drilled in the middle of the Kaituna Valley as part of a mineral exploration program in 1995 encountered an aquifer at a depth of around 40 metres. The aquifer is associated with a mineral assemblage peculiar

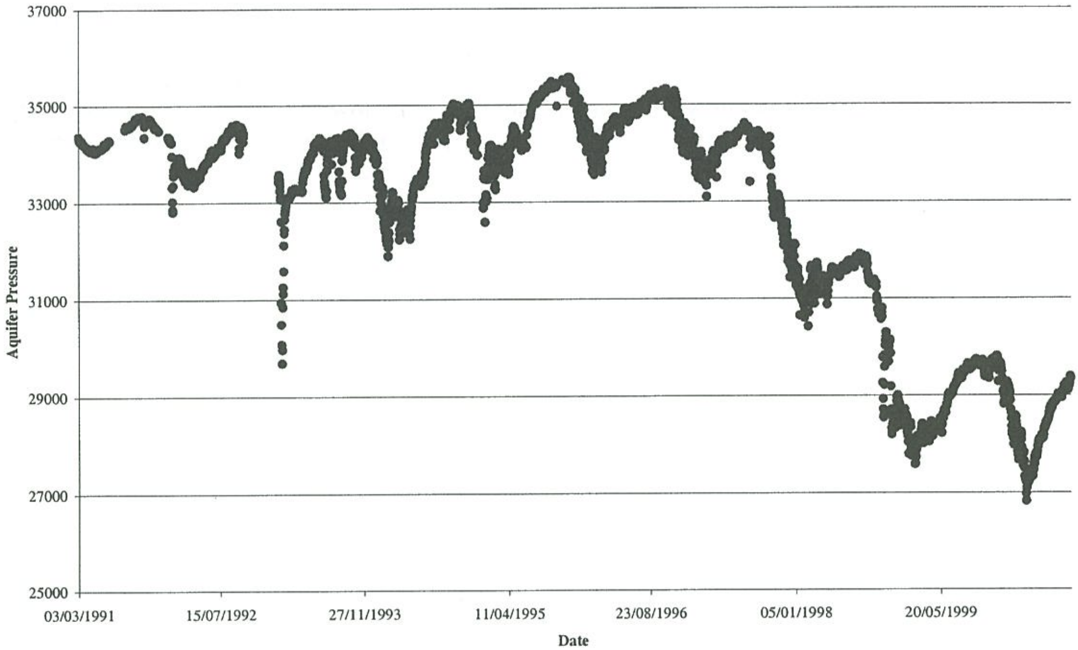


Figure 22.11 *Benmorven Aquifer groundwater levels in Well 2022 (Fig 22.2).*

to the modern day Pelorus Group. This indicates that the historic flow direction of the Kaituna River was the opposite to what we see today (Mortimer and Wopereis 1997).

Upper Wairau Valley

The Wairau Valley is the westward extension of the Wairau Plain towards the western boundary of the Marlborough District (Fig 22.1). Little is known about the extent of the groundwater resource, except that the Wairau River is the principal source of recharge for the area north of the West Coast Highway. Groundwater is the preferred water supply for reasons including the potential damage to river intakes by floods.

The Wairau Fault bisects the Wairau Valley and water chemistry measurements suggest the fault influences local water flow patterns and supports the idea of tectonically-related seepage.

A distinction is generally made between groundwater resources occurring above and below the river terrace near the West Coast Highway. Drilling results suggest a relatively high-yielding shallow aquifer layer associated with the Wairau River and a low-yielding medium-depth layer underlying the more southerly terraces. The existence of deeper sources of groundwater is uncertain, due to the lack of drilling, and merits investigation because groundwater demand is likely to increase in the future.

Lower Awatere Valley and east coast

Little is known about the existence of economic aquifers in the Lower Awatere Valley, Blind River and Flaxbourne areas (Fig 22.1), but it has been generally accepted that local geology precludes high-yielding deep aquifers. Until recently the easy accessibility of the Awatere River provided a disincentive to deep drilling, although this may change as the river becomes fully allocated.

Numerous shallow wells draw water from the alluvial terraces associated with the Awatere, Flaxbourne and minor rivers. Aquifer yields are low and reliability under drought conditions is uncertain, given the limited size of the host formations and their dependence on surface flow for recharge.

This area is attracting many new vineyard developments, especially in the Lower Awatere area, and the expansion is likely to spread further south in the future. Water is a limiting factor over summer and more information is needed for future management.

AQUIFER MANAGEMENT

The finite nature of the Wairau Plain aquifers has long been recognised, along with the potential adverse effects of over-pumping such as reduction of spring flows, seawater intrusion and land subsidence. To protect the aquifers from overuse, interim allocation limits were incorporated in the Wairau-Awatere Resource Management Plan. Allocations for most of the Southern Valleys aquifers are now approaching, or have reached, these limits. A comprehensive understanding of the Wairau Aquifer water balance has resulted in more precise estimates of safe yields for this system, and further water is available for allocation.

There is some uncertainty associated with the aquifer allocation limits. They were established in the mid 1990s and are being refined over time as understanding of the resource improves. The limits were derived using a combination of aquifer through-flow rates, seasonal aquifer storage and numerical simulation of pumping effects.

The introduction of water meters in the Southern Valleys Aquifers in the mid 1980s was an important development in aquifer management. Along with improving water use efficiency and ensuring compliance, records of consumption show that actual use is generally significantly less than allocation. Unfortunately water metering is not yet universal, and excludes most of the Wairau Aquifer.

While catchment or aquifer allocation is formalised in resource management plans, seasonal aquifer management, for example during the 1997/98 drought, depends on the regional well monitoring network to indicate short-term aquifer status. The importance of the network will increase in the future with the likely introduction of B-class groundwater allocation shares and the approaching full allocation of many aquifers.

Future initiatives to meet the demand for irrigation water are likely to involve a combination of water transport from the northern Wairau Plain, improved water efficiency and the harvesting of spring runoff. Surface sources of aquifer recharge are also being protected from depletion by setting limits to stream abstractions. As groundwater resources become scarcer and limits are approached, Marlborough District Council is attempting to manage local aquifer systems in conjunction with water user groups. For example, the coastal Wairau Plain residents are kept aware of the significance of salinity levels in the local early warning network. Updates of aquifer status, and individual and catchment consumption are circulated on a regular basis.

The region is approaching a crossroads in water management, with a growing deficit between natural supply and demand. Future groundwater management issues include the potential for seawater intrusion of the coastal Wairau Plain aquifers and the reduction of Wairau Plain spring flows. Modelling studies, and an expanded monitoring network, are being used to define environmental triggers for controlling usage in times of environmental stress. Stream depletion will become increasingly important as water harvesting becomes a more popular alternative to well drilling. Since this chapter was written, Marlborough has endured the worst drought on record, during the 2000/2001 period

REFERENCES

Brown, L.J. 1981: Water Well Data Northern Marlborough. New Zealand Geological Survey, Department of Scientific and Industrial Research. 126p.

Brown, L.J.; Cunliffe, J.J.; Taylor, C.B. 1985: Groundwater in Tuamarina Valley, Northern Marlborough, New Zealand Geological Survey, Geological Record 8, 64-70.

Brown, L.J. 1999: Southern Wairau Plain Deep Aquifers – Geology and Hydrogeology. Unpublished report. 10p.

Callander, P. 1994: Report on Numerical Groundwater Model for Omaka River Valley Resources and Management Evaluation. Pattle Delamore Partners Ltd, unpublished report. 13p.

Close, M. 1999: Deep Wairau Aquifer Investigation – Groundwater Chemistry Aspects. Institute of Environmental and Scientific Research. 20p.

Marlborough Catchment and Regional Water Board 1988: Water and Soil Resources of the Wairau – Volume 2 (J.J. Cunliffe, ed.). 105p.

Marlborough District Council 1998: Deep Wairau Aquifer Supporting Technical Document, unpublished report. 23p.

MORTIMER, N.; WOPEREIS, P. 1997: Change in direction of the Pelorus River, Marlborough, New Zealand: evidence from composition of Quaternary gravels. New Zealand Journal of Geology and Geophysics, 40: 307-313

RUSSELL, W. 1999a: Deep Wairau Aquifer - Downhole Flow Measurements. Woodward-Clyde, unpublished report. 64p.

RUSSELL, W. 1999b: Deep Wairau Aquifer - Pumping Test Review. Woodward-Clyde, unpublished report. 105p.

SUGGATE, R.P. 1965: Late Pleistocene Geology Of The Northern Part Of The South Island, New Zealand, New Zealand Geological Survey - Bulletin n.s. 77. 91p.

TAYLOR, C.B.; BROWN. L.J.; CUNLIFFE, J.J.; DAVIDSON, P.W. 1992: Environmental tritium and ^{18}O applied in a hydrological study of the Wairau Plain and its contributing mountain catchments, Marlborough, New Zealand. Journal of Hydrology (Amsterdam) 138. 269-319.

TAYLOR, C.B. 1999: Provenance, Age and Chemical Evolution of Groundwater in the recently discovered - Deep Wairau Aquifer, unpublished report. 15p.

23

Canterbury

LEN J BROWN

INTRODUCTION

The Canterbury region extends from the Clarence River to the Waitaki River and inland to the main divide of the Southern Alps (Fig 23.1).

In North Canterbury fault and fold bounded intermontane and coastal basin structures, including the Hanmer, Parnassus, Culverden and Waipara basins and the Kaikoura plain, contain Quaternary fluvial gravel aquifers. Further south, the Canterbury Plains were formed over the last 2 million years as rivers deposited erosion products from the actively uplifting Southern Alps, in a subsiding regional syncline. The plains are 160 km long, 50 km wide, and 8000 km^2 in area, and are formed by coalescing glacial outwash and alluvial gravel fan deposits. These are up to 600 m thick in the Ealing oil exploration well on the north bank of the Rangitata River and contain an extensive layered aquifer system. In South Canterbury, because of a less active tectonic environment than North Canterbury, there is less disruption and dislocation of early Quaternary, Tertiary and Cretaceous strata. Here regional aquifers comprise a wider range of rock and sediment lithologies, including schist basement, Tertiary quartz gravel, sandstone and limestone, and Quaternary gravel. At Banks Peninsula, the Miocene–Pliocene volcanic complex contains aquifers within zones of fracturing and jointing, pore spaces, cavities and rubbly layers between lava flows. Basement greywacke rock can contain groundwater in zones of jointing, fracturing and faulting, as demonstrated in the Arthur's Pass railway tunnel through the Southern Alps (Farr et al. 1919).

Canterbury's groundwater resources are one of New Zealand's most important in terms of contribution to the national economy. Canterbury groundwater allocations total 19% in volume of the total New Zealand consumptive water allocation and 66% of the total New Zealand groundwater consumptive allocation (Robb 2000). The aquifers throughout Canterbury are allocated to supply 96 m^3/s (Ettema, Environment Canterbury pers. comm.) and the groundwater resource has not been fully explored and prospected. This volume will increase as more groundwater supplies are proven to meet the increasing demand for water. Groundwater also sustains spring flows that are the source of coastal rivers, including the Avon and Heathcote rivers in Christchurch, which are scenic and tourist attractions. Groundwater-sourced springs and high water tables also form wetlands, which are important ecology habitats and of cultural significance to Maori.

NORTH CANTERBURY

Kaikoura Plain

The Kaikoura plain (Fig 23.1) is formed from last glaciation and postglacial fan deposits of the Hapuku, Kowhai and Kahutara rivers, and connects the Miocene siltstone and limestone Kaikoura Peninsula to the "mainland". The plain is underlain by fluvial gravels containing unconfined, semi-confined and confined aquifers. Miocene siltstone and mudstone, and greywacke form the basement. In the Kowhai area the Quaternary gravels are at least 84 m deep.

Piezometric contours, oxygen-18 isotope analyses and chemical analyses show that the groundwater is derived from the Kowhai River and streams with catchments on the southern slopes of Mt Fyffe, and from local rain. Groundwater flow in the unconfined and semi-confined aquifers is rapid, in contrast to flow

Brown L.J. 2001: Canterbury. *In* Groundwaters of New Zealand, M.R. Rosen and P.A. White *(eds)*. New Zealand Hydrological Society Inc., Wellington. p441-459.

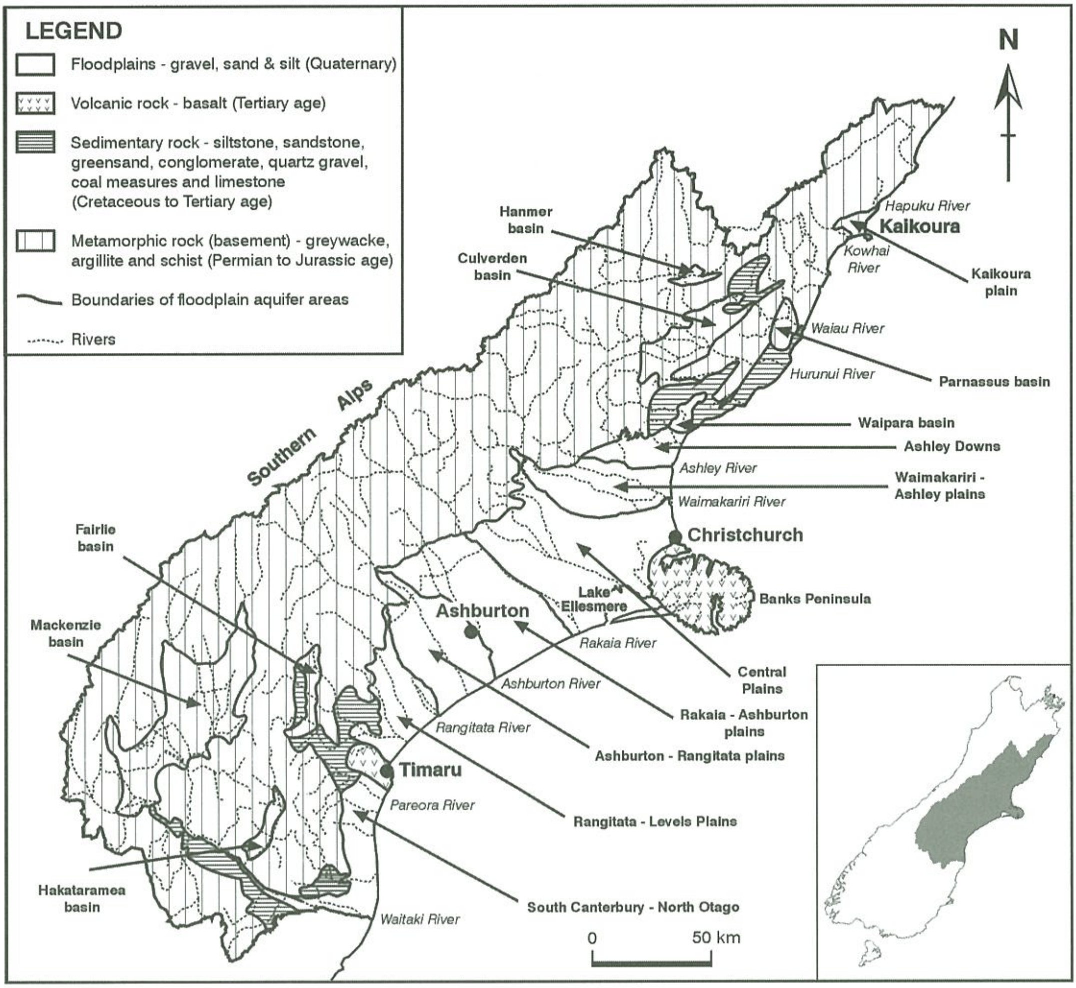


Figure 23.1 *Canterbury region with summary of geology and aquifer locations.*

in a confined flowing artesian aquifer to the north of the peninsula, where tritium analyses of groundwater indicate slow through flow rates of more than 30 years (Brown and Taylor 1974). The groundwater chemistry of the confined aquifer in the vicinity of the peninsula suggests interaction with groundwater derived from the underlying Tertiary sediments. The age and mineralisation of the groundwater suggest restricted outflow from the aquifer.

Seasonal water level fluctuations normally show high winter groundwater levels and low summer levels, in response to rainfall (Brown 1988). A few wells yield irrigation supplies (1500 m^3/day) and aquifer yields tend to decrease towards the peninsula in the north and increase towards the coast to the south of the peninsula. A crude water balance (Sheppard 1995) suggests that Kaikoura groundwater resources are underutilized. The shallow unconfined aquifer is potentially vulnerable to contamination should intensive dairy farming continue to expand on the Kaikoura plain.

Hanmer Basin

Groundwater, including thermal water, is present in Quaternary gravel aquifers in the "pull-apart" graben that forms the Hanmer basin (Clayton 1966). Gravity surveys suggest up to 850 m of sediment infills the southern

Figure 23.2 *Canterbury region and location of Environment Canterbury groundwater monitoring sites.*

and central part of the basin (Anderson 1987). The Hanmer thermal springs are a result of deep circulation groundwater heated within a basement fault zone. On the up throw side of the fault, wells encounter greywacke and thermal water 55 m below ground surface. A water well drilled on the down throw side of the fault penetrated 160 m of Quaternary sediments overlying greywacke basement (Brown 2000). Reliable groundwater supplies are obtained from shallow wells in the postglacial riverbed gravels of incised streams flowing north to south across the Hanmer basin. A few deep (>50 m) wells yield limited (10 L/s) groundwater supplies.

Parnassus Basin

The Parnassus basin is a warped synclinal basin extending from the Conway River to Gore Bay. The depth to greywacke basement in the axis of the syncline is about 1000 m (Hicks 1989). Tertiary age sediments overlie basement rock and form rolling hill country at the basin margins. Reverse movement on the Kaiwara

Fault has divided the basin into two sectors, with the Waiau River, the main river flowing across the basin, having been excluded from the southern Mina–Cheviot sector since the late Quaternary. As a result well-sorted late Quaternary gravels are absent and aquifers are low yielding in the southern sector. Groundwater flow is west to east; groundwater recharge occurs from local rain and from stream infiltration when there is surface flow, and groundwater discharges to springs and drains in the winter at the eastern margin of the basin. Domestic and stock water supplies are obtained from shallow wells, but maintenance of supply depends on local rainfall.

Shallow wells in the northern part of the basin adjacent to the Waiau River yield irrigation supplies with aquifer transmissivities up to 7700 m^2/d. Piezometric contours show recharge of the aquifers by the Waiau River in the western part of the basin and groundwater flow back to the Waiau River at the eastern margin. Flow net calculations indicate a Waiau River input to groundwater of about 570 L/s, and intermittent contributions from local streams, depending on local rain (Lawler 1988).

One groundwater management problem in the Parnassus basin is maintenance of water quality in the low transmissivity, rain recharged, shallow water table aquifer in the Mina–Cheviot sub-basin. There is also a need for test drilling in the Parnassus–Spotswood area to establish the extent and total depth of the high permeability aquifer for efficient groundwater allocation.

Culverden Basin

The Culverden basin, extending from Waikari to Waiau, is inferred to be a syncline from the attitudes of beds at its margin. Outcrop of basement greywacke at Rotheram suggest the structure may be more complex in the northeast (Field and Browne 1989). The greywacke basement is estimated to underlie the axis of the syncline at depths of over 1000 m (Hicks 1989). Tertiary sediments overlie the greywacke and outcrop at several localities (Gregg 1964), suggesting major fault dislocation of the Tertiary age sediments. Quaternary gravels are estimated to be a maximum thickness of 100 m (Close 1985). Groundwater is obtained from wells up to 30 m deep for farm domestic and stock water supplies.

Piezometric contours (Close 1985) suggest outflow of water from the Waiau River to groundwater in the Achray area, although flow gaugings along the Waiau River do not show any significant loss of surface flow (Bowden 1974). Groundwater flow is towards the Waiau River to the east of Isolated Hill and towards the Hurunui River in the center of the basin. In 1980 the Waiau Irrigation Scheme began operation and water from the Waiau River was fed down a network of water races in the area from Culverden north to the Waiau River. The general trend of declining groundwater levels during the summer followed by winter recovery was changed by recharge due to the irrigation (Weeber and Talbot 1984). Winter groundwater levels are now maintained during the summer irrigation season.

The availability of groundwater from aquifers underlying the Culverden basin has never been properly investigated and deep aquifers may provide irrigation supply in the areas not covered by the Waiau Irrigation Scheme. Groundwater pollution occurred at Culverden before the flood irrigation scheme was commissioned, when a combination of high water table levels and septic tank discharge contaminated private wells. A town supply well was drilled away from the town to avoid the pollution source (Bowden 1974).

Waipara Basin

The Waipara basin extends from Omihi south to Amberley and is a northern continuation of the regional Canterbury Plains synclinal structure (Hicks 1989). Quaternary uplift associated with folding and faulting has formed an aquifer system separate from the Canterbury Plains aquifers. Waipara basin water wells penetrate over 100 m of gravel overlying Tertiary sediments, including limestone (Loris 2000a). The gravels are correlated with last glacial (Burnham Formation) and penultimate glacial deposition (Windwhistle Formation) and unconformably overlie the Pliocene-Pleistocene Kowai Formation gravel (Wilson 1963). The Kowai Formation gravels have been dislocated by faulting, folding and erosion, the penultimate glaciation gravels have been tilted, and the last glaciation gravels are almost horizontal with minor fault dislocation. Well water levels show a seasonal pattern of summer low to winter high in response to rain and river flow (Brown and Weeber 1983). Domestic and stock water supplies are generally available from shallow wells. The highest yielding shallow wells are located in the present riverbeds and derive groundwater from permeable channels recharged by river flow infiltration.

Over the last decade the Waipara area has undergone major change in land use from dry land farming to viticulture, with an expanding area of grape production. This has increased demand for groundwater. Several deep wells (>100 m) have been drilled and some of these have been successful in locating gravel aquifers supplying enough water for grape irrigation, although transmissivities are low (maximum of 90 m^2/d). The deepest and highest yielding well in the basin is 160 m deep with a 40 m length screen and yields 22 L/s from Kowai Formation gravel (Loris 2000b). Groundwater management problems include the need to determine the extent of the aquifers (including limestone) and to determine groundwater recharge processes, so that the sustainable yield of the groundwater can be established.

BANKS PENINSULA

On Banks Peninsula, the groundwater within the volcanic rocks of the Miocene-Pliocene craters is important, as it provides water supplies for stock and domestic use during periods of prolonged drought (Parker 1989; Sanders 1986). Wells and springs are the source of water for several small communities (e.g. Wainui and Governors Bay), and supplement the Akaroa town supply (Sanders 2000). The success of wells depends on their penetrating aquifers within fractured basalt lavas. Transmissivities of wells range from 1.8 to 14 m^2/d. On the Canterbury Plains adjacent to the Lyttelton crater, from Redcliffs to Lake Ellesmere, wells encounter groundwater that is more mineralised and of higher temperature than the groundwater in the adjacent Canterbury Plains (Brown and Weeber 1994).

CANTERBURY PLAINS

New Zealand's largest alluvial plain is the Canterbury Plains; here sediments infill a regional synclinal structure that extends for over 200 km from Waipara to the Waitaki River (Hicks 1989). Geophysical surveys have delineated folding and faulting of basement greywacke rock, with ridge and trough structures forming sub-basins infilled with sediment up to 2500 m deep beneath the Canterbury Plains (Hicks 1989). Miocene to early Quaternary volcanic vents intrude the sediments to form crater complexes (Banks Peninsula), intrusions (Burnt Hill) and flows (Timaru and Geraldine). Over the 2 million years of the Quaternary period alternating cold and temperate climate cycles, uplift of the Southern Alps and slow subsidence of the syncline to the east, have resulted in the formation of a sequence of layered gravel aquifers and interbedded aquicludes and aquitards.

For discussion the Canterbury Plain's aquifers are grouped on a geographic basis into sectors bounded by major rivers (Fig 23.1).

Ashley Downs

Ashley Downs is the North Canterbury area between the Kowai and Ashley rivers. The Ashley Downs and the coastal plain were formed by the same geological processes as the plains to the south, but there has been more tectonic uplift in this area. On the Ashley Downs, surfaces correlated with the Hororata Formation (Nemonan glaciation, 350 – 380 000 years ago) are uplifted, tilted and dissected by local streams to produce downland topography. Beneath the coastal plain wells penetrate the aquifer–aquiclude sequence of the Christchurch artesian system (Brown and Wilson 1988).

On the Ashley Downs domestic and stock water supplies are generally available from dug and drilled wells tapping gravel aquifers within late Quaternary glacial deposits and the Kowai Formation. Well water levels show a seasonal trend of summer low to winter high in response to rain and river flow (Brown and Weeber 1983). Piezometric contours indicate groundwater flows from Ashley Downs toward the southeast (Bowden 1982).

On the plains adjacent to the Ashley River, piezometric contours show outflow from the river into shallow gravel aquifers in the postglacial Springston Formation floodplain (Brown 1977). The Ashley River differs from other major Canterbury Plains rivers in that its low flow normally occurs in summer (February), rather than in autumn and winter for rivers with alpine catchments. Summer pumping from wells in the river recharged shallow aquifer increases recharge from the river and reduces river flow (Callander 1988). Saltwater Creek lagoon and its wetlands are fed by springs, streams and drains maintained by Ashley River derived groundwater. The impact of summer irrigation pumping from shallow wells on surface water bodies is thus an important consideration in management of the groundwater of the Canterbury Plains adjacent to the Ashley River.

Groundwater recharge sources and flow rates for the confined aquifers of the Christchurch artesian system north of the Ashley River have not been investigated. Well logs confirm the typical plains coastal depositional pattern, with interfingering interglacial marine fine sediment deposits (aquicludes) and fluvial gravels (aquifers). Also the channeling of the eastward flowing groundwater into gravel aquifers with water pressure increasing with depth is observed to depths of at least 150 m at Leithfield Beach, where the Wainoni Gravel aquifer occurs. Because this northern margin of the Christchurch artesian system is remote from river recharge sources, there is potential for aquifer stress from excessive local abstraction, including abstraction south of the Ashley River. This may produce declining artesian heads, changes in groundwater chemistry or even seawater intrusion. Sustainable yield needs to be investigated for the artesian aquifers.

Waimakariri – Ashley plains

This sector of the Canterbury Plains covering about 1000 km^2 is bounded by the Ashley River in the north and the Waimakariri River to the south, and includes the local Cust and Eyre rivers, which maintain intermittent flow in courses across the plains depending on local rain. Hicks (1989) identifies a basin structure underlying the plains and deepening from the north, west, and south towards the Waimakariri River mouth, where the greywacke basement is more than 2 km deep. Here the overlying sediments, including Quaternary deposits, could be at their deepest in North Canterbury. Greywacke remnants protrude through the plains surface at Waimakariri Gorge and View Hill, and Tertiary age volcanics crop out at View, Burnt and Starvation hills. The aquifers underlying the Waimakariri-Ashley plains are typical fluvial heterogeneous aquifers, with well yields and aquifer transmissivities that vary considerably over short distances and with aquifer depth.

Large tracts of the inland Waimakariri–Ashley plains away from the Eyre and Cust river flood plains are short of water (Sanders 1997), with well drilling to date suggesting the aquifers will provide only enough water for stock and domestic water requirements. Deeper drilling may locate higher yielding aquifers. Also a water race provides Waimakariri River water for irrigation for a 110 km^2 area of this sector of the plains. Wells tapping water-table and deeper semi-confined aquifers on the Eyre and Cust river floodplains, and on the plains from Fernside south to Eyreton, can generally supply sufficient water for irrigation. These aquifers are recharged by the local rivers and by rain. The Eyre River rarely flows over its entire course and can be dry for several seasons. This results in declining water levels and diminished yields from wells.

Of the major rivers bounding this plains sector, the Ashley and the Waimakariri, the Ashley River's contribution to groundwater recharge is most significant. The aquifers recharged by the Ashley form a wedge shaped zone extending from Fernside to Woodend; they are unconfined to semi-confined in the Fernside area and confined further east. Flow gauging of the Ashley River indicates a flow loss of 2.5 m^3/s between the Makerikeri River confluence and the Rangiora road bridge (Bowden 1982). Flow gaugings and piezometric contours show the Waimakariri River contributing 1.5 m^3/s to groundwater on the north bank in the vicinity of Clarkville (Pattle Delamore Partners 1993). The Waimakariri River contribution is confirmed for shallow and deep aquifers in the Kaiapoi area by groundwater oxygen-18 analyses (Taylor et al. 1989).

At the boundary between the unconfined and confined aquifer in the Ohoka–Eyreton area, spring fed streams contribute to the Kaiapoi River, which occupies a former north branch of the Waimakariri River. In summer 1998, following an extended drought with no flow in the Eyre River since winter 1997, declining spring flows in this area resulted in low flow in the streams and fish strandings (Sanders 1997). A crude water balance model for the coastal artesian aquifer system of the Waimakariri–Ashley plains sector, estimates annual offshore leakage of 100 x 10^6 m^3 with annual abstractions of 40 x 10^6 m^3 (Pattle Delamore Partners 1993).

Groundwater chemistry varies within the aquifer groups of the Waimakariri–Ashley plains (Brown et al. 1984). In the confined aquifers of the Christchurch artesian system south of the Ashley River, groundwater has high chloride, iron, manganese and dissolved carbon dioxide levels (Bowden 1982). The water quality improves towards the south, where recharge from the Waimakariri River predominates. Elevated concentrations of dissolved carbon dioxide also occur in localized areas including Rangiora, leading to slightly corrosive acidic water. The Rangiora town water supply is treated with hydrated lime to neutralize the water.

Groundwater in shallow unconfined aquifers, where rain is the source of recharge, is vulnerable to contamination from animal wastes and septic tank effluent. Subdivision of farms into smaller units is increasing land use and settlement. Sanders and Lovell (1999), reporting on low spring flows in the Ohoka-Eyreton area during the 1997-98 drought, note that the first indicator of possible aquifer stress will be a decline in the spring flows at the unconfined - confined aquifer boundary. This suggests prolonged drought on this sector of the plains will affect the coastal Christchurch artesian system. Conversely, wet conditions on the inner plains can cause high water tables and drainage problems on low-lying areas at the coast. Flood irrigation on the inner plains is expanding and its effect on coastal water levels requires monitoring.

CENTRAL PLAINS AND CHRISTCHURCH CITY

(i) Geology

The central plains sector of the Canterbury Plains extends from the Waimakariri River to the Rakaia River and includes Christchurch City. The structure of the basement greywacke underlying the central plains is complex. The Leeston-1 oil exploration well at Brookside encountered greywacke at a depth of 1112 m and this is on a ridge (Mt Peel–Banks Peninsula ridge) identified by Hicks (1989). The depth to basement increases north and south of this ridge. Deep wells drilled for water at Weedons (259 m) and Darfield (270 m) penetrate late Quaternary glacial and interglacial gravel sequences. Pollen from a peat at 245 m in the Weedons well identified the strata as post-Kowai Formation (Mildenhall IGNS pers. comm.). At the coast where wells penetrate alternating fluvial gravels (mainly glacial) and interglacial marine and swamp deposits, dating of strata and correlation of aquifers of the Christchurch artesian system with the stratigraphic units of Brown and Wilson (1988) presents few problems. A 433 m deep groundwater exploration testbore drilled for the Canterbury Regional Council and the Christchurch City Council, at the eastern Christchurch suburb of Bexley, penetrated deposits from eight interglacial and eight glacial stages, unconformably overlying Kowai Formation marine deposits at 241 m (Brown 1998).

The glacial outwash deposits of the Waimakariri and Rakaia rivers form the central plains. The late Quaternary surfaces are mapped by Brown (1973), Suggate (1973), Wilson (1989), Brown and Weeber (1992) and Sewell et al. (1993). Waimakariri River deposits form about two-thirds of the central plains area and extend to the sector occupied by the Selwyn River, which occupies an interfan depression between the penultimate glaciation Waimakariri River fan and the last glaciation Rakaia River fan (Wilson 1989). Rakaia River deposits are south of the Selwyn River. The position of the Selwyn River course varied from one glaciation to the next, depending on the courses of its larger neighbours. The present Selwyn River course would have been determined by the Rakaia River last glaciation outwash surface (Wilson 1985).

(ii) Hydrogeology

The hydrogeology and groundwater of the aquifer system is related to the river that deposited the gravel in which the aquifers occur. For the central plains, aquifer systems are connected to the Waimakariri, Selwyn and Rakaia rivers. The aquifers coalesce towards the coast into the confined aquifers of the Christchurch artesian system. At the unconfined–confined aquifer boundary the groundwater either flows below the confining strata into the aquifers, or above the strata into near surface gravel channels. These channels contain springs that form the sources of the South Branch–Waimakariri, Styx, Avon, Heathcote, Halswell, L-II and Irwell rivers. The groundwater recharge derived from the Waimakariri River is the most important, because it is directed towards the major abstraction area for the densely populated Christchurch sector of the plains. Delineation of specific river recharge sources is difficult for deep inland aquifers that are related to ancient drainage patterns not typified by the present surface geology. Also unconfined inland aquifers derive groundwater from rain infiltration and water race leakage.

There are too few wells on the plains inland of Kirwee to establish reliable piezometric contours. Further east on the central plains, contours show a general trend of groundwater flow east to southeast from Halkett and the Waimakariri River towards Christchurch and Lake Ellesmere (Wilson 1973). Piezometric contours for the aquifer adjacent to the Selwyn River and its tributaries show outflow to groundwater from the rivers up stream of SH1 and inflow to the river down stream. This corresponds to the zone where the Selwyn becomes effluent, as identified from multiple flow gaugings (Anderson 1994). In the southeast towards Taumutu, the contours bend around Lake Ellesmere, implying groundwater loss to the lake and the presence of groundwater derived from the Rakaia River. Similar bending of the contours at the northern shore of the lake near Banks Peninsula implies inflow of groundwater derived from the Waimakariri River.

The Waimakariri River down stream of Waimakariri Gorge is incised in a 2 km wide floodplain to Halkett, 30 km from the coast. Down stream of Halkett the river is aggrading. Also down stream of Halkett surface flow losses of 5 – 8 m^3/s (Chapter 6) have been measured in the Waimakariri River in several surveys (North Canterbury Catchment Board 1986). The extent of the Waimakariri River contribution to groundwater can be assessed by groundwater oxygen-18 content (Taylor et al. 1989). From Halkett to Christchurch groundwater is derived almost exclusively from the Waimakariri River. To the southeast towards West Melton and Weedons the oxygen-18 indicates a blending of Waimakariri River water and local rain in the groundwater. Further southeast, groundwater derived from the Selwyn River may also be mixing with groundwater derived from the Waimakariri River and Canterbury Plains rain.

It is difficult to determine the contribution of the Rakaia River to the recharge component of a water balance for the Selwyn–Rakaia sector of the Canterbury Plains, as uncertainty surrounds estimates of Rakaia River derived recharge, especially in the river course between the Rakaia Gorge and SH1 (Chapter 6). The water balance suggests that in the winter some 10.7 m^3/s. is flowing as through-flow into the offshore portions of the aquifers (Anderson 1994). In summer the increased extraction for irrigation means outflows exceed inflows by 1.2 m^3/s. and some storage is being depleted. A high degree of uncertainty is associated with these estimates. In particular, Rakaia River recharge, rainfall recharge, and artificial recharge are "best guesses" based on available information (Anderson 1994).

The seasonal and long-term range of well water level fluctuations is a function of the efficiency of groundwater recharge and the aquifer response to groundwater withdrawal. North Canterbury Catchment Board (1983) presents a map showing a piezometric level range for the central plains for May and September 1978, which was the period of greatest

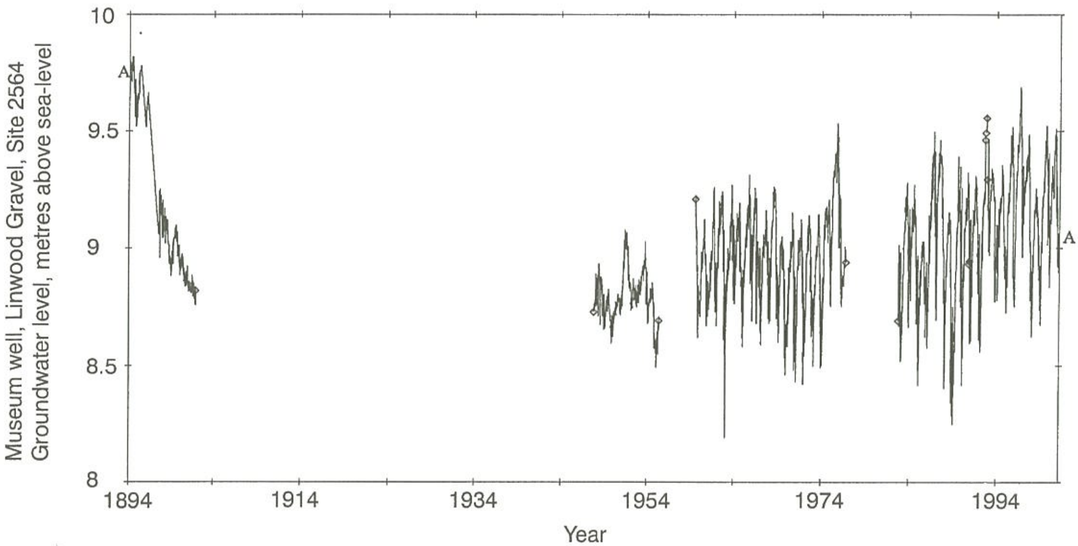


Figure 23.3 *Canterbury museum well – groundwater levels in the Linwood Gravel aquifer, 1895 to 2001.*

seasonal difference from 1974 to 1982. The fluctuations are greatest in the Kirwee area, with variations of 50 m. Wells in the area from Halkett to Christchurch fluctuate less than 3 m. Deep wells tapping the Christchurch artesian aquifers display static water levels close to or above ground level and fluctuations of less than 1 m. Artesian well water levels fluctuate seasonally in response to abstraction, with summer lows and winter recovery. Weekly fluctuations show Friday lows and weekend recovery and daily fluctuations show decline during the day and recovery at night (industrial effect). Coastal artesian well water levels respond to tidal fluctuations, local rain, heavy weights (e.g. trains), barometric pressure changes (Oborn 1956, 1960), and earthquakes.

Long-term fluctuations in confined aquifer water levels are a direct measure of the change in groundwater storage. Abstractions from the aquifers beneath Christchurch has always affected water levels during the summer, resulting in a reduction in artesian and spring free flow. Christchurch is fortunate in that water level measurements have been made since 1895 for two wells at the Canterbury Museum, which obtain water from the Riccarton and Linwood gravel aquifers. These show average levels declining by about 0.5–1.0 m over the period 1895–1905 (Fig 23.3). Since then they have remained steady, apart from seasonal fluctuations (McCammon 1976; North Canterbury Catchment Board 1986). There is a trend of increasing amplitudes of seasonal fluctuations with lower summer levels followed by a winter recovery to normal levels. This is despite the fact that 20 times more groundwater is being abstracted now than one hundred years ago. At present the groundwater resource does not appear to be over exploited.

(iii) Groundwater Availability

The transmissivity data derived from the calculations and modelling of Hunt (1974), supplemented by test pumps, have been used to provide information on the availability of groundwater. There is in general a marked increase in aquifer yield towards the coast (Wilson 1976). There is also lateral and vertical variations in the distribution of higher yielding wells related to geological processes and buried river channels. The Springston Formation–Riccarton Gravel unconfined and semi-confined aquifers, recharged by the Waimakariri River, form a high transmissivity zone (about 3000–20 000 m^2/d) extending southeast from the Waimakariri River to Harewood and Christchurch beneath the Yaldhurst Member surface (Brown and Wilson 1988). The high transmissivity zone is associated with a network of former river channels, including the Islington channel and other historic Waimakariri River channels to the north (Brown and Weeber 1992), that provide conduits for preferential recharge to the confined aquifers of the Christchurch artesian system.

North Canterbury Catchment Board (1983) produced a transmissivity contour map of the central plains that shows a zone of high transmissivity extending from Kirwee to Rolleston to Selwyn Huts on the shore of Lake Ellesmere. Bal (1996) used 54 pump test transmissivities to calibrate specific capacities from about 3500 wells on the Canterbury Plains and to produce broad scale transmissivity and hydraulic conductivity maps. The spatial distribution of the data indicated five "high permeability corridors", 5 to 10 km wide, which were ascribed to river "cut and fill" during interglacial periods. The Harewood and the North Canterbury Catchment Board (1983) high transmissivity zones are confirmed by Bal's (1996) study. Between these two zones, in the Halkett, West Melton and Templeton areas, transmissivities are lower, suggesting less efficient groundwater recharge from the Waimakariri River. Tritium analyses of groundwater from wells along the lower yielding zone from Halkett to Templeton show slower lateral groundwater flow than beneath the Waimakariri River–Christchurch sector and oxygen-18 suggests the groundwater is derived from rain and the Waimakariri River (Taylor et al. 1989). There are as yet too few tritium analyses of groundwater from wells within the higher transmissivity channel to the south to suggest faster flow.

Although pump test estimates of transmissivity are limited for the Selwyn–Rakaia sector, there is enough data to establish a broad spatial pattern (Anderson 1994). The highest transmissivities (up to 30 000 m^2/d) are in the Springston Formation and confined Riccarton Gravel aquifers in the plains area from Lake Ellesmere to the Rakaia River. These transmissivities are the highest for Canterbury aquifers. Inland of SH1 the aquifers underlying the Selwyn River floodplain show a wide range of transmissivities. Wells near the Selwyn River and its tributaries range from 500 to 15 000 m^2/d. South of the Selwyn River in the Te Pirita area transmissivities range from 800 to 8000 m^2/d (Brooks 1998a) for wells ranging in depth from 47 to 137 m. A general trend of decreasing transmissivity with depth and distance inland is broadly evident.

(iv) Groundwater management

In the central plains the predominant groundwater problem is the sustainable management of the Christchurch artesian system, and the associated spring-fed rivers, and wetland areas, including Lake Ellesmere, that depend on springs and surface water sources for their maintenance. Inland of the confined aquifers, shallow groundwater in the high water-table, low transmissivity aquifers recharged by rain, is vulnerable to contamination as land use changes and subdivision intensifies. In particular, expansion of dairy farming in the Selwyn to Rakaia sector of the plain and the subdivision of farms into "life-style blocks" on the plains inland and to the south of Christchurch provides the potential for groundwater management problems.

The large margin of error associated with measuring Waimakariri River recharge to the Christchurch aquifers, the failure of attempts to relate rainfall recharge to well water-level variation (Little 1997), the difficulties in accurately gauging the outflow of groundwater from the many springs at the unconfined–confined aquifer boundary (Cameron 1993), and the impossibility of estimating the Waimakariri and Rakaia river contribution to aquifers flowing to the south of Banks Peninsula, make the exercise of estimating a water balance for the central plains nothing better than a "best guess" (Anderson 1994; Brown 2000).

At Christchurch the rate of spring flow forming the local rivers, including the Avon and Heathcote rivers, provides the best indicator of stress in the aquifer system. Spring flow diminishes in summer in response to increased abstraction of groundwater from the confined aquifers and decreased rainfall recharge. The spring flow is dependent on the groundwater pressure in the confined aquifer, and the contributing springs in stream beds progressively stop flowing in a down stream direction in response to the seasonal and climate related abstraction of groundwater. The objectives of the Christchurch groundwater management plan (Dicker 1993) include ensuring that existing spring low flow patterns are maintained and, if possible, enhanced, and maintaining existing wetlands or other ecosystems dependent on groundwater. This is achieved by restricting and controlling groundwater takes in specific Avon and Heathcote spring discharge zones. The groundwater management plan is based on the concept of sustainable yield, which seeks to produce water resources beneficially, but not necessarily optimally (Sharp 1998).

Piezometric levels in wells tapping the Riccarton Gravel aquifer in the coastal Woolston-Heathcote Valley-Ferrymead area of Christchurch, are below mean sea level (Brown and Weeber 1994). Groundwater chemistry data suggest sea water intrusion and mixing with groundwater from the adjacent Banks Peninsula volcanic complex may be occurring. Hertel (1998) established that saline water and landfill leachate were leaking into the Riccarton Gravel aquifer through the overlying Christchurch Formation confining strata. This was facilitated by industrial and public water supply pumping in the Woolston-Heathcote Valley-Ferrymead area, producing depressed water levels in a "recharge shadow" caused by irregularities in the volcanic rock "basement" and a low transmissivity aquifer (200 m^2/d – Ettema 1999). Groundwater levels and water chemistry are being monitored with a network designed to determine the "optimum yield" for the aquifers in the area (Hertel et al. 1998).

Rakaia – Ashburton plains

This sector of the Canterbury Plains covers an area of about 1350 km^2 and is bounded by the Rakaia River in the north and the north branch and main Ashburton Rivers in the south. The Rakaia–Ashburton plains are unique in that this is the only sector of the Canterbury Plains where there is no perched river between the fans of the major rivers.

Hicks (1989) identifies greywacke basement structures that trend east-west rather than north-south as in North Canterbury. The Rakaia trough extends westwards across the Rakaia River and merges into the Hinds trough south of the Ashburton River. Rakaia River deposits dominate over this sector of the plains. Suggate (1973) maps surfaces correlated with deposition back to the penultimate Waimean glaciation Woodlands Formation. The coastal plains between the Rakaia and Ashburton river mouths are underlain by about 2.5 km of sediment. Oil exploration bores and a few deep water wells provide information about the late Quaternary glacial and interglacial deposits underlying the Rakaia–Ashburton plains. The logs of oil exploration bores J.D.George-1 and Chertsey-1 show 550 m of Quaternary gravel deposits beneath the Rakaia-Ashburton plains at Seafield and 410 m at Chertsey. The deepest irrigation well in the Canterbury Region is located at Lauriston: it is 248.9 m deep and has three screens set between 190 and 248 m.

The Rakaia–Ashburton plains were commonly short of water. This has been partially overcome by the Ashburton–Lyndhurst Irrigation Scheme, which takes 12.5 m^3/s. from the Rangitata Diversion Race for irrigation on a 260 km^2 ha area of the plains. This scheme has been operating since 1945. Groundwater provides a source of water for irrigating the rest of the Rakaia–Ashburton plains. Transmissivity data from aquifer test pumps using a variety of methods are listed in Scott and Thorpe (1986) and Sanders (1996). High transmissivities (1000 to 10 000 m^2/d) are obtained for wells near the Rakaia River on the postglacial floodplain, on the Ashburton River postglacial floodplain coastwards of Ashburton, and along the coast. Further inland the transmissivities for deeper aquifers tend to be lower. Apart from Ashburton's town water supply and the water supply for meat processing plants at Fairton and Seafield, groundwater is used predominantly for irrigation. The Rakaia-Ashburton plains sector is at present the fastest growing part of the Canterbury Plains in terms of the number of wells being drilled for irrigation water and the quantity of groundwater being abstracted (Sanders 1996, 1999).

Aquifers in the almost continuous gravel sequences penetrated by wells are correlated by grouping them into broad bands based on depth (Sanders1999) and specific capacity (Scott 1980). Five aquifer bands are suggested: a shallow 10 to 20 m aquifer adjacent to the rivers, 30 to 40 m aquifers adjacent to the rivers and the coast, and two persistent aquifer zones at 50 to 85 m and 130 to 160 m in the middle part of the plains between Chertsey and the coast. The few wells drilled to 200 m show an aquifer zone at 200 m and Chertsey-1 suggests an aquifer at 350 m.

Groundwater piezometric contours (Scott and Thorpe 1986) on the south bank of the Rakaia River at and below Rakaia township show loss of river flow to groundwater. Contours adjacent to the Ashburton River are more complex, with areas of loss and gain of flow. Close et al. (1995) used oxygen-18 isotope analyses to investigate groundwater recharge for wells on the Rakaia–Ashburton plains. They identified groundwater recharge from the Ashburton and Rakaia rivers, rain, the Rangitata Diversion Race, irrigation and channels, and mixed recharge sources. South of the Rakaia, groundwater from wells from Highbank to Dorie contained more than 50% of Rakaia River water. In the middle of the plain groundwater from wells ranging from 18 to 109 m deep contained more than 50% of Rangitata Diversion Race water. For these areas rain was assumed to make up the remainder of the groundwater recharge input. Water samples were collected in 1999 from 30 m and 80 m in a Canterbury Regional Council groundwater exploration well at Seafield. The 30 m sample is predominantly plains rain that has been underground for less than three years. The 80 m sample may contain some Rangitata Diversion Race recharge and has a mean residence time of 52 ± 2 years (Morgenstern IGNS pers. comm.).

Initially, the Rangitata Diversion Race and the border strip Ashburton–Lyndhurst Irrigation Scheme aroused concern about possible drainage problems from seepage of excess irrigation water. A network of observation wells was drilled and have been monitored monthly since 1944. There is no evidence of long-term changes in groundwater level, either from irrigation return water or increased pumpage (Scott and Thorpe 1986). In the coastal Rakaia–Ashburton plains, water levels in deep and shallow wells correlate with long-term rainfall. Winter rainfall influences the amount of recharge occurring, while summer rain influences the amount of irrigation water pumped.

Crude water balances for the Rakaia–Ashburton plains (Scott and Thorpe 1986; Sanders 1999) indicate significant groundwater through flow. Scott and Thorpe (1986) estimate annual recharge at 853×10^6 m^3 and total annual abstractions including spring flow at 285×10^6 m^3. Measurement of accurate river flow losses, especially for the Rakaia River and spring flows, is very difficult.

A proposed irrigation scheme taking 17 m^3/s. from the Rakaia River for irrigation of 400 km^2 in the Barrhill area between Methven and Rakaia may reduce demand for groundwater should construction proceed (Sanders, Environment Canterbury pers. comm.). The effects of the scheme further down the plain on groundwater, including higher water levels, will need to be considered. Maintenance of groundwater quality is another important aspect of groundwater management for the Rakaia–Ashburton plains because a high proportion of groundwater recharge is from rain, leakage from water races and seepage of irrigation water, and involves interaction of the infiltrating water with the ground, soil, subsoil and vadose layer. Close et al. (1995) resampled and chemically analysed groundwater from several wells originally sampled by Quin and Burden (1979) for their study in 1978. Between the two study periods the number of wells with significant increases in concentrations of chemicals approximately equaled the number with significant decreases. Nitrate levels generally decreased or differed little between 1978/79 and 1990/91. Apart from two wells, land use changes had no evident effect on groundwater quality. Groundwater quality was affected more by the flushing effect of rain and irrigation return water. Close et al. (1995) conclude that consideration of recharge sources and patterns is vital to understanding changes in groundwater quality and that studies looking at the effects of land use on groundwater quality also need to consider recharge variability.

Ashburton-Rangitata plains

Less is known about groundwater resources in the Ashburton–Rangitata sector of the Canterbury Plains than in any other part of the plains. This is because irrigation and stock water supplies of up to 22.5 m^3/s are provided by the Rangitata Diversion Race and associated irrigation schemes on the inner plains. Prospective groundwater resources in deep gravel aquifers have thus not been investigated and the need for more water, as is occurring elsewhere in Canterbury, has not been as intense. Between SH1 and the coast shallow aquifers and drains, streams and creeks, deriving water from local rain and up plain irrigation water seepage, provide a reliable year round water supply for irrigation and stock requirements. In the future, as water demand increases, current water supply sources will be unable to cope, and will have to be supplemented by groundwater (Brown 2000).

The basement structure is dominated by the Hinds trough extending west from the Ashburton River mouth towards Hinds (Hicks 1989). The late Quaternary surfaces of this sector of the plains are mapped by Suggate (1973), Gair (1967) and Barrell et al. (1996). Surfaces and remnants correlated with postglacial Springston Formation, and the last four glaciations back to Nemonan glaciation (Hororata Formation) are mapped. The course of the Rangitata River is toward the south side of its last glaciation fan, which extends from the Hinds River postglacial floodplain in the north to at least the Orari River in the south. The Hinds River has a foothills catchment (160 km^2) and maintains an intermittent flow across the plains inland of SH1, dependant on catchment and plains rain. The Hinds River is not deeply entrenched and in its lower reach below SH1 flowed into swampy flats before the area was drained for farming about 1900.

Well depths of 589 wells in the area suggest that the aquifer bands identified from specific capacities in the Rakaia–Ashburton plains (Scott 1980) also occur beneath the Ashburton–Rangitata plains (Brown 2000). Six wells are 100 m or deeper and the deepest well, at Westerfield, is 149.8 m deep (Brooks 1996, 1998b). The well log indicates a continuous sequence of clay-bound gravel and sand. Aquifers were encountered at 12 m, 94 m, 132.7–138.8 m and 144.8–146.3 m. The two deeper aquifers were screened and pumped at 29 L/s, with a drawdown of 110.7 m. In the Mayfield–Hinds–Winslow area shallow wells yield 10 L/s (Brooks 1996) and in the Hackthorne–Winslow–Tinwald area there are wells with yields up to 50 L/s. A few deeper wells in the Windermere–Flemington–Tinwald areas yield up to 75 L/s. Between the Hinds and the Rangitata rivers and on the inland margin of the plains, yields greater than 10 L/s are the exception. Aquifer pump test data is available from nine shallow wells on the Ashburton–Rangitata plains (Brooks 1996). Transmissivities range from 24 to 4700 m^2/d.

Piezometric contours are available for a few areas of the Ashburton–Rangitata plains. These are in unpublished New Zealand Geological Survey maps compiled in 1946 (Oliver 1946) and 1995 (Environmental Consultancy Services 1995). The contours suggest the Ashburton River (South Branch) between Ashburton Forks and Ashburton could be losing water to aquifers underlying the south bank postglacial floodplain. However flow gauging of the river indicates a gain of flow through this reach, although it is suggested that there could be a transfer of water via groundwater from the slightly higher north branch to the south branch (Scott and Thorpe 1986). Below Maronan the Hinds River is perched (Environmental Consultancy Services 1995) and when the river goes dry the underflow is confined to the channel and comes to the surface in the riverbed coastwards of SH 1. On the Rangitata River floodplain seepages and springs on the face of the north bank terrace indicate groundwater flow towards the river (Oliver 1946).

The initial operation of the Rangitata Diversion Race and its associated border strip irrigation schemes aroused worries about possible drainage problems from seepage of excess irrigation water. There was concern that the coastal area of drained swamp from Lowcliffe to Waterton, originally drained about 1900, could revert to swamp. The Ashburton–Hinds drainage scheme was constructed in 1945 to prevent high groundwater levels and improve farm drainage, and levees were built to control a 3.5 km long section of the lower Hinds River (Britten 1991). The drains are now used as a source of water for stock, irrigation and fisheries. Water levels are affected by inland irrigation from about Winslow to Hinds, with shallow wells normally having high water levels in summer and low water levels in winter. Towards the coast where the water table is high the influence of irrigation water is less obvious.

The availability of groundwater from deep aquifers underlying the Ashburton–Rangitata plains has never been properly investigated. Also there is no water quality data listed in available reports. Environmental Consultancy Services (1995) reports that for the Hinds–Tinwald area groundwater quality is considered to be good. However the extensive use of flood irrigation combined with intensive land use and a shallow water table, could affect nitrate-nitrogen levels. The results of the groundwater quality studies on the Rakaia–Ashburton plains, especially by Close et al. (1995), are also relevant to the Ashburton–Rangitata plains.

Rangitata-Levels Plains

The Rangitata-Levels Plains sector of the Canterbury Plains is bounded by the Rangitata River in the north and the South Canterbury downs in the west and south. Hicks (1989) showed an almost flat basement surface beneath coastal South Canterbury, with a slight basement high (800 m below msl) at the Opihi River mouth. The late Quaternary surfaces of this sector of the plains are mapped by Gair (1967) and Barrell et al. (1996) (between the Rangitata and Orari rivers). Surfaces and remnants correlated with postglacial Springston Formation, and the last four glaciations back to Nemonan glaciation (Hororata Formation) were mapped. The Rangitata River last glaciation (Burnham Formation) and penultimate glaciation (Waimean Glaciation) outwash fans extend south to Temuka and the Opihi River. Between the gorge and SH1 Orari River flow seeps into the riverbed and the river is dry unless local rain boosts flow. Down stream of SH1 springs in the riverbed and spring fed tributaries and drains combine to provide Orari River flow through to the coast. Down stream of Pleasant Point, at 18 km from the coast, the Opihi River crosses the Levels Plain and flow measurements indicate loss of channel flow (Fancourt 1973). The Opihi River can go dry in this stretch of river course, with flow reappearing at the confluence with the Temuka River.

Between the Rangitata and Orari rivers Aitchison-Earl (1999) differentiated three aquifers based on depth within the gravel sequences: a shallow unconfined to semi-confined aquifer less than 15 m deep, a confined aquifer at 30 to 60 m that is flowing artesian on the north bank of the Orari River at Clandeboye through to the coast, and a 75 to 90 m aquifer. On the inland margin of the plains from Peel Forest to Geraldine and Temuka, wells encounter aquifers at varying depths, suggesting discreet channels rather than laterally connected aquifer systems. On Rise Road, about 5 km north of Temuka, a 115 m deep town supply well yields 27 L/s from a flowing artesian aquifer screened at 100 to 114 m. At the Temuka saleyards, a well is logged that penetrates shingle to 35.1 m, then soft sandstone to 61.9 m, where drilling stopped. This sandstone may correlate with the Miocene sandstone mapped by Wellman (1953) in the Kakahu River bed about 12 km west of Temuka. If this correlation is valid this would suggest that Temuka overlies a ridge of Tertiary sediments and lies at the southern margin of the Rangitata River floodplain, and that the deep late Quaternary gravel aquifers do not continue south beneath the Levels Plain. The occurrence of the confined artesian aquifer in the Clandeboye coastal area with groundwater levels affected by ocean tide, also is evidence supporting permeability constraints to groundwater flow and aquifer connections to the south and the Levels Plain (Brown 2000). Most wells on the Levels Plain are shallow (<20 m) and tap aquifers within postglacial gravels of the Opihi River floodplain, or in last glaciation gravels of the plains adjacent to the South Canterbury downs. Deeper wells show

Cannington Gravel (c.f. Kowai Formation-North Canterbury) becoming shallower towards the downs, while the overlying late Quaternary fluvial deposits and the contained gravel aquifers become thinner and less permeable.

Piezometric contours are available for the Rangitata River to Temuka area (Environmental Consultancy Services 1997) and the Levels Plain (Fancourt 1973). Overall piezometric contours show a general flow of groundwater down plain, apart from specific areas where river recharge is indicated. Groundwater flow occurs from the Rangitata River southern bank down stream of Arundel beneath the RG2 surface of Barrell et al. (1996) to Kapunatiki Creek. Further south Coopers Creek and the Orari River show stretches of riverbed with gains and losses of flow due to groundwater inflow and outflow. Contours adjacent to the Waihi River down stream of Geraldine suggest river flow to recharge groundwater aquifers. The Levels Plain piezometric contours indicate Opihi River flow loss to groundwater from the Kerrytown ford to the southern bank postglacial floodplain. The Levels Plain Irrigation Scheme began operation in the 1940s and the Seadown drainage system was constructed at the coast to drain coastal swamps that might have increased in extent due to irrigation. This proved to be correct and the drainage system has greater flows in summer compared with winter (Fancourt 1973).

Environmental Consultancy Services (1997) reports transmissivities for wells in the Rangitata to Levels Plain area, with 87 to 12 000 m^2/d for shallow water table aquifers, 450 to 800 m^2/d for 30 to 60 m deep confined aquifer and 118 m^2/d for the 115 m deep flowing artesian aquifer. These vary in reliability, but also show lateral and vertical variation in transmissivity, indicating preferential flow channels within the postglacial and last glaciation gravels (Aitchison-Earl 1999).

There is no groundwater chemistry data given in published reports. Environmental Consultancy Services (1997) note that the shallow unconfined aquifers could become contaminated from a variety of sources, especially in areas of intensive farming. Disposal of animal effluent on to land, the use of fertilizers, septic tank discharges, and the disposal of dairy factory wastes on to land all occur on the Rangitata-Levels Plains. Localised groundwater contamination associated with the Seadown fertilizer manufacturing plant has been reported. On many parts of this sector of the Canterbury Plains the combination of intensive land use, flood irrigation, high water table, and low transmissivity unconfined aquifers create conditions conducive to groundwater contamination.

For the Rangitata-Levels Plains a major management problem is the maintenance of minimum surface flows in the rivers and streams for ecological, environmental and recreational reasons, while at the same time efficiently using groundwater in aquifers hydraulically connected to the surface water bodies for irrigation. A management plan is in place to control groundwater abstraction from shallow wells in the vicinity of the Opihi River (Scott and Callander 1995).

SOUTH CANTERBURY

This area includes coastal downs from Timaru south to the Waitaki River valley and inland to The Hunter Hills. The main basement structural feature is the Waimate depression, which is a 1500 m deep elongated depression underlying the Waimate area (Hicks 1989). Tertiary sediments overlie and are faulted against greywacke at the eastern base of The Hunter Hills. These sediments comprise coal measures, marine silt and sandstone, greensand and limestone. They are exposed in sections in the Pareora, Otaio and Waihao river valleys (Aitchison-Earl 2000) and are penetrated by a few water wells. The Tertiary sediments are overlain by the Pliocene to early Pleistocene Cannington Gravels, which include marine beds in a river terrace at Makikihi (Gair 1959). In the Timaru area the Cannington Gravels are overlain by the early Pleistocene Timaru Basalt. Timaru Basalt and the other downs surfaces are capped by wind-blown loess. In South Canterbury, Pleistocene uplift and deformation has been less intense than elsewhere in Canterbury. Pliocene-Pleistocene deposits dip gently east-southeast. Quaternary glacial and interglacial sequences in river valleys and at the coast are almost undeformed. Between Timaru and the Waitaki River, the Pareora, Otaio and Waihoa rivers, with catchments in the Hunter Hills, have valleys and associated high and low level terraces, and last glaciation and postglacial floodplains that dissect the rolling downland country. The Waitaki River, with its alpine catchment, wide floodplain, and glacial outwash fan deposits with degradational terraces cut into them during high sea level interglacial periods, is at the southern boundary of the South Canterbury region.

Because tectonic activity has been less intense during the Quaternary, the Tertiary sediments are less disrupted and form relatively continuous strata. They thus have a potential to contain regional aquifers. The uniform, relatively gentle coastwards dipping strata determine groundwater flow to the coast. The overlying and juxtaposed Pliocene-Pleistocene gravels contain aquifers with rapid lateral and vertical permeability changes over short distances–this is a result of deposition by small coastal rivers with a limited capacity to rework and redeposit gravel. Aitchison-Earle (2000) provides a comprehensive review of South Canterbury groundwater resources and Brown and Somerville (1979) list well data for the area.

Most wells in the South Canterbury region are shallow (< 30 m deep), and tap late Quaternary gravel aquifers on the coastal plains, river floodplains, river valleys and downs. Apart from the Waitaki River there is no permanent high flow groundwater recharge source in the South Canterbury region: groundwater recharge occurs from rain, seepage of local rivers, irrigation return water and leakage from stock and irrigation water races. High-yielding wells are generally associated with river floodplain groundwater recharge. A transmissivity range of 1500 to 2000 m^2/d was obtained by test pumping a shallow water hole on the Pareora River postglacial floodplain (Waugh 1987).

A 152.4 m deep groundwater exploration bore at the base of the sea cliff near the Timaru railway station encountered three aquifers in Cannington Gravels (Gair 1961). At Pareora, a 139 m deep well penetrating fluvial gravels interbedded with sand, silt and clay is screened from 89 to 97 m and pumped at 36 L/s, with a drawdown of 0.5 m. Another deep well in this area yields 92 L/s. Tritium analyses indicate that the groundwater is at least 30 years old and the water quality is excellent (Waugh 1987). Other deep wells have been drilled in South Canterbury, but until more wells are geologically logged in detail, correlation of subsurface Pleistocene–Pliocene sequences with the Quaternary terrace deposits mapped by Gair (1967) and Mutch (1963) will remain tentative. There are a few wells tapping aquifers in Tertiary sediments. At Kelchers a 73.2 m deep well yields 10 L/min from limestone. At Arno a 19.5 m deep well yielding 9 L/min was drilled through limestone at 15.2 m and into greywacke. A 91 m deep well at Douglas penetrated Tertiary mudstone and siltstone interbedded with quartz and greywacke gravels to the bottom of the well at 95.0 m. Quartz gravels at 61 to 67 m yielded 17 L/s, with a drawdown of 12.3 m. This aquifer may be the Papakaio Formation (Gage 1957), which provides groundwater from quartzose gravel artesian aquifers in North Otago (Brown 2000). Scott (1977) reports artesian water in Papakaio Formation beneath the Waitaki River floodplain at Waikaura.

The groundwater resources of the Lower Waitaki River floodplain between Kurow and Black Point on the south bank and Hakataramea and Ikawai on the north bank, have been studied by Scott (1977). The structural geology of the area is complex and fault dislocation of aquifers in Quaternary alluvium and Tertiary sediments appears to affect groundwater flow. At Black Point basement schist rock underlies the south bank floodplain at the relatively shallow depth of 8 m and on the north bank a greywacke ridge projects into the Waitaki River bed. This basement structure at Black Point impedes groundwater flow and forms a boundary between two distinct groundwater basins. Further up stream at the Otekaike–Waitaki river confluence an extension of the Otekaike Fault (Gage 1957) across the Waitaki River river floodplain forms another barrier to groundwater flow. On the north bank between the road and the Waitaki River there is an area of groundwater emergence forming high flowing springs that could be related to the northward extension of the Otekaike Fault impeding groundwater flow.

Piezometric contours presented in Scott (1977) show groundwater flow towards the Waitaki River on the south bank with tributaries, the Kurow, Otiake, Otekaike and Maerewhenua rivers, making significant contributions to groundwater at their confluences with the Waitaki. Hydrographs for south bank wells from Kurow to Black Point show summer lows and winter highs related to local rain (Brown and Somerville 1979). From downstream of Black Point through to Pukeuri and the coast summer lows and winter highs were common until 1971, when the Lower Waitaki Irrigation Scheme began operation. Irrigation return water resulted in steadily rising water levels, but with the summer water-level rise leveling off in comparison with the winter rise.

Well water levels in South Canterbury have been monitored since 1950 (Brown and Somerville 1979) in anticipation of the establishment of irrigation schemes using surface water. The well water levels fluctuated, with summer lows and winter highs being the usual pattern. As irrigation schemes were progressively commissioned and extended over areas from Ikawai to Glenavy and Willowbridge on the north bank of the Waitaki River, and from Kurow to the coast on the south bank, the water level pattern in monitoring wells in the scheme areas changed to summer highs or steady water levels.

A systematic study of the hydrogeology of South Canterbury–North Otago region is required to establish the relationship between the Pleistocene and Pliocene gravel aquifers and the underlying Tertiary sediments. Permeable strata within the sequence have the potential to form significant regional aquifers. The conservation of wetlands such as the Wainono Lagoon, the maintenance of flows in creeks and streams for ecological and cultural reasons, and the intensification of land use and settlement that can result in declining water quality (Hayward et al. 1998) are important factors for groundwater management.

REFERENCES

Aitchison-Earl, P. 1999: Rangitata-Opihi and Levels Plains aquifer test review. Canterbury Regional Council, Christchurch, Technical Report no. U99/29. 10p.

Aitchison-Earl, P. 2000: The Pareora-Waitaki groundwater system review and project proposal. Canterbury Regional Council, Christchurch, Technical Report no. U00/6. 24p.

Anderson, B. 1994: Groundwater between the Selwyn and Rakaia rivers, Canterbury, New Zealand. Unpublished MSc thesis, University of Otago.

Anderson, H.J. 1987: A gravity survey of the Hanmer Depression, North Canterbury. Geophysics Division, Department of Scientific and Industrial Research, Research Report 214a: 4-9.

Bal, A.A. 1996: Valley fills and coastal cliffs buried beneath an alluvial plain: evidence from variation of permeabilities in gravel aquifers, Canterbury Plains, New Zealand. Journal of Hydrology (New Zealand) 35: 1-27.

Barrell, D.J.A.; Forsyth, P.J.; McSaveney, M.J. 1996: Quaternary geology of the Rangitata fan, Canterbury Plains, New Zealand. Institute of Geological and Nuclear Sciences Science Report 96/23. 67p.

Bowden, M.J. 1974: The water resources of the Waiau catchment. North Canterbury Catchment Board, Christchurch. 65p. + 2 appendices.

Bowden, M.J. 1982: The water resources of the Ashley Catchment. Resources Investigation Division, North Canterbury Catchment Board and Regional Water Board, Christchurch.

Brooks, T. 1996: Ashburton-Rangitata plains: groundwater information, review, issues and recommended future investigations. Canterbury Regional Council, Christchurch, Technical Report no. U96/29. 27p.

Brooks, T. 1998a: Groundwater resources near Te Pirita, Central Plains. Canterbury Regional Council, Christchurch, Technical Report no. U98/42. 43p.

Brooks, T. 1998b: Hydrogeologic cross sections between the Ashburton and Hinds Rivers. Canterbury Regional Council, Christchurch, Technical Report no. U98/40. 27p.

Brown, L.J. 1973: Sheet S76-Kaiapoi. Geological map of New Zealand 1:63 360. Map (1 sheet) and notes (16p.). Department of Scientific and Industrial Research, Wellington.

Brown, L.J. 1977: Water well data, sheet S76/1-2, Rangiora-Waikuku 1:25 000. Report New Zealand Geological Survey 80. 18p. + map and cross sections.

Brown, L.J. 1988: Water well data, geohydrology and Quaternary geology, southern Marlborough. Report New Zealand Geological Survey 111. 57p.

Brown, L.J. 1998: Bexley groundwater testbore results. Institute of Geological and Nuclear Sciences client report. 68p. + tables and figures.

Brown, L.J. 2000: Groundwaters of the Canterbury Region. Environment Canterbury, Christchurch, Technical Report no. U00/10.

Brown, L.J.; Somerville, M.J. 1979: Water well data, South Canterbury – North Otago. Report New Zealand Geological Survey 91. 137 p.

Brown, L.J.; Talbot, J.D.; Weeber, J.H. 1984: Water well data, North Canterbury, Waimakariri River to Ashley River. Report New Zealand Geological Survey 100. 255p.

Brown, L.J.; Taylor, C.B. 1974: Geohydrology of the Kaikoura Plain, Marlborough, New Zealand. *In:* Isotope techniques in groundwater hydrology 1974. Proceedings of a symposium, International Atomic Energy Agency, Vienna, 1:169-189.

Brown, L.J.; Weeber, J.H. 1983: Water well data, North Canterbury, Ashley to Waipara River. Report New Zealand Geological Survey 98. 81p.

Brown, L.J.; Weeber, J.H. 1992: Geology of the Christchurch urban area, 1:25 000. Institute of Geological and Nuclear Sciences map 1 (1 sheet) and book (104 p.). Institute of Geological and Nuclear Sciences, Lower Hutt.

Brown, L.J.; Weeber, J.H. 1994: Hydrogeological implications of geology at the boundary of Banks Peninsula volcanic rock aquifers and Canterbury Plains fluvial gravel aquifers. New Zealand Journal of Geology and Geophysics 37: 181-193.

Brown, L.J.; Wilson, D.D. 1988: Stratigraphy of late Quaternary deposits of the northern Canterbury Plains. New Zealand Journal of Geology and Geophysics 31: 305-335.

Britten, R. 1991: Between the wind and the water. Ashburton County Council 1876-1989. Ashburton District Council, Ashburton. 203p.

Callander, P.F. 1988: Calculation of rate of depletion of Ashley River caused by bores. North Canterbury Catchment Board and Regional Water Board, Christchurch. Report no. R88/2, 10p.

Cameron, S.G. 1993: A hydrogeological study of the interaction between Avon River baseflow and shallow groundwater, Christchurch, New Zealand. Unpublished MSc thesis, University of Canterbury.

Clayton, L. 1966: Tectonic depressions along the Hope Fault, a transcurrent fault in North Canterbury. New Zealand Journal of Geology and Geophysics 9: 95-104.

Close, M.E. 1985: Simulating the effects of the Waiau Irrigation Scheme on recharge and groundwater level. Journal of Hydrology (New Zealand) 24: 49-63.

Close, M.E.; Tod, J.L.; Tod, G.J. 1995: Effect of recharge variations on regional groundwater quality in Mid-Canterbury, New Zealand. Journal of Hydrology (New Zealand) 33: 1-16.

Dicker, M.J.I. 1993: Christchurch groundwater management plan. Canterbury Regional Council, Christchurch, Technical Report no. U93/12. 22p.

Environmental Consultancy Services 1995: A summary of groundwater resources between Hinds and Ashburton with regard to Ashburton District stock and domestic water needs. Canterbury Regional Council, Christchurch, Technical Report no. U95/4.

Environmental Consultancy Services 1997: Rangitata-Temuka groundwater review, issues and recommended future investigations. Canterbury Regional Council, Christchurch, Technical Report no. U97/34.

Ettema, M. 1999: Aquifer test at Woolston-Heathcote M36/979 in the Riccarton aquifer. Canterbury Regional Council, Christchurch, Technical Report no. U99/20. 41p.

Fancourt, T.L. 1973: The resources and usage of water in the Opihi catchment. South Canterbury Catchment and Regional Water Board, Timaru. 63p.

Farr, C.C.; Hogg, E.G.; Page, S.; Wild, L.J.; Hilgendorf, F.W. 1919: Report on the natural features of the Arthur's Pass tunnel. Transactions of the New Zealand Institute 51:422-426.

Field, B.D.; Browne, G.H. 1989: Cretaceous and Cenozoic sedimentary basins and geological evolution of the Canterbury Region, South Island, New Zealand. New Zealand Geological Survey Basin Studies 2.

Gage, M. 1957: The geology of Waitaki subdivision. New Zealand Geological Survey Bulletin 55. 135p. + 3 maps.

Gair, H.S. 1959: The Tertiary geology of the Pareora district, South Canterbury. New Zealand Journal of Geology and Geophysics 2: 265-296.

Gair, H.S. 1961: Drillhole evidence of the Pliocene-Pleistocene boundary at Timaru, South Canterbury. New Zealand Journal of Geology and Geophysics 4: 89-97.

Gair, H.S. 1967: Sheet 20-Mt Cook. Geological map of New Zealand 1:250 000. Department of Scientific and Industrial Research, Wellington.

Gregg, D.R. 1964: Sheet 18 – Hurunui, Geological map of New Zealand 1:250 000. Department of Scientific and Industrial Research, Wellington.

Hayward, S.; Smith, V.; Smith, Z. 1998: Groundwater quality monitoring in South Canterbury. Abstract of paper presented at New Zealand Hydrological Society Annual Conference 1998, Dunedin.

Hertel, I. 1998: Groundwater contamination in the Heathcote/ Woolston area, Christchurch, New Zealand. Unpublished MSc thesis, University of Canterbury.

Hertel, I.; Griffiths, E.; Ettema, M.; Daly, A. 1998: Background report for the Woolston-Heathcote groundwater users meeting of 7 September 1998. Canterbury Regional Council, Christchurch, Technical Report no. U98/60.

Hicks, S.R. 1989: Structure of the Canterbury Plains, New Zealand, from gravity modeling. Geophysics Division, Department of Scientific and Industrial Research, Research Report 222. 14p.

Hunt, B.W. 1974: Aquifer transmissibilities of the Canterbury Plains. Department of Civil Engineering, University of Canterbury, Christchurch, Research Report 74-1.

Lawler, M.E. 1988: The hydrogeology of the Cheviot region, North Canterbury, New Zealand. Unpublished MSc thesis, University of Canterbury. 125p.

Little, R. 1997: Christchurch-West Melton groundwater. Issues and management options. Volume 1. Prepared by Woodward-Clyde (NZ) Limited for Canterbury Regional Council. Technical report no. U97/28/1.

Loris, P. 2000a: Hydrogeology of the Waipara alluvial basin, North Canterbury, New Zealand. Unpublished MSc thesis, University of Canterbury.

Loris, P. 2000b: Hydrogeology of the Waipara alluvial basin: MSc. thesis summary. Environment Canterbury, Christchurch, Technical Report no. U00/59.

Lovell, M.J. 1998: A Hydrogeological model for the Kaiapoi aquifer system. Unpublished BSc (Hons.) project, University of Canterbury.

McCammon, R.B. 1976: A computer-based study of long-term well hydrograph records in metropolitan Christchurch. New Zealand Geological Survey unpublished report M48.

Mutch, A.R. 1963: Sheet 23-Oamaru. Geological map of New Zealand 1:250 000. Department of Scientific and Industrial Research, Wellington.

North Canterbury Catchment Board and Regional Water Board 1983: Interim report on the groundwater resource of the Central Plains. Resources Investigation Division, North Canterbury Catchment Board and Regional Water Board, Christchurch.

NORTH CANTERBURY CATCHMENT BOARD AND REGIONAL WATER BOARD 1986: The Christchurch artesian aquifers. Resources Division, North Canterbury Catchment Board and Regional Water Board, Christchurch. 159p.

OBORN, L.E. 1956: Groundwater in metropolitan Christchurch. New Zealand Geological Survey, Hydrological Report 128. 32p.

OBORN, L.E. 1960: The incompetent and elastic nature of the Christchurch artesian system. New Zealand Journal of Geology and Geophysics 3: 81-97.

OLIVER, R.L. 1946: Report on ground water survey of part of Ashburton County (5 reports + maps and cross sections). New Zealand Geological Survey.

PARKER, S.K. 1989: The hydrogeology of the Diamond Harbour region, Banks Peninsula. Unpublished MSc thesis, University of Canterbury.

PATTLE DELAMORE PARTNERS. 1993: Waimakariri-Ashley Irrigation Scheme. Report on groundwater study. Prepared for Waimakariri-Ashley Irrigation Committee.

QUIN, B.F.; BURDEN, R.J. 1979: The effects of land use and hydrology on groundwater quality in Mid-Canterbury, New Zealand. Progress in Water Technology 11: 433-448.

ROBB, C.A. 2000: Information on water allocation in New Zealand. Lincoln Environmental Client Report 4375/1 to Ministry for the Environment, 180p.

SANDERS, R.A. 1986: Hydrogeological studies of springs in Akaroa County, Banks Peninsula. Unpublished MSc thesis, University of Canterbury.

SANDERS, R.A. 1996: The Ashburton-Rakaia groundwater system. Review and project proposal. Canterbury Regional Council, Technical Report no. U96(20). 30p.

SANDERS, R.A. 1997: Groundwater of the Waimakariri-Ashley Plains. Canterbury Regional Council, Christchurch, Technical Report no. U/97(43). 101p.

SANDERS, R.A. 1999: Groundwater in the coastal Ashburton-Rakaia plains area: a recent perspective. Canterbury Regional Council, Christchurch, Technical Report no. U99/31.

SANDERS, R.A. 2000: Aquifer tests in the Akaroa area. Canterbury Regional Council, Christchurch, Technical Report no. U00/3. 66p.

SANDERS, R.A.; LOVELL, M.J. 1999: Observations of the Ohoka Stream system in a drought. Canterbury Regional Council, Christchurch, Technical Report no. U99/32. 114p.

SCOTT, D.M.; THORPE, H.R. 1986: Groundwater resources between the Rakaia and Ashburton rivers. Hydrology Centre, Christchurch publication no. 6. 105p.

SCOTT, D.M.; CALLANDER, P.F. 1995: Effect of groundwater abstractions on surface water flows in the Opihi River catchment. Canterbury Regional Council, Christchurch, Technical Report no. U95/37. 21p.

SCOTT, G.L. 1977: Lower Waitaki groundwater investigations. Unpublished report prepared for Ministry of Works and Development. 10 p. + 10 figures.

SCOTT, G.L. 1980: Near-surface hydraulic stratigraphy of the Canterbury Plains between Ashburton and Rakaia Rivers, New Zealand. Journal of Hydrology (New Zealand) 19: 68-74.

SEWELL, R.J.; WEAVER, S.D.; REAY, M.B. (1993): Geology of Banks Peninsula, 1:100 000. Institute of Geological and Nuclear Sciences map 3. Institute of Geological and Nuclear Sciences, Lower Hutt.

SHARP, J.M. JR. 1998: Sustainable groundwater supplies – an evolving issue: examples from major carbonate aquifers of Texas, USA. *In:* Weaver, T.R., Lawrence, C.R. (eds), Groundwater sustainable solutions. Proceedings International Conference, 8-13 February 1998, International Association of Hydrogeologists, Melbourne, pp. 1-12.

SHEPPARD, G.M. 1995: The hydrogeology of the Kaikoura Plains, North Canterbury, New Zealand. Unpublished MSc thesis, University of Canterbury. 228p.

SUGGATE, R.P. 1973: Sheet 21-Christchurch (2nd ed.). Geological map of New Zealand 1:250 000. Department of Scientific and Industrial Research, Wellington.

TAYLOR, C.B.; WILSON, D.D.; BROWN, L.J.; STEWART, M.K.; BURDEN, R.J.; BRAILSFORD, G.W. 1989: Sources and flow of North Canterbury Plains groundwater. Journal of Hydrology 106:311-340.

WAUGH, J.R. 1987: Pareora catchment water and soil resource report. South Canterbury Catchment Board and Regional Water Board, Timaru. Publication no. 54.

WEEBER, J.H.; TALBOT, J.D. 1984: Preliminary report on the groundwater resource of the Culverden Plain. Unpublished North Canterbury Catchment Board and Regional Water Board Report, Christchurch. 6p.

WELLMAN, H.W. 1953: The geology of Geraldine subdivision. New Zealand Geological Survey Bulletin 50. 72p. + map.

WILSON, D.D. 1963: Geology of Waipara subdivision. New Zealand Geological Survey Bulletin 64. 122p. + map and cross sections.

WILSON, D.D. 1973: The significance of geology in some current water resource problems, Canterbury Plains, New Zealand. Journal of Hydrology (New Zealand) 12: 103-118.

WILSON, D.D. 1976: Hydrogeology of metropolitan Christchurch. Journal of Hydrology (New Zealand) 15: 101-120.

WILSON, D.D. 1985: Erosional and depositional trends in rivers of the Canterbury Plains, New Zealand. Journal of Hydrology (New Zealand) 24: 32-44.

WILSON, D.D. 1989: Quaternary geology of the northwestern Canterbury Plains, 1:100 000. New Zealand Geological Survey miscellaneous series map 14, map (1 sheet) and notes (35p.). Department of Scientific and Industrial Research, Wellington.

24

West Coast

TREVOR JAMES

INTRODUCTION

Information on groundwater resources in the West Coast region is limited and fragmental. This is a reflection, in part, of the limited need for groundwater, as surface water supplies in the region are relatively reliable, and of the limited resources available for collecting groundwater data. Nevertheless, groundwater resources are important to some industries on the West Coast, particularly dairy farming, and to a number of communities for drinking water supplies. The West Coast Regional Council is currently upgrading its groundwater information and this chapter presents the preliminary results of this effort.

LOCATION AND DESCRIPTION OF PRIMARY AQUIFERS

The primary aquifers studied or monitored in the West Coast region are generally in unconfined recent alluvial gravel outwash. The thickness of the alluvial gravels is typically 20 – 40 m, and up to 60 – 70 m in parts of the Grey Valley. The basement of these aquifers is sandstone, mudstone (Kaiata Bluebottom Group in particular) and conglomerate. Most groundwater abstraction is from shallow aquifers.

GROUNDWATER USE

Groundwater in the West Coast region is particularly important to the dairy farm community for stock water and dairy-shed washdown. In addition, groundwater is also used for drinking water supplies for ten communities of over 25 people, the largest being Greymouth and Reefton. Use by the industrial sector is high, but for only a few sites. High annual rainfall and high-relief surface catchments mean that restrictions on groundwater allocation are not common. There are few limits on the quantity of water abstracted from West Coast aquifers, the exception being for a few industries outside the areas of town water supplies. The quantities of water abstracted are thus not regularly recorded and there is limited information on the amount of groundwater used in the region. Resource consents are not required for either groundwater abstraction or bore construction for domestic or farm use. Often groundwater bores are constructed by the landowner using trenching and backfilling methods. Gathering information on groundwater use in the region is thus difficult. However, a groundwater bore inventory has been compiled (West Coast Regional Council 2000) (Fig 24.1).

There are approximately 300 wells in the West Coast groundwater bore inventory at the present time (26/01/2000). About 22% of the wells are located in the South Westland area between Haast and Hari Hari, 68% are in the Hokitika/Kokatahi/ Kowhitirangi area, 20% are in the Grey Valley and a further 11% are in the Reefton/ Inangahua area. Some 9% of the wells are in the northern part of the West Coast between Westport and Karamea, 7% are situated around Lake Brunner and the final 2% are in the Greymouth area.

GROUNDWATER LEVELS AND QUALITY

Groundwater levels lie typically 1.5 – 3.0 m below the surface in spring-fed alluvial plains such as those at Whataroa, Harihari, Kokatahi, Kowhitirangi, Hokitika and Westport. In other areas further inland, such as the raised river terraces of the Grey Valley, the water table is greater than 30 m below the land surface.

A manual Groundwater Level Monitoring Programme was initiated in February 2000. The

James T. 2001: West Coast. *In* Groundwaters of New Zealand, M.R. Rosen and P.A. White *(eds)*. New Zealand Hydrological Society Inc., Wellington. p461-464.

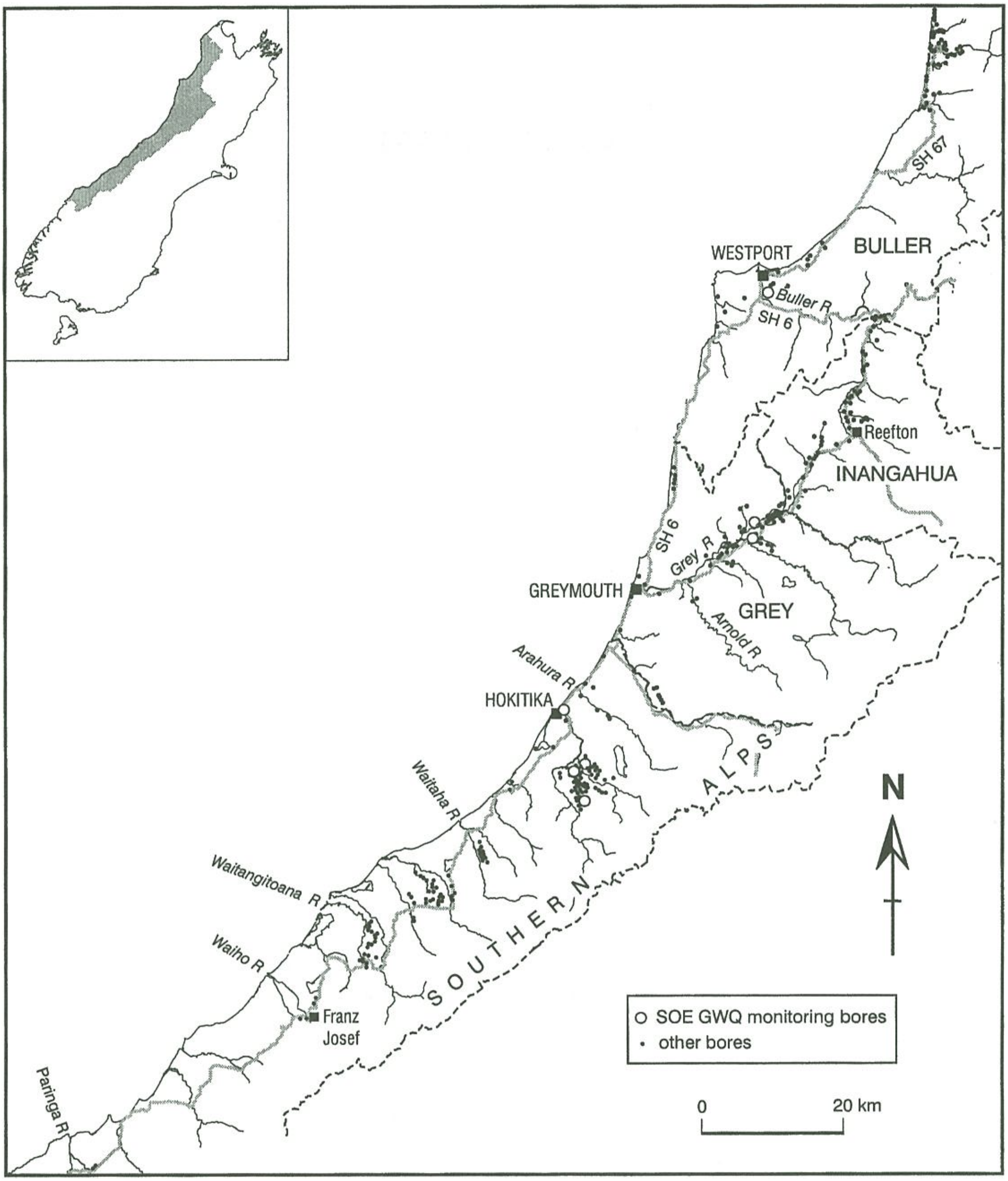


Figure 24.1 *Location of groundwater wells in the West Coast groundwater well inventory. Approximately 300 wells are represented, including the seven wells used for the NGMP and the West Coast State of the Environment Groundwater Quality Monitoring Network (SOE GWQ).*

programme currently monitors 28 bores in the Hokitika and Greymouth valleys to detect seasonal changes in groundwater levels. Following an initial assessment of seasonal groundwater fluctuations, two sites will be selected for continuous measurements to monitor the effects of rainfall and river level fluctuations on groundwater levels.

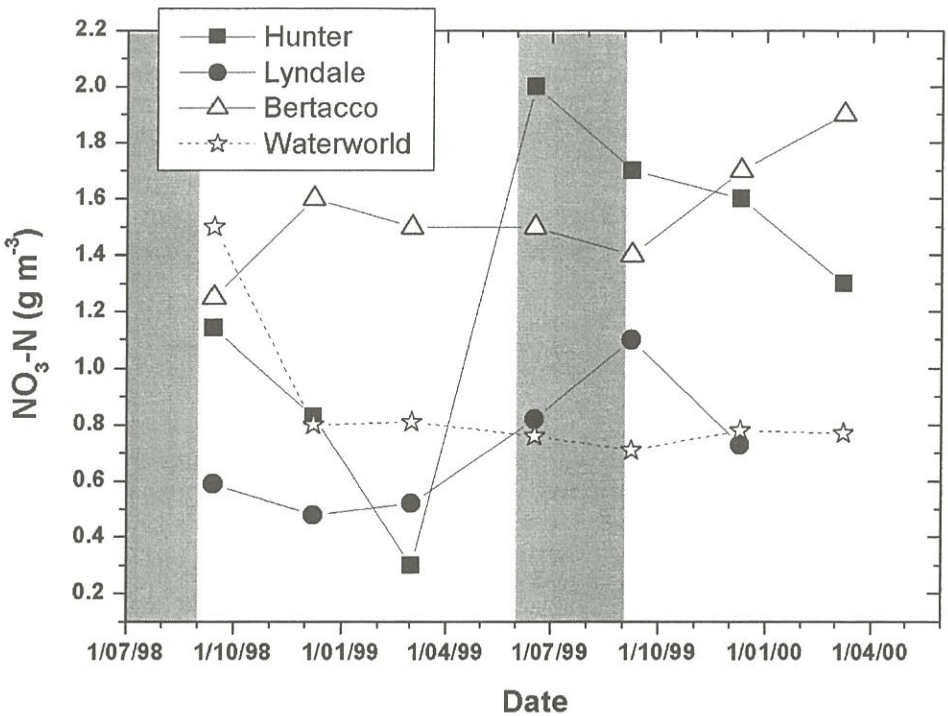


Figure 24.2 *Plot of nitrate-nitrogen concentrations against time for four wells in the West Coast groundwater monitoring network. Some wells show higher NO3-N concentrations in the winter, but the records are not yet long enough to determine accurate trends.*

A groundwater quality monitoring programme was set up in September 1998 to determine the effects of various land uses on groundwater quality and to determine trends in groundwater quality in the region. The West Coast programme was set up in conjunction with the National Groundwater Monitoring Programme (see Chapter 4) and both programmes monitor the same wells. In total, seven bores are monitored throughout the region (Fig 24.1). The following site selection criteria for the West Coast 'State of the Environment' Groundwater Quality Monitoring Programme (SOE GWQ) were considered:

- amount of information supplied in the bore log,
- long term ease of access,
- variety of land uses to be represented in the programme, including reference sites e.g. urban, dairy farming, mining etc.,
- achieving a balance between a reasonable geographic spread of sampling sites versus the practicalities of regular sampling i.e. the cost of driving more than 1.5 hours from Greymouth to any one site. Therefore sites north of 'greater' Westport, east of Reefton and south of Ross were not considered.

Groundwater bore logs were obtained from three of the five drilling companies who construct groundwater supply wells for the West Coast. West Coast Regional Council staff, in conjunction with Institute of Geological and Nuclear Sciences staff, selected a 'short-list' of possible monitoring sites. As most of the existing groundwater production bores in this region are associated with farm dairies, there is therefore a bias towards monitoring this type of site. Five of the seven 'SOE' groundwater bores are located in dairy farms. One bore is located in an urban environment and one in a rural-residential area.

Most wells are relatively shallow, accessing unconfined aquifers. No contamination has

Table 24.1 *Selected groundwater chemistry data from the West Coast groundwater monitoring programme. Median concentrations are in g m^{-3}.*

Well ID	No. of analyses	HCO3	Cl	NO3-N	Na	Ca	Total dissolved Fe	PO4-P
Agnew	7	31	3.3	0.98	3.3	9.8	0.09	<0.03
Anderson	7	32	2.4	0.90	3.3	8.4	<0.02	<0.03
Bertacco	7	35	5.2	1.50	7.8	8.7	0.03	0.03
Hunter	7	39	6.3	1.30	9.4	8.2	0.13	<0.03
Lyndale	6	45	2.4	0.66	2.9	13	0.06	<0.03
Milne	6	30	6.5	0.06	5.5	7.4	0.53	<0.03
Waterworld	7	33	10.4	0.78	10	5.8	<0.02	<0.03

been detected in the seven bores in the programme to date (Table 24.1). Although the mean total dissolved iron concentrations of Milne well is above the NZ Drinking Water Guideline concentrations for staining of laundry (see Chapter 4), the cause of the high iron concentration is due to the naturally low levels of dissolved oxygen in the aquifer. This bore has recently been deepened. As a result, the quality of this groundwater should improve. Presently, there are not enough data to assess long-term trends, but the current information indicates some seasonal variation in nutrient inputs (Fig 24.2).

No pesticides were detected in the December 1999 sampling round of three bores (Agnews, Lyndale and Andersons). Preliminary information suggests that heavy metal contamination of groundwater is present in a few localities associated with historic mining activity. However, the risk posed by the majority of these sites is likely to be low as they are in areas remote from human habitation.

ACKNOWLEDGMENTS

I would like to thank Michael Rosen for providing the water quality information from the NGMP and assisting with the editing of the chapter. Reviews by Dave Murray and Catherine Moore greatly improved the quality of the manuscript. Westmere Drilling Ltd and the West Coast dairy farming community have kindly provided information for West Coast Regional Council's Groundwater Bore Inventory.

REFERENCE

West Coast Regional Council 2000: Groundwater Bore Inventory. Unpublished report RMTR# 0006.

25

Otago

TOM HELLER

INTRODUCTION

Groundwater in Otago provides a source of water supply for both urban and rural areas, and plays an important part in the region's ability to withstand drought in the agricultural sector.

Otago's climate and topography are highly variable, and most surface water resources are heavily utilised, so an alternative to surface water supply is needed in most areas. The Otago region has few large regional aquifers; most aquifers generally lie within a number of disconnected basins (Fig 25.1). These basins are usually associated with glacial outwash or moraine deposits in river valleys. The basins may contain multiple aquifers, depending on the environment in which they were formed. The geology of the Otago region is such that groundwater is present within the substrata in most localities. However, areas where wells are of sufficient capacity to reliably sustain stock water schemes, town supplies or irrigation are limited, because of the low permeability and storage capacity of the strata (Table 25.1).

Geological strata containing aquifers in the Otago region include:

- Quaternary outwash and recent alluvial gravel (unconfined)
- Tertiary units of varying properties (normally confined or semi-confined)
- volcanic deposits
- claybound alluvial gravels and sediments in higher terraces (unconfined)
- other units such as limestones, basal quartz conglomerates and fractured schists.

GEOLOGICAL SETTING

North Otago downlands

The North Otago downland area is tectonically stable with a simple structure and a number of faults, generally trending northwest. Successive formations are nearly horizontal in attitude. Tertiary-age formations are quartz pebbles, sands and clays containing coal seams deposited in fresh water. These beds are lithologically similar to mid-Tertiary beds in the inland basins. Subsequently, the freshwater beds were covered by marine sediments deposited as the sea transgressed over North Otago in the lower Tertiary (Otago Catchment Board and Regional Water Board 1971). Marine deposits include: sulphurous siltstone and mudstone; concretionary sandstone and greensand; and calcareous mudstone and limestone. Submarine eruptions of lava and tuff in the vicinity of Oamaru occurred during the Tertiary period.

The Tertiary sequence is overlain by Pleistocene gravels. Slightly weathered remnants of the Pleistocene gravels remain on high terraces adjoining the major rivers (Otago Catchment Board and Regional Water Board 1971).

Inland basins

In Central Otago, long narrow northeast-trending tectonic basins have been infilled with soft mid-Tertiary sediments and early Pleistocene gravels. The basins are commonly faulted at the margins and are flanked by parallel block mountains of schist. To the north, the basins are bounded by greywacke ranges. The basins contain a succession of terraces, possibly as a result of lateral planation, with a veneer of Pleistocene gravels overlying the Tertiary beds. A coalescing apron of low-angle rock fans occur at the margins of the basins and narrow flood plains of recent alluvium flank most streams (Otago Catchment Board and Regional Water Board 1971).

Heller T. 2001: Otago. *In* Groundwaters of New Zealand, M.R. Rosen and P.A. White *(eds)*. New Zealand Hydrological Society Inc., Wellington. p465-480.

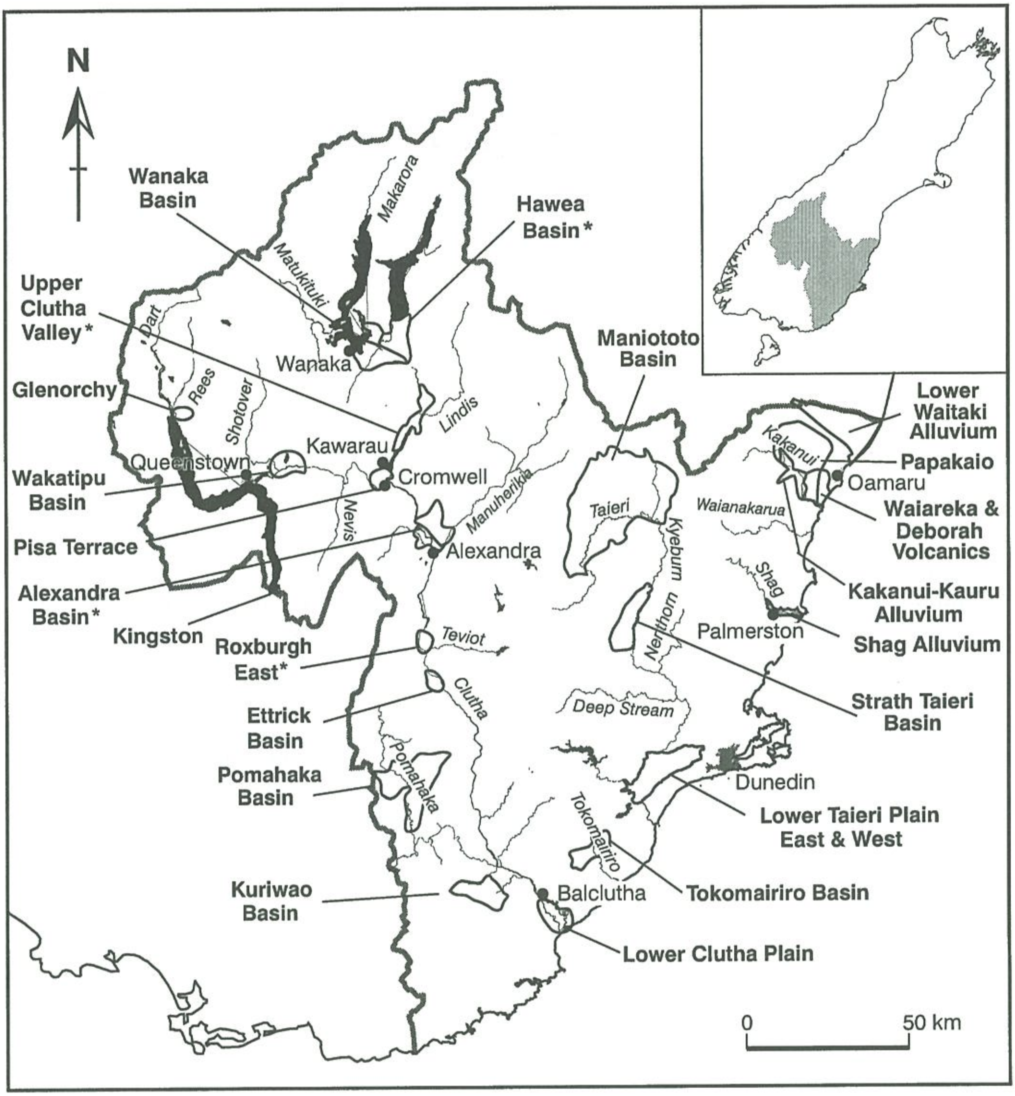


Figure 25.1 *Groundwater basins in Otago*
**Groundwater basins containing more than one designated aquifer. The Alexandra Basin includes Dunstan Flats, Earnscleugh Terrace, Manuherikia Alluvium and Springvale Terrace. The Upper Clutha Valley includes the Lindis and Lowburn valleys. The Hawea Basin includes the Maungawera Valley, Roxburgh East includes Coal Creek Terrace.*

The Taieri Graben

The Taieri Graben is bounded by the Titri and Maungatua faults and has been infilled with Pleistocene and Recent sediments. Estuarine and lacustrine organic muds, oozes, shellbeds and peats are laterally extensive. Interbedded fluviatile gravels, sands and silts occur in narrow elongated channels and lenses. Coarser sediments occur where rivers debouch onto the flood plains (Otago Catchment Board and Regional Water Board 1971).

South Otago basins

Basin areas in South Otago generally contain

Table 25.1 *Stratigraphy and hydraulic properties of aquifer units*

Aquifer basin	Broad lithologic description and geo-hydrologic reference documents	Aquifer type e.g. confined/ semi confined or unconfined	Saturated thickness (m)	Transmis-sivity	Storativity % or Specific (m^2/day) yield	Water age in years
Lower Waitaki Alluvium - Zone A	Quarternary gravels and alluvium (Mason R 1994; Irricon Irrigation Consultants and Landcare Research NZ Limited 1996)	Unconfined	12		20%	
Lower Waitaki Alluvium - Zone B	Quarternary gravels and alluvium, clays and loess sediments (Mason R 1994; Waitaki Catchment Commission 1985)	Unconfined	20			
Waiareka/Deborah Volcanics	Volcanic tuff rock, fractured (Otago Regional Council 1993)	Unconfined	250	10-100	8%	50+
Papakaio Formation	Tertiary basal quartz conglomerate (Otago Regional Council 1993a)	Confined	20-120	70-450	3.6×10^{-4} to 8.5×10^{-4}	5000-30000
Kakanui-Kauru Alluvium	Recent alluvium (Otago Regional Council 1993b)	Unconfined	7	<500	10-20%	
Shag Valley	Recent floodplain alluvium and sediments (Irricon Consultants 1995b)	Unconfined	5			
Tokomairiro Basin	Tertiary: Taratu formation, quartz conglomerate. Quarternary: Fan gravel, alluvium, Loess sediments (Irricon Consultants 1998c)	Unconfined and Semi Confined				
Maniototo Basin	Tertiary and quarternary sediments, sands, gravels, fine lenses, recent alluvium (Stone Environmental Inc 1997a)	Unconfined and Confined				<200-<2000 est
Strath Taieri Basin	Unconsolidated sandy gravel sediments and schist deformations (Stone Environmental Inc 1997b)	Unconfined				<150-600 est
Lower Taieri Plain - East	Alluvial deposits, sands, silts, some clays. Silty colluvium and loess alluvial fans (Irricon Irrigation Consultants and Royds Consulting 1994; Irricon Consultants and Institute of Environmental Science Research 1997a; Otago Regional Council 1999b)	Unconfined, Confined	10-25	500	$1\text{-}5 \times 10^{-4}$	
Lower Taieri Plain - West	Same as for East Taieri including: former depositional environments e.g. lakes/marshes (Irricon Irrigation Consultants and Royds Consulting 1994; Irricon Consultants and Institute of Environmental Science Research 1997a and 1997b; Otago Regional Council 1999b)	Confined	20 +	350-1530	$2\text{-}3 \times 10^{-4}$	
Kingston	Glacial till deposits, alluvial gravels/sands Pea gravels (J K Lindqvist Research 1997b)	Unconfined and semi confined				
Glenorchy	Alluvial fan deposits (J K Lindqvist Research 1997a)	Unconfined				
Wakatipu Basin	Sedimentary alluvial flats and river deposits. Glacial outwash and till, unconsolidated sediments (Rosen et al. 1997; Otago Regional Council 1999a)	Unconfined	5-30			<40

Table 25.1 *Stratigraphy and hydraulic properties of aquifer units. (continued)*

Aquifer basin	Broad lithologic description and geo-hydrologic reference documents	Aquifer type e.g. confined/ semi confined or unconfined	Saturated thickness (m)	Transmis-sivity	Storativity % or Specific (m^2/day) yield	Water age in years
Wanaka Basin	Quaternary glacial outwash sediments and till. Moraine. Recent outwash gravels (Rosen et al. 1997; Otago Regional Council 1999a)	Unconfined	>30			<40
Hawea Basin	Gravels, unconsolidated outwash Moraine and glacial till (Kingston Morrison Ltd 1999c)	Unconfined	20 +	50 – 1900	20%	
Lindis Valley	Moraine deposits and floodplain alluvium (J K Lindqvist Research 1997c)	Unconfined				
Lowburn Valley	Lindis formation clay sandy gravels (J K Lindqvist Research 1997a)	Unconfined	<30			
Manuherikia Alluvium	Floodplain alluvium, clay sandy gravels (Irricon Consultants 1998a)	Unconfined	5-10			
Springvale Terrace	Quaternary: Moraine, till and claybound gravels of fluvio-glacial deposition (Irricon Consultants 1998a)	Unconfined	10-50			
Dunstan Flats Zone A	Quaternary: Moraine, tills, outwash gravels interlain by Manuherikia claybounds (Irricon Consultants 1998a)	Unconfined	5	<300		
Dunstan Flats Zone B	Moraine, till, recent outwash gravels (Irricon Consultants 1998a)	Unconfined	10-15	1000+		
Earnscleugh Terrace	Moraine, till, recent outwash gravels (Irricon Consultants 1998a)	Unconfined	15+	1000-15000		
Coal Creek & Roxburgh East	Unconsolidated Pleistocene outwash gravels, Moraine and glacial till (Irricon Consultants, 1995a; Irricon Consultants 1997; Kingston Morrison 1999d); Otago Regional Council 1999a)	Unconfined	10			
Ettrick Basin	Quaternary outwash gravels and sediments (Irricon Consultants 1995a; Irricon Consultants 1997)	Unconfined	10+			
Pomahaka Basin	Glacial deposits, alluvial sediments and gravels (Kingston Morrison 1999b)	Unconfined		10-126	10%	
Kuriwao Basin	Unconsolidated alluvial, glacial deposits incl schist, argillite rock (Kingston Morrison 1999a)	Unconfined		12-53	10%	
Lower Clutha Plain	Quaternary deposits: Gravel, sand and mud. Quartz, sandstone & schist. Tertiary sediments (Irricon Consulting 1998b)	Unconfined	25+			

surficial Pleistocene outwash gravels and glacial till, which are commonly underlain by weathered faulted gravels and Tertiary sequences of quartz sands, quartzite, clays, lignite seams, and beds of mudstone, sandstone and conglomerate. The regional basement comprises tuffaceous greywacke and argillite, which grades northward into faulted and folded semi-schistose greywacke, non-foliated schist and phyllite (Kingston Morrison Ltd 1999a and 1999b).

AQUIFER REPORTING AND MONITORING

The Otago Regional Council monitors 32 aquifers in Otago that are used extensively

Table 25.2 *Specific monitoring and reporting in selected aquifer basins (Otago Regional Council 1999)*

Aquifer Basin	Wells survey	Piezo-metric data	GW level contours	Hydraulics testing	Water quality	Geology review	Reporting
Lower Waitaki Alluvium	Y	Y	Y	N	Y	Y	Water Quality survey/ Management report
Waiareka/Deborah Volcanics	Y	Y	Y	Y	Y	Y	Investigation report/ Management report
Papakaio Formation	Y	Y	Y	Y	Y	Y	Management report
Kakanui-Kauru Alluvium	Y	L	N	N	L	Y	Management report
Shag Valley	Y	Y	Y	N	Y	N	Preliminary investigation and monitoring review
Tokomairiro Basin	Y	L	L	N	L	N	Preliminary investigation only
Maniototo Basin	Y	Y	Y	N	Y	N	Preliminary investigation and monitoring review
Strath Taieri Basin	Y	Y	Y	N	Y	N	Preliminary investigation and monitoring review
Lower Taieri Plain – East	Y	Y	Y	Y	Y	Y	Preliminary report, monitoring report, investigation reports
Lower Taieri Plain – West	L	Y	Y	Y	Y	Y	Preliminary and monitoring reports
Kingston	Y	Y	Y	N	Y	N	Preliminary investigation only
Glenorchy	Y	Y	Y	N	Y	N	Preliminary investigation only
Wakatipu Basin	Y	Y	Y	N	Y	Y	Preliminary report, monitoring report
Wanaka Basin	Y	Y	Y	N	Y	Y	Preliminary report, monitoring report
Hawea Basin	Y	Y	L	N	Y	N	Preliminary investigation only, monitoring review
Lindis Valley	Y	Y	N	N	Y	N	Preliminary investigation only
Lowburn Valley	Y	Y	N	N	Y	N	Preliminary investigation only
Manuherikia Alluvium	Y	L	Y	N	Y	N	Preliminary investigation only
Springvale Terrace	Y	L	Y	N	Y	N	Preliminary survey only
Dunstan Flats Zone A and B	Y	Y	Y	L	Y	Y	Preliminary investigation, monitoring report
Earnscleugh Terrace	Y	Y	Y	Y	Y	Y	Various reports
Coal Creek and Roxburgh East	Y	Y	Y	N	Y	N	Preliminary investigation and monitoring report
Ettrick Basin	Y	Y	Y	N	Y	N	Preliminary investigation and monitoring report
Pomahaka Basin	Y	L	L	N	L	N	Preliminary investigation only
Kuriwao Basin	Y	L	L	N	L	N	Preliminary investigation only
Lower Clutha Plain	Y	L	N	N	L	N	Preliminary investigation only

Y= to a reasonable detail, L= information gained but limited, N = not known

(Otago Regional Council 1999c) (Table 25.2). The council's monitoring programme, and the location of monitoring sites, is determined by factors such as: the intensity of groundwater use and degree of local dependency on groundwater; the level of aquifer stress; the complexity of the aquifer system; the type of information sought; and budgetary constraints. Aquifer hydraulic properties can be difficult to measure, particularly in groundwater basins with multiple aquifer systems (Fig 25.2), for example, the Alexandra basin (Irricon Consultants 1998a).

Groundwater modelling

Regional aquifers that have been modelled include: the Papakaio Formation to understand the water balance; Kakanui/Kauru to estimate the water balance and to understand groundwater/surface water interaction; Lower Taieri West to model the impact of groundwater development options; Dunstan Flats to model

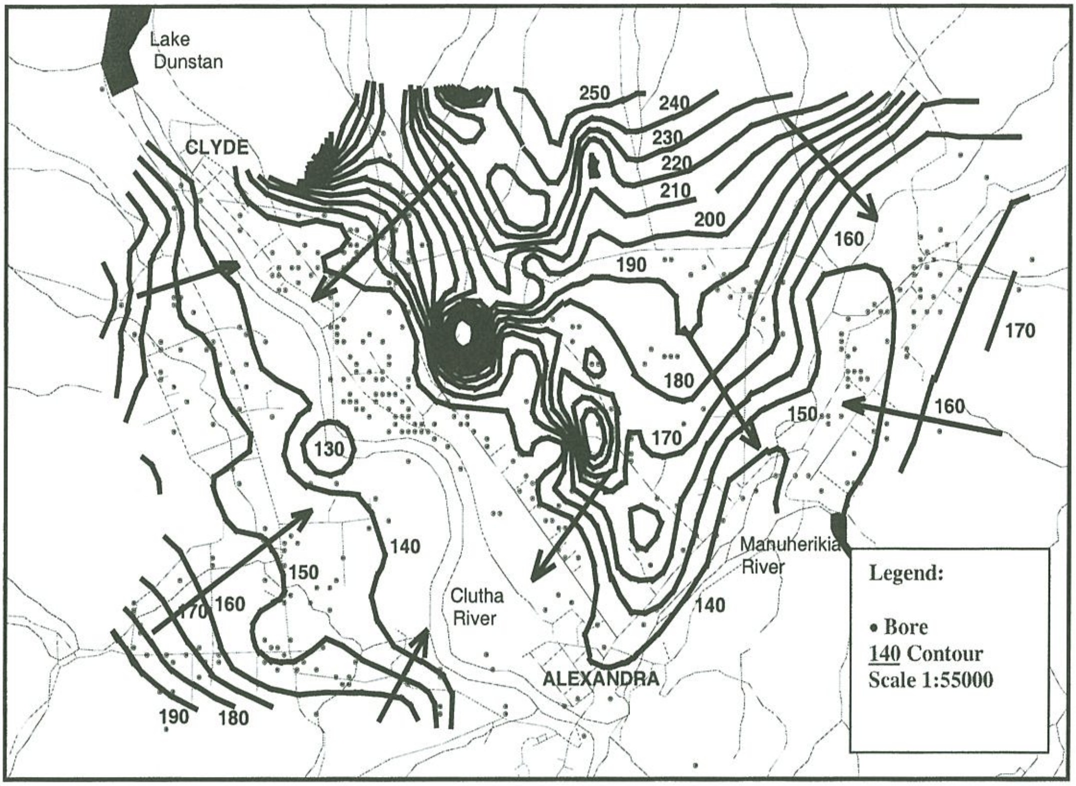


Figure 25.2 *Example of monitoring undertaken in the Alexandra basin, with the groundwater contour map at 10 metre intervals showing indicative groundwater direction and height relative to mean sea level.*

the effects of deepening the Clyde Dam tailrace on groundwater levels; and Earnscleugh Terrace where the effects of deepening the Clyde Dam tailrace and the effects of mine dewatering were modelled.

GROUNDWATER USE AND WATER BALANCE

Most aquifers in Otago are used for potable water supply where water is of sufficient quality. Other uses include irrigation, stock water, and dairy shed wash-down. There are limitations on abstractions from some Otago aquifers.

Table 25.3 summarises information on water uses and aquifer water balance. In most aquifers, recharge rates are well in excess of abstraction rates. However, prolonged dry spells, coupled with limited storage capacity in aquifers, can cause shortfalls in groundwater supply and increase competition for available groundwater resources.

GROUNDWATER LEVEL

The most notable changes in groundwater level are in heavily used aquifers or in those that are more susceptible to drought. Table 25.4 summarises aquifer status or levels where data is available. The most significant changes are in three aquifers: the Ettrick Basin, the Waiareka/Deborah volcanics and the Papakaio Formation.

Ettrick Basin groundwater levels

The average rate of decline of groundwater level is 225 mm/year since 1996 in the Ettrick basin (Fig 25.3).

In the latter stages of the 1998/99 irrigation

Table 25.3 *Water use and water balance information from selected aquifers.*

Aquifer/ Basin	Water uses	Reported annual average use million m³	Estimated average annual recharge million m³	Recharge sources	Significant outflows
Lower Waitaki Alluvium Zone A and B	stockwater dairy shed, domestic supply		115	Waitaki irrigation scheme and Awamoa Stream	Waitaki river, Welcome Creek, Pacific Ocean
Waiareka/Deborah Volcanics	irrigation, stock water	1.4	2.7	Rainfall/Inter-aquifer transfer	Awamoa Ck, Waiareka Stream, Oamaru Ck, Pacific Ocean
Papakaio Formation	irrigation, stock water	1.3	4.5	Rainfall to unconfined outcrop	Kakanui river, Waiareka Volcanics, Waiareka Stream
Kakanui-Kauru Alluvium	irrigation, stock water domestic, town water supply	1.1		Kakanui River, Kauru River	Kakanui River, Unnamed Stream
Shag Valley	domestic and stock water town water supply, irrigation, domestic			Shag River and tributaries	Shag River
Tokomairiro Basin	domestic, stock water, dairy shed and irrigation	0.08	4		Tokomairiro River
Maniototo Basin	domestic & stock water, dairy shed, irrigation			Rainfall, tributaries of Taieri River	Taieri River
Strath Taieri Basin	domestic and stock water				Taieri River
Lower Taieri Plain – East	domestic and stock water, town supply industrial/ commercial irrigation dairy farm supply	2.4	3.2	Silverstream River 80%, Mill Creek	Taieri River, West Taieri Aquifer
Lower Taieri Plain – West	domestic and stock water dairy shed	0.24		Taieri River, Waipori River, East Taieri aquifer	Taieir River, West Taieri Drainage scheme
Wakatipu Basin	domestic supply, stock water, irrigation			Mill Creek	Mill Creek, Shotover River, Arrow River, Lake Hayes
Wanaka Basin	domestic & stock water, irrigation			Cardrona River	Cardrona River, Lake Wanaka, Bullock Ck, Clutha River
Hawea Basin	domestic & stock water, irrigation	0.64	51	Lake Hawea, tributaries of Hawea River	Hawea, Clutha rivers
Lowburn Valley	domestic water supply, stock water, irrigation			Lowburn River, Lake Dunstan	Lowburn River, Lake Dunstan
Manuherikia Alluvium	domestic, stock water, irrigation, public water supply			Galloway scheme irrigation by-wash, some leakage by small tribs of Manuherikia River	Manuherikia River
Springvale Terrace	domestic, stock water, irrigation, public water supply			Springvale scheme irrigation by-wash	Manuherikia River, Waikerikeri Stream
Dunstan Flats Zone A and B	domestic and stock water, irrigation			Irrigation by-wash from Springvale, Waikerikeri Creek	Clutha River

Table 25.3 *Water use and water balance information from selected aquifers. (continued)*

Aquifer/ Basin	Water uses	Reported annual average use million m^3	Estimated average annual recharge million m^3	Recharge sources	Significant outflows
Earnscleugh Terrace	domestic, stock water irrigation			Fraser River, Earnscleugh scheme irrigation by-wash	Clutha River
Coal Creek and Roxburgh East	domestic, stock water, irrigation			Coal Creek artificial recharge	Clutha River
Ettrick Basin	domestic, stock water, irrigation			Bengerburn River	Clutha River
Pomahaka Basin	domestic, dairyshed, stock water	0.09	92.0		Pomahaka River
Kuriwao Basin	domestic, dairyshed, stock water	0.03	29.3		Waiwera River, Kaihiku Stream

Table 25.4 *General trends in groundwater level in selected basins.*

Aquifer/ Basin	Current trend 1998/99	Historic trend last 5 yrs+	Reason for trend	Possible solution or mitigation required
Lower Waitaki Alluvium Zone A and B	Static, seasonal variation	Some increase in levels due to irrigation by-wash	Adequate recharge/ irrigation surplus	
Waiareka/ Deborah Volcanics	Falling 850mm/ year	General decline	Lack of rainfall recharge	Restrictions on takes, allocation limit review
Papakaio Formation	Falling 200mm/ year	Decline in pressures since early 90s	Increased water usage	Restrictions on takes, allocation limit review
Shag Valley	Static	Reduction in levels by 200mm	Low Shag River flows	Groundwater takes linked to surface water management
Maniototo Basin	Static		Limited use	
Lower Taieri Plain – East	Falling 350mm/ year	Small decline	Lower recharge, increased use	Review of water balance
Lower Taieri Plain – West	Falling 550mm/ year	Small decline	Lower than average recharge, increased use	Review of water balance and allocation limit
Wakatipu Basin	Static	General decline	Increasing use	Bore siting, abstraction limitations
Wanaka Basin	Static	Increase in level	Adequate recharge	
Dunstan Flats Zone A and B	Static	General decline	Increased number of bores/ takes, reduction in irrigation recharge, Possible effects of Clyde dam tailrace deepening	Bore siting, review of allocation limit
Earnscleugh Terrace	Static	General decline	Reduction in irrigation recharge, possible effects of tailrace deepening	
Coal Ck and Roxburgh East	Static	Static	Artificially recharged	
Ettrick Basin	Falling	General decline by 1.0 m	Reduction in recharge from Bengerburn River, increased use	Allocation limit review

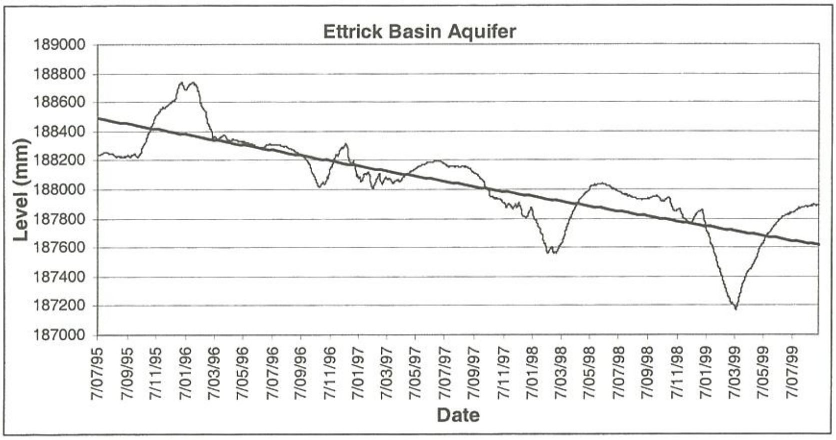


Figure 25.3 *Recent groundwater level trend and linear trend line in the unconfined Clutha outwash gravels, Ettrick basin.*

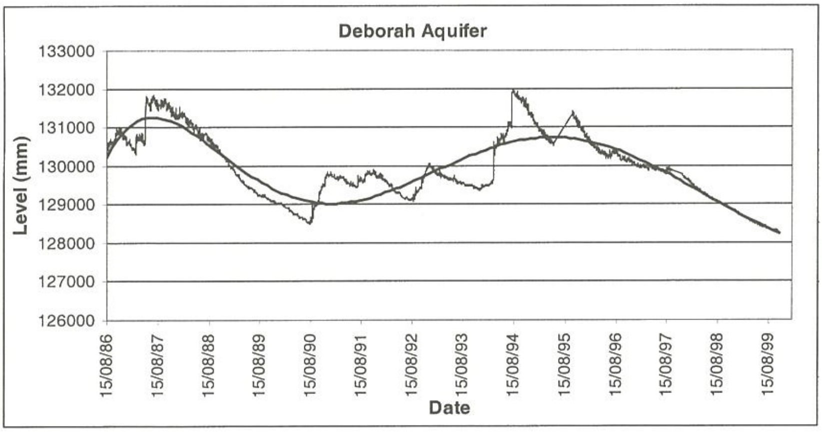


Figure 25.4 *Groundwater level trend and polynomial trend line in the Deborah volcanic aquifer*

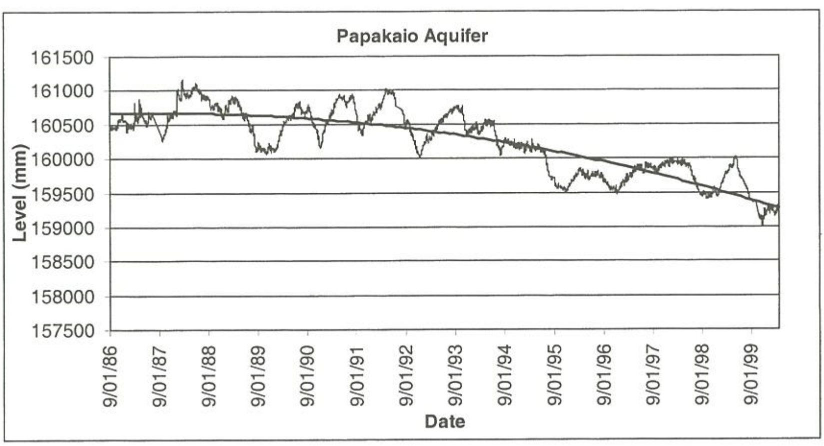


Figure 25.5 *Groundwater trend and polynomial trend line in the Papakaio aquifer*

season, the lowest recorded level within the aquifer was 187.2 metres, which is 1.5 metres below the full storage level. The level was only 0.5 metres above the nominated level for a 25% restriction in aquifer use in the Proposed Regional Plan: *Water for Otago* (Otago Regional Council 1998a and 1998b).

A significant source of recharge, the Bengerburn River, was reported to have continual flow throughout the 1998/99 low flow period, with normally dry reaches continuing to flow during the summer. This may indicate that the river-bed has become clogged by fine sediment due to the prolonged periods of low flows, thus reducing aquifer recharge.

Deborah/Waiareka volcanic aquifers groundwater levels

Piezometric levels in the Deborah/Waiareka volcanic aquifers of North Otago have declined steadily since October 1995 (Fig 25.4), reducing bore yields in most cases.

Some wells have failed, and have been deepened or re-drilled. Wells drilled to depths of up to 120 metres tap poorer quality groundwater and one bore produces water unsuitable for irrigation due to a high concentration of sodium. Implications of this trend to drilling deeper bores include an increased rate of head decline in some parts of the aquifer from the overall deepening of bores. This could lead to salt water intrusion and/or a decrease in aquifer water quality by tapping older waters.

Papakaio aquifer groundwater levels

Water levels in wells in the Papakaio Formation (a confined aquifer system) have shown a decline since November 1991 (Fig 25.5). This trend coincides with increased use, and lower-than-average rainfall recharge for the November 1991 to July 1999 period. Levels in the aquifer are now 1 – 1.5 metres below the aquifer full storage level. This represents a significant loss of groundwater from storage, as the aquifer is elastic and able to yield large volumes initially for a given reduction in head (Jacob 1940).

GROUNDWATER QUALITY

Most aquifers in Otago have water quality of potable standard with the exceptions of some

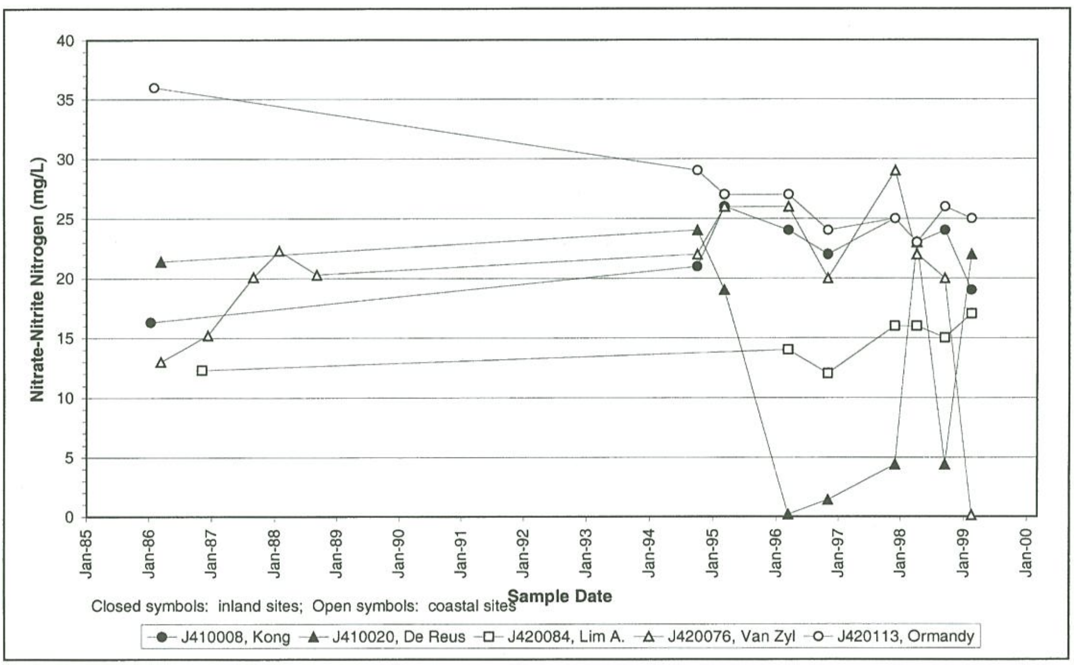


Figure 25.6 *Time series plot for NNN – Deborah volcanic aquifer*

Table 25.5 *Water quality limitations in reported aquifers (where applicable)*

Aquifer/ Basin	Water quality problem	Source of problem	Suggested mitigation
Lower Waitaki Alluvium	bacteria, nitrates, ammonia	Dairy shed effluent, offal pits, soak pits, Septic tanks, well head protection	Consent requirements in groundwater protection zone, well construction standards
Deborah/Waiareka Volcanics	nitrates, high chlorides, sodicity, SAR, EC, bacteria	Fertilizer leaching, dissolution of salts, saline environment	Appropriate nutrient budget, SAR testing for all consents
Papakaio Formation	low pH, high iron & manganese/aluminium, high sulphate & chloride	Dissolution of salts, water age	Test requirement for all consent applications, possible on-site treatment
Lower Taieri Plains	nitrates, iron & EC, manganese, TDS, salinity	Surface recharge pollutants, leachates, land use activities, saline environment	Control of discharges in protection zone, minimum head levels to prevent saline mixing
Kingston	low level bacteria, nitrates	septic tank/outfalls	Control of bore placement via land use consents
Wakatipu Basin	bacterial contamination, nitrates, ammonia	Well head protection, high water table, septic tank/outfalls	Bore placement criteria via land use consents
Coal Ck and Roxburgh East and Ettrick Basin	Nitrates	Land use, fertilizer application, on site effluent disposal	Consent requirement in protection zone
Pomahaka Basin	Nitrates	Land use, fertilizer application, on site effluent disposal, dairy shed effluent	Appropriate nutrient budget, control of dairy discharges
Kuriwao Basin	low level nitrates, chlorides, TDS, hardness	Land use activities, shallow water table, dissolution of salts	Routine testing of water quality for consents process
Lower Clutha Plain	salinity, manganese	Dissolution of salts, sea water intrusion	Minimum pumping levels for coastal bores

Table 25.6 *Groundwater quality statistics for selected aquifers (Otago Regional Council 1999c)*

Aquifer zone or basin	Statistic	Electrical Conductivity (Ms/m)	Nitrate-Nitrite Nitrogen (mg/L)	Dissolved Reactive Phosphorus (mg/L)	Chloride (mg/L)	Sulphate (mg/L)	Sodium (mg/L)	Magnesium (mg/L)	Faecal Coliforms (cfu/ 100 mL)
Lower Waitaki Zone A and B	Min	6	0.013	0.001	1	4.2	2	0.001	0
	Max	25	6	0.061	15	22	2.3	5.8	1600
	Mean	14	2.5	0.014	5.5	10.9	9.3	2.9	24.5
	Median	13	2.5	0.006	3.9	10.8	7	2.8	1
Papakaio Formation	Min	39	0.003	0.001	59	81	35	15	0
	Max	140	4.5	0.127	370	437	159	57	0
	Mean	97	0.26	0.04	180	200	99	23.6	0
	Median	96	0.08	0.017	162	199	97	23.5	0
Waiareka and Deborah Volcanics	Min	27	0.01	0.001	2.4	0.8	1.5	0.27	0
	Max	150	36	0.7	946	455	1230	65	530
	Mean	115	15	0.059	113	40.3	110	28.6	35.5
	Median	92	14	0.027	84	25	77	28.5	1
Kakanui-Kauru Alluvium	Min	5.8	0.1	0.005	4.2	3.1	5.1	1.1	0
	Max	48.8	10.8	0.028	96	58	48.5	22	350
	Mean	15	1.7	0.015	23.3	12	17.4	4.9	70
	Median	7.5	1.1	0.014	10	5.7	11.5	1.9	1

Table 25.6 *Groundwater quality statistics for selected aquifers (Otago Regional Council 1999c) (continued)*

Aquifer zone or basin	Statistic	Electrical Conductivity (Ms/m)	Nitrate-Nitrite Nitrogen (mg/L)	Dissolved Reactive Phosphorus (mg/L)	Chloride (mg/L)	Sulphate (mg/L)	Sodium (mg/L)	Magnesium (mg/L)	Faecal Coliforms (cfu/ 100 mL)
Shag Valley	Min	7	0.003	0.001	12	1.3	12	-	1
	Max	62	20	0.008	260	140	240	-	6500
	Mean	21	4.2	0.002	200	120	120	-	193
	Median	17	1.2	0.001	162	93	110	-	1.5
Lower Taieri Plains	Min	3	0	0	7.6	0	6.6	-	0
	Max	162	11	0.17	1600	160	970	-	1900
	Mean	40	1.9	0.03	67	13	70	-	42
	Median	30.5	0.27	0.008	27	9	28	-	1
Maniototo and Strath Taieri	Min	4.7	0	0	3.3	0.8	5.6	1.9	0
	Max	57.9	17	0.19	98	140	200	3.3	16
	Mean	22	2.2	0.03	25.6	26.8	29	8.2	1.4
	Median	16	1.7	0.022	16	9.9	21	5.4	0
Tokomairiro	Min	8.9	0	0.001	11	1.2	5.3	1.5	-
	Max	42.8	2.5	0.038	60	26	41	14	-
	Mean	24.3	0.4	0.013	37.7	8.5	29	6.7	-
	Median	23.7	0.018	0.005	36	7.3	27	5.8	-
Lower Clutha and Pomahaka and Kuriwao	Min	7.6	0	0	6	0	6.7	0.6	0
	Max	330	12	0.23	2700	270	1400	170	1100
	Mean	37	2.4	0.018	78	17.6	51	8.5	55.8
	Median	18	1.7	0.009	18	6.6	15	4.6	1
Ettrick and Roxburgh	Min	5.1	0.01	0	4.9	0	6.7	2.7	0
	Max	61.8	6.7	0.046	56	27	34	7.3	42
	Mean	24.4	3.4	0.005	16.3	12	15.8	4.4	1.9
	Median	19.5	2.7	0.005	15	11.9	12	3.2	0
Alexandra Basin	Min	1	0.047	0	0.7	1	1.7	1.2	-
	Max	50.5	5.2	0.14	55	85	53	29	-
	Mean	11	1.18	0.028	7.3	10.5	11.3	6.2	-
	Median	10.7	0.9	0.006	3.2	6.2	7.8	4.8	-
Wakatipu Basin	Min	5	0.007	0	0	1.7	1.6	0.5	0
	Max	58.2	14	0.054	13	74	23	15	2400
	Mean	22.4	1.9	0.004	2.26	14.2	4.5	3.8	24.5
	Median	20.3	1.4	0.002	2.15	9.5	4.5	3.1	1
Kingston and Glenorchy	Min	1	0.005	0	0	0	1	0.6	0
	Max	33.7	0.81	0.012	3.1	5.4	5.8	3.6	6
	Mean	12	0.21	0.005	1.5	2.1	2.7	2	0.5
	Median	10	0.095	0.004	1.3	1.5	2.5	1.6	0
Lowburn/ Lindis and Tarras/ Cromwell	Min	7.6	0.16	0	0.8	3	3.8	2	0
	Max	61	3.3	0.1	13	56	26	23	72
	Mean	25.7	1.12	0.007	3	9.8	9.8	7.1	7.3
	Median	22	1.1	0.002	2.9	6.5	9.3	5.2	0
Hawea	Min	9	0.025	0	0	0.8	1.9	1.8	-
	Max	23	2.2	0.1	4	13.1	9.7	6	-
	Mean	14	0.8	0.019	0.8	5.3	3.6	2.9	-
	Median	11	0.6	0.001	0.5	3.8	2.4	2.1	-
Wanaka	Min	2.9	0	0	0	1.2	2	1	0
	Max	72	42	0.1	32	97	21	21	14000
	Mean	21.4	1.7	0.003	1.4	14.7	5.5	4.6	113.7
	Median	15	0.6	0.002	0.8	4.4	3	2.2	0

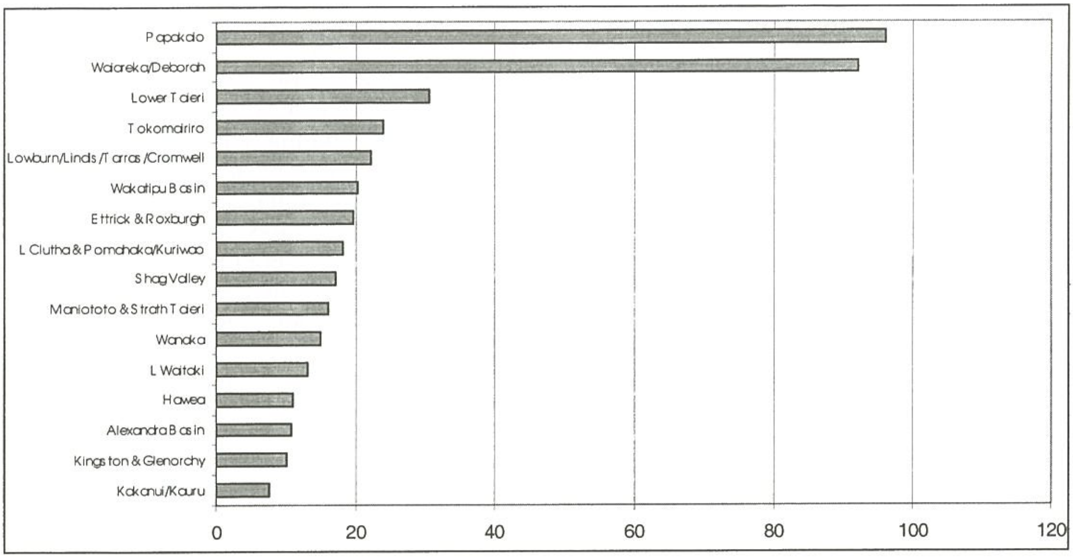


Figure 25.7 *Median EC values in ms/m for selected aquifers*

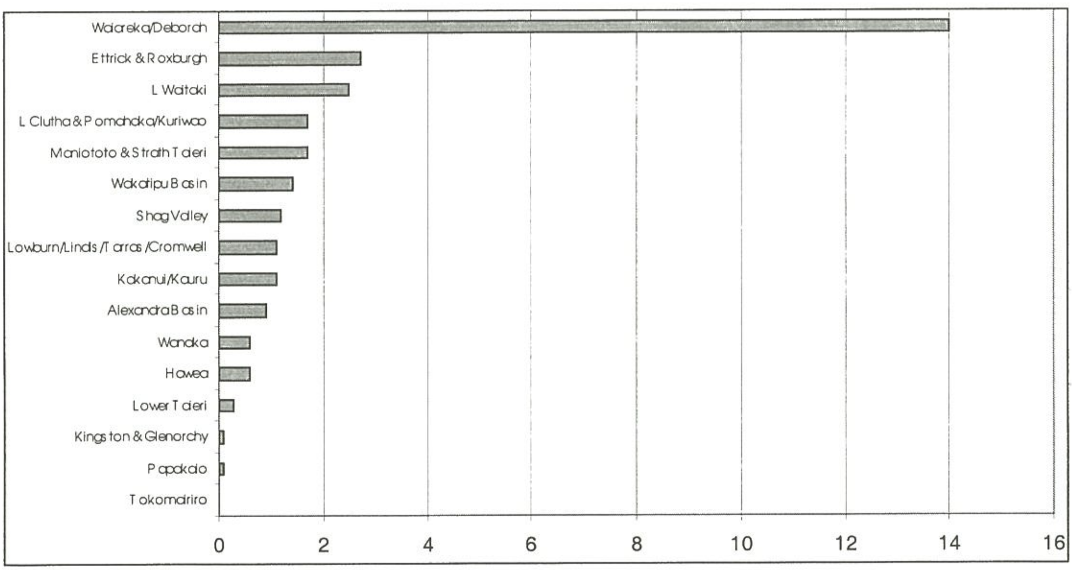


Figure 25.8 *Median NNN values in mg/L for selected aquifers*

deep artesian sources, volcanic aquifers and sites where groundwater is derived from marine sediments. Table 25.5 lists some common water quality problems in Otago aquifers and Table 25.6 gives summary statistics of water quality variables for selected aquifers.

Figures 25.7 and 25.8 present median values for electrical conductivity (EC) and nitrate-nitrite nitrogen (NNN) in specific aquifer basins. Potentially the poorest quality groundwater in Otago is in the Waiareka/Deborah, Papakaio, Ettrick/ Roxburgh and Lower Waitaki aquifers. Electrical conductivity in the Papakaio and Waiareka/Deborah is very high, with the Waiareka/Deborah also reflecting significant nitrogen levels. The Ettrick/Roxburgh and Lower Waitaki aquifers also show elevated nitrogen levels. Figure 25.6 shows how nitrogen levels in some wells in the Deborah aquifer have varied between 1985 and 1999.

Intensive agricultural development and applications of nutrient-rich fertiliser are the cause of these elevated NNN levels (Otago Regional Council 1998c). Other aquifers that show a minor elevation of nitrogen levels include the South Otago aquifers, Maniototo basin, Strath Taieri and Wakatipu basins (Table 25.6).

GROUNDWATER MANAGEMENT

The Otago Regional Council manages the taking of groundwater so that the total take does not exceed the annual renewable yield, surface water resources are not extensively depleted, groundwater or surface waters are not contaminated (including saline intrusion), and soil degradation is avoided (Otago Regional Council 1998a).

Various aquifers in Otago have specific management criteria that are controlled through resource consents. Some groundwater abstractions are controlled to reduce effects on nearby surface water sources; other general management criteria are specified in the Proposed Regional Plan: *Water for Otago* (Otago Regional Council 1998a and 1998b) including criteria for bore drilling, groundwater take, and discharge to land in groundwater protection zones (Table 25.7).

Permitted takes for groundwater

The taking of groundwater in Otago up to specified maximum rates and volumes is permitted without a resource consent, providing no lawful take of water is adversely affected as a result. The take is restricted to one bore from any landholding, and back flow of any contaminated water to the aquifer is not permitted (Otago Regional Council 1998a).

Table 25.7 gives rates of permitted take for each aquifer. Other permitted rates of take not listed in Table 25.7 include:

- Lower Clutha Plain, 3.5 L/s to a maximum of 50000 L/day
- Maniototo Basin Tertiary Aquifer, Wanaka Basin, Earnscleugh Terrace and Pomahaka and Kuriwao basins, 2.5 L/s to a maximum of 30000 L/day
- Manuherikia alluvium and Springvale areas, 1.5 L/s, to a maximum of 10000 L/day
- Elsewhere in Otago the take should be no greater than 1.5 L/s, to a maximum of 25000 L/day.

Bore construction and drilling

The construction of a bore is a controlled activity, requiring a resource consent specifying siting, construction and operation details. Drilling where no water is to be taken is permitted provided no contaminants enter the hole at any level, the hole is sealed when the work is done, and the drilling does not occur over zoned areas that require a resource consent (Otago Regional Council 1998a).

Control of discharges and excavations

The discharge of human sewerage is permitted for a single dwelling, as long as the septic tank and disposal field are more than 100 metres from any bore. The discharge of agricultural waste (e.g. offal pits) must be at least 100 metres from any bore, and the discharge of animal waste or effluent must not be within 100 metres of any bore, and not in any Groundwater Protection Zone A without a resource consent (Otago Regional Council 1998a).

Excavations in a Protection Zone A or B must comply with Territorial Local Authority land-use consents.

Limits of acceptable interference

The criteria for acceptable interference be-

Table 25.7 *Management criteria placed on specific aquifers/groundwater related activities in Otago*

Aquifer/ Basin	Management type or issue	Management criteria or requirement	Anticipated environmental result
Lower Waitaki Alluvium	Groundwater quality protection. Permitted takes in Zone A 3.5 L/s, 50000 L/day Zone B 2.5 L/s, 30000 L/day	Controls on land based discharges and excavations in protection zones	Continued use for potable supply, maintenance of quality
Deborah/ Waiareka Volcanics	Groundwater abstraction/ allocation limit, continued access to supply, effects on soils (SAR) of poor quality groundwater, salinity	Stepped reductions in commercial takes given key groundwater levels, water quality sampling required for all takes, minimum pumping levels near coast	Maintenance of supply to most consumers, protection of degrading groundwater quality, mitigate saline intrusion
Papakaio Formation	Groundwater allocation limit, bore standards, groundwater quality. Permitted take 2.5 L/s 30000 L/day	Stepped reductions in commercial takes given key groundwater levels, minimum standards for bore construction, allocation limit	Maintain artesian flow rates, maintain base flow to Kakanui River, avoid risk of aquifer compression, resource managed within sustainable limits
Kakanui-Kauru Alluvium	Effects on surface waters. Permitted take 1.5 L/s, 10000 L/day	Takes subject to Kakanui River management/minimum flows	Preservation of flow in Kakanui River
Shag Valley	Effects on surface waters. Permitted take 1.5 L/s, 10000 L/day	Takes subject to Shag River management/minimum flows	Preservation of flow in Shag River
Lower Taieri Plains	Depletion of surface waters, potential for contamination, salinity, bore leakage. Permitted take 2.5 L/s 30000 L/day	Stepped reductions in commercial takes given key groundwater levels, protection zones to control discharges and excavations, bore certification program, minimum pumping levels.	Maintain minimum flows in Silverstream and Taieri Rivers, maintain artesian flow rates and aquifer yield, maintain potable quality where applicable, avoid risk of aquifer compression, risk of saline intrusion or flow reversal minimized.
Hawea Basin	Cumulative effect of takes. Permitted take Zone A 1.5 L/s, 10000 L/day, Zone B 2.5 L/s, 30000 L/day	Higher order of interference criteria placed on takes in Zone A.	Minimize bore interference
Wakatipu Basin	Groundwater quality protection, cumulative effect of takes. Permitted take 1.5 L/s, 10000 L/day	Bore construction standards, protection zone to control discharges	Bore interference minimized, improvement in levels of Bacterial and Nutrient contamination
Dunstan Flats	Cumulative effect of takes. Permitted take Zone A 1.5 L/s, 10000 L/day, Zone B 2.5 L/s, 30000 L/day,	Higher order of interference criteria placed on takes in Zone A	Minimize bore interference
Coal Ck and Roxburgh East	Permitted take 1.5 L/s, 10000 L/day. Groundwater quality protection, aquifer yield	Stepped reductions in commercial takes given key groundwater levels, protection zone to control discharges and excavations	Maintenance of supply for consumers, potable supply maintained, bore interference minimized
Ettrick Basin	Depletion of surface waters, groundwater quality protection, aquifer yield	Stepped reductions in commercial takes given key groundwater levels, protection zone to control discharges and excavations	Maintenance of supply for consumers, surface flows in Bengerburn River not adversely affected, potable quality maintained

Note: The location of Groundwater Protection Zones A & B are detailed in the Proposed Regional Plan: Water for Otago (Otago Regional Council 1998b). Aquifers with specific protection zoning for control of discharges and excavations are also detailed in Table 25.7.

tween bores is based on the rate of draw-down per day exerted on any neighbouring bore by the pumped bore (Freeze and Cheery 1979). For unconfined conditions the rate of interference is I=T/5000, and for confined conditions: I=T/500 (I = maximum permitted interference rate in metres/day, T= Transmissivity in m^2/day). The average slope on the time/drawdown graph for any observation bore should not exceed the calculated interference rate. These formulae are used as a guide only for the placement of new bores and the expected level of information required for resource consent applications (Otago Regional Council 1998a).

Saline intrusion in coastal aquifers

For bores within 1000 metres of the coast, a minimum elevation of pumped water level above mean sea level in metres must be maintained. Placing bores less than 150 metres from the coast is a discretionary activity. The general formula applied to potential areas of saline intrusion (Fetter 1988) is:

Minimum elevation (m) = Distance from coast (m)/150

This formula is applicable in coastal aquifers having a hydraulic gradient of approximately 0.01 (Irricon Irrigation Consultants Landcare Research (NZ) Ltd, 1996).

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REFERENCES

FETTER, C. W. 1988: Applied Hydrogeology. Second edition: Merril Publishing Company, Columbus, Ohio. 592p.

FREEZE, R. A.; CHERRY, J. A. 1979: Groundwater. Prentice Hall, Inc, Englewood Cliffs, N.J. 640p.

IRRICON IRRIGATION CONSULTANTS; ROYDS CONSULTING 1994: Lower Taieri Groundwater: Preliminary Study. 80p.

IRRICON CONSULTANTS 1995a: Ettrick and Coal Creek Groundwater. 18p.

IRRICON CONSULTANTS 1995b: Shag Valley Groundwater. 10p.

IRRICON IRRIGATION CONSULTANTS, LANDCARE RESEARCH (NZ) LIMITED 1996: Recommendations for Management and Protection of Groundwater in Otago. 68p.

IRRICON CONSULTANTS 1997: Ettrick and Coal Creek Groundwater: A Review and Proposal for Further Investigations August 1997. 40p.

IRRICON CONSULTANTS; INSTITUTE OF ENVIRONMENTAL SCIENCE RESEARCH 1997a: Lower Taieri Groundwater Study. 118p.

IRRICON CONSULTANTS; INSTITUTE OF ENVIRONMENTAL SCIENCE RESEARCH 1997b: West Taieri Groundwater Yield Investigations and Review of Lower Taieri Monitoring Requirements. 53p.

IRRICON CONSULTANTS 1998a: Groundwater of the Alexandra Basin: A Preliminary Survey. 66p.

IRRICON CONSULTANTS 1998b: Groundwater of the Lower Clutha Plain: A Preliminary Survey. 36p.

IRRICON CONSULTANTS 1998c: Groundwater of the Tokomairiro Plain: A Preliminary Survey. 45p.

JACOB, C. E. 1940: The Flow of Water in an Elastic Artesian Aquifer. Transactions. American Geophysical Union, on.22. 586p.

J K LINDQVIST RESEARCH 1997a: Groundwater Investigations 1996/97 Glenorchy. 30p.

J K LINDQVIST RESEARCH 1997b: Ground Water Investigations 1996/97 Kingston. 28p.

J K LINDQVIST RESEARCH 1997c: Ground Water Investigations 1996/97 Lindis (Ardgour Valley). 30p.

J K LINDQVIST RESEARCH 1997d: Groundwater Investigations 1996/97 Lowburn Valley. 30p.

KINGSTON MORRISON LTD 1999a: Kuriwao Basin Groundwater Report. 23p.

KINGSTON MORRISON LTD 1999b: Pomahaka Basin Groundwater Report. 23p.

KINGSTON MORRISON LTD 1999c: Hawea Basin Groundwater Report. 23p.

KINGSTON MORRISON LTD 1999d: Roxburgh East Groundwater Report. 20p.

MASON, R. 1994: Lower Waitaki Plains Groundwater Quality Survey Report 1993-1994. 13p.

OTAGO CATCHMENT BOARD AND REGIONAL WATER BOARD 1971: The Water Resources of Otago: NZIAS Otago Section Miscellaneous Report. 70p.

OTAGO REGIONAL COUNCIL 1993a: North Otago Groundwater Investigation - Volume I: Main Report. 231p.

OTAGO REGIONAL COUNCIL 1993b: North Otago Groundwater Investigation - Volume II: Appendices. 224p.

OTAGO REGIONAL COUNCIL 1998a: Proposed Regional Plan: Water. 520p.

OTAGO REGIONAL COUNCIL 1998b: Proposed Regional Plan: Water – Maps. 40p.

OTAGO REGIONAL COUNCIL 1998c: Proposed Regional Plan: Water - Background Report 3: Groundwater. 68p.

OTAGO REGIONAL COUNCIL 1999a: Clutha River Catchment Monitoring Report (in Press). 214p.

OTAGO REGIONAL COUNCIL 1999b: Taieri River Catchment Monitoring Report (in Press). 153p.

OTAGO REGIONAL COUNCIL 1999c: Otago's Groundwater Resource. 28p.

ROSEN, M.R.; REEVES, R.R.; STEWART, M.K.; TAYLOR, C.B. 1997: Ground water quality of the Wanaka and Wakatipu Basins, Central Otago, New Zealand. Institute of Geological and Nuclear Sciences science report 97/1. 98p.

STONE ENVIRONMENTAL INC. 1997a: Groundwater Study of the Maniototo Basin. 76p.

STONE ENVIRONMENTAL INC. 1997b: Groundwater Study of the Strath Taieri Basin. 60p.

WAITAKI CATCHMENT COMMISSION 1985: Lower Waitaki Dairy Farm Survey Report including Appendix of Power Division Groundwater Monitoring July 1985 - July 1986. 80p.

26

Southland

BRYDON HUGHES

INTRODUCTION

Groundwater resources are found throughout the Southland Region in a variety of hydrogeological settings. Significant aquifers occur in the catchments of the Waiau, Aparima, Oreti and Mataura Rivers, as well as across the downlands and plains of central and eastern Southland.

Groundwater is an integral part of the hydrological cycle in the Southland Region. Many parts of the flat-lying central Southland Plains lack surface drainage, and soil moisture recharge forms a major component of the regional water balance. Groundwater also contributes to baseflow in the major river systems and the many spring-fed lowland streams.

Despite widespread use of groundwater for domestic, municipal and farm supplies, information on the groundwater resources of Southland is limited. The recent shift in rural land use from traditional sheep farming to beef and dairy farming has focussed increased attention on both the quantity and quality of the region's groundwater resources.

GEOLOGICAL SETTING

The land mass of the Southland Region comprises at least four distinct geological terranes. The oldest consists of the igneous and metamorphosed sedimentary rocks of Cambrian to Lower Permian age that form the rugged topography of the Fiordland Block. The igneous and volcanogenic sedimentary rocks of the Takitimu Block form the Takitimu and Longwood Ranges, which divide central and western Southland.

Murihiku Supergroup meta-sedimentary rocks of Mesozoic age make up the mountains of the Taringatura, Catlins and Hokonui Hills in central and eastern Southland. Permian age volcanogenic greywacke and ultrabasic volcanics of the Caples Group form the basement rock for much of the northeast of the Region. The Caples Group rocks in turn grade into the Haast Schist of the Eyre, Garvie and Umbrella Mountains of northern Southland.

The dominant geological structure in the Region is the Southland Syncline. The steeply dipping sandstone and mudstone beds on the northern limb of this structure form the prominent strike ridges of the Hokonui Hills and Catlins areas.

Contacts between the various geological terranes are frequently overlain by deep sedimentary basins infilled with thick sequences of Tertiary sediments. In western Southland, the Waiau Basin is filled with a sequence of predominantly deep water marine sediments, over 3000 metres thick.

The Eastern Southland basin contains a sequence of terrestrial and marginal marine lignite, sandstones and mudstones. Deposits of continental shelf marine limestones, sandstones and mudstones outcrop around the basin margin. This sedimentary sequence also extends into the Waimea Basin, which lies to the north of the Hokonui Hills.

Much of Southland below an elevation of 100 metres is overlain by a veneer of alluvium deposited during late Quaternary glacial advances. Some of this material has been reworked as the major rivers have entrenched during post-glacial times, resulting in a series of broad terraces flanked by recent floodplain deposits.

Along the southern coast a number of marine terraces of Quaternary age record changes in sea level resulting from Quaternary climatic fluctuations.

Hughes B. 2001: Southland. *In* Groundwaters of New Zealand, M.R. Rosen and P.A. White *(eds)*. New Zealand Hydrological Society Inc., Wellington. p481-485.

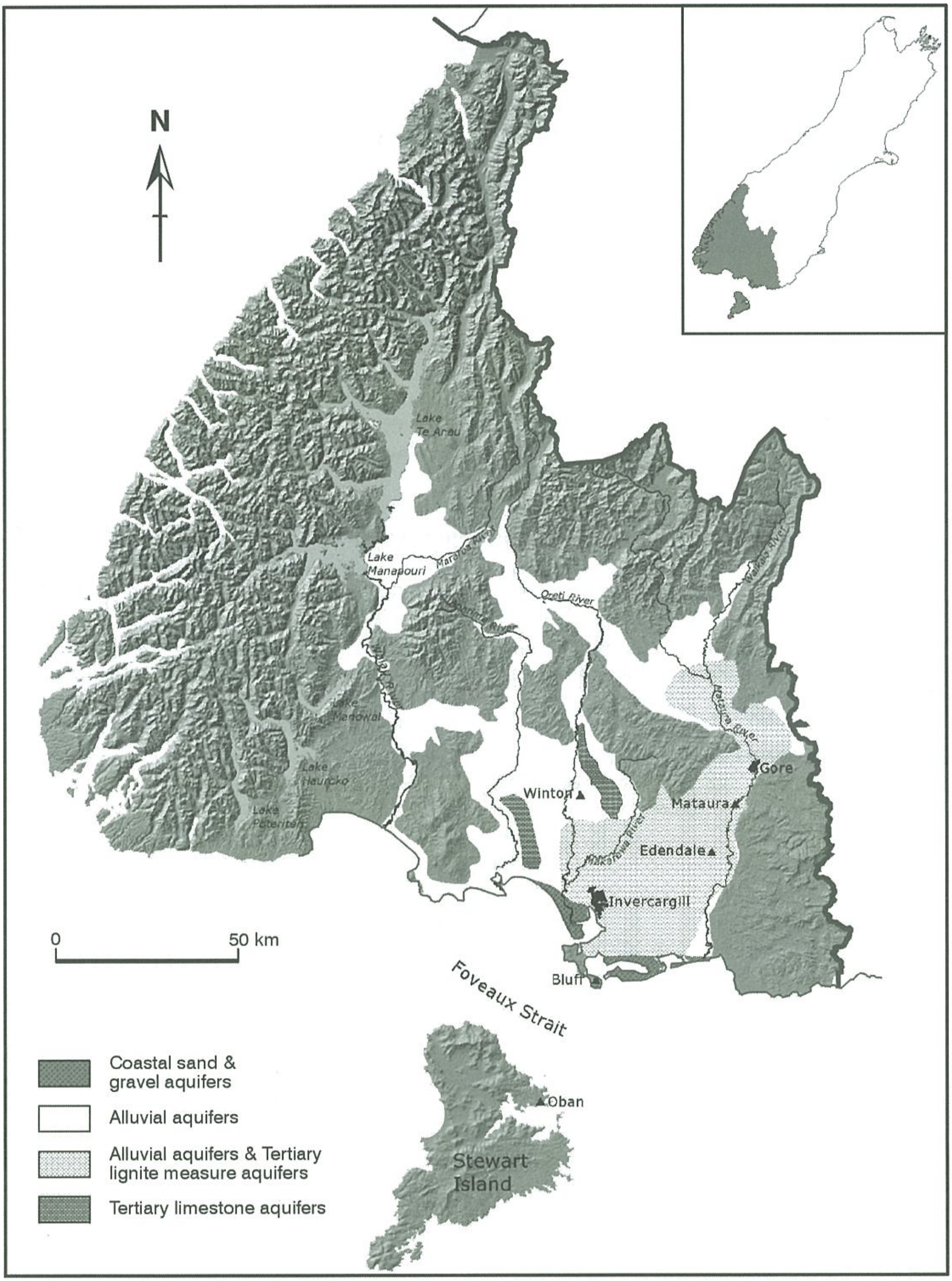

Figure 26.1 *Distribution of major groundwater resources in the Southland region.*

LOCATION AND DESCRIPTION OF PRIMARY AQUIFERS

Alluvial gravel deposits occur extensively across the plains and downlands of central and eastern Southland and the Waimea Plains in northern Southland. These deposits form shallow unconfined aquifers that are the most commonly exploited groundwater resources in Southland (Fig. 26.1).

In general, the alluvial gravel deposits that form the higher terraces of the central Southland and Waimea Plains and mantle the downlands of eastern Southland are composed of quartz gravels in a highly weathered clay and sand matrix. Due to their low matrix permeability, these gravel deposits form relatively low-yielding aquifers. Specific capacities of bores are generally less than 40 $m^3/m/day$.

The permeability of the alluvial gravel deposits increases in the lower terraces and recent flood-plain deposits, reflecting the greater degree of reworking of these materials. For example, aquifer tests on the Edendale Terrace, adjacent to the Mataura River, show aquifer transmissivities in the range of 5-10,000 m^2/day.

Other regionally significant aquifers in Southland include:

Eastern and Central Southland

Tertiary lignite measures underlie the Quaternary alluvial deposits at relatively shallow depths (<30 metres) throughout much of eastern and central Southland. Groundwater pervades the lignite measure sediments, occurring primarily in thick sandstone units that form extensive semi-confined to confined aquifers.

The permeability of the water-bearing sandstone units within the lignite measures appears to be highly variable. Many bores screened in these deposits exhibit specific capacities of less than 50 $m^3/m/day$, however others are highly productive and produce significant artesian flows (Isaac and Lindqvist 1990).

Toward the south coast, the lignite measures overlie a thick shelly sandstone unit known as the Chatton Formation. This unit is up to 80 metres thick and contains a significant groundwater resource in the Bluff/Awarua area.

The coastal barrier beach sediments of the Tiwai Peninsula form a shallow unconfined aquifer recharged by local rainfall. This aquifer system is used to supply water to the Tiwai Point Aluminium smelter.

A localised aquifer is developed in the sandy limestone of the Forest Hill Formation where it crops out toward the western margin of the central Southland Plains. This unit provides yields similar to those of the overlying alluvial gravel aquifers.

Western Southland

The Waiau River catchment covers a large portion of western Southland. Significant aquifers are developed in the thick alluvial gravel sequences filling the Manapouri and Te Anau Basins. In the lower Waiau River, an unconfined alluvial aquifer overlies thick deposits of Tertiary mudstone and siltstone.

Other locally significant water-bearing deposits in the Southland region include colluvial deposits on the slopes of the larger mountain ranges. Bores capable of producing significant quantities of groundwater are also reported in the basement rock of the Caples and Murihiku Terranes, where secondary porosity is developed along joints and fractures.

GROUNDWATER USE AND DEVELOPMENT

Groundwater is used extensively for domestic, municipal and farm supplies throughout Southland. The water supplies for the towns of Gore, Winton and Te Anau, as well as a number of rural communities, are derived from groundwater.

Groundwater is used for industrial supply by the dairy, meat and fertiliser industries, although in many cases abstraction is restricted by the available yield. Limited use is also made of groundwater for horticultural and pastoral irrigation.

Groundwater use has increased significantly in rural Southland during the 1990s, primarily due to the expansion of the dairy industry, which uses groundwater for stock drinking, wash-down and cooling water. Between 1990 and 1999 the total dairy herd in Southland increased from 30,000 to 233,000. This expansion has increased pressure on groundwater resources in terms of both abstraction and contaminant load.

In eastern Southland much of the increased abstraction has been from the lignite measure aquifers, as only limited yields are available from the overlying gravel aquifers.

Groundwater use in areas of Southland is limited by high concentrations of iron and manganese. High levels of iron are common in water derived from lignite measure aquifers, while elevated iron and manganese are also common in unconfined aquifers in many low-lying areas of the Southland Plains. Hardness is a problem in some parts of the central Southland Plains due to the interaction between the shallow unconfined gravel aquifers and underlying limestone deposits.

The municipal supply for Invercargill was derived from confined lignite measure aquifers underlying the city until the early 1970s. Due to problems caused by high levels of iron, this supply was discontinued in favour of a treated supply from the Oreti River.

Little information exists on the number and location of bores and wells in the Southland Region. Based on anecdotal evidence it is estimated that about 60-70 percent of rural properties in Southland rely on groundwater for stock and/or domestic water supply. Current figures suggest that approximately 75 new bores are drilled per year.

MONITORING AND INVESTIGATIONS

Limited monitoring and investigation of groundwater resources has been undertaken in Southland. The available historical information is summarised in Rekker (1994).

A structured groundwater level and quality monitoring program has recently been initiated by Environment Southland; it currently comprises 32 groundwater quality sites sampled quarterly, and 60 groundwater level sites monitored monthly.

Edendale Aquifer

The Edendale Aquifer is the only aquifer system in Southland that has been the subject of a structured monitoring or investigation program. This aquifer underlies an elevated alluvial terrace adjacent to the Mataura River floodplain and is the most heavily used groundwater resource in Southland.

Measurements of groundwater quality in the Edendale Aquifer began in the mid-1980s, after Public Health monitoring of the Edendale township water supply showed elevated nitrate levels. Subsequent investigations indicated that the likely source of the contamination was the land disposal area for the nearby dairy factory. Improved management practices have subsequently reduced nitrate to acceptable levels.

Because of concern about the impact of the expansion of dairying on surface and groundwater quality in Southland (Robertson Ryder and Associates 1993), the Edendale Aquifer was intensively monitored between 1995-97. The monitoring was part of a Sustainable Management Fund investigation into the impact of land use on surface and groundwater quality in the Oteramika catchment (Thorrold et al. 1998)

The Edendale Aquifer system consists of a relatively thin unconfined gravel aquifer (<25 metres) overlying Tertiary lignite measure sediments. The aquifer is composed of moderately permeable Quaternary sandy gravel (k = 400-800 m/day). Based on groundwater levels and springflow measurements the aquifer was determined to be exclusively rainfall recharged, with a throughflow of approximately 70,000 m^3/day (Rekker 1995, 1997).

Groundwater at the majority of sampling sites exhibited low pH values (5.5-6.3) and contained relatively low levels of dissolved ions. The average nitrate-nitrogen concentration of 6.1 g/m^3 indicated the aquifer was affected by non-point source contamination from horticultural and agricultural land use and land disposal of dairy factory effluent (Rekker 1998).

Modelling of various scenarios indicated that widespread changes in land use would have a significant impact on groundwater quality: in particular, increases in dairying would result in an elevation of nitrate levels in the unconfined aquifer to close to Drinking Water Standards limits.

In addition, Environment Southland is currently monitoring the magnitude and extent of organonitrogen pesticide residue in the Edendale Aquifer. Results to date show that pesticide residues are present up to 3.5 kilometres down-gradient of the likely source.

Regional Snapshot Survey

During the summer of 1997/98 the Southland Regional Council undertook a snapshot survey of groundwater quality throughout Southland (Hamill 1998). The survey involved the sampling of 350 sites distributed across the region for a limited range of physical, chemical and microbial parameters. The location and physical condition of each bore was recorded prior to sampling.

Of the bores sampled, 4 percent showed nitrate levels above the New Zealand Drinking Water Standard, while a further 30 percent exhibited concentrations greater than 50 percent of MAV. Faecal coliform indicator bacteria were detected in 40 percent of bores sampled. Results of the survey reflect two major causes of localised groundwater contamination in Southland:

1. Bores sited close to sources of contamination such as septic tanks, offal pits, wintering pads and silage pits; and
2. Inadequate wellhead protection, resulting from poor construction and/or maintenance.

REFERENCES

Greenwood, P.B. 1999: Irrigation of Farm Dairy Effluent in Southland. SoilWork Ltd Report SW-MR-0196. 131p

Hamill, K.D. 1998: Groundwater Quality in Southland: A Regional Overview. Southland Regional Council Publication No. 96. 43p

Issac, M.J.; Lindqvist, J.K. 1990: Geology and Lignite Resources of the East Southland Group, New Zealand. New Zealand Geological Survey Bulletin 101. ISSN 0077-9628

Rekker, J.H. 1994: Southland Region Groundwater Resource; Scoping Study. Southland Regional Council and AquaFirma Limited. 108p

Rekker, J.H. 1995: Edendale Aquifer Characterisation Study. Southland Regional Council and AquaFirma Limited. 32p

Rekker, J.H. 1997: Report on the Hydrological Delineation of the Oteramika Catchment; Aerial Extent and Water Balance. Southland Regional Council and AquaFirma Limited. 38p

Rekker, J.H. 1998: Oteramika Trial Catchment Groundwater Studies. Studies into Non-point Source Groundwater Effects in Southland. Southland Regional Council and AquaFirma Limited. 84p

Robertson Ryder and Associates 1993: Southland Dairy Farming Expansion. Southland Regional Council, September 1993.

Thorrold, B.; Rodda, H.; Monathan, R. 1998: Modelling Land Use Effects on Water Quality in the Oteramika Catchment. AgResearch, Private Bag 3123, Hamilton. 48p

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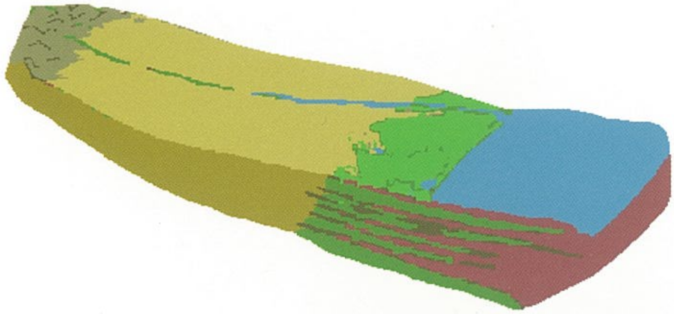
Groundwaters of New Zealand is the definitive new source for information on the groundwater resources of New Zealand. Written by many of New Zealand's leading experts, the book covers varied aspects of groundwater research, assessment, use, and management in New Zealand.

Chapters document the history of groundwater development in New Zealand, and current research on interactions between groundwater systems and other components of the hydrological cycle. Groundwater quality is explored in chapters on groundwater chemistry and microbiology, and the health aspects of groundwater. The book also contains detailed regional summaries, covering the location, use, quality, and management of groundwater resources, for the entire country.

This book will be the essential reference text for all environmental, engineering, and resource management professionals working with groundwater, and students of the many scientific and engineering disciplines that contribute to groundwater investigations. Senior secondary school, undergraduate university students, and the many groundwater users will find this book a valuable reference that adds significantly to their understanding of groundwater resources.



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