Floods and Droughts: the New Zealand Experience

edited for the New Zealand Hydrological Society by

M. Paul Mosley and Charles P. Pearson

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Preface

Ever since intensive European settlement of this land mass - and no doubt before - floods and droughts have presented threats to the welfare and livelihood of people in New Zealand. The dynamic inter-relationships between uplift and topography, weather and climate, vegetation, erosion and sedimentation create physical conditions in which hydrological extremes have potentially major impacts upon economic activity, property, transport and communications, and human safety. Human activity is believed to have heightened hydrological extremes, particularly through widespread vegetation change and the accelerated runoff, erosion and sedimentation which has resulted in so many places. And, of course, in the urban areas inhabited by over 80% of New Zealand's population, the impervious surfaces presented by buildings and roads accelerate runoff, causing heightened flood peaks and reduced low flows.

To these physical factors must be added the implications of land use and settlement patterns. Throughout New Zealand, people have established settlements and farms, and have constructed railways, industrial premises and other infrastructure, in locations which have proved highly flood-prone. Farming systems have developed in many parts of the country which, under the pressures of present-day economic conditions, have difficulty in accommodating the extremes of weather, particularly periods of drought, which are in statistical terms a normal feature of our climate.

Flooding was among the first signs of environmental degradation and inappropriate land settlement and use to be recognised by European settlers (Roche 1994). In the 1860s and 1870s, considerable flood damage was suffered in much of the eastern and southern South Island, and along rivers such as the Matai River (Nelson) and the Hutt River (Wellington). To a large extent, such flood damage was probably a result of the impact of natural hydrological processes on settlements which had unknowingly been sited in inherently risky locations. However, some observers (cited by Roche 1994) were able to recognise the effects of human impact on hydrological processes:

> There is every reason to believe that Christchurch is in imminent danger from the recurrence of floods like those which have so frequently occurred of late in the Waimakiriri River, and that the works at present executed would prove quite inadequate to avert the calamity (James Hector, director of the Geological Survey, 1868).

> (Sawmilling and land cultivation ...) increased the rapidity with which the rainfall is carried into the river, and the floods necessarily rise higher than before (Arthur Dobson, surveyor, 1871)

and

> Many causes, too, resulting from men's foolish and wanton interference with natural operations, had contributed to bringing about a rapid accumulation of rainfall to the main rivers. (W T Locke Travers, parliamentarian, 1881)

As early as 1868, the Canterbury Rivers Act provided a vehicle for flood mitigation, and rapidly was succeeded by similar legislation in other provinces, and nationally by the River Boards Act of 1884. The subsequent history of New Zealand's efforts to cope with hydrological extremes includes a series of landmark events such as the Esk Valley floods of 1938 and passage of the Soil Conservation and Rivers Control Act of 1941. It includes, too, the work carried out over many decades by catchment boards, many dedicated individuals, and an evolving set of central government agencies which made up the National Water and Soil Conservation Organisation (Poole 1983; Roche 1994).

From the first, engineers, soil conservators, and scientists have played a key role in dealing with floods and droughts. In the early decades of flood mitigation, much of the work was of an engineering nature and based on scant information. Frederick Furkert, an engineer who became head of the Public Works Department in 1920, recognised the dearth of hydrological data on which to base river engineering and land management. However, it was not until after formation of the Soil Conservation and Rivers Control Council that, in 1946, a hydrological survey of New Zealand was commenced. The subsequent development of hydrological data collection and research shows the growing recognition of the importance of a reliable information and knowledge base as a foundation for cost-effective management of our environment and resources (Roche 1994, p 94-6; Waugh 1992).

This volume, then, is a contribution to the Society's goal: "*to further the science of hydrology and its application to the understanding and management of New Zealand's water resources*". It explores in some detail the New Zealand experience in coping with and managing hydrological extremes - floods and droughts, in common terms. It complements the Society's earlier volume, *Waters of New Zealand* (Mosley 1992), which presented an overview of water resources science and management in this country.

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Acknowledgements

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1
Introduction: hydrological extremes and climate in New Zealand

Paul Mosley and Charles Pearson

Introduction

Weather and climate are pervasive influences on all aspects of the hydrological cycle, because they control the inputs to a catchment, and influence a significant proportion of the outputs. This chapter will explore the attributes of New Zealand's weather and climate that produce hydrological extremes, with emphasis on the heavy rainfalls that generate floods and the prolonged dry spells or periods without rain that cause droughts. It will then examine the relationship between climate and river flow regimes.

Precipitation and the climate of New Zealand

New Zealand is a maritime country, surrounded for thousands of kilometres in every direction by ocean, so that air masses arrive laden with moisture. Much of its precipitation is determined by major (synoptic scale) weather systems, such as depressions and anticyclones, frontal zones, troughs of low pressure, and tropical or extra-tropical cyclones.

At New Zealand's latitude and longitude, annual precipitation over the ocean would be expected to be about 600 to 800 mm. Much of New Zealand, however, has ranges of mountains and hill country oriented transverse to the prevailing winds. Some of this terrain receives phenomenal amounts of rain and snow, condensed from air masses rising over the mountain barriers. The current holder of the world record for the highest mean annual rainfall is Mawsynram, Meghalaya State, India, which averages, according to the *Guiness Book of Records*, 11.87 metres per year. Sections of the New Zealand Southern Alps receive an estimated 12 to 15 metres per year (Griffiths and McSaveney, 1983), but we cannot claim the record because our alpine raingauges are not part of an official weather station.

As an island country, New Zealand has no true desert areas -- the region with the lowest rainfall, north-central Otago, lies in the rain shadow of the mountains and averages about 400 mm per year.

New Zealand lies in a zone of westerly winds for much of the year, to the south of a belt of high pressure which in turn lies to the south of the southeast tradewinds (Tomlinson, 1992). The axis of the belt of high pressure moves from about 26 degrees south in winter to about 36 degrees south in summer; the axis of the zone of westerly winds similarly moves from just to the south of New Zealand in winter to latitudes considerably further south in summer. The belt of high pressure consists of a series of anticyclones moving in a westward direction, between which are troughs of low pressure associated with depressions moving within the zone of westerly winds to the south. The nature and behaviour of these weather systems, and the weather that they bring to New Zealand, is highly variable. However, they tend to have a life span of 3 to 10 days, and bring to our weather a periodicity on the order of a week.

The nature of precipitation events and dry periods is strongly influenced by the intensity, frequency, duration, speed of travel and other characteristics of the major weather systems, and the way in which they interact with the topography of New Zealand. In turn, the major weather systems are influenced by atmospheric circulations at the global scale, and particularly by the El Nino-Southern Oscillation (ENSO) phenomenon (Gordon, 1986). Airflow over New Zealand changes during different phases of ENSO, which are indicated in terms of the Southern Oscillation Index (SOI), the normalised pressure difference between Tahiti and Darwin. (During El Nino periods, this index is negative). For example, Gordon notes that "for a negative SOI, the correlation fields imply anomalous southwesterly flow over New Zealand in September/October/ November (SON) and March/April/May (MAM), anomalous westerly flow to the north in December/January/February (DJF), and anomalous southerly flow over the country in June/July/August (JJA). These variations in air flow and the nature (temperature, direction of travel, moisture content, etc.) of the air masses result in commensurate variations in precipation patterns. For example, Gordon (1986, p 382) found that:

- "In MAM, negative SOI gives anomalous southwesterlies which bring above normal rainfall to the South Island and southwestern parts of the North Island, and below normal in the northeast.
- In JJA, the anomalous flow for a negative SOI is southerly, and this drier air results in lower than average rainfall for most of the country.
- In SON, the significant correlations are in the northern half of the North Island, partly as a result of sheltering giving lower rainfall in the east for negative SOI and anomalous southwest flow, but also because a negative SOI is associated with generally higher pressures and more settled weather in the north.
- In DJF, the anomalous flow is more westerly with lower pressures in the far south, and a negative SOI is associated with wetter conditions in the south and west and drier in the east."

Gordon's findings refer to seasonal precipitation rather than to specific precipitation events, but there are implications for the incidence of the heavy rainfalls often associated with the passage of fronts, or for the occurrence of longer dry spells or droughts during settled weather. A further linkage between the Southern Oscillation and river flows also has been established (McKerchar *et al.*, 1996). Indeed, there is considerable evidence for a series of linkages between episodes of erosion and sedimentation, floods, precipitation patterns, and a variety of long-term fluctuations or cycles in weather conditions (Grant, 1985).

Precipitation extremes generally reflect the pattern of annual precipitation -- the heaviest and most intense falls tend to be experienced where annual totals are greatest, and dry spells and droughts where annual totals are least. Heavy rain is most frequent in the west and north; Northland, Auckland and Bay of Plenty receive the heaviest short-duration rainfalls in convective showers and thunderstorms, whereas the West Coast receives the heaviest long-duration rainfall, from active troughs crossing the South Island (Tomlinson, 1976). On the other hand, the areas of greatest rainfall variability, which are most susceptible to unusually dry years and prolonged droughts, are in the east -- north Otago, Canterbury, Marlborough, Wairarapa, Hawkes Bay, Gisborne. Considerably more detail on the regional climatology of New Zealand is available from a series of reports prepared by the former New Zealand Meteorological Service (now NIWA) (Table 1.1). Each of these reports provides a general description of the weather systems affecting each region. They also give detailed descriptions of the nature and occurrence of rainfall and other phenomena such as thunderstorms, and discuss meteorological conditions which are relevant to hydrology, including evaporation, energy balance, and temperatures.

Heavy rainfall events

Certain types of synoptic-scale weather system produce heavy rainfall in different regions of the country (Tomlinson and Thompson, 1992). The types that Tomlinson and Thompson identified are:

- Tropical cyclone
- Cyclone of sub-tropical origin
- Extratropical low-pressure centre
- Frontal system
- Frontal system with waves

- Quasi-stationary frontal system
- Strong northwest airstream

Table 1.1. New Zealand Meteorological Service Miscellaneous Publications on regional weather and climate. (Note: NZ Meteorological Service ceased to exist in 1992, and climatological information is now provided by NIWA).

115(1), 1984	Bay of Plenty (2nd edition)
115(2), 1986	Northland (2nd edition)
115(3), 1965	Nelson
115(4), 1968	Otago
115(5), 1971	Hawkes Bay
115(6), 1972	Wanganui
115(7), 1974	Waikato-Coromandel-King Country
115(8), 1980	Gisborne
115(9), 1981	Taranaki
115(10), 1982	Westland
115(11), 1982	Wairarapa
115(12), 1983	Marlborough
115(13), 1983	Chatham Islands
115(14), 1984	Tongariro
115(15), 1984	Southland
115(16), 1984	Wellington
115(17), 1987	Canterbury

They suggested that, in terms of the types of storms which produce heavy rain, New Zealand can be divided into three principal regions:

The North Island and the north and east of the South Island.

The heaviest falls are produced by former tropical cyclones as they pass close to or across New Zealand. Rainfall is determined by the intensity and speed of movement of the depression, and its track across the land mass. The storm of April 1938, which caused the Esk Valley floods, is an example of this type of event (Tomlinson and Thompson, 1992). Heavy rain fell over an area of about 1,000 sq km in inland Hawkes Bay, with up to about 300 mm in the Lake Tutira area on 24 April. The rainfall was caused by a warm, moist airflow between an extra-tropical depression moving southeast across East Cape and a large anticyclone to the east of New Zealand (Fig. 1.1).

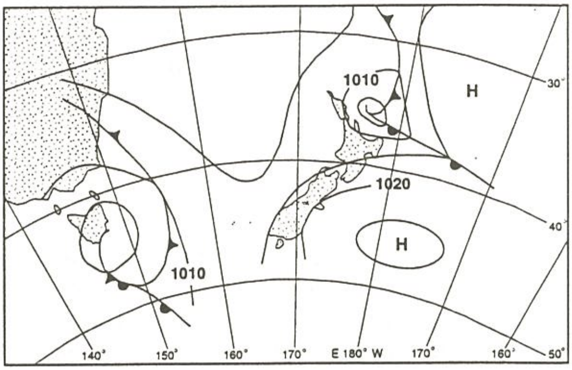

Figure 1.1. The weather situation during the height of storm in April 1938 which caused the Esk Valley (Hawke's Bay) floods.

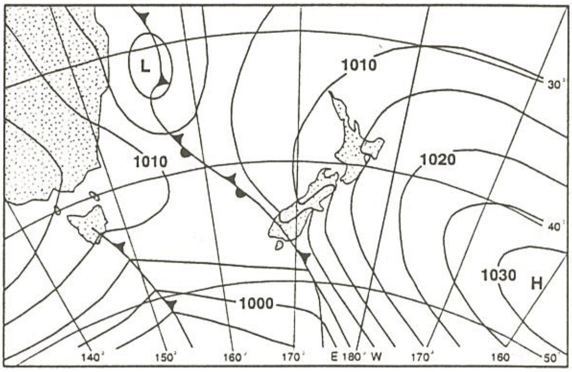

Figure 1.2. The weather situation during the March 1967 storm in the Southern Alps.

West Coast and alpine region of the South Island, and Southland.

Heavy rainfalls tend to be associated with slow, eastward-moving frontal zones embedded in west or northwest airstreams. Extensive heavy rain along the west coast usually occurs when a slow-moving anticyclone lies to the north or northeast of the North Island, with a deep depression moving eastwards to the south of the Tasman Sea, and a strong northwest airstream ahead of it. One of the heaviest rainfalls experienced in the region, with three-day totals exceeding 900 mm in the Southern Alps, occurred in March 1967 (Tomlinson and Thompson, 1992). The synoptic situation (Fig. 1.2) included an intense, slow-moving anticyclone east of the Chatham Islands, a deep depression south of Tasmania, an eastward-moving cold front in the Tasman Sea, and a moist north to northeast airstream over New Zealand which was responsible for the rainfall.

Southeast South Island

The heaviest and most prolonged rainfalls can occur in a variety of synoptic situations, including (a) where a slow-moving depression lies off the east coast of the South Island, bringing strong onshore easterly winds; and (b) where a slow-moving frontal zone lies in a north-south direction between a shallow depression in the Tasman Sea and an intense anticyclone to the southeast of the South Island.

At any location, the exact nature of the rainfall, and the resulting flood, can be strongly influenced by the synoptic situation, and also by seasonal differences in weather conditions. Extreme rainfalls and flood events in a given catchment can come from different populations, which may be associated with different synoptic situations, and which may be best fitted by different statistical distributions (see Tomlinson, 1980, sections 3 and 4). In Hawkes Bay, then, heavy rain caused by east to southeast airstreams might come from a different statistical population than rain associated with extra-tropical cyclones (see Thompson, 1987a). On the other hand, Painter and Larsen (1995) concluded, for the Hakataramea River catchment of south Canterbury, that although three distinct types of synoptic situation commonly generate rainfall, the characteristics of the storms and resulting floods are not clearly different. However, they did conclude that there are distinct seasonal differences in *flood* events, as a result of different antecedent conditions and weather patterns (time distribution of prior rainfall, evaporation, etc.) which are likely to be causally associated with season.

Mesoscale (sub-synoptic scale) weather patterns which result from topographic modification of synoptic-scale airflow also may modify the nature of precipitation events. For example, Salinger and Smith (1986) identified five patterns of mesoscale precipitation distribution in the Wellington region, which could be associated with six sets of synoptic situation. Hutchinson (1973) carried out a similar study in the Dunedin area of the interaction between synoptic situation, topography, and the mesoscale characteristics of rainstorms. Other accounts of particular precipitation events provide insight into the specific meteorological and topographic circumstances which can lead to heavy rainfalls and floods (e.g. Collen and Hessell, 1982; Painter and Larsen, 1995; Tomlinson, 1977).

Rainfall characteristics also reflect weather phenomena at the sub-synoptic scale. Particularly important are thunderstorms, which can produce local heavy falls of rain or hail, and are the principal cause of flash flooding in New Zealand (Tomlinson, 1992). For example, a destructive flash flood was generated in the Roxburgh area in November 1992 by a rainfall of 80 mm in 45 minutes, which was associated with cumulonimbus cloud. Thunderstorms tend to occur in large, unstable air masses, in association with orographic forcing or surface heating, and produce heavy rainfall as air rises in intense convective systems of towering cumulus or cumulonimbus clouds (Sturman and Tapper, 1996, p. 284-291).

The geographical distributions of heavy rainfall events, measured by a variety of indices, have been presented by various authors, including:

- mean annual maximum amount of precipitation per event of 1-, 2-, and 3-day durations (Thompson, 1987b, p. 5);
- amount of precipitation in events of 24-hour, 6-hour, 1-hour, and 10-minute durations with a return period of 5 years (Tomlinson, 1980);
- highest rainfall for one day, expected once in 20 years (Tomlinson, 1976, p. 89).

These indices show similar patterns, which reflect the complex and interacting set of causal factors. Broadly, the most intense 24-hour, 5-year rainfalls (Fig. 1.3) are experienced in:

- the Coromandel and inland Bay of Plenty (> 200 mm/24 hour);
- the axial ranges of the eastern North Island (Raukumara, Ruahine, Tararua: > 300 mm/24 hour);
- the hill country between Hawke Bay and Poverty Bay (>240 mm/24 hour);
- Mount Taranaki (>320 mm/24 hour); the axial

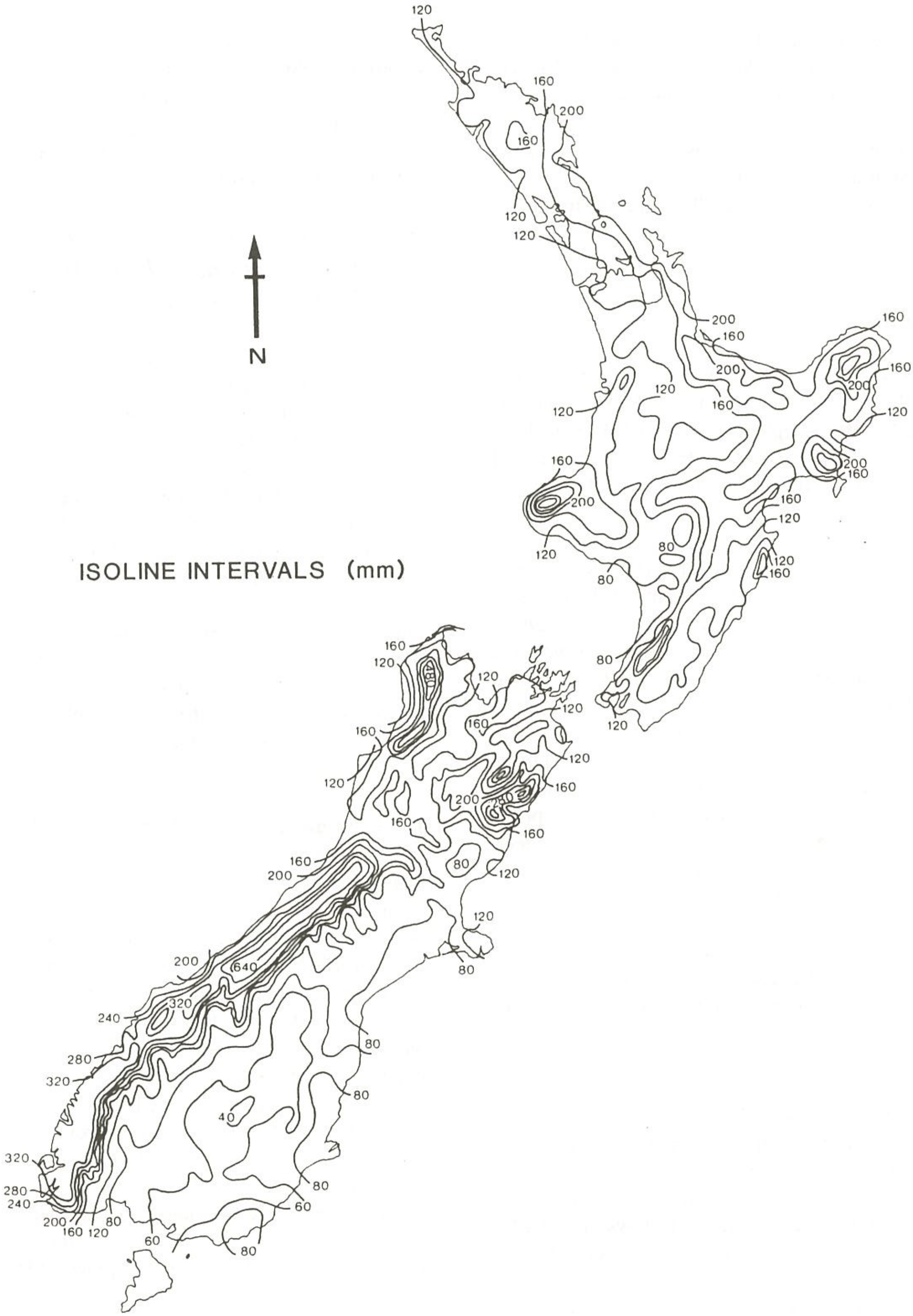

Figure 1.3. The distribution of 24-hour, 5-year rainfall (from Tomlinson, 1980).

ranges of the South Island west coast (Fiordland, Southern Alps, Paparoa Range, Tasman Mountains, ranging up to > 640 mm/24 hour in the south and centre);
- Richmond Range and Seaward Kaikoura Range (> 280 mm/24 hour); and
- small outliers along the hill country of the South Island east coast (> 100-140 mm/24 hour).

Droughts

Most New Zealanders believe, or at least believed before the hydroelectricity crisis of 1992 and the Auckland water supply crisis of 1994, that New Zealand has abundant water. However, the risk of drought has been recognised by meteorologists and hydrologists for decades, and of course by the farming community and water resource managers in those areas of the country most likely to be affected.

Droughts can be defined in terms of the duration of days without rain. A *meteorological drought* is defined as a period of 15 days with no measurable rain (<0.1 mm per day), and a *dry spell* as a period of 15 days with no more than 1 mm of rain each day). In practice, the start of a drought is not easy to pinpoint, although its end, when the drought is "broken" by heavy rain, may be. As Tomlinson comments: "They appear slowly, spread amorphously, and can end in various ways. We tend to know when we have one, but find it difficult to know when one is beginning or ending".

Even though in simple terms a drought results from the persistent absence of rain-producing systems (Tomlinson, 1992), a drought is not simply a meteorological phenomenon. Current definitions of drought also may refer to the end use of the water:

> "drought occurs whenever the supply of moisture from precipitation or stored in the soil or hydrological reservoirs is insufficient to fulfill the optimum water requirements of plants, water supply for urban dwellers, inflows into hydro lakes or some other purpose" (Salinger, 1995).

As with intense rainfalls, the characteristics of a drought reflect the interaction between synoptic situation and New Zealand's topography. They also reflect the influence of the ENSO phenomenon (Gordon (1986). Droughts tend to be of regional extent, in contrast with the normally localised nature of heavy rainfalls.

Salinger identified three principal regions which are susceptible to drought.

Northern and western areas of the North Island, Wellington, Nelson-Marlborough, and North Canterbury

Droughts are most frequent in summer, particularly in February when the belt of subtropical anticyclones is at its most southerly extent. Droughts occur when anticyclones become slow-moving, strong and persistent, and there is a lack of intervening troughs which might bring precipitation. In Northland, at Kerikeri, dry spells have lasted as long as 71 days (with a drought of 63 consecutive rainless days) during December 1945 to February 1946, although the average duration is about 20 days (Moir *et al.*, 1986). In parts of Marlborough, the average frequency of dry spells and droughts can reach 4.1 events/year (Blenheim) and 2.6 events/year (Molesworth) respectively; the longest drought recorded at Blenheim was 38 days in 1970 (Pascoe, 1983).

Eastern areas of the North Island

This region is sheltered from westerly winds, and so droughts are most frequent or prolonged when westerly winds predominate. This is particularly the case in El Nino years (a negative phase of the Southern Oscillation Index); droughts in this region usually reach their maximum intensity in early summer. On average, lowland Hawkes Bay experiences about three dry spells and at least one drought per year (Thompson, 1987a).

Prolonged dry conditions can prevail in this part of the country as a procession of large anticyclones moves eastwards across the country. This was the case, for example, during February-March 1978, when a drought was widespread in the Wairarapa, lasting up to 29 days in some places (Thompson, 1982; Fig. 1.4).

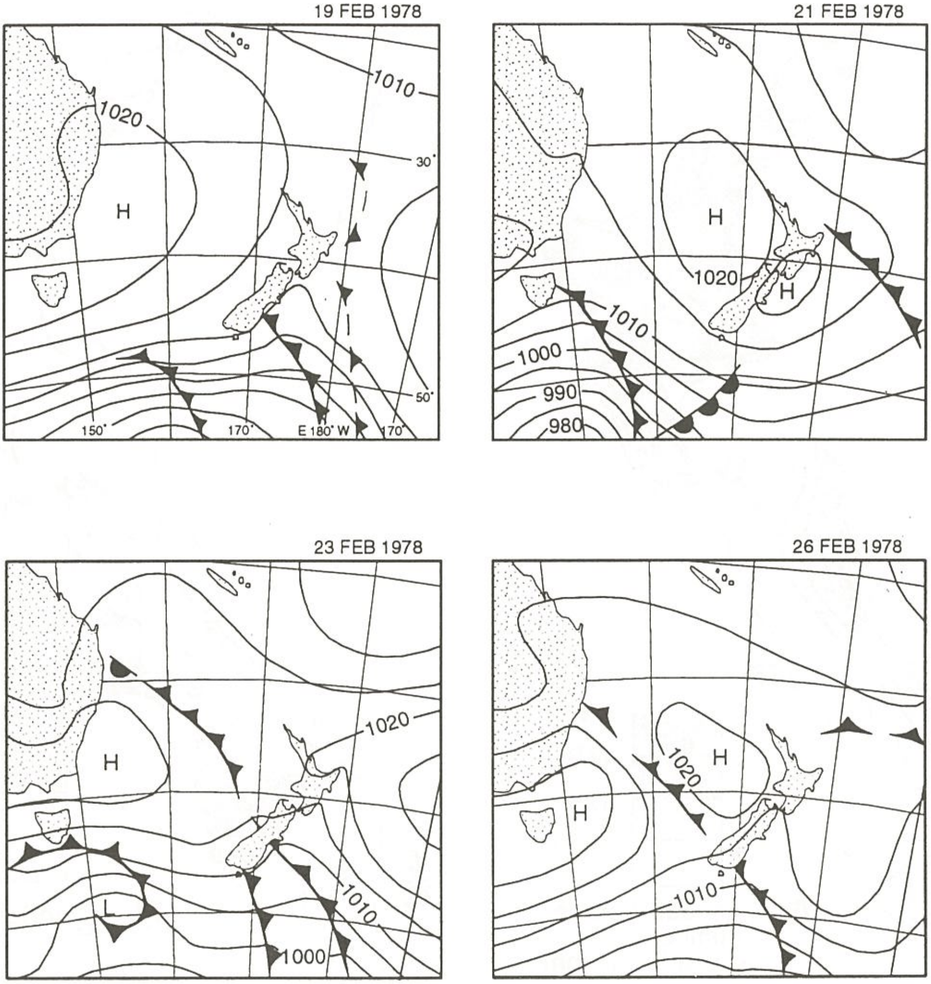

Figure 1.4. The weather situation during the period of drought in Wairarapa, February-March 1978 (from Thompson, 1982).

Central and South Canterbury, and Otago

Droughts are normally most frequent in winter, as a result of slow-moving, "blocking anticyclones" which usually track over southern New Zealand at this time of year. The average annual number of dry spells and droughts is as high as 5 and 4 respectively in the upper Waitaki Valley, with average durations of 20-22 days (Ryan, 1987). Periods without rain as long as 65 days have been experienced in the region, for example at Cashmere Hill (Christchurch) in 1959.

Partly because of the difficulty of defining droughts, it has proved difficult to present in map form the geographical distribution of drought susceptibility. Salinger (1995) suggested that the pattern of agricultural drought can be indicated by the average number of days at wilting point (average annual water deficit), although this statistic does not directly reflect the durations and frequencies of individual dry spells or droughts. The former New Zealand Meteorological Service (1985; see also Tomlinson, 1976) has published maps of the variability of annual average rainfall (standard deviation/mean), the number of raindays, and rainfall reliability. Carefully interpreted, these

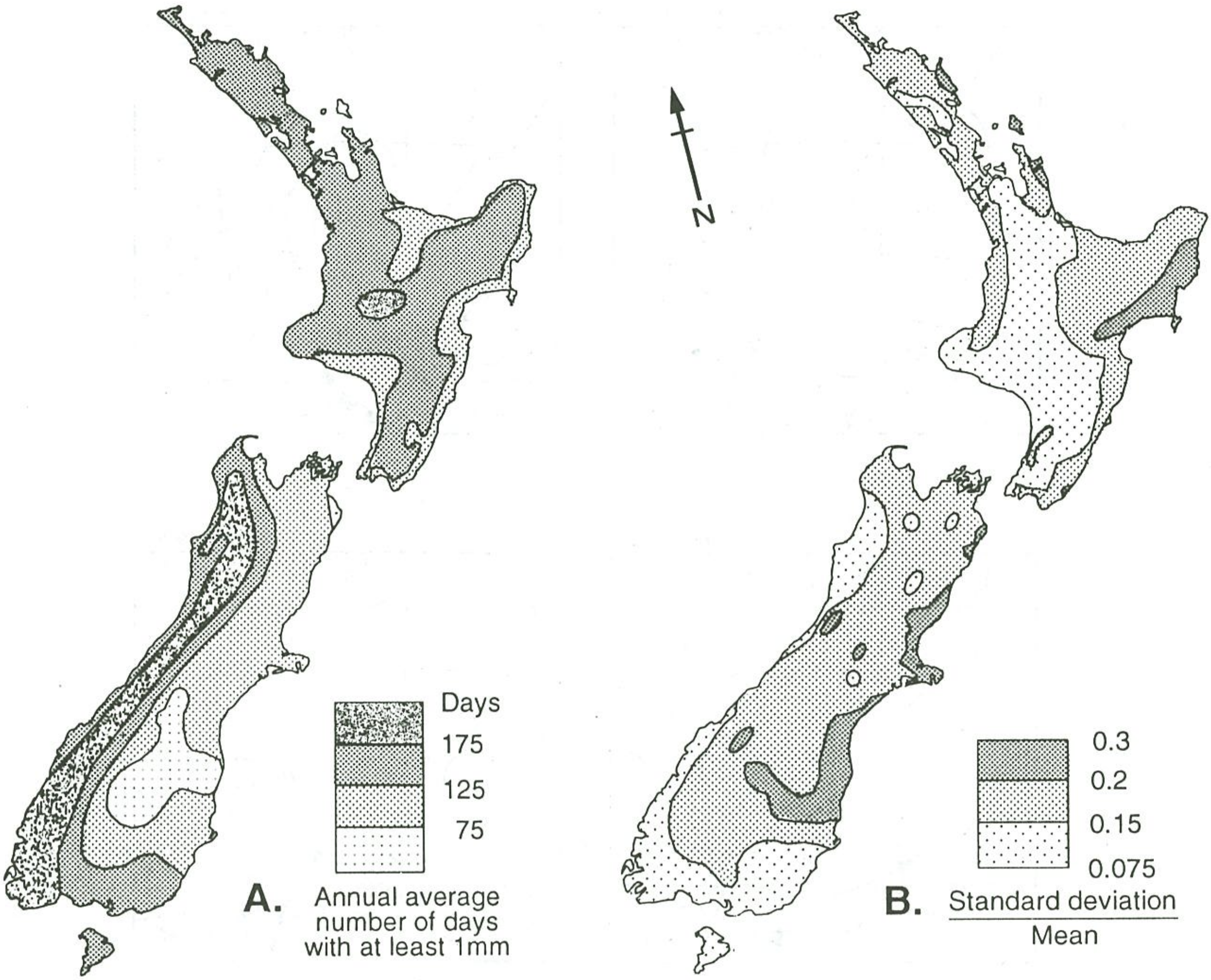

Figure 1.5. Annual average number of raindays and variability of annual average rainfall (from New Zealand Meteorological Service, 1985).

statistics provide a good picture of the distribution of drought susceptibility in New Zealand (Fig. 1.5).

Meteorological and hydrological extremes and river flow regimes

The flow regime of a stream or river is the unique way in which its flow changes from day to day, season and season, and from year to year (Duncan, 1992, p. 13). The extremes of flow - the floods and dry period low flows - are important, particularly from the perspective of the biota which live in the watercourse, human use of the water resource, and management of the river channel for such purposes as gravel extraction and flood mitigation.

The flow and storage regimes of other water bodies in the hydrological cycle - lakes, glaciers, aquifers, and soil moisture (Fig. 1.6) - generally vary slowly, and changes in the amounts of water stored in and flowing through them are rather less obvious, and more difficult to measure, than are those of rivers. Extreme conditions in these water bodies have until received rather less attention than flow changes in streams and rivers, with the notable exception of lakes, which are vital to hydroelectricity generating schemes. Nevertheless, as demands on New Zealand's water resources increase, information on the regimes of all components of the hydrological cycle will be needed for sustainable management of water resources.

Hydrological processes in a catchment, and the regimes of the water bodies within the catchment are controlled by a number of factors (Fig. 1.6; Duncan, 1987, 1992):

- The weather and climate of the catchment control water inputs (as precipitation and snowfall) and some outputs (as evapotranspiration from soil surfaces and vegetation).
- Bedrock type and other geological characteristics control the rate at which water moves through interstices and joints in the rocks, and the amount of water which can be stored as groundwater.
- Topography, including elevation, surface gradients, and drainage network attributes, influences the nature of precipitation and the rates of meteorological processes such as evaporation, and controls the way in which water collects and moves down the catchment towards to the sea.
- Soil and regolith characteristics influence the partitioning of precipitation into evapotranspiration, overland flow, subsurface flow, and groundwater recharge, and control soil moisture storage and rates of evapotranspiration.
- Vegetation cover and land use control the amount of precipitation which reaches the ground surface and rates of evapotranspiration, and -- like soil characteristics -- influence the partitioning of precipitation into overland and subsurface flow.

Human activity can modify some of these natural factors, particularly vegetation cover, land use, soil characteristics, and aspects of topography such as river channel geometry.

Each factor has a different influence on the regime of each component of the hydrological cycle, and particularly on hydrological extremes. For example, topography has a major influence on peak discharges in rivers, since steep hillsides rapidly transmit precipitation downslope into stream and river channels at their base. Another, contrasting, example is the effect of bedrock type on the amount of water stored in aquifers and the rate at which it is released during dry periods. In the Volcanic Plateau, rainfall percolates through the fractured pumice into the groundwater system and is released at an even rate by spring-fed streams, so that flows during periods with little rainfall do not diminish as much as they might in areas with another type of bedrock.

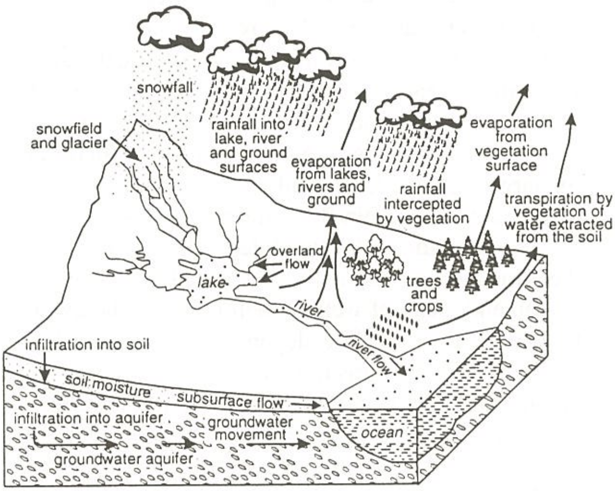

Figure 1.6. The basin hydrological cycle.

In practice, many meteorological and other factors interact with each other to cause floods or droughts, or modify their severity. For example, antecedent conditions influence the severity of a flood which results from a given storm; rainfall onto an already saturated catchment or one mantled by a ripe snowpack is likely to lead to a more extreme flood than rainfall onto a relatively dry catchment; high temperatures, winds, and low relative humidity may exacerbate the effect of a dry spell in creating an agricultural drought. The use of the word "severity" implies, also, a human value judgement about the nature of the flood and the precipitation that causes it, which reflects their effects on human activity more than simply their physical characterisitcs. In a similar way, the severity of a drought is controlled not just by the duration of the period without precipitation (meteorological drought), but by the effect of weather on plant growth, water supplies, and human activity.

Extended dry spells or severe storms affect the hydrological storages and fluxes within New Zealand's catchments, and may cause severe deficits or surpluses of streamflow, groundwater and soil moisture. Other chapters of this book will examine these processes and effects in more detail, and only a brief introduction is provided here.

Variations in weather patterns are reflected in fluctuating river flows. The peaks in a river's flow are responses to rainfall and snowmelt. Flows rise sharply in response to rainfall or warm westerly winds which cause rapid snowmelt, and decrease more slowly as the soil and rocks in the catchment gradually release the water that did not run off immediately, but was stored during the event. The flows of many rivers in New Zealand are modified by large lakes, which tend to reduce the size of floods and to maintain flows during rainless periods.

The magnitude of a flood depends principally on the amount and duration of rainfall, and on the catchment's state of wetness beforehand. The extent to which flows decline depends on the period of time to the next precipitation event, and on the amount of water stored in the catchment in the form of groundwater, soil moisture, snowpack, and in lakes.

The principal questions asked about floods and low flows are "How severe, frequent, and prolonged are they?", and "When will the next one happen?" The first question is asked when the engineer or water resource manager must design a structure like a stopbank or irrigation scheme, or prepare a water management plan. The second is asked when preparations must be made to mitigate the immediate effects of a flood or drought, for example by evacuating stock from flood plains or scheduling thermal electricity generation to conserve hydroelectricity generating capacity.

A flood is a discharge in a river or stream which exceeds the capacity of the channel and inundates neighbouring areas of normally dry land. Floods are commonly caused by heavy rainfall, but may also result from rapid snowmelt during warm weather, or from more unusual occurrences such as the collapse of a dam, such as the Opuha Dam in South Canterbury in 1997.

Floods may be described by reference to their peak discharge or water level, the time to peak, and the volume of storm runoff. A commonly used statistical index is the return period of a flood, which is related to the probability that a given discharge is equalled or exceeded. For example, a flood peak discharge with a 1% probability of being equalled or exceeded in any one year (a 1% annual exceedance probability, AEP) is often described as the flood with a 100-year return period. This is commonly, but incorrectly, called the 100-year flood.

The most common method of analysing flood frequencies for a given location is to fit a statistical distribution to a series of annual maximum flood peaks. McKerchar and Pearson (1989, 1990) reviewed New Zealand flood frequencies. For mean annual flood peak, 343 annual series were used, each of which had at least 6 values. Contour maps of mean annual flood peak (scaled by each catchment's drainage area) for the 343 catchments indicated smooth trends over New Zealand (Fig. 1.7). The contours generally reflect the pattern of annual rainfall (NZ Meteorological Service, 1985) and rainfall intensity (Tomlinson, 1980), with high values along the main mountain ranges and around the North Island volcanoes, and low values in areas of rain shadow. Low values in the central North Island, north of Taupo, are attributed to the layer of absorbent volcanic ash in that area (Duncan, 1987, 1992).

Similarly, contour maps of the ratio of estimated 100-year return period flood peaks to mean annual flood peak showed smooth variations. Values are low along the western sides of the main mountain ranges and the North Island volcanoes, and are high where rainfall is low and infrequent, for example in South Canterbury. This reflects the fact that year-to-year variations in the size of the largest floods are relatively small in wet areas, which receive a regular succession of heavy rainfalls. On the other hand, in dry areas rainfall is less frequent, but occasionally comes in intense frontal or convectional storms.

The greatest specific discharges (discharge per unit area) ever recorded in 343 New Zealand catchments occurred in the Haast and Cropp Rivers, which flow from the western Southern Alps. These flows resulted from heavy rainfall during very strong north-westerly air flows, and may be approaching the probable maximum flood.

Figure 1.7. Distribution of mean annual flood peak ($m^3/s/km^2$). Mean annual flood is divided by catchment area $A^{0.8}$. (from McKerchar and Pearson 1990)

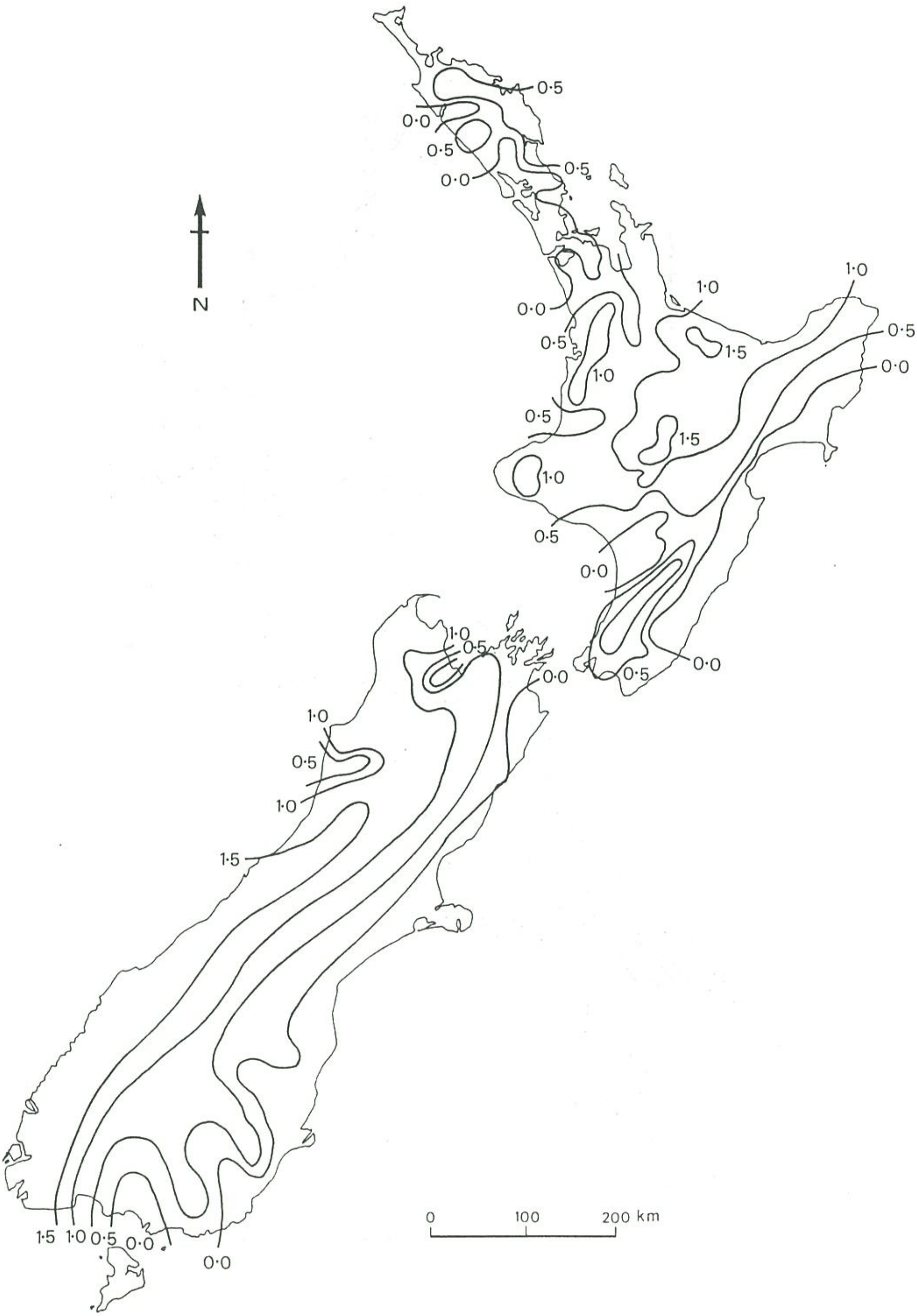

Figure 1.8. Distribution of mean annual 7-day low flows, in $\log_{10}[l/s/km^2]$ units. (from Pearson, 1995).

At the opposite end of the spectrum, low streamflows also have distinct regional patterns in New Zealand. Pearson (1995) analysed annual minimum series of 7-day duration mean flows for nearly 500 New Zealand catchments. Ten per cent had at least one annual value of zero (i.e. the stream had stopped flowing for more than one week). One per cent stopped flowing for at least one week in every year. Zero flows were more likely to occur in small streams in lower rainfall areas.

Contours of the mean annual minimum 7-day flows (scaled by catchment area) showed smooth variations over New Zealand (Fig. 1.8). Low mean values occur in dry eastern areas of the country and high values occur in wet western regions and volcanic areas. Soil and bedrock in volcanic areas tend to have high storage capacity and flows in the rivers of the volcanic plateau are well sustained.

Hydrologists are principally interested in whether or not a river or stream can supply a given demand for water. Water may be needed for domestic or industrial use, for irrigation of farmland, for hydroelectric power generation, for recreational river use, or to maintain wildlife habitat. If demand cannot always be met, the amount of water which must be stored in order to meet probable water deficits must be estimated. To do this, frequency analysis of low flows and of water-deficiency volumes is required.

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2
Hydrological processes of extreme events

Richard Ibbitt, Ross Woods and Alistair McKerchar

Introduction

The most straightforward definition of an "extreme event" is something that occurs infrequently, and that is in some way bigger or smaller than conditions that exist for most of the time. When this definition is applied to a river basin most people think of floods or droughts. But what are floods and droughts? To a person who is drowning the important aspect of a flood is the level of the water, while to a boat that has lost engine power the deadliness of a flood is in the velocity of the current that can carry it onto the rocks. Conversely, to a person dying of thirst a drought is a total absence of water, while for boats a drought may mean that stretches of a river become too shallow for navigation. Clearly, different aspects of the same event have different degrees of importance that depend upon the viewpoint of those most affected. To make sensible comparisons between different occurrences of the same type of extreme event, some standard definitions therefore are desirable.

Since extreme events are multi-faceted, the first step in comparing events of the same type is to decide which characteristic is the most important. For example, in the case of floods, are water levels more important than the velocity of the flow? Once this question has been answered, we must consider which property of the chosen characteristic is of greatest concern. Floods and droughts can be characterised by three properties:

1. The magnitude: how severe or intense was it at its most severe?
2. The duration: how long did the event last?
3. The frequency: how long, on average, is it since the last event of similar size?

For floods in New Zealand magnitude is often the most important characteristic because of the short duration of most events. They can be characterised in physical, rather than in economic or social terms, by one or more of:

- the maximum flow in the river;
- the highest level to which flood waters rise;
- the total volume of flow over a given period of time;
- the area of land that is inundated by the flood waters;
- the velocity of the flow;
- the volume of sediment carried by the flood waters.

For low lying flood plains with poor natural drainage, the duration of flooding can be more important that the magnitude, because grass dies when inundated for long periods of time and the land becomes unproductive. Duration of flood inflow is also important for lakes with artificial outlet controls, since duration largely can determine the total volume of inflow and the height to which the lake level subsequently rises. For hydro-electric storage lakes there are both short term and long term effects from floods. The short term effects can threaten the safety of the dam, while a frequent occurrence of floods can threaten a scheme's economic viability because of loss of water storage to storage of sediment.

While floods tend to be compared more commonly on the basis of their relative magnitudes, droughts tend to be compared on the basis of their duration. Comparison of droughts is often complicated by the type of drought that occurs and the relationship between them. For the meteorologist, a drought is primarily a lack of rainfall; for the farmer a drought is lack of soil moisture for pasture or crop growth; for the river ecologist a drought is a lack of flow in the river. To distinguish between the different types of droughts the following qualitative definitions will be used.

- a meteorological drought is a prolonged period of below average rainfall;
- an agricultural drought is a prolonged period of below average soil moisture;
- a hydrological drought is a prolonged period of unusually low river flow;

where "prolonged" is used to imply a continuous sequence that is regarded as extreme in terms of the economic, ecological, or physical damage done by the drought. A fuller discussion of what constitutes significant values for "prolonged" and "unusually low" are given in the section on droughts.

Much of the difficulty in quantitatively defining a flood or a hydrological drought arises because both types of events are generally composed of combinations of extreme events which are usually upstream of where the event is observed. High water levels can be caused by water backing up behind a downstream obstruction, so that it is incorrect to regard all extreme events as being caused by upstream conditions).

While floods need heavy rainfall, extreme floods generally require heavy rainfall to be combined with saturated or frozen ground, so that the rain is unable to be stored in the soil and quickly reaches the stream channel. Similarly, dry periods can be turned into extreme droughts by high winds and high temperatures which increase the rate at which plants use soil moisture. Thus, different sets of circumstances may cause extreme events that have similar impacts. In broad terms, an extreme event may be considered to have two parts: a set of precursor conditions and a trigger that causes the event to occur. Extremeness in both parts is more likely to lead to an overall extreme event than extremeness in only one part.

Weather patterns are dynamic, and their movement can have dramatic effects upon the occurrence of both floods and droughts. In general, extreme floods are generated by:

- heavy rainfall over an entire river basin;
- stationary or slow moving weather systems that prolong the period of heavy rainfall;
- weather systems that move downstream with a flood wave, constantly adding water to the river where it is already in flood;
- sequences of storms that fill up headwater lakes.

Floods typically last for periods of hours to days in New Zealand catchments, but droughts are events lasting months to years. Consequently, the passage of an individual weather system, which can take up to a week to traverse the North and South Islands, has little impact on the severity of a drought unless the system results in extreme rainfall over the drought affected areas. What is important for droughts is the persistence of particular spatial patterns so that, for example, rain bearing winds frequently bypass those areas experiencing drought conditions.

In summary, then, to draw correct conclusions from a comparison of different events, it is necessary to consider their magnitude, duration, frequency, and spatial extent.

Meteorological conditions causing floods

The underlying cause of most floods is precipitation (rain, hail, and snow). Precipitation is the result of moisture in the atmosphere condensing to form droplets, and temperature and humidity conditions in which droplets do not evaporate before they coalesce into drops that are heavy enough to fall to the ground surface. For condensation to occur, the atmosphere must contain nucleii to start droplet formation. In New Zealand, the surrounding oceans provide ample quantities of suitable particles, such as dimethyl sulphide to initiate condensation (Kristament *et al.* 1993).

Once the atmosphere is charged with a supply of nucleii, a drop in temperature is needed to bring the humidity level to saturation. A moist air mass can have its temperature reduced by contact with another colder air mass, by an increase in altitude, or by contact with a cold ground or water surface. Contact of moist air with cold surfaces is essentially a two dimensional phenomenon that can lead to fog or mist formation, but the fog or mist can be readily dispersed. The mixing of air masses of different temperature or the elevation of moisture laden air is likely to lead to the formation of raindrops. Mixing and elevation of air can result from:

- currents of cold air meeting less dense currents of warm air and forcing the warm air upward (frontal conditions);
- moist air being forced up over mountainous terrain (orographic conditions);
- air being heated at a moist surface by solar radiation, becoming lighter than surrounding air, and rising upwards to form clouds and possibly generate thunderstorms (convective conditions).

The significance of these different condensation mechanisms for flood generation lies in how quickly the cooling occurs, the spatial extent of the cooling, and the ability of the atmosphere to keep supplying warm moist air to the source of cooling.

Spatially limited, rapid cooling is characteristic of convective or thunderstorm precipitation. The precipitation is often of great intensity but short duration, and much may arrive in the form of hail. This type of event leads to "flash floods" in small catchments which are of similar spatial size to the storm. In rural catchments, considerable surface erosion may occur, leading to loss of topsoil, severe siltation of downstream channels, and smothering of aquatic biota. In urban catchments, blockage of drains by hail can cause serious surface flooding, and rapid runoff from paved areas hastens the generation of flood peaks. Where the ground surface is exposed, such as on construction sites, major runoff of silt can occur. Although floods generated by convective rainfall generally affect areas of less than 10 km², their impact can be economically serious. The small spatial extent of such storms means that the most intense rainfall is frequently under-recorded. This coupled with their rapid development and equally rapid dissipation, makes forecasting difficult, and their short duration hinders the provision of useful warnings. The response that New Zealand society has developed to deal with such events is to design urban infrastructure to cope with events up to a particular size and to treat the occasional disruption from larger events as tolerable. Unfortunately the utility of this approach is not always appreciated by society when an extreme event occurs.

Spatially extensive rainfall events are more likely to occur due to the passage of a weather front, the rapid uplift of warm moist air over high ground (orographic rainfall), or a combination of the two. The effects of frontal systems, particularly those associated with decaying tropical cyclones are less predictable than those caused by the passage of warm moist air over a mountain range. The passage of frontal and cyclonic rainfall is determined by the movement of high and low pressure areas, whereas orographic rainfall is determined primarily by the location of mountains. Orographic precipitation generally increases with altitude, particularly on the windward side of mountain ranges. The West Coast of New Zealand provides a dramatic example of this. North-westerly winds blowing in from the Tasman Sea have high relative humidity and within 10-20 km of the coast the moisture laden air is forced to cross the Southern Alps at altitudes between 2,500 m and 3,500 m. This is one of the highest rates of atmospheric uplift in the world, and the ensuing cooling causes very heavy rainfall. Annual rainfalls of 15 m/yr have been recorded with daily falls in excess of 500 mm. Although these falls are large compared to those in many places in the world, extreme floods on West Coast rivers are rare. It is, however, not uncommon for there to be a flood every few days on West Coast rivers. The regular, heavy rainfalls, the short, steep courses of most West Coast rivers and limited in-catchment storage ensure that floods tend to rise and fall quickly, and there is little opportunity for one flood to be still in progress when the second arrives. Many of the factors that complicate the flood behaviour in other parts of New Zealand are missing. When heavy precipitation occurs, it is generally as rainfall, and snow at higher altitudes soon melts owing to the relatively warm air temperatures associated with north-westerly events.

Conditions for flooding in the rest of New Zealand are more complicated. Many North Island areas and the eastern and southern areas of the South Island have soils that are deep enough to absorb a large fraction of the initial rainfall in a major event. This is particularly pronounced for the volcanic ash soils in the central North Island. The amount of available soil moisture storage is also dependent upon the time of year and antecedent weather conditions. New Zealand's rainfall generally shows only weak seasonal variations, but river flow can show marked seasonal responses to weather conditions (Duncan 1987). Many rivers have summer low flows which reflect increased evapo-transpiration, which reduces seepage from the soil into stream channels.

In catchments which contain large lakes (e.g. Waikato, Clutha, Waitaki), large inflows from the headwaters can be absorbed if lake levels are low, so that lake outflows are only of moderate size. A lake acts as a buffer, absorbing the effect of a flood by storing the flood water. Of course, floods entering a lake that is already nearly full can lead to high flows from the lake, and to high water levels around the lake shore. Examples of such flooding occurred in the Clutha River in 1957-58 and again in 1995.

In the southern parts of the South Island and inland areas of both main islands, severe winter frosts can lead to soil moisture turning to ice. This effectively seals the ground surface, so that rainfall is forced to run off rather than being able to infiltrate into the ground. In this case, nearly all rainfall may flow to the stream network, and moderate rainfall events on frozen ground may generate extreme river floods, as is the case of the Fraser River flood of 1978 (Fitzharris *et al.* 1980).

The magnitude of floods in other parts of New Zealand can vary not only because of variation in the rainfall event itself, but also variation in antecedent conditions. McKerchar and Pearson (1989) showed this variation statistically by plotting a function related to the coefficient of variation of the largest floods in each year of record for many rivers through New Zealand. The West Coast of the South Island has consistently low values for the coefficient of variation, showing that the size of West Coast floods varies little from year to year, whereas for east coast rivers in both islands the year to year variation is large. These rivers are subject to greater variation in rainfall, because much of the rainfall comes from the less predictable frontal events, and they have a wider range of antecedent events.

Rainfall with flood-producing potential is less predictable if it is caused by frontal or cyclonic conditions, because these types of rainfall do not always follow the same paths. The direction in which the main rain-bearing clouds pass across a catchment can also have a dramatic effect upon streamflow. For a long narrow catchment, quite different flood characteristics are likely if the rain-bearing clouds travel across rather than along the main axis of the catchment. A storm moving across such a catchment affects a spatially smaller area, and passes more quickly than a storm that travels along the axis of a catchment.

For storms that traverse a catchment along its main axis, a storm that moves down the catchment generally produces a larger flood than one that moves up-catchment. This is because rain falling from storm clouds moving down a valley is more likely to make tributary streams rise at the same time as runoff from further up the catchment passes the tributary confluences. The effects of storm direction can be reduced or amplified by the temporal features of the precipitation. Sustained uniform rainfall may saturate whole catchments, so that all further rainfall rapidly runs off into the channel system. The geometry and density of the drainage network then influence how quickly the flood will reach the catchment outlet. However, there are very few recorded cases in which sustained, uniformly heavy rainfall has brought a catchment to a steady state condition, in which the rate of input matches the rate of outflow. More commonly, the rainfall is temporally variable, and then the timing of bursts of heavy rainfall with respect to the movement of the flood wave through the channel system is all important. If bursts of heavy rainfall generate tributary flood waves that are synchronous with the main channel flood wave, extreme flooding may result. Heavy rainfall at the end of an event is usually considered to be more potentially dangerous that the same rainfall at the start of an event, when ground conditions enable much of the initial rainfall to be absorbed.

Topographic conditions exacerbating flooding

When extreme floods occur, alluvial stream channels often are unable to contain the flow, and the excess water spills onto adjacent low lying land. The seriousness of this "inundation" flooding

Fig. 2.1. Siiltation along the Waipaoa River flood plain as a result of flooding during Cyclone Bola. (Photo courtesy of Gisborne District Council.)

depends upon the type of land inundated, and the depth and duration of inundation. Inundation of urban land can result in serious damage to property, loss of life, and public health problems where water supply becomes contaminated or sewage is forced back into streets and houses. Inundation of rural land can also result in bacterial contamination, but this is likely to be localised. The main impacts of rural flooding are loss of livestock, damage to fences when they collect debris and form "dams" that fail as water levels rise, and damage to crops and productive land (Fig. 2.1). Although water that inundates riparian land is seldom fast-flowing, it carries fine sediment and can take days or weeks to drain away. In cases where the depth of water is great, large amounts of floating debris also may be left by the draining flood waters. Inundation of pasture for more than a few days "kills" many plant species, and fine sediment can clog the surface so that the soil becomes unproductive. Ploughing to reaerate the soil and re-sowing can restore the quality of the ground, but this is expensive and often comes on top of the loss of a harvest.

Inundation of land is essentially the result of large volumes of water arriving on the ground surface coupled with the inability of the terrain to drain it away quickly. Flat land alongside rivers is notoriously difficult to drain (Fig. 2.2), and the problem can be aggravated by stopbanks which were actually intended to prevent river flows from invading the land. Water trapped behind a stopbank cannot drain away until the river level falls and an opening in the stopbank can be made to allow drainage back to the river. The latter course of action is not always practical, particularly where the inundated land is near the coast and high tides may result in saline water flowing onto the land. While stopbanks protect against inundation by moderate

Fig. 2.2. Flooding of low lying land along the Hakataramea River.

floods, they are often no defence against events greater than they were designed for. Once structural flood defences like stopbanks fail, they tend to make the situation worse. Sometimes they even do this before they fail. By constricting the flow in a river, flood protection works can increase upstream water levels above what they would naturally have been, which can lead to the flood flow breaking out upstream of and outflanking the stopbank system. This has occurred on a number of occasions at the mouth of the Clutha River when an incoming tide, increased by a storm surge, has blocked flood waters flowing to the ocean and has caused flooding of adjacent low-lying farm land.

Inland from the coast, rivers can be blocked by natural landslides as occurred in the Upper Gorge of the Buller River in 1968 following the Inangahua earthquake (Figs. 2.3, 2.4; Soons and Selby 1992, p. 427), lahars from volcanic eruption (Soons and Selby 1992, p. 299) and where rivers of different flood characteristics meet. Queenstown has been flooded on a number of occasions because of high levels in Lake Wakatipu, when the Shotover River, downstream of the lake outlet, has effectively dammed the main Kawerau River which flows from the lake. During times of heavy rainfall the Kawerau River rises only slowly, because of the buffering effect of Lake Wakatipu. The Shotover River has no such buffering effect, and rises rapidly to flows well in excess of those in the Kawerau. During times of flooding the Shotover carries large amounts of coarse sediment, which are deposited as a delta at its cofluence with the Kawerau. This partially blocks the flow of the Kawerau, and causes the level of Lake Wakatipu to rise. Because of the large amount of sediment deposited by the Shotover River during a relatively short time, and the fact that weather conditions that cause the Shotover to flood also generate large flows in the rivers feeding Lake Wakatipu, the lake can continue to rise for many days after the Shotover River has returned to normal flows. Eventually the much larger average flows of the Kawerau erode the delta formed by the Shotover, and lake levels fall. The quantities of sediment involved make mechanical removal impractical. The most extreme situations occur when a second sequence of events occurs before the Kawerau has been able to fully remove the temporary delta formed by an earlier event.

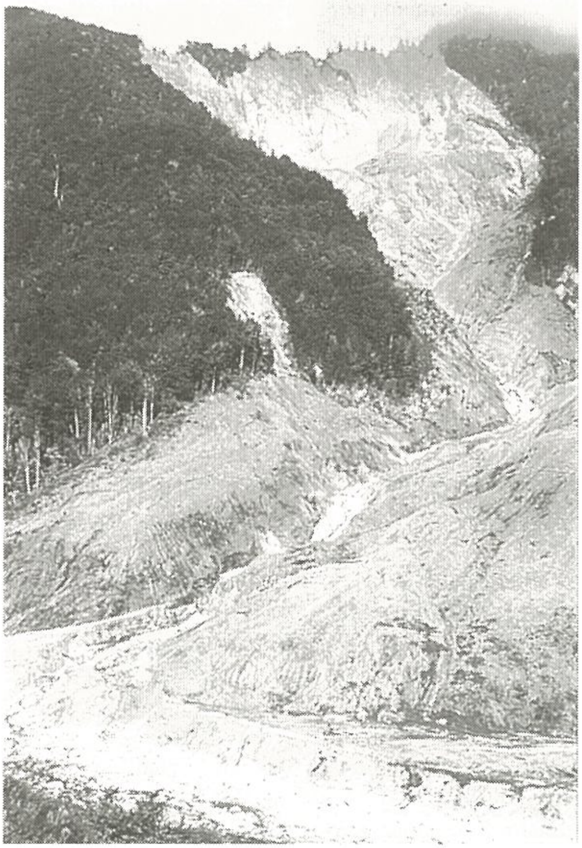

Fig. 2.3. The "Buller earthquake slip" which occurred during the Inanganhua Earthquake of 1968.

Although volcanic lahars block stream channels in other countries, the areas of New Zealand where this might happen are restricted to the small areas around Mounts Ruapehu, Ngarahoe and Taranaki. Nevertheless, volcanic activity has had some far-reaching and unexpected effects on flooding. The 1992 eruption of Mt Pinatubo in the Philippines had a profound effect upon the climate in New Zealand for 2-3 years afterwards. This eruption added much fine dust to the stratosphere, which reduced the solar radiation reaching New Zealand. The result was a general lowering of temperatures and reduction in evapotranspiration, which led to higher soil moisture levels and less soil moisture storage available to absorb any potentially flood-producing rainfalls. New Zealand was perhaps lucky that during the period that the Pinatubo eruption affected its climate, there were no serious incidents of flooding. Another indirect effect of volcanic activity is illustrated by the floods which resulted from the failure of canals leading water to the Whaeo and Ruahihi power schemes. These floods were generated when embankments of the man-made canals failed because the volcanic material used in the construction of the canal lacked adequate cohesive properties.

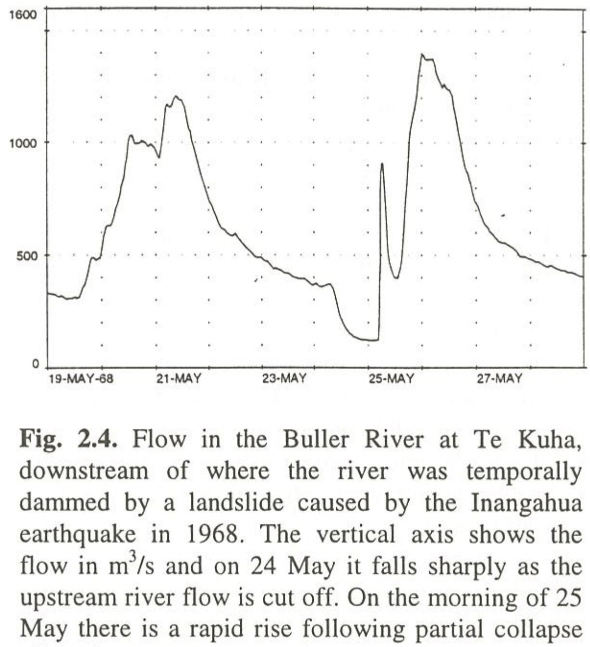

Fig. 2.4. Flow in the Buller River at Te Kuha, downstream of where the river was temporally dammed by a landslide caused by the Inangahua earthquake in 1968. The vertical axis shows the flow in m^3/s and on 24 May it falls sharply as the upstream river flow is cut off. On the morning of 25 May there is a rapid rise following partial collapse of the dam.

Summary: influences on flooding

The main purpose of this section has been to examine what circumstances cause floods, and turn an otherwise ordinary flood into an extreme event. A large number of factors can influence the way in which heavy rainfall is transmitted out of a river basin:

- type of precipitation event, e.g. convective, frontal, orographic;
- form of precipitation, e.g. rainfall, snow or hail;
- direction of travel of a storm with respect to the main axis of the catchment
- speed of travel of a storm;
- temporal pattern of precipitation within a storm;
- antecedent moisture storage conditions in a catchment;
- antecedent ground surface conditions, e.g. frozen or cracked;
- catchment shape;
- characteristics of the land draining to stream channels, e.g. slope angle, depth, porosity and permeability of the soil;
- drainage network pattern and drainage densities;
- the amount of within-bank storage in the channel system;
- characteristics of the stream channels, e.g. slope, roughness.

Flood levels also can be exacerbated by obstructions to runoff by:

- in-coming tides;
- raised sea levels caused by storm surge;
- artificial constrictions to river channels and growth of willow trees;
- landslides into the stream channel;
- sedimentation in the channel, e.g. at a tributary confluence;
- stop banks;
- lahars.

Most of New Zealand's most damaging floods have been related to the coincidence of several of the factors listed above. The factors are generally self-exclusive, in the sense that they can have only a single impact on a single flood. For example, if a flood is exacerbated by frozen ground this factor will exert its influence only once, since repeated freezing of the ground, even if it were plausible, would not alter the fact that no rainfall could infiltrate into the ground since it became frozen. An exception is the effect of precipitation upon a previous snowfall. The extreme flood of 1978 in the Fraser River (Fitzharris *et al.* 1980) was a consequence of this phenomenon. While this type of rain-on-snow event is the norm in areas where there is seasonal snowfall, it is less common in New Zealand. This is possibly because most of the high altitude catchments contain large lakes that are now operated for hydro-electric power generation, and so are generally at low levels when the spring thaw occurs. Nevertheless, extreme rain-on-snow floods have occurred in New Zealand, and the potential for future occurrences exists in a number of catchments.

Processes of flood generation

Floods result from large amounts of water entering the river channel network. But what controls how much of the precipitation leaving the atmosphere becomes water in the channel network? The answer to this question depends on the properties of the terrain on which the precipitation falls and the physical state of the precipitation, i.e. rainfall or snow.

An individual raindrop or snowflake falling from the atmosphere can either directly strike the ground or it can be intercepted by some object above the ground surface, such as a leaf. Although the hydrological effects of interception are diverse, interception seldom has a significant impact on flood events, because of the small size of interception losses, about 3-4 mm during a rainstorm, compared to the total storm rainfall. The exceptions are when intense convective storms generate small amounts of rainfall very quickly. In dense vegetation, such storms have little impact: in urban environments flash floods may occur, especially when interception of rainfall is minimal.

The process of flood generation really commences when rainfall reaches the ground surface. If the ground is pervious, rainfall will pass through into soil moisture storage. If it is impervious, or nearly so, rainfall will be diverted along the ground surface into the drainage system. Where the rainfall intensity exceeds the infiltration capacity of the ground surface some of the rainfall will remain on the surface producing "infiltration excess" overland flow. Such overland flow used to be considered unlikely in rural New Zealand, but opinions have changed in recent years in response to the realisation that phenomena which may be unimportant at large scales, over areas on the order of square kilometres, may be very significant at small scales on the order of hectares. One environment in which infiltration excess is the primary generator of surface runoff is in urban areas, where paved surfaces convert all the rainfall that falls on them into surface runoff. The periodic severe floods in urban areas in New Zealand mirror those experienced in many of the world's cities; they may cause serious disruption to traffic and communications, and the inundation of and damage to property in low lying areas. The urban areas affected by flash floods in New Zealand seldom exceed more than 10 km^2, because as the area potentially affected by an event increases, rainfall intensity away from the storm centre declines and the potential for infiltration in parks and gardens increases.

Studies in forested areas demonstrated that overland flow over the mineral soil, in association with rapid subsurface flow, can be responsible for very rapid hydrograph rises during storms (Mosley 1979). Recent measurements at Whatawhata near Hamilton have demonstrated that infiltration excess runoff also can occur on steep rural basins. Fig. 2.5 shows the runoff from two sites after two intense rainfall events that occurred a day apart. The first rainfall event was three times larger than the second one, in volumetric terms, while the peak rainfall intensity at the 15 minute recording interval was 50% greater for the first event. So why was the peak rate of runoff from the first event for the hillslope site which drains an area of 0.03 km^2 so much greater (400%) than that for the second? Furthermore, why did the rate of runoff between the two events recede to almost the rate before the first event? (Normally in double-peaked events with similar rainfall the second peak is greater than the first and delayed drainage of water through the soil ensures that the post-event runoff rate does not decline to the pre-event rate for many hours.) The explanation that best fits the observations is that the first event contained a burst of rainfall that was sufficiently intense that only a small amount entered the soil with the majority being diverted overland to quickly reach the stream channel. When the second rainfall event occurred, runoff from the first event had effectively ceased, hence the return to pre-event streamflow values. The second event was less intense so that more of the rainfall entered the soil and less was available to quickly reach the stream channel. The second event was accordingly characterised by a lower rate of runoff with a lower decline from the maximum value as delayed drainage through the soil maintained elevated rates of stream discharge. Infiltration excess runoff at Whatawhata has been confirmed using special collectors placed on the ground surface which have collected large amounts of water flowing over the surface. (Rodda et al., 1997). Trampling by stock is a factor in reducing infiltration rates at Whatawhata.

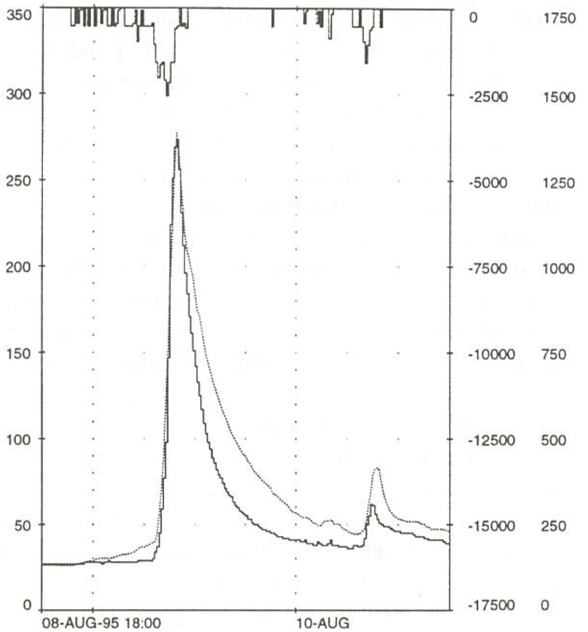

Fig. 2.5. Runoff from two sites at Whatawhata for two intense rainfall events. Rainfall is plotted downwards while runoff (mm x 1000 per 15 min) from the hillslope is the continuous line and flow at the Upper Mangaotama Stream weir is the dotted line. The flows from the two sites have been scaled to have the same peak value.

Examination of the rate of runoff from the larger (2.59 km^2) area draining to the Mangatoama flow measurement station at Whatawhata, also shown in Fig. 2.5, shows behaviour that is a little more in keeping with the traditional expectation of runoff from two similar rainfall events that occur in quick succession, i.e. the flow does not recess to the pre-event flow and the second peak, while still small, is rather more consistent with the size of the rainfall that caused it. So how does runoff from individual hillslopes change its character as many hillslopes respond together? The answer relates to a relatively new concept in hydrology called scaling. At different spatial and temporal scales, different runoff mechanisms prevail. At the hillslope scale (areas up to about 1 km^2) the infiltration excess mechanism can be the dominant generator of runoff provided suitable conditions exist, that is rainfall rates exceed the infiltration rate of the soils, ground slopes are steep enough to ensure that overland flow is rapid, and the opportunities for ponding in depressions and subsequent infiltration are small. At scales greater than 1 km^2, the dominant runoff mechanisms may change. Firstly, the larger the area the smaller is the chance that the rainfall everywhere will exceed the infiltration rate. Two effects are important in this situation: rainfall rates lessen away from the centre of a storm; and average infiltration rates increase as area increases. This latter effect has several causes. Larger areas generally contain more diverse slope, vegetation and soil types, so that as area increases there is a greater chance of milder slopes, bigger openings in the soil around plant stems, and the inclusion of soil units with higher infiltration rates. The net effect is that as area increases the opportunity for rainfall to enter the ground increases, and large source areas of infiltration excess runoff become less likely. Instead, the nature of the topography starts to dominate the runoff production process. Since relatively, more water enters the soil in a larger area, the question arises as to what happens to this water. Once water enters the soil, the factors that control its movement change. The influence of gravity becomes modified by capillary forces. Although gravity draws water downwards into the soil, viscosity and surface tension can greatly reduce the rate of moisture movement, and suction forces within the soil can cause the water to move upwards rather than downwards as the soil dries out. This latter phenomenon is discussed more fully below, with respect to droughts.

In relatively wet soils, downward movement of moisture predominates. Eventually the moisture reaches a barrier to vertical movement, such as an impervious layer or soil that is already saturated, so that there is no space for additional downward percolating water. In these circumstances the percolating water tends to flow parallel to the surface of the impeding layer, in a generally downhill direction towards the nearest stream channel. As the water approaches the stream channel the ground slope may gradually lessen; and/or the surface or bedrock topography may become convergent, so that the paths of water movement are forced together. As a result, the movement of the water is impeded and slowed down. Since water continues to arrive from upslope, it tends to "pile" up - that is, air in the soil is displaced by the incoming water, and the level of saturation rises towards the ground surface. In a number of places, mainly, but not exclusively, along stream channels the ground surface becomes saturated. Rainfall on such saturated areas cannot enter the already saturated soil and either ponds in depressions on the ground or flows downslope towards the stream channel. This form of storm runoff is referred to as saturation overland flow. The areas producing such runoff expand as the duration of the storm and total storm rainfall increase, and subsequently shrink as the catchment drains and dries out after rainfall. This phenomenon, the partial/variable contributing area concept (Betson 1964), is the dominant cause of surface runoff in most rural catchments in New Zealand.

For some catchments in New Zealand, particularly in the central North Island volcanic soils, surface runoff seldom occurs because the soils and underlying rocks are so porous that all rainfall is absorbed and flows underground through the soil and rock to the stream channels. Such catchments are characterised by high baseflow rates with only moderate increases during rainfall events. The annual runoff hydrograph for the Puruorakau basin (Fig. 2.6a) shows a slow increase in discharge with the onset of winter and a decline as summer approaches. The "spikes" superimposed on the annual trend arise from precipitation falling directly into the channel.

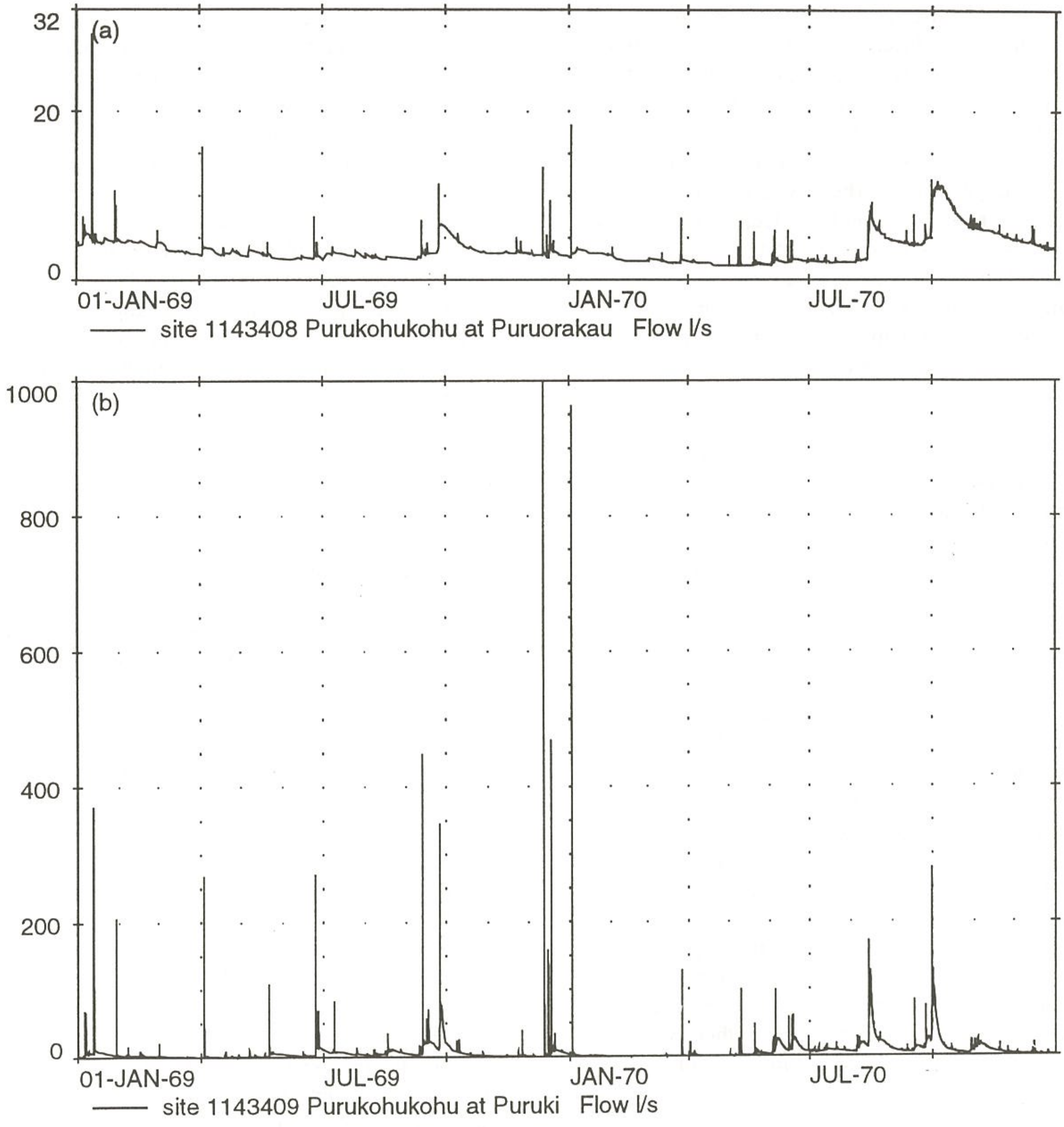

Fig. 2.6. Flow in *l*/s for two similar sized catchments in the Purukohukohu basin. The upper plot shows the runoff from the Puruorakau catchment which is covered in indigenous native forest. Note that the scale runs from 0 to 30 *l*/s. The lower plot shows the flow from Puruki catchment which is covered in pasture. Note that the scale for the lower plot runs from 0 to 1000 *l*/s.

The porous nature of the central North island volcanic soils can be radically altered by anthropogenic activity. The flow hydrographs shown in Fig. 2.6a is for a small basin still covered in indigenous forest. By contrast. Fig. 2.6b shows flow from an adjacent small basin that is in pasture. Two differences are noticeable: the much higher flood flows from the pasture covered catchment;

and the higher baseflows in the forest catchment. The reason for the differences relates to alteration in the near-surface soil properties. In the pasture catchment, the surface soils have been compacted by machinery and animals, and in some cases may have become hydrophobic. In the forest catchment the soil is largely undisturbed, with the mineral soil protected from compaction by a deep layer of plant litter. Floods flows in such catchments tend to be smaller than corresponding events in pasture catchments, with most of the runoff coming from rainfall on to the stream channel and wetland areas adjacent to the stream channel.

The foregoing discussion of the mechanisms that lead to flood flow generation focuses on how ground surface conditions affects infiltration. Frozen ground, urbanisation, soil compaction and saturation all limit the ability of the ground to infiltrate water. On the other hand, the presence of plants and soil fauna generally increases the infiltration capacity of soils. Animal burrows and passages left by decayed roots enable faster transmission of water into and through the soil. The roots and stems of plants expand with growth and push the soil apart over time, creating cracks that aid the entry of water into the soil. Infiltration can also be enhanced by drying of the soil, since many plant roots contract as they dry out and provide pathways for infiltration and storage of future water. In extremely dry conditions, soils containing large percentages of clay can develop major cracks at the surface, that can sometimes extend downwards more than a metre. Such cracks can direct potentially flood producing rainfalls away from stream channels and into soil storage. While large cracks in the soil surface can mitigate flooding, their presence is often the result of the opposite hydrological extreme, a drought.

Droughts

Underlying causes and exacerbating factors

Droughts can be classified into three main types: meteorological, agricultural and hydrological. Although not fully independent of one another, it is possible to have a meteorological drought without necessarily having a hydrological drought. This section focuses on hydrological droughts, but it will be necessary also to consider interactions with the other two types of drought.

The definition, introduced earlier, of a hydrological drought as a "prolonged period of unusually low river flow" gives few clues as to what causes such events. A key question is why has there been insufficient runoff from the land to maintain "normal" river flows? Tracing runoff production backwards to the atmosphere suggests that unusually low amounts of precipitation are the ultimate cause of hydrological drought. In general this is true. Low flows also can occur when low temperatures result in precipitation in the form of snow, and immobilise soil moisture by freezing. Winter low flows are characteristic of South Island alpine catchments, and since they tend to occur every year, they should not be regarded as hydrological droughts. Flows increase as soon as temperatures rise above freezing.

The association of low temperatures with low winter flows shows that extreme aspects of the climate, other than amount of rainfall, can influence the incidence of droughts. In the paradoxical case in which agricultural droughts on the east coasts of the North and South Islands are associated with floods in the major rivers of these region, the reason is that the meteorological conditions that lead to low rainfalls over the east coast also lead to very high rainfalls in the main source areas of the main rivers, in the mountains to the west. Thus, in the Rakaia River, rainfall in the headwaters is ten times greater than over the Canterbury Plains across which the Rakaia flows (Ibbitt 1979).

So what causes lower than average runoff? Lack of rainfall in the main source areas of a river is clearly one ingredient, but may also be insufficient to generate serious hydrological drought. High temperatures and winds can reduce soil moisture to low levels and with it, seepage to stream channels. Other factors can exacerbate the situation. The planting of forests in place of grassland can greatly increase the return of moisture from the soil to the atmosphere evapotransporates (Duncan 1992). Upstream abstraction or impoundment of water for irrigation may seriously reduce downstream flows, although enforcement of the Resource Management

Act may eventually mitigate river droughts from such anthropogenic activity.

An account of the causes of drought would not be complete without mention of two factors: timing of low rainfalls and the role of global ocean circulation. Droughts may not immediately follow the onset of drier than usual meteorological conditions. Indeed, incipient drought conditions may exist for many months, perhaps as a result of an unusually dry winter, before either dissipating because of higher than average spring and summer rainfalls or developing into a severe drought because of high summer temperatures, high winds and low rainfalls. Thus a drought may have multiple causative and exacerbating factors, which are so inextricably linked to underlying atmospheric circulation that little purpose is served trying to disentangle them.

A more fundamental issue is why there are occasional years with meteorological conditions suitable for causing droughts. El Nino (negative) phases of the El Nino-Southern Oscillation (ENSO) phenomenon tend to cause enhanced frequencies of SW winds over New Zealand, and cooler land temperatures, (Chapter 1; Gordon 1986). In addition, summers with positive (La Nina) phases tend to be associated with more NE wind, warmer temperatures, more rain in the North Island, reduced rainfall in the west of the South Island, and lower flows in the rivers draining the Southern Alps (McKerchar *et al.* 1997). However, the ENSO phenomenon explains only a modest portion of the inter-annual variation in climate and hydrology. The role of sea-surface temperatures adjacent to the land affected by drought, and the causes of inter-annual variations in these temperatures are largely unknown.

Mechanisms and characteristics

Unlike floods, which depend crucially upon rainfall intensity and the infiltration capacity of the ground surface, hydrological droughts reflect what happens to infiltrated water long after the rainfall lhas ended. Sunshine, wind, atmospheric moisture deficit and downslope seepage of soil moisture combine to start reducing the amount of water that has entered the soil.

Solar radiation, filtering through vegetation to strike the soil surface, quickly dries out sandier soils and effectively seals their surface against further direct loss of moisture to the atmosphere. Plants, however, extend their network of roots deep into the soil, draw moisture from the ground, and transpire it back to the atmosphere, as long as there is a vapour deficit in the atmosphere and energy available to the plant. At the same time subsurface movement of moisture downwards and laterally towards stream channels is another mechanism which reduces soil moisture storage, but maintains baseflow.

In the absence of further rainfall, soil moisture levels will continue to decline until the plants can no longer draw water from the soil (agricultural drought), and seepage reaches the stream network only where the stream channels still intersect the water table. Where the water table falls below the level of the stream bed, water will flow away (exfiltrate) from the stream channel, reducing streamflow even further.

The rate of soil moisture depletion depends primarily upon prevailing meteorological conditions, since downslope seepage of moisture under the force of gravity can be regarded as a "constant". Prevailing meteorological conditions can enhance or reduce evaporation, depending upon the nature of the terrain that is drying. Rough terrain and tall vegetation cause more wind-induced turbulent transfer of moisture away from the ground surface while the reflective properties of different forms of vegetation may suppress radiation absorption and thereby reduce near surface temperatures. Terrain is a further complicating factor, since south-facing slopes receive less incoming solar radiation than north-facing slopes, and so dry out less quickly.

The above discussion leads to the conclusion that drought-prone areas have many of the following characteristics:

- low potential for soil moisture storage, including shallow soils with low infiltration capacities that ensure most rainfall does not infiltrate;
- sandy soils from which the vegetation can readily extract moisture for transpiration and through which infiltrating water quickly seeps away;

- steep slopes able to drain rapidly under the influence of gravity;
- north facing hillsides able to receive above average amounts of solar radiation;
- areas across which drying winds can blow strongly, e.g. Canterbury.

The effect of these factors upon river flows depends upon the proportion of drought-prone land in each catchment. As already mentioned, Canterbury can be in the grip of an agricultural drought while the region's main rivers are in flood. Thus, in studying hydrological droughts, the reasons for low river flows may not at first sight be obvious, and careful analysis of the variables affecting a region is necessary.

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3
Historic floods and droughts in New Zealand

John Waugh, Horace Freestone and Darryl Lew

The cost of floods to New Zealand

New Zealand is a mountainous and geologically active land, with numerous natural hazards such as volcanoes, earthquakes, and landslides. By far the most common Civil Defence emergency experienced by New Zealand citizens, however, arises from flooding, by both rivers and the sea. New Zealand spent over $1 billion (1984 dollars) between 1951 and 1984 on trying to prevent floods or in repairing the damage caused by floods. This sum included both central government subsidies, expenditures by Catchment Boards and local authorities, and local funds raised by individual landowners.

About two-thirds of New Zealand's population lives in areas that are prone to flooding. The majority of these areas (68% in 1976) have populations of less than 10 000, but nearly 70% of New Zealand towns and cities with populations of over 20 000 also have a river flood problem (Ericksen 1986, p. 53). These larger towns and cities include Whangarei, Gisborne, Palmerston North and the Hutt Valley in the North Island, and Motueka, Nelson, Blenheim, Christchurch, Greymouth, Mosgiel, Balclutha, Gore and Invercargill in the South Island (Ericksen 1986).

One of the largest threatened areas in New Zealand (Poole 1983) is the catchment of the Opihi River, containing the towns of Fairlie, Pleasant Point, Geraldine, Winchester and Temuka. All have suffered major floods: Temuka in 1945, Pleasant Point and Temuka in 1986, and Fairlie in 1994. In 1997 areas were flooded by the Opuha Dam burst. The Opihi River Flood Control Scheme in South Canterbury was constructed to protect some 50 000 hectares of land.

Floods in South Canterbury on the 13 March 1986 affected a region of more than 1000 km^2 extending from Ashburton southward into North Otago. Persistent rain over 48 hours peaked at the end of the storm with 50 mm in 2 hours, to give storm totals up to 250 mm. The flooding which resulted in the Opihi, Tengawai (around Pleasant Point township), Pareora, Waihao (near Waimate) and in the Hakataramea Rivers led to one of the larger Civil Defence evacuations in recent times, when some 2000 people from Pleasant Point township and other localities were evacuated (South Canterbury Catchment Board,1987). In less than 24 hours, the floods caused an estimated $66 million (1986 NZ$) of damage - $60 million to property, roads, railway lines, bridges, crops and livestock, and $6.17 million in damage to river control works such as embankments, groynes, and plantings.

The costs of flood damage have led to a considerable expenditure on flood mitigation. Flood control works have been constructed on most of New Zealand's larger rivers (Acheson 1968; Poole 1983; Ericksen 1986; Williman and Smart 1987). It was well into the 20th Century, however, before engineers (many trained in the UK) came to terms with New Zealand's extremely intense storm rainfalls, and the consequences for dams, bridges, and river control works.

For example, the majority of bridges in Northland were swept away by severe flooding in 1917. This event was probably caused by one of the numerous storms of tropical origin which affect Northland, the Coromandel Peninsula, and East

Cape. Umawera recorded 231 mm in 24 hours and 302 mm over 12 days in 1917. Fallen trees washed down the rivers and contributed to the destruction of the early wooden bridges. A factor which made bridge design difficult in Northland was the very large flood rise on many rivers. In 1937 a major flood on the Mangakahia River rose 19.5 m (64 ft) above normal water level, submerging the deck of the bridge and rising to the top of the handrails.

Regional Councils (and their forerunners, the Catchment Boards) play a major role during floods, in monitoring the developing floods and passing this information to the police and local Civil Defence controllers. The Councils monitor rainfall, river levels and flows, often using automated instruments which can telemeter the data.

In recent years, satellite weather photographs and information from weather radar have added to the data available for flood forecasting. Some Regional Councils operate computer-assisted flood forecasting systems, which use interactive rainfall-runoff models to predict the time and maximum level of the flood peak, and the shape of the flood hydrograph. The Wellington Regional Council operates such a system for the Hutt, Otaki and Waikanae Rivers, the Manawatu-Wanganui Regional Council for the Manawatu, and the Canterbury Regional Council for the Waimakariri River.

Early experience of floods

The early settlers from Britain and Europe had to face an environment that was very different from that of the countries they had left. One of the greatest hazards in New Zealand was the very heavy rainfall and consequent flooding, which could rapidly turn small, seemingly harmless streams into raging torrents.

By 1870, just a few decades into the period of European settlement, New Zealand rivers had been responsible for 1115 *recorded* drownings (Cumberland 1985); drowning became known as "the New Zealand death". Comments in the diaries of early settlers note the exceptional severity of flooding.

Early floods of the Hutt River

The pattern of early European settlement in the Wellington area was influenced by major floods of the Hutt River.

Settlers in the Wellington region were initially attracted to the flat lands of the lower Hutt Valley. On 2 March 1840, less than two months after the arrival of the first four ships of settlers, a Hutt River flood inundated huts and tents in the Petone area to some depth. About 40 settlers moved temporarily to higher ground at "Cornish Row", a raised shingle ridge (Easter 1991), but within a few months most of the settlers abandoned the Hutt valley for the Thorndon area in central Wellington (Butterworth 1988).

A major flood of the Hutt River occurred in January, 1858. A description of the flood is contained in the Kilmister Reminiscences, (Alexander Turnbull Library MS 1117, dated 12 May 1932):

"In the year 1858 there was a tremendous flood in the Hutt River; the water reached from hill to hill; great trees came floating down carrying away houses with them; thirteen people were drowned."

"The Maori called it the rata flood because there were often heavy rains about the middle of January, when the rata trees were in flower. This flood gave the Hutt Valley a great set back; a lot of settlers shifted to Sandon."

Modern day estimates put the peak discharge for the January 1858 flood at 2000 m^3/s at Taita Gorge (NZ Hydrological Society 1996). A flood of similar magnitude occurred in June 1898; these two events are the largest floods recorded on the Hutt River to date.

The description of water reaching from hill to hill is a clear warning of the area that the Hutt River is capable of inundating. No river control works existed until a stopbank was built at Petone in 1894; it was overwhelmed by the 1898 flood, so more extensive, higher stopbanks were built between 1900 and 1906 (Wellington Regional Councl 1996).

Throughout the 20th Century, New Zealand has spent huge sums trying to contain rivers with flood control works, to safeguard valuable and fertile agricultural lands and the numerous towns and cities which have grown up in areas subject to flooding. In contrast, the early Hutt Valley settlers response was to relocate to what they hoped was a less flood-prone location.

Floods on the Clutha and Waitaki Rivers 1878 and 1995

The Clutha and Waitaki floods of September 1878

The largest flood recorded on the Clutha River up to the present (1997), occurred in September 1878. This flood is particularly well documented, and numerous reports provide eye-witness descriptions and photographs of the flood and the destruction it caused (Richardson 1983; Griffiths 1978; Gillies 1956; Rivers Commission 1920). The reports have been of considerable value in analysing more recent events, in particular the December 1995 flood, which was close to the design flood for the Clyde Dam.

The 1878 flood had two major peaks, with the first high flood level on 25-26 September, and the second, larger flood on 29-30 September. The main flood therefore flowed into lakes that were already high.

The 1878 storms that produced floods in the Clutha also generated the largest floods ever recorded on the Waitaki River, where the peak discharge at the main railway bridge is estimated to have been 4000 m^3/s (Table 3.1; Jowett 1980). Only one maximum lake level was recorded in the upper Waitaki for the 1878 flood. Lake Tekapo is reported to have risen to more than 3.35 m above its then normal level. Using the "natural" outflow rating curve this gives a peak outflow of 638 m^3/s (Table 3.1). The Tekapo outflow and lake level in 1878 is considered to have a return period of about 2500 years (Jowett 1980, p. 39).

The Clutha and Waitaki floods - December 1995

The December 1995 floods on the Clutha and Waitaki Rivers were the largest this century, in terms of the peak discharge passing Clyde, Roxburgh and Waitaki Dams. The floods were generated by very heavy rainfall in the Southern Alps, although lower catchment tributaries like the Otematata River were flowing low and clear on 14 December 1995. Rain and snowmelt had raised the lakes in early December to close to the maximum control level, prior to the main storm rainfall on 12-13 December 1995.

The flood discharges on 14-15 December 1995 were "clean" water, blue-green in colour with high visual clarity, as the water was being discharged from the storage lakes (Photograph 1). Even though the storage lakes were full at the start of the storm, they still significantly reduced flows through the lower Waitaki River.

Table 3.1. Flood discharges in the Waitaki catchment, 1878 (Jowett 1980).

	Discharge (m^3/s)
Lake Tekapo	638#
Lake Pukaki	1850#
Lake Ohau	830#
Ahuriri River	500*
Forks, Maryburn, Irishman and Twizel	160*
Estimated discharge in the Waitaki River (Railway Bridge)	4000

\# Lake outflow.
* Return period of flood equal to that of rainfall for second storm - estimated at 50 years (Jowett and Thompson 1977, p 24-6).

The 1995 flood in the Waitaki

The 3-hour peak outflow discharge at Benmore Dam (2550 m^3/s) and at Waitaki Dam (3000 m^3/s) were close to the design flood discharges for these two dams. At Waitaki Dam the total discharge was by far the largest in the 69 years of record since 1927, and greatly exceeded the 1830 m^3/s recorded during the previous highest flood in November 1948. On both rivers the peak discharge in 1995 was smaller than the historic 1878 flood, but the 1995 flood is nevertheless of considerable interest to hydrologists.

Figure 3.1. Waitaki Dam spillweir and powerhouse discharging "clean" flood water on 14 December 1995 (A Pattle).

The inflow of 3200 m^3/s at Waitaki Dam on 14 December 1995 has an estimated return period of about 100 years, while the equivalent natural inflow to Lake Pukaki has a return period of 46 years. During an earlier flood in the Waitaki catchment in January 1994, inflows into the headwater lakes were even larger, but the lakes were relatively low and the flood inflow was absorbed into storage.

A number of factors contributed to the magnitude of flooding in the Waitaki catchment:

- Because of a very wet spring, the lakes rose well above their long-term mean level in September-October and late November 1995, and thus were high prior to the flood. The natural lakes Wakatipu and Wanaka were also high.
- In early December, lakes Tekapo and Pukaki exceeded their maximum control levels a few days before the main flood began, as high temperatures had caused substantial snowmelt.
- Very heavy 48-hour rainfalls in the Southern Alps were recorded on 12-13 December 1995, with 445 mm at Mt Cook, 746 mm at Eade Hut, and up to 840 mm at Panorama Ridge in the Tekapo catchment. Elcho Flats in the Ohau catchment received 326 mm and Cassinia Moraine gauge in the upper Ahuriri received 249 mm in 48 hours.
- There was very heavy rainfall (more than 25 mm/hr) towards the end of the storm.

The 14 December 1995 flood was clearly a major event at a number of locations within the Waitaki catchment (Fig. 3.2):

- The Lake Tekapo mean daily peak inflow of 1670 m^3/s (2100 m^3/s 3-hour mean) is the second largest since 1925, and was exceeded only slightly by the 1700 m^3/s recorded on 9 January 1994.
- Lake Pukaki's peak inflow of 2630 m^3/s is the second largest since 1925, (3100 m^3/s was recorded on 9 January 1994).

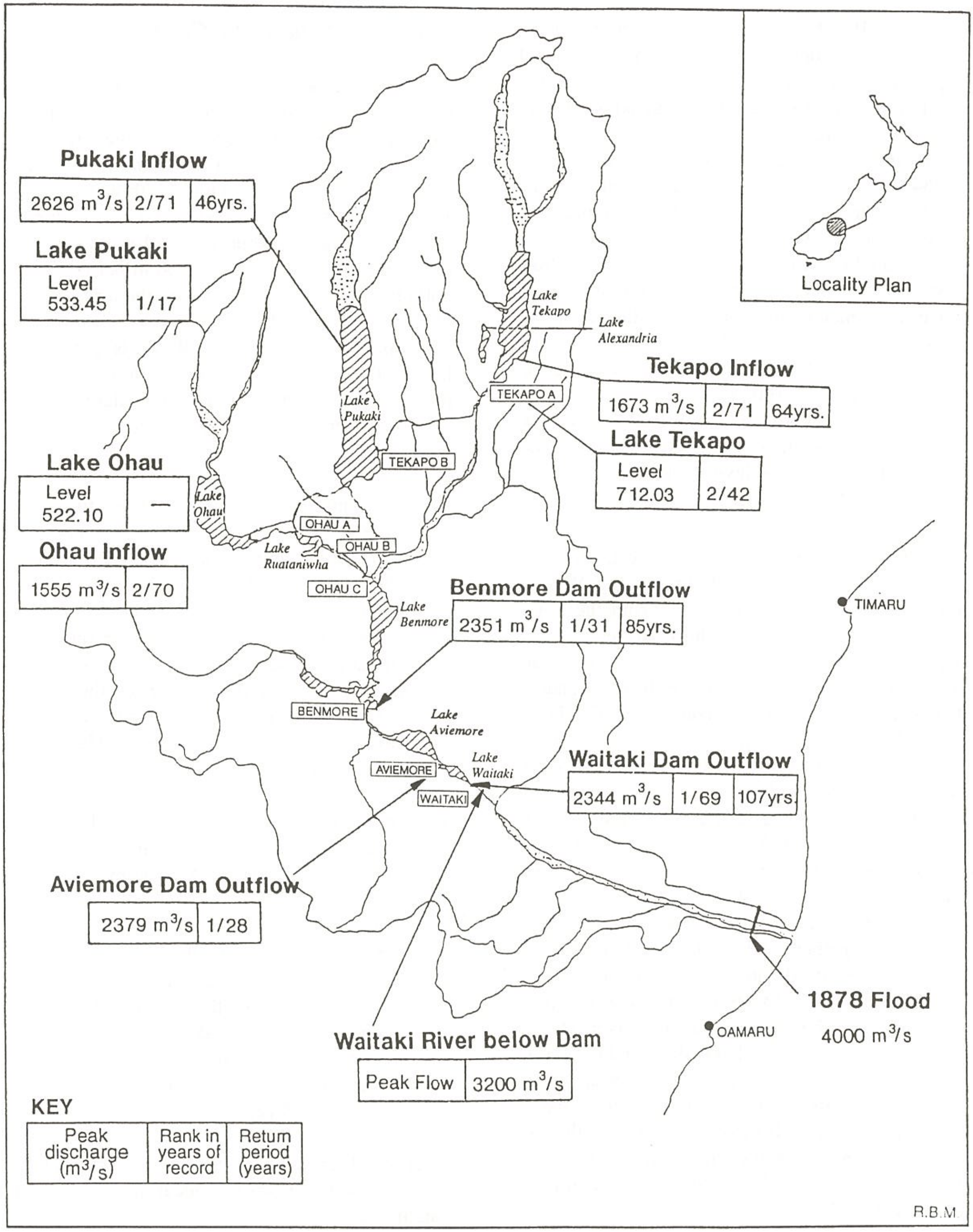

Figure 3.2. Key statistics for the 1995 flood in the Waitaki catchment (source: Works Consultancy Services Ltd 1996)

- At Lake Pukaki, the 1300 m^3/s mean daily peak outflow, including inflow from Tekapo B power station, was the largest on record, with a 1090 m^3/s spillflow down the Pukaki River into Lake Benmore.
- The inflow to Benmore Dam was estimated at 2540 m^3/s, close to the design flood, and the largest in the 31 years since Benmore was commissioned in 1965.
- At Waitaki Dam the mean daily peak outflow was 2340 m^3/s (2610 m^3/s 3-hour mean). Current meter measurements indicated an instantaneous peak discharge of 3000 m^3/s on 14 December 1995, which has a return period of approximately 100 years.
- The peak discharge in the Waitaki River just below the Waitaki Dam (site 71110) was estimated from flood level surveys at 3200 m^3/s (I. Halstead, pers. comm.).

There was a good match between flows at Benmore and the adjusted flows passing Waitaki Dam. Summing the daily outflows from the upper Waitaki catchments and the Ahuriri River gives an independent inflow estimate of 2440 m^3/s. There are further inflows to Lake Benmore from ungauged catchments, including the Twizel River. The Forks River added a mean flow of 36 m^3/s on 14 December 1995. The peak inflow was estimated as 2540 m^3/s (2850 m^3/s 3-hour mean), and was reduced as it passed through Lake Benmore to an outflow of 2350 m^3/s (2550 m^3/s 3-hour mean). This is substantially the same as the inflow to Lake Waitaki of 2330 m^3/s on 14 December 1995.

The large upper Waitaki lakes, Tekapo, Pukaki and Ohau, together with Lake Ruataniwha and Benmore, hold considerable volumes of flood flows in storage. This usually greatly reduces the peak flood flows in the lower Waitaki River (below Waitaki Dam). Lake Pukaki data indicate how effectively storage lakes reduced the peak flows. Lake Pukaki's inflow of 3070 m^3/s (3-hour mean) was reduced to an outflow of 1300 m^3/s, with 1090 m^3/s discharging down the Pukaki River into Lake Benmore and the rest (217 m^3/s) into Benmore via the Pukaki Canal.

The 1995 flood in the Clutha River

On 14 December 1995 a flood peak of 3050 m^3/s passed Clyde Dam. Some hours later high flows in the Clutha River coincided with the arrival of a flood peak of 600 m^3/s in the Manuherikia and led to flooding around Alexandra, with a peak level of 141.91 m. The inflow flood peaks at Clyde Dam (3050 m^3/s) and Roxburgh (3350 m^3/s) were close to the design flood flows of 3200 m^3/s for Clyde and 3600 m^3/s for Roxburgh, and are the largest event in 66 years of record at Roxburgh. The December 1995 flood on the Clutha River is probably the largest flood, relative to design floods, which has passed over a major dam in New Zealand to date.

A number of factors contributed to the size of the flood in the Clutha:

- High antecedent lake levels prior to the flood resulted from rain in early December. Rain around 6 December had already raised the lake levels above the December average before the major storm rainfall on 12-13 December 1995.
- Heavy rainfalls were recorded throughout the Clutha catchment (e.g. 296 mm in 48 hours at Makarora), but especially across the middle to upper catchment. Over 150 mm in 48 hours was recorded from Wanaka, Hawea Flat, across the Lindis, and into the Upper Manuherikia catchment.
- The 169 mm in 48 hrs at Hawea Flat exceeds the expected 1-in-100 year rainfall, as does the 103 mm in 48 hours at Alexandra.
- There were very large inflows from the tributary rivers downstream of the lakes e.g.
  Shotover at Bowens Peak, 491 m^3/s
  Arrow at Beetham Creek, 130 m^3/s
  Nevis at Wentworth Stream, 355 m^3/s
  Lindis at Lindis Peak, 273+ m^3/s, the largest flow in 24 years of record
  Manuherikia at Ophir, 600 m^3/s, the largest flow in 118 years

The 14 December 1995 flood was clearly an extreme event at several locations in the Clutha catchment:

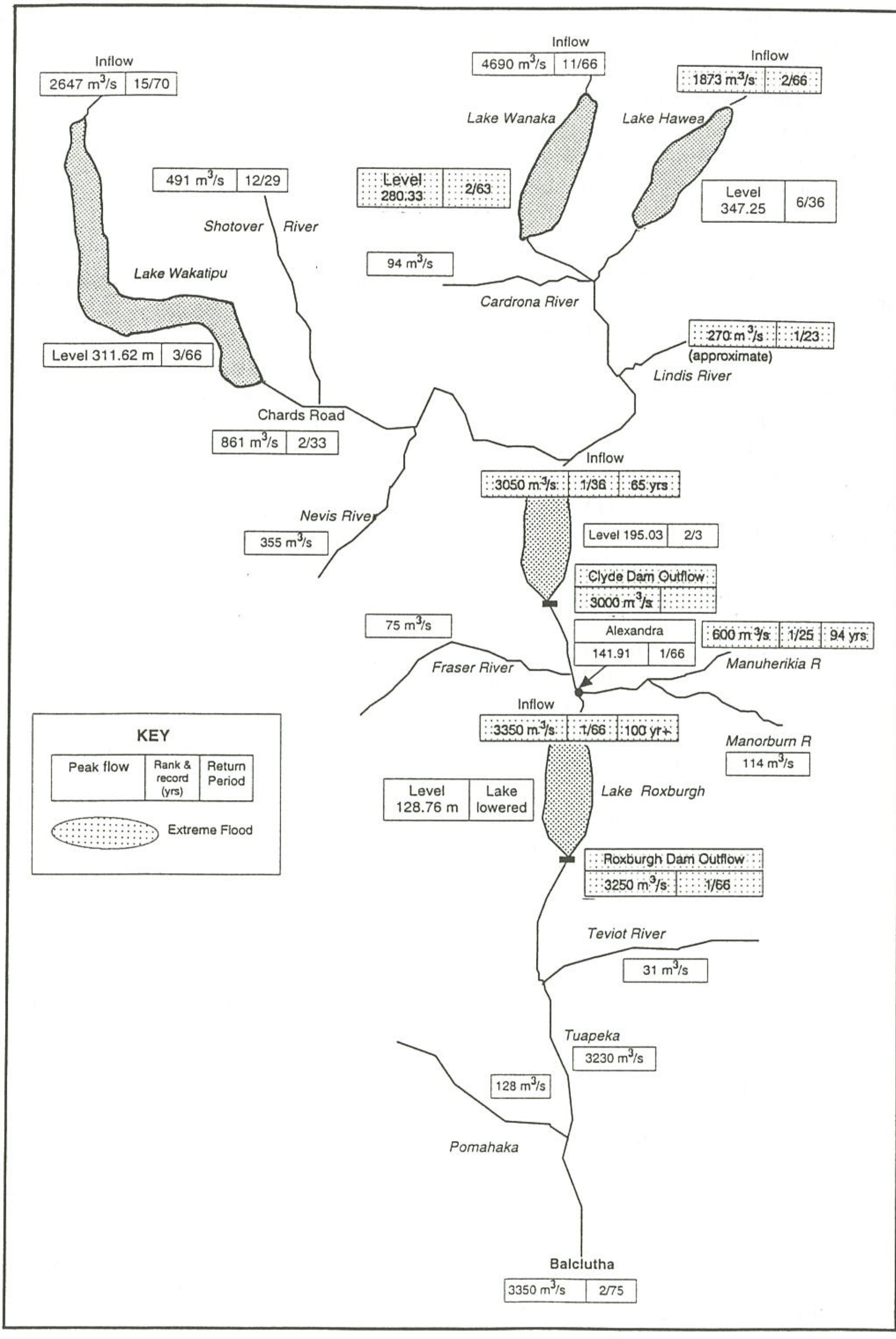

Figure 3.3. Key statistics for the 1995 flood in the Clutha catchment (source: Works Consultancy Services Ltd 1996)

- The Lake Hawea inflow of 1870 m^3/s was the second largest in 66 years of record and was exceeded only by the 2320 m^3/s inflow recorded on 9 January 1994 (Fig. 3.3).
- The flood peak for the Lindis River at Lindis Peak, estimated to be 273 m^3/s, was the largest in 24 years of record and was substantially larger than the January 1994 flood peak.
- The inflow of 3350 m^3/s (adjusted for current meter measurements) into Lake Roxburgh was the largest in 66 years of record and is estimated to have had a return period of greater than 100 years.
- At Lake Dunstan the inflow of 3050 m^3/s (adjusted for current meter measurements) was the largest in 36 years of record. The maximum water level of 195.03 m recorded at 1:35 am on 14 December 1995 was very close to the design flood level for Clyde Dam (195.10 m), and the outflow of 3000 m^3/s was very close to the design flood discharge of 3200 m^3/s.
- The Manuherikia River at Ophir had a peak flow of 600 m^3/sec, which was the largest flood in 21 years of record. It was slightly larger than the 1878 flood peak (584 m^3/sec) or the 11 March 1987 flood (550 m^3/sec) and is the largest flood in 118 years of observation.

The adjusted peak discharge at Roxburgh Power Station of 3250 m^3/s was close to the lower estimate for the 1878 flood (3310 m^3/s). Storage in Lake Dunstan and Roxburgh reduced the flood peak downstream of Roxburgh by about 150 to 200 m^3/s, compared with a natural flood. The peak flow on the Clutha River at Tuapeka is estimated to have been 3230 m^3/s. Downstream at Balclutha, the Clutha River peaked at 3350 m^3/s on the 15 December 1995. This was the second largest flood since 1919, being exceeded only by the 1978 flood, when the Pomahaka River added an exceptional flow of 1300 m^3/s (cf. 128 m^3/s in December 1995).

Because of the effect of siltation and upper gorge constriction in Lake Roxburgh, the very large flood flow (3350 m^3/s) resulted in a peak water level at Alexandra of 141.91 m, submerging the 1878 flood marker in Tarbert Street. The 1878 flood mark on the Manuherikia River at Shaky Bridge was also submerged by about 1.3 m.

Comparisons between the 1878 and 1995 floods

Using the more than 20 years of hydrological data available for Clutha tributaries such as the Manuherikia, Lindis, Nevis, Shotover and Kawarau at Chards Road, historic flood levels, a flood profile from Clyde Dam to Roxburgh for the December 1995 flood, and computer model studies, it is possible to draw some useful comparisons between the 1878 and 1995 floods:

- Maximum lake levels and lake outflows were substantially higher in 1878 than in 1995, by 1.5 m at Wanaka and 1.0 m at Wakatipu. Hence, the Clutha River flow from the three lakes, 3380 m^3/s, was much larger than the 1360 m^3/s flow in December 1995 (Jowett and Thompson 1977).
- The Manuherikia at Ophir flow in 1878, estimated at 584 m^3/s [or 567 m^3/s by Jowett and Thompson (1977)], was slightly smaller than the peak flow of 600 m^3/sec in December 1995.
- The largest estimate of the instantaneous peak inflow into Lake Roxburgh on 14 December 1995 is 3400 m^3/s. This is less than the 3620 m^3/s reported by Jowett and Thompson (1977) for the 1878 flood.
- A recent study by Otago Regional Council and investigations by Works Consultancy Services into the December 1995 flood suggest that the estimate by Gillies (1956) of 4600 m^3/s for the combined flow downstream of Alexandra in 1878 should be reduced to around 4400 m^3/sec (Scarf and Johnstone 1996). In light of the flows measured and observed in December 1995, a peak flow below Alexandra in 1878 of 4400 m^3/s is realistic.

The 1878 flood level in Alexandra is generally accepted as 140.52 m (MSL, Dunedin) although 140.28 m is also reported. A plaque in Tarbert Street, Alexandra, near the Bendigo Hotel, purports to mark the level of the 1878 flood. It was resurveyed in December 1995 at 141.59 m (MSL, Dunedin) but earlier reports quote its level as 141.68 m (MSL, Dunedin), and a level of 140.72 m was used for this marker in the 1950's. There is considerable doubt about the reliability of this marker, and Scarf and Johnstone (1996) state that "it has been discounted as a possible flood level at Alexandra Bridge".

Flood level profiles for the lower section of the Manuherikia River, using data from Works Consultancy Services Ltd, National Institute of Water and Atmospheric Research Ltd (NIWA), and Otago Regional Council (ORC), suggest that a level of 140.52 m for the 1878 flood is realistic for the reach between Shaky Bridge and the Manuherikia - Clutha confluence, especially when compared to the profiles for the December 1995 and January 1994 floods.

Fisher (1948, p. 61) noted that "there is a restriction in the gorge where the river narrows to 130 ft (40 m) between high schist bluffs. At high flows the restriction has the effect of ponding water and causing a backwater curve, which affects the water level at the gauge at the (Alexandra) bridge". The report suggests this ponding or backwater effect occurs for flows about 700 m^3/sec. This natural ponding of flood flows occurred before Roxburgh Dam was constructed in 1956.

A maximum water level profile was pegged at the standard cross-sections between Clyde and Roxburgh dams immediately after the 14 December 1995 flood. This is the first occasion that an actual flood slope has been observed over this reach of river when Lake Roxburgh was drawn down. Subsequently, a further cross-section was surveyed on 12 January 1996 at The Narrows, approximately 5.5 km downstream of Alexandra. The width of the gorge was 56.5 m at water level on 12 January 1996, between steep schist bluffs. Lake Roxburgh tapers down to this narrow gorge section, then about 40 m below The Narrows it widens out to about double the width. Other narrow sections occur at Doctors Point, and The Neck just below Alexandra.

Photographs taken on 14 December 1995 of the Manuherikia - Clutha confluence near the flood peak indicate that the floodwater is ponded or at least not flowing swiftly. The flood profile measured in the field and a computer-fitted profile (Fig. 3.4) show the marked decrease in water levels through the Upper Roxburgh gorge or constricted section (5 to 8 km) downstream of Alexandra. This suggests that the Upper Roxburgh gorge acts as a natural control on water levels around Alexandra especially in large flood events, quite apart from the influence of siltation in Lake Roxburgh.

The computer modelling also showed that a flow of 4400 m^3/s was needed to give a level of 140.52 m at Alexandra in 1878. In their recent model studies, Scarf and Johnstone (1996) reach a similar conclusion.

The effect of river control works and land drainage: the Waikato River

In its natural state prior to European settlement, the Waikato River spilled out of its channel and overflowed across swampy berms into the numerous lakes and wetlands around its lower reaches below Ngaruawahia. A major "historic" flood in 1907 is still the largest flood recorded for the Waikato River. It reached its peak after rising for 14 days (a marked contrast to flash floods elsewhere in NZ), and the main trunk railway line south of Pokeno was submerged to a depth of nearly 5 m.

A series of disastrous floods in the 1950s led to the Government establishing the Waikato Valley Authority (WVA) in 1956. The WVA had powers to act within the Soil Conservation and Rivers Control Act (1941), to erect river control works to protect towns and farmland from flooding. The WVA had barely been formed when the 1958 flood occurred, the largest flood on the Waikato since 1907. WVA staff did an excellent job of documenting the 1958 flood and its effects, and their reports were subsequently used as the basis of the design of flood control works, including the Lower Waikato, Waipa Control Scheme (LWWCS).

This scheme involves extensive stop-banking, river-training works, and the use of off-channel storage at Lake Waikare and in the Whangamarino wetland. Control structures and large radial gates at the confluence of the Whangamarino and Waikato River allow water from the upper portion of the flood wave to be diverted into storage around the lake and wetland, to be released back into the Waikato River once the flood peak has passed. This mimics the pre-European natural conditions, and reduces the flood peak on the lower river, since the 10 320 ha storage area is able to hold 95 million m^3 of water.

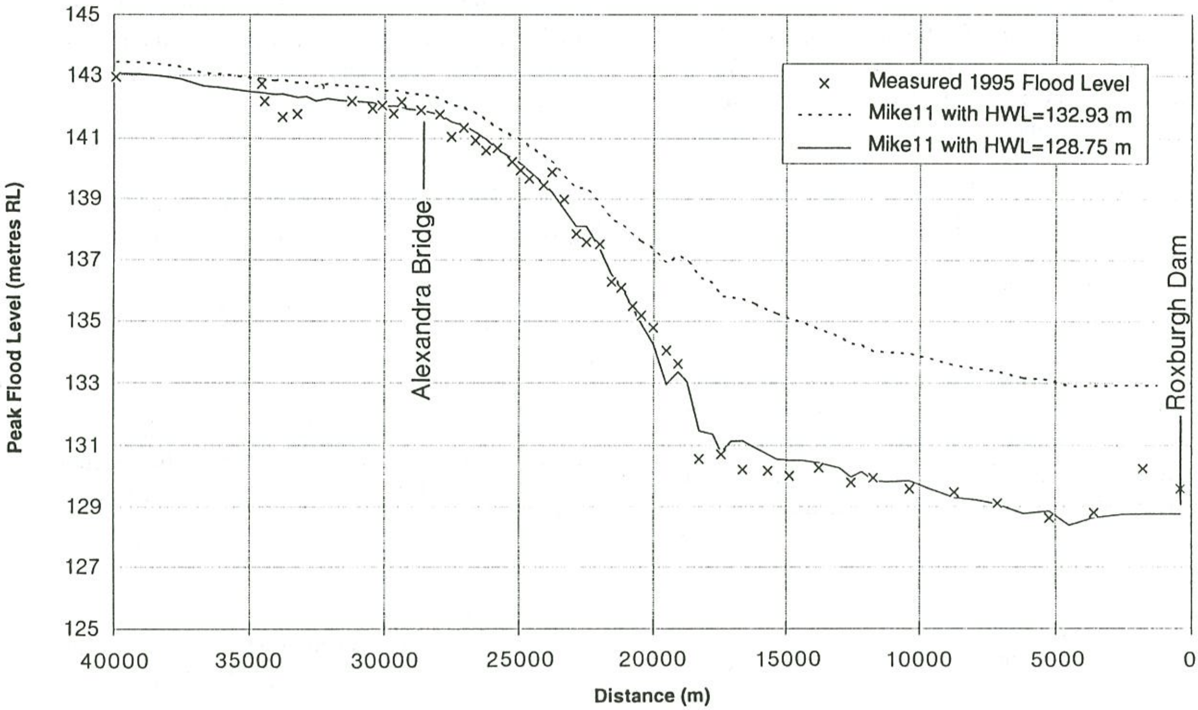

Figure 3.4. Clutha River flood levels upstream of Roxburgh Dam for the 1995 flood flow of 3350 m^3/s.

Over many decades, sand has been dredged from the lower Waikato River for building and construction in the Waikato and Auckland. Sand removal was beneficial for river control, as it increased the waterway cross-section and lowered the water level. During the period 1958 to 1989, the level of the Waikato River at its confluence with the Whangamarino was lowered by 1.3 m. As a consequence, the water levels in the Whangamarino River also dropped, and large areas of wetland intermittently dried out, becoming wet only seasonally in winter and spring or during floods (Fig. 3.5).

Even a small change in the frequency of inundation can significantly alter the wetland ecosystem. The Whangamarino wetland, administered by the Department of Conservation (DOC), is a wetland of international importance and an important habitat for native plants and birds. DOC and the Auckland/Waikato Fish and Game Council sought to protect the wetland characteristics of Whangamarino by building a water-level control weir in the Whangamarino River channel.

New Zealand experience of droughts

Drought is a relatively common occurrence in New Zealand. One of the earliest recorded droughts is from the most unlikely region, namely the West Coast. In February 1867, this region, which regularly receives more than 2500 mm of rain per year, experienced a drought. The gold miners were forced to stockpile pay dirt until the drought broke and the creeks flowed again, and they could once more use their pans, cradles and sluices to extract the gold (Warden Keogh, in May 1962, p. 243).

Since 1990, the economic importance of droughts has been dramatically demonstrated to the New Zealand public, firstly with the "power crisis" of 1991-92 and secondly with the "Auckland water-supply drought" of 1993-94. Because manufacturing is concentrated in the Auckland metropolitan region, there was real concern that the water shortage would adversely affect the New Zealand economy. Fortunately, the drought broke before Auckland actually ran out of water.

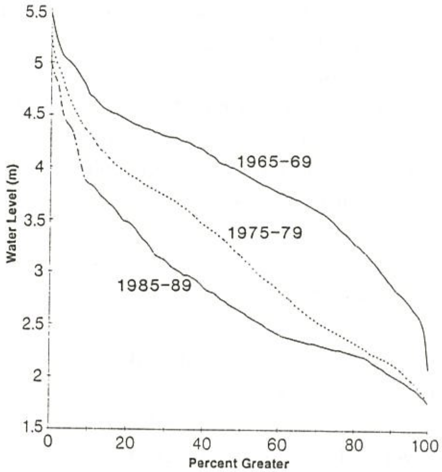

Figure 3.5. Water-level duration curves for the Whangamarino River.

Farmers have been aware of the economic importance of droughts for decades, however. For example, the major drought of 1945-46 had a severe impact on dairy production. The Northern Advocate of 1 April 1946 reported that the March 1946 dairy production average for all Northland factories was 76% below the figure for March 1945.

Again in Northland, a drought in 1964 had a major impact on the farming industry. In January 1964 the Northern Advocate announced that "all dairy companies from Whangarei north report a drop in butter production. Already the loss exceeds $440,000 in value, for butter alone". By 11 February 1964 the manager of the Bay of Islands Dairy Company reported that some farmers had already dried off their herds, and ceased supplying the factory. This represents 3 to 4 months of lost production, as the Northland dairy season normally ended in May. Dairy tankers were "being used to carry water to replenish household supplies in most areas throughout the north" (Northern Advocate, 8 January 1964). Tankers were also used to take water to schools. Similar, but less severe effects of drought on dairy production in North Auckland were observed for the 1961-62 and 1967-68 droughts.

More recent large droughts on the South Island East Coast similarly had a major impact on the regional economy. The 1988-89 drought (which coincided with a La Niña event) caused a loss of agricultural production that cost farmers $365 million (McKerchar 1994). Major droughts are particularly damaging to livestock farming, as sheep coming through a drought are often in poor breeding condition. This in turn results in lower numbers of lambs the following spring, even if the drought has ended some months earlier.

In New Zealand droughts typically last 3-4 months and are most common in the December to March period. More severe droughts begin in spring, in September or October, and run right through the summer, ending as late as April or May. Droughts in New Zealand often end in a flood or a series of floods that clearly mark the end of the drought. The most severe droughts in NZ always extend over more than one summer or year. Recent examples in Canterbury are the 1972-73 and 1984-85 droughts.

Rickard and Fitzgerald (1969) analysed droughts for 41 seasons in mid-Canterbury by calculating day-to-day changes in soil moisture. The average number of days of agricultural drought per season was 40, varying from none to 88 days. Approximately two-thirds (65%) of all drought days occurred during summer months (Dec-Jan-Feb), while a further 28% of agricultural droughts in Canterbury occur in autumn (March-April-May).

Historic droughts

1913-1914-1915

Bondy (1950) noted that the winter-spring of 1914 was "very dry over the greater part of the Dominion". This drought was very severe on the eastern side of the South Island, but also affected Auckland, North Auckland, and Hawkes Bay. Grant

(1968) noted that in Napier the longest partial droughts were in 1913-14 (114 days) and 1914-15 (150 days). These periods fell within the longer period referred to as the "great drought" (1911-16) in Hawke's Bay (Harrison 1988).

1930-31

These two years had persistently below average rainfall, with a very dry summer and autumn in 1930. This drought was most severe in eastern and central districts of the South Island (Bondy 1950), and in eastern areas of the North Island. March-April and May of 1931 were also very dry in South Canterbury and North Otago. The severity of this drought can be judged from newspaper reports which mentioned cattle being driven several miles to drink from "water-holes" along the Opihi River. Huge areas were totally devoid of surface water, such as the areas between the Opihi and Pareora Rivers and down to Waimate. De Joux (1981) noted that the Opihi River dried up naturally in the 1931 drought, before the Levels Plains Irrigation Scheme (LPIS) was constructed.

1945-46

This major drought affected large areas of New Zealand. The worst of the drought persisted from October 1945 to February/March 1946. The drought was "severe in parts of North Auckland and Hawkes Bay, where the dairy industry suffered" (Bondy 1950). Forest fires were recorded in the Taupo area. There was no rain for 34 consecutive days at Taupo and Napier; only 28.4 mm of rain was recorded in 122 days at Napier. This drought also affected the Gisborne area with 101 days of partial drought (Grant 1968).

The Rangitikei-Kiwitea hill-country, inland from Marton and Feilding, was so dry that sheep and cattle were moved to the lower Manawatu-Horowhenua coastal country, because of the lack of feed and water.

1962 and 1964

The earlier summers in the 1960's saw quite severe droughts in many parts of New Zealand, especially in Northland and eastern areas of both islands.

1972-73

In South Canterbury a major drought occurred in 1972-73, with a dry summer in 1972 followed by even drier conditions in 1973. Similar, but less severe conditions also occurred in Northland. In the Nelson area, the drought in 1973 caused major water shortages for Nelson City, as it occurred before the Maitai Dam had been constructed.

In Taranaki, a dry summer in 1973 allowed Ministry of Works staff to carry out low-flow stream gauging around Mt Egmont. This summer was almost as dry as 1970, and provided hydrological data to supplement the work reported by Morrissey (1972). McKerchar and Dymond (1981) summarised the data available and provided low-flow frequency estimates for streams in Taranaki.

1982 and 1984-85

Tomlinson (1980) predicted major drought in the early 1980's, and his prediction subsequently proved correct. In South Canterbury, from the Rakaia to the Waitaki Rivers, there was a short, but severe drought in the summer of 1982. The Opihi River was dry from the Temuka confluence for 10 km upstream to the Levels Plains Irrigation Scheme (LPIS) intake near Pleasant Point, just below Saleyards Bridge. This was largely caused by over-allocation of the water to stock-water schemes, town supply (Timaru City), and irrigation, both individual private irrigation and community schemes like LPIS. LPIS held a water right, an Existing Use Notice under the Water and Soil Conservation Act 1967, which allowed the scheme to take up to 3.06 cumecs from the Opihi River to irrigate up to 4850 hectares. This was clearly an excessive quantity of water, as the mean annual low flow of the Opihi River at Saleyards Bridge is only 3.2 cumecs.

The 1982 drought and drying-up of the Opihi River led to large-scale operations by the South Canterbury Acclimatisation Society (now Fish and Game Council) to save fish. Trout were rescued from isolated pools before the pools dried up or became too warm or deoxygenated. Revision of the Opihi River Water Management Plan (Scarf *et al.* 1984) in 1983-84 involved public consultation and the adoption of a water sharing regime to maintain

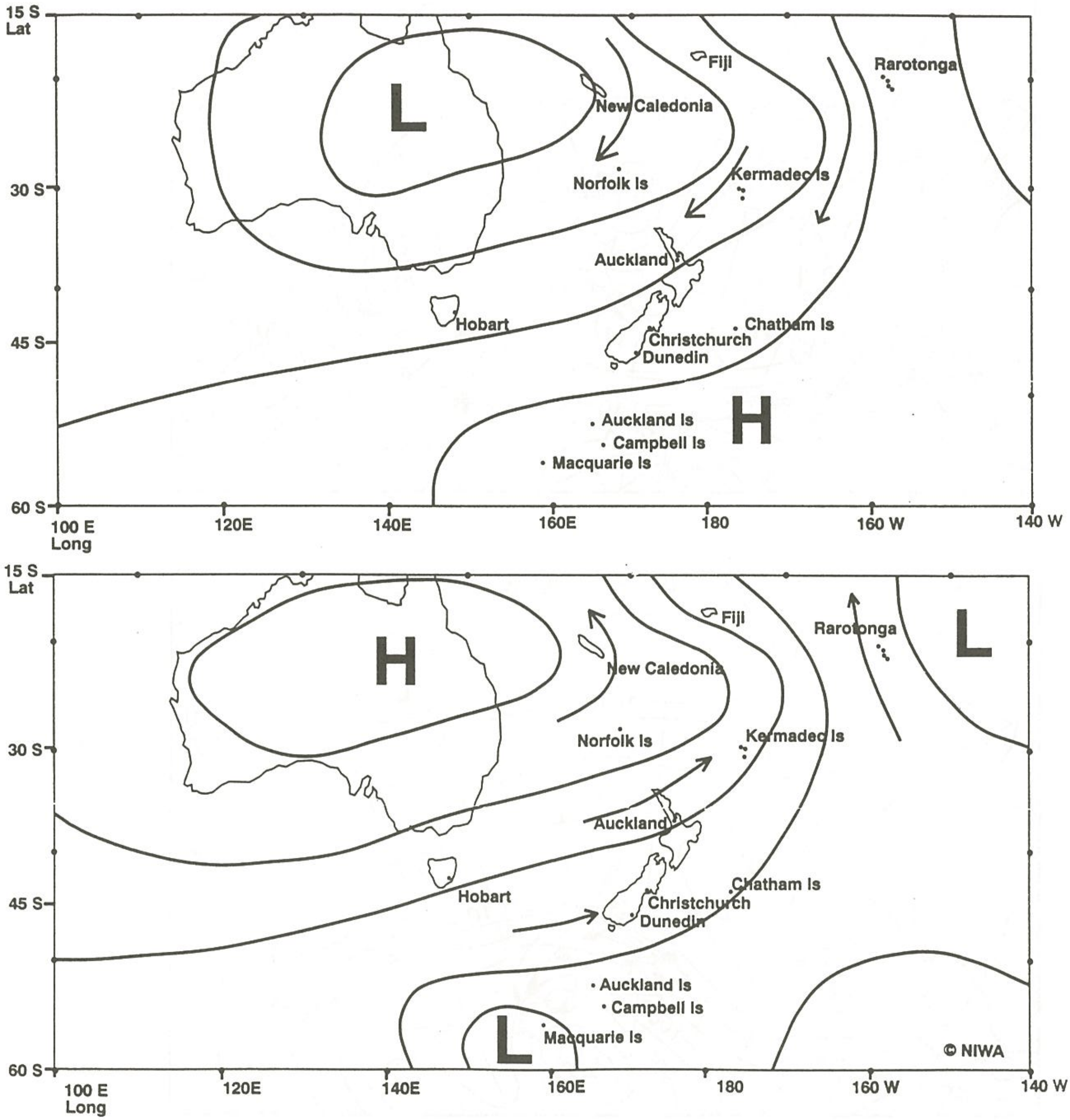

Figure 3.6. General effects of (upper) La Niña and (lower) El Niño events on New Zealand weather (Brett Mullan, pers. comm. 1997)

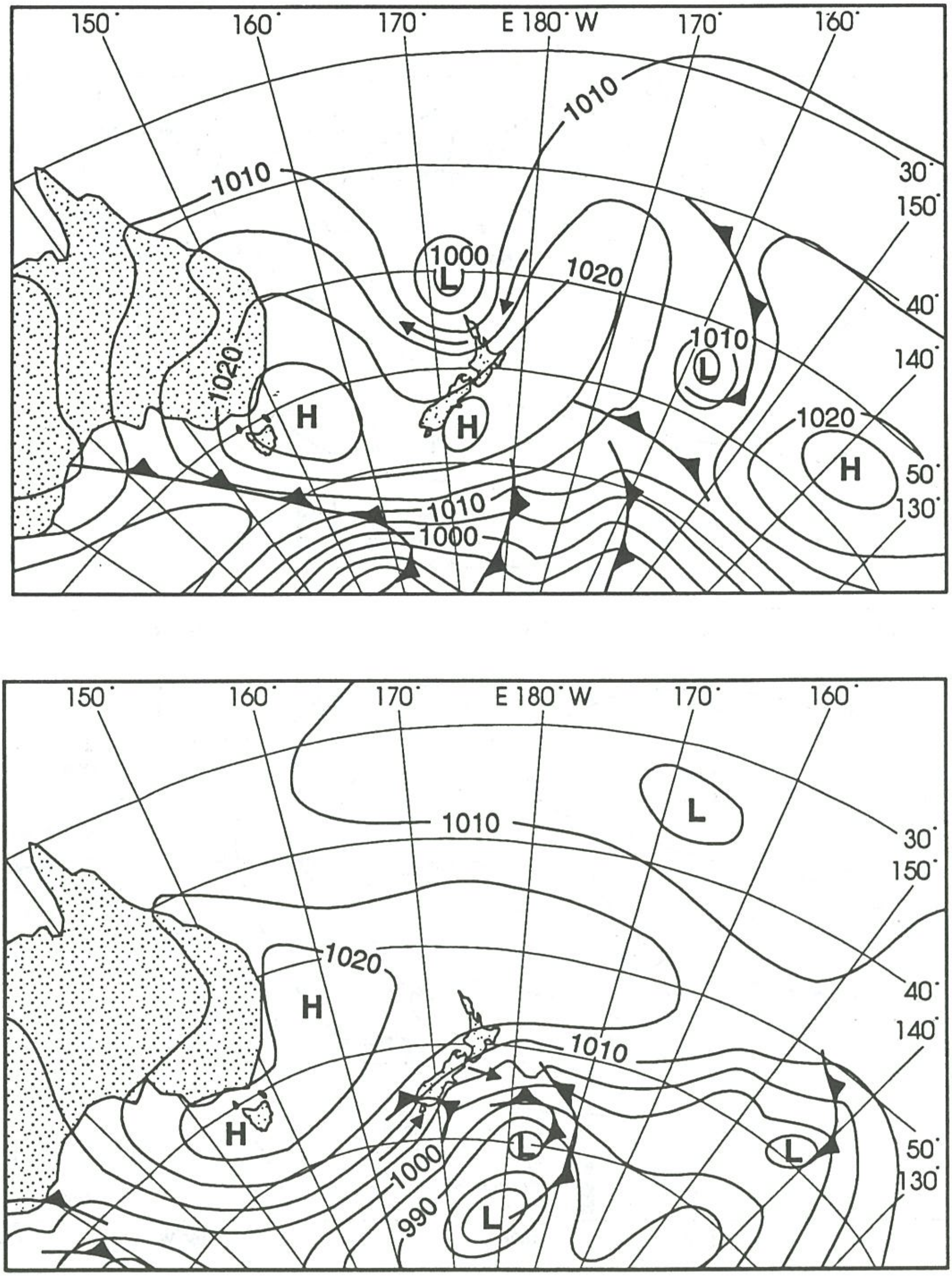

Figure 3.7. Typical synoptic weather maps during (upper) La Niña and (lower) El Niño events (after Benstrom 1992)

flow from Saleyards Bridge to the Temuka Confluence. A minimum flow of 2 cumecs was set for the river at Saleyards Bridge, with a progressive reduction of irrigation allocations when the Opihi River flow fell below 7 cumecs.

In the Nelson area the 1982-83 summer saw the most severe drought since 1958, in terms of its impact on the Nelson City water supply. Auckland, the Gisborne area, and Hawkes Bay also experienced severe drought in 1982-83. For some rivers in Hawkes Bay, the event had a return period of 40 years (Harrison 1988). Harrison recognised the link between the Hawkes Bay drought and persistent El Niño - Southern Oscillation (ENSO) conditions: "A precipitous drop in the Southern Oscillation Index (SOI) in May-June 1982, followed by continued decline, resulted in a record low by December". Dry conditions in 1982 developed into a severe drought which lasted through to March 1983.

The 1984-85 drought was widespread in eastern areas of the South Island and was particularly severe in South Canterbury. A dry year in 1984 was followed by a drought which persisted through the summer months and into April-June 1985. It was one of the more severe droughts in the 20th Century in South Canterbury. Irrigation from surface water was totally banned for three months for the Opihi-Temuka system, and for the Pareora and Waihao Rivers south of Timaru. The ban covered both direct pumping from rivers and streams, and pumping from shallow groundwater in defined zones close to river channels.

Drought and El Niño-Southern Oscillation

During the 1990s, we have become much more aware of the linkage between El Niño, the Southern Oscillation, and droughts (Chapter 1). A number of scientists have described the characteristic weather patterns in New Zealand during El Niño-Southern Oscillation (ENSO) events (Gordon 1986; Ward 1985). During an El Niño event, the westerly wind belt is displaced northwards, and cold fronts are able to penetrate further north and east (Trenberth and Shea 1987). This results in cooler than average temperatures over New Zealand due to increased south-westerlies, and below normal rainfall in the north and east of the country (Figs. 3.6 and 3.7).

The positive La Niña phase of the Southern Oscillation results in an increased frequency and intensity of north-easterly air flow over New Zealand. This is due to a southward shift in the mean subtropical anticyclone track (Salinger 1991). Rainfall tends to be higher on the east coast and over Northland, and lower in west coast areas and in Southland. Temperatures tend to be above average over the country (Salinger 1980). The southward movement of the subtropical highs increases the tropical influence on New Zealand, increasing the chance of tropical cyclones reaching North Island latitudes (Figs. 3.6 and 3.7). A good correlation exists between below average rainfall in the lower North Island and the La Niña phase (Gordon 1986).

The South Island hydro-electric and Auckland water supply droughts led to the first in-depth studies of the relationship between the Southern Oscillation Index (SOI) (see Chapter 1) and low rainfall and river flows in New Zealand, and attempts to predict droughts using the SOI. Moss *et al.* (1994) concluded that "the SOI can yield information about subsequent streamflows on the South Island of New Zealand; however the relationship between streamflow and the SOI may be nonlinear and heteroscedastic". They also concluded that there is a significant relationship between the SOI in one season and the inflow into the hydro-electric lakes during the following season. Work on predicting droughts in the Auckland region using the SOI was summarised by Keyte (1994): "There is a distinct positive correlation between (Auckland's) annual rainfall and the SOI".

Using a similar approach to Moss *et al.* (1994), Lew (1996 a and b 1997) successfully developed drought prediction methods for Wellington's water supply catchments, to be used in drought management planning. A conclusion of the study was that "the SOI based streamflow forecasts give the greatest lead in time, but also have the highest associated error. As lead in time decreases, forecast error decreases with tools such as recession curves, and real time data being employed". Hence, used in the right context and together with other hydrological techniques, SOI-generated streamflow forecasts can play a very useful role in management of New Zealands water resources (Fig. 3.8).

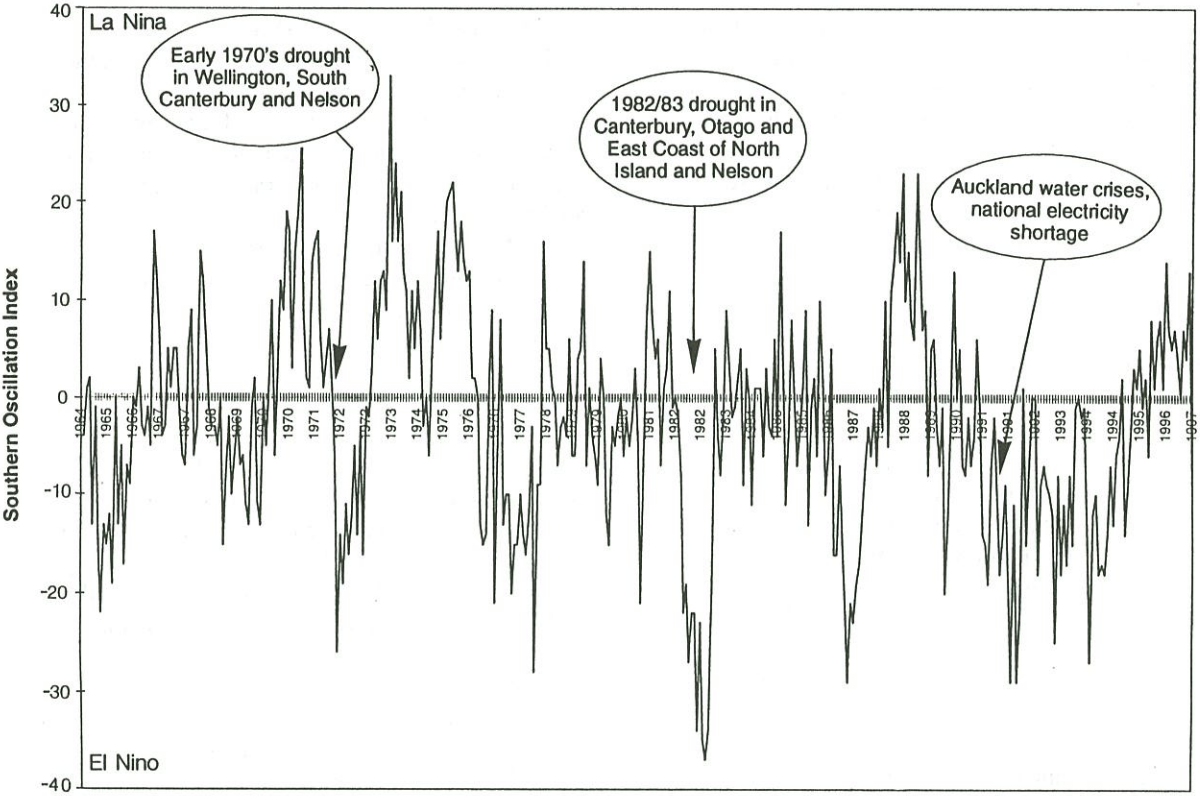

Figure 3.8. The SOI and New Zealand droughts 1964-1997

Recent droughts

Two recent droughts have shown the social and economic costs of a major water shortage. The 1991-92 electricity crises affected the entire nation. Low water levels in the South Island hydro-electric lakes resulted in nationwide electricity shortages throughout the winter of 1992. All sectors of New Zealand society were affected. Two years later the Auckland water crisis occurred. The drought in the Auckland water supply catchments caused widespread social and economic disruption through water shortages.

The South Island electricity shortage of 1992

The drought of 1991-2 is an example of an event that surprised the nation because of its nature. The "electricity shortage" that it caused was the subject of an official enquiry in 1992 (the Electricity Shortage Review Committee 1992). The shortage arose from persistent, cool southwesterly weather conditions, which brought low rainfall to the central Southern Alps. This resulted in a severe and prolonged period of very low flows into the hydro-electric lakes. It seems likely that global cooling, consequent upon the Mt Pinatubo eruptions in the Philippines, played a part in the event. The widespread volcanic aerosol layer in the upper atmosphere led to cooler temperatures over New Zealand. In the southern hydro-lakes catchment, lower temperatures lowered the freezing level, effectively reducing the catchment area contributing flow into the hydro-lakes. A larger than usual proportion of the precipitation was locked up as snow during the "power crisis" period.

The drought continued for 7 months, from November 1991 to May 1992, and was most severe in the upper Waitaki catchment, affecting Lakes Tekapo, Pukaki and Ohau. It extended south

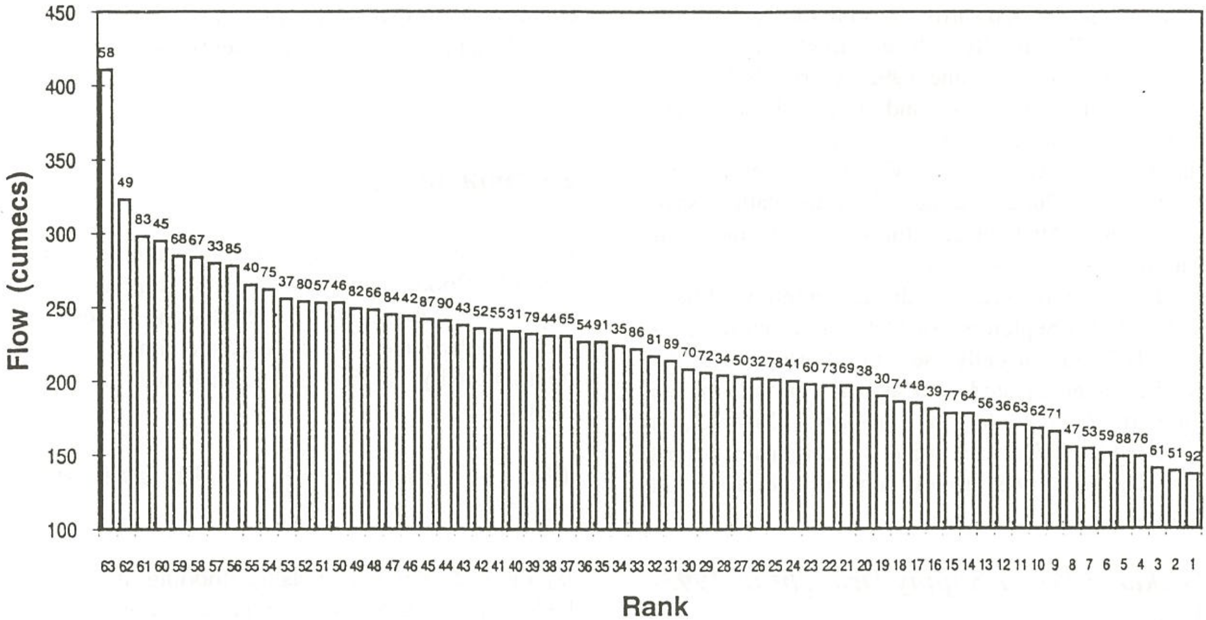

Figure 3.9. Lake Wanaka inflows, November-May period.

through Lakes Hawea and Wanaka, but was less severe at Lakes Te Anau and Manapouri. The decreased rainfall also affected the northern South Island, leading to "winter drought" in Nelson's water supply reservoirs. The Central North Island was also unusually dry, and this was reflected in low lake levels at Lake Taupo. In the Waitaki catchment, the lake inflows rank lowest in 62 to 67 years of record for Lakes Pukaki, Ohau, Hawea and Wanaka, while Lake Tekapo had the second lowest inflow in 67 years. The average level in May 1992 of Lake Wanaka, which is an uncontrolled lake, was the lowest in 62 years of record (Fig. 3.9). A frequency analysis indicated that the drought had a return period of about once in 60 years.

The drought caused much controversy because initial public reaction was fed by claims that the drought was not very extreme. Subsequent analysis of shorter periods, rather than a conventional 12-month period, confirmed the severity of the drought in the critical seven-month period during which the hydro storage lakes are filled. In 1992 they did not fill. In the last two weeks of April, inflows were exceptionally low, especially in the South Island, where inflows for the month dropped to 59% of average. As a result, the severity of the cumulative event increased markedly, from a 1:9 year return period to at least 1:33. Conditions proceeded to worsen, with inflows for May/June well below average - South Island inflows were 48% and 50% of average. By the end of May the event was extreme.

Monthly lake inflows can deviate considerably from the expected average, with a standard deviation of 40% in the South Island. What was unusual in 1991-2 was the prolonged sequence of low inflows. Inflows were below average from November 1991 onwards, but the event, in cumulative terms, was not extraordinary until the end of March 1992. From April onwards the situation worsened markedly.

Under normal conditions, Lakes Tekapo and Pukaki contain around 75% of New Zealand's hydro-storage, and this exacerbated the problem in 1992. Effectively, NZ has a run-of-river hydro-electric power system, with most stations having relatively little operational storage. In 1992 ECNZ made extensive use of thermal and geothermal generation. Many households and businesses endeavoured to conserve electricity use. Many shops turned off their advertising and display window lighting. Towards the end of the "crisis", Wellington City finally reduced street lighting, and for a week or two in June 1992 central Wellington after 5 pm was dark and drab. There were interesting contrasts around New Zealand - Christchurch Airport turned off its escalators, pensioners in Dunedin almost froze to death to save power, and Aucklanders turned down their air conditioners a degree or two.

In an average year, the drought might well have persisted into September or October, when the nor-westerly rains usually set in. Fortunately, the weather relented and unseasonal rainfall in the Southern Alps broke the drought. However, it reminded New Zealands citizens and industry of just how dependent we are on regular and abundant rainfall.

Auckland Water Supply Drought in 1993-94

Another notable recent drought led to the Auckland water supply crisis in 1993-94. The 12 month period ending in May 1994 was slightly drier than the driest 12 month period in the 1982-3 drought. Auckland obtains its water from ten storage reservoirs in the Waitakere and Hunua ranges. The 1993-4 drought extended to June 1994, and in the final months there were restrictions on water use within the supply area. A drought plan was prepared by a group of the City Councils affected. Public opinion was roused, and an emergency proposal to pipe water from the Waikato River to Auckland was put to Parliament. When the drought broke in July 1994, voluntary savings had been in place for several months and plans for the emergency pipeline were at an advanced stage.

In the Waitakere Range, the drought had a return period, for the 9 to 15 months ending May 1994, of approximately 25 years. This is based on 120 years of rainfall record at Albert Park and 78 years of record from the Lower Huia raingauge. In the Hunua Range, return periods of rainfalls for the critical periods of drought6 to 9 months, 15 to 21 months and 36 months ranged from 1 in 45 years to 1 in 120 years. Drought over the whole water supply system, as defined by rainfall, was in the order of 1 in 60 years for periods from 9 months to 3 years up to May 1994. The short inflow series showed the event to be similar to the 1982/83 drought, and the rainfall data show these two events to be of similar severity.

Legislation

From the early years of European settlement, river control, flood management, and drainage have required collaboration and regulation. A series of Acts of Parliament have, in their time, provided internationally innovative approaches to these matters.

The Soil Conservation and Rivers Control Act (1941)

By the late 1930's, increasing flooding and erosion had become matters of national concern. A whole series of reports had been prepared in 1920-21 by the Rivers Commission, on flooding and sedimentation problems on major rivers, especially in the South Island, but no action had been taken.

However, further reports to Parliament on flood control, land use, vegetation cover, and erosion - coupled with the devastating Esk Valley floods of 1938 - led a Parliamentary Select Committee to recommend effective and unified legislation. The Soil Conservation and Rivers Control (SC&RC) Act was passed in 1941, and at the time was considered to be among the most advanced legislation of its type anywhere in the world. It brought together soil conservation, river control, and land drainage matters under unified control at both national and local levels. The Act established Catchment Boards and several Catchment Commissions (in Northland, Waitaki, and Bay of Plenty), with national overview and coordination provided by the Soil Conservation and Rivers Control Council. The Council was serviced by the Ministry of Works for both secretarial and technical advice. In 1956 a special empowering Act set up the Waikato Valley Authority, as an independent authority with slightly different powers and functions to catchment boards.

The SC&RCC Act empowered catchment boards to carry out river control works to protect towns and farmland from flooding. Boards were also able to promote subsidised soil conservation works on farms to prevent soil erosion, to reduce the sediment supply to rivers, and to mitigate off-site effects. Later, in the 1970's and 1980's, entire catchments were placed under integrated control schemes which involved both soil conservation works (on farms) and river control activities. Within the Ministry of Works, the Chief SC&RCC Engineer was also responsible for irrigation work, and for the operation of a hydrological section _ initially the Hydraulic Survey and later the Hydrological Survey _ which carried out hydrological data collection and research at a national level. The principal hydrological work was investigations for hydro-electric power schemes, irrigation schemes and flood control works. Other works of national importance, such as the Marsden Point Oil Refinery and a proposed nuclear power station on the Kaipara Harbour (at Oyster Point or South Head), also involved hydrological investigations of water supplies, tidal flow and current velocity.

The SC&RCC Act 1941, in keeping with its times, promoted development. It permitted and encouraged river control schemes, land and swamp drainage, and soil conservation and erosion control schemes. It was ahead of its time in bringing all these activities together under one Act and envisaging "integrated" catchment management which could include soil conservation works, conservation forestry in eroding headwater catchments (e.g. Mangatu in the Waipaoa catchment), river control, stop-banking, and other flood protection works. Little consideration was given to the environmental effects of such works, or the impact of land development, land drainage, and more intensive land use on water quality.

Nevertheless, the construction of extensive river control schemes on most of our larger lowland rivers in the period from 1950 to 1980 allowed the best agricultural land to be used more intensively as floods became largely confined to the river channels. This more intensive use of the fertile flood plains contributed to the general prosperity of New Zealand in the post-war decades.

At the same time, large-scale irrigation schemes such as Ashburton-Lyndhurst, Lower Waitaki, Morven-Glenavy, Waiau Plains, and Balmoral provided irrigation water to many thousand hectares of drought-prone land in Canterbury and Otago. This allowed land use to intensify from dry-land sheep farming to mixed crop and livestock farming, and subsequently in the 1980's and 1990's to intensive dairying. In Canterbury, the key to the prosperity of Ashburton County, between the Rangitata and Rakaia Rivers, was the availability of irrigation water, initially from the Rangitata Diversion Race built in the 1930's and more recently from groundwater wells in the coastal zone between State Highway One and the sea.

The Water and Soil Conservation Act (1967)

The Water and Soil Conservation Act was another "advanced" piece of legislation when it was enacted in 1967. It provided for integrated management of water and soil resources and for the "multiple use" of water. The Act brought together all management of natural water, including flood control and drainage, water supplies, irrigation and water pollution, as well as soil conservation and catchment control schemes. The former catchment boards became catchment and regional water boards. Their boundaries were adjusted to cover the whole of the North and South Islands. They included coastal waters, which was especially important dealing with water pollution and coastal flooding. At the national level, the Soil Conservation and Rivers Control Council was joined by a new Water Resources Council, and a new coordinating and policy body was created _ the National Water and Soil Conservation Authority, NWASCA. The whole structure, called the National Water and Soil Conservation Organisation (NWASCO) was serviced by the Water and Soil Division of the Ministry of Works and Development (Poole 1983).

The 1967 Act introduced a policy of fundamental importance: the right to use natural water was vested in the Crown. Under this act, water rights were required to take, use, dam, and divert water and to discharge waste. The Crown delegated the management and administration of water rights to the Regional Water Boards and at the same time expunged any former riparian rights to water. The water right system enabled the orderly development of both surface and groundwater resources. Regional water boards developed water management plans to establish policy and water management "rules" in areas of intensive water resource development. It is no accident that some of the earliest non-statutory water management plans were developed and put into effect for rivers in water-short areas such as South Canterbury, including the Opihi River (1984), Ashburton (1983), and Rangitata (1977 and 1986). The 1967 Act did not provide a statutory backing and process for the development and implementation of water management plans, but this was eventually remedied by the Resource Management Act of 1991.

The 1967 Act was very timely, as it was introduced prior to the rapid expansion of private irrigation in the 1970's and 1980's. Droughts in the early 1970's and again in 1982 1983 and 1984-85 spurred on the rapid expansion of private irrigation in New Zealand. Repeated droughts and the availability of loan finance for irrigation development saw a rapid growth in groundwater-based irrigation in Canterbury in the decade 1975-1984. Similar developments took place in Marlborough (Wairau Plains) and in Nelson Province around Motueka and on the Waimea Plains. The termination in the 1980s of government subsidies for major irrigation scheme construction, and the effect of Water Conservation Orders on rivers such as the Rakaia, discouraged any further large-scale community irrigation schemes, even in highly drought-prone areas.

In times of drought and during prolonged periods of extremely low flows, it is important that the water quality of rivers and streams be maintained in a satisfactory condition. Low flows often coincide with high water temperatures in summer months, and high nutrient loads often lead to algal blooms and excessive growth of aquatic weeds in rivers. The 1967 Water and Soil Conservation Act did provide for water rights to control discharges to natural water; one could argue that New Zealand's present "clean green" image has arisen largely because of the regulatory provisions of the Water and Soil Conservation Act 1967. Virtually every factory in New Zealand, town sewage schemes, cow milking sheds, and piggeries were required to have a discharge permit and to comply with the conditions attached to the permit. The water quality of lowland rivers, streams, and lakes has generally improved as the worst point-source discharges have been steadily cleaned up.

Under the Water and Soil Conservation Act, soil erosion on individual farms was tackled through "farm plans". In many cases, farm plans led to re-organising fences to alter grazing pressure on erosion-prone areas, for example fencing out eroding gullies and planting them in trees.. In a similar manner, in the South Island high country, "run plans" were developed for the large high country runs. Large areas of Class VII and VIII land were retired from grazing and fenced off, and improvements to lower country were subsidised to allow stock numbers to be maintained. The land-use classification, based on a national "land-use capability survey", under-pinned much of the erosion control work in New Zealand.

By integrating water and land management, the 1967 Act led to the treatment of entire catchments under subsidised integrated catchment control schemes. These schemes involved erosion control works across the entire catchment, as well as downstream river control works, and in some cases land drainage and pumping schemes.

The Resource Management Act (1991)

The Resource Management (RM) Act (1991) replaced the Water and Soil Conservation Act 1967 and parts of the Soil Conservation and Rivers Control Act (1941), but built on the experience and mechanisms developed under those Acts. The RM Act has as its purpose "the sustainable management of natural and physical resources". It enables integrated management of water, soil, and other resources, and provides a statutory process and backing for water management plans. Section 8 of the Act requires that the principles of the Treaty of Waitangi be taken into account in managing natural and physical resources, filling a gap left by the earlier legislation.

Regional Councils, which replaced catchment boards and regional water boards, are required to produce Regional Policy Statements. These provide an overview of the resource management issues of the region, and set out policies and methods to integrate management of the natural and physical resources of the whole region (Section 59). In many regions the problems arising from flooding and accelerated erosion, and those arising during droughts, are major resource management issues.

Regional Councils have continued to prepare water management plans using the procedures set out in the RM Act. An example is the Oroua Catchment Water Allocation and River Flows Regional Plan, produced by the Manawatu-Wanganui Regional Council (1995) after wide public consultation and the hearing of submissions from interested parties.

Regional Councils have also taken a wider approach to flooding and the issues of the land use of flood plains, producing flood plain management plans for specific catchments. The Soil Conservation and Rivers Control Act 1941, amended by the RM Act (Schedule 8), is still the legislation which empowers Regional Councils to undertake flood control works. For example, Section 126(1) of the SC&RCC Act was amended to read: "(1) It shall be a function of every Catchment Board to minimise and prevent damage within its district by floods and erosion". Previous Catchment Board bylaws for river control have been incorporated into Transitional Regional Plans under the RM Act. Under the RM Act, it may be necessary to obtain resource consents to divert river channels, in order to carry out river control works. In some regions river control activities, especially routine maintenance works, have been designated "permitted activities" in regional plans.

The RM Act provides a statutory framework for dealing with the "effects" of floods and droughts, through planning mechanisms such as the preparation of Regional Policy Statements, Regional Water Management and Allocation Plans, and District Plans. To date, this opportunity has not really been recognised by the resource management profession, but as local government bodies complete the first phase of implementing the Act, they will no doubt seek innovative ways of using it to achieve good environmental management.

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4
Analysis and estimation of extreme events: deterministic methods

Alistair McKerchar, Richard Ibbitt and Ross Woods

Introduction

The qualitative descriptions in Chapter 2 provide an understanding of what causes floods and droughts. To be of practical use, they must be quantified so that definitive statements can be made about such matters as how extreme are floods and how severe are droughts. This is necessary because often the magnitude of a hydrological extreme is "measured" by its impact on the community, a measure that may not accurately reflect the physical size of the event, but rather may be a statement of the community's preparedness at the time of the event. So, for example, was the 1988/1989 drought on the East Coast of the South Island more severe than the drought of 1970? An objective comparison of the causative factor in both cases, a shortage of rainfall, showed (Ibbitt and Shankar 1995) that the 1989 event:

- lasted months longer than the 1970 event;
- affected a greater area of the Canterbury Plains;
- was more intense than the 1970 event, with the rainfall being only 70 % of the long term regional average.

Such information has many purposes:

- it can be used to plan mitigation measures during an event;
- it can be used to prepare cases for disaster relief funding after an event;
- comparison with previous similar events may indicate reasons why an event is perceived as worse than previous occurrences, and clarify whether it was an exceptional event, or one that could have been anticipated and should have been planned for;
- based on the degree of extremeness, economic arguments can be provided for upgrading community infrastructure in order to better handle a future occurrence.

To provide the information that is needed for decisions, whether these are within-event mitigation procedures, or post-event strategies to avoid or minimise the impacts of similar future events, measurements are required. In the case of floods, measurements of the water discharge, velocity and water level at the flood peak, are usually enough to enable floods to be compared and conclusions to be drawn about the most damaging aspects of floods in particular locations. Information about floods uses measurements of something that is physically present. Droughts on the other hand are more difficult to measure, because their significant characteristics relate to something that is physically *absent* or in short supply. Another difficulty is that the physical properties or attributes of droughts are obscured by emotional and political concerns, which become manifest during the comparatively long time over which a drought evolves.

To minimise the influence of social and political factors, hydrological techniques for the estimation and analysis of extreme events need to be:

- objective, and to measure the same "dimension" of an event in a consistent way;

- accurate, and to measure the essence of the size of the factor being measured;
- applicable to the same type of event at other places and times;
- easy to make understand.

Unfortunately, few of today's hydrological tools possess all of these desirable characteristics. Thus, analysis of hydrologically extreme events requires an appreciation of the strengths and weaknesses of the available techniques. Throughout an analysis, the hydrologist must keep asking if all the facts are compatible with one another, or whether there are conflicts between them. The latter must be resolved, either by revision of the analysis to explain the available facts, or by assigning reduced credibility to those facts which are most likely to be erroneous. One of the best ways to develop an analysis is to base it on analysis of similar events by others. In the following sections, specific case studies provide New Zealand "models" on which to build experience. However, before considering case studies some issues fundamental to the analysis of most hydrological extremes are discussed. The first of these is a brief distillation of why we do analysis. The second is the need for access to data about previous extreme events.The third is how the results of analysis can be turned into tools to help estimate what might happen in events that have not been previously experienced.

Analysis

Why do analysis?

The primary role of data analysis is to provide an understanding of the hydrological processes, to enable the data to be transformed into useful information. For example, a time series of flow measurements for a river are data, whereas flood flows for specified probabilities of exceedence comprise information. Significant assumptions are necessary, and models of processes are used implicitly or explicitly, in proceeding through an analysis from data to information.

The analysis of hydrological data provides a sense of proportion for the phenomena under consideration. The analysis must not be divorced from the detail of measurement, because the quality of the raw data can be appreciated only from an understanding of the instrumentation and measurement procedures being used, and the field conditions in which they are deployed. An appreciation of data quality is necessary to identify measurements that depart from other adjacent values because of instrumentation problems, errors in data processing, or because they are unusual or exceptional values. This in turn enables an appreciation of the limitations of the measurements and the magnitude of their uncertainties.

Analysis precedes estimation and prediction. The quantity of data available and their characteristics determine what prediction methods should be used and what may be inapplicable.

Mitigation measures require estimates of the sizes of future events. For example, forecasts of peak flows are required for flood warning purposes and predictions of extreme flows in hypothetical storms may be required for resource planning and engineering design studies. Such predictions commonly are associated with estimates of probability of occurrence (see Chapter 5). For example, a design flood is often associated with a probability of exceedance, although methods also exist to estimate the "probable maximum flood" (PMF) or the largest possible flood which is physically possible in the meteorological and hydrological circumstances pertaining.. It is akin to the concept of the "maximum credible earthquake" in seismic engineering, and is not associated with a probability.

The need for data archives

Hydrological phenomena such as floods and droughts share with other events such as earthquakes and volcanic eruptions the feature that they occur randomly and are not repeatable. They can only be observed directly as they happen, or be inferred from evidence left in the field. They are not controllable or repeatable in the sense of experiment in many other areas of science. Continued availability of historical measurements therefore is vitally important. Their value does not diminish with time, and may even increase, provided they are in an accessible archive, and information is available about their quality and instrumentation

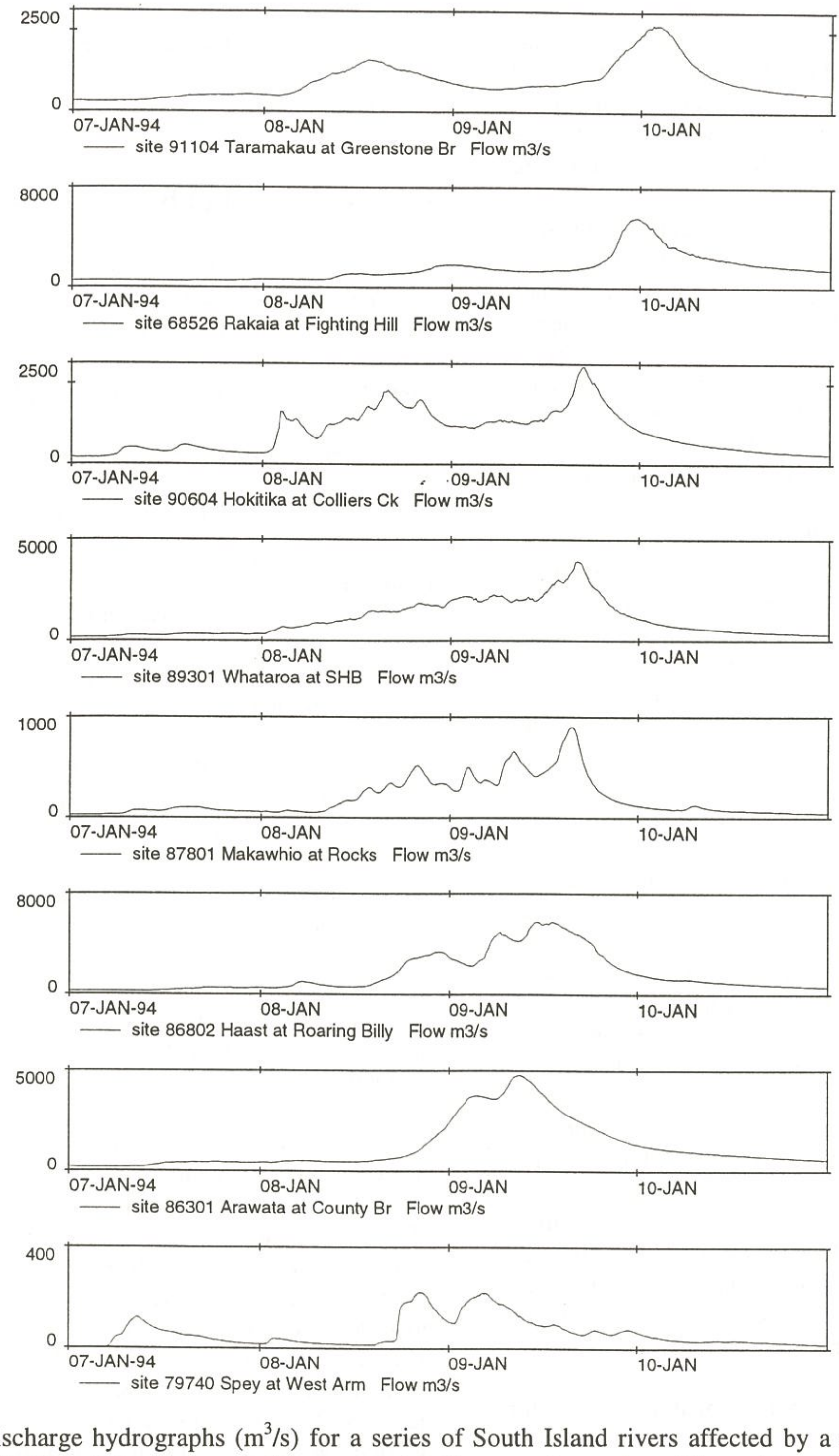

Fig. 4.1. Discharge hydrographs (m^3/s) for a series of South Island rivers affected by a major storm on 7-9 January 1994. The plots are arranged in geographically ascending order of the catchments from southwest to northeast. The Taramakau catchment, (top of page) is approximately 500 km northeast of the Spey catchment (bottom of page). Note the progressive shift in time of the flood peaks from southwest to northeast. The peaks shown are the largest recorded for the Rakaia, Hokitika, Makawhio and Arawata Rivers, and the second largest for the Haast River.

used (Mosley and McKerchar 1989). Thus maintenance of hydrometric programmes and associated data archives are essential parts of a strategy for mitigating hydrological hazard. The aphorism that "those who forget their history are bound to repeat it" is apt.

Hydrometric data commonly form long sets, termed time series, of successive observations of attributes such as water levels and discharge. Such data are of interest at many time scales, ranging from minutes or hours for analysis of flood wave movement, to decades for assessment of long term changes in runoff. Computer packages for efficiently handling voluminous time series are relatively rare. In New Zealand, the adoption by many agencies of a hydrological database management system (dbms) named Tideda (Time Dependent Data) (Taylor *et al.* 1984) by many agencies has provided a common format for exchange of data. The financial savings enabled by use of this common dbms format, and its widespread use on low-cost computers, must be significant compared with the plethora of systems and data formats in many other countries.

Most stream gauges are operated by regional and unitary councils or the National Institute for Water and Atmospheric Research Ltd (NIWA) (Walter 1994). Regional and unitary councils collect data for implementing the Resource Management Act, and to fulfil functions such as flood forecasting. NIWA operates stations for a range of clients, but principally the hydroelectric industry and the Foundation for Research Science and Technology. Much of the data are available in Tideda format.

These agencies also operate recording and storage raingauges Walter (1989). Manual (daily read) and recording raingauge data for a complementary set of gauges, and other climate station data, operated by Met Service are archived by NIWA in a Climate Data Base (CLIDB) (Penney,1996). Lists of stations can be generated by logging into the database and using processes described in the manual.

Analysis of past events provides a basis for planning for future events. Archives of meteorological and hydrological data provide a context from which the severity of an event can be assessed. Archives of hydrological data are an essential resource for comprehensive management and planning in the face of the inherent variability of natural phenomena.

Floods and droughts: case studies

Extremes of flood and drought impinge on communities in many ways. Understanding is needed to mitigate their effects and examining past events helps predict the possible future scenarios against which communities seek protection.

Case study: the storm of January 1994

On 7-9 January 1994 a severe storm moving over the Southern Alps caused damage at a number of locations. One way to examine the extent of this storm is to display the hydrographs for eight of the affected rivers arranged in order from southwest to northeast (Fig. 4.1). The hydrograph for the Spey River, a tributary to Lake Manapouri, is at the bottom of the plots, and that for the Taramakau River, which enters the sea between Hokitika and Greymouth, is at the top. The distance between these two catchments, about 500 km, demonstrates the spatial extent of the storm. The storm's severity is indicated by the fact that it yielded the maximum recorded discharges for four of the eight rivers shown.

The plots show the progressive change in the time of maximum discharge as the storm moved up the South Island: the maxima occur over an interval of about 18 hours. It is expected that this feature would be replicated in rainfall data, but few raingauges are located within the catchments. However, there are some raingauges in the Hokitika catchment, and Fig. 4.2 compares the record for one of these raingauges with the flow record for the Hokitika River, rescaled from discharge units to units of runoff (mm/h) averaged over the catchment area. Peak rainfall rate for the three hour rainfalls is 38 mm/hr, and peak runoff rate is 25 mm/h. Fig. 4.2 shows that the pattern of runoff follows the rainfall quite well, but more detail about the spatial distribution of the rainfall would be needed to adequately model the rainfall-runoff process.

The quantities of rainfall and runoff illustrated in Fig. 4.2 are extraordinary; for the three day storm a

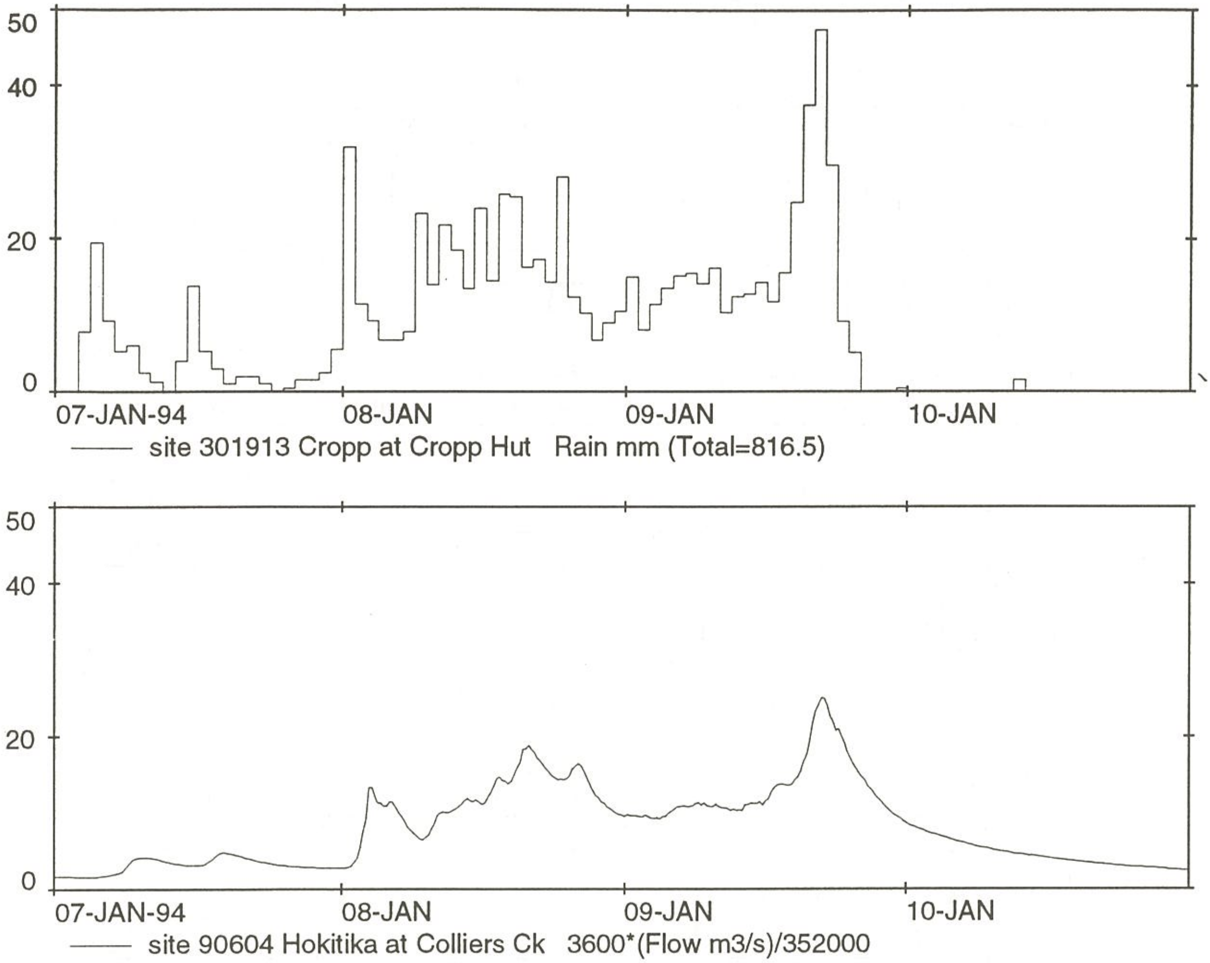

Fig. 4.2. Three-hourly rainfalls (mm/h) for a raingauge in the Hokitika catchment and discharge expressed as runoff (mm/h) over the area of the catchment for the January 1994 storm.

total of 817 mm was recorded at the raingauge, and the quick response runoff from the storm, (assessed assuming a constant baseflow rate of 200 m^3/s) is 580 mm. This storm rainfall total exceeds the annual rainfall at many locations in the eastern part of New Zealand.

As shown in Fig. 4.2, the peak runoff rate for the Hokitika was 25 mm/h: this is more than three times the peak rate of 8 mm/h for the Rakaia River, the headwaters of which are to the east of the Hokitika across the Main Divide. These rates are the maxima for records that commence in 1971 and 1958 respectively, and demonstrate the large variation of extremes that can occur in short distances between catchments. Methods for handling this degree of spatial variation, such as models that encapsulate the dynamics of the rainfall to runoff processes implied in Fig. 4.2, are essential tools for the hydrologist. In practice, rainfall-runoff models are used to estimate flows that will result from rainfall, so that in real-time extreme situations flood warnings can be issued, and in design situations, the flows resulting from a hypothetical (design) rainfall can be estimated.

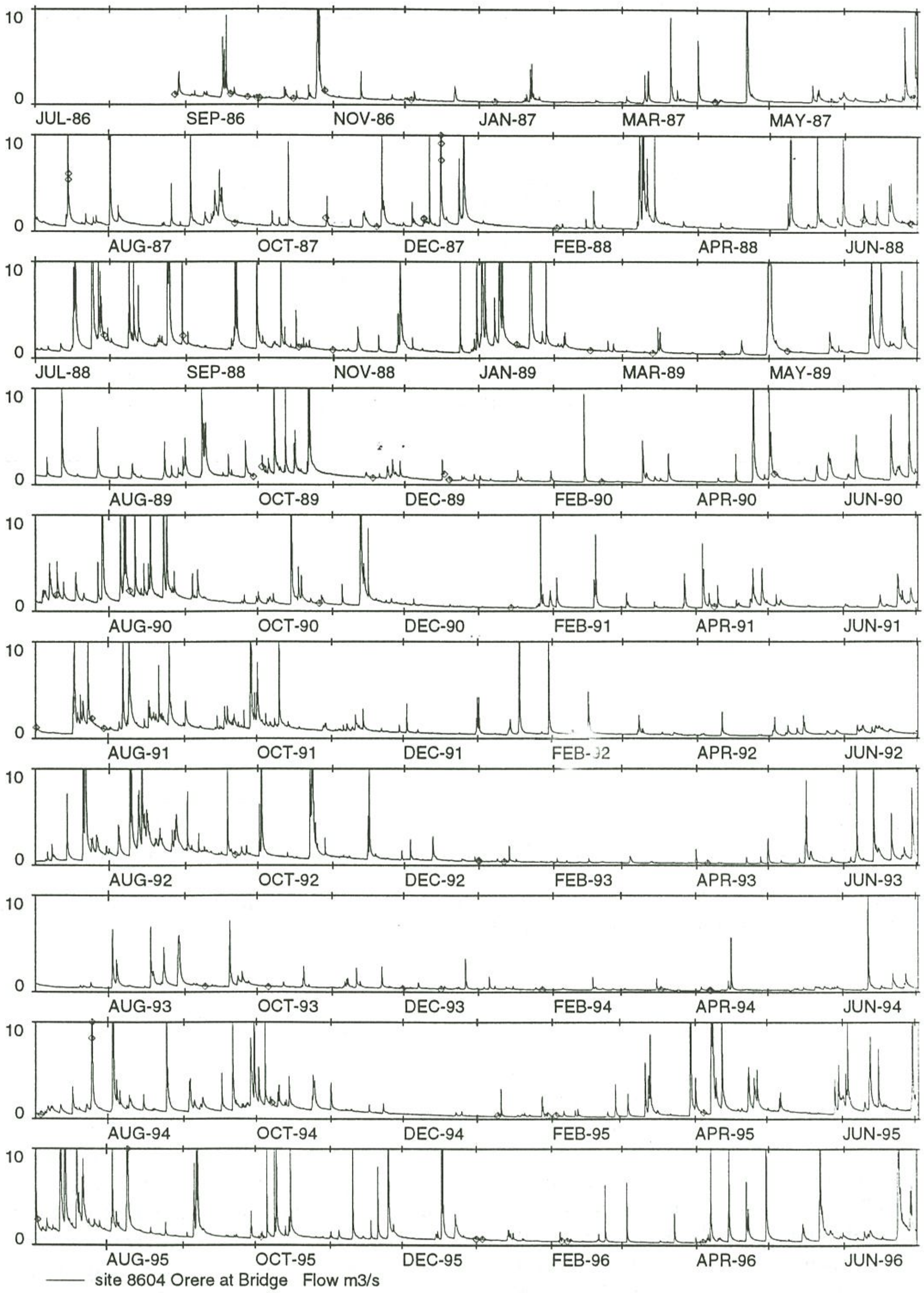

Fig. 4.3. Recorded flow data (m^3/s) for the Orere River (station number 8604, catchment area 40.8 km^2) for the ten year period July 1986 through June 1996. Note the sustained low flows from January 1993 through June 1994.

Case study: the Auckland water supply crisis 1993-1994

Water supplies for metropolitan Auckland are obtained mainly from reservoirs that impound runoff from catchments in the Waitakere Ranges to the west of the city, and the Hunua Ranges to the southeast. During the first six months of 1994, levels in the reservoirs became depleted, and water use restrictions were introduced. One way that the crisis was illustrated was to present plots of the quantities of water stored in the reservoirs compared with guideline levels for the time of year. These plots were useful for demonstrating the severity of the crisis, but they are not independent of water demand, which in an expanding urban area is likely to increase from year to year.

Because droughts are cumulative over periods of months or years, plots over long time intervals are useful way to illustrate their severity. Figure 4.3 shows ten years of annual discharge hydrographs for the Orere River, from July 1986 to June 1996. The Orere is a rural catchment draining northwards from the Hunua Ranges, and its flows are expected to correlate closely to inflows into the water supply reservoirs. Inspection of the hydrographs shows immediately a hydrological drought which extended from January1993 to June 1994, an 18 month interval. This was the driest 18 month period since records commenced in 1978. Mean discharge was 521 L/s, significantly less than the previously recorded driest 18 month period from January 1982 to June 1983, when mean discharge was 612 L/s. Median discharge for the whole record from 1978 through 1996, (with a gap of 19 months in 1985-1986), is 1,030 L/s.

This example of flow data to illustrate drought demonstrates several issues. The first is the use of hydrological records to assess drought severity. This is relatively novel, since drought is more commonly defined in meteorological terms. From the point of view of metropolitan Aucklanders who are concerned about a water shortage, the hydrological definition is helpful because it relates more closely than rainfall to the quantity that is in short supply, namely inflows into the water supply catchments. Also, since streamflow is the residual of rainfall minus evaporation and transpiration, integrated over a catchment, streamflow data provide an areal measure, whereas rainfall is measured at specific points. A second issue is that in the case shown, the flow record is relatively short, and a longer period of record is desirable to place the 1993-1994 drought into a long term context, so that its severity can be adequately assessed. Another issue is whether there would be a gain of information about droughts if longer relevant rainfall records could be used to synthesise streamflows, for the periods when no streamflow records are available. This is another area where rainfall-runoff models have proven useful. Finally,the duration of the drought, which extends over an interval of at least 18 months, is notable: droughts of this duration have rarely been described in the New Zealand context. Both this event, and the earlier drought of 1982-1983 coincide with El Niño phases of the El Niño-Southern Oscillation (ENSO) phenomenon: this apparent connection merits further examination.

Estimation

The examples in the previous section demonstrate that straightforward presentation of relevant data can enable valuable interpretation of extreme events, and indicate how models of the rainfall-runoff process could usefully assist analysis of data and preparation of mitigation strategies. In this section, forecasts and predictions are distinguished, a model that has been found useful in the New Zealand context is described, and future developments of models are indicated.

Many models are available to represent the translation of precipitation through a catchment to the outlet point. Models have three main uses:

- forecasting;
- prediction;
- assessing the hydrological consequences of changes.

Forecasting and *prediction* are distinguished as follows: *Forecasting* means the estimation of conditions at a specific future time, or during a specific time interval, whereas *prediction* is the estimation of future conditions without reference to a particular time (Lettenmaier and Wood, 1993). The flow and stage of a river at noon tomorrow is forecasted, as is a lake inflow during the next three months. The time ahead to the event being forecasted is termed the *lead time*. In contrast to forecasts, a flood with a 1 in 100 annual exceedance probability is *predicted*, as is a 7-day low flow with a 1 in 10 annual exceedance probability. Chapter 5 addresses methods for prediction. Assessing the hydrological consequences of changes includes considering the effects of climatic change, for example changes in flood frequency as a consequence of projected changes in precipitation (Leong *et al.*,1992) and manipulation of the catchment, for example assessment of the consequences of afforestation of a previously pastoral catchment (Chapter 6).

Forecasts

Forecasts are used to provide warning of extreme high or low flow conditions by most regional councils in New Zealand. Short-term forecasts of floods that have a time horizon not exceeding several days have a *real-time* component. *Real-time* refers to the fact that new observations up to the present moment are continually available and can be used to update the forecasts. The widespread use of telemetering poses particular challenges for updating hydrological forecasts in near real-time (e.g. Lettenmaier and Wood, 1993). As these methods model the movement of water that is already in the catchment system, the maximum forecast time is limited to the hydrological response time of the catchment. This is commonly taken as the *time of concentration*, which is defined as the time required for water to flow from the most distant point of the river network to the catchment outlet.

Models for forecasting discharge can be classified as *channel routing* or *rainfall-runoff* models. *Channel routing models* are based on hydraulic principles and involve estimating the flow at a downstream location by using observations from one of more upstream stream gauges. In practice, for this type of model, the maximum forecast lead time is the time of transit between the upstream and downstream stream gauges. An application of a linear systems analysis procedure to provide flood forecasts for the town of Greymouth, at the mouth of the Grey River on the West Coast of the South Island is described by Goring *et al.*, (1984). Here records telemetered from two tributary stream gauges provided a basis for forecasting flow for several hours ahead of the present time at a stream gauge just upstream of Greymouth.

For longer lead times, *rainfall-runoff models* must be used to estimate the rates at which water moves over and through the land surface before reaching the drainage system. Such models are representations within a computer of the translation of precipitation to appear as streamflow at the catchment outlet. They require rainfall measurements, and they can be used to provide forecasts of discharge for lead times equivalent to the response time of the catchment. Forecasts for extended lead times require quantitative precipitation forecasts, and these are now being provided by Met Service, particularly in the case of extreme rainfall. Practical application of forecasting models (see example below) commonly involves both rainfall-runoff and channel routing components.

Pearson and Jordan (1991) surveyed Regional Councils throughout New Zealand, and found that those using objective, automatic methods gave more reliable results than those which depended on subjective, manual assessments of rainfall and catchment conditions. With reliable forecasts defined as those having a forecasted flood peak being within 20% of the actual recorded value, and made three or more hours in advance, 45% of all forecasts were found to be reliable. Automatic forecasts had 83% reliability, and manual forecasts had 24% reliability.

Case study: flood forecasting at Kemp House

Built in 1821-22 as a mission house for clergyman John Butler, Kemp House in Northland is believed to be the oldest wooden building in New Zealand. In 1832 it was assigned to the mission blacksmith, James Kemp, and members of the Kemp family lived in the house for over 140 years, before it was gifted to the Historic Places Trust in 1974. Many of the Kemp family possessions are

Fig. 4.4. Kemp House during a flood in March 1981. (photograph copyright: Northern Advocate).

displayed in Kemp House, which is open to the public. These, and the house itself, are periodically threatened by flood waters from the Kerikeri River. On the night of 19-20 March 1981, exceptionally heavy rain fell over Kerikeri, and Kemp House was inundated up to windowsill level on the ground floor. The gardens around the house were destroyed, and irreplaceable items were damaged inside the house (Fig. 4.4). To minimise the damage from future floods of this size, the staff at Kemp House need warning of floods, so that they can remove precious items from the ground floor, before a flood arrives.

A flood forecasting and warning system has been installed to protect Kemp House (Fig. 4.5). Water level recorders are located at Peacock Gardens, about 1 km upstream from Kemp House, and at Mangaparerua, 12 km upstream near the centre of the Kerikeri River catchment. There is also an automatic rainfall recorder at Mangaparerua. Rain typically takes about 2 hours from the time it falls until it reaches the Mangaparerua flow recorder. In this time the water travels through or over the land surface to the stream network, and then flows along the many small tributary streams (not shown on the map) into the main Mangaparerua stream. Water takes another 2 hours to travel to travel from Mangaparerua to Peacock Gardens. The maximum forecast lead time is 4 hours, which is just enough time to enable Kemp House staff to shift the contents of the ground floor at Kemp House.

The measurements of rainfall and flow are sent by radio telemetry to a NIWA hydrological office, where models of the rainfall-runoff and channel routing processes are used to make forecasts of water levels near Kemp House. When flows are forecast to rise above critical levels, hydrologists issue a warning.

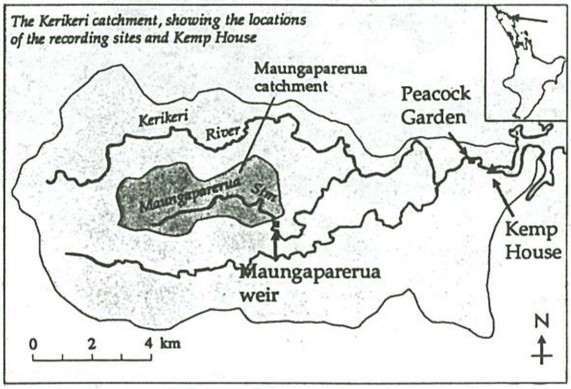

Fig. 4.5. Outline of the Kerikeri River catchment, Northland.

A HYCEMOS rainfall-runoff model (Fig. 4.6 on the following page) predicts river flows at Mangaparerua by calculating the movement of water through and over the land surface of the small catchment, and along the stream network (see Leong et al, 1992 for more details on HYCEMOS). The model used for Kemp House has seven hillslopes, but more complex combinations of hillslopes and streams are possible. Each hillslope in the model includes water flow by mechanisms such as saturation excess runoff, saturated subsurface flow, unsaturated flow, evaporation and overland flow (Fig. 4.7, see Chapter 2).

A separate flood routing model (Goring, 1984) is used to estimate the water level at Peacock Gardens, near Kemp House. This model propagates Mangaparerua flows down the catchment towards Kemp House; it automatically compensates for the fact that the Mangaparerua catchment is less than 15% of the whole Kerikeri catchment.

Figure 4.8 shows an example of these two models working together to provide maximum lead time in the forecast. The peak water levels obtained by running the two computer models compare very well with those actually measured. Since it was installed, the forecasting package has provided warning to enable the worst effects of two extreme events to be avoided.

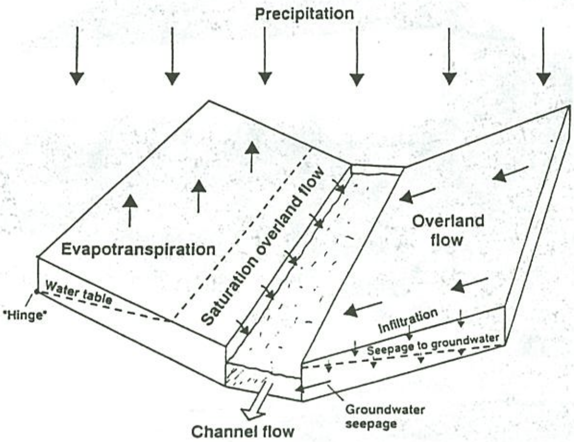

Fig. 4.7. Two hillslopes feeding a gutter in a HYCEMOS model, showing the different water transport mechanisms.

Future directions for modelling

The models commonly used for rainfall-runoff traditionally focus on how river flow changes over time at one location. The explosive growth of computer databases containing maps and digital terrain models is revolutionising hydrological modelling, and at the same time placing much greater demands on our hydrological understanding. New Zealand already has a nationwide Land Resource Inventory for soil type, vegetation, land slope, and geology, and much of the country's topography is available in digital form as a Digital Elevation Model (DEM). Radar estimates of rainfall can provide detailed rain maps every 15 minutes, and although these estimates are at present not often used quantitatively, they provide a valuable adjunct to New Zealand's network of raingauges. The challenge for hydrologists is to use this 'flood' of information to improve their estimation techniques, not just for floods, but also for low flows. The increasing demands on limited river water resources mean that it is just as important to predict when rivers fall to critical low flows.

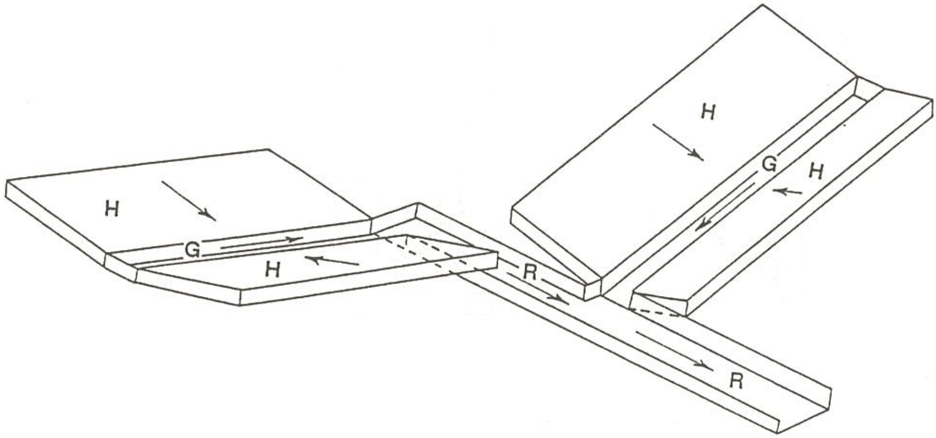

Fig. 4.6. A sample HYCEMOS network, showing hillslopes (H), gutters (G), reaches (R), and the direction of water flow.

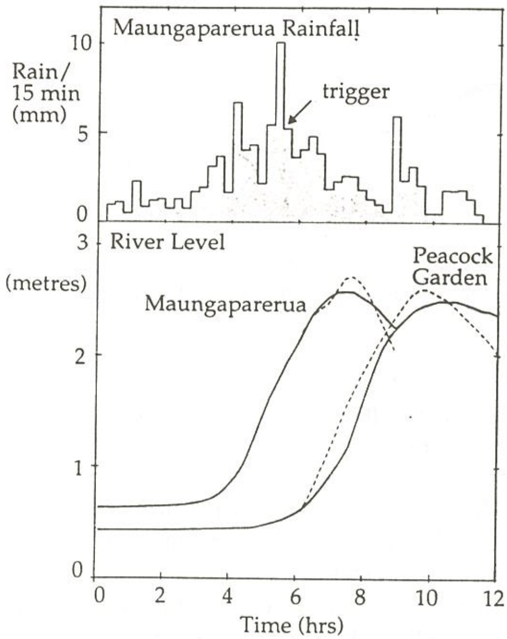

Fig. 4.8. Example of flood forecasting for Kemp house, for a flood in the Kerikeri catchment in July 1979. Both the observed (full line) and the forecast (dashed) water levels are shown. The peak water levels obtained by running the two computer models compare very well with those actually measured. The Mangaparerua forecast data are produced by the rainfall-runoff model and the Peacock Garden forecast data are produced by the flood routing component.

TOPMODEL (Beven and Kirkby, 1979) is one member of this new generation of models. It makes use of DEM data to predict the location of runoff-generating areas in catchments (e.g. valley bottoms and locations with low relief). It also predicts how these runoff-generating areas expand and contract, both seasonally, and during floods. This makes it a valuable tool for investigating not just source areas of water, but also sources of pollutants. It has recently been applied to the identification of stream nutrient sources, so that riparian zones can be designed to intercept some of the material carried towards the drainage system by floods. The model clearly displays the expansion and contraction of runoff-producing areas during a flood in August 1995, on a small hillside near Hamilton (fig. 4.9).

A further enhancement is to add to the topographic data more information on the spatial variation of soils, vegetation, weather and geology. This add to the complexity of the modelling system, but makes detailed hydrological estimates possible for much larger areas. For large catchments, highly detailed information is not always appropriate or necessary: on-going research is focused on identifying the dominant sources and scales of variability in a catchment, and designing models which are appropriate for those circumstances. Given the huge diversity and complexity of river

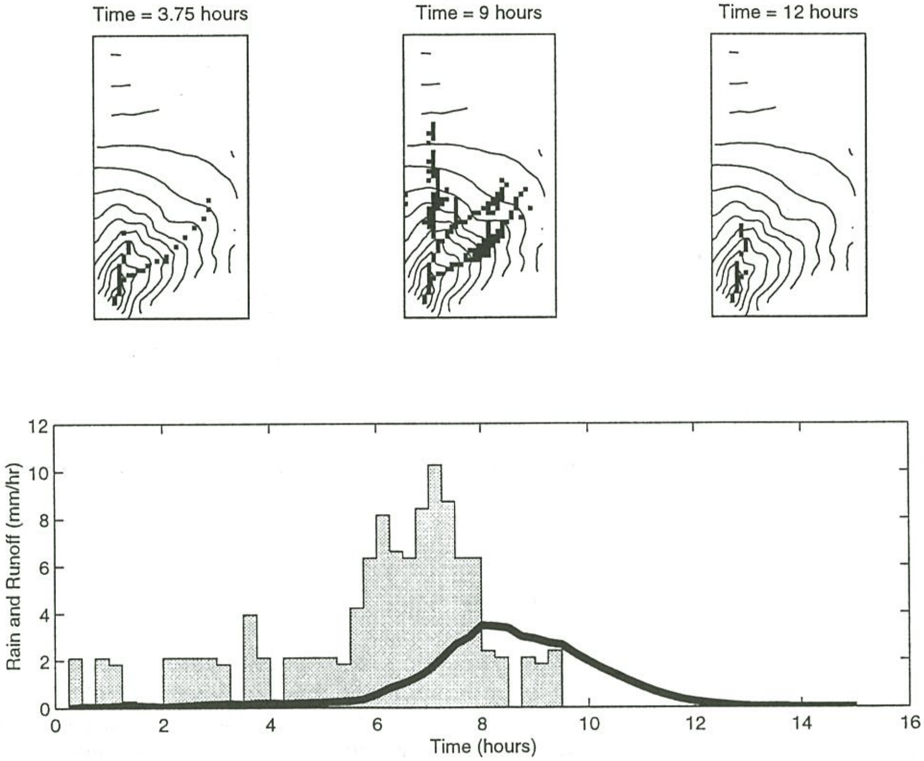

Fig. 4.9. Lower graph; runoff rate (heavy line) and rainfall rate at 15 minute increments (histogram). Upper three graphs. contours of a small catchment elevation and black squares indicating the areas of ground surface that is saturated at given times during the storm.

basins, it seems unlikely that a single model will ever provide answers to all our hydrological questions. Future research on rainfall-runoff modelling is likely to focus on developing a 'toolkit' of models, and guidelines for selecting tools to fit the task.

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5
Stochastic methods

Charles Pearson and Tim Davies

Introduction

To answer questions such as "what is the chance of the flow in the river overtopping this stopbank in the next ten years?" or "how often will there be no rain for a six weeks?", we need to analyse available hydrological data in a statistical way. The methods used are often referred to as a stochastic, in reference to the mix of probability and time, or frequency analyses.

Stochastic methods are needed to describe extreme hydrological events, since the complexity of the physical processes often precludes the use of deterministic methods. Stochastic methods are usually used to estimate the frequency of occurrence of extreme hydrological events. Frequency distributions of variables such as river flood peaks are basic characteristics of hydrological processes. Knowledge of these distributions allows planning for extreme events.

Stochastic methods, philosophies, and issues related to drought and flood frequency analysis are presented and illustrated in this chapter, using New Zealand examples. The next section gives some useful background to statistical techniques. The following two sections present New Zealand examples of flood and drought analyses, focusing on streamflow and precipitation. Finally, a decision support table of recommended frequency analysis methods is provided.

Statistics

A range of commonly used methods for statistical and stochastic treatment of extreme hydrological data are covered briefly: essential statistical definitions; extreme hydrological data types and definitions; methods to analyse these data at their points of measurement, and for transfer to points where no measurements are available; methods for estimating upper and lower bounds for extrema.

Statistical definitions

Important definitions and concepts for understanding frequency methods are described below (more details can be found in, for example, Stedinger *et al.* 1993, Pearson 1992):

- Statistical event. A statistical event is a defined occurrence which can be observed, such as the event of obtaining a "six" on the throw of a dice.

- Probability. For a given event we can define a probability of occurrence. Probabilities range from zero to one (full confidence that the event will occur).

- Sample. A sample is a data set of observations e.g. the sample of annual minimum seven day low flows extracted from a streamflow record.

- Independence or randomness. To analyse a sample we usually assume and check that each observation is not influenced by earlier observations. If we select events which are too close together (such as weekly flow maxima) then we may find that they are correlated (not independent) in some way, which will violate the assumptions underlying most statistical analysis.

- Distribution functions F. For random variables which can take a value anywhere between a minimum and maximum, we can define a probability density function (such as the Normal distribution's bell-shaped curve) to apportion probability to the random variable. The distribution function F(X) is the probability of the random variable being less than X. Distribution functions are defined using mathematical formulae with a number of unknown parameters (usually two or more). With more parameters, the function has more flexibility.

- Moments. Moments of a sample and a statistical distribution are the mean, variance, skewness, kurtosis, and so on.

- Parameter estimation. There are numerous methods of fitting statistical distributions to sample data, e.g. graphical, methods of moments, maximum likelihood, least squares, maximum entropy, probability weighted moments, etc. All methods have in common the aim of quantifying parameters of statistical distributions using the sample data.

- Extreme value distributions. The Extreme Value Type 1 distribution (EV1 or Gumbel distribution) is the simplest of the extreme value family of distributions. It is not symmetrical, like the more familiar Normal distribution. The EV1 distribution is positively skewed, with most values in the lower range, and fewer in the tail of higher values. Other statistical distributions used for flood frequency analysis have longer and/or thicker tails, reflecting differences in the flow regimes of the rivers.

  In contrast to other statistical distributions used for extremes, the EV1 distribution has theoretical justification, although strict application of extreme-value theory requires that the number of events (floods) in each time period (years) is large (so that the maximum for each year is the maximum of say 10 or more events). The EV1 distribution belongs to a family of extreme value distributions, the Generalised Extreme Value (GEV) distribution (Hosking et al. 1985). It has three parameters which describe its shape, the third one determining whether the distribution is of Type 1, 2, or 3 (EV1, EV2, or EV3). When the third parameter k has a value of zero the distribution is Type EV1 (that is, it becomes a two-parameter distribution). When $k < 0$ the distribution is termed EV2, and when $k > 0$ the distribution is termed EV3. On "Gumbel" paper an EV2 distribution curves upwards, and an EV3 distribution curves downwards. A statistical test can be used to test whether the EV1 distribution is a better fit than the EV2 or EV3 alternatives (Hosking et al. 1985).

- Stationarity. Stationarity is a key assumption of frequency analysis: that the maxima or minima exhibit no trends or cycles, and that they are drawn randomly (independently) from the same statistical distribution that has applied in the past and will continue to apply in the future. McKerchar and Pearson (1989) and Withers and Pearson (1991) found no conclusive trends in recent New Zealand flood data. However, Grant (1965 1977 1985) found evidence for long-term variations in storminess, erosion, and flood flows, on time scales of decades and centuries. Improved understanding of climate change, land-use change and El Nino-Southern Oscillation patterns should provide greater awareness of variations in time of the frequency and magnitude of floods and droughts.

- Plotting positions. Plotting positions are formulae for plotting data against probabilities. Plotting positions are important for visually checking the behaviour of the frequency distribution at the tails. The formula used most often to calculate plotting positions is that of Gringorten (1963; see e.g. Pearson 1992).

- Annual exceedance probabilities, percentiles, quantiles, return periods. Floods may be described by reference to their peak discharge or water level, the time to peak, and the volume of storm runoff. A commonly used statistical index is the return period of a flood, which is related to the probability that a given discharge is equalled or exceeded. For example, a flood peak discharge with a 1% probability of being equalled or exceeded in any one year (a 1%

annual exceedance probability, AEP) is often described as the flood with a 100-year return period. A 1% AEP event is defined by X where F(X) = 0.99; X is defined as the 0.99 quantile or 99% percentile.

It should not be assumed that a flood discharge with a 100-year return period will occur or be exceeded once every 100 years. The probability of this discharge being exceeded at least once in a 100-year period is only 63%. On the other hand, there is a probability of 1.7% that two or more events which exceed the flood with a 100-year return period will occur in a given 20-year period. Hence, there is a finite probability that rare events may recur in a short time interval, as the occurrence of two major floods, considered to have return periods of 13 years and 36 years, in Greymouth during 1988 demonstrated.

The form of the probability distribution of low flows is restricted. Flow minima cannot be less than zero, and annual series of flow minima are usually positively skewed. Distributions recommended for low flows include the Weibull (Nathan and McMahon 1990) and the log-Normal distributions. The return period T of flow minima is taken as the reciprocal of the probability of non-exceedance, T = 1/F = 1/(1-AEP).

- Risk. If the design life of a proposed structure such as a stopbank is known, and the acceptable risk that it might fail or be damaged can be specified, it is necessary to estimate the return period of the flood which the structure must be able to withstand - the design flood. The binomial risk formula may be used for this purpose. It enables the engineer to estimate the risk or probability that a flood with a specified return period will be equalled or exceeded during a specified interval, such as the next 200 years. The risk r of the T-year return period flood being exceeded at least once in the next L years is:

$$r = 1 - (1-1/T)^L = 1 - (1 - AEP)^L$$

- For example, the probabilities that the flood with a 100-year return period will be equalled or exceeded at least once in the next 20, 50, 100, and 200 years are 18%, 40%, 63%, and 87% respectively. Hence, for instance, if the design life of a stopbank is 100 years and the acceptable risk of failure during that period is 1%, the return period of the design flood is 9950 years; that is, the structure must be designed to withstand the 9,950 year flood. Such a low level of risk might be justified when, for example, a major city like Christchurch is threatened by overtopping and failure of a stopbank.

- L-moments. L-moments are *linear* moments of statistical distributions (Hosking 1990). An advantage they have over conventional statistical moments is that they avoid raising data to powers of 2, 3 and 4 as required for variance, skewness and kurtosis respectively. This gives better parameter estimates when the data contain outlying values. Another advantage is that L-moment ratio analogues of conventional moment ratios such as coefficients of variation, skewness and kurtosis are more reliable for discerning homogeneous regions and identifying likely parent statistical distributions. L-moments have been estimated for 275 annual maximum flood peak series from New Zealand as an illustration of the L-moments approach for regional flood frequency studies (Pearson 1991a).

- L-moment ratios (L-CV, L-skewness, L-kurtosis) are analagous but superior to conventional moment ratios (coefficients of variation, skewness and kurtosis). L-moment ratio diagrams are used to compare sample values from a number of sites with population values of several statistical distributions. Decisions on regional groupings and likely distributions for flood frequency analysis can be made using these diagrams. Hosking and Wallis (1993) have developed statistical tests for these purposes.

Data types and issues

Frequency analysis can be applied to a variety of defined hydrological events. A number of data related issues are discussed below.

Sources of data. Continuous climate and hydrological time series data, and catchment characteristics, are available from a number of national and regional databases. Long records of New Zealand rainfall and river flows extend back to the mid-1800s and early 1900s respectively.

Sampling. The most common method of analysing flood frequencies for a given location is to fit a statistical distribution to a series of annual maximum flood peaks. Another common method, the "peaks-over-threshold" or “partial duration series” (PDS) approach, considers the largest flood peaks above a fixed threshold value. The difference between the annual series and peaks-over-threshold methods is that the annual series uses the single largest flood each year, whereas the peaks-over-threshold may use none or several peaks from any one year. For large events, the two approaches give similar results.

Traditionally, the exponential distribution has been used to model exceedances above the threshold level in the PDS (Shane an d Lynn 1964; Todorovic and Zelenhasic 1970). Recent research has focused on the generalized Pareto (GP) distribution [e.g. Van Montfort and Witter 1986; Hosking and Wallis 1987; Davison and Smith 1990; Wang 1991; Rosbjerg *et al.* 1992] which contains the exponential distribution as a special case. The assumptions of, respectively, GP-distributed exceedance magnitudes and a Poisson-distributed number of threshold exceedances in the PDS imply that the annual maxima follow the generalized extreme value (GEV) distribution with the same shape parameter (k) as in the GP distribution.

Errors, uncertainties, accuracy and precision. Observed data are subject to measurement and systematic errors because of the equipment and procedures used. Similarly, analyses of the data provide estimates which have sampling and model errors (bias). The accuracy of data and estimates relates to the extent of systematic error in the data and bias in the method. Similarly, the precision of data and estimates relates to the randomness of the data.

Data checking. Before frequency analysis is carried out, the data must be checked for errors, using data from nearby catchments. For example, a period of missing record might have contained the largest flood for that year. If an accurate estimate cannot be made, then no other value should be used for that year.

Rainfall. Types of rainfall data for analysis include:

- annual maximum storm totals of durations ranging from 10 minutes to 3 days;
- mean totals of durations ranging from 1 day to 1 year;
- annual minimum totals of durations ranging from 1 month to seasonal.

At-site analysis

For sampling locations with more than ten observations, a statistical analysis of these data can be carried out using a two parameter distribution to obtain return period estimates. A rule of thumb is not to extrapolate to return periods too far beyond twice the sample size (if dealing with annual minima or maxima).

Regional analysis

It has long been recognized that time series available in hydrology usually are too short to make reliable predictions of extreme events. The use of regional information allows a reduction of the uncertainty by introducing more data from gauging stations in a region having extreme hydrologic behaviour similar to that of the site being considered. A widely used method of regional estimation is the index-flood method which was originally introduced by Dalrymple (1960).

Hydrograph upper and lower bounds

Hydrological variables are in general left-skewed, being bounded below by a small positive or zero amount, and bounded above by an unknown maximum. (The existence of the latter for floods was debated in the literature during the 1960s and 1970s.) Estimation of the most extreme flood possible is required for designing structures whose flooding or failure would have disastrous consequences, such as nuclear power stations or large hydro-electric dams. Several methods are used to estimate the largest flood that a catchment can discharge in response to the heaviest possible rainfalls.

The maximum rainfall is termed the probable maximum precipitation and the maximum flood is the probable maximum flood. Use of the word probable in these definitions is not strictly correct, since the methods normally used to estimate probable maximum precipitation and probable maximum flood take little account of the probabilities of occurrence.

Methods to estimate probable maximum flood normally use a rainfall-runoff model for a catchment, together with estimates of probable maximum precipitation. Because of the assumptions necessary in the estimation of probable maximum precipitation and rainfall- runoff modelling, the accuracy and precision of estimates of probable maximum flood vary from method to method, but cannot be precisely quantified. Greatest discharges ever recorded in 343 New Zealand catchments, as a function of drainage area, were shown in Pearson (1992). An envelope curve through the most extreme floods may be approaching the probable maximum flood. However, Costa (1987) reported that measured maximum peak floods were on average 75% of estimated probable maximum floods for nine catchments in the United States which had flood maxima near his upper envelope curve.

Flood frequency analysis

Variations in weather patterns are reflected in fluctuating river flows. The peaks in a river's flow are responses to variations in rainfall and snowmelt. Flows rise sharply in response to rainfall, and decrease more slowly as the soil and rocks in the catchment gradually release the water that was stored during the storm. The flows of many rivers in New Zealand are modified by large lakes, which tend to reduce the size of floods and maintain flows during rainless periods.

The magnitude of a flood depends principally on the amount and duration of rainfall, and on the catchment's state of wetness beforehand. The extent to which flows decline depends on the period of time to the next rainfall, and on the amount of water stored in the catchment in the form of groundwater, soil moisture, snow, and in lake storage.

At-a-site analysis

Several statistical distributions may be fitted to the annual flood series in a river, as a basis for estimating the discharge of a flood with a given recurrence interval. The EV1 is satisfactory for the annual flood series in most New Zealand rivers (McKerchar and Pearson 1989 1990). This distribution has been widely applied in New Zealand since its introduction by Benham (1950).

Three-parameter distributions such as the GEV should not be used to analyse flood frequency at single sites, unless the annual series is at least 30 years long, since sampling errors are much larger than for two-parameter distributions. Where the annual series is less than 30 years long and the EV1 distribution provides an unsatisfactory fit, regional methods which use information from neighbouring and similar catchments should be used. Indeed, frequency analysis of single sites should, if possible, be compared with the results of a regional analysis. Regional information is needed to satisfactorily estimate the probabilities of exceedance of extreme floods for sites with ten or fewer years of record.

Where there are long rainfall records but short discharge records, mathematical rainfall-runoff models may be used for estimating the size of design floods. They provide an estimate of the full design hydrograph, rather than just the peak discharge. They can, therefore, be used to estimate the durations and volumes of high flows, which might be important, for instance, to the river control engineer who must design a stopbank to withstand the erosion by prolonged high flow.

On the other hand, rainfall-runoff models require data on or estimates of rainfall, and many assumptions are made in calibrating a model for a catchment and in extrapolating to large events with high return periods. Model parameters need to be identified for a catchment during calibration, using rainfall and runoff data from at least one recorded flood. The set of calibration parameters can then be used to predict design flood flows under an assumed set of extreme conditions, such as heavy rainfall onto an already saturated catchment.

A flood with a particular return period can be caused by a range of combinations of rainfall and antecedent catchment wetness. A short burst of intense rainfall can produce a sharply peaked flood with a maximum discharge as great as that reached in a flood which results from less intense rainfall with a longer duration. Similarly, heavy rainfall onto a dry catchment can cause a flood peak as large as that caused by less intense rainfall onto a saturated catchment.

Regional analysis

Beable and McKerchar (1982) divided New Zealand into several regions with comparable flood frequencies, using the method adopted for the UK Flood Study (Natural Environment Research Council 1975). Regression equations were developed for each region, to predict mean annual flood using as independent variables such properties as catchment area and rainfall.

Dimensionless factors were also estimated for each region, which by multiplying by the mean annual flood provide estimates of floods with other return periods. McKerchar and Pearson (1989 1990) reviewed New Zealand flood frequencies, using nearly ten more years of data than were available to Beable and McKerchar. Maps of a form of specific mean annual flood indicated smooth trends over New Zealand, for which contours could be drawn (Fig. 1.7). The contours generally reflect the pattern of annual rainfall (NZ Meteorological Service 1985) and rainfall intensity (Tomlinson 1980), with high values along the main mountain ranges and around the North Island volcanoes, and low values in areas of rain shadow. Low values in the central North Island, north of Taupo, are attributed to the layer of absorbent volcanic ash and fractured volcanic rocks in that area.

Although the map approach provides the best available estimates of mean annual flood for New Zealand catchments, multiplicative regression equations, as used by Beable and McKerchar (1982), are still valuable. They can be used to analyse the spatial and temporal variations in mean annual flood estimates, to seek improvements in the locations of the recording stations in a region (Pearson 1991b). They may also be preferred for estimating quantile estimates because of the suspected inappropriateness of index methods when analysing a range of catchment sizes (Gupta et al. 1994).

It is possible to estimate the discharge of floods with other return periods, using estimates of mean annual flood obtained from contour maps (Fig. 5.1). The EV1 distribution is satisfactory for 228 of 275 catchments used by McKerchar and Pearson (1989 1990), and contours of the ratio of the 100-year return period flood to the mean annual flood were plotted over New Zealand. Values are low along the western sides of the main mountain ranges and the North Island volcanoes, and are high where rainfall is low and infrequent, for example in South Canterbury. This reflects the fact that year-to-year variations in the size of the largest floods are relatively small in wet areas, which receive a regular succession of heavy rainfalls. On the other hand, in dry areas rainfall is less frequent, but occasionally comes in intense frontal or convectional storms.

The range of variation of the 100-year return period flood to the mean annual flood is much less in the North Island (2 to 3) than in the South Island (1.8 to >5). Values increase from west to east across the South Island and, to a lesser extent, from southwest to northeast in the North Island.

McKerchar and Pearson's study assumed that annual maximum flood series in New Zealand are fitted by the EV1 distribution. In fact, a later comparison (Pearson 1991a) of the 275 actual flood series with 275 randomly generated EV1 series indicated that the real floods tend to be better fitted by an EV2 distribution with a value of the parameter k of -0.07, which gives an upward curve on Gumbel paper. However, for return periods of 100 years or less, the difference between EV1 and EV2 flood estimates are negligible, with k = -0.07.

Two regional estimation schemes, based on, respectively, partial duration series (PDS) and annual maximum series (AMS), were compared by Madsen et al. (1997) using New Zealand data. The PDS model assumes a generalized Pareto (GP) distribution for modelling threshold exceedances corresponding to a generalized extreme value (GEV) distribution for annual maxima. For estimation in typical regions assuming a realistic degree of heterogeneity, the PDS/GP index-flood model has better statistical properties. The regional PDS and AMS procedures were applied to flood records from 48 South Island

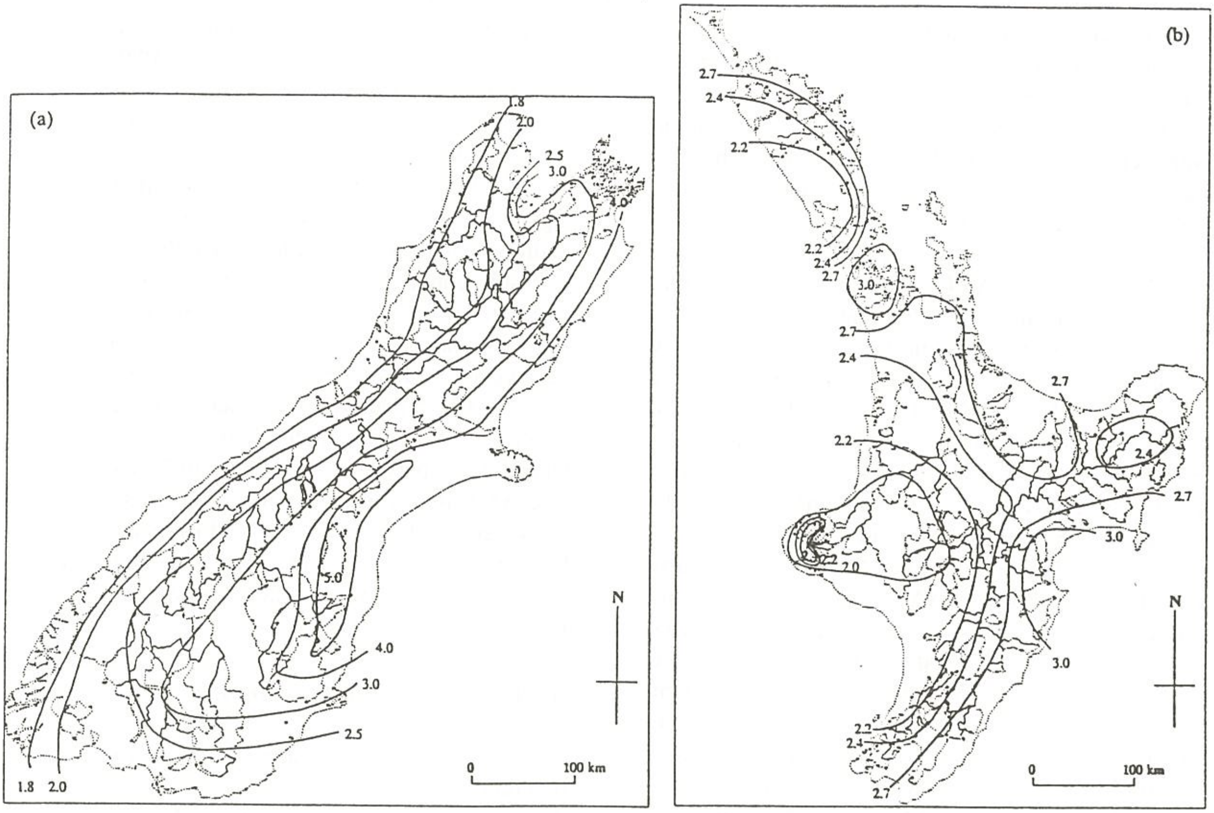

Figure 5.1. Isopleth map of the ratio of the 1% AEP flood peak to the mean annual flood peak (from McKerchar and Pearson, 1989).

catchments. To identify homogeneous groupings of catchments, a split-sample regionalization approach based on catchment characteristics was adopted. The defined groups were more homogeneous for PDS than AMS data; a two-way grouping based on annual average rainfall is sufficient to attain homogeneity for PDS, whereas a further partitioning is necessary for AMS. In determination of the regional parent distribution using L-moment ratio diagrams, PDS data, in contrast to AMS data, provide an unambiguous interpretation, supporting a GP distribution.

In the context of regional frequency analysis, only minor attention has been given to the PDS model.

The regional AMS and PDS estimation procedures were applied to South Island rivers. A minimum record length of 20 years was used, and rivers dominated by lake outflows or with flows significantly controlled or modified were avoided. This resulted in 48 stations with recording periods ranging from 21 to 42 years with an average of 26 years.

The regional PDS analysis involves two important aspects: (1) determination of the threshold level, and (2) identification of independent exceedances (and not multiple exceedances corresponding to the same event). The 2%-quantile was used (i.e. the flow which is exceeded 2% of the time). In order to ensure independent exceedances in the PDS, the United States Water Resources Council guidelines (USWRC 1982) were used. In this case, independent peaks must be separated by at least 5+ln(A) days where A is the catchment area in square miles, and, in addition, the inter-event discharge must drop below 75% of the lowest of the two peaks. A slightly different independence criterion was used by Cunnane (1979).

The main geographical feature of the South Island that most influences its hydrology is the Southern Alps, a mountain range running southwest to northeast along the island (see for example McKerchar *et al.* 1996). To the west of this barrier, due to predominantly moist westerly airflows, there is high rainfall, whereas on the eastern side there is low rainfall. It has been shown in earlier flood studies (e.g. Mosley 1981; McKerchar and Pearson 1990; Pearson 1991a) that rivers draining either coast form reasonably homogeneous but distinct flood frequency regions. However, in this application an objective procedure (Wiltshire 1985; Pearson 1991b) was used to divide the 48 catchments into homogeneous groups (which are not necessarily contiguous geographically) using basin characteristics, so as to fairly compare the PDS and AMS regional procedures.

Basin characteristics investigated were basin annual average rainfall (AAR) and slope (S). These two characteristics were found useful in an earlier study to classify AMS flood frequency groups in New Zealand (Pearson 1991b). The annual average rainfall ranges from 680 mm for an east coast catchment to 7,400 mm for a west coast catchment. The slope measure is an areal-weighted mean slope extracted from the national land resources inventory (Hutchinson 1990; Pearson 1991b), ranging from 2° to 33° for the drainage basins used in this study. For each data set (AMS and PDS), AAR and S were used separately to split the data into two groups, and jointly for a four way grouping.

Homogeneity of the defined groups was investigated using Hosking and Wallis' (1993) tests based on L-moment ratios. Estimated L-moment ratios, L-skewness versus L-kurtosis, for the 48 catchments are shown in Fig. 5.2 and compared to the theoretical relationships for a number of parent distributions, including the GP, Exponential (EXP), GEV, EV1, 3-parameter log-Normal (LN) and Pearson Type 3 (P3) distributions. The theoretical relationships between L-skewness and L-kurtosis for these distributions are given by Hosking (1990) and Stedinger *et al.* (1993). For the PDS data, the two-way grouping based on AAR yields two virtually distinct groups of points corresponding to each region (Fig. 5.2a). The L-moment ratio diagram indicates that a GP parent distribution is adequate for both groups, which is also confirmed by Hosking and Wallis' (1993) goodness-of-fit test. For the AMS data, the points in the L-moment ratio diagram (Fig. 5.2b) are more dispersed than those based on PDS data, and there is no clear distinction between the two groups of points, although the record-length-weighted average points differ significantly.

This illustrates two important advantages of the regional PDS approach as compared with the traditional AMS method. First, since the PDS method generally contains more data than the corresponding AMS, the PDS method yields more stable sample estimates, and hence provides a more unambiguous interpretation of L-moment ratio diagrams. Secondly, the PDS better captures the structure of flood series. From our knowledge of the hydrology of the South Island we expect two distinct hydrological regions. The AMS may censor too much data, especially on the West Coast where large flood events occur more frequently than once per year. The PDS method provide a fuller picture of the hydrology of the South Island.

Analysis of small catchments

Most of the small streams in New Zealand are unmonitored. However small streams present a large threat to life during floods, particularly in urban areas. In regional studies the proportion of small catchments represented in the flood database has been small. Commonly used methods for small catchment flood frequency analysis include the rational method, which estimates return period flood peaks as a product of design rainfalls, catchment area and a constant representing catchment type.

Regional studies were carried out by McKerchar (1991) and Pearson (1991c) using flood data from over 100 small (area less than 100 km^2) New Zealand drainage basins, where each basin had annual maximum flood peak series of length 10 or more years. L-moment statistics of the flood series and basin physical characteristics were used to classify the basins into six non-geographic flood frequency groups. Dimensionless flood frequency growth curves for each group offer robust alternatives to geographical regionalisation and flood contour maps.

Pearson (1991c) applied the robust regional flood frequency estimation procedures developed by

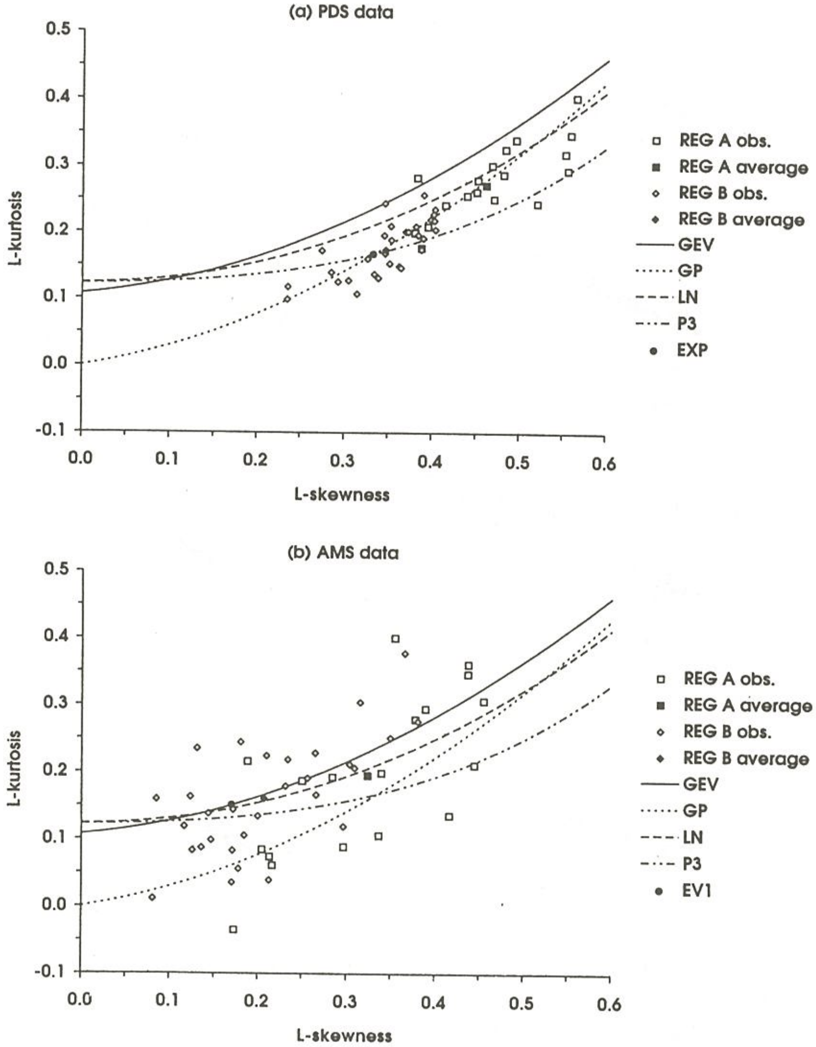

Figure 5.2. L-moment ratio estimates for the two groups, AAR < 1300 mm (REG A) and AAR > 1300 mm (REG B), compared to theoretical relationships for different parent distributions. (a) PDS data. (b) AMS data (from Madsen et al. 1996).

Wallis (1980 1988) to small basins to derive dimensionless flood frequency growth curves for groupings of physically similar small basins. The 5-parameter Wakeby distribution fitted by L-moments or probability weighted moments is a robust, accurate and efficient regional flood frequency procedure for *homogeneous* groupings of catchments, (Kuczera 1982; Hosking *et al.* 1985; Wallis and Wood 1985; Cunnane 1989). These qualities of Wallis' (1980) regional flood frequency procedure are preserved even when there is significant correlation present amongst annual series of a region's drainage basins (Hosking and Wallis 1988), or when the region is heterogeneous (Lettenmaier *et al.* 1987). Hosking and Wallis' (1993) statistical tests based on L-moments were used to investigate the homogeneity of a *given* group of drainage basins. Homogeneous groups of basins were identified not on the basis of location

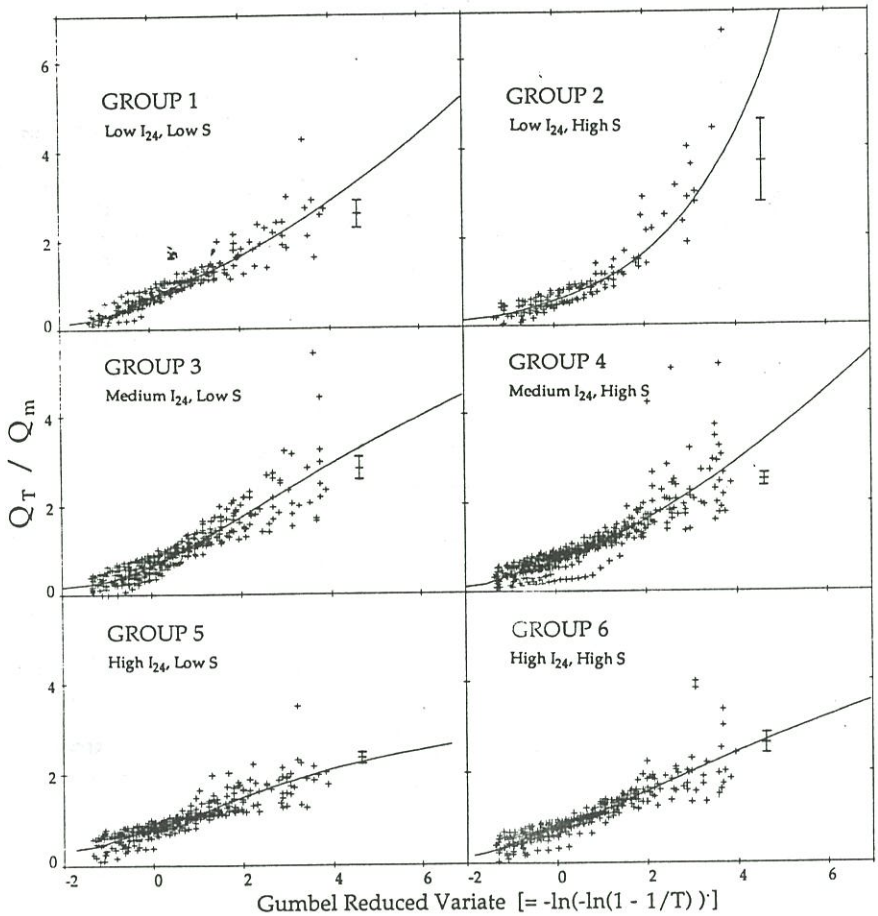

Figure 5.3. Dimensionless flood frequency Wakeby distribution plots with annual flood peak data for six rainfall-slope groups for 117 small catchments (Pearson 1991c). 95% confidence intervals are shown for mean McKerchar and Pearson (1989, 1990) values for each group

but on catchment characteristics, using a scheme developed by Pearson (1991c).

Figure 5.3 shows the Wakeby distribution fitted to each group, using the Gumbel reduced variate horizontal scale for each plot, for which an EV1 distribution plots as a straight line. Wakeby plots for groups 1 to 4 (low to medium rainfall, I_{24}) are steep (slope S), and three exhibit upward curvature for larger discharges (EV2 tendencies), whereas for groups 5 and 6 (high rainfall) the Wakeby curves are flatter and show opposite curvature (EV3 tendencies). Also shown in Fig. 5.3 are mean McKerchar and Pearson (1989 1990) map values for each group, with 95% confidence intervals for each mean. For the low and medium rainfall groups (1-4), the map estimates are below the Wakeby plots. Map estimates are based on the EV1 distribution (straight line on EV1 plot) whereas many of the annual maximum flood series from small drainage basins exhibit EV2 tendencies (upward curvature). This explains the difference between map and Wakeby estimates in Fig. 5.3 for groups 1 to 4. Straight line EV1 distributions underestimate discharges of high return period for groups 1 to 4, but are satisfactory for high rainfall groups (5 and 6). As rainfall increases, the curves become flatter, and for fixed rainfall, basins with higher average slopes have steeper flood frequency curves.Both rainfall and slope influence upper tail steepness of flood frequency curves for small New Zealand basins. Lower rainfall groups are associated with steeper frequency curves (Fig. 5.3) than higher rainfall groups. As explained by Wiltshire (1985), this is physically reasonable as annual flood peaks from basins in drier regions are more variable than those from wetter regions. (Greater variability in annual floods is directly related to steepness of flood frequency curves). A physical explanation for steeper average basin slopes relating to steeper flood frequency curves might be that steeper slopes are faster draining, and offer less storage opportunities, and hence antecedent wetness conditions are more variable, translating into more variable annual flood peaks and so steeper flood frequency curves.

Issues in the application of flood frequency analysis

Flood frequency analysis produces information about the statistics of past floods. If sufficient historical (and sometimes geomorphic) evidence is available, it allows a magnitude-frequency relationship to be developed, so that the average period of time between exceedences of a flow of a given magnitude can be found.

In practice, this information is used as the basis for making decisions about what size of flood it is economical to control. Floods of all sizes are going to occur in any river, but the cost of controlling the biggest possible floods is uneconomic, especially when it is considered that these will occur very infrequently and money spent in protecting a community against them might not be useful within the next 1,000 years. On the other hand, it is very cheap to protect a community against very small floods, but this money is also not very well used since small floods do very little damage, and slightly bigger ones will still cause damage frequently. There should therefore be an intermediate size of flood which gives the best return on money invested in controlling it.

If a number of possible strategies are available to control floods, then flood frequency analysis enables estimation of the range of river flow rates under which these strategies will have to operate during the design life of the scheme. For each flow rate (and corresponding flood water level) it is possible to estimate the damage that will be caused under each of the strategies, and under the present (no strategy, unmodified flooding) situation. The cost of the damage due to, say, a flood that occurs on average every 20 years is then calculated as *"average annual damage cost"* by dividing the actual cost of the event by 20, or multiplying it by the annual exceedence probability 0.05. This procedure can be repeated for the full range of possible flood flows, and the total average annual damage for each strategy calculated. Subtracting the average annual damage under the present situation gives the gross benefit of each of the proposed strategies; subtracting the cost of implementing the strategy then gives the net benefit, and e strategy with the greatest net benefit is the most economic way of providing flood protection. This is a rational procedure and is described in most textbooks as a classical example of scientific knowledge being applied to cost-benefit analysis to yield optimal investment strategies.

In reality there are a number of facts that need to be considered in applying flood frequency analysis to flood mitigation. Firstly, it is assumed in the above rationale that the series of flows that will occur in the river during the design life of the flood protection scheme will be statistically identical to the past flows from which the statistics are derived. This is undoubtedly the most likely situation, in that it is more likely than any other individual situation; however, it is much more likely that one of the (infinitely many) other situations will occur, in other words that the statistics of floods over the next, say, 100 years will not be identical to that of floods over the period of record of the river in question. It would be a remarkable coincidence if the statistics of flows over the two separate periods were in fact identical - but this is what the method assumes. As a parallel example, the average of all the numbers between 1 and 100 is 50; but if we select at random any 5 of these numbers, how likely is it that their average will also be 50? Indeed, it is sometimes *impossible* for the short-term statistics to match those of the long-term - for example, the most likely number of exceedences of the 0.01 aep flood in the next 100 years is 0.62; but the actual number of exceedences *cannot* be 0.62 - it will be an integer, either 0, or 1, or 2 .... It is impossible to have 0.62 of an exceedence. A further factor is that the past statistics are not very accurately known, since rather few years of record are available for most rivers in New Zealand. Finally, there is no guarantee that the processes that generate river flows will be unchanged between the past and the future - climate and catchment land use can both change, and either will cause the flow series and its statistics to alter.

The second factor that tends to undermine the above procedure for identifying the optimal flow against which to protect a community is that the procedure involves identifying rather small differences between rather large and imprecise numbers. The accuracy of flood damage estimates is not infinite, so the damage cost calculations have associated errors, and the differences between various costs have larger errors. A numerical example will make this clear. Suppose the damage cost without any mitigation strategy is $10M +/- 15%, (ie somewhere between $11.5M and $8.7M) and the damage cost with a particular strategy in place is calculated as $5M +/- 15% (ie somewhere between $5.75M and $4.4M); then the benefit of the strategy is somewhere between $7.1M and $2.95M: ie $5M +/- 42%. From this gross benefit the cost of imple menting the strategy must be subtracted to give the net benefit; from the known cost variations in hydraulic structural work the likely error here is between +/- 5% and +/- 50%. Taking the optimistic figure, the cost of the strategy might be $3M +/- 5%. Subtracting this from the gross benefit gives a net benefit of $2M +/- 115%, that is, somewhere between $4.5M and -$204K. It seems unlikely that the cost-benefit technique would give useful precision in identifying the most economic strategy in a case like this.

It must also be borne in mind that damage costs can be estimated for present financial conditions, but are very much more difficult to calculate for the distant future. Since the design life of a flood control project is often of the order of 100 years, there is an implicit assumption that financial conditions will not alter over this time, and this is unlikely to be true.

The final problem with the procedure for deciding on the flow against which protection can most economically be provided is the use of average annual damage to represent the cost to the community of a flood event. For relatively small events this is realistic - spreading the cost of a 10-year flood over 10 years makes reasonable sense. The problem comes when considering large and therefore infrequent floods. The damage caused by a 1 in 5,000 year flood will be immense - and the cost to the community in the years following the event will be will be *much* greater than 1/5,000 of the total cost, because the community will not be willing to spend the next 5,000 years gradually repairing the damage. Neither will it be able to borrow the repair money and repay it over 5,000 years.

These remarks are not intended to devalue the use of flood frequency analysis in flood mitigation planning. There is no doubt that knowledge of the flood statistics of a river is invaluable in gaining an informed appreciation of the range and likelihood of floods in the river. Serious problems can arise, however, when frequency analysis-driven cost-benefit calculations are the sole, or overriding, determinant of choice of design flood or strategy. It is recommended that all professionals responsible for such decisions be very clear about this; although the standard procedure, as outlined above, would undoubtedly be sufficient proof of competent design in a court of law, the question of whether the decision-maker responsible for a structure (thus designed) that failed would find the moral questions in his or her mind comfortable is an entirely different one.

Drought frequency analysis

There are indications that drought cost on an annual basis is on a par with flood damage in New Zealand (e.g. Pearson 1992). Droughts are caused by sustained periods without significant rainfall. River catchments integrate the effects of rainfall over large areas, so that analysis of low streamflows is most important in advancing knowledge on droughts, as well as providing important information to river users.

Low river flows

In low flow hydrology, hydrologists are principally interested in whether or not a river or stream can supply a given demand for water. Water may be needed for domestic or industrial use, for irrigation of farmland, for hydroelectric power generation, for recreational river use, or to maintain wildlife habitat. If demand cannot always be met, either water must be stored or restrictions must be placed upon abstractions.

As with analysis of flood flows, analysis of low flows gives estimates of the low flow with a probability of occurrence of 1/T. If the value of a given low flow is large in comparison with the demand flow, then the river can meet the demand satisfactorily. Particular care needs to be taken in analysing low flows to ensure the flows have not been affected by upstream abstractions. If they have been, they need to be adjusted by comparison with unaffected upstream or nearby flow records, rainfall records, or records of known abstractions.

Low flow statistics used in frequency analyses are usually annual minimum n-day mean flows, where n is often taken to be 7 days i.e., the week in a year with the lowest average flow.

Return period (T) in the context of minima is the reciprocal of F, the cumulative probability function for annual minima, i.e. T = 1/F for minima. For a given design probability 1/T of failure (i.e. unable to meet water demand), if the value of a low flow quantile is large in comparison to the demand flow, then the river is capable of supplying the demand satisfactorily. On the other hand, if the quantile is less than, or of the same order of magnitude as, the demand flow then the river alone, without some form of regulation, could not be considered satisfactory for supplying the demand.

Difficulties arise in the frequency analysis of low flows when the data include zero values. Nathan and McMahon (1990) addressed the zero flow problem by first carrying out low flow frequency analysis for the non-zero flows, and then modifying this result by considering the probability of zero flows.

Pearson (1995) used annual minimum low flow series (1-day, 7-day and 30-day mean flows) from 500 catchments to investigate regional patterns and frequency distributions of low flows within New Zealand. Catchment characteristics (rainfall, soil porosity, vegetation, slope, elevation, hydrogeology) were used to help explain regional variations. Maps of logarithms of mean annual minimum 7-day specific mean flows indicated that contour estimation of this statistic may be worthwhile for many regions (Fig. 1.8). Probabilities of zero flows in annual minimum series were estimated using logistic regression on river catchment area and mean precipitation. L moment ratios of non-zero low flow series were used to test homogeneity of regional and non-geographic groupings of river catchments, and to identify candidate statistical distributions for each group. Regional groupings based on Hutchinson's (1990) low flow regions were of varying homogeneity. A homogeneous Bay of Plenty / Rotorua sub-region was identified from the heterogeneous North Island central volcanic region. The heterogeneous nature of most of the groupings analysed corresponded to the wide range of frequency distributions required to describe adequately New Zealand annual low flow series.

Storage reservoirs are designed to meet the demand flow for an acceptable fraction of the time, consistent with the cost of construction. Reservoir capacity can be made equal to the water deficiency volume which is exceeded with an acceptable probability of occurrence or return period T. If the storage provided is less than the actual water-deficiency volume in a particular year, then failure occurs. Hence, the annual maximum series of drought volumes can be analysed in the same way as for floods. Such analyses assume constant demand. However, if there is a danger that the water-deficiency volume may exceed storage, then demand can be reduced, for example, by increased reliance on thermal rather than hydroelectric electricity generation.

As with flood flows, regional analyses of low flow can be used to predict flows for locations for which no flow measurements are available. In such a regional study, the low flow series at all sites in the region are analysed, and the minimum flows having some specified return period are estimated. These values, commonly in the form of specific low flows (discharge per unit area), can then be applied to catchments for which measurements are not available.

Two methods of predicting flow in ungauged catchments have been used in New Zealand. Flow may be measured in as many streams in an area as possible, during a period of low stable flow. Correlations may then be developed between the flows in streams which have continuous records of flow, and those which do not (e.g. a study of low flows of Taranaki rivers by McKerchar and Dymond (1981)). A second method involves development of regression equations for low flows, using as independent variables catchment attributes such as catchment area, mean rainfall, hydrogeology, and slope. Hutchinson (1990) identified 11 New Zealand low flow regions for which he provided regression equations for 7-day, 5-year return period specific low flow.

There is considerable practical interest in improving understanding of climate and streamflow variability and in its prediction, relating to community and environmental benefits that can accrue if flood and drought conditions can be predicted. Our growing understanding of the climate patterns associated with the El Nino-Southern Oscillation phenomenon provides a potentially powerful tool for medium to long term forecasting of droughts and low flows. Several recent dry periods are ENSO-related. The El Nino-Southern Oscillation is an irregular inter-annual fluctuation in global climate and the circulation of the tropical Pacific Ocean and atmosphere. The Southern Alps drought of 1992 was associated with a low Southern Oscillation Index. There were few weather systems bringing moist westerly winds to the west coast of the South Island (of national importance for inflows to hydroelectric lakes). The Canterbury drought of 1987-1989, on the other hand, was associated with a high Southern Oscillation Index.

McKerchar *et al.* (1996) showed that for rivers draining into major Southern Alps lakes there is an inverse correlation between the summer (December/January/February) inflows and the precursor spring (September/October/November) Southern Oscillation Index (SOI). On average, summer inflows are lower and less variable when the spring SOI is positive (indicating the La Nina state), as compared with summer inflows when the spring SOI is negative, indicating the El Nino state (Fig. 5.4). The result is of interest for long term prediction and has practical significance for scheduling the operation of lake storages for hydroelectric power generation. The reason for the observed dependency is that summer rainfalls for long term gauges in the wetter parts of the Southern Alps also show some dependency on SOI, in that inflows and rainfalls are reduced in years when the SOI is positive. Conversely, summer snowmelt, which contributes on average 70 percent of the summer inflow to the Waitaki lakes, tends to be greater in years when the SOI is positive, which is consistent with generally enhanced temperatures when SOI is positive.

Streamflow droughts

Prolonged streamflow droughts can imply high economic or even human loss where rivers act as water supply systems or as inflows to hydropower, and fauna habitats can be damaged especially in areas where rivers are used as sewage recipients. The drought phenomenon has therefore been studied for long, though it has been difficult to establish a universal definition of hydrological drought (Dracup *et al.* 1980; Beran and Rodier 1985; Ozga-Zielinska 1989).

Clausen and Pearson (1995) carried out a regional frequency analysis of annual maximum streamflow drought as a method for investigating the spatial and temporal variability of droughts, using three geographical regions in New Zealand with different climate and physical properties. Using the truncation level approach, the critical parameter becomes the truncation level, whereas in the low flow analysis it is the fixed duration. Examples of applied truncation levels are the mean (Bonacci 1993), the median (Griffiths 1990), and lower percentage exceedances, e.g. 90% or 95% exceedance flows found from flow duration curves (Zelenhasic and Salvai 1987; Chang and Stenson 1990).

The above studies using the truncation level approach consider droughts at one site and do not discuss the choice of truncation level when drought characteristics from more sites are to be compared. Regional streamflow drought analysis using the truncation level approach was considered theoretically by, among others, Dracup et al. (1980) but actual applications have been scarce so far.

The usual regional approach entails identification of a homogeneous grouping or region of catchments, where homogeneity refers to catchments having the same statistical distribution for the hydrological variable of interest, except for a scaling, dimensionalising factor (e.g. the mean annual value, "index flood" for flood frequency analysis). Once the homogeneous group is identified, the appropriate distribution can be found, fitted to the dimensionless data and used, with an estimate of the mean annual quantity, to provide (extreme) quantile estimates for catchments belonging to the group.

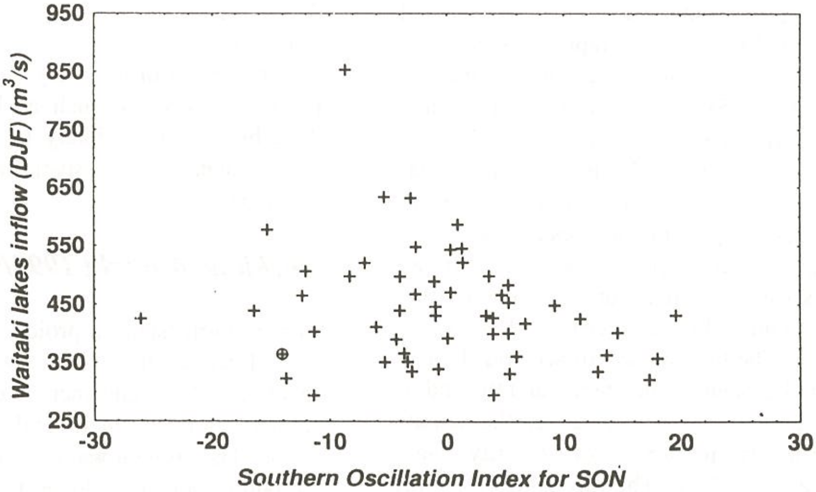

Figure 5.4. Waitaki lakes summer (DJF is December/January/February) mean inflows versus spring (SON is September/October/November) Southern Oscillation Index for the period 1935-1992. The circled point is for 1991-92, which preceded the 1992 winter hydro-electric drought (from McKerchar et al. 1996).

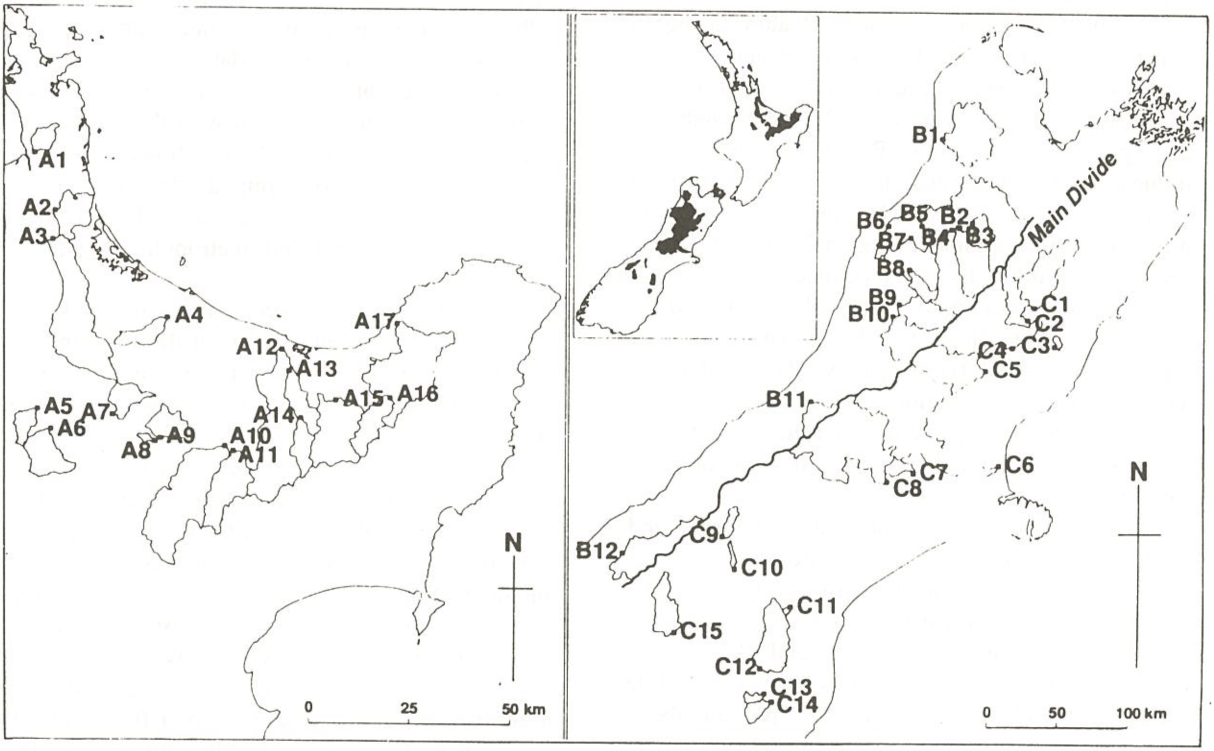

Figure 5.5. Location of the catchments used for the streamflow drought study of Clausen and Pearson (1995).

The study catchments used by Clausen and Pearson are located in three geographical regions: A. Bay of Plenty, B. West Coast of the South Island and C. Canterbury (Fig. 5.5). Records of daily streamflow from 44 sites with lengths from 20 to 44 years (average 27.8 years) were used. The catchment areas range from 22 to 6,350 km^2, and the rivers are not influenced artificially or by major lakes or glaciers.

The drought selection procedure was: first, all drought events were identified, and the severity, the duration, and the time of occurrence of each drought were assembled. The time of occurrence was defined as the midpoint between the beginning and the end of the drought. Then, from this data set the annual maximum droughts in terms of severity were identified (see Fig. 5.6). The drought year was defined to start at the beginning of July because most low flows in many catchments occur in the late summer or autumn. This technique avoids splitting up droughts occurring in different drought years (Fig. 5.6c) and is suitable for catchments with no multi-year droughts. The most distinctive feature of region A is the very permeable Quaternary volcanic deposits dominating the region except in the eastern area where the geology consists of Mesozoic sandstone and greywacke. Regions B and C are highly influenced by the Southern Alps and prevailing westerly winds causing high values of rainfall in region B, and low rainfall in region C. In region B the geology is dominated by plutonic igneous rocks to the north and metamorphosed rocks to the south, and the land is covered by dense rain forest. The geology in region C consists of Triassic greywacke, argillite and sandstone and the vegetation is mainly grass.

The three regions were selected as they are amongst the most hydrologically diverse of New Zealand regions (e.g. Mosley 1981). A recent regional study (using L moments) demonstrated contrasting flood frequency behaviour of the wet West Coast (B) and the dry east coast (C) of the South Island (Pearson 1991a).

L moment ratios L_{CV}, L_{SK} and L_{KUR} were calculated for each dimensionless annual S and D series for the 44 catchments. Fig. 5.7 presents the L moment ratios for S_{75} along with the theoretical relationships for the five distribution functions examined. For each group (A, B, C, and A,B & C) the three-parameter Log-Normal distribution was selected as the best distribution for both severity and duration by using the L-moment ratio goodness-of-fit tests (Fig. 5.7).

The results of the analysis can be used to address practical questions, such as how often a specified drought severity is likely to occur, and to provide some insight into the spatial and temporal nature of droughts.

Auckland drought 1993/94

In the North Island a prolonged drought in 1993/94 caused water shortage in the Auckland metropolis (McPike 1995), and increased water demand in the drought-prone northern and eastern regions of the island. The drought was associated with a long lasting El Nino event (the longest since the mid 1910's), where persistent anticyclonic conditions over eastern Australia brought westerly and south-westerly winds and dry conditions over the North Island (Salinger 1995). How extreme was the drought? Clausen and Pearson (1997) investigated frequencies of the 1993/94 drought using different indicators of drought, using streamflow and rainfall data.

Frequencies of streamflow deficit and duration were estimated and compared with the frequency of the annual minimum 7-day flow. Also, the frequencies of the total rainfall deficit over three month seasonal periods, half-annual and annual periods for the Auckland metropolitan area were estimated.

The non-exceedance probabilities of the 1993/94 7-day minima are compared with the frequencies of the streamflow drought measures in Fig. 5.8 for four regions including Auckland. The non-exceedance probabilities of the 7-day minima are generally higher (most values > 10%) than the exceedance probabilities of the drought measures (most values < 10%). Note that a high non-exceedance probability for annual minimum flow means that it is likely that the minimum flow will be less than the given value; in other words, the given flow is not especially low. On the other hand, a flow less than say the 10% annual non-exceedance probability value is expected in only 1 in 10 years (on average). Thus a flow with 10% annual non-exceedance probability might be taken to signify drought conditions.

The non-exceedance probabilities of the rainfall (Table 5.1) show that the longer duration rainfalls were more extreme than the shorter duration rainfalls.

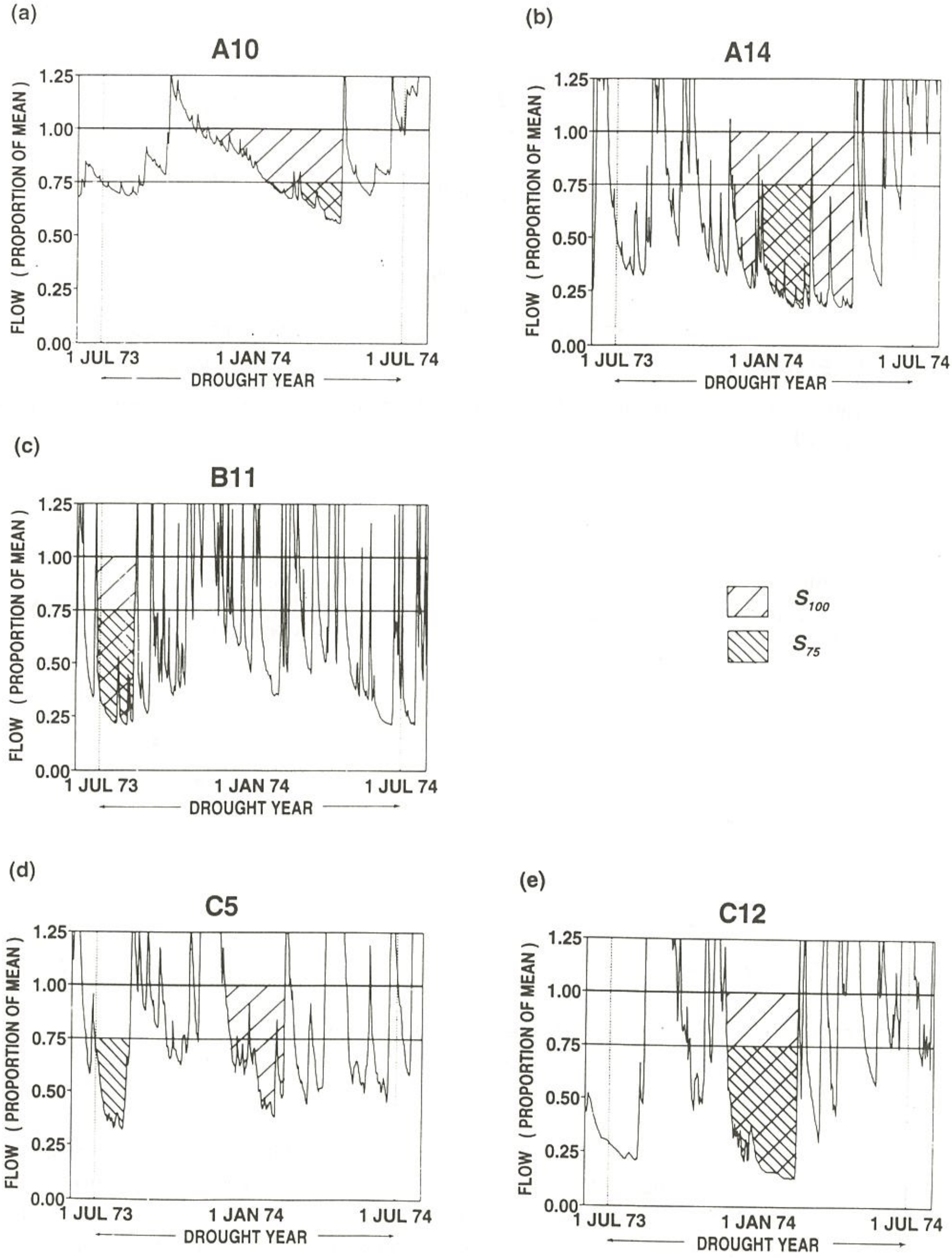

Figure 5.6. Hydrographs for the drought year 1973/1974 for (a) catchment A10, (b) catchment A14, (c) catchment B11, (d) catchment C5, and (e) catchment C12 (see the location in Fig. 5.5). The hatched areas mark the maximum drought severities (from Clausen and Pearson 1995).

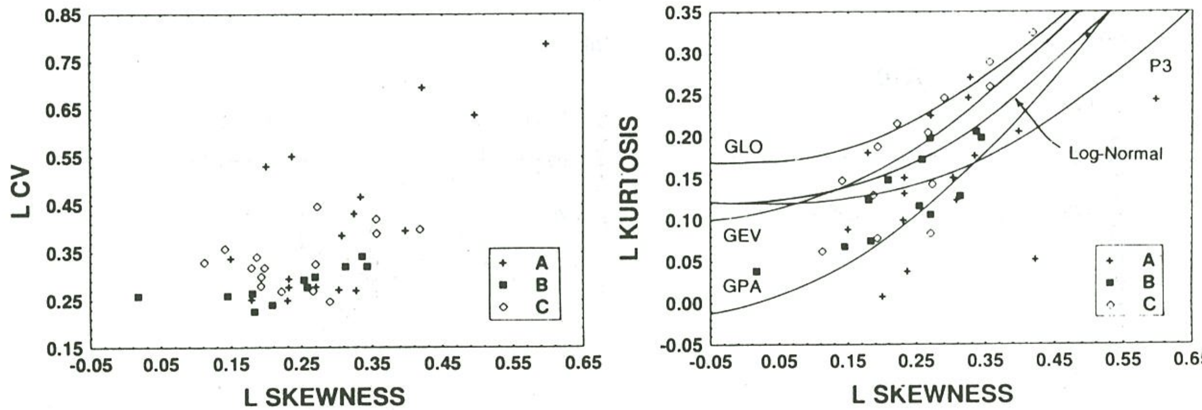

Figure 5.7. L moment ratios for streamflow drought severity, and relationships for five theoretical distributions (from Clausen and Pearson 1995).

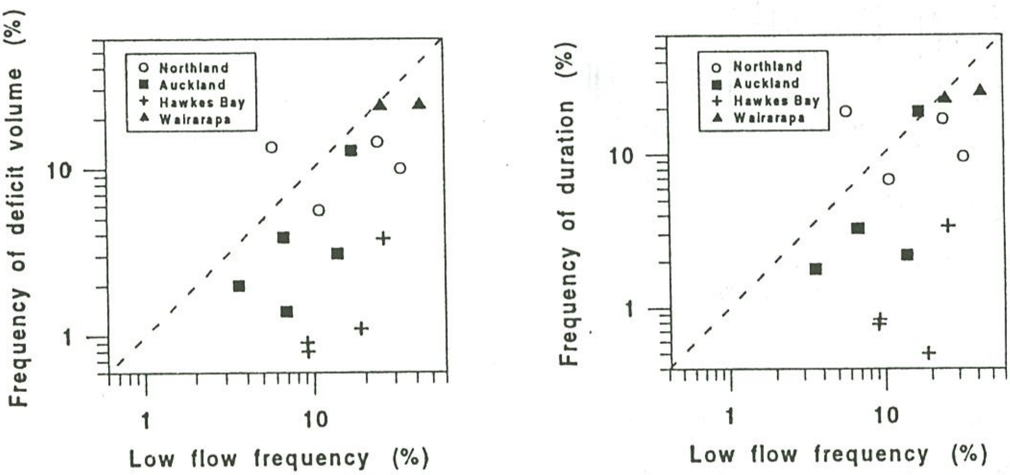

Figure 5.8. Frequencies of 1993/94 maximum drought deficit volume and duration versus 7-day annual minimum flow frequency for 16 flow recording river sites (Clausen and Pearson 1997).

Average non-exceedance probability of the July 1993 - June 1994 year was 2%, corresponding to a return period of 50 years. Of the four seasons examined, the average non-exceedance probability of spring 1993 rainfall was most extreme (13 %, or a return period of 7-8 years).

The results revealed the importance of distinguishing between different definitions of droughts, in that droughts can be extreme in one way, but not in the other. The study showed that the accumulated deficit in flow for streams was particularly extreme, which led to a water supply crisis facing Auckland during 1994. Paradoxically the 7-day minimum for 1993/94 was not exceptionally low compared with other years. The drought in Auckland was caused by low rainfall during all of 1993/94, an event occurring only once every 50 years on average. However, shorter duration rainfall totals within that year were not particularly extreme.

With regard to streamflow deficit volume and duration the exceedance probabilties ranged from 1 to 25%; however, the 7-day annual minimum flows in 1993/94 were less extreme, with non-exceedance probabilities from 10 to 34%. With regard to rainfall

Table 5.1 Estimated percentiles (non-exceedance probabilities; %) for 1993/94 rainfall totals at eight raingauges located within the greater Auckland metropolitan region.

Site no.	Name	Years of record	Winter 1993	Spring 1993	Summer 1993/94	Autumn 1994	Last 6 months 1993	First 6 months 1994	July 1993 - June 1994
647702	Albany	1967-94	57	15	22	13	7	5	4
648701	Albert Park	1872-1993	59	12	18	-	9	-	-
648601	Henderson	1925-94	53	19	16	22	12	6	3
649901	Howick	1964-94	22	18	15	12	5	6	2
649742	Mangere	1960-94	34	8	18	33	2	8	2
649704	Onehunga	1965-94	36	6	20	14	3	7	2
649740	Owairaka	1950-94	20	13	14	16	3	5	1
649803	Pakuranga	1972-94	21	14	18	13	6	5	2

the drought in the Auckland region was most extreme (on average 2% exceedance probability) when annual rainfall totals were analysed, compared to seasonal totals (on average 6% exceedance probability for half-annual totals and 13-38% for three-month totals). Thus, the conclusion was that the 1993/94 drought was extreme because of its duration rather than its magnitude. It is clear that short-term, fixed duration measures of drought (e.g. 7-days) cannot always indicate the extremity of a drought.

Which method to use?

Appendix 5.1 presents a form of decision support system to help answer the question of which frequency methods are appropriate for use in different situations. Cunnane (1989) and Stedinger et al. (1993) provide comprehensive details and background reading for frequency analysis.

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Appendix 5.1 Decision support table for hydrological frequency analysis.

Step	Methods	Software
1. Data • Compile and check time series and spatial data in and around catchment of interest, and from physically similar catchments, from national and regional hydrometric, climate, and land characteristics databases. • The extent of data assembly and checking will relate directly to the return period quantile you wish to estimate.	• Check for gross measurement and recording errors • Check water-level - streamflow rating curves • Check for abstractions or lake controls upstream; standardise data if necessary • Check continuity and stationarity (no trends) of time series • Cross-check with time series from nearby sites • Delete years with missing record • Include historical data	Statistical packages; hydrological data handling packages (e.g. Tideda, Hydsys, Hydrol, Ricoda).
2. At-site Analysis • sample size n > 30	• Plot data on Normal and/or Gumbel probability scales using appropriate plotting position (see Stedinger et al. 1993) • Visually inspect linearity of plot • Fit two-parameter distributions: Gumbel (EV1) distribution to maxima; Normal distribution to minima and means; Exponential distribution for PDS. • Apply goodness of fit tests • If acceptable obtain quantile estimate and its standard error (if possible) • If not acceptable, fit three-parameter distribution, plot to check fit acceptable; obtain quantile estimate	Statistical and spreadsheet packages; hydrological data handling packages (e.g. Evan; Stedinger et al. 1993 lists others available).
• 10 < n < 30	As above, but if two parameter fit not acceptable, prefer regional estimate with at-site mean	
• n < 10	Use at-site mean with regional method and rainfall-runoff method; make use of flow gauging data	
3. Regional Analysis	• Establish homogenous grouping of catchments (either in the same region or with the similar climate and catchment characteristics) • Obtain multiplicative regression estimator for the mean and also the quantile of interest (using at site quantile estimates if reliable) based on catchment characteristcis and rainfall variables	The L-moments approach is the best to use - routines freely available from Statlib by sending an email to statlib@lib.stat.cmu.edu and including "send lmoments from general" in the message. Compare with Beable

Step	Methods	Software
	• Estimate best frequency distribution for the dimensionless data (each sample divided by its site mean) • Obtain and compare regional quantile estimates • Also estimate quantile using published New Zealand regional methods	and McKerchar (1982), McKerchar and Pearson (1989) for floods; Hutchinson (1990) for low flows; Tomlinson (1980) for storm rainfalls.
4. Rainfall-Runoff Analysis	• Select, fit and test a rainfall-runoff model to the catchment of interest, using available rainfall, streamflow, and catchment data (e.g. digital elevation data) • Input design storm or drought rainfalls of required return period • Obtain modelled output hydrographs and recessions	Models used in New Zealand include Rorb, Hycemos, Topmodel, Topog. Use Hirds rainfall estimation package for New Zealand storm rainfall estimates.
5. Pooling Quantile Estimates	• The best two estimates from the above methods should be pooled to provide the final estimate	(see McKerchar and Pearson 1989, p46)

6
Effects of land use on floods and low flows

Lindsay Rowe, Barry Fahey, Rick Jackson and Maurice Duncan

Introduction

In New Zealand, how land use affects floods and low flows is a contentious issue and the subject of much debate among territorial authorities and land managers as they put together local land management plans. Historically, the largest change in land use occurred during the Polynesian era, when native forest was cleared by fire and replaced by tussock grassland and scrub. A thousand years ago there were about 20 million hectares of forest; by the time the early European settlers arrived only 11.3 million hectares remained (Cameron 1962). Large tracts of lowland and high country forest were in turn cleared for pastoral farming by the European settlers between the early 1800s and the 1950s, reducing native forest to only 5.7 million hectares, much of it on steep and mountainous terrain (Thompson *et al.* 1972). A similar area of tussock grassland remains, but much of it has been severely depleted by burning, overgrazed by stock and introduced animal pests, and infested by noxious weeds and introduced pasture species. Thus, the vegetation seen today is generally not that which had evolved in response to the extremes of the temperate climate of the region. Consequently, major storms such as Cyclone Bola, which hit the East Cape in 1988, often result in severe land degradation (see Fig. 15.1 in Fahey and Rowe 1992) and flooding.

Since the 1960s, land use has changed rapidly in response to economic factors. For example, when meat and wool prices fell and farming subsidies were withdrawn, much hill country pasture was allowed to revert to scrub, the first stage towards forming new forests. Major changes in land use are taking place today: hill country pasture is being converted to plantation forest (Fig. 6.1), sheep and beef farmers are changing to dairying, and urban areas are expanding through the development of both high-density suburbs and 'lifestyle' blocks.

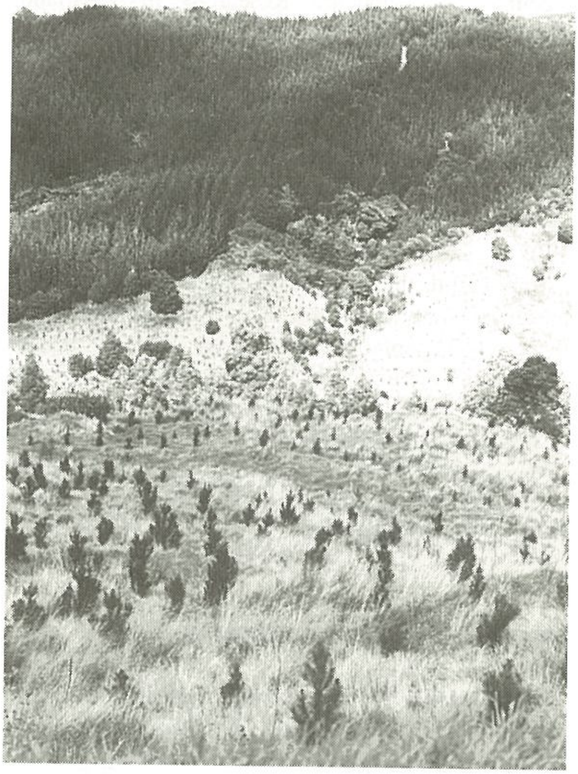

Figure 6.1. Conversion of dairy farmland to pine plantation, as shown here in Northland, is a common land-use change in New Zealand in the 1990s

As a result of these recent changes in land use, a number of issues have arisen concerning current water resources and their allocation. For example, what is the effect of converting pasture to forest on the amount of water available downstream for irrigation and municipal supplies? In water-short areas, will enough water be left in streams in summer to maintain the habitats of the stream biota?

Hydrological studies within experimental catchments began in the 1950s at Makara, Moutere and Taita; other catchment studies at Puketurua, Purukohukohu and Otutira followed under the UNESCO-sponsored International Hydrological Decade Programme. In the 1970s, at a time when many of these studies were being reduced in scale or closed down, additional experimental catchments, focusing on the hydrological effects of land use changes then considered important, were being established by the former Forest Service (a precursor of Landcare Research) in Westland, Nelson and east Otago.

There are now a wealth of data available from studies of water resources and land use changes in small catchments in New Zealand (for example: Duncan 1980, 1995; Rowe and Fahey 1991; Fahey and Watson 1991; Rowe and Pearce 1994; Fahey and Rowe 1992; Fahey 1994; Fahey and Jackson 1997). These data, however, are difficult to extrapolate to the large-scale catchments that are of more interest to territorial authorities. In spite of all these experimental studies, gaps still exist in our knowledge, particularly of the effects of land use change on flood flows and low flows.

This chapter presents the results from a number of land use change experiments, mainly in small New Zealand catchments, on extreme flows - both floods and low flows.

Some fundamental concepts

The proportion of runoff or water yield from a given amount of rainfall depends on both the vegetation cover and the storage characteristics of the soil and underlying bedrock. Much of the water intercepted by leaf surfaces and plant canopies is returned to the atmosphere as wet canopy evaporation. Substantial amounts of soil water can also be lost through transpiration (dry canopy evaporation). Land use changes in which one type of vegetation is replaced with another will alter runoff through changes in both interception and transpiration. The interception losses (wet canopy evaporation) become increasingly important as annual rainfall increases, whereas in drier climates or those with pronounced seasonal differences in rainfall, wet and dry canopy evaporation losses may be equally important. Thus, the effects of conversion of a short to a tall vegetation cover will vary with the area's rainfall: in a high rainfall region it will have a major impact on storm flows, whereas in areas with strong seasonal differences in rainfall less water may be available for baseflow during dry spells.

Storm runoff or quickflow has a number of sources - channel precipitation, and overland flow occurring when the rate of rainfall exceeds the rate of infiltration or when the ground becomes saturated i.e. where the water table intersects the ground surface adjacent to stream channels. Rainfall entering the soil can also flow laterally via macropores and micropores as subsurface storm flow. The source of base flow or delayed flow is water stored in the soil and underlying bedrock, which eventually enters the stream channel. During dry periods, an area covered in larger, deep-rooted vegetation will lose more water from this store by evaporation than an area covered with short vegetation.

Sources of information

Much of our understanding of the hydrological impacts of land use changes comes from experimental catchment studies. In this chapter we draw mainly on the results of four catchment studies that have contributed high-quality hydrological data on the effects of afforestation and harvesting over the last 15 to 25 years. Data from a number of other catchment experiments are also included (Fig. 6.2).

Moutere

The oldest of these hydrological datasets is from the multiple-catchment study at Moutere, which is the first in the country to assess the effects of a complete forest rotation on water yield. The study area comprises six catchments ranging in size from

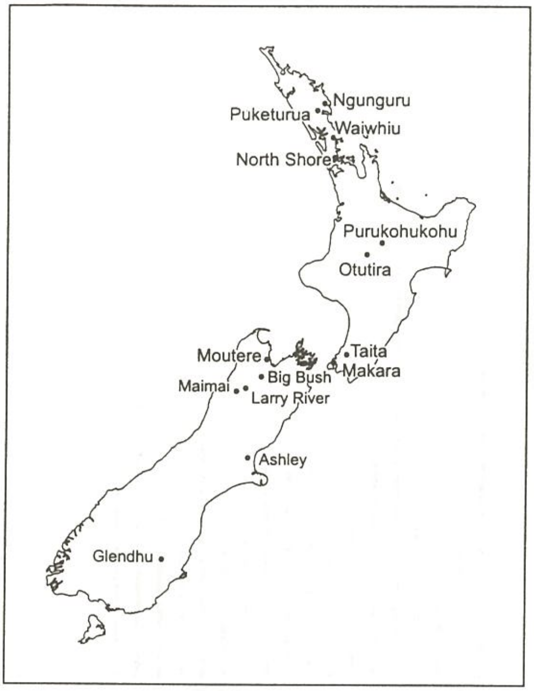

Figure 6.2. Location of New Zealand hydrological experiments described in this chapter.

2.71 to 7.65 ha in dissected Moutere Gravel hill country 20 km south west of Nelson. Two catchments have been left in pasture, and three were planted in *Pinus radiata* at 1500 stems per ha, pruned twice to a production stocking rate of 300 stems per ha, and logged in 1991.

Glendhu Forest

The hydrological consequences of converting tall tussock grassland to pine plantation has been studied using a paired-catchment approach at Glendhu Forest in the uplands of east Otago since 1980. The site is located in an area of mid-altitude grassland in the upper Waipori catchment 70 km west of Dunedin. It consists of two catchments, one left in tussock (*Chionochloa* spp.) as a control (GH1, 218 ha), and the other (GH2, 310 ha) planted in *P. radiata* at 1250 stems per ha over 67% of its area in 1982. In 1989 the lower quarter of the catchment was thinned to 270 stems per ha.

Big Bush

The Big Bush study area is located in the upper Tadmor valley, south-west Nelson, in an area of mixed evergreen native forest dominated by hard beech (*Nothofagus truncata*) and red beech (*N. fusca*) and plantations of *P. radiata* and Douglas fir (*Pseudotsuga menziesii*). It comprises four catchments, the smallest (DC2, 4.8 ha) left in undisturbed beech forest and the others subject to harvesting and afforestation. The catchments are typical of the dissected hill country in this area which is underlain by the Moutere Gravel Formation. High intensity storms can occur in any season and are often highly localised. Catchment DC1 (8.57 ha) and DC4 (20.19 ha) were harvested over 87% and 94% of their respective areas in 1980 and planted in *P. radiata* in 1981.

Maimai

At Maimai, near Reefton on the South Island West Coast, seven small steepland catchments (2-9 ha) within Powerline Creek have been cleared of native forest (mainly *Nothofagus* species) and pines planted after various land preparation techniques (burning versus no burning; with and without small riparian reserves). In this region annual rainfall is about 2450 mm and the underlying geology is the almost impermeable Old Man Gravel Formation.

Flood flows

Flood flows, or high flows, vary considerably from region to region and from year to year, and their size depends on the duration and intensity of the storm rainfall. For small native forest catchments, the average annual flood peak was 11.5 l/s/ha in the lower rainfall Nelson Big Bush catchments (annual rainfall 1530 mm), and 25 l/sec/ha at Maimai in Westland (annual rainfall 2450 mm) (Fig. 6.3). Flood flows for Big Bush show greater year-to-year variation (18-fold) than at Maimai, where variation was 8-fold.

Afforestation of tussock grassland

The effect on storm peak flows and associated

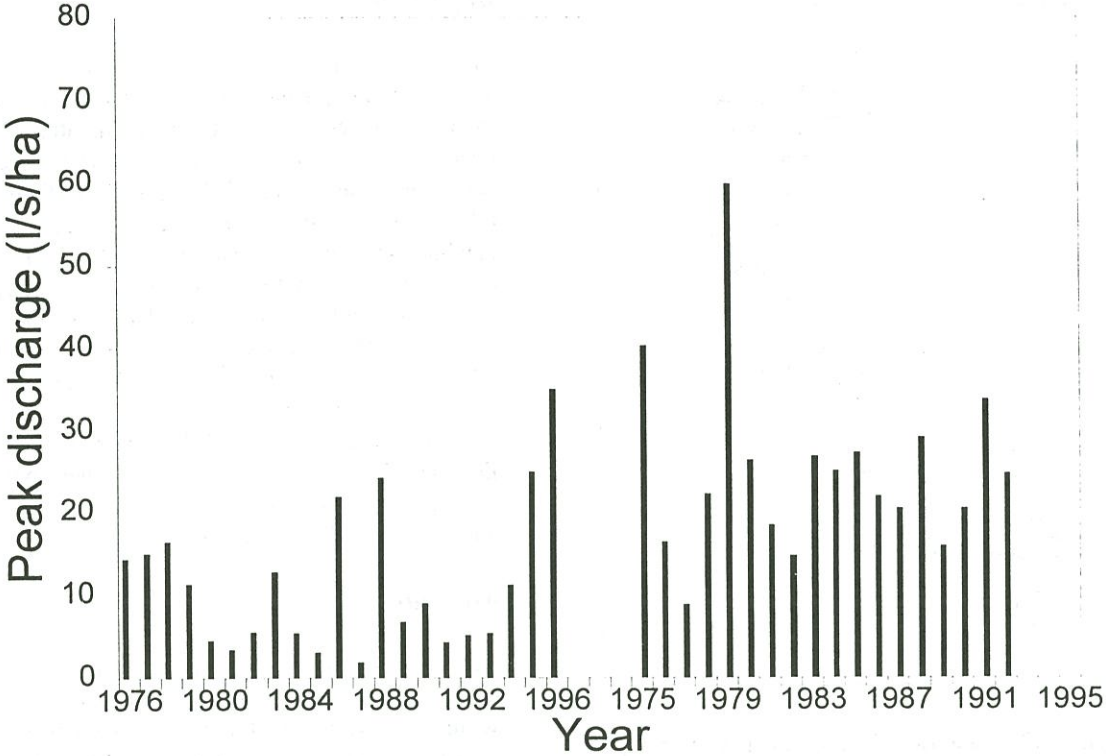

Figure 6.3. Annual flood peaks from catchments DC2 at Big Bush, Nelson (left) and M15 at Maimai, Westland (right).

quickflows of planting forest on tussock grasslands at Glendhu has been examined by Fahey and Watson (1991), Fahey (1994) and Fahey and Jackson (1997), and is up-dated here. Four classes (2-5, 5-10, 10-15, and >15 l/s/ha) were chosen to categorise peak flows on the basis of the return periods of the annual flood peaks for the control catchment in tussock (GH1). The means in each class were calculated for this catchment for two periods, one representing conditions before the paired catchment GH2 was planted (1980-1982) and the other conditions during the post-planting period when GH2 had a full forest cover (1994-1996). The means were then calculated for the corresponding storms at GH2 for the same two periods. The differences in peak flow means between GH1 and GH2 for all 4 size classes in the pre-planting period were not significant ($p>0.3$), but were so for the post-planting period ($p<0.04$). The effects of afforestation on peak flows appear as lower mean values for GH2 in the 1994-96 period, compared with means for GH1 over the same period (Fig. 6.4). Reductions for the 2-5, 5-10, 10-15, and >15 l/s/ha flow classes were 70%, 64%, 68% and 74% respectively. There was also a substantial reduction in the number of flood events in all classes.

A comparable pattern of change was observed in the quickflows (Fig. 6.5). The biggest percentage decrease for GH2 occurred in the smallest quickflow depth class, with correspondingly smaller percentage decreases occurring at progressively larger depth classes, from 65% for the 5-10 mm class to 48% for the > 40 mm depth class. The impact of afforestation on floods can also be assessed by comparing the return periods and annual exceedance probabilities of annual peak flows and quickflows for GH1 and GH2, using the tussock control catchment GH1 as the base. For example, in the period 1994 to 1996, the highest peak flow in GH1 was 17.8 l/s/ha, which has a return period of about 3 years. The corresponding peak flow for GH2 was only 5.3 l/s/ha, which has a return period of about one year, based on the Gumbel distribution for GH1. Over the same period the largest quickflow depth at GH1 was 42.9 mm (return period of 2.6 years). The corresponding quickflow depth at GH2 was 21.0 mm, which has a return period of just over 1 year according to the GH1 data. Thus afforestation has sufficiently reduced peak flows and quickflows from GH2 that a rain storm producing flows with a return period of about 3 years from the tussock catchment now produces lower flows from the forest catchment with a return period of about 1 year.

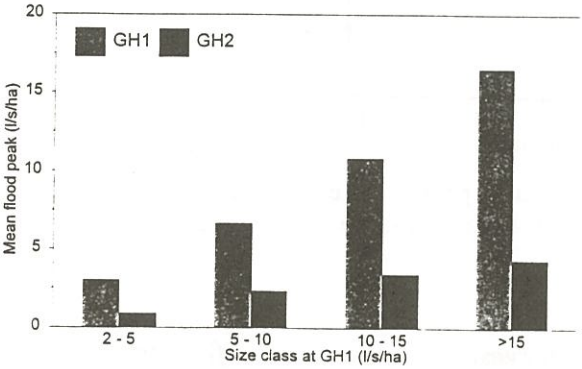

Figure 6.4. Mean of 1994-96 (post-planting period) flood peaks by flow class at Glendhu catchments GH1 (tussock grassland) and GH2 (planted in 1982). The equivalent paired histograms for 1980-82 (pre-planting period) show no significant differences between GH1 and GH2.

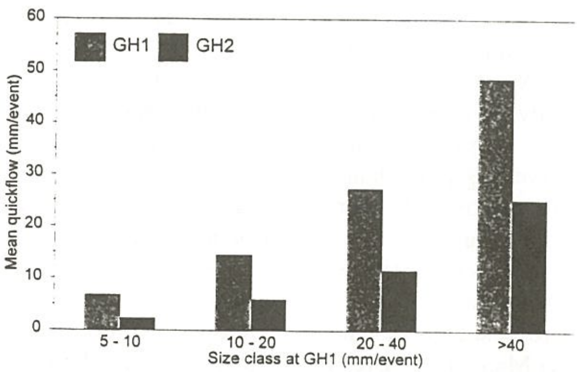

Figure 6.5. Difference in 1994-1996 storm quickflow at Glendhu catchments GH1 (tussock grassland) and GH2 (planted in 1982).

Afforestation of pasture

No difference in flood peaks from the small catchments (4.0 - 7.7 ha) was apparent during the establishment of pine forest at Moutere, Nelson, where *Pinus radiata* were planted in three catchments at 1500 stems per hectare into a vigorous ryegrass white clover pasture. However, some small, initial reduction in flood peaks might be expected from the afforested catchment because evaporation would be greater from the taller pasture (it was no longer being grazed) and because infiltration rates were higher without stock trampling and compaction of the soil surface.

Duncan (1980) showed that peak discharges during freshes from small, gorse or *Pinus radiata* catchments are only about 20% of those from pasture catchments at Moutere. More extreme floods (Duncan 1995) also showed large differences, over a wide range of annual exceedance probabilities (AEP), between flood peaks from three pasture catchments and those from three closed-canopy *Pinus radiata* catchments at Moutere (Fig. 6.6). The mean annual flood peaks from pines average about 35% of those from pasture and the 0.02 AEP peaks averaged about 50% of those from pasture.

For a storm in June 1980 that produced the largest recorded flood from the pines catchments (rainfall 119 mm; runoff 25.5 mm from pine catchments; runoff 101 mm from a pasture catchment), the flood peak discharges from the pine catchment averaged 32% of those from the pasture catchment (Fig. 6.7) (Duncan 1995). The reduction in flood peaks by the pines is attributed to both the evaporation of intercepted water from the pine trees during storms (Pearce *et al.* 1980), and the difference in soil moisture between the pine and pasture catchments. This soil moisture difference over a soil depth of 2.3 m at Moutere is, on average, of the same order as the 0.02 AEP 24-hour rainfall of 153 mm. In this June 1980 storm, interception by pines was 24.5 mm and that from pasture was assumed to be nil, and about 31.5 mm more rainfall was absorbed by the soil under the pines because the soil moisture content under the pines was smaller when the storm began.

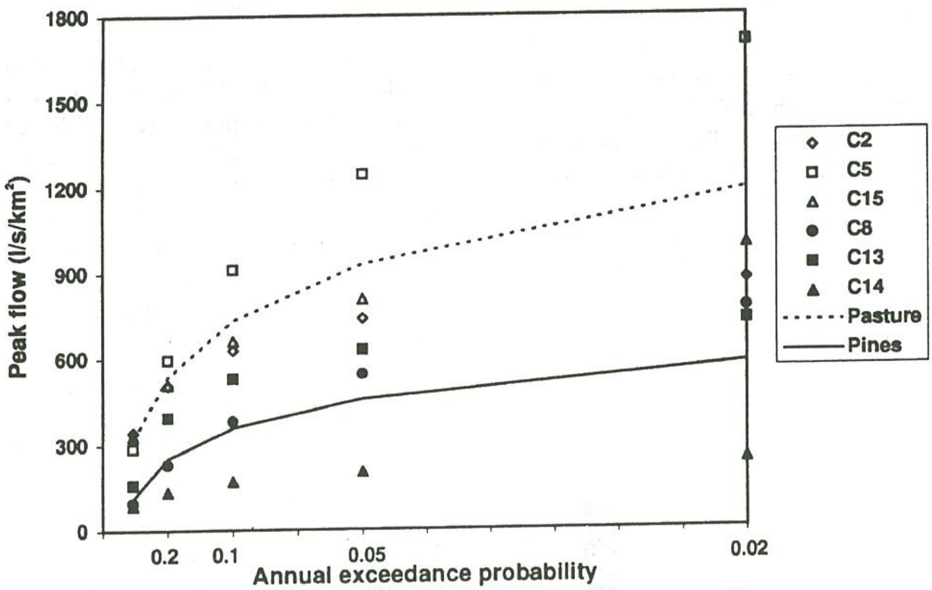

Figure 6.6. Relationship between annual peak flow and return period for catchments that were either predominantly pasture or gorse/pines between 1964 and 1993. Pasture catchments have open symbols, pine catchments closed symbols.

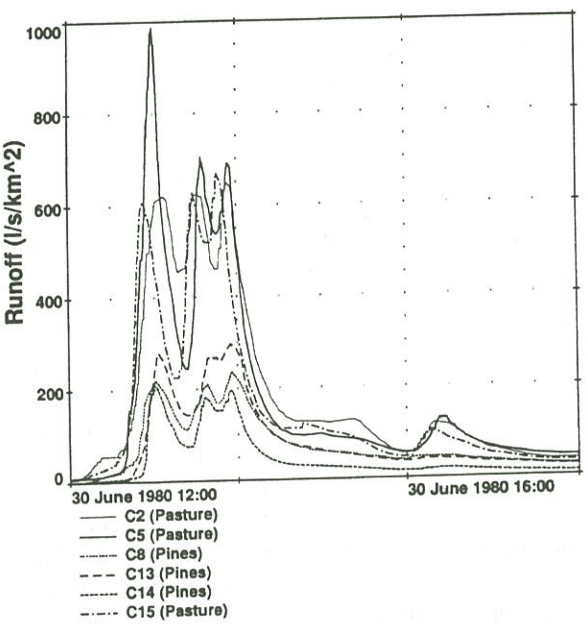

Figure 6.7. Hydrographs from pine and pasture catchments for the flood of 30 June 1980.

Harvesting pine or native forests

Against expectations, flood peaks from previously forested catchments at Moutere, Nelson, in the first and second year after harvesting, were respectively 20% and 62% of those from a pasture catchment. This was attributed to the very low soil moisture levels beneath the trees at harvest and the long time, during which tall weeds grew, needed to recharge the soil moisture levels (M.Duncan, unpubl. data).

Apart from the work of Duncan (1995) and the study at Ashley, there is little information in the New Zealand literature on the likely effects of harvesting pine plantations on storm flows and low flows. However, interception and transpiration data from a variety of forested areas in New Zealand and overseas (Pearce and Rowe 1979) suggest that differences in water use between native and exotic forests should be small. Therefore the results from the Maimai and Big Bush experimental catchments, although derived for harvesting native forests, are broadly applicable to plantation forests.

We can use the data for the undisturbed beech forest catchment DC2 at Big Bush (Fig. 6.3) to provide information on natural variation in flood magnitudes, and data from DC1 and DC4 as indicative of logged catchments, and compare peak flows (in l/s/ha) and quickflows (in mm depth per event) for selected classes in the same way as was done with afforestation effects at Glendhu. The flow classes of flood peaks at the control catchment were defined in relation to the annual exceedance probability using the Gumbel distribution to analyse the 17-year series of annual flood maxima. The data are grouped according to the peaks at DC2.

The mean flood peaks in each class for the same storms during the pre-treatment period (1978-1980) at the three catchments are similar. However, in the post-harvesting period (1981-1986) the mean peak flows for given storms at DC1 and DC4 are markedly higher than flows at undisturbed catchment DC2 (Fig. 6.8). At DC1 the peak flow for the biggest storm in the pre-treatment period was 15 l/s/ha whereas in the post-treatment period there were two storms with a mean of 38 l/s/ha. The latter flow represents a return period of about 25 years for DC2. The actual peak discharge for the same storm at DC2 was 24.2 l/s/ha, which has a return period of 19 years.

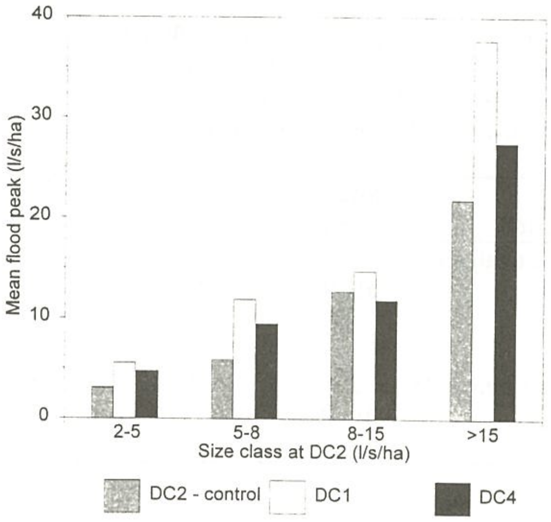

Figure 6.8. Difference in flood peaks after harvesting Big Bush catchments DC1 and DC2.

The data for storm quickflows were analysed in the same manner as those for peak flows. The following quickflow depth classes were selected: 20-40 mm, 40-60 mm, and 60-80 mm (which included the largest storm), and the data sets matched among the three catchments using DC2 as the base for the pre-treatment period (1978-1980) and for the post-treatment period (1980-1986). For the latter period average quickflow depth and number of events increased (Fig. 6.9). In percentage terms the increase was greatest for the smallest depth class and decreased with increasing depth class. The >60 mm depth class at DC4 showed no increase in quickflow depth. Thus relative increases in quickflow after logging are small for large events. Most of the increase in quickflow is thought to come from extra rainfall reaching the soil once the canopy is removed, rather than from higher surface runoff due to increased soil compaction during harvesting. Quickflow increases are more variable than those noted for Maimai because both soil water retention and interception contribute to losses. In most summers, soil water depletion under beech forest at Big Bush is about 80-100 mm, compared with about 20 mm after harvesting (Jackson and Rowe, 1996). In 1983 the largest storm occurred in April, when soils in the control catchment were much drier than those in the recently harvested catchments. Rainfall of 135 mm gave peaks of 15 l/s/ha from the harvested catchments, with a total storm runoff of 90 mm, compared with 5.4 l/s/ha and 35 mm from DC2. Interception accounted for about 25 mm of the lower water yield from the forest catchment DC2, but the larger difference was in soil water retention.

At Maimai, about a year after felling and slash-burning, peak flows from catchments M7 and M8 were higher than for comparable native forest catchments (Pearce *et al.* 1980). The largest changes, in percentage terms, occurred in the smaller storms. Flood peaks averaged about 60% greater than the control in the 2-5 l/s/ha flow class, 45% greater in the 5-10 l/s/ha flow class, and 30% greater in the >10 l/s/ha flow class.

The effect of soil moisture status on peak flow is demonstrated using 4 storms of similar magnitude from Maimai in 1980, shortly after catchments M5 and M13 were harvested (Fig. 6.10). Storm flows in summer from the native forest catchment (M6) were much smaller than those from the two recently harvested catchments, where soil moisture would be considerably higher than in the forest catchment. During winter, when soil moisture levels would have been similar in each catchment, flood peaks were similar.

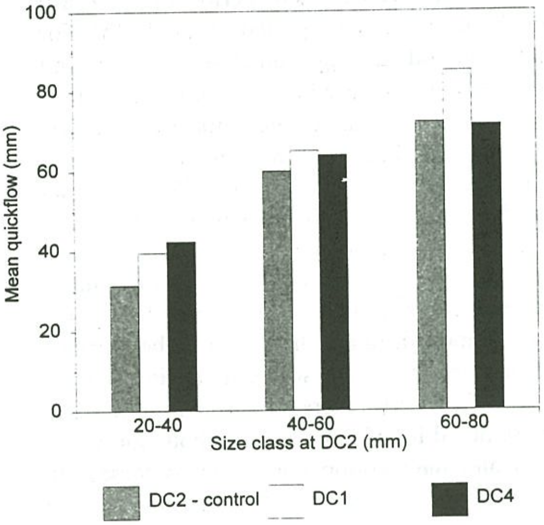

Figure 6.9. Change in storm quickflow following harvest of Big Bush catchments DC1 and DC4.

Scrub clearance

Prior to afforestation at Moutere, gorse scrub was cleared by line dozing in one catchment and burning and cultivation in another. The peak of a flood that occurred during the brief time when the cultivated paddock was bare was 3 times larger than the average from two pasture catchments. Vegetation regrowth was rapid in both catchments and for the first 3 years after treatment flood peaks from the cleared catchments were similar to those from pasture, after which they became smaller.

Also at Moutere, the land use of another catchment was changed from gorse to green feed cropping, which required cultivation twice per year. Scarf (1970) reported increases in peak discharges (up to 10 mm/h, a 2.5 times increase in flood volume) and decreases in flood durations after the change in land use.

Drainage of pakihi wetlands

Drainage is part of standard forest management practice of pakihi wetlands on the West Coast of the South Island, formerly to encourage growth of pasture species for sheep and dairy farming but more recently as a prelude to establishment of pine plantations. Data from three catchments, about 10 ha each, in Larry River near Reefton (Jackson 1987) are believed to show a typical hydrological response to scrub clearing and then drainage, using bulldozers equipped with v-blades (see photograph in Fig. 15.12, Fahey and Rowe 1992).

Afforestation of pakihi using these preparation techniques can lead, in the short term, to increased water yields, and higher and more frequent peak flows. In the 18 months after drainage works were carried out in Larry River catchment L3, there were 31 events in L3 with peak discharges greater than 10 l/s/ha, compared with 4 events at the undisturbed control catchment L2. In many larger events, peak flows from drained catchments were 2-4 times greater, and quickflows were up to 30% greater, than those from the undrained catchment, whereas in the pre-treatment period they were similar (Table 6.1). Small rainfall events (< 10 mm) often produced stormflow from the drained catchment but not from the control catchment (Jackson, 1987).

Table 6.1 Average peak flow (l/s/ha) from Larry River catchments L2 (control) and L3 (treated). Note: as flow classes are set by storms at L2, other high events at L3 may not be included.

Period	Size class at L2	No. of storms	L2	L3
Pre-treatment	5-9.99	13	7.3	8.9
	10-19.99	8	12.9	14.0
	>20	4	22.7	23.4
Post-treatment	5-9.99	10	7.4	21.3
	10-19.99	3	13.4	22.5
	>20	2	22.3	76.9

Urbanisation

The effects of urbanisation on hydrology have been fully covered by McConchie (1992) and are summarised here. Urbanisation changes a catchment's runoff characteristics: vegetation is removed, which allows more rainfall to reach the

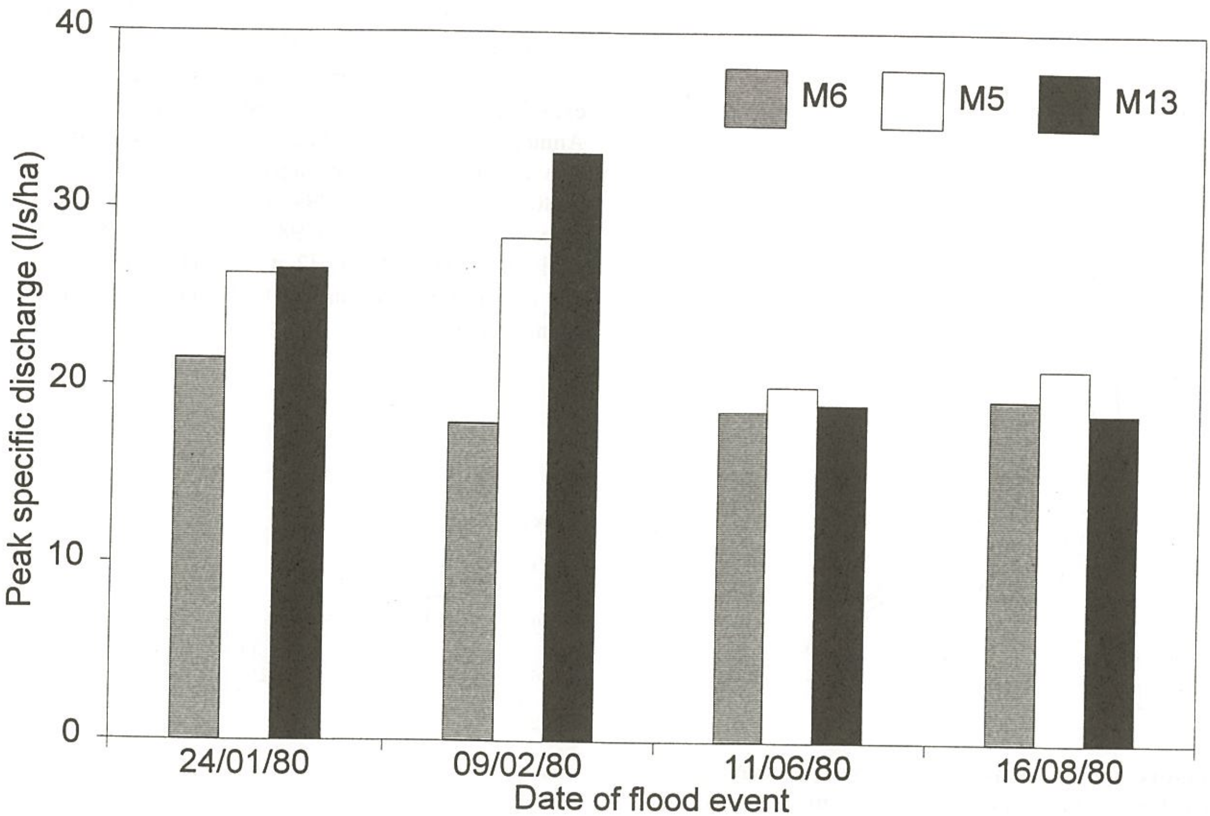

Figure 6.10. Flood peaks at Maimai catchments showing the influence of higher summer soil moisture at recently harvested catchments (M5 and M13) giving rise to higher flood peaks.

ground, and the amount of impervious area increases, thereby reducing infiltration. In urban areas natural channel networks are replaced by artificial drainage, which allows runoff to be concentrated quicker.

As a catchment becomes more and more urbanised, the effects of decreasing vegetation and increasing impervious areas combine so that floods become briefer, and flood peaks increase and occur earlier. Williams (1976) presented an example from the North Shore (Fig. 6.11). The number of small floods increases almost as soon as urbanisation begins.

A later study also concluded that the peak flow of a 2 year storm will increase by about 4 times. However, large magnitude floods (50- and 100-year events) may increase only 2.5 times, as factors other than urbanisation (e.g. rainfall intensity/duration) can influence flood magnitude. Short duration high-intensity rainfalls that produce floods from urban areas with a 20% impervious area may not have produced floods under rural conditions (Auckland Regional Authority 1983).

Low flows

Afforestation of tussock grasslands

The lowest average flow for seven consecutive days is a useful measure of the impact of a change in land use on minimum low flows. The minimum 7-day low flows at Glendhu are in the range 0.5 to 1.0 mm/day in nearly all years, and the difference between the lowest average 7-day flow for the

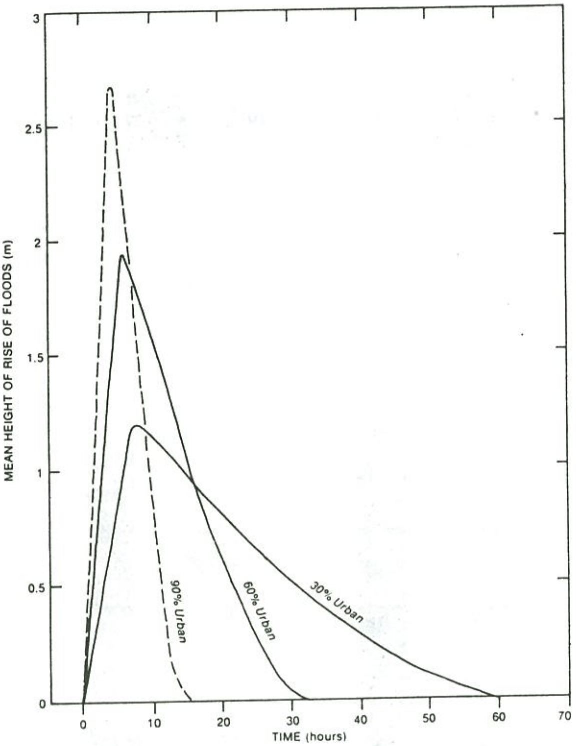

Figure 6.11. Change in hydrograph shape as a catchment becomes more and more urbanised (Williams 1976).

control tussock catchment GH1 and the afforested catchment GH2 in each year can be used to indicate the impact of afforestation (Fig. 6.12). The growth of trees planted in 1982 began to noticeably reduce on low flows from 1987 onwards. Between 1994 and 1996 the annual average difference between the lowest average 7-day flow for the two catchments was 0.13 mm/day, that is, the mean of the lowest average 7-day low flow for that period was 16% lower in the afforested catchment than the tussock catchment.

The Gumbel distribution was used to analyse the 17-year record of annual 7-day low flows for the tussock catchment. In 1993 the minimum 7-day low flow mean, 0.127 l/s/ha or 1.10 mm/day, has a recurrence interval of 1 year. The equivalent mean value for the planted catchment (GH2), 0.089 l/s/ha or 0.77 mm/day, when plotted on the Gumbel distribution for the tussock catchment, has a recurrence interval of 4 years. Thus the presence of trees in GH2 could be said to have made the low flow regime more extreme than before.

Flow duration curves can also be used to examine the impact of afforestation on low flows. Annual flow duration data were calculated for the two catchments and arranged for the two periods 1980-1982 and 1992-1994. For GH1 the minimum flow was 0.10 l/s/ha for 98% of the time for both periods, whereas for GH2 it was 0.09 l/s/ha in the pre-planting period and 0.07 l/s/ha for the post-planting period.

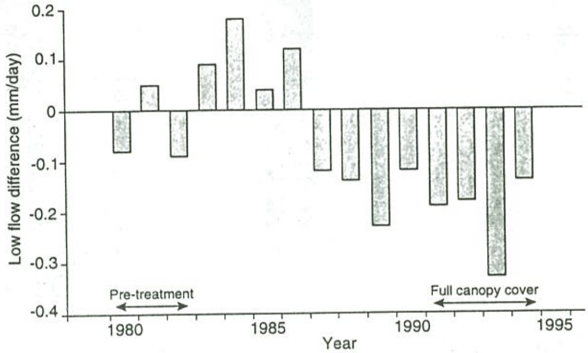

Figure 6.12. Difference between 7-day low flows, tussock and afforested catchments, Glendhu..

Afforestation of pasture

Ephemeral flows at Moutere preclude extreme-value analysis of low flows. Flow duration curves averaged over 7 years show that, for much of the time, the flow from three closed-canopy pine catchments was about 25% of that from three pasture catchments (Duncan 1995) (Fig. 6.13). Analysis of flow records suggests that as the canopy began to close, the pine catchments began to have more days without flow than pasture catchments. When the canopy had closed the pine catchments averaged 157 zero-flow days per year, compared to the pasture catchments with 64 zero-flow days per year.

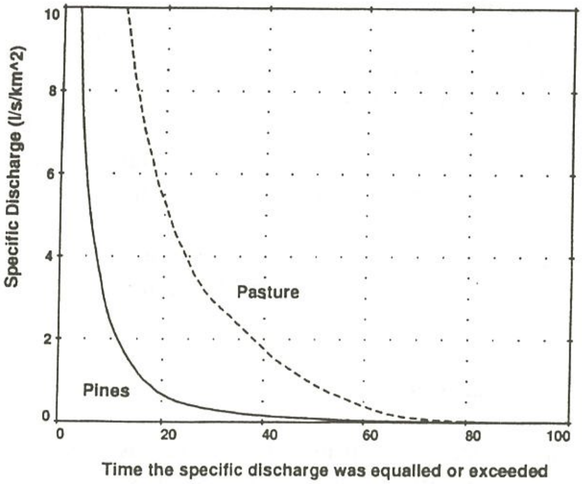

Figure 6.13. Flow duration curves for 1978-85 from mature pine and pasture catchments.

Harvesting forests

For the two years after clear felling of the forest from three catchments at Moutere, the flow duration curves from those catchments show sustained base flows, with some flow occurring at least 85% of the time. In contrast, flow occurred only 50% of the time from the pasture catchment. The flow duration curves show that when the pasture catchment ceased flowing, flows from the clear-felled catchments were at least 1 l/s/km, a reflection of higher soil moisture levels in the recently felled catchments compared to the pasture catchment. In the clear-felled catchments, aspect had a marked effect on flows, with a southerly-aspect catchment having higher flows than two northerly-aspect catchments.

The impact of forest harvesting on low flows can be studied by comparing the lowest average flow for seven consecutive days between catchments, but it is more difficult to quantify low flows in the case of Big Bush because the control catchment exhibited periods of zero flow. The total number of days with zero flow in a year frequently exceeded 45 and in 1991 it reached 80 days. Low flows were compared by calculating the mean for all catchments over the same 7-day period. This was chosen as either the 7 days immediately before flow at control catchment DC2 reached zero or, in the 4 years when DC2 did not reach zero flow, as the 7 consecutive days with the lowest average flow at DC2. The difference between the average 7-day low flow at DC2 and that for both DC1 and DC4 increased from 0-0.01 mm/day in the pre-treatment period (1978 to mid-1980) to 0.3-0.5 mm/day after harvesting (1981-1986). Low flows in the 5 years after harvesting were typically 2-3 times the value expected if the trees had not been harvested.

Scrub clearance

Clearing of tall dense gorse from two small catchments at Moutere, Nelson, one by burning and line dozing and the other by burning and cultivation, resulted in a dramatic increase in the magnitude and persistence of low flows during the three years following burning. During the period when the catchments were in gorse, flows were zero for 50 % of the time, whereas after the gorse was burnt flows persisted in both for over 90% of the time, and for 50% of the time were at least 4 $l/s/km^2$ for the shady aspect catchment and 1.5 $l/s/km^2$ for the sunny aspect catchment. The high-flow portions of the flow duration curves fell much more steeply when the catchments were in gorse than after they were cleared.

For five years when the two catchments were covered in gorse, zero-flow days per year averaged 158, compared to 52 days from pasture (Duncan 1995). In the seven years following gorse clearance and while young pines were growing, those catchments averaged 71 days per year of zero flow compared to 80 days per year from pasture.

Larger catchments

The data from small catchment studies in New Zealand and elsewhere clearly show that afforestation can reduce flood peaks, flood volumes and low flows, while harvesting has the opposite effect. However, the question remains as to whether the resultant changes can be proportionally scaled-up to larger catchments. It appears from results presented for the Tarawera River catchment (25 000 of 90 600 ha planted) that annual water-yield changes caused by afforestation were similar to changes for a nearby small catchment at Purukohukohu (Dons 1986).

But does this proportionality apply to flood peak and low flow changes? In a large forest, for example, only 100 ha may be harvested at any one time, and we do not know to what extent an increase in flood peaks and quickflows accompanying such an operation will be filtered out as the area of the forest increases. However, it is unlikely that harvesting up to 100 ha of forest in the headwaters of a large forest will have much of an impact on peak flows and flood volumes downstream, as the amount of precipitation in the catchment far outweighs any effect of reduced interception loss in small clearfelled areas. In Washington state, USA, for example, Duncan (1986) could not detect any increase in flood peaks from a 232 km^2 catchment which was harvested at an average annual rate of 1.5% (344 ha) of its area over a 30-year period. The lack of change observed in that study may have reflected the distributed nature of the harvesting operations throughout the catchment and the continuing regeneration of the forest.

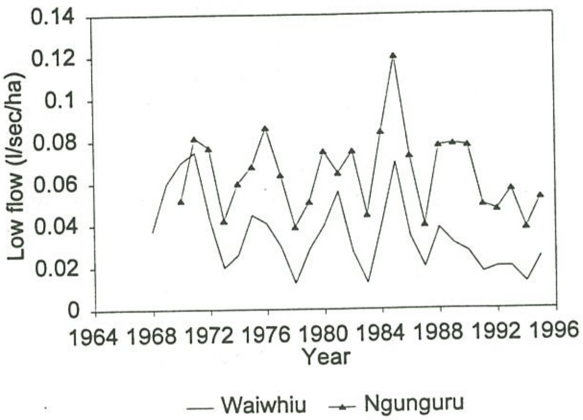

Figure 6.14. Annual minimum 7-day low flows for the Ngunguru (▲) and Waiwhiu (▲) River catchments.

Closer to home, about 47% of the Waiwhiu River catchment near Warkworth in Northland was planted in 1975 and 1977. A comparison can be made with the Ngunguru River catchment, a native forested catchment about 85 km away which has previously been used as a reference catchment (Waugh 1980). While small catchment studies elsewhere suggest that about 7 years after planting annual water yields begin to decrease, results here suggest that about 15 years after planting land use change may be affecting the annual minimum low flow regime during wetter years. However, the reasons for the downward trend are not clear cut as this was a period of lower than normal rainfall. Is the trend a result afforestation, low rainfall or both? That the extreme minima have not changed implies that there could also be a geological control on water being delivered from groundwater stores in dry years (Fig. 6.14) (Rowe and Jackson 1997).

Conclusions

This chapter has considered only land use changes that seem pertinent today, and changes in stream hydrographs show trends similar to overseas work. Changes of land use that are of minor importance today have not been considered. However, some data are available for pasture management in small steep catchments at Makara (Toebes *et al.* 1968; Yates 1971).

While there is evidence that land use can affect floods in small catchments, there are still questions to be answered for the larger catchments, especially with respect to low flows. Methods of presenting data often differ, especially for low flows, and climate and geological factors are difficult to isolate from land use change when data sets are small; many large-catchment studies do not really contribute to a comprehensive understanding of the effects of land use change. Use of methods in the chapters by Ibbitt *et al.* and Pearson and Davies (this volume) could contribute to uniformity of presentation.

There are considerable data held in NIWA, Landcare Research and territorial authority archives that could contribute significantly to our understanding of the magnitude of hydrological change as a consequence of land use change. These data need to be collated, reviewed, re-analysed and reported. All that is needed is adequate funding.

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7
Environmental effects of extreme flows

Ian Jowett

Stream ecosystems

Extreme flows are part of a natural stream ecosystem and many riverine species have evolved to survive floods and droughts. In harsh dry environments, such as Australia, floods and/or droughts may even be essential for the continued survival of a species (e.g. Meffe 1984).

The effects of floods on New Zealand stream biota have usually been reported only for relatively minor events, and there is virtually no information on the effects of droughts or low flows on biota in New Zealand rivers. This chapter will examine the ways in which aquatic species in New Zealand rivers are affected by extreme events, relationships between biological effects and the magnitude of the event, and recovery times.

New Zealand has a temperate and maritime climate with relatively frequent floods and freshes and without the extremes of drought experienced in some continental climates, although eastern regions and central Otago can experience long periods without rain during summer. In biological terms, floods are classed as "disturbances". Resh *et al.* (1988) define a disturbance as "any relatively discrete event in time that disrupts ecosystem, community, or population structure, and that changes resources, availability of substratum, or the physical environment". The term "disturbance" seems particularly appropriate when applied to floods because one of the main effects is the disturbance of the stream bed (Fig. 7.1). A disturbance alters the ecosystem, often providing a stimulus for renewed or different biological activity. Disturbances "reset" the successional clock of the ecosystem without influencing ultimate or long-term composition or abundance (White and Pickett 1985). Biological systems, like many natural systems, are in a constant state of change, and disturbances tend to introduce a stochastic component into community composition and abundance that makes it difficult to predict species abundance and community composition at a given point in time.

Several studies have concluded that disturbances may enhance species diversity, by reducing the dominance of one or a few species and freeing resources for other species and/or by increasing habitat diversity (Denslow 1985). Disturbances may be critical for the survival of some species, but for others, repeated disturbances may have long-lasting effects or lead to the elimination of the species. The intermediate disturbance hypothesis (Connell 1978) suggests that a moderate degree of disturbance will support the greatest species diversity and that streams with a high disturbance regime will be dominated by the most successful colonisers, whereas streams with a low disturbance regime will be dominated by the most competitive taxa. For example, New Zealand gravel-bed rivers that are subject to a high level of bed movement are most successfully colonised by the mayfly species, *Deleatidium* spp. (Sagar 1986), whereas streams with more stable substrate have more diverse insect communities (Death and Winterbourn 1995).

The long-term effects of floods or disturbances on an ecosystem will depend on the frequency, magnitude and duration of the events, as well as the life history strategies of its aquatic species (Resh *et al.* 1988; Biggs 1996a). However, many species have evolved life history strategies to mitigate the effects of floods and droughts. Fish and some benthic invertebrates can avoid the worst effects of floods by moving to sheltered locations, whereas

Figure 7.1. An example of the extreme velocities and turbulence to which biota are subjected in a mountain stream.

plants may be dislodged. Salmonid eggs can survive in moist gravel without water for several weeks. Floods carry the eggs or larvae of diadromous fish out to the sea, where they grow and return to the fresh water environment as juveniles. Some fish can breath through their skin and survive long periods without water providing they are in a moist location (McDowall 1990). New Zealand mudfish, eels, and some whitebait species survive low or zero flow in small streams in this way.

The effect of floods on stream biota is largely a result of the high water velocities and sediment movement during floods that displace or kill aquatic species. The reshaping of a stream that occurs during large floods can alter habitats, creating oxbows and backwaters, and scouring or filling pools. In contrast, biotic changes that occur during extreme droughts are slower and are caused by either biological processes or changes in water quality, with the development of communities favoured by low water velocities, low dissolved oxygen levels and high water temperatures. In extreme cases, communities may be limited to those that can survive periods without flow or even without water. The degree of disturbance varies in a river. Pools have been shown to be the areas of greatest disturbance, with a large increase in velocity (Fig. 7.2) and erosion during floods and deposition during normal flows (Keller 1971; Andrews 1984). Riffles, particularly the upstream slopes or the highest point in their longitudinal profile, tend to be the areas least disturbed by floods, and the increased abundance of stream insects in these locations may be related to this stability (Resh *et al.* 1988).

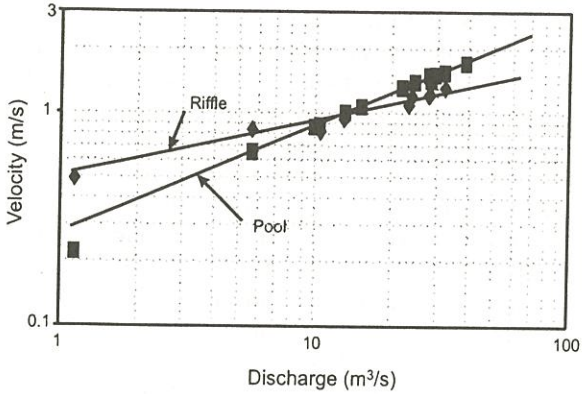

Figure 7.2 Variation of mean velocity with discharge in a pool and riffle (from Andrews 1984)

Streams will usually recover from extreme events, the rate depending on the species involved and the severity of the event (Young and Niemi 1990). For example, the invertebrate population of a tributary of the Grey River that had been mined had returned to normal in less than a year, whereas fish populations had not re-established in that time (Jowett *et al.* 1996). Fish re-colonise streams by migration from up or down stream or from the sea for some (diadromous) species. Insects re-colonise a stream bed by passively drifting into the area from upstream or from eggs laid by flying insects. Plants re-colonise from plant material, such as spores, propagules or root stock, drifting into the reach from upstream or by re-introduction from external sources. The rate of re-colonisation also depends on the availability of colonists that, for primary producers (periphyton) and secondary consumers (macroinvertebrates), largely come from upstream sources. Thus, re-colonisation is slower following a very large flood than a more moderate event because the number of available colonists will vary with flood severity (Biggs 1996a), with the stability and preservation of headwater ecosystems playing an important part in the maintenance of ecosystems further down stream.

Floods

Long-term effects of physical changes

Changes to the instream environment caused by large floods are less obvious than the physical change to the stream banks and margins (Jowett and Richardson 1989). The long term effects of extreme floods are associated with morphological change caused by bed movement and its effect on habitat suitability for biota. Extreme events can also cause profound and long-term changes to the sediment regime, with effects can be both beneficial and detrimental. Floods remove deposits of fine material from interstitial spaces of river gravel, which creates better habitat for juvenile trout, native fish, and benthic invertebrates. Floods can improve instream cover for trout by deepening pools and creating undercut banks (Jowett and Richardson 1989) or destroy cover for galaxiids by washing out instream debris (Fig. 7.3). Large floods can deposit sediment on long grasses in the lower reaches of rivers and estuaries, causing a loss of spawning habitat of inanga, until new grasses are able to grow through the flood sediments. Depending on land use and geology, extreme floods can cause land movements and bank instability that increases base-flow sediment loads to such an extent that they are detrimental to invertebrate production and successful incubation of trout eggs. Such events can also cause long-term changes to the substrate composition, usually increasing the amount of fine gravel and bed mobility and causing a reduction in primary production and habitat quality for benthic fish and invertebrates.

Periphyton

It is obvious from casual observations that floods remove periphyton from rivers. There is little or no accumulation of periphyton (algae attached to substrate) in rivers with frequent floods, and the stones on the beds of rivers with high bedload transport are usually clean and free of the slipperiness that results from a thin layer of periphyton. The accumulation of periphyton biomass is determined by the balance between the processes of accrual and loss (Biggs 1996a). Accrual comprises two stages: colonisation, where

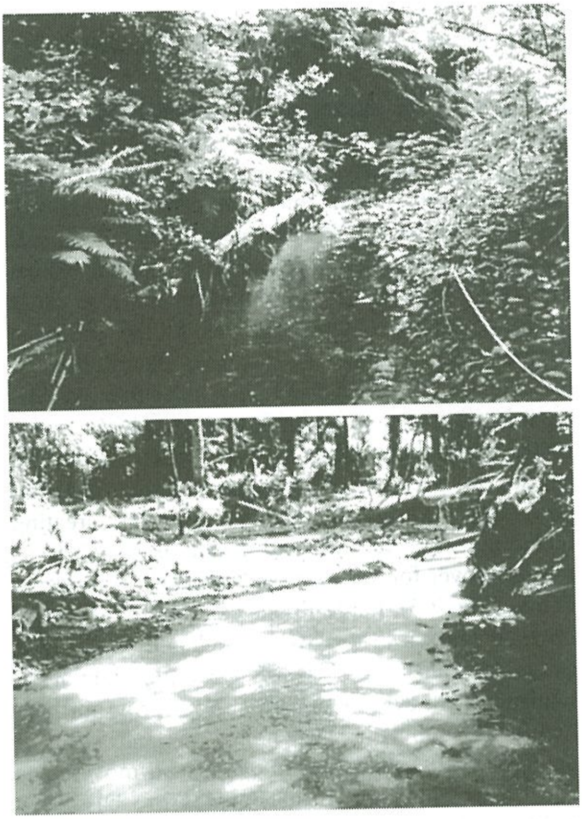

Figure 7.3 Loss of cover as a result of a 20-year flood in a small forested Coromandel stream. Before the flood shown above and after below (photos J. Quinn).

algal spores from upstream are deposited on the substrate, and growth, where the rate of growth is determined by light and nutrient supply. Losses occur most commonly by flood scour and invertebrate grazing. The biomass of periphyton in a stream has been related to both the magnitude of flood in the 60 days prior to sampling (Quinn and Hickey 1990) and the frequency of floods that cause the average cross-section velocity to exceed 1 m/s (Fig. 7.4).

In laboratory tests, Biggs and Thomsen (1995) showed that some periphyton communities were more resistant to sloughing than others. Filamentous algae were the most easily removed, with a 50% loss of biomass when there was a two-fold increase in mean column velocity from 0.4 m/s to 0.8 m/s. Non-filamentous diatom mats required a water velocity of more than 1.8 m/s before there was a 50% loss of biomass. This suggests that streams dominated by filamentous algae (usually moderately nutrient-enriched streams) will be affected more by minor floods than streams dominated by non-filamentous diatoms (usually unenriched streams and/or streams with abundant benthic invertebrate grazers) (Biggs 1996a). However, during large floods in gravel-bed rivers, physical abrasion by sediment movement or the movement of substrate is probably more important than the effect of velocity alone. For example, Jowett and Biggs (1997) found that a 5-fold increase in the flow of the Tongariro River resulted in the total removal of periphyton from artificial substrates (Fig. 7.5), whereas in another river with less sediment movement, there was little change in the amount of periphyton on artificial substrates after a 4-fold increase in flow.

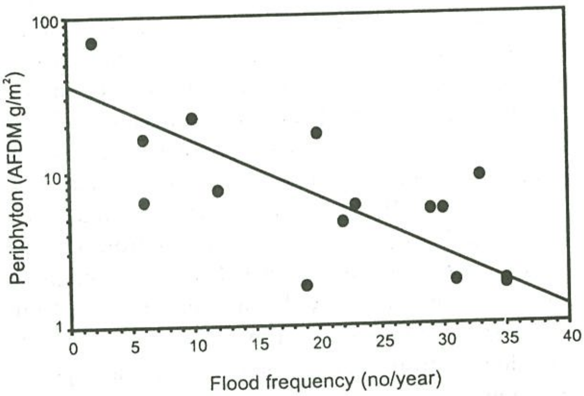

Figure 7.4 Reduction in periphyton biomass with increasing frequency of floods with an average velocity greater than 1 m/s (from Biggs 1995).

Recovery of periphyton communities after floods varies with the availability of propagules (which in turn varies with the severity of the event) and growth rate (Biggs 1996a; Biggs and Stokseth 1996). In some streams recovery can take as little as 14 days, whereas in others it may take up to 100 days (e.g. Stevenson 1990; Biggs and Stokseth 1996).

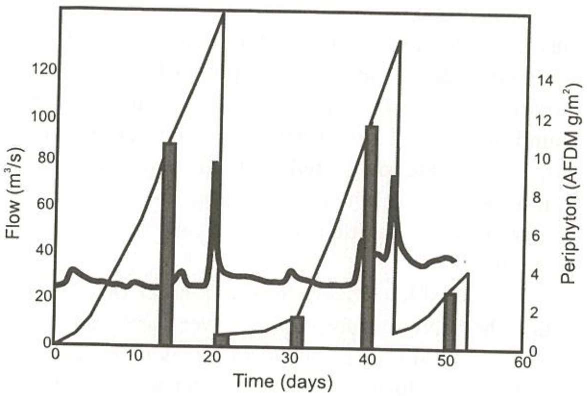

Figure 7.5 Effect of floods on periphyton growth on artificial substrates in the Tongariro River (from Jowett and Biggs 1997).

After a flood of about 30 times the mean flow (454 m^3/s, return period 10 years) in the Ashley River, levels of chlorophyll *a* in periphyton increased from near zero to 0.2 mg/m^2 after 37 days (Scrimgeour *et al*,. 1988). After a small flood (about 4 times the mean flow) in the Tongariro River, levels of chlorophyll *a* at 1, 21, and 40 days following the flood were respectively 0.3, 3.2, and 16.5 mg/m^2, showing the rapid exponential growth of periphyton that is typical of many rivers in early recovery stages (Fig. 7.5).

Macrophytes

Macrophyte beds usually develop in slow flowing areas of rivers with relatively stable flow regimes (Henriques 1987; Biggs 1996b). Macrophytes are affected by floods in a similar manner to periphyton, in that large floods will scour the plant beds from the substrate. Macrophytes are able to resist the effect of minor floods because an increase in velocity causes them to flatten into a zone of low velocity near the bottom and the roots, rhizomes, and other portions of the plant growing within the stream bed tend to stabilise substrate (Henriques 1987). However, if water velocities are sufficiently high or substrate movement sufficiently widespread, macrophytes will be torn from the stream bed, by breaking off plant stems or by undermining of the substrate. Before a flood of 1450 m^3/s in the Kakanui River (300 times the mean flow, 28 year return period) 80% of the river bed was covered by macrophytes (*Elodea canadensis*). After the flood, there was one macrophyte bed intact and some remnant beds (Jowett and Richardson 1989).

Re-colonisation by macrophytes is slow, especially in winter when light levels and water temperatures are low. After a flood, plant beds will gradually develop from remnants of the former beds or from fragments of plant material deposited in low velocity areas of the river.

Invertebrates

Invertebrate abundance and composition are reduced by floods. This may occur because invertebrates are carried away by the current, often in association with periphyton or because of substrate movement which results in invertebrates being dislodged and/or crushed (Scrimgeour and Winterbourn 1989). The amount of substrate that moves during a flood generally increases with flood magnitude and decreases with increasing substrate size, and thus so does the effect on the invertebrate community. Using marked substrates in tributaries of the Taieri River, Scarsbrook (1995) found that a four-fold increase in discharge resulted in the movement of 40% of marked particles in a small stream with an average bed particle size of 32 mm. In another stream with an average bed particle size of 70 mm, he found less than 20% movement for a four-fold increase in discharge. He estimated that 100% of the substrate would be moved by a flood that occurred on average five times a year in the stream with smaller substrate and once a year in the stream with coarser substrate. Average invertebrate abundance in the stream with less frequent substrate disturbances was two to three times higher than in the stream with frequent substrate disturbance. A minor flood (frequency about two-three times a year) had little effect on invertebrate abundance in the frequently disturbed stream, whereas invertebrate abundance was halved in the less frequently disturbed stream. Association of low invertebrate abundance with frequent floods has also been noted in Canterbury Rivers (Sagar 1986; Scrimgeour and Winterbourn 1989).

The intermediate disturbance hypothesis suggests that streams with an intermediate level of disturbance will contain more invertebrate species than either streams with frequent flooding or streams that flood infrequently. This has proven difficult to demonstrate in New Zealand rivers (Death and Winterbourn 1995). Comparisons of taxonomic richness (number of species) between rivers with different flow regimes indicates that taxonomic richness generally declines with increasing flood frequency and with the magnitude of preceding floods, whereas invertebrate abundance tends to be highest with a moderate degree of disturbance depending on the species present (Quinn and Hickey 1990; Clausen and Biggs, in press). Clausen and Biggs (in press) defined moderately disturbed rivers as those with 10-15 floods a year greater than three times the median flow, whereas Quinn and Hickey (1990) defined moderate flooding as a flood of 20-60 times median flow within 60 days prior to sampling. Quinn and Hickey (1990) found that *Deleatidium* spp. and *Psilochorema* spp. (mayfly and caddis larvae respectively) were more abundant in moderately flooded rivers, but that chironomids were most abundant in non-flooded rivers. Townsend *et al.* (in press) compared physical and hydrological measures of disturbance in a group of Taieri River tributaries and found highest species richness associated with moderate substrate disturbance, supporting the intermediate disturbance hypothesis. They concluded that bed movement was a more appropriate measure of disturbance than flow for stream invertebrates. The increase in invertebrate abundance that is associated with moderate disturbance regimes may be a result of an improvement to either habitat or food suitability. Floods improve invertebrate habitat by coarsening the substrate and removing fines (Jowett and Richardson 1989) and alter the food available to them by replacing thick periphyton mats with thin layers on which some benthic invertebrates are able to feed effectively (Rounick and Winterbourn 1983).

Invertebrate populations recover quickly from the effects of floods, with recolonisation either from upstream, from more stable tributaries, from within the gravel substrate (hyporheic zone), or by oviposition by adult insects (Scrimgeour and Winterbourn 1989; Scarsbrook 1995). The hyporheic zone is the transition between the flowing surface water and groundwater. Scarsbrook (1995) sampled stream insects to a depth of 0.45 m in the stream beds of two Taieri River tributaries, and found 30-40% of stream insects in the benthic zone (top 9 cm). He suggested that the hyporheic zone could provide 60-70% of stream insects with a refuge from a flood that disturbed only the top 9 cm of stream bed.

In the Ashley River, Scrimgeour *et al.*, (1988) found that invertebrate numbers were low (230 /m^2) immediately after a flood of 454 m^3/s (30 times the mean flow, return period 10 years) and had more than doubled in three weeks and increased to 7910 /m^2 after 132 days, despite 11 small floods greater than twice the mean flow during that time (Fig. 7.6). Scarsbrook (1995) found that invertebrate densities recovered to near pre-flood levels within three weeks.

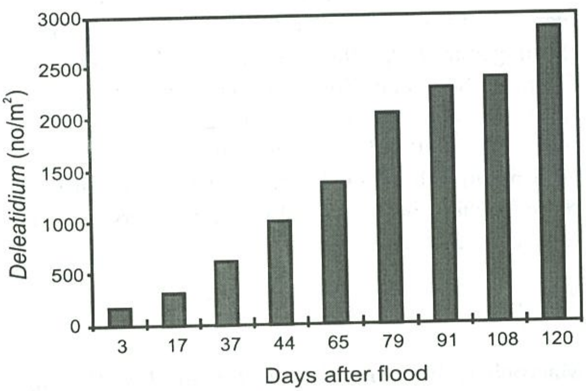

Figure 7.6 Re-colonisation of the Ashley River by *Deleatidium* spp. after a 10 year flood (from Scrimgeour *et al.* 1988).

Trout and salmon

It is generally accepted that floods can reduce trout populations and that the effect on adults is not as severe or as predictable as on juvenile trout (Allen 1951; Jowett and Richardson 1989). During floods, trout can die because of physical injury caused by substrate movement, stranding on river banks or in isolated pools, or by being swept out to sea.

Brown trout survive floods better than rainbow trout, and this may be reflected in the distribution of trout in rivers. Rainbow trout tend to be found in rivers with stable flow regimes or in rivers that are connected to lakes or large low-gradient rivers, whereas brown trout are found in rivers with a wide variety of flow regimes (Jowett 1990). Brown trout use instream cover more than rainbow trout and seem to prefer the types of cover that are least susceptible to movement during floods, such as bedrock and boulders (Jowett 1992). In a study of the effect of a large flood on trout numbers in sections of seven rivers, Jowett and Richardson (1989) found that after the flood rainbow trout were absent in two of three rivers that had previously contained them, whereas brown trout had managed to survive in all seven rivers. In six of the seven rivers, the number of small (10-20 cm) brown trout was reduced by 90-100%, the number of medium (20-40 cm) brown trout by 62-87%, and the number of large (>40 cm) brown trout by 26-57%. The percentage of trout surviving the flood was negatively correlated with river gradient and positively correlated with the amount of instream cover for fish. Although the severity of the flood varied between rivers, with estimated return periods ranging from 20 to 500 years, there was no correlation between the relative severity of the flood and trout survival.

The effect of floods on trout and salmon populations also varies with the time of year. Floods during spawning and/or emergence of alevins (early life stage of salmonid fry) from the gravel can have severe effects on recruitment and eventual adult stocks. Floods greater than 290 m^3/s (c. 60 times mean flow, return period 4 years) between August and November in the Kakanui River caused almost 100% mortality of trout fry, whereas a flood of 816 m^3/s in March had no apparent effect on the survival of juvenile trout (Hayes 1995). Adult trout stocks in the Kakanui River were relatively unaffected by floods of this magnitude, but the increased recruitment from one flood-free spawning season caused a three-fold increase in adult trout numbers three years later (Jowett 1995). Movement of bed substrate can disturb trout redds, washing away eggs or alevins. Observation of marked trout redds in the Tongariro River showed that the effect on redds varied with the magnitude and duration of the flood (Jowett *et al.* 1995). A period of 16 days of flow greater than twice median flow (60 m^3/s), with a peak discharge of 147 m^3/s (5 times median flow), resulted in the total destruction of marked redds. However, the following year, a short duration flood of 400 m^3/s did not disturb marked redds, but a second flood of 700 m^3/s scoured out all redds. The effect of floods on salmon is similar to that on trout in that redds can be destroyed by floods. A study of the salmon run in the Hakataramea River indicated the return of adult salmon was linked to the occurrence of floods during the incubation period of the salmon eggs three years previously (Jowett and Deverall 1983).

Unwin (in press) has related increased survival and hence return of salmon to flows in the Rakaia River. He found that in years of high survival, flows were low and stable during October and November and were followed by a few short, sharp floods that seemed to increase the chance of survival of salmon smolts. Low survival was associated with early floods (August/September) before the salmon were ready for the transition to the sea or with high flows and frequent freshes that provided poor instream habitat.

Trout may move in response to floods. Minor freshes in the Tongariro River tended to encourage upstream movement, particularly early in the spawning season, whereas large floods caused downstream displacement (Jowett *et al.* 1995). Six of seven rainbow trout monitored during a flood of 717 m^3/s (26 times median flow) in the Tongariro River were displaced downstream by an average of 500 m and resumed upstream travel 6-8 days after the flood (Jowett *et al.* 1995).

Trout populations recover from severe floods slowly, taking two or more years of successful spawning and recruitment to re-establish adult populations. The degree of recovery can be influenced by changes to instream habitat caused by floods.

Native fish

There are few observations of the effect of floods on native fish populations, although it seems reasonable to expect that fish numbers are probably reduced by floods. Mortality during floods may be caused by physical injury, stranding, or displacement to areas where they are susceptible to predators. Alibone (1996) monitored non-diadromous galaxiids in seven small Taieri River tributaries and found that a large flood (c. 48 times mean flow) reduced fish densities at some sites but not at others. He related the changes to the degree of disturbance and the life stage of the fish. Young of the year were affected more than adults and fish were less affected at sites with a stable substrate. Native fish can avoid the worst hydraulic forces of a flood and also take advantage of newly created food sources by moving with the river margin as water levels change (Jowett and Richardson 1994). However, native fish can be stranded by recessions, and this may be more likely at night than during the day, as is the case with juvenile salmonids. During flow tests below the control gates on the Monowai River, juvenile common bullies were found stranded by a sharp reduction in flow at night but not after a similar flow change during the day (author's obs.).

Floods may play an important part in the diadromous life cycle of native fish by carrying larval fish to the sea before their eventual return to adult fresh water habitats. Some of the whitebait species (koaro, banded kokopu, shortjawed kokopu, and giant kokopu) probably spawn in the vicinity of their adult habitats by laying eggs on vegetation along stream margins or on instream debris and floods carry larval fish or eggs to the sea (Ots and Eldon 1975; Hopkins 1979; McDowall 1990). Dispersal of the eggs or larvae of torrentfish may occur in a similar manner but less is known about these species than about whitebait (McDowall 1976). Diadromous bullies (common bully, redfinned bully and bluegilled bully) usually attach their eggs to the substrate, and substrate disturbance could destroy egg clusters. Floods may also encourage the whitebait runs that occur between August and November. There is a belief that large whitebait runs occur on the first flood of the spring (McDowall 1984) and that there are large runs on or after floods. However, the relationship between whitebait movement and floods is not clear (McDowall 1968; McDowall and Eldon 1980).

Although there have been no studies of the recovery of native fish populations from the effects of floods, studies of the effects of mining indicate that native fish and trout populations in West Coast streams recover within in a year, whereas invertebrate populations recover within a much shorter time (Eldon *et al.* 1989; Jowett *et al.* 1996).

Birds

A number of bird species feed and nest on the banks of rivers, and large floods can destroy their nests and eggs. Blue ducks and waterfowl use sheltered locations alongside rivers for nesting, and banded dotterel, black stilt, pied stilt, black-fronted tern, black-billed gull, wrybill, black-backed gull, caspian tern, black-fronted dotterel, and pied oyster catcher all nest and feed in wide, open gravel-bed rivers. Blue ducks nest between September and October and floods during this time can destroy nests. Of 61 blue duck nesting attempts in the Manganuiateao River over 10 years, 10% (6) failed because of flooding (Williams 1991). Loss of nests by flooding has also been reported for caspian terns (11% failed because of flooding), pied stilts (54%), and black stilts (14%) (Pierce 1984 1986), but there was no mention of floods contributing to egg loss in 8 years of observation of banded dotterels in the Cass River (Bomford 1988; Pierce 1989). Annual variation in wrybill numbers in the Rakaia River was negatively correlated with the peak discharge during the previous breeding season (10 September to 20 November). There were about 300 one year-old wrybill in years without floods and 100 or less in years when the discharge exceeded 2000 m^3/s (Hughey 1985).

Droughts

Physical effects

The effects of droughts are less well documented than those of floods, possibly because the effects are less severe or occur over a longer time. Although low flow in streams is a topic of great interest to water managers, there are few studies that demonstrate the effect of extended low flows on aquatic communities in New Zealand rivers. A drought is a sustained period of low flow during which water velocities and depths are reduced below those normally experienced. This causes a reduction in the amount of suitable habitat for stream fauna, and its effect on stream biota depends on the amount of habitat remaining and the duration of the event. Droughts can result in streams drying up entirely, with a total loss of the stream ecosystem in that stream or part of the stream. Low velocities associated with droughts can reduce dissolved oxygen, particularly if macrophytes are present, although shade and meteorological conditions have more influence on water temperature than flow. Water quality can deteriorate if flows do not adequately dilute contaminant discharges. The effect of droughts on stream fauna can be exacerbated by land-use changes, floods, sediment yield, and their combined effect on stream morphology. For example, the frequency of pools as low flow habitat is important for some of the galaxiid species, adult eels, and trout. Increased sediment yield and removal of riparian vegetation from small streams reduces the incidence and size of pools, reduces habitat diversity and increases the potential for high water temperatures and algal proliferation (Fig. 7.7).

Figure 7.7 "Nuisance" growths of filamentous algae in a gravel-bed stream (photo. B. Biggs).

Periphyton

Periphyton and organic detritus accumulate during long periods of low flow, and floods remove these accumulations and "reset" the instream environment. During low or stable flows periphyton grows exponentially, with the rate of accrual determined by the amount of periphyton that is lost through invertebrate grazing, death, sloughing, or emigration. The rate of growth is determined by water temperature, light, and nutrients. Nutrients tend to control growth in unshaded streams, whereas light levels can limit growth in heavily shaded streams. Depending upon colonisation processes and water temperature, periphyton communities can build up to peak biomass in as little as two weeks or as long as 70-100 days (Biggs 1996a). Droughts are usually accompanied by the accumulation of periphyton to levels that are unsightly and are generally considered a "nuisance". This nuisance level is considered to be reached when periphyton covers 40% of the stream bed, and/or the biomass reaches 100 mg/m^2 chlorophyll *a* or 40 g/m^2 ash free dry weight (Ministry for the Environment 1992; Biggs 1996a).

Macrophytes

Low flows and their associated low velocities tend to favour the growth and extension of macrophyte beds (Biggs 1996b), although macrophyte beds that are exposed to the air die. The most common native macrophytes are milfoils (e.g. *Myriophyllum triphyllum*), pond weeds (*Potamogeton* spp.) and turf forming species *Glossostigma* sp. (Fig. 7.8). Most native macrophytes are able to survive exposure to air better than exotic macrophytes, because they propagate from seeds which germinate once the area is inundated again (J. S. Clayton, pers. comm.). Exotic macrophytes, such as *Ranunculus* sp. and the oxygen weeds (*Elodea canadensis* and *Egeria densa*), are more common in New Zealand rivers than native macrophytes, re-establish slowly because they propagate from the spread of plant material, either from surviving sources in tributaries or back water areas or by re-introduction from external sources.

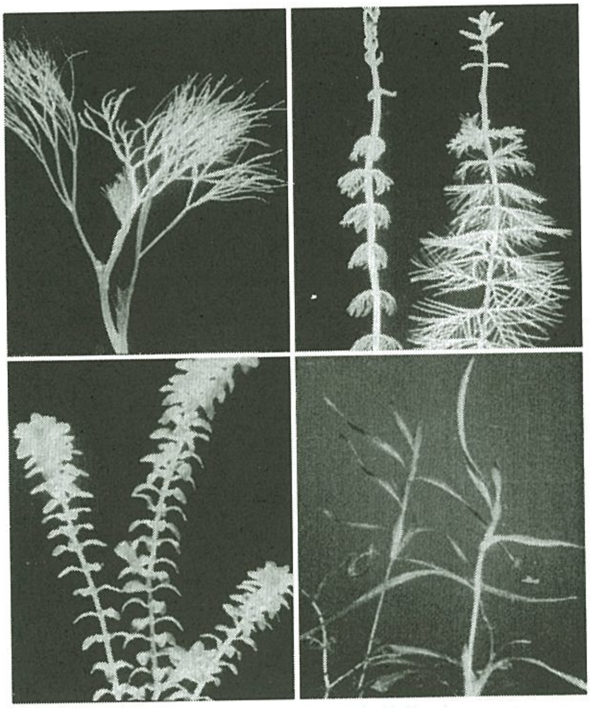

Figure 7.8 Common New Zealand river macrophytes; top left: *Ranunculus* sp., top right: two species of milfoils, bottom left: *Elodea canadensis*, bottom right: *Potamogeton* sp. (photos J. Clayton).

Invertebrates

Most benthic invertebrates prefer relatively high water velocities (Jowett *et al.* 1991), so a reduction in water velocity and stream area during droughts can have a direct impact on the invertebrate community. As a result of habitat change, droughts cause community change from fast-water species that usually live on stone surfaces to species that can live within the bed sediments or algal matrix. The species that survive or dominate during droughts will depend on the duration of the event and stream morphology, but aquatic worms, snails, and chironomids in association with filamentous algae are the low velocity taxa that are most likely to dominate during low flows (Jowett and Duncan 1990; Jowett *et al.* 1991). Collector-browser ("clean water") communities, such as *Deleatidium* spp., are most common in rivers with frequent floods, and communities comprising aquatic worms and snails develop in rivers that have long periods without floods (Jowett and Duncan 1990). However, in the unstable Ashley River, Scrimgeour *et al.*, (1988) found little evidence of a successional shift in invertebrate composition in a 132 day period after a flood. The community in the Ashley River was dominated by *Deleatidium*, *Aoteapsyche*, *Hydrobiosis*, Chironomidae, and Limoninae) for most of the time, although in the last two weeks of the study the proportion of chironomid and Elmidae (riffle beetle) larvae increased.

High water temperatures during droughts may also influence species composition. Snails, riffle beetles, and a few species of caddisfly are particularly resistant to high water temperatures, whereas stoneflies are particularly sensitive and are usually restricted to rivers with summer water temperatures that do not exceed 19°C (Quinn and Hickey 1990; Quinn *et al.* 1994). Temperatures of 24-26°C are lethal to many stream invertebrates, suggesting that thermal stress is widespread among stream insects in many poorly shaded lowland New Zealand rivers during a severe summer drought.

Re-establishment of stream insect communities after a drought appears to be relatively fast, with drift from upstream communities and oviposition by adult insects, although the re-setting mechanism of a flood is important to create the clean substrates usually preferred by fast-water insects. The hyporheic zone may also provide a refuge for stream invertebrates during droughts if sub-surface flow and dissolved oxygen levels are maintained within the gravel stream bed during the drought.

Trout and salmon

The ability of fish communities to survive a low flow that persists for a long time, as in a severe drought, will depend on the suitability of the remaining instream habitat (including water quality) and the availability of food. Low flows, or at least the amount of habitat available at low flows, appear to be a "bottleneck" that can regulate trout stocks (Jowett 1992). During low flows, trout tend to congregate in the pools or backwaters that provide refuge from both predators and high water temperatures. Movement either to upstream areas where water temperatures are lower or downstream to estuaries where more food and deeper water is available may occur, although there have been no studies of movement of trout in response to low flows. Low water velocities can lead to high water temperatures and the combination of low velocity, high periphyton or macrophyte biomass, and high temperature can create low oxygen levels. Of New Zealand fishes, trout are the species least able to tolerate high water temperatures. Lethal temperatures for native fish exceed 30°C (Richardson *et al.* 1994), whereas the lethal temperature for trout is less than 30°C. Trout deaths have been reported in Hawkes Bay rivers when water temperatures reached 28°C and deaths elsewhere when temperatures reached 26°C. Low flows can expose trout and salmon redds (Hardy 1963) and the eggs within the gravel will eventually die, although measurements in salmon redds in the Mathias River showed that eggs can survive in damp gravel for at least three weeks (Hawke 1978).

Native fish

Little is known about the effects of droughts on native fish, although, as with salmonids and invertebrates, it is likely native fish populations would be affected if habitat is degraded during droughts. Native fish are generally small stream species and are probably less affected by droughts than salmonids. Some species have adaptations that allow them to survive out of water. Most galaxiids can breath through their skin and can survive out of water for some months provided they are moist. Banded kokopu can live in the pools of very small streams (< 5 l/s) that would not flow in a drought. These fish feed predominantly on terrestrial insects, so are not necessarily dependent on flowing water and a benthic invertebrate community. Mudfish are an example of an extreme adaption to droughts and can survive months in seasonally dry habitats (Hicks and Barrier 1996). Reproductive strategies also allow fishes to survive droughts, either by laying eggs in stream-side vegetation or among instream debris to be carried to the sea by floods or by spawning frequently over extended periods. The non-diadromous upland bully appears to survive extreme events by spawning frequently (McDowall and Eldon 1997).

Birds

There have been few studies of the effect of drought on river birds. Droughts may favour some river birds, as fish become more susceptible to predation and the area of shallow water for wading birds increases. However, in extreme situations this supply of food may become limited. Williams (1991) noted that there was an accumulation of algae and low benthic invertebrate density in the Manganuiateao River during one dry winter and blue duck ducklings did not survive beyond five weeks. Black-fronted terns and black-billed gulls tend to nest on islands (P. Sagar, pers. comm.) and droughts could make their nests on islands more susceptible to predation, but at other times, the mobility of adult birds would suggest that they are less likely to be affected by droughts than aquatic species.

Summary

Floods and droughts are part of a natural ecosystem and contribute to species diversity and the cyclic or episodic nature of aquatic communities. The effect of floods on biota and the time for the ecosystem to recover depends on the severity of the event, the time of year with respect to the life cycles of the biota, and the amount of physical disturbance. With droughts, the effect is less dependent on the severity of the event and more dependent on stream morphology and the hydraulic conditions during the drought.

Low flows during droughts limit the amount of suitable instream habitat for most aquatic species, and ultimately this will have an effect on the instream populations. If the drought results in zero flow, then most aquatic biota will not survive. However in many New Zealand rivers, water velocities and depths during a drought will be sufficient for biota, even in the most extreme event. Droughts tend to change the aquatic species composition from one that favours swift flowing water to one that favours slow flowing water and high water temperatures if droughts occur in summer. On the other hand, the main effect of floods on stream biota is the physical disruption caused by high water velocities and movement of substrate. Substrate disturbance is a common factor in reducing the abundance of periphyton, macrophytes, benthic invertebrates and fish during floods.

The resilience of aquatic communities is high and recovery of aquatic communities after extreme events is surprisingly fast, unless there have been major changes to the instream environment as a result of increased sediment supply. Recovery will be assisted by the presence of stable tributary streams as a source of periphyton, invertebrates and fish for re-colonisation and the presence of refuges, such as an undisturbed hyporheic zone or stable substrate elements. Periphyton and invertebrate communities can usually re-establish within weeks, whereas fish communities re-establish within one or more years, either from the survivors of extreme events or from new migrants, depending on the species.

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8
Erosion and sedimentation in extreme events

D Murray Hicks and Tim Davies

Introduction

Getting your feet wet during a flood is one thing, but cleaning up the mess afterwards is another. A feature of erosion and sedimentation effects of floods is that they are a large part of the mess that is left after floodwaters recede. These effects can be:

- a scour-hole in the river bed under a bridge pier
- bed aggradation, reducing the clearance under a bridge or the water conveyance capacity of the channel
- thick silt deposits over a floodplain (and through any buildings unfortunate enough to be on the floodplain)
- a road crossed by a gully scoured by a debris flow or covered by a debris flow deposit
- the partial or complete filling of a reservoir with sediment
- damage to river bed habitat through such effects as substrate entrainment, abrasion of streambed vegetation by mobile sediment, and substrate clogging with fine sediment deposits.

For the practising hydrologist, key considerations in dealing with the effects of flood-induced sedimentation and erosion are to (i) define the problem, (ii) locate appropriate methods and information to assess effect magnitudes for individual events, and (iii) consider the long-term, cumulative effects of a sequence of extreme events.

The first challenge is to formulate the key parameters of the erosion/sedimentation problem. For example, is the interest in the total volume of sediment delivered by a particular flood event, the peak suspended sediment concentration during the flood, the depth of sediment deposited on the floodplain, or what?

The second challenge is to obtain adequate quantitative methods and time-series information on these parameters in order to estimate their probability of occurrence. What the hydrologist will find is that, with a few exceptions such as estimating scour depth and sediment trapping in reservoirs, there is not much quantitative design methodology available to estimate the magnitude of sedimentation or erosion parameters for individual events. Indeed, in most textbooks and case-examples, design work for floods involves dealing with the peak water discharge or level, and the sedimentation and erosion issues are either ignored or dealt with using planning rather than engineering methods. For many sedimentation issues, investigations tend to be more geomorphologic in style, producing only qualitative or semi-quantitative results - for example, the likelihood of a debris flow demolishing a bridge.

As well as considering flood effects on an event basis, it is often necessary to consider their long-term effects. For example, we can be interested in the contribution of extreme floods to the long-term average yield of sediment. There we must balance the magnitude of the sediment yield during the flood event against its frequency of occurrence. A complication here is that extreme storms, if they are large enough to exceed a geomorphic 'threshold' in the river basin and create widespread erosion, can initiate a non-stationary sediment yield response - that is, for some years after the threshold is exceeded, the river may carry a higher sediment load for a given water flow.

In this chapter, our aim is to introduce currently available methods for estimating the erosion and sedimentation effects of floods in river channels, illustrating these wherever possible with New Zealand examples. Since many of these effects are specific to discrete morphological settings - within river channels, over alluvial fans, on floodplains, and in reservoirs - we will address each of these in turn. Then we will expand to the basin scale to consider the contribution of floods to the long-term yield of sediment and channel formation. Lastly we will touch on flood sedimentation and erosion impacts on stream ecosystems, a topic detailed in Chapter 7 of this volume.

In-channel erosion and sedimentation

The type and scale of flood-induced erosion and sedimentation problems experienced in rivers, and the approach to follow when assessing them, depends a lot on the geomorphic setting. For rivers that are confined (at least during engineering time-scales) by bedrock in gorges, incision into alluvial fans or floodplains, or artificial stop-banks, the issues centre on (vertical) changes in bed levels and (lateral) shifts in the banks. In unconfined rivers, such as those crossing currently active alluvial fans, there is the additional concern of not just having a river erode its banks but of having the river relocate to another channel altogether. In this section, we address the 'classical' erosion and sedimentation problems experienced in confined channels - those of local to bed-wide vertical aggradation and scour and of lateral channel migration by bank erosion.

Changes in the vertical - scour and aggradation

Aggradation and scour induced by flood flows may be classified as *local* and *general* in scale. Local effects arise from local perturbations to the flow hydraulics, whereas general aggradation or erosion arise from imbalances between the supply of bed material to a reach and the sediment transport capacity through it. Local and general effects can superimpose, for example, around bridges general erosion worsens the effect of local scour around piers (Fig. 8.1).

Local scour is induced by accelerating flows through constricted waterways (such as where the channel is forced to narrow under a bridge) and by turbulence and secondary currents around obstructions (e.g. bridge piers and boulders). Theoretical to semi-empirical approaches for estimating the constriction scour depth expected from a given flood flow and constriction ratio are covered in various hydraulics texts (e.g. Vanoni 1975, p. 58; Raudkivi 1990, p. 243). At bridge piers, the flow diversion around the piers and turbulence from their bow-wave and wake cause a scour-hole. For a given flood flow, the depth of scour depends on the local flow hydraulics, the pier size, shape, and orientation with respect to the flow, the bed material size and size grading, and whether or not the bed is mobile (*clear-water scour* or *live-bed scour*). Also, if the piers are sufficiently close together, then their fields of disturbance overlap and a broader scour area develops with a geometry dependent on the configuration of the pier group. Because of the complexity of processes involved with pier scour, particularly under live-bed conditions, methods for predicting pier scour depth during floods are largely semi-empirical, relying on calibration from laboratory experiments (Vanoni 1975, p. 62; Raudkivi 1990, p. 245).

General aggradation and scour relate to a variety of processes that influence the supply of bed material relative to the bedload transport capacity of the flood flows. At time scales of individual floods, these typically relate to the effect of bedforms. In streams with riffle and pool structures, aggradation or erosion results from variations in the supply of bedload from upstream and by changes in the hydraulic conditions over the riffle-pool structure as the water surface profile alters during a flood (Keller 1971; Andrews 1979). By the same processes, "standing" patterns of erosion and accretion are found where pools are anchored to bedrock outcrops. In braided channels, migrating plane-topped, steep-fronted gravel bars are common. Their height during floods was shown by Fahnestock and Bradley (1973) to match the average flow depth.

Over longer time scales, spanning many floods, factors that influence the sediment supply to the

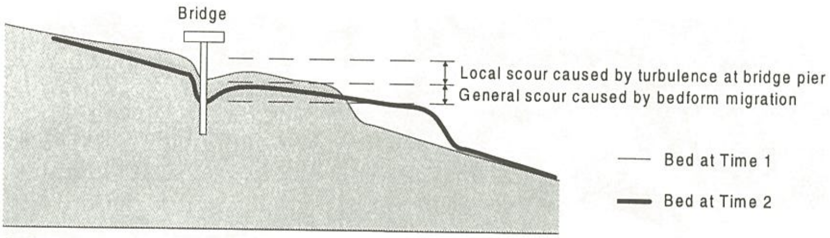

Fig. 8.1. Schematic river profile showing local scour at a bridge pier superimposed on general scour associated with downstream migration of a bed wave.

reach of interest become important, since the net scour or aggradation from sequential floods accumulates. These include larger scale bed "waves"; factors which increase erosion in the basin headwaters, such as landuse activities, extreme rainstorms, and climatic cycles; prolonged in-channel activities such as gravel mining, dredging, and river-training works; or a combination. There are many examples of these long-term effects.

Beschta (1983a and b) and Hoey (1994) used aerial photographs and cross-sections to identify lobate bed waves moving down the Kowhai River, a tributary of the Waimakariri. These waves moved downstream in 'jumps' during floods. Hoey reports the waves as approximately 1-1.5 m high. Beschta (1983b) attributed one of the Kowhai bed waves to a large flood in 1951, although it appears that other bed waves originate from cycles of bed material storage at tributary confluences. These may arise from the cyclical aggradation on tributary stream fans and subsequent erosion of the fans by the Kowhai mainstream; alternatively, these cycles may stem from sediment being temporarily stored in the main Kowhai upstream of the confluence while the tributary's fan aggrades, then being released when the fan erodes back. Whatever the bed wave origin, however, the combination of floods with irregular bed material supplies induces an extremely irregular sequence of bed level changes in space and time.

Griffiths (1979) identified wave forms comprising groups of bars moving down the the lower reaches of the Waimakariri River. He showed also that gravel supplies from bed and bank erosion associated with river training works would be causing chronic aggradation in the reach within 18 km of the coast if it were not kept in check by ongoing gravel extraction.

Aggradation rates in the North Branch of the Ashburton River, on the Canterbury Plains, have been much higher where the once braided channel has been confined between stopbanks. The channel bed in the confined reach is now perched more than two metres above the level of old channels on the abandoned braided bed (Fig. 8.2).

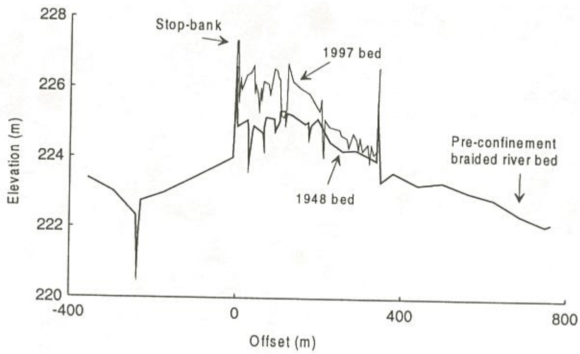

Fig. 8.2. Section across North Branch of Ashburton river near Thompson's Track Bridge. Present river channel is confined between stop-banks and perched above pre-confinement braided river bed. Data: Canterbury Regional Council.

In contrast to these aggrading rivers, the Lower Manawatu River has degraded in recent decades due to the combined effects of aggregate mining and abrasion exceeding the gravel supply from upstream (Hicks and Macky 1993). While the gravel mining may occur reasonably continuously at specific localities, the effect of floods is to spread the deficit across and along the riverbed. This degradation may have a short term benefit in increasing the flood clearance of stopbanks but with time it may lead to

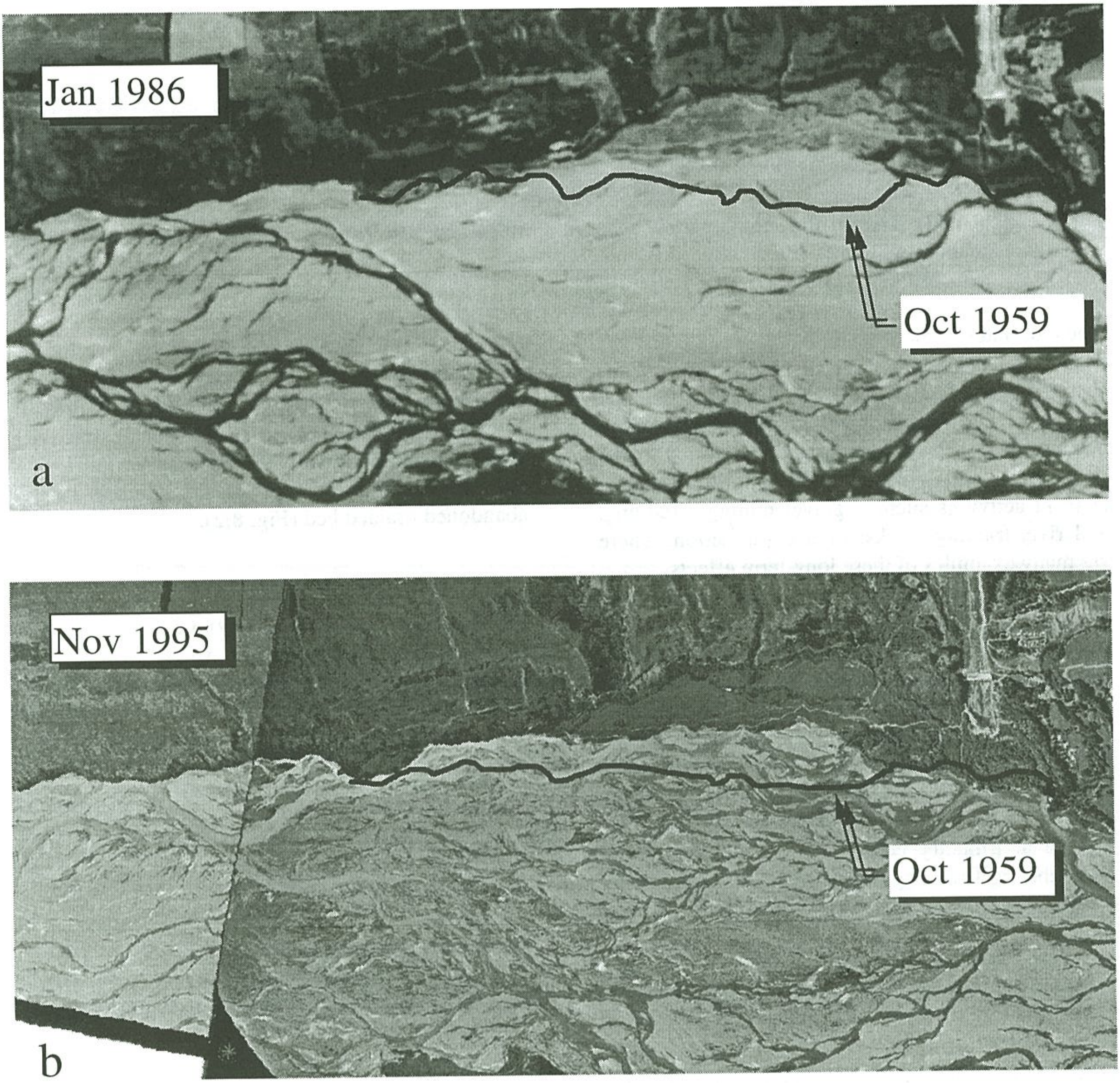

Fig. 8.3. Rakaia River near Coleridge Power Station. In 1986 (a), main braids were located towards southern (bottom) bank. In 1995 (b), main braids had swung back against northern (top) bank. Note erosion of northern bank since 1959.

the undermining of bridge foundations and cause banks to collapse.

With many of these examples, the effect of individual floods is incremental. While no damage may result on a flood-by-flood basis, as time progresses the threshold for major impacts is progressively lowered and the risk of damage increases (as, for example, where stopbank clearance is reduced by aggradation or where bridge pier foundations are exposed by degradation).

Thus when assessing the effects of floods on general aggradation and scour, a longer term

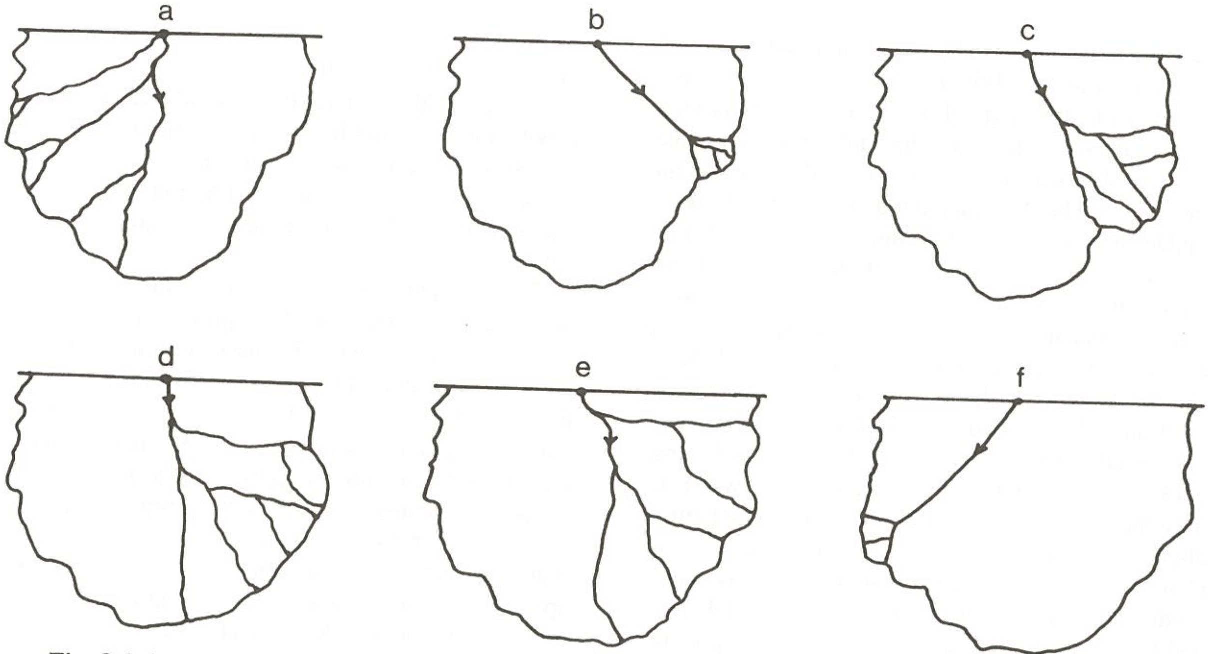

Fig. 8.4. Sequence of channel patterns and positions on alluvial fan model of Zarn and Davies (1994).

perspective should always be included. Cross-section and topographic surveys, aerial photographs, and sediment budget information are all useful for this purpose.

Lateral changes - bank erosion

Flood flows tend to erode river banks, whether they are naturally formed banks or artificial ones designed to fix the river channel to a line. The erosion occurs through two main processes - scour of bank and bank-toe material by currents, and sub-aerial/sub-aqueous weakening and weathering of the bank material (see Thorne 1982, for a review). Combinations of these processes typically induce the most severe erosion.

Direct current scour of the bank depends on the flow hydraulics, the bank slope, and the bank material properties. It typically results in undercutting, which leads to gravity failure of the banks. Scour of the river bed at the base of the bank increases the bank height and slope, which can also lead to gravity collapse. Scour is most common at the outside of bends since this is where the flow tends to be deepest and fastest and where the boundary shear stress is high. Also, secondary currents plunge down the outer bank, continually sweeping eroded material from the bank toe towards the inside of the bend.

The propensity for gravity failure of banks, and the mechanism of failure, depends on the size, geometry, and geotechnical properties of the bank material (particularly whether the material is cohesive, non-cohesive, or composite). These factors also relate to the *in situ* processes that weather and weaken the bank material. These are strongly influenced by its moisture content. In poorly drained banks, pore water pressure reduces the effective strength. This typically occurs during heavy or prolonged rainfall or after rapid falls in water level, as on the recession of a flood. An example can be observed on any sandy beach where a stream incises as the tide drops - the stream banks erode with a characteristic 'plopping' sound. Bank strength is also influenced by its pre-flood soil moisture content and any planes of weakness opened by frost, rain-wash, and incipient failures from previous floods (Richards 1982, p. 164).

The balance between the supply of bank material through mechanical failure and its removal from the bank toe by current scour exerts important control on the profile, stability, and retreat rate of a bank. For example, where the flow is capable of removing all the material fallen from the bank, it will continue to scour the bed, destabilise the bank, and sustain the retreat. On the other hand, where the flow is unable to remove all the accumulated material, this material forms a wedge that buttresses the bank against further failure. Identifying the state of this material balance is a key consideration when designing bank protection strategies (Thorne 1982).

In natural channels, it is often hard to predict the location and severity of potential bank erosion since it depends on the bank material, prior conditions, bank geometry, and local flow hydraulics, which in turn may alter due to upstream shifts in channel alignment and configuration. In meandering channels, the areas of erosion are reasonably predictable, being locked to the outside of bends, and the result after a sequence of floods is a gradual evolution of local bend geometry and/or lateral migration of the bend.

In contrast, in braided or semi-braided channels, the stretches of bank under attack depend on the configuration and alignment of channels upstream, which may vary in a chaotic fashion over periods spanning from one flood to years, with only a weak correlation with flood magnitude. For example, in the braided Rakaia River upstream of the Rakaia Gorge, bank erosion by flood flows tends to be episodic in space and time. This is in response to the main thread of channels swinging from one side of the kilometre wide river bed to the other over a period of ten years or so (Fig. 8.3). The severity of a bank erosion event may depend more on the flow in the braid that impinges against the bank than on the total flood flow.

When managing bank erosion problems, key prerequisites are to thoroughly understand the rates, mechanisms, and underlying causes of the erosion. For example, bank protection works may prove ineffective in the long-term if the underlying cause is channel degradation associated with a reduced sediment supply.

Identifying historical erosion rates and patterns is necessary to scope the erosion hazard. The main data sources for identifying historical bank erosion rates and trends, and identifying the effects of individual floods, are vertical aerial photographs, cross-section surveys, and field inspection. The more comprehensive the time-series gleaned from these sources the better, since a bank erosion trend may be localised and intermittent. A field inspection is essential for identifying the key erosion processes, assessing spatial variation of erosion magnitudes, and relating this to the channel configuration.

Management strategies can either adopt a planning approach (e.g. by limiting development within an erosion hazard zone) or aim to fix the bank position to a line. When the situation calls for the bank to be stabilised, there are a number of engineering options designed to strengthen the bank and/or reduce the erosive power of the flow. These include armouring with rock riprap, gabians, revetments, transverse fences and groynes, tree planting, channel realignment, and combination approaches (e.g. Acheson 1968; Vanoni 1975, p. 525-546; Richards 1982, p. 164; Clarke and Daniel 1986; Evans 1986; Smith 1986). Bank erosion also needs to be considered when designing stopbanks whose prime function is to contain flood flows within a floodway. Many stopbank failures occur by breaching from scour rather than by overtopping, thus the stopbank face needs to be armoured appropriately and the toe needs to be protected from undercutting.

Alluvial fans

Processes, variability, and conceptual models

Many of the rivers of New Zealand's South Island flow on alluvial fans. These are depositional landforms, built up over many thousands of years by the river itself as it leaves the confined valleys of the mountains and flows onto the broad lower-gradient plains. During floods, alluvial fan channels tend to exhibit extremely dynamic, varied, and often hazardous sedimentation and erosion processes - rapid aggradation, active erosion of cohesionless banks, and channels that may suddenly switch location.

This behaviour stems from the combined effects of reduced slope and confinement as the river leaves its mountain valley. The reduction of slope reduces the bedload transport capacity, so it deposits some of its load on its bed causing aggradation; being less confined, flood flows are then more able to spread onto the surrounding land, further reducing the in-channel bedload capacity and increasing aggradation further. In time the bed aggradation becomes so great that the river is liable to avulse (break out of its existing channel and occupy a completely different channel) to a different position on the fan. It then continues to build up the fan surface by aggrading its new bed, and this process repeats itself over and over again, resulting in the classical fan shape.

With some fans, the river is entrenched below the general fan surface at the fanhead (where the river leaves the mountain valley); this seems to reflect both processes that occur further down the fan and the interplay of sediment supply and transport capacity, which over the geological history of the fan can be affected by climate change, tectonism, and changes in base-level (Schumm 1977). On the west coast of the South Island, few if any fans have fanhead trenches, while on the east coast many do (e.g. Rakaia), perhaps reflecting the greater erosional activity and lower sediment storage opportunity of the former and reduced sediment supply in postglacial times in the latter.

The general uniformity of fan surfaces suggests that the river must visit all positions on the fan (and deposit sediment there) rather regularly, in a long-term sense. In other words, nowhere on an alluvial fan is safe from inundation by the river in the long term, but the suggested regularity of river migration over the fan surface might allow areas of high immediate risk to be identified. Historical shifts can be assessed from a combination of field inspection, aerial photographs, and anecdotal information. To do this with confidence, however, requires some knowledge of the variability that will undoubtedly exist within the long-term regularity of river movement; this is difficult to acquire in the field due to the long time-scale of large fan development and to the aerially extensive monitoring needed. Laboratory studies of the development of small-scale fans, however, allow the basic characteristics of evolving fans to be recorded under controlled (if idealised and simplified) conditions, and such experiments have been popular in the past (eg Hooke 1967; Hooke and Rohrer 1979; Schumm *et al.* 1987). Recently Zarn and Davies (1994) carried out a series of such tests in order to investigate flood risk distribution on a laboratory fan, and reported a consistent sequence of events that seems likely to underlie the behaviour of rivers on alluvial fans in the field.

The sequence is that illustrated in Figs 8.4a-8.4g. In Fig. 8.4a, the stream is flowing in a number of channels spread over the left half of the fan, having been building this region up over some time; in Fig. 8.4b, the stream has avulsed due to aggradation at the fan-head, and now flows down the steeper right half of the fan. Because of the steeper gradient, the stream has higher bedload transport capacity in its new course, and is able to incise itself into the fan surface, degrading the channel bed temporarily; this gives it a high sediment load farther downstream, causing a small aggrading subfan to develop at the edge of the main fan. Over time (Figs 8.4c-8.4e) this subfan builds headward, until (Fig. 8.4f) aggradation is occurring at the fanhead; the stream is then unstable at the fanhead and avulsion is again likely to occur with the stream establishing a new course on the now steeper left half of the fan (Fig. 8.4g). The entire process then repeats itself, and the fan increases in size by alternate building of the right and left halves. These patterns of behaviour are similar to those noted by Schumm *et al.* (1987) on laboratory alluvial fans.

Such models simplify the prototype alluvial fans, which experience unsteady sediment and water inputs, occasional debris flows (on small steep fans), the effects of streamside vegetation, the effect of longer term climate change, and in some cases tectonic influences. Nonetheless there have been attempts to apply these model concepts. Thompson (1991) and Davies (1997b), for example, applied fan model concepts to the Waiho fan on the South Island west coast in order to understand its behaviour and to develop a long-term management strategy for this rapidly-aggrading river.

Perhaps the key point to appreciate with alluvial fans is that predicting the deposition and erosion impacts of floods requires an understanding of the whole fan behaviour, and its stage of evolution. The management of rivers on alluvial fans must therefore be based on knowledge both of the river processes and of the current and future behaviour of the fan itself.

A good example is provided by the Waimakariri River, north of Christchurch (Griffiths 1979; Blakely and Mosley 1987). The Waimakariri emerges from entrenchment within a Pleistocene fan some 30 km from the coast, and from that point it crosses an alluvial fan of recent construction. Prior to any river control work, Waimakariri channels diverged across this fan, reaching the coast both north and south of Banks Peninsula, some passing through the present area of Christchurch. At that stage, deposition was focussed on the higher part of the fan but was spread over a broad area. To control flooding, the river has been confined by stopbanks and now crosses its fan in a single wide braided channel. This confinement increased the stream power per unit area and sediment transport capacity on the upper fan, increasing the sediment supply from the bed and banks there, and led to increased sedimentation further down the fan. The locus of fan building was shifted downstream, reducing the flood conveyance across the lower fan. Gravel now has to be extracted at some 150,000 m^3/yr to limit this aggradation and further loss of flood capacity. Thus, keeping a river to a permanent but inherently unstable position on an alluvial fan can require considerable effort and expense.

Debris flows

Smaller, steep alluvial fans (surface gradients greater than about 7°) can be susceptible to the occasional occurrence of debris flows (Costa 1984; Davies *et al.* 1992).

Typically, debris flows arise in small, steep catchments underlain by highly shattered rock. In such places, intense rainstorms are not only able to cause high streamflows but they can also cause severe hillslope erosion, together resulting in delivery of very large quantities of sediment to the stream. With very high sediment concentrations (several hundred thousand parts per million), particularly of fine material, flow turbulence is severely damped and the flow properties and behaviour change markedly. Coarse sediment is no longer dragged along at the bottom of the flow as bedload, but is dispersed throughout the whole depth of the flow. In so doing, it increases the mean density of the flow, and thus increases the erosion stress on the bed, allowing more coarse material to be eroded from the bed and become dispersed through the flow.

It is easy to see that a stream flowing in this way will be capable of eroding its bed very deeply and of carrying huge quantities of sediment. The resulting debris flow is a spectacular sight, though rarely seen - it has the appearance of wet concrete moving rapidly down the stream in a series of surge waves, carrying the largest available boulders with it as it roars along faster than the water that precedes it (Fig. 8.5).

Fig. 8.5. Debris flow in trench across alluvial fan, Mt. Thomas, North Canterbury. Note figure on far bank for scale. Photo: M.P. Mosley.

Certain New Zealand catchments have a reputation for generating debris flows, examples are Mt. Thomas in Canterbury (Mosley 1980; Pierson

1981), several streams along the Kaikoura Coast, and the Tarndale Slip at East Cape (Derose *et al.* 1997). Debris flows can probably take place in most catchments that are steep, easily eroded and liable to experience intense rain or snowmelt; however, they occur very infrequently in a given catchment, and so are difficult to study in the field. Correspondingly, it is also very difficult, if not impossible, to predict their occurrence and size. It is, however, possible to determine whether a given catchment will yield debris flows by examining the morphology of its channel, banks, and alluvial fan. The fan surface normally exhibits an uneven appearance with lobate downfan ridges where old debris flow deposits remain.

Debris flows are very much more destructive than water floods because they can flow much faster (up to 7 m/s), carry large boulders several metres in diameter, and move in distinct surges rather than steadily. That their surface velocity is greater than that at the bed causes large boulders to accumulate at the front of the surge, forming a 'battering ram'.

The immediate flood risk on fans from debris flows extends potentially over the whole fan area. This is because a debris flow surge that halts in a fanhead trench can block the trench and force succeeding flows to avulse out of the entrenched reach. It is therefore important to identify this situation when assessing flood risk on an alluvial fan. As an example, the Black Birch fan at Mt Cook village, South Island, was for many years considered a debris flow risk (Whitehouse and McSaveney 1990) until a more searching assessment (McSaveney, Davies and Gough 1996) concluded that the fan was not steep enough for debris flows to move down it, nor was there sedimentary evidence of previous flows on the fan surface.

Buildings exposed to debris flows on alluvial fans are a very serious danger to occupants, due to the extreme flow depth in a debris flow surge and to the large boulders and tree trunks typically carried at the front of surges. The rarity of debris flows also means that the possibility of their occurrence is often neglected; if one does occur, normal flood protection measures are likely to be ineffective, as are flood warning and evacuation measures. The hazard assessment of Mt. Cook village mentioned above, while considering that Black Birch fan was unlikely to carry debris flows, pointed out for the first time the potential debris flow danger on the smaller, steeper Glencoe fan, on which is sited the Hermitage Hotel.

The most often observed effect of debris flows, however, is on roads. In hill country, roads frequently cross streams draining small, steep catchments through culverts beneath the road. The size of such culverts is such that they will be able to pass the water flow generated by a design rainstorm, and normally they work very well. If a debris flow should occur, however, the maximum discharge rate will be very much higher than would occur with normal storm water because the flow is bulked by the high concentration of sediment and because the flow occurs in surges. Under these conditions, it is very likely that the culvert will be incapable of coping with the debris flow and will become blocked. The flow will then pass over the road, eroding it and rendering it impassable. Many of the road 'washouts' experienced in major rainstorms in the Southern Alps (for example, the widspread damage to the Haast highway in 1994 - McSaveney 1995) are of this nature. If a catchment is suspected of generating debris flows it will need a much larger culvert or bridge than one that does not.

It is very difficult to design measures to protect assets from debris flows (Davies 1997a). In Europe and Japan, huge sums are spent on check-dams - cross-stream structures intended to prevent stream bed erosion and discourage debris flow formation. In those regions, however, due to the population density, there is little prospect of relocating assets and disasters are not uncommon when debris flows occur - in spite of countermeasures (for example the damage due to the 1987 storms in Switzerland). In New Zealand, relocation is almost always a technical possibility and should be considered when a debris flow is identified as being a possible hazard to life.

In America, debris basins are used to protect dense urban development from debris flows (Johnson *et al.* 1991). Where space is available and the asset warrants the investment, this is an effective strategy. The key design and operational principles are that the basin should be large enough to contain all the material delivered by a debris flow and that it should be emptied after events.

Debris flows in forested catchments are complicated by the presence of logs in the stream channel. If the logs are long enough compared to the width of the channel, log jams can occur forming temporary dams during intense storms; these jams will fail, either soon due to the pressure of water backed up behind them or eventually due to the rotting of the logs. When this occurs, a 'dam-break flood wave' (or 'flash flood') may surge rapidly downstream, again eroding large quantities of sediment and possibly transforming into a debris flow. Such an event took place at Blandswood, Peel Forest, South Canterbury in January 1975 when an intense summer thunder-storm dumped 200 mm of rain on a steep, partly forested 4 km^2 catchment in 90 minutes. The resulting surges were about 3.5 m high, carrying boulders and dead trees, and roared down the previously idyllic forest stream and through the holiday settlement, carrying away a bach and drowning four children. Subsequent investigation revealed that events like this had occurred in this catchment previously (Hall 1992). These events illustrate the main danger of debris flows and other flash floods - they occur so infrequently that the intense danger they pose is often forgotten.

Debris flow management, then, is less a matter of managing the debris flow than of managing the behaviour of the people exposed to its occurrence. The rarity of debris flows at a given location means that it is relatively easy to ignore the threat they pose, particularly as they are extremely difficult to control. World wide, however, debris flows are becoming recognised as a significant hazard and an intense research effort is being devoted to solving the problems of dynamics and prediction posed by the phenomenon. Because of its low population density, New Zealand is less intensely affected by debris flows than other mountainous countries. Nonetheless, the threats to life, communications and assets posed by debris flows in this country are real and need to be considered by the authorities responsible for public safety and land use planning.

Floodplains

Typically in the lower reaches of a river valley, as the valley widens, the main river channel is contained within a wider floodplain. The floodplain is built of both in-channel deposits and overbank deposits. In-channel deposits typically accumulate laterally on point bars as bends migrate. They accumulate at all flood flows, including those lower than the bankfull flow, and they account for the bulk of floodplain sedimentary sequences (Richards 1982, p. 141). Being within the channel banks, however, these deposits are usually less of a problem than the overbank deposits that accumulate vertically. Overbank deposits may be levees, splays, or floodplain deposits.

Levees are built naturally on channel banks from coarse suspended sediment deposited from overbank flood-flows. This deposition occurs because of the sharp discontinuity in the sediment transport capacity between the channel and floodplain. Natural levees are rarely noticeable on New Zealand river banks, as most (where present) have been superseded by higher artificial stopbanks. Splays occur where levees and stopbanks are breached locally by flood flows. They are lobate in form, often gravelly, since they are composed of the eroded bank material or sometimes even bedload if the breach is cut deeply enough into the channel, and they thin and fine away from the breach. While the depth of individual splays may be of the order of one metre near the breach, their lateral extent is relatively localised.

The term 'floodplain deposit' refers to the blanket of fine sediment deposited from overbank flows. This fine material falls from suspension due to the lower velocities and reduced turbulence in the generally shallow, often ponded flows over the floodplain. The sedimentation thickness is of prime concern. While a thin flood deposit, up to a few cm deep, is generally welcomed, at least on rural floodplains (since it often adds fertility to the topsoil), thicker deposits are not – they bury and damage pasture and crops, foul buildings and streets, clog drains, and the cost of the damage and clean-up quickly mounts (Vanoni 1975, p. 614). Deposit thickness varies considerably from flood to flood and spatially, depending on the concentration and size grading of the suspended sediment, the duration of overbank flow, distance from the main channel, and the depth and velocity of water, which in turn depend on the flood discharge, floodplain topography, and vegetation type and patchiness.

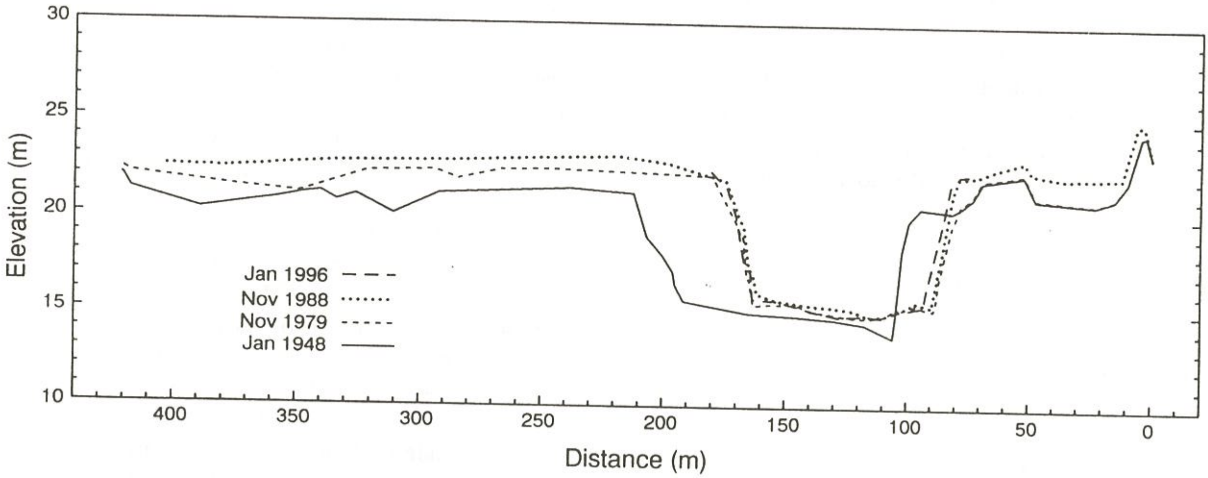

Fig. 8.6. Floodplain and point-bar accretion at McPhail's Bend, Waipaoa River. Source: B. Gomez.

Sometimes, floodplain deposition rates reduce as flood flows get larger, owing to the increased competency of the flows across the floodplain. Gomez *et al.* (1997) studied floodplain stratigraphy at McPhail's Bend on the Waipaoa River at East Cape, North Island. They found that the rate of vertical accretion during the record flood associated with Cyclone Bola in March 1988 (6 mm/hour) was less than for smaller floods (typically 14-18 mm/hour). Unlike the silty deposits of the smaller floods, however, the Bola deposit was gravelly sand, indicating that it had been transported over the floodplain as bedload rather than in suspension. Estimates of velocities over the floodplain during the Bola flood confirmed that silt should have remained in suspension except for a short period on the flood recession.

Predicting floodplain sedimentation depths then, in terms of a magnitude-frequency type analysis, is not a straight-forward matter; indeed, it is rarely given the same consideration as analysis of the actual water depths over the floodplain. Nonetheless, two approaches are available for estimating depth of floodplain deposits: floodplain surveys and numerical modelling.

Floodplain surveys may deal only with the deposits from a single recent flood, or, by coring into the floodplain, they may yield a history of sedimentation depths. With post flood surveys, aerial photographs (taken during or soon after the flood) can be used to map the margins of the flood deposit, and depths can be probed along ground traverses while the deposit remains easily distinguishable from the underlying soil and/or vegetation. Levels across transects may also be used where baseline data exist. Recommendations on transect spacings are given in Vanoni (1975, p. 385). With deeper surveys, cores are taken or bore-holes are logged along similarly-spaced levelled transects. The core stratigraphy is analysed to identify and size horizons of past flood deposits and to date them. Dating techniques include radio-carbon analysis of wood fragments, Cs^{137}, 'finger-printing' tephra horizons, and pollen analysis (e.g. Page *et al.* 1994). When interpreting core stratigraphy, it is important to have adequate spatial coverage of the cores over the floodplain. It is also important that the depositional environment is appreciated and that the historical and ideally pre-historical location of the channel is known. This is to avoid confusing true floodplain deposits with point-bar deposits or the fills of abandoned channels, which may be many metres thick. Floodplain surveys and coring have shown that the floodplain of the Waipaoa River at McPhail's Bend accreted by over two m from 1948-1995, at an average rate of 43 mm/year (Fig. 8.6; Gomez *et al.* 1997).

Numerical modelling of floodplain sedimentation, calibrated with floodplain survey results, probably offers the best means of predicting sedimentation depths, although this is limited to time scales within which the channel form and position remain stable. Nicholas and Walling (1997) described such an application for the River Culm in Devon. They used a simplified numerical model for predicting flow depths and velocities within a finite difference grid, coupled the hydraulic output to models that predict sediment transport and dispersion, and combined these in a mass balance relation to predict deposition over the grid. The required boundary conditions included: water discharge, water level, and suspended sediment concentration and size distribution at the upstream boundary; floodplain topography; and initial estimates of hydraulic roughness coefficients.

Calibration of the hydraulic part of the model to measured water levels was achieved by adjusting roughness coefficients. The sedimentation depths were calibrated against field measurements (sediment traps on the floodplain) by adjusting an empirical coefficient that controlled the proportion of sediment in suspension that was deposited. When run over a flood, the model output was a map predicting the maximum flow depth and total deposit thickness. When run over years of flow and sediment load data, spanning many floods, mean annual deposition rates were able to be mapped.

Limitations of the numerical approach lie in the simplifying assumptions and approximations required to produce a tractable solution to the complex 2-dimensional exchanges of mass and momentum across the flood plain, particularly between the main channel and overbank areas. Model resolution is limited by the detail to which the floodplain topography and roughness are represented (Bates *et al.* 1992). Nicholas and Walling (1997) noted also the importance of using the actual, *in situ* size distribution of the sediment, which includes composite particles, rather than the size distribution after the particles have been artificially disaggregated. Artificial disaggregation, unfortunately, is often the standard preparation for a laboratory analysis of particle size.

Over decades and longer, the magnitude-frequency distribution of floodplain deposition events may change as a result of changes in climate, catchment hydrologic regime and sediment load, and channel form. The latter three changes may follow a landuse conversion. For example, on the Waipaoa floodplain near Gisborne, the frequency of overbank flooding apparently increased in the early part of this century as the bed aggraded and the channel conveyance was reduced. The aggradation resulted from increased erosion in the catchment headwaters as they were converted from forest to pasture from the late 1800's (Gomez *et al.* 1997; Trustrum *et al.* 1997).

Additionally, the frequency of overbank flooding may decline simply because the floodplain aggrades beyond reach of all but the largest flood flows. Stopbank construction can change both the magnitude and frequency of floodplain deposition. Obviously, the frequency of flooding is reduced, but the magnitude of deposition may be increased if the flood-control scheme is designed to pond floodwaters or decreased if the floodwaters are to be channelled.

Reservoirs

Sedimentation is a common problem in reservoir management; moreover, by trapping sediment, reservoirs can induce degradation in the channel downstream. While all reservoirs trap sediment introduced by flood inflows, the nature of the sedimentation problem depends on the reservoir size with respect to the catchment size. With relatively large reservoirs, the main concern is the accumulated deposition over long time periods, spanning decades and many floods, and the problem is to predict the average annual deposition rate and hence the storage life. In contrast, small reservoirs may be filled with sediment during a single flood, and so the prime concern is to know the likelihood that the reservoir will fill in a short period - say one year.

Large reservoirs and the long-term sediment yield

A sediment budget approach is used to predict the long-term deposition in a large reservoir, which may collect sediment from many tributaries. The deposition can be measured directly, by surveying the reservoir bathymetry periodically, or it can be estimated from the sediment inflows assuming a trap efficiency. Ideally, a combined approach is best so that the trap efficiency can be verified.

Typically in New Zealand, the suspended sediment inputs to reservoirs from tributaries are estimated by combining suspended sediment 'rating curves' (concentration versus water discharge relationships) with flow records. Bedload inputs are usually either estimated by bedload formulae or as a percentage of the suspended load (Hicks and Griffiths 1992). The bedload and coarser fractions of the suspended load deposit on a delta in the upper reaches of the reservoir, and, where the reservoir is narrow, this deposition can reduce the flood carrying capacity of the river channel upstream, increasing the risk of flooding.

The sediment trap efficiency depends on the reservoir volume and geometry, the sediment particle size, and the flow conditions. The trap efficiency may reduce considerably during extreme floods when the reservoir behaves more like a river. Lajczak (1966) presents a general model that distinguishes two phases of reservoir filling: the first phase during which the deeper part of the reservoir silts-up and the trap efficiency gradually reduces, and the second phase marked by much reduced deposition rates and zero suspended sediment deposition.

Various empirical to semi-theoretical methods that use 'bulk' or average properties of the system are available for estimating the average trap efficiency (Vanoni 1975, p. 590; Heineman 1984). However, the best approach is to use a numerical hydrodynamic model coupled with a sediment transport and deposition module that, ideally, deals with all size grades of the inflowing sediment. The output of these models includes not only a time series of the trap efficiency but the spatial distribution of deposition along the reservoir. One-, two-, and three-dimensional models are now available. One-dimensional (1-D) models are suited to narrow, 'drowned-river-valley' shaped reservoirs. The MIKE 11 modelling system (DHI 1993) is commonly used for this purpose in New Zealand. The MIDAS model (Van Niekerk *et al.* 1992; Vogel *et al.* 1992) is an alternative 1-D model. FLOODSIM (Bechteler and Nujia 1996) is an example of a 2-D model, while SSIIM (Olsen 1994) has 3-D capabilities.

The hydro-electric reservoirs on the upper Clutha River (Fig. 8.7) have been well studied. Roxburgh Dam was commissioned in 1956, with an initial storage volume of 1.17×10^8 m^3. Subsequent surveys showed rapid infilling with sediment, averaging 1.46×10^6 m^3/year between 1961 and 1979 (Jowett and Hicks 1981). A two year period of monitoring daily the suspended sediment inflows from the main tributaries and the outflows at Roxburgh Dam traced the main sediment source to the Shotover River and showed an average trap efficiency of Lake Roxburgh of 80% (Jowett and Hicks 1981). This monitoring, together with bed surveys of Lake Roxburgh, allowed a sediment budget to be constructed for the 20-year return-period flood of 13-16 October 1978. Over these four days, while the average trap efficiency of Lake Roxburgh reduced to 53%, the suspended sediment input to Lake Roxburgh almost equaled the annual average input. The surveyed deposition in the lake over the period July 1978 to February 1979 was almost twice the annual average deposition.

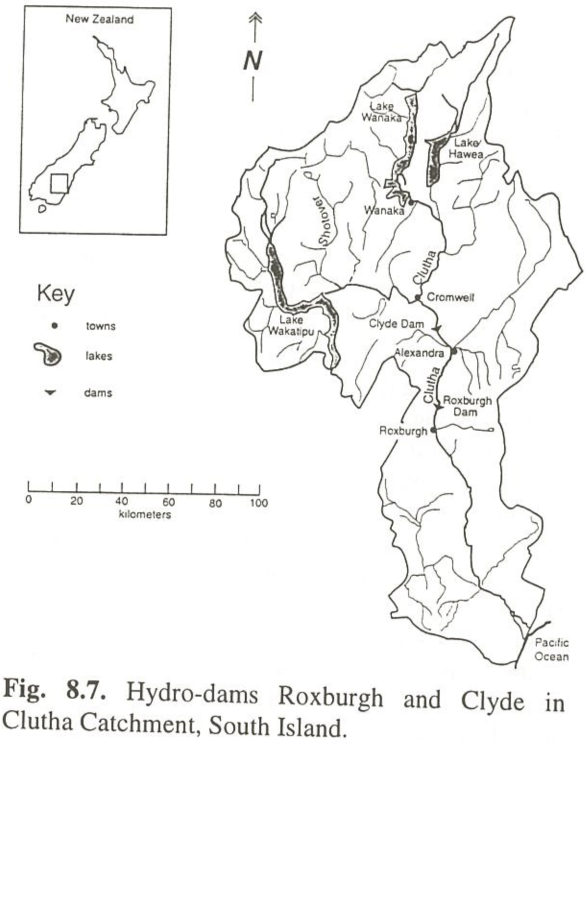

Fig. 8.7. Hydro-dams Roxburgh and Clyde in Clutha Catchment, South Island.

The infilling of Lake Roxburgh has since been stemmed by the construction of the Clyde Dam and the formation of the much larger Lake Dunstan (4.3 x 10^8 m^3), which has a storage life of approximately 200 years and an average trap efficiency estimated at 95-98%. An additional benefit of the Clyde Dam is that its outflows during floods have excess sediment transport capacity. Thus there is the potential for sediment to be transferred from the delta at the upper end of Lake Roxburgh into deeper storage. The dam operators have attempted to assist this sediment redistribution process by controlling the water surface slope through Lake Roxburgh during floods.

Jowett (1984) reviewed sedimentation in other hydro-electric reservoirs around New Zealand, noting that it has not generally constituted a major problem because most dams have been located on rivers where a large proportion of the sediment has been trapped by natural lakes upstream. This situation may well change in the future as more rivers without upstream lakes are developed.

Small reservoirs and event sediment yields

From the sedimentation perspective, a small reservoir is defined here as one where its storage volume is similar to or less than its annual average inflow of sediment. Depending on their size, sediment supply, and the occurrence of storms, small reservoirs may fill over years or overnight, during a single event. Once filled, they need to be cleared either by hydraulic flushing or by machinery. Knowledge of the magnitude-frequency distribution of *event* sediment yields is therefore important, both in the initial design of the reservoir and in estimating the cost of its maintenance.

Determining a magnitude-frequency relationship for event sediment yields at a site ideally requires continuously monitoring stream sediment loads or reservoir deposition for a period of years. In some rivers in some countries, for example, the United States and China, daily records of stream sediment load are available. Elsewhere, however, and certainly in New Zealand, continuous records of stream sediment load are rare to non-existent, while records of reservoir in-filling or even excavation tend to be patchy and span many events.

An alternative is to establish a relationship between event sediment yield and some correlated index of the event magnitude that is more easily monitored. Event peak flow typically correlates well with event sediment yield and can be used for this purpose (e.g. Neff 1967; Hicks 1990; Fig. 8.8). Given a long flow record, the event sediment-yield vs. peak-flow relationship can be used to simulate a many-year, unbroken series of event sediment yields from which a magnitude-frequency distribution can be extracted. Alternatively, the relationship can be used to estimate the event yields associated with peak flows of given return period. Hicks (1994) used this approach to estimate event sediment yields from several small catchments in northern New Zealand, finding that the event yields could be modelled by an Extreme Value type II distribution.

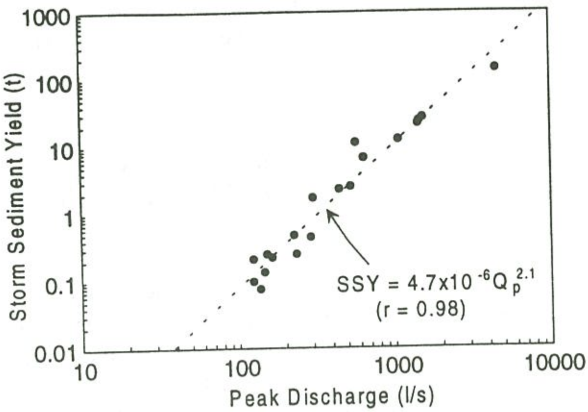

Fig. 8.8. Storm sediment yield vs. Storm peak flow relationship during urban development phase, Alexandra Basin near Auckland.

Parker and Troutman (1989) present a similar approach that incorporates the uncertainty in the event yield versus peak flow relationship. They used a log-Pearson type III distribution to model the probability density function of the annual peak flows (Y) and a quadratic regression relation between the logarithms of annual flood peaks and associated sediment yields (Y_s). They assumed a normal distribution of the errors in the Y versus Y_s regression relation in order to estimate the conditional probability density of the event sediment yield given a peak flow value. Finally, they combined the functions for the probability of Y and the conditional probability of Y_s given Y to derive a function which, when integrated numerically, predicted the sediment yield for a given return period. While Parker and Troughtman dealt with annual maxima events, their approach can also be applied to a *peaks-over-threshold* (or *partial duration*) series of events.

The 'event sediment rating' relationship can be compiled over a relatively short period of time (say one-two years), allowing that a good range of event magnitudes are sampled and that the relationship remains 'stationary' over the total period of flow record (i.e. the nature of the sediment sources and erosion processes in the catchment do not change appreciably, such as might occur during a landuse conversion).

Automatic pumping samplers are well suited for such short-term event-sampling deployments (e.g. Hicks 1994). When coupled with a data logger and a stage recorder, auto-samplers can be set to sample through flood events when the stage exceeds a threshold value. When programmed to sample on a flow-proportional basis, the event sediment yield can be computed directly from the product of average sampled concentration and average flow over the event; otherwise, the event sediment yield can be computed by integrating the sediment concentration and flow records. The start and end of the averaging or integration can be matched to the onset and cessation of quickflow. It is not necessary to sample all events over the monitoring period, thus storms missed or inadequately sampled through mechanical breakdown of the auto-sampler or when it has filled all of its bottles can be discarded.

A turbidity sensor may be used instead of an auto-sampler, providing water samples are collected to calibrate turbidity against sediment concentration. Point concentration at an auto-sampler intake should also be calibrated against the cross-section mean concentration by collecting auto-samples concurrently with depth-integrated samples (Hicks and Griffiths 1992, p. 233).

Care is required in the type of regression model fitted to the event yield versus peak flow relationship and in extrapolating it outside the range of the data. Unrealistic extrapolation can induce large errors in the yields estimated for extreme (large return period) events (Parker and Troutman 1989, p. 1570).

Where the reservoir storage volume is of similar order to or larger than the average annual sediment yield, then the use of annual yield statistics becomes appropriate. Working with continuous records of sediment load, several researchers have found that annual sediment yields, at least in small catchments, typically show an approximately log-normal distribution and high variability (Rehnard and Lane 1975; Van Sickle 1981). The approximately log-normal behaviour seems to be a consequence of (i) the sediment load being carried mainly during brief intense runoff events and (ii) the power relation between sediment load and runoff. One implication of the log-normal distribution, with its inherent skewness towards high magnitude events, is that the arithmetic mean is a poor indicator of 'expected' annual conditions. The *median* annual yield is a more appropriate summary statistic (Van Sickle 1981).

Importance of floods for long term sediment yields and channel morphology

We turn now from questions more oriented to engineering applications to those concerned with river geomorphology. Specifically, we ask the questions: "which floods transport the most sediment on average" and "which floods are most influential in shaping and scaling the channel"?

Floods and long-term average sediment yields

Which high flow events transport the greatest sediment load in the long term – the freshes that occur every month or so, 'average annual' events, or the 'once-in-a-lifetime' floods? The answer depends on the magnitude-frequency relationship of the flood sediment yields.

The frequency part of this relationship depends on the frequency of rainstorms and runoff events, that is, on the hydrological regime.

The magnitude part depends on the rate of sediment supply from the catchment and the transport capacity of the river. The bed material load (i.e. the bedload and coarser fractions of the

Table 8.1. Statistics of flows, long-term average suspended sediment yields, and event suspended sediment yields. 50% and 90% of the long-term average suspended sediment yields are transported by events with return periods less than or equal to the $T_{50\%}$ and $T_{90\%}$ values, respectively.

River	Location	Lithology	Area (km^2)	Mean flow (m^3/s)	Mean annual flood MAF (m^3/s)	Suspended sediment yield ($t/km^2/y$)	% load at flows < MAF	Most effective flow (m^3/s)	$T_{50\%}$ (y)	$T_{90\%}$ (y)
Shotover	Western Otago, S. Is.	Schist	1088	41	450	1210	94	130	0.41	4.2
Hokitika	West coast, S. Is.	Schist	322	99	1740	6130	96	1130	0.45	4.7
Rakaia	East coast, S. Is.	Greywacke & argillite	2640	204	2520	1640	93	680	0.87	8.6
Whanganui	Western N. Is.	Tertiary sediments	6643	214	2250	690	87	800	0.57	6.0
Waipaoa	East cape, N. Is.	Tertiary sediments	1580	35	1320	6190	86	360	1.15	13

suspended load derived from the bed - Hicks and Griffiths 1992, p. 230) is limited by the stream's transport capacity and competence, and so it is reasonable to expect the frequency of event bed material load yields to match the frequency of peak flows that exceed the threshold flow required to initiate bed material transport. In contrast, the washload (i.e. the fine fractions of the suspended load) tends to be limited by the supply from the catchment rather than by the capacity of the stream to transport it. The sediment supply depends on the intensity of catchment erosion processes, which in turn depends upon rain intensity, catchment rock-type and tectonic activity, steepness, soils, vegetation, and landuse.

There is a general appreciation that in temperate climates most river sediment transport occurs during intermediate-sized floods of moderate frequency (e.g. Wolman and Miller 1960). Neff (1967) combined frequencies of peak streamflows calculated for a 100-year period with relations between storm peak flow and sediment yield to derive the sediment transported within each frequency band. This study showed that about 90% of the long-term load is transported by events more frequent than the 10-year event. Neff also found, however, that the more variable the flow regime, the larger the contribution from the less frequent events.

This tendency was also noted by Nolan *et al.* (1987) among rivers of northwestern California. For the Black Butte and Eel Rivers and Redwood Creek, Nolan *et al.* found that while the distribution of the long-term sediment yield by flow band attained a maximum in the moderate-flow frequency band, it increased again for very large, low frequency flows. They ascribed this to two features of the NW California river basins: large flows are much larger than moderate ones and the basement rocks are very weak, providing abundant sediment and creating steep sediment transport relations.

Relatively frequent events also appear to carry much of the load in New Zealand rivers. By combining sediment ratings with flow records for 204 rivers widely distributed around New Zealand, the first author has found that on average 84% of the long term load is carried by flows less than the mean annual flood. While this result does not explicitly define the contribution of the larger events (as against the contribution of a discrete flow range), it nonetheless suggests the long-term importance of the more common, small-medium size floods.

This was confirmed for five large New Zealand Rivers (Rakaia, Shotover, Hokitika, Wanganui, Waipaoa) when their sediment ratings were used to generate event yields for the 25 year period from 1970-1995. For these five rivers, all carried 50% of their load in events with a recurrence interval of less than 1.15 years and 90% of their loads in events less than 13 years (Fig. 8.9; Table 8.1). There was a trend for greater importance of more extreme events going from west to east (in the sequence Shotover and Hokitika, Wanganui, Rakaia, Waipaoa). This reflects the general trend for a more variable flood regime from west to east across New Zealand; indeed, the 'dog-legs' on the cumulative distribution curves for the Rakaia and Waipaoa Rivers suggest two populations of extreme events.

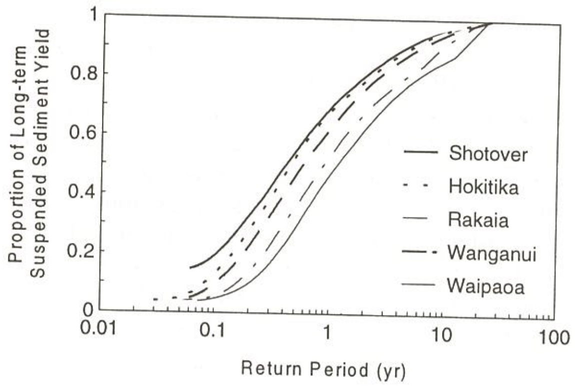

Fig. 8.9. Proportion of long-term suspended sediment yield transported by floods of return period up to the plotted value for five large New Zealand rivers.

The effect of landuse on event sediment-yield magnitude-frequency relationships was demonstrated by Hicks (1994) using storm yield data from four small basins in the Auckland region. There, a basin undergoing urbanisation yielded more sediment over all events, but much more during less frequent events, than did basins with established urban or rural landuses. The slopes of the magnitude-frequency plots for these basins reflected the availability of sediment (Fig. 8.10a). The plot was steepest for the urbanising basin, where sediment was abundant, flattest for the mature urban basin, where sediment became exhausted during large events, and had intermediate slopes for the pasture and market-gardening basins.

Calculating the sediment yields by event frequency band over 20 years showed (Fig. 8.10b) that the bulk of the long-term sediment yield from the urbanising basin (if it was assumed to remain in its 'under development' state) was carried by events with return period longer than one year, whereas it was the weekly and monthly events that carried the most sediment from the mature urban and market-gardening basins. For the pasture basin, the less than annual and greater than annual events were of approximately equal importance.

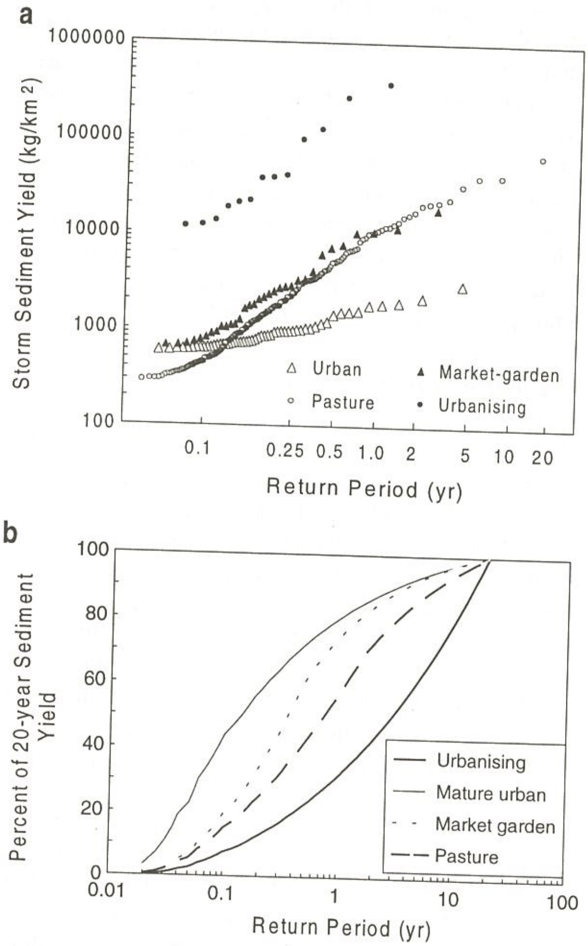

Fig. 8.10. (a) Storm sediment yield vs. Return period relationships for four basins near Auckland with different landuses. (b) Percent of 20-year sediment yield moved by storms of return period up to the plotted value.

In contrast to the predominance of moderate-frequency events in transporting river and stream sediment loads, it is typically the more extreme events that do most of the geomorphic work in eroding sediment from hillslopes in catchment headwaters (Wolman and Gerson 1978; Pearce 1978; DeRose *et al.* 1997; Trustrum *et al.* 1997). This up-shift in frequency from hillslope erosion to stream transport events relates mainly to two factors: (i) the larger thresholds required to initiate substantial hillslope erosion and (ii) only a portion of the eroded sediment is delivered to the stream channels. While smaller, more frequent hydro-meteorological events may not exceed the thresholds required to initiate hillslope erosion, they may nonetheless flush sediment from riparian storage sites. Where erosion thresholds are lower, for example because of weak bedrock or vegetation removal associated with urbanisation or forest clearance (e.g. Waipaoa, northwestern California, and urbanising Auckland basins), the links between the hillslopes and streams become more direct and extreme events become more important for transporting the stream sediment load.

Channel-forming floods

Intuitively, we might expect that the floods that transport most of the long-term sediment load of a river should be closely related to those that set the long-term average geometry and size of its channel. This follows from the concepts of river regime, where, with imposed water discharge, sediment supply (quantity and type), valley slope, and often non-fluvial bank material (i.e. the independent variables), a river channel maintains an 'equilibrium' morphology that over the long-term conveys the supplied water and sediment (e.g. Blench 1969).

In most rivers, it is the component of the sediment load found in the bed that determines the regime channel since the bed material load is transported at capacity and so is directly related to the water discharge. Certainly in New Zealand rivers, concentrations of the fine washload component are typically well below its theoretical transport capacity, even during the largest floods. Since the bulk of the bed material load is transported in the main river channel rather than over the floodplain, and there is often a discontinuity of the bed material transport capacity when flows spill over the floodplain (Richards 1982, p. 140), it is the bank-filling flow that is usually considered to be the most effective determinant of the channel morphology, or at least to be representative of the range of flows that dominate the channel forming process. Richards (1982, p. 136) reviewed approaches for estimating this bankfull discharge.

Bankfull conditions are often linked to the mean annual flood. Wolman and Leopold (1957) suggested from North American river data that bankfull discharges had a return period of 1-2 year on an annual series (which straddles the annual average value on a partial duration series), a result generally confirmed world-wide although with some variability (Richards 1982, p. 139).

Various studies have confirmed the connection between bankfull flows (or the mean annual flood) and channel morphology. Numerous empirical studies of river hydraulic geometry relations (i.e. the relationships between water discharge and channel width, depth, slope, velocity, cross-section area, flow resistance, and sediment load - Leopold and Maddock 1953) show a high degree of consistency among rivers (in different river basins, regions, and countries) when the bankfull or mean annual discharge is used as an index (see Griffiths 1980, and Mosley 1981, for New Zealand examples). Carson and Griffiths (1987), however, caution that at least for channels with easily scoured gravel banks, the bankfull channel geometry may simply reflect the effect of the last erosion event rather than be an indicator of a constant-value dominant event.

Andrews (1980) determined total sediment load for streams in the Yampa River basin, computing the 'most effective' sediment-transporting discharges and finding that these matched the bankfull discharges. In contrast, Nolan *et al.* (1987) found that for rivers in northwestern California the bankfull discharge exceeds the most effective discharge several-fold for both the suspended load and bedload. They suggest that this may relate to channel entrenchment due to confinement by bedrock and more rapid overbank deposition than lateral channel migration. Thus the frequency of the bankfull flow may also be a function of channel shape and all the factors controlling that.

The braided rivers on the Canterbury Plains provide an interesting contrast as well. For the Rakaia River (Fig. 8.3), Davies (1988) estimated that the most effective flow at transporting bedload was approximately 800 m^3/s, and, based on the suspended sediment rating, the most effective flow for transporting suspended load is approximately 700 m^3/s (D.M. Hicks, unpublished results). While the bankfull flow of the Rakaia's braided channel is difficult to define, its mean annual flood is over 2500 m^3/s - more than three times the most-effective sediment transporting flow. As with the northwestern California rivers, however, the distribution of the Rakaia's sediment load by flow band is broad rather than concentrated around the most-effective flow, and larger flood flows make a significant contribution to the long-term average load (Fig. 8.11). A similar broad distribution of the average suspended load and bedload over flows less than the mean annual flood was demonstrated by Griffiths (1979) for the Waimakariri River. Thus with braided rivers, it is likely that channel form is influenced by a broad range of flood flows, and linking channel form to a single dominant flood flow is an overly simple concept.

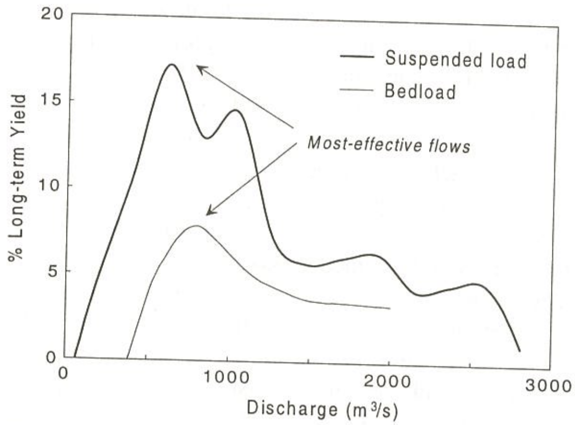

Fig. 8.11. Proportion of the long-term average bedload and suspended load by flow, Rakaia River.

Extreme floods and geomorphic thresholds

Extremely rarely, very large, catastropic events may occur that trigger radical catchment erosion (Schumm 1979). While the rarity of such events diminishes their significance to the long-term average yield, they may still contribute vast amounts of sediment and they can impose 'non-stationarity' on the sediment yield regime.

This non-stationarity arises because the hillslopes may take years or decades to recover from catastrophic erosion (typically as revegetation occurs). In the meantime, sediment deliveries to the drainage network are elevated and a 'slug' of sediment passes downstream, changing channel morphology, erosion and deposition patterns, and sediment loads. Thus while the catchment 'average annual' sediment yield decays exponentially back to the 'normal' regime, the sequence of event sediment yields is non-stationary, and a magnitude-frequency distribution of flood sediment yields based on a short series of events cannot be used to predict the likelihood of future sedimentation events.

Kelsey (1980) suggests that while the threshold required to trigger catastrophic erosion is lowered during the hillslope recovery phase of a previous catastrophic event, it can also be lowered by landuse. Thus widespread forest clearance and harvesting, over-grazing by stock, and urban development can all significantly increase the likelihood of a catastrophic erosion event.

Cyclone Bola, which struck New Zealand's East Cape region in 1988 and induced widespread hillslope failure (Derose *et al.* 1997), might be viewed as a recent example of a catastrophic event. Certainly, the East Cape landscape was rendered more vulnerable to erosion by the forest clearance associated with European settlement, and this has induced greater sediment loads, marked floodplain aggradation, and channel change along the Waipaoa River this century (Gomez *et al.* 1997). The suspended load of the Waipaoa River during Cyclone Bola was 33 million tonnes, over three times the mean annual suspended load. The suspended sediment rating for the Waipaoa at Kanakanaia gauging site showed that for three years following Cyclone Bola, sediment concentrations at given water discharges were approximately twice as high as they were before Bola (Fig. 8.12). After these three years, the sediment rating "fell back" to its normal trend.

A clearer signature of an extreme event is often recorded in the downstream progression of a bedload wave, with attendant adjustment of channel morphology. For example, Beschta (1983a and 1983b) and Mosley (1992, p. 299) describe a sequence of channel aggradation and widening, then degradation and narrowing, in the Kowhai River basin in the decades following a large storm in April 1951. In northern California, Madej and Ozaki (1996) observed an aggradation wave still moving down Redwood Creek over 30 years after it was triggered by a storm in December 1964.

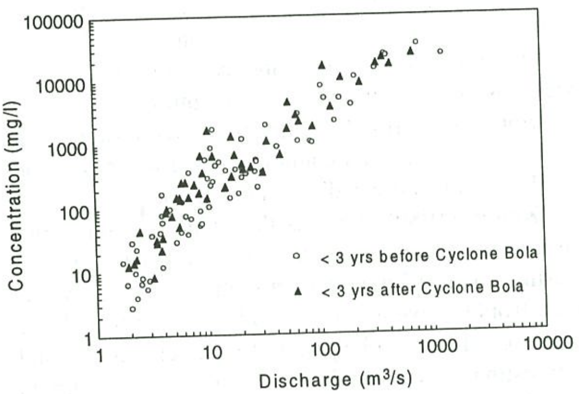

Fig. 8.12. Suspended sediment concentration vs. water discharge for Waipaoa River at Kanakanaia Bridge, spanning period from 3 years before to 3 years after Cyclone Bola (March 1988). Data: Gisborne District Council.

Effects of extreme sedimentation events on river channel ecosystems – a focus for future research?

The concept of extreme is a matter of perspective. If we were two cm high and lived under cobbles on a streambed, then events that carried away our homes or buried us in silt would seem catastrophic, even though on a human scale they were modest in magnitude and occurred frequently. This perspective of in-stream biota has forced stream ecologists and hydrologists to pay greater attention to the whole distribution of flood events.

The direct impacts of extreme flows on ecosystems are addressed by Jowett in Chapter 7 of this volume. However, a given change in flow can have quite different effects on ecosystem structure and function among different streams, as well as within the same stream (Scarsbrook and Townsend 1993; Biggs 1995). One of the key factors in this variability is the stability of the substrate (Poff 1992). On the rising stage of a flood, increasing velocity can remove many of the weakly attached periphyton and invertebrates (Biggs and Thomsen 1995), but, so long as the sediment on which they are anchoring stays in place, some form of residual community tends to remain to re-populate the streambed after the flood (Biggs, *et al.* 1997).

Also, many bottom-dwelling insects and fish are highly mobile and, detecting changes in velocity, will escape to pore-spaces within the stream bed. However, the fewer stable patches of bed there are to retreat to, or that hold residual communities, the more destructive a flood will be. Being able to assess the degree of bed destabilisation, and consequently the extent of refugia for biota, is now seen as a fundamental issue for understanding (and managing) ecosystem characteristics and the effects of anthropogenic disturbance in streams.

These issues involve some classical problems of river sediment transport, such as deposition and initial motion, which have received considerable - and some may say adequate - treatment over the years in the engineering and geomorphological literature (Carson and Griffiths 1987, p. 8-24; Buffington and Montgomery 1997). However, their application to understanding ecosystem functions requires much greater accuracy and spatial detail. Thus it is no longer adequate to assume uniform flow, or to work with the cross-section averaged shear stress and the median size of the bed material. Instead, one needs to know the spatial variation of the turbulent boundary shear stress as it varies with channel geometry, bed morphology, and substrate roughness, and the characteristics and packing of the substrate, which depend on depositional history and subsequent reworking. The need for such detail to aid ecosystem management has become an important focus for river hydraulics research.

Summary

Erosion and sedimentation invariably accompany floods. The processes vary broadly with location, and are often complex. During individual events, these processes can cause major damage to infrastructure, agriculture, and ecosystems within the floodway. Over time and many floods, even large reservoirs can be filled with sediment and the morphology and bed levels of river channels can change, creating chronic problems that require ongoing management. Thus dealing with flood induced erosion and sedimentation problems can be complicated and requires a broad range of knowledge and approaches.

Some erosion and sedimentation processes lend themselves to engineering-type analysis. In such cases (e.g. reservoir deposition, local scour at bridge piers), the sediment transport processes are driven by the flow hydraulics and so the effects of individual flood flows can be predicted from hydraulic theory. Also, a sequence of flood flows may be used as a proxy to estimate the magnitude-frequency characteristics of the erosion/sedimentation events.

Many other erosion and sedimentation processes, however, are too complex or occur too rarely to be dealt with wholly by a quantitative approach, and a geomorphological/geological perspective is required. This may involve compiling evidence of past events, identifying long-term large-scale processes such as aggradation or erosion waves, or making empirical comparisons with observations made elsewhere.

With bank erosion, for example, it is important to identify and manage the underlying cause as well as the mechanism of bank failure. Protection works may prove ineffective if the river bed at the base of the bank continues to be degraded as a result of a long-term reduction in bed material supply or a slowly migrating erosion wave. Moreover, along braided channels, bank erosion can be expected to show chaotic characteristics, since it relates to the migrations of the main channels and processes therein.

Channels across alluvial fan show extremely dynamic and frequently hazardous sedimentation and erosion during floods. The processes at any point and time on an alluvial fan also relate to the behaviour of the fan overall, and to its stage of morphologic evolution. Management of alluvial fan channels, therefore, must be based on knowledge of both river processes and fan geomorphology.

Debris flows on small, steep alluvial fans during extreme rainfalls impose serious hazards to mountain settlements and roads. Their rarity in space and time means that they are difficult to predict and are often ignored. The potential for debris flows can, however, be identified by a geomorphological inspection of the catchment headwaters and fan deposits.

In New Zealand, as elsewhere where the climate is temperate, most of the long-term average sediment yield of river basins is transported by floods of moderate size and frequency, not by the extremely large and rare floods. Related to this, it is floods with return periods of 1-2 years that typically determine channel morphology. However, over long time-scales and many events, the supply of sediment to river channels typically shows a complex response. There is usually an up-shift in the frequency of the most effective events between hillslopes and stream channels. Also, extremely rare, catastrophic storms can trigger dramatic hillslope erosion which may take decades or longer to 'heal'. Following such an event, a wave of sediment and morphologic change may pass through the drainage system, and the sequence of sediment yields from subsequent floods may not be stationary.

Traditionally, the main needs to manage flood-induced erosion and sedimentation in New Zealand have been directed at river crossings, maintaining the banks and conveyance of flood channels, and maintaining the storage of reservoirs. A recent, additional concern is with the effects of flood-induced sedimentation processes on in-stream habitats. With this, the effects of the smaller, more common floods are possibly more important than those of the extreme events; consequently, there is a need for more detailed information on sedimentary processes induced by these modest events and on ecosystem responses to these processes.

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9
Hydrological extremes and the groundwater system

Paul White

Introduction

Groundwater systems are part of the hydrological cycle and, as such, are subject to variability in level and flux. Natural variability in groundwater storage can have significant impact on human use of water as groundwater aquifers are important throughout the world for industrial, agricultural and domestic water supply. Rainfall and rivers are the two main sources of groundwater recharge, and groundwater levels commonly adjust in response to changes in rainfall and river recharge. Adjustment in groundwater levels typically occurs over a longer time span than any particular rainfall or river extreme "event" because aquifer reservoir volumes are usually large, in comparison with surface storage, and groundwater seepage velocities are usually low in comparison with water velocity in surface water bodies.

Volumetric storage in groundwater reservoirs is usually larger, and less variable with time, than storage in surface reservoirs and rivers. It has been estimated (Toebes 1972) that 80% (1.7×10^{12} m^3) of New Zealand's total water storage is in groundwater. The primary cause of relatively low groundwater storage variability is larger residence times for groundwater, due to the physical properties of the aquifer and relatively low groundwater velocity. For example, Todd (1980) calculates that the mean residence time for shallow groundwater in the United States is 200 years. By comparison, the mean residence time for surface water in the United States is estimated at several days.

This chapter reviews the effects of river floods and meteorological droughts on groundwater systems in New Zealand and overseas, and their effects on groundwater use. A survey of the problems caused by excessively low and high groundwater levels, in New Zealand's 159 recorded aquifer systems (Figs. 9.1 and 9.2), is presented. Hydrological extremes in surface water catchments and reservoirs are statistically compared with groundwater reservoirs using a case study of the Nelson area, where both surface water and groundwater are used for water supply and the aquifer systems are among the most heavily utilised in the country.

Groundwater and surface hydrological extremes

Floods

Floods are usually short-lived hydrological events and can have measurable effects on groundwater systems, especially in arid areas. The flood of October 1983 in the Gila River, Arizona (Konieczki and Anderson 1990) recharged the associated groundwater system, and well water levels had increased by an average of 8 m by March 1984. Hardt (1969) reported that the floods of January and February 1969 in the Mojave River Basin caused $6 to $12 million damage. However, these floods also provided substantial groundwater recharge to a basin where groundwater abstraction exceeds natural recharge. It was estimated that about 260×10^6 m^3 of the flood flow in the period January to March 1969 went to the aquifer. This is the equivalent of 2 years normal recharge. Water level, in a well 800 m from the river, rose a total of 5.3 m. Recharge water in the

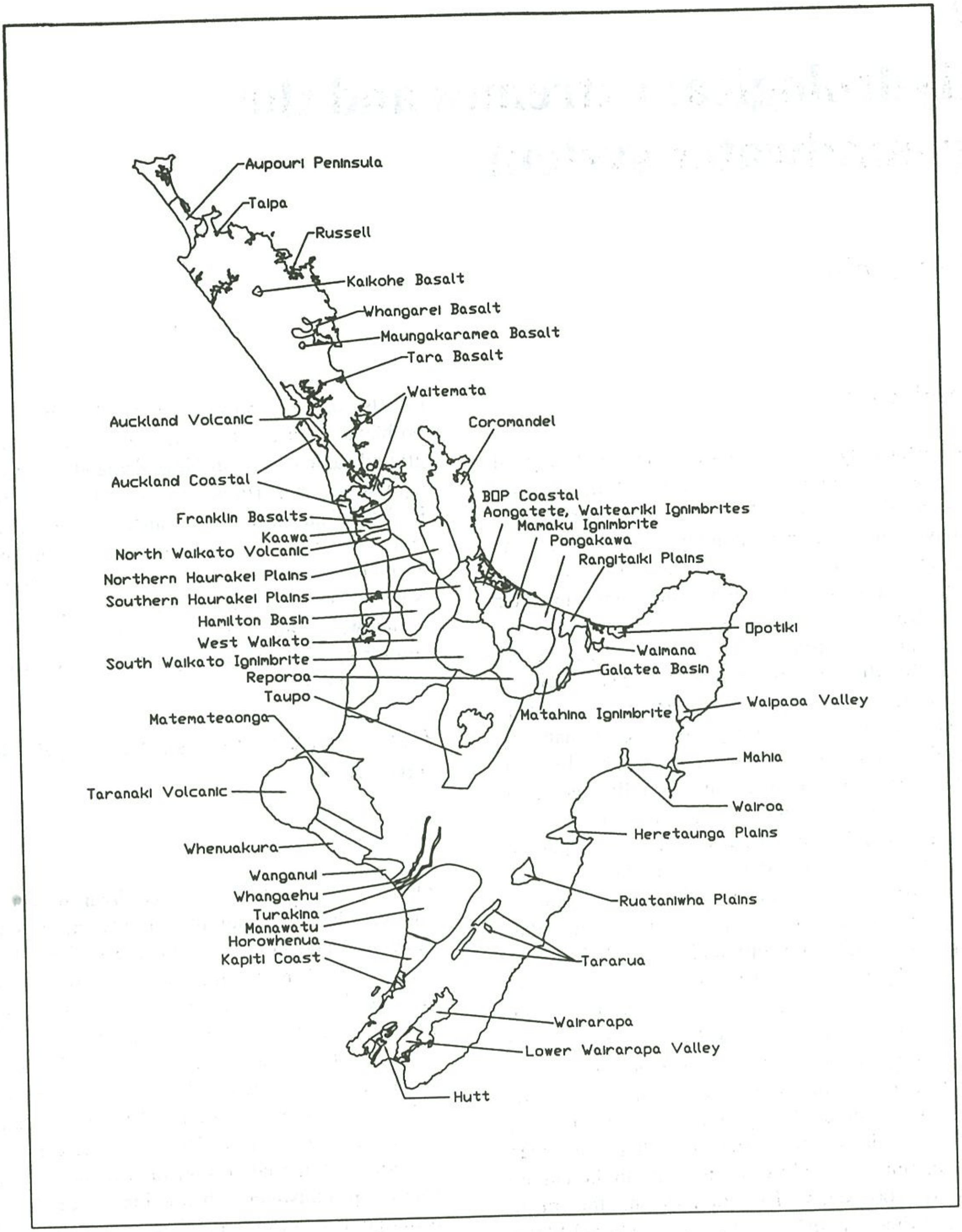

Figure 9.1. Aquifer systems in the North Island.

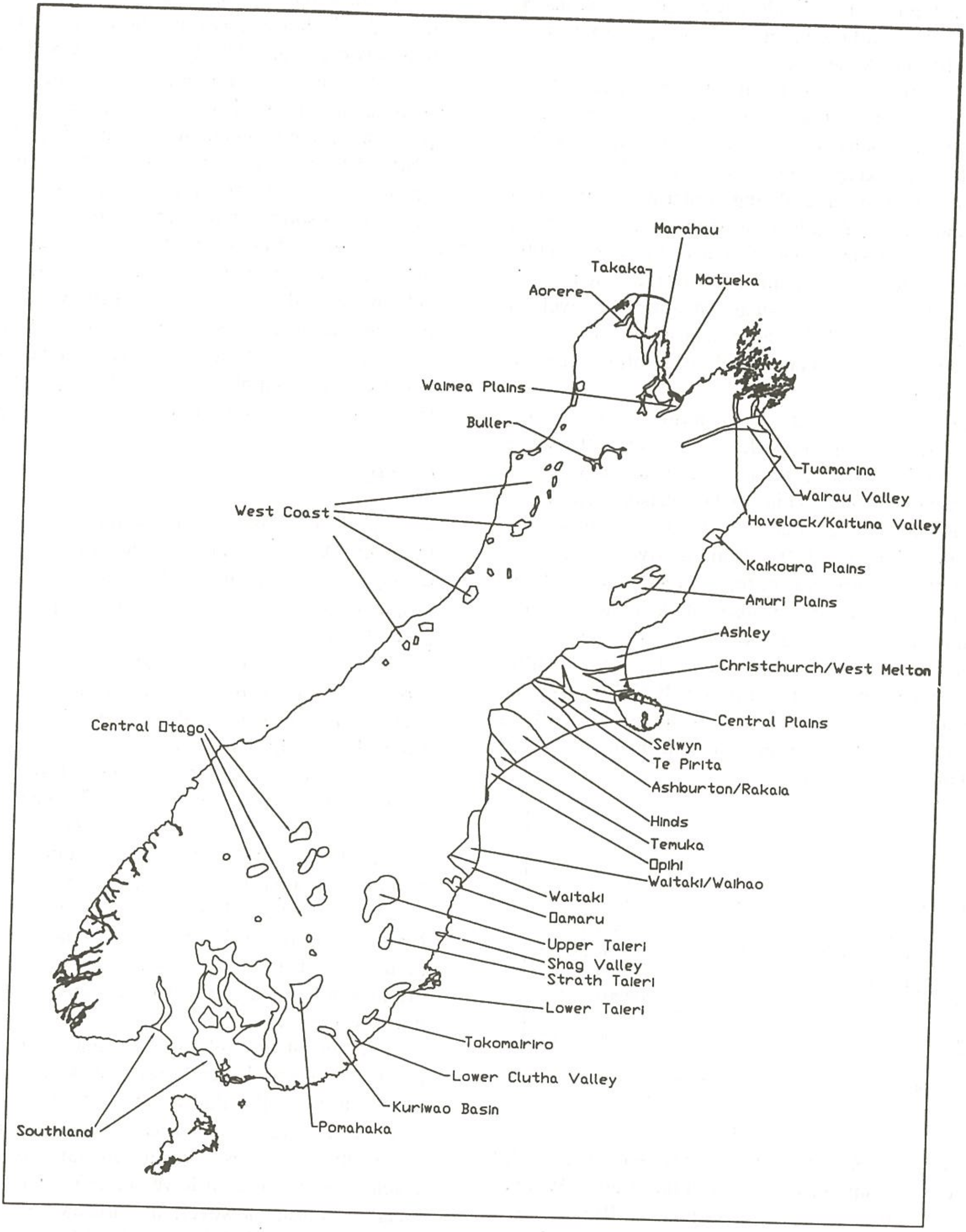

Figure 9.2. Aquifer systems in the South Island.

period January to March 1969 had an estimated value of $12 million, based on the cost of water from the California Aqueduct.

The midwest US flood of 1993 (Job 1994) affected about 12 000 public water systems and 1 000 private wells across nine states. Groundwater supplies drinking water for over 75% of the population of the area. Rising groundwater infiltrated and damaged subsurface structures such as septic tanks and sewer lines. Damage to some septic systems allowed contaminated water to enter water supply wells. Bacteriological contamination levels in wells were 5 to 50% higher than normal and some wells became recontaminated even after repeated disinfection.

Level response in an unconfined aquifer to a flood event commonly decreases away from the river. For instance, a flood wave of about 1.7 m in the Wairoa River (Fig. 9.3), Nelson, caused a groundwater level rise of about 0.7 m in the unconfined aquifer 160 m from the river, but of only 0.3 m 990 m away. Level response in the unconfined aquifer is delayed because of a relatively low groundwater seepage velocity. For example, groundwater level peaked 41 hours after commencement of a flood in a well 520 m from the river (Fig. 9.3). The peak level response to the flood occurred 137 hours after commencement, in a well 990 m from the river.

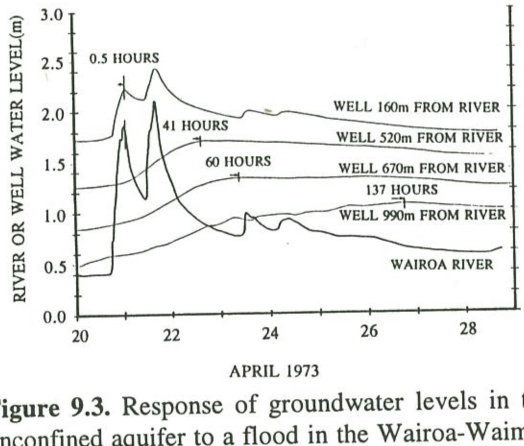

Figure 9.3. Response of groundwater levels in the unconfined aquifer to a flood in the Wairoa-Waimea River (after Fenemor 1988). River level measurements are at the Wairoa Gorge. Groundwater level measurements are in wells near the confluence of the Wairoa and Wai-iti Rivers.

Groundwater was used as an emergency water supply for Gisborne City after the floods of Cyclone Bola between 5 and 10 March 1988 (DSIR 1988a). Up to 900 mm of rain fell in 72 hours at some locations, and flood flow in the Waipaoa River was approximately equivalent to a 1-in-100 year event (DSIR 1988b). Flooding and erosion destroyed sections of the 35 km pipeline supplying drinking water to Gisborne City, and repair took many months. Groundwater from two sources and a sediment-free stream were used as a water supply and by 24 March local industry was able to recommence operations. New wells were drilled and by 3 April a limited, but adequate, volume of water to the city was supplied entirely from groundwater. This supply was used until the pipeline was repaired.

Droughts

The 1988-92 drought in western and southern England (Warren 1994) was the longest and most severe in this century. This area depends on groundwater for 70% of its water supply. Winter groundwater recharge averaged about 50% of normal in the period October 1988 - March 1992; groundwater levels in the Chalk aquifer fell to record low levels in Kent and summer baseflow was reduced in spring-fed streams.

The 1988 drought in Indiana (Fowler 1992) began towards the end of 1987 when annual precipitation decreased to 115 mm below the long-term average. Groundwater levels declined by up to 6 m in many areas of the State, and record low water levels were observed at 12 of 20 monitoring wells. Many domestic wells had to be deepened, and thousands of new wells were drilled. A 90-day groundwater emergency was declared in parts of northwest Indiana.

Groundwater levels in Georgia (Carter 1983) declined to the lowest observed levels in many observation wells during the 1980-81 drought. Declines in levels were measured for as many as 20 consecutive months. Mean annual groundwater levels were up to 5 m lower in 1981 than in 1980. Near the coast, however, the artesian groundwater levels were only slightly lower in 1981 than in 1980.

It is common for groundwater levels in New Zealand's aquifer systems to decline in summer. The combined effects of a reduction in natural recharge and an increase in groundwater use during drought usually result in increased, and/or prolonged, well water level drawdowns. Water management authorities, particularly in regions where groundwater is a crucial water supply, have developed plans for water use. Monitoring of groundwater levels and groundwater usage is an important requirement in these circumstances. For example, the Tasman District Council has defined a usage area for the Lower Confined Aquifer in the Waimea Valley, and consults with a groundwater users' committee when groundwater levels are stressed. The Council has set an allocation limit of 203 l/s for the usage zone. Groundwater levels are monitored continuously at five locations (Fig. 9.4) and groundwater usage data are collected, on a weekly basis, between the irrigation season of November and April. Water use in the Lower Confined Aquifer zone (Tyson, pers. comm.) was a maximum during the 1982/83 drought (White 1997), although maximum usage was lower than the zone allocation limit (Fig. 9.5). The 1982/83 drought in Nelson corresponded to a 1-in-34 year event for seven-day minimum flow at the Wairoa Gorge and a 1-in-6 year event for two-month minimum rainfall at Nelson Airport. Groundwater levels in the Chipmill well (Figs. 9.4, 9.5) were below sea level for most of the period December 1982 to April 1983. Groundwater levels below sea level allow the possibility of sea water intrusion into the aquifer, and preventing sea water intrusion is an important aim of many groundwater management regimes.

It is common in droughts for shallow groundwater wells to go dry, as groundwater levels fall below the well screen or base of the well, or decline to the extent that there is insufficient head to accommodate drawdown. This happened, for example, in Canterbury in the drought of 1983 (Weeber, pers. comm.). Declining groundwater levels can also cause artesian wells to cease flowing (Hawkes Bay Herald-Tribune 1995). Droughts commonly result in increased drilling activity as existing wells are deepened and new wells are drilled to provide new supply. For example, well drilling activity increased during the 1994 Auckland water shortage (Smaill, pers. comm.).

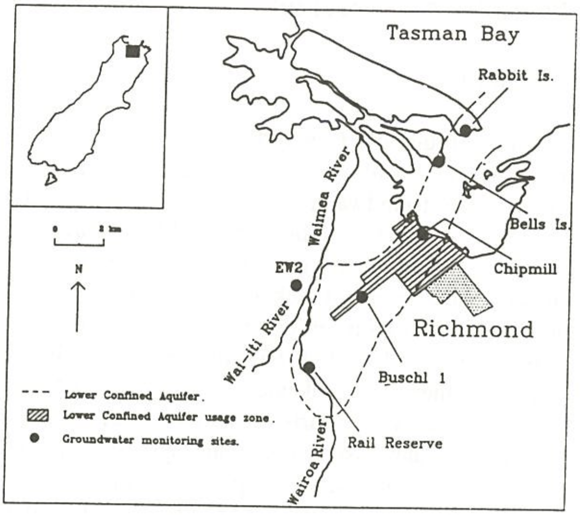

Figure 9.4. Location of the Lower Confined Aquifer, the Lower Confined Aquifer usage zone and wells monitoirng groundwater level in the Lower Confined Aquifer. Well EEW2 monitors groundwater level in the Unconfined Aquifer.

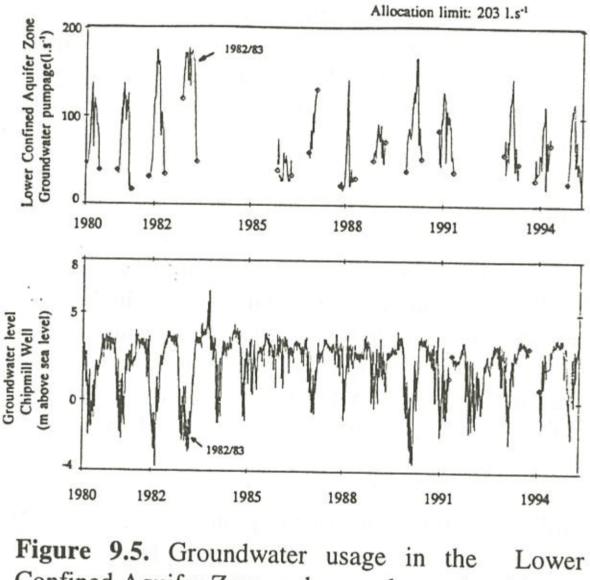

Figure 9.5. Groundwater usage in the Lower Confined Aquifer Zone and groundwater level in the Chipmill Well, 1979-1995 (after White 1997).

Groundwater extremes

Subsidence

Extreme groundwater withdrawals usually cause groundwater drawdown and can lead to ground subsidence. Groundwater abstractions in Tokyo City (Inaba *et al.* 1969) are closely related to subsidence. Land subsided by over 4 m in the period 1892 - 1965 and substantial areas of Tokyo were below sea level by 1968. A decline in groundwater level of up to 24 m between 1953 and 1965 corresponded with a maximum measured subsidence of up to 1.5 m. Subsidence has made parts of the city susceptible to flooding. It has also caused an apparent lift in masonry buildings and deep well pumps. The government began to control groundwater withdrawal in the subsidence-affected area in 1961. Groundwater levels began to increase in 1965 and by 1968 levels had recovered by up to 12 m. The annual rate of land subsidence began decreasing after 1965.

Land subsidence due to water supply-related groundwater withdrawals have not been observed in New Zealand. Fluid abstraction related to the Wairakei Geothermal Field between 1951 and 1991 (Hunt and Glover 1996) has caused localised groundwater level declines of up to 30 m. Localised ground surface subsidence of 13 m has been measured. Subsidence rates reached 450 mm/year in the 1970s.

Inundation

Declining industrial activity in Britain has caused a decline in groundwater demand which in the last few decades has resulted in rising groundwater levels (Nield 1986). Water demand in an area of Birmingham is estimated to have fallen from 20 x 10^3 m^3/day in the 1950s to 2 to 3 x 10^3 m^3/day in 1986. The water table has risen by as much as 5 metres since 1972 and in places water now lies within a metre or two of the ground surface. Rising groundwater levels in Liverpool have caused increasing water flow rates into tunnels, requiring increased pumpage to keep the structures drained. There is also concern that rising groundwater levels may affect building foundations. Groundwater levels are rising in London at a rate of 1 metre a year. The architects of the new British Library have designed the library in anticipation of rising groundwater levels by enlarging the piles to spread the load over a larger surface area to prevent the building from sinking.

There has been considerable effort in New Zealand in the last century to drain large areas of coastal plain. Drainage works are now crucial to maintaining the fertility of some of New Zealand's best agricultural land, such as large areas in the Waikato, Bay of Plenty, Manawatu, Hawkes Bay, Marlborough, Canterbury, West Coast and Southland. Dewatering by pumpage for the purpose of preventing soil inundation, is occurring in Hawkes Bay.

Extremes in New Zealand

Regional authorities are responsible for managing New Zealand's groundwater aquifers (Figs. 1 and 2). A survey (Appendix 9.1) of all the regional authorities has been carried out to define aquifer boundaries, and qualitatively assess the occurrence of groundwater deficits and surpluses in the country's aquifer systems (Appendix 9.2).

A total of 159 aquifers or aquifer systems are recorded from the survey. Five questions in the survey (Appendix 9.1) assess the degree to which groundwater deficits are a problem. Question A requests information on the state of knowledge about an aquifer, including geological data, groundwater flow directions, recharge and groundwater usage. Often the need to investigate aquifer hydrogeology is driven by the importance of the groundwater resource to the water users. The more important aquifer systems, particularly those that are stressed, are also often those where local and national resources are focused on research and investigation. A dramatic increase in usage (question B) coupled with significant effects of usage (question C) indicates an aquifer that is more stressed. Comparisons of stress in question C, such as "mild" and "significant", are interpreted individually by each regional authority. Question D attempts to quantify, as a return period, the degree to which regional groundwater drawdowns affect groundwater users. Questions C and D ask managers to consider the stress that aquifer systems would be under in absence of any management regime. Generally the aquifer under the greatest stress are likely to have the most active management regime, although some regional authorities argue that this is not the case. They maintain that management of an aquifer is independent of the pressure on the groundwater resource, although it is the writer's opinion that most regional authorities apply more rigorous management criteria in the aquifer systems that are more stressed.

Numerical responses to questions A, B, C, D and E (Appendix 9.2), are combined into a "deficit index" (equation 1) which is scaled to a range of 0 to 100.

$$\text{"deficit index"} = 5 \times (A + B + C + D + E - 5) \qquad (1)$$

This "index" should be compared with care between aquifer systems because answers based on the criteria in Appendix 9.1 may not be consistent between regional authorities. Nevertheless, the fact that a "deficit" index of 55 is calculated for the Kaawa Formation from independent responses from Auckland Regional Council and Environment Waikato indicates consistency in this case.

Aquifers and aquifer systems that have a "deficit index" over 75 (Heretaunga Plains, Lower Hutt, Moutere, Waimea Valley aquifers, Omaka River Valley and Papakaio Formation) are all crucial to the water resources of their area. These aquifers are often the only source of water for agriculture and significant sources of water for domestic and industrial supply. Groundwater management regimes are very important to the maintenance of groundwater volumes and quality in those aquifers; all but the Papakaio Formation would have significant regional drawdowns in 1-in-5, or less, years in the absence of a groundwater management regime. Groundwater usage has increased in all these aquifer systems in the last twenty years, highlighting the importance of long term monitoring of levels and quality and appropriate management regimes to the maintenance of groundwater reservoir capacity.

The more stressed aquifers, by New Zealand standards, do not show some of the effects of severe stress seen in aquifers overseas. High volumetric flow rates, relatively low usage, and prudent management of some of the more heavily used aquifer systems explain the relative lack of stress of New Zealand's aquifer systems.

Question F in Appendix 9.1 is designed to identify aquifer systems where surplus groundwater is a problem. The response to question F (Appendix 9.2) is scaled, by equation 2, to a range of 0 to 20.

$$\text{"surplus index"} = 5 \times (F - 1) \qquad (2)$$

"Surplus" groundwater is usually dealt with by natural drainage and man-made drainage. Aquifers and aquifer systems where excess groundwater is rated as a problem ("surplus index" greater than or equal to 10) include: Rangitaiki Plain, Manawatu, Lower Wairarapa Valley, Wairau (Marlborough), Ashley, Hinds, four Otago aquifers and Southland aquifers.

Statistics of groundwater extremes and surface hydrological extremes

Water use in the Nelson area is from both surface water and groundwater (Nelson - Marlborough Regional Council 1990). Nelson City took an annual average of 7.9 X 10^6 m^3 from the Maitai Dam and the Roding River between 1993 and 1995 (Dougherty pers. comm). Usage on the Waimea Plains is from both ground and surface water sources was an annual average of 6.3 x 10^6 m^3 between 1993 and 1995 (Tyson, pers. comm. and White 1997). The following example compares the statistics of low storage dam levels, low groundwater storage, and low river flow, in the Nelson area.

Maximum storage in the Maitai Dam is 3.1 x 10^6 m^3 (Table 1). This storage is sufficient to ensure continuous supply to Nelson City in the event of a 1-in-75 year low flow in the Maitai River.

The maximum volume of fresh water in the Waimea Plains aquifer system is estimated as 190 x 10^6 m^3 based on the following assumptions:

1. Fresh water is contained in the permeable lithologies predicted by 3D computer modelling of the Waimea Plains geology based on data from drill holes (White and Reeves 1996), bounded at the sides by the Moutere Hills, Barnicoat Range and the Waimea Estuary.

2. The porosity of the aquifer system is 25% (Dicker *et al.* 1992).

Table 9.1 Variability of storage in the Matair Dam and the Waimea Plains aquifers in low flow and low level conditions.

Event (daily minimum)	Maitai Dam[1] Volume (x 10^6 m^3	% of total storage	Waimea Aquifers Volume (x 10^6 m^3	% of total storage	Well EW2 groundwater level Daily minimum level (m)
1-in-2 years	2.2	71%	170	89%	10.8
1-in-5 years	1.5	48%	160	84%	10.6
1-in-10 years	1.1	35%	160	84%	10.4
1-in-20 years	0.7	23%`	160	84%	10.3
Maximum storage	3.1	100%	190	100%	maximum level (m) 13.8

[1] These figures are presently under revision (Dougherty pers. Comm.).

3. The top-bounding surface is a 1-in-40 year high groundwater level in the Unconfined Aquifer. Dicker *et al.* (1992) measured groundwater levels in the Waimea Plains Unconfined Aquifer in August 1978. At this time the level in well EW2 (a well in the unconfined aquifer), (Fig. 9.4) averaged 12.3 m. Return period analysis on annual daily maximum levels between 1975 and 1995 calculates a 1-in-40 year high level of 13.8 m in the EW2 well. A 1-in-40 year groundwater level surface for the Waimea Plains is estimated by increasing all August 1978 level contours by +1.5 m.

4. The bottom-bounding surface is the base of the permeable gravels (Dicker *et al.* 1992).

Groundwater storage volumes vary significantly less than surface reservoir storage volumes (Table 1). Waimea aquifer volumes are calculated to two significant figures using the 3D geological model (White and Reeves 1996) with an upper bound that approximates summer groundwater low levels between 1-in-2 year and 20 year return period. Return period analysis on daily maximum levels in the EW2 well shows that a minimum level of 10.8 m is equivalent to a 1-in-2 year low and a level of 10.3 m is equivalent to a 1-in-20 year low (Table 1). Piezometric levels in the Waimea Plains in April 1978 (Dicker *et al.* 1992) were adjusted by the difference between April 1978 EW2 well water level (10.6 m) and predicted minimum levels.

Piezometric levels in April 1978 in the EW2 well were equivalent to a 1-in-5 year event for minimum daily level. The difference in level (Table 1) between a 1-in-2 year minimum (10.8 m) and a 1-in-20 year minimum (10.3 m) is small relative to the thickness of permeable sediments. Permeable sediments are about 10 m thick near the EW2 well and up to 70 m thick (Dicker *et al.*, 1992) in the Waimea Basin. Changes in aquifer storage in extreme hydrological conditions are thus relatively small.

Groundwater reservoir storage is less variable than river flow. For example, the ratio of a 1-in-20 year low flow to mean flow is 75% for flow in the Maitai River and 61% for flow in the Wairoa River (Doyle, pers. comm.). The ratio of a 1-in-20 year low aquifer storage volume to mean storage volume is 89% for groundwater storage in the Waimea aquifers. Groundwater in the Nelson area is a more secure water supply than the Maitai Dam reservoir because of the significantly larger volume and lower variability of aquifer storage. However, it is unlikely that the full volume of groundwater in the Waimea Plains aquifers could be abstracted because the environmental effects, such as salt water intrusion, river depletion, and surface run-off, would be unacceptable.

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Appendix 9.1.

Questionnaire on groundwater deficits and surpluses in New Zealand acquifers.

Please circle a rating of 1 to 5 for **each** aquifer system in your area as mapped.

Aquifer name:____

A: What is the state of knowledge on the aquifer?				
1	2	3	4	5
Nothing known	Between 1 and 3	Some geological data, preliminary hydrogeological interpretation completed. Some groundwater recharge and usage data.	Between 3 and 4	Hydrogeology very well understood. Groundwater recharge and usage patterns very well understood.

B: Groundwater usage in the aquifer has changed how in the last 20 years?				
1	2	3	4	5
Nothing known	Dramatically decreased	Stayed the same	Increased a little	Dramatically increased

C: Give subjective rating of the degree of usage stress in the aquifer, <u>in the absence of a groundwater management regime.</u>				
1	2	3	4	5
Nothing known about the system	Local drawdowns which sporadically cause level problems in neighbouring wells only.	Drawdowns on a regional scale which negatively affect groundwater users occur in the occasional summer.	Drawdowns on a regional scale which negatively affect groundwater users usually occur in summer. Proven (mild) effect of drawdowns on groundwater quality.	Permanent drawdown caused by groundwater usage. Significant groundwater level reductions to greater than 90% of users. Significant on-going effects of drawdown on groundwater quality.

D: Indicate the return period of regional drawdowns affecting g/w users, <u>in the absence of a groundwater management regime.</u>				
1	2	3	4	5
No known problems	1 in 20 years	1 in 10 years	1 in 5 years	1 in 2 years, or 1 in 1 year

E: Please indicate the severity of any management regime that is currently in place to control groundwater usage.				
1	2	3	4	5
No management regime	Usage reductions in the occasional summer recommended by the regional council.	Usage restrictions every summer	All users given an annual allocation. Monitoring of usage is by users. Allocated use is approximately similar to demand.	All users given an annual allocation. Compulsory installation of water meters for groundwater users. Demand is substantially greater than allocation. Up-to-date records of usage are kept by the Council. Council makes efforts to keep usage within allocation.

F: Please indicate the degree to which excess groundwater is causing problems.				
1	2	3	4	5
No problems	Increased spring flow has resulted in some nuisance	Increased spring flow has led to surface flooding and some economic impact	Local dewatering of the aquifer required to prevent local surface flooding	Large scale dewatering of the aquifer system is required to prevent significant surface flooding

Appendix 9.2.

New Zealand aquifer systems and qualitative evaluations of groundwater deficit and surplus.

AQUIFER NAME AND REGION	REGIONAL COUNCIL	A	B	C	D	E	F	Deficit Index	Surplus Index
NORTH ISLAND									
Aupouri Peninsula Sand & Shell Bed	Northland R.C.	3	4	1	1	4	1	40	0
Taipa Sand	Northland R.C.	2	4	2	1	4	1	40	0
Russell Gravel/Weathered Greywackes	Northland R.C.	4	4	2	1	4	1	50	0
Kaikohe Basalt	Northland R.C.	4	4	2	1	4	1	50	0
Whangarei Basalt	Northland R.C.	4	4	2	1	4	1	50	0
Maungakaramea Basalt	Northland R.C.	2	4	1	1	4	1	35	0
Tara Basalt	Northland R.C.	2	4	1	1	4	1	35	0
Waitemata Sediments	Auckland R.C.	3	3	3	2	2	1	40	0
Auckland Volcanic Aquifers	Auckland R.C.	5	4	2	2	5	2	65	5
Auckland Coastal Aquifers	Auckland R.C.	2	3	2	1	1	1	20	0
Franklin Basalts	Auckland R.C.	5	4	2	3	5	1	70	0
Kaawa Formation	Auckland R.C.	4	4	2	2	4	1	55	0
Kaawa Formation	Environment Waikato	4	5	2	1	4	1	55	0
North Waikato Volcanic Aquifers	Environment Waikato	4	4	2	1	4	1	50	0
Northern Hauraki Plains	Environment Waikato	4	3	1	1	1	1	25	0
Southern Hauraki Plains	Environment Waikato	4	4	2	1	1	1	35	0
Hamilton Basin	Environment Waikato	4	4	2	1	1	1	35	0
West Waikato Aquifers	Environment Waikato	2	1	1	1	1	1	5	0
South Waikato Ignimbrite	Environment Waikato	3	4	2	1	1	1	30	0
Reporoa	Environment Waikato	3	4	1	1	1	1	25	0
Taupo	Environment Waikato	3	4	1	1	1	1	25	0
Coromandel Aquifers	Environment Waikato	4	4	2	1	1	1	35	0
BOP Coastal Aquifers									
Waihi Beach Rhyolite	Env. Bay of Plenty	3	3	3	3	1	1	40	0
Katikati Gravel	Env. Bay of Plenty	3	5	3	3	1	1	50	0
Mt Maunganui sand	Env. Bay of Plenty	3	3	3	4	1	1	45	0
Matakana Island Sand	Env. Bay of Plenty	3	3	3	3	1	1	40	0
Maketu warm water	Env. Bay of Plenty	2	3	3	3	1	1	35	0
Maketu Pumice	Env. Bay of Plenty	2	5	3	4	1	1	50	0
Aongatete Ignimbrite	Env. Bay of Plenty	2	4	3	3	1	1	40	0
Waiteariki Ignimbrite	Env. Bay of Plenty	2	5	2	3	1	1	40	0
Mamaku Ignimbrite	Env. Bay of Plenty	2	3	3	3	1	1	35	0
Pongakawa	Env. Bay of Plenty	2	5	2	3	1	1	40	0
Rangitaiki Plains	Env. Bay of Plenty	3	5	3	4	1	3	55	10
Opotiki Gravel	Env. Bay of Plenty	2	3	3	4	1	1	40	0
Waimana	Env. Bay of Plenty	2	3	3	4	1	1	40	0
Galatea Basin	Env. Bay of Plenty	3	3	3	4	1	1	45	0
Matahina Ignimbrite	Env. Bay of Plenty	2	5	2	1	1	1	30	0
Waipaoa Valley Aquifers									
Waipaoa Gravel (confined)	Gisborne D.C.	3	5	1	1	5	1	50	0
Makauri Gravel (confined)	Gisborne D.C.	3	5	3	2	5	1	65	0
Matokitoki Gravel (confined)	Gisborne D.C.	3	4	1	1	5	1	45	0
Te Hapara Sand (unconfined)	Gisborne D.C.	2	5	3	2	5	2	60	5
Mahia	Hawkes Bay R.C.	2	1	1	1	1	1	5	0
Wairoa	Hawkes Bay R.C.	2	4	1	1	1	1	20	0
Heretaunga Plains	Hawkes Bay R.C.	4	5	3	4	4	1	75	0
Ruataniwha Plains	Hawkes Bay R.C.	2	5	4	4	3	1	65	0
Matemateaonga Formation	Taranaki R.C.	3	3.5	1	1	1	1	22.5	0
Taranaki Volcanics	Taranaki R.C.	3	3	1	1	1	1	20	0
Whenakura Formation	Taranaki R.C.	3	4	2	5	1	1	50	0

Appendix 9.2. Continued

AQUIFER NAME AND REGION	REGIONAL COUNCIL	A	B	C	D	E	F	Deficit Index	Surplus Index
Wanganui	Manawatu-Wanganui R.	2	1	1	1	1	2	5	5
Whangaehu/Turakina	Manawatu-Wanganui R.	2	1	1	1	1	1	5	0
Manawatu	Manawatu-Wanganui R.	4	4	3	4	1	3	55	10
Horowhenua	Manawatu-Wanganui R.	4	4	2	3	1	1	45	0
Tararua	Manawatu-Wanganui R.	2	1	1	1	1	1	5	0
Kapiti Coast Aquifers									
Raumati/Paekakariki	Wellington R.C.	2	3	2	1	4	1	35	0
Waikanae	Wellington R.C.	3	4	2	1	4	1	45	0
Coastal	Wellington R.C.	2	4	2	2	4	1	45	0
Hautere	Wellington R.C.	3	3	2	3	4	1	50	0
Waitohu	Wellington R.C.	3	4	2	3	4	1	55	0
Otaki	Wellington R.C.	3	4	2	3	4	1	55	0
Hutt Aquifers									
Mangaroa	Wellington R.C.	1	1	1	1	1	1	0	0
Upper Hutt	Wellington R.C.	3	2	2	1	4	1	35	0
Lower Hutt	Wellington R.C.	5	5	3	5	5	1	90	0
Wainuiomata	Wellington R.C.	1	1	1	1	1	1	0	0
Wairarapa Aquifers									
Fernridge	Wellington R.C.	2	4	1	1	1	1	20	0
Upper Plain	Wellington R.C.	2.5	3.5	1	1	1	1	20	0
Upper Opaki	Wellington R.C.	2	3	1	1	1	1	15	0
Opaki	Wellington R.C.	3	4	1	1	1	1	25	0
Masterton	Wellington R.C.	3	3.5	1	1	1	1	22.5	0
West Taratahi	Wellington R.C.	3	3	1	1	1	1	20	0
East Taratahi	Wellington R.C.	2.5	3.5	1	1	1	1	20	0
Parkvale	Wellington R.C.	4	5	2	5	1	1	60	0
Fern Hill	Wellington R.C.	2	3	1	1	1	1	15	0
Rathkeale	Wellington R.C.	3	4	1	1	1	1	25	0
Te Ore Ore	Wellington R.C.	4	5	2	5	1	1	60	0
Middle Ruamahanga	Wellington R.C.	3	5	2	5	1	1	55	0
Riverside	Wellington R.C.	3	5	1	1	1	1	30	0
Tawaha	Wellington R.C.	4	5	1	1	1	1	35	0
Matarawa	Wellington R.C.	3	3	1	1	1	1	20	0
Mangatere	Wellington R.C.	3	5	1	1	1	1	30	0
Hodders	Wellington R.C.	3	4	1	1	1	1	25	0
Carterton	Wellington R.C.	3	4	1	1	1	1	25	0
Greytown	Wellington R.C.	3	4	1	1	1	1	25	0
Ahikouka	Wellington R.C.	3	5	1	1	1	1	30	0
Tauherenikau	Wellington R.C.	3	5	1	1	1	1	30	0
South Featherston	Wellington R.C.	2.5	4	1	1	1	1	22.5	0
Battersea	Wellington R.C.	3	5	2	5	1	1	55	0
Moroa	Wellington R.C.	4	5	1	1	1	1	35	0
Woodside	Wellington R.C.	3	3	1	1	1	1	20	0
Matinborough	Wellington R.C.	3	4	1	1	1	1	25	0
Pirinoa Terraces	Wellington R.C.	2	3	1	1	1	1	15	0
Huangarua	Wellington R.C.	2	3	1	1	1	1	15	0
Lower Wairarapa Valley Aquifer	Wellington R.C.	4	4	4	5	1	3	65	10

Appendix 9.2. Continued

AQUIFER NAME AND REGION	REGIONAL COUNCIL	A	B	C	D	E	F	Deficit Index	Surplus Index
SOUTH ISLAND									
Marahau	Tasman D.C.	3	4	2	3	1	1	40	0
Takaka Aquifers									
Takaka Limestone	Tasman D.C.	2	4	1	1	1	1	20	0
Takaka Marble	Tasman D.C.	3	4	3	3	2	1	50	0
Takaka Gravel (unconfined)	Tasman D.C.	2	4	1	1	1	1	20	0
Takaka /Collingwood	Tasman D.C.	1	1	1	1	1	1	0	0
Aorere	Tasman D.C.	2	1	1	1	1	1	5	0
Motueka Aquifers									
Moutere	Tasman D.C.	4	5	3	4	4	1	75	0
Motueka Plains	Tasman D.C.	4	5	3	3	2	1	60	0
Upper Motueka	Tasman D.C.	2	4	1	2	1	1	25	0
Waimea Plains Aquifers									
Waimea Upper Confined	Tasman D.C.	5	4	4	4	5	1	85	0
Waimea Lower Confined	Tasman D.C.	5	4	4	4	5	1	85	0
Waimea (Hope Minor Aquifers)	Tasman D.C.	5	4	2	4	5	1	75	0
Waimea (Appleby Gravel Unconfined)	Tasman D.C.	5	5	2	4	5	1	80	0
Buller	Tasman D.C.	1	1	1	1	1	1	0	0
Tuamarina	Marlborough D.C.	3	4	1	1	1	2	25	5
Wairau Valley Aquifers									
Wairau	Marlborough D.C.	4.5	5	2	1.5	2	3	50	10
Rarangi Shallow	Marlborough D.C.	3	4	2	4	1	1	45	0
Taylor-Burleigh	Marlborough D.C.	2	1	1	1	1	1	5	0
Benmorven	Marlborough D.C.	3	5	2	1	1	1	35	0
Fairhall River Gravels	Marlborough D.C.	4	5	3	4	2	1	65	0
Brancott	Marlborough D.C.	3	5	2	1	1	1	35	0
Omaka	Marlborough D.C.	4.5	5	2	3	1	2	52.5	5
Omaka River Valley	Marlborough D.C.	4	5	4	4	4	1	80	0
Lower Waihopai	Marlborough D.C.	4	5	2	3	1	2	50	5
Havelock	Marlborough D.C.	2	5	2	1	1	1	30	0
Kaituna Valley	Marlborough D.C.	2	4	1	1	1	2	20	5
Kaikoura Plains	Canterbury R.C.	4	4	2	1	1	1	35	0
Amuri Plains	Canterbury R.C.	2	3	1	1	1	2	15	5
Ashley	Canterbury R.C.	5	5	3	4	1	3	65	10
Christchurch/West Melton	Canterbury R.C.	5	5	4	3	2	1	70	0
Central Plains	Canterbury R.C.	4	5	3	3	1	1	55	0
Selwyn	Canterbury R.C.	4	5	3	3	1	1	55	0
Te Pirita	Canterbury R.C.	3	5	2	3	1	1	45	0
Ashburton/Rakaia	Canterbury R.C.	4	5	4	4	1	1	65	0
Hinds	Canterbury R.C.	3	4	2	1	1	3	30	10
Temuka	Canterbury R.C.	3	4	2	4	1	2	45	5
Opihi	Canterbury R.C.	4	3	3	4	2	2	55	5
Waitaki/Waihao	Canterbury R.C.	2	4	1	1	1	2	20	5
West Coast Aquifers	West Coast R.C.	2	3.5	1	1	1	1	17.5	0
Waitaki Alluvium	Otago R.C.	3	4	2	1	2	1	35	0
Oamaru Aquifers									
Papakaio Formation	Otago R.C.	5	5	4	5	2	1	80	0
Deborah Volcanics	Otago R.C.	5	5	3	4	2	3	70	10
Waiareka Volcanics	Otago R.C.	5	5	2	2	2	2	55	5
Kakanui Alluvium	Otago R.C.	5	5	2	2	2	1	55	0
Upper Taieri Gravels	Otago R.C.	1	1	1	1	1	3	0	10
Shag Valley Alluvium	Otago R.C.	2	4	1	4	2	1	40	0
Strath Taieri Alluvium	Otago R.C.	2	4	1	1	1	4	20	15
Lower Taieri Gravels	Otago R.C.	4	5	3	3	2	1	60	0
Tokomairiro Gravels	Otago R.C.	1	1	1	1	1	1	0	0

Appendix 9.2. Continued

AQUIFER NAME AND REGION	REGIONAL COUNCIL	A	B	C	D	E	F	Deficit Index	Surplus Index
Lower Clutha Valley Gravels	Otago R.C.	1	1	1	1	1	1	0	0
Kuriwao Basin Gravels	Otago R.C.	1	1	1	1	1	1	0	0
Pomahaka Gravels	Otago R.C.	1	4	1	1	1	1	15	0
Central Otago Aquifers									
Ettrick Gravels	Otago R.C.	2	5	3	3	2	1	50	0
Coal Creek Gravels	Otago R.C.	2	5	4	5	3	1	70	0
Clutha Outwash Gravels -Earnscleugh	Otago R.C.	3	4	2	3	1	1	40	0
Clutha Outwash Gravels -Dunstan Flats	Otago R.C.	3	5	3	3	2	1	55	0
Manuherikia Alluvium	Otago R.C.	1	5	2	4	1	1	40	0
Manuherikia Claybound Gravels	Otago R.C.	1	5	1	1	1	1	20	0
Upper Clutha Outwash Gravels	Otago R.C.	2	4	1	1	1	1	20	0
Lowburn Gravels	Otago R.C.	1	5	1	1	1	1	20	0
Lindis Valley Gravels	Otago R.C.	1	1	1	1	1	1	0	0
Cardrona Gravels	Otago R.C.	3	5	2	2	2	1	45	0
Hawea Outwash Gravels	Otago R.C.	1	1	1	1	1	1	0	0
Wakatipu Basin Sediments	Otago R.C.	3	5	3	3	2	3	55	10
Wakatipu Sediments -Kingston	Otago R.C.	1	1	1	1	1	1	0	0
Wakatipu Sediments -Glenorchy	Otago R.C.	1	4	1	1	1	2	15	5
Southland Aquifers	Southland R.C.	3	4	2	1	1	5	30	20

10
Principles of managing extreme events

George Griffiths and Peter Ross

Come rain or shine

A rainy day can deliver salvation or disaster by breaking a drought or submerging a floodplain. Floods caused by rainfall and droughts caused by its absence are natural, recurring but unpredictable phenomena. From the earliest times of Maori and European settlement there have been numerous oral and written accounts of floods and droughts inflicting major loss or damage to life and property. These events are not things of the past faced by our grandparents, nor do they only happen to other people: they may occur at any time and affect anybody virtually anywhere in New Zealand.

Vulnerability to the effects of extreme floods and droughts is undoubtedly increasing. This trend is not because more events are occurring than ever before, but because development is placing more assets at risk of damage. (Assets include people and anything of value to them) The potential for floods or droughts in their different ways to harm a community is a hazard and its severity can be assessed in terms of potential damage to these assets.

In a particular droughty area or on a given floodplain the chance of an extreme drought or flood occurring in any one year is remote. But over decades the probability of an extreme event happening in that period increases substantially. Also, when the whole of New Zealand is considered it is a virtual certainty that a major flood or drought will occur every few years. For example, the probability of an event of a magnitude which is exceeded on average once every 100 years occurring in some area at least once in a three year period is 3%. The chance of this 100 year event happening in any one of 100 different areas in a three year interval is 95%. The improbable is inevitable. (Figure 10.1)

Floodplains and droughty regions frequently furnish convenient and attractive areas for settlement and other endeavours. For instance, floodplains usually have rich soils and a flat and extensive riparian region with a convenient water supply and high amenity values. Drought prone areas are commonly free of dense vegetation and suitable for intensive agricultural and horticultural production under favourable seasonal conditions.

The occurrence of floods and droughts presents a serious impasse. On the one hand it is neither practicable nor desirable to abandon permanent occupation of flood or drought prone regions, on the other, complete flood or drought control is an illusion.

The logical response is to minimise the hazard by strategic planning so that if an extreme event does occur its effects on a community will be substantially reduced.

A more proactive approach that emphasises the principles of risk management, and sustainable management of natural and physical resources, is now being promoted in New Zealand. This is timely given that the 1990s is the International Decade for National Disaster Reduction, but much remains to be achieved. The new approach is founded on a careful and comprehensive analysis of the benefits and costs of hazard management activity over decades. Whether any flood or drought damage reduction measures are implemented depends on community will; and the strength of response is determined by the community's perception of the risk involved and its willingness and ability to pay for a management programme which secures a good return on investment. Despite the fact that floods

Fig. 10.1. Ranging floodwaters of the Tengawai River near Mackenzie Pass, South Canterbury in March 1986. (Photo: Brian Patterson, Manahune).

and droughts may severely impact on communities, in the intervals between occurrences it is difficult to spark real public concern and action: many societal constraints work against a community recognising future risk and taking measures to avoid, remedy or mitigate long term future losses. (Burby *et al.* 1988; Interagency Floodplain Management Review Committee 1994).

There are three main principles for reducing potential damage or future loss. These involve actions before, during and after a flood or drought event. They are avoidance, alleviation and recovery. Management measures used in all three phases will be most efficient and effective when they are part of an integrated response program covering all probable magnitudes of floods or droughts.

The measures which reduce a hazard may themselves have adverse effects on the environment; these should be incorporated within an overall benefit-cost analysis of the program. Finally, once local government, working with an affected community, has implemented a hazard management plan or response, monitoring should be undertaken to assess its suitability and effectiveness. If performance is unsatisfactory a review of the management program should commence.

This chapter deals with the principles of managing flood and drought hazards within New Zealand. The first three sections give a broad introduction to the nature of the hazards and the legislative, administrative and policy background to contemporary management practice. Hazard perception and assessment is discussed in Section 4 and then approaches to hazard management are reviewed in Section 5. The last three sections treat management processes and the implementation, monitoring and review of responses or plans aimed at reducing potential losses from flood and drought hazards.

At present no operative hazard management plans prepared under current legislation are available in New Zealand. Indeed, only one plan, the Proposed Waimakariri Floodplain Management Regional Plan has so far been notified, and accordingly provides the source of most examples in this chapter. Even this Plan has been Now withdrawn owing to: (i) lack of support by City and District Councils for proposed rules in the plan controlling land-use for building purposes; (ii) public perception that proposed flood protection measures were too restrictive; and (iii) discriminatory imposition of land use controls on rural ratepayers.

Legislation and administration

Resource Management Act and other Acts

From the earliest times of European settlement, flooding has been the subject of numerous legislative provisions, and implementation has required a steadily evolving range of public bodies - river control boards, drainage boards and catchment boards. Following the 1989 local body amalgamations these functions were mostly assumed by the new regional councils, though some went to consolidated territorial authorities.

The Land Drainage Act 1908, the Soil Conservation and Rivers Control Act 1941, and the Water and Soil Conservation Act 1967 had been of particular importance: the first two continue to be. In 1991 the Resource Management Act (RM Act) subsumed both the Town and Country Planning Act 1977 and the Water and Soil Conservation Act, and at the same time government subsidisation of flood control works ended.

Floods and droughts are included in the RM Act's definition of natural hazard. With these and the other examples omitted, that definition reads as follows:

> *"Natural hazard means any atmospheric or earth or water related occurrence ... the action of which adversely affects or may adversely affect human life, property, or other aspects of the environment;" (s2, RM Act).*

An important subtlety is that an occurrence which "adversely affects or may adversely affect" is a natural hazard, whereas an occurrence that does not have that potential is not a hazard. It follows that natural hazards do not have effects: they are effects. They are the adverse effects of a possibly damaging interaction between various natural occurrences, and people, property or the environment, as will be discussed later.

Central Government and Local Authorities

With the termination of subsidies for river protection, central government's commitment to hazard event mitigation came to an end. It is now only pledged to maintain the Earthquake Commission, and, in partnership with local authorities, civil defence capability. The RM Act has effectively devolved natural hazard responsibility to local authorities.

Under the RM Act sustainable management is achieved through a hierarchy of instruments at the top of which are national policy statements. (No national policy statements other than the mandatory New Zealand Coastal Policy Statement have so far appeared.) Ranked next are regional policy statements, then regional plans, and district plans. Regional policy statements, regional coastal plans and district plans are all mandatory. Documents lower in the hierarchy may not be inconsistent with those above.

Regional policy statements are intended "to achieve integrated management of the natural and physical resources of the whole region" (s59), tackling "the significant resource management issues of the region" (s62(1)(a)).

The functions of regional councils enable them to establish, implement and review objectives, policies and methods "to achieve integrated management of the natural and physical resources of the region" (s30(1)(a)). Of particular relevance to drought is their control of the taking and use of water (s30(1)(e)). Regional councils also have power to control the use of land for the purpose of avoiding or mitigating natural hazards (s30(1)(c)(iv)).

For their part, territorial authorities are able to establish, implement and review objectives, policies and methods to achieve integrated management of the *effects* of the use of land and associated natural and physical resources (s31(a)). They are also to control any actual or potential *effects* of the use of land for the purpose of avoiding or mitigating natural hazards (s31(b)). (Emphasis has been added to the word "effects", but it has generally been accepted before the Planning Tribunal that there is no practical difference between controlling land use itself and controlling the effects of land use. What still remains to be tested however is whether, if specific effects were not able to be clearly linked to the land use in question, a territorial authority could still exercise its s31(2) function, which is to deal with the *effects* of land use.)

One way of avoiding or mitigating potentially damaging interactions between natural occurrences and uses of land is land-use control. Significantly, under the RM Act the land-use control functions of territorial authorities and regional councils overlap (Court of Appeal 1995). In ruling on this question, McKay J (ibid.) commented: "There will no doubt be occasions where such matters need to be dealt with on a regional basis, and occasions where this is not necessary, or where interim or additional steps need to be taken by the territorial authority."

Prior to the RM Act, the Town and Country Planning Act had also enabled development to be restricted in hazard-prone areas, but throughout there has been little willingness on the part of local authorities to take this approach.

With flood damage, the Soil Conservation and Rivers Control Act continues to enable regional councils to carry out a wide range of works related to "water courses", but in the strictest sense, does not oblige them to do so. Any obligation to maintain or enhance river controls generally comes from historical involvement rooted in previous flood experience, and from the commitment implicit in the existence and operation of special rating areas set up under the Rating Powers Act 1988 for that purpose. Regional council functions under s37S of the Local Government Act 1974, and the consultative procedure under s716A of that Act allow the necessary financial provision to be made in regional councils' annual plans.

Other flood mitigation measures, such as site and building design modifications, are also amenable to regulation under the RM Act. This was clarified in a declaration sought by Christchurch International Airport Ltd. In its decision, the then Planning Tribunal indicated that provisions in the Building Act 1991 do not limit rules in a district plan (and by inference, a regional plan) (Planning Tribunal 1994). This is important, because in the case of "surface water resulting from a storm" (ie, flooding), the maximum protection enforceable under the Building Act is set at the level of the 50-year flood (2% annual exceedence probability (AEP)). In such an event water is not to enter houses.

A widely accepted standard for river control schemes has been 1% AEP - the 100-year flood - and the trend is to higher standards. If the Building Act were to limit the RM Act, no rules under the latter could have applied where river control standards were better than 2% AEP.

There has been a long statutory history related to flooding, but the RM Act may be the first New Zealand legislation to expressly recognise the adverse effects of drought. Territorial and regional councils share some abilities to deal with drought, while others are exclusive to one or the other. Both regional and territorial councils can impose land-use controls. They can also provide such things as drought-onset warnings, information, and education in the use of drought-resistant plant species, the adequate stockpiling of feed, and the conservation of drinking water. Only regional councils, however, may issue or vary water permits.

Under the Local Government Act territorial authorities have powers to expend funds in many ways not available to regional councils. It is open to them, for example, to provide direct assistance such as transport of stock or feed, or tankers of water.

Table 10.1. Recurring issues in natural hazards chapters of Regional Policy Statements. (Source: Regional Policy Statements from all 15 local authority regions in New Zealand as at November 1996.)

Adverse effects issues	Knowledge/understanding issues	Response issues
1. Natural hazards pose a threat to people, property and the environment. *Auckland, BOP, Taranaki, Manawatu-Wanganui, West Coast, Otago.*	1. Poor community perception/ understanding of the significance of natural hazards. *Waikato, BOP, Hawkes Bay, Manawatu-Wanganui, Otago, Southland.*	1. The appropriateness of development control in hazard-prone areas. *BOP, Otago, Southland.*
2. The actual or potential costs of natural hazards to communities. *Manawatu-Wanganui Canterbury.*	2. Need to know acceptability to community of risks. *Wellington, Otago.*	2. Maintenance of existing protection. *Northland, Otago.*
	3. Understanding existing threats, their frequency and magnitude. *Northland, Manawatu -Wanganui, Wellington.*	3. Adverse effects of hazard measures. *Northland, BOP, Canterbury, Otago, Southland.*
	4. Identification of risk areas. *Northland, Southland.*	
	5. Effects of climate change/sea level rise. *Northland, Gisborne, BOP, Hawkes Bay, Wellington, Tasman, West Coast.*	
	6. Amplification of hazard events by certain land uses. *Northland, Otago, Southland.*	

Notes:

1. The Waikato RPS identified the division of responsibilities between Region and districts as an issue.
2. The Wellington RPS identified inadequately prepared people in the region as an issue.
3. The Proposed RPS for Southland also listed the following issues: Apportionment of costs, means of adjustment that have not been explored in the past, the spreading of pollutants by floodwaters, lack of financial provision for disaster recovery.
4. The following specific sources of hazard were also identified as issues: Landslip and slope erosion, flooding, earthquakes, volcanic eruption, drought, storm, fire.

Policy Instruments

Each region must at all times have a regional policy statement, and each territorial authority a district plan. Regional plans are not mandatory, except for regional coastal plans. The present generation of regional policy statements has identified a range of issues, a summary of which is given in Table 10.1.

Policy Development

History

From almost the beginning of European settlement in New Zealand, rising flood losses more or less paralleled the rate of land development. Two factors were involved in this natural hazard's growth. One was deforestation, which typically increased the rate of rise of flood peaks and increased their size; the other was the ill-advised siting of settlements on fertile but flood-prone floodplains. The outcome, as noted by Roche (1994), was that by the mid-1980s approximately 1000 communities comprising 1.7 million people were prone to flood damage. As we shall shortly see, neither underlying factor received attention from policy-makers. From the beginning their efforts were concentrated on keeping rivers to their courses.

As agricultural production intensified, drought losses were almost certainly rising at a similar rate, but analysis is partly hampered by a dearth of agreed definitions of what constitutes drought. Definitions range from "an overall shortage of water at critical times of the year" (Dickenson and Sandrey 1986) to "30 or more consecutive days of negligible rainfall" (Canterbury Regional Planning Authority 1977). The Dickenson and Sandrey variant (and also Wilhite 1996, p.12) leave moot the extent to which "shortage of water" may be a function of over-intensive or inappropriate land use, while in some areas 30 consecutive days without rain may be quite normal.

Farming, which is the chief casualty of drought effects, has by and large accepted the inevitability of drought with stoicism - as just another of farming's difficulties. (Figure 10.2). As Batey (1982) observed, "... farmers have consciously farmed with the probability of drought in mind". Drought's probability, particularly in eastern areas of New Zealand is quite high. For example, in a 57-year period between 1914 and 1970 there were seven growing seasons when Timaru received less than 65% of its 1941-1970 average rainfall (Crabb 1982).

Whether accounted for by stoic acceptance or the lack of an event-modifying remedy comparable to stopbanks - such as rain induction or irrigation - drought history has been marked by an absence of pro-active attempts at management. Although in the past there have been numerous instances of drought-affected farmers receiving financial relief from both local and central government, this has always been on an *ad hoc* basis.

National policy

Flood management as distinct from disaster relief has long been legislated for in New Zealand, at least insofar as restraining rivers is concerned. The first statute setting up a public body with power to carry out river works and able to levy landowners to meet the costs was enacted in 1868 (Roche 1994). For many years attempts to control rivers were authorised on a region-by-region basis, and it was only in 1941 with the Soil Conservation and Rivers Control Act that a comprehensive national policy direction came into being.

No similar approach to drought has ever been attempted. There were disjointed efforts that could have led to concerted government action, such as research into rain induction, but these proved fruitless. While there was government assistance with irrigation schemes, this was primarily intended to increase production. Although the schemes did also mitigate drought, the areas served by irrigation were not the most drought prone.

Despite attempts to prevent flooding, there have continued to be flood disasters, and in the past central government often provided emergency relief. As has already been noted, drought assistance had also been forthcoming on numerous occasions. Whereas there had been no clear policy on disaster relief prior to the late 1980s, since that time central government has made it clear that it does not intend to provide significant compensation when disasters occur.

Fig. 10.2. The after effects of drought: soil eroded pastures in Hakataramea Valley 1985. (Photo: Alistair Shearer, Twizel).

Notwithstanding this, a number of tax laws have and still do provide relief after "adverse events" such as droughts and extreme rainfall. See for example the Income Tax Act 1976, the Goods and Services Tax Act 1985 and the Income Tax Act 1994.

Drought has been and still is also accepted as a valid reason for failure to supply water, and until recently, electricity (Electric Power Boards Act 1925, Local Legislation Act 1960, Electricity Act 1968, Local Government Act 1974).

Regional policy statements

The Resource Management Act obliges each region to prepare a regional policy statement (RPS) setting out, among other things, "the significant resource management issues of the region". Without exception, flood damage has been accepted as such an issue, and in the nation's first batch of RPSs river protection works remain prominent among policies to mitigate natural hazards. Newer, and as yet included by only a few, are policies that seek to reduce the damage potential of floods by controlling development on flood-prone land.

The emphasis on flooding is understandable for several reasons. It has a life-threatening dimension and there is often the prospect of large numbers of people being affected in other ways. The onset of flooding is usually sudden. The functions exercised under the RM Act also sit easily with floodplain (as against purely river) management. Land use can be controlled to exclude development from flood-prone areas and measures such as elevated sites or raised floors can now be enforced. There is no question that potential losses are high, which justifies considerable expenditure on mitigation measures.

Drought losses, too, may be high. For example the Canterbury drought of 1987/88 cost the community an estimated $360 million in lost earnings, transport of stock and feed. Seemingly, such losses are not a significant resource management issue for so far not one RPS has a specific drought policy.

This may come with time. In many respects the RM Act's philosophical base is new, and to reduce drought losses under its provisions may also call for novelty. What may prove at least as important is whether loss-mitigation can be accomplished cost-effectively. Dickenson and Sandrey (1986) were sceptical of the net benefit from compensation payments made in the wake of past droughts; it not only remains to be seen whether the issue will be taken up under the RM Act, but if so, whether new kinds of intervention fare any better.

(These last comments are specific to RPSs. In general regional council functions and powers in relation to natural hazards are limited to those conferred by the RM Act and the Civil Defence Act 1983. By contrast, many territorial authority powers derive from the Local Government Act 1974, which among other things enables direct drought assistance such as the transportation of water and stock feed, and even financial assistance.)

Regional and district plans

As already mentioned, flooding is a leading focus of regional and district planning in the natural hazards field. In Canterbury alone, seven regional plans to manage floodplains are currently in preparation (in at least three cases jointly with affected territorial authorities).

On the face of it, there is quite a contrast between this level of activity and equivalent attempts to apply planning to drought mitigation. Canterbury, along with Marlborough, Otago and the east coast North Island, is one of New Zealand's most drought-prone regions, yet to date it has no planning initiatives aimed expressly at reducing drought losses.

As noted earlier, a partial explanation for this may lie in the lack of a drought counterpart to the stopbank. Despite recent progress to more holistic management of flood risk, stopbanks remain a prime tool in flood mitigation.

While the RM Act has enabled land use to be controlled for the purpose of natural hazard avoidance or mitigation, so far even for flood avoidance or mitigation, rules restricting land use have proved politically difficult. Drought potential is more widespread and less predictable than flooding, and it seems even less likely that regional or district rules attempting to limit what may be grown or to set stocking rates would be acceptable to any degree.

As already suggested, the rough drought equivalent of the stopbank is irrigation. In the absence of regular rainfall, irrigation maintains soil moisture and thus alleviates the effects of drought. The most drought-prone areas, however, very often lack accessible sources of irrigation water. Sometimes engineering can surmount this problem, and Canterbury, for example, has two regional plans in preparation which provide for river augmentation to enhance the availability of irrigation. No-one claims that drought mitigation is the main aim - that is to boost normal farm production - but in those areas drought mitigation will be a significant secondary benefit. (In river augmentation means are used to increase flows at times when they would otherwise be at their lowest. In the case of the Opihi River in South Canterbury this is to be achieved by use of a dam and a storage lake on the Opuha River. The proposal for the Ashley River in North Canterbury is to transfer water from the Waimakariri River.)

Hazard Perception and Assessment

From the legal definition of natural hazard given above it is evident that flood and drought hazard each involve the intersection of two elements - the physical event itself and the assets which may be potentially harmed (Eriksen 1986). If the two interact then the damage, if any, may range in level from a nuisance to a catastrophe and is a cost to the community concerned. (Figure 10.3)

A simple formula for this is:

$$\text{natural occurrence} \wedge \text{assets} = \text{hazard} \qquad (10.1)$$

in which $\wedge$ denotes the operation of intersection and where, for instance

$$\text{drought} \wedge \text{assets} = \text{drought hazard} \qquad (10.2)$$

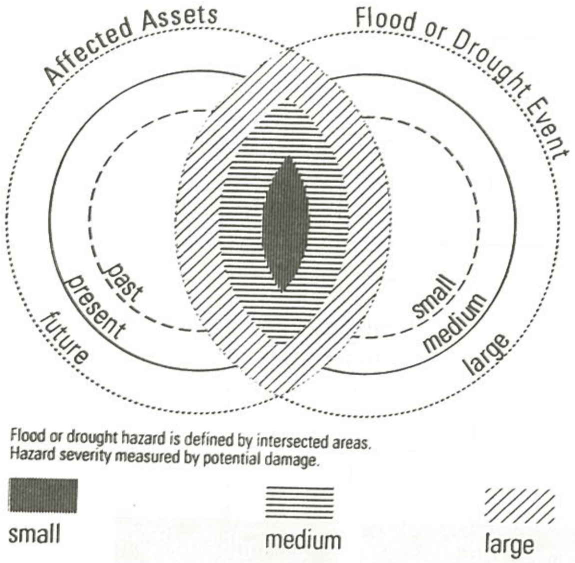

Fig. 10.3. Definition of flood or drought hazard. Diagram assumes positive growth in affected assets. This trend may be reversed by protection measures. (Figure based on Eriksen, 1986, p65)

The severity of a hazard is measured by the size of the potential damage and from Equation 10.1 this depends on the size of both the natural occurrence and the assets which may be harmed.

In order to fix ideas and to be precise a flood is defined as an overflowing of water beyond the natural or artificial banks of a river reach: a drought is defined as occurring when demand for water exceeds supply as a result of lack of rainfall (Dracup *et al.* 1980; Wilhite 1996).

Issues and Objectives

In approaching hazard management there are two principal issues or significant matters of concern. The first issue is the actual or potential costs of flood or drought hazards to communities: the second is the impact of hazard protection measures on aspects of the environment, especially on people, physical and biological resources and taonga (treasured possessions of the Maori (Canterbury Regional Council 1995).

Hazard management is about resolving these issues within some community for some specified period of time through a public process. The outcome sought is a significant reduction in potential damage costs so that protection gained is greater than costs incurred, or a net benefit is delivered.

In this resolution a comprehensive and integrated approach is recommended which considers the full spectrum of both event sizes (from the very small to the probable maximum) and possible flood or drought protection measures.

The objectives are: (i) to avoid or mitigate the actual or potential costs of loss or damage to life, property, or other parts of the environment from flood and drought hazard; and (ii) to avoid or mitigate significant adverse effects on the environment as a result of measures used to mitigate hazards.

Risk and its Perception

Risk management for hazards is a burgeoning area of investigation (Tweeddale 1997).
At bottom, two kinds of risk may be distinguished. One is technical risk, which is concerned with the probability of events occurring in some interval, n (years), and can be described mathematically by the formula

$$r = 1 - [1-(1/T)]^{n} \qquad (10.3)$$

Where T (years) is the return period of the event under consideration. The other is perceived risk which is psychological and has to do with the chance or likelihood that an individual or community ascribes to events and their effects, based on its knowledge and experience. It is psychological risk which contributes most to decision making by a community about the nature and cost of hazard protection measures.

In describing the technical risk of floods or droughts of various magnitudes occurring, it is often useful to educate the public about risk and to place the risk in the context of more familiar events such as the incidence of house fires. People are generally familiar with the value of their assets and the outlay in insurance and other protection measures they are

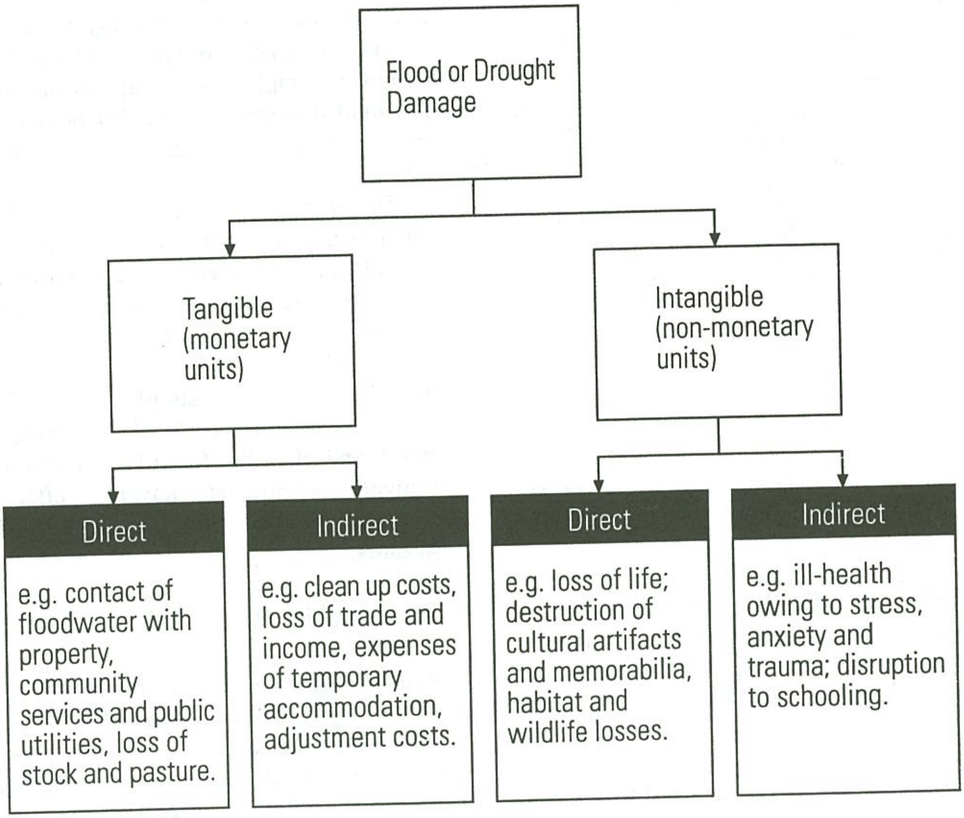

Fig. 10.4. Types of flood and drought damage.

prepared to make to avoid or mitigate fire, and to remedy its effects should it occur.

Damage Types and Costs

Damage from floods and droughts can be classed as either tangible or intangible and for each of these as direct or indirect (Figure 10.4). Direct tangible damage can almost invariably be calculated in dollar terms and indirect tangible costs may be estimated as a percentage of direct damage cost. Intangible damage is commonly estimated using surrogate variables for dollar costs such as "numbers of people directly affected". Another example is damage to biological resources which may be assessed on an ordinal or ranking scale (Siegel 1956) ranging from a very low level to a very high level of damage.

Assessment Techniques

A powerful technique for assessing potential damage at a given location is the scenario method. Here, various sequences of events are postulated ranging from the small and frequent up to the probable maximum; and the damage resulting from each is estimated to give the potential damage from one scenario. All scenarios may then be combined and statistics calculated for use in economic and other evaluations. The method may be used to estimate statistics of potential damage from existing flood or drought protection systems and for new, extended or even reduced systems.

For example, for a floodplain each scenario might involve a flood in a river, one or more failures in a protection system (if one exists), and for each failure an outflow of floodwaters onto the floodplain which causes damage of various kinds.

Associated with each scenario is the probability of it happening within some arbitrary time period. If E_1 is the occurrence of a discrete range of flood size in a river, E_2 is a breach in the protection system at some site, and E_3 is an outflow onto the floodplain through the breach, then the probability of all three events or the scenario happening is P $(E_1E_2\ E_3)$ and is given by the rule for conditional probabilities

$$P(E_1E_2\ E_3) = P(E_1)\ P(E_2/E_1)\ P(E_3/E_1E_2) \quad (10.4)$$

Where $P(E_1)$ is the probability of E_1 occurring, $P(E_2/E_1)$ is the probability of E_2 occurring given that E_1 has occurred, and $P(E_3/E_2E_1)$ is the probability of E_3 occurring given that both E_1 and E_2 have occurred.

The technical risk is the probability of the scenario happening at least once in a given period of time (Equation 10.3).

For example, consider the scenario of an outflow of $200m^3s^{-1}$ through a breach in a stopbank in a given river reach during the passage of 50-70 year return period floods. Then $P(E_1) = 1/60$, say, which is the probability of the flood range being equalled or exceeded in any year. $P(E_2/E_1)$ is the probability of a breach occurring over the length of the stopbank affected and is, say, 1/10. $P(E_3/E_2E_1)$ is the probability of $200m^3s^{-1}$ flowing out through the breach and is, say, 1/5. Thus the probability of the scenario, $P(E_1E_2E_3)$, is from Equation 10.4, $(1/60)(1/10)(1/5) = 1/3000$. The technical risk of this scenario happening at least once in a 40 year interval is from Equation 10.3, $r=1-[1-(1/3000)]^{40} = 1.3\%$.

After each outflow has been hydraulically routed down the floodplain and damage costs have been estimated, then knowledge of those scenario probabilities allows calculation of a statistic such as the expected annual cost (in dollars, say) of potential damage caused by flooding. This is simply calculated by weighting the cost of flood damage under each flooding scenario by the scenario probability and then summing them all. All these calculations may be conveniently carried out using a decision tree (Griffiths 1991).

A similar calculation can be performed where the cost of damage is intangible, and is assessed for example using units of numbers of people directly affected as noted above.

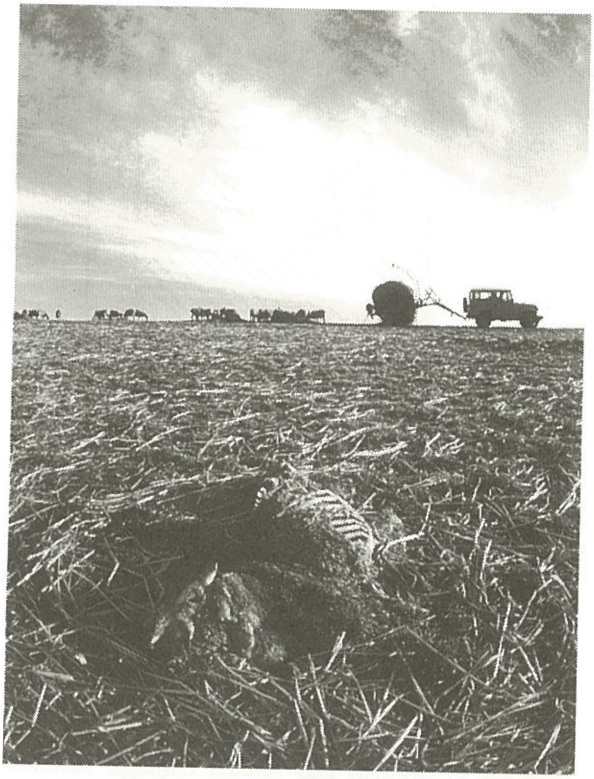

Fig. 10.5. Dead stock: mute witness to the severity of the South Canterbury drought of August 1989. (Photo: Brian High, Timaru.)

Fig. 10.6. A collapsed dwelling at Kainga, near Christchurch, after the Waimakariri River flood of December 1957. (Photo John Drew, Christchurch.)

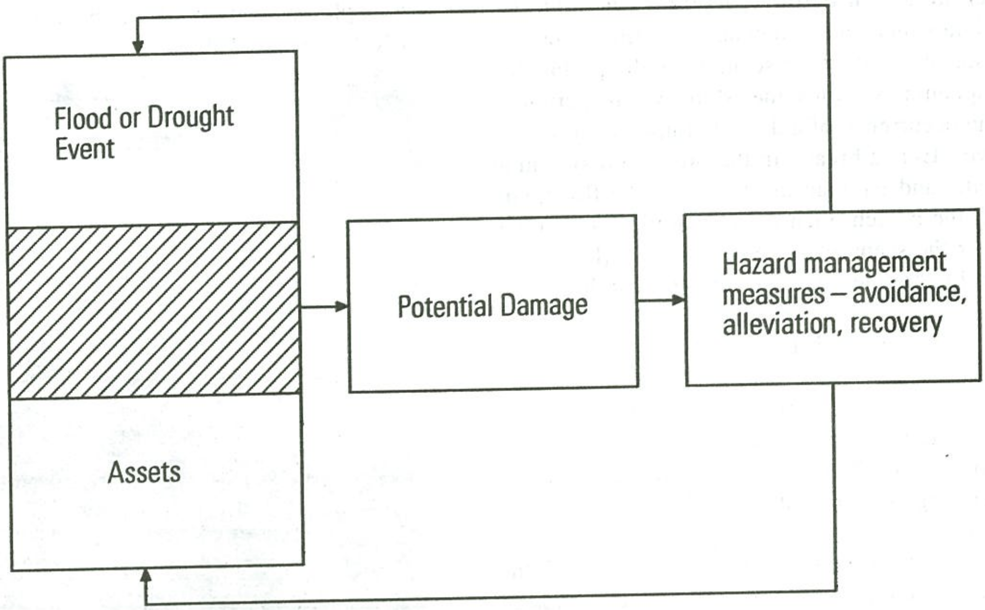

Fig. 10.7. Simplified model of response to flood or drought hazard.

With drought the situation is more complex although the same technique may be used based on scenarios involving the intensity, frequency and duration of drought and related damage. A New Zealand example is given in Griffiths (1990) based on the 1988-89 Canterbury and Otago drought (McGann 1991).

In all assessments it is essential that an error analysis is undertaken. Hydrological records in many areas are short and even with the use of regional frequency methods (see, for example, McKerchar and Pearson 1989) reasonable precision can only be obtained for small to medium sized events and for periods of 2 to 3 decades. Because most of the contribution to expected annual damage costs comes from the smaller events, the effect of short records is not too serious but it does suggest (as will be discussed later) different approaches to managing the effects of small and frequent, as opposed to large and infrequent, events.

Approaches to Hazard Management

It is certain that floods and droughts which inflict losses will continue to occur. There are many communities where the potential for severe loss is unacceptably high and needs to be mitigated, if not avoided. (Figures 10.5, 10.6). Also, if a hazard is realised then remedial action will be required.

Three main principles apply to managing flood and drought hazards - avoidance, alleviation and recovery. (Figure 10.7) For maximum efficiency and effectiveness a comprehensive and integrated approach is necessary in the application of these principles. Specifically, hazard response should consider all probable magnitudes of floods and droughts and all possible management measures to reduce their effects (Erikson 1986). The outcome should be a suite of measures which acting together provide optimal protection against extreme events within the constraints of suitability and affordability prescribed by the community concerned.

The principles and their associated hazard management measures are discussed in turn below.

Avoidance

The objective of avoidance is to not place assets where they might be endangered. Management measures involving land use and stock management, community preparedness and emergency actions

Table 10.2a. Flood management measures.

Purpose	Class		Type	
AVOIDANCE	1	Land use management	(i)	zoning policies and ordinances
			(ii)	encroachment lines
			(iii)	subdivision requirements
			(iv)	building codes
			(v)	land/building acquisition
			(vi)	urban renewal policies and plans
			(vii)	floodplain development policies and plans
			(viii)	removing/rebuilding structures
	2	Community preparedness	(i)	education and public information
			(ii)	flood warning/forecasting
			(iii)	evacuation plans
			(iv)	rescheduling of activities
			(v)	elevation/protection of building contents
	3	Emergency actions	(i)	civil defence
			(ii)	flood-fighting
ALLEVIATION	1	Weather modification	(i)	cloud seeding
	2	Land treatment	(i)	afforestation
			(ii)	conservation farming
			(iii)	onsite ponding
			(iv)	natural storage
	3	River control	(i)	dams
			(ii)	detention basins
			(iii)	channel improvements
			(iv)	diversions
			(v)	stopbanks
			(vi)	local drainage
	4	Floodproofing	(i)	banks, walls
			(ii)	elevation of structures
			(iii)	waterproofing structures
RECOVERY	1	Insurance		
	2	Tax deductions		
	3	Loans and related financial arrangements		
	4	Relief funds		
	5	Feeding and sheltering victims		
	6	Rehabilitation of services		
	7	Social welfare and rehabilitation		

Table 10.2(b). Drought management procedures.

Purpose	Class	Type	
AVOIDANCE	1 Land use and stock management	(i)	drought resistant species and species mixin
		(ii)	pasture renovation and renewal
		(iii)	flexible stocking and appropriate stock breeds policy
		(iv)	flexible grazing systems
		(v)	agistment arrangements
		(vi)	fencing patterns
		(vii)	direct drilling
		(viii)	diversification of farm activity
	2 Community preparedness	(i)	education and public information
		(ii)	drought warning and forecasting
		(iii)	rescheduling of activities
		(iv)	fire hazard management
		(v)	electricity supply alternatives (to hydroelectricity)
	3 Emergency actions	(i)	water rationing
		(ii)	water conservation
		(iii)	wildlife and fish rescue
		(iv)	water quality treatment
	4 Stock feed supply	(i)	buffer feed resources
		(ii)	fodder banks
		(iii)	pest management
ALLEVIATION	1 Weather modification	(i)	cloud seeding
	2 Land Treatment	(i)	afforestation
		(ii)	conservation farming
		(iii)	onsite ponding
		(iv)	natural storage
	3 Water storage and distribution	(i)	reservoirs and ponds
		(ii)	underground storage
		(iii)	wetland development
		(iv)	irrigation
		(v)	water distribution systems
RECOVERY	1 Insurance		
	2 Tax deductions		
	3 Loans and related financial arrangements		
	4 Relief funds		
	5 Rehabilitation of water supplies		
	6 Social welfare and rehabilitation		

attempt to reduce potential damage by altering the use of floodplains or droughty areas to be more compatible with existing risk. Examples of specific measures are listed in (Table 10.2(a) and 10.2(b)).

Table 10.3. Evaluative criteria for hazard management measures.

Category	Main factors considered
Physical	1. damage reduction performance 2. maintenance level 3. implementation problems 4. timing of effect 5. limitations and conditions 6. future flexibility
Economic	1. cost level 2. benefit to cost ratio 3. user pays 4. market distortions
Social	1. disruption 2. recreation opportunities 3. cultural and political matters 4. land acquisition 5. health and safety 6. diversion of hazard 7. public information
Environmental	1. ecology (plant and animal communities and habitat 2. visual or aesthetic amenity 3. water quality

Alleviation

The objective of alleviation is to control or remove sources of danger or the susceptibility of assets to damage. Measures such as weather modification, irrigation, land treatment, river control, flood proofing, water storage and distribution and stock feed supply attempt to change the cause of the physical event as well as the event itself (Table 10.2(a) and 10.2(b)).

Recovery

The objective of recovery is to deal with the consequences of disaster. Measures such as insurance, relief funds and rehabilitation of services, attempt to modify flood and drought losses when they occur by sharing the burden of individual loss and reparation with others, particularly beyond the affected area (Table 10.2(a) and 10.2(b)).

Evaluation of Hazard Management Measures

In considering measures to reduce potential damage some can be eliminated from a possible set immediately where they are clearly inappropriate, prohibitively expensive or will have little remedial effect. Those remaining may then be evaluated. Evaluation criteria for hazard management measures fall within four main categories - physical, social, economic and environmental. Each category is composed of several factors (Table 10.3). These criteria may be used to assess the feasibility and appropriateness of measures and hence their overall acceptability for possible uses to form a set of ptions for hazard protection. An example is given in Table 10.4.

Hazard Management Options

The combined effect of a set of hazard management measures in affording protection is normally greater than the sum of their individual contributions. Because the detailed nature of the constraints of suitability and affordability of a hazard management plan or response are not known before its formulation, it is useful to form and evaluate options composed of sets of management measures to assist decision making by the affected community.

A simple method to compile the options is to put those measures with the highest overall acceptability, as determined above, in the first option; and all measures in the final option. Intermediate options grade between the two (Table 10.5). Three to five options should be sufficient and all suites of options should include the "do nothing" option (which includes no hazard management measures at all) unless there are specific reasons to exclude it.

Table 10.4. Evaluation of floodplain management measures (after Griffiths 1991).

Measures	Evaluative categories				Assessment of overall acceptability
	Physical	Economic	Social	Environmental	
Waterproofing of structures	• low performance • very high maintenance level • limited to building type and materials • protection limited to specific flood range • wastewater surcharging may occur	• high cost • moderate benefit cost ratio (BCR) • user pays	• neutral effect	• neutral effect	Low
Technical advice programme	• low performance • high maintenance level	• low cost • very high potential BCR	• increase awareness and preparedness • reduces social impacts of flooding generally • essential for emergency action	• neutral effect	Very High
Development of floodwarning systems	• very high performance • high maintenance level • applies over full flood range	• low cost • very high BCR	• informs community • reduces social disruption • provides time for effective social response	• neutral effect	Very High
Evacuation	• moderate performance • no maintenance • difficult to implement • often no alternative	• low cost • moderate BCR	• very high social disruption	• neutral effect	High
Elevation/protection of contents	• very high performance • no maintenance	• moderate cost • very high BCR	• reduces losses of artifacts and memorabilia • maintains operation of emergency services	• neutral effect	High

When forming options it is vitally important to bear in mind that structural or physical measures such as stopbanks and water storage can only provide effective and reliable protection for the smaller and more frequent floods and droughts - events with return periods up to 50 years perhaps. Reasons include limitations on their size and cost but also our ability to undertake both appropriate design and benefit-cost analysis based on short term hydrological, economic, social and other records.

Another problem here is that these types of measures may encourage people to invest in hazard-prone areas and underestimate or forget the danger because they believe the measures afford complete protection, or at least the degree of protection desired. (Tobin and Montz 1988). When the measures are overwhelmed or become ineffective the cost of damage may well be much higher than if the measures were not implemented in the first place. This phenomenon, known as catastrophe potential, is described by Eriksen (1986).

For larger magnitude infrequent events the most appropriate measures may be controls on land-use, warning and forecasting, and community preparedness.

Finally the provision of too much emergency relief after a flood or drought disaster may act as a disincentive to other communities to make provision for hazards because it does not promote self-reliance (see, for example, Bruwer 1993; Dickinson and Sandrey 1986).

Evaluation of Hazard Management Options

The same four categories of criteria as for hazard management measures above may be employed to evaluate options. Factors within the categories and considerations of those factors are, however, quite different (Table 10.6).

Option evaluation based on these criteria is aimed at deducing the precise effect of an option in reducing potential damage. This is normally a complex and lengthy process because one has to suppose an option has been implemented before determining its likely performance. Calculation of net present value is difficult: the costs of the option itself must be included as well as the benefits of the option assuming, as is usually the case, the measures of the option are put in place at particular times over a given period. An example is given in Table 10.7.

Management Planning and Processes

Contingency arrangements for the reduction of flood or drought losses centred around a preferred option as described previously, can take various forms. These include regional or district plans, joint regional and district plans, memoranda of agreement between local authorities, provisions in regional or district plans and so on. All these instruments have in common a proactive approach to reducing the vulnerability of a community to a hazard. The alternative is to adopt a reaction or crisis management approach. This is unacceptable nowadays because it is inconsistent with the principles of sustainable management and is almost invariably inefficient, ineffective and untimely (Eriksen 1986; Wilhite 1993).

To illustrate management planning and processes, the example is taken of the development of a regional hazard management plan or the equivalent section of a district plan. The structure and general content of a management plan for the Waimakariri River is illustrated in Figure 10.8. If a plan is to be accepted it must be prepared in consultation with the community concerned. Planning needs to take account of political, socio-economic and technological trends and be suitable for, and affordable by, that community.

This requires clear identification of the affected community, education, consensus building, regular communication and community decision making before the plan is likely to obtain formal approval under the Resource Management Act. All the above requires convincing and comprehensive technical support and needs to be driven by strong leadership and unwavering political will. These elements are discussed in detail below.

Affected Community

For some flood or drought hazards, for example, a drought in Canterbury and Otago the affected community may include the whole nation. Effects occur at different levels - local, district, regional and national; the contribution from each level in terms

Table 10.5. Floodplain management options (after Griffiths 1991).

FLOODPLAIN MANAGEMENT OPTIONS					
Floodplain ManagementMeasures	FloodplainManagement Options				
	Option1	Option 2	Option3	Option4	Option 5
1. Extension of protection planting	x	x	x	x	x
2. Upgrading of existing floodplain groynes	x	x	x	x	x
3. New groynes			x	x	x
4. Extension of rock protection			x	x	x
5. Development of gravel extraction	x	x	x	x	x
6. Upgrading of existing stopbanks				x	x
7. Extension of existing stopbanks	x	x	x	x	x
8. New stopbanks					x
9. Outflow control structures					x
10. Restriction of urbanisation	x	x	x	x	x
11. Re-zoning				x	x
12. Raising of floor levels		x	x	x	x
13. Control, relocation or exclusion of dangerous uses		x	x	x	x
14. Building line restrictions			x	x	x
15. Elevation of building sites			x	x	x
16. Secondary flowpaths					x
17. Extension of existing building codes				x	x
18. Banks and walls					x
19. Waterproofing of structures				x	x
20. Technical advice programme	x	x	x	x	x
21. Development of floodwarning systems	x	x	x	x	x
22. Evacuation		x	x	x	x
23. Elevation/protection of contents		x	x	x	x
24. Flood fighting techniques		x	x	x	x
25. Insurance					x
26. Assessment of numbers and location of victims		x	x	x	x
27. Assessment of services disruption		x	x	x	x
NUMBER OF MEASURES IN OPTION	7	14	18	22	27

of planning and particularly funding of protection measures should at least, from an equity viewpoint, be proportional to benefit received. This supplies a basis for deciding which principal stakeholder groups in an affected community should be directly involved in consultation and decision making for hazard management. A guideline is that those directly affected (and who receive a direct benefit from, and pay the most for, protection measures) should be directly represented, for instance those who are likely to have floodwaters on their property or their water supply reduced in a drought. Over-representation by an particular group of stakeholders should be avoided on equity grounds.

Table 10.6. Evaluative criteria for hazard management options.

Category	Factor	Main considerations
Physical	1. Future flexibility	Scope for future alteration and implementation of alternatives
	2. Implementation	Ease or difficulty of construction or instalment
	3. Effectiveness	Efficiency and reliability
Economic	1. Net present value	Net costs and benefits arising from implementation in dollar terms
Social	1. People affected	Number of people with property directly affected plus number indirectly affected in a flood or drought.
	2. Preparedness	Extent to which community is able to respond effectively to flood emergency or drought.
	3. Recovery	Extent to which community is able to deal with victims and restore services.
	4. Political	Strategic, legal, policy and equity aspects; acceptability of operation.
	5. Recreation	Improvement or otherwise in scope, type and frequency of leisure, sports and related activities.
	6. Cultural	Tangata whenua issues and concerns; historic sites buildings and amenities of cultural significance.
Environmental	1. Ecology	Degree of improvement or otherwise to plant and animal communities and habitat.
	2. Landscape	Enhancement or detraction of aesthetic values; scenic appeal; harmony with existing features.
	3. Amenity	Enhancement or detraction of living environment.

A group to represent the interests of the natural environment is also desirable.

Communications and Role of Media

The importance of regular communication and consultation between the planning authority and the affected community cannot be overemphasised, and ought to commence at the earliest stage when the hazard issues are being defined. Nowadays, people are busier than ever and there is strenuous competition for their attention and concern. A communication strategy needs to be devised using print, radio and television because the media are the conduits to the public. It may be necessary to change attitudes and perceptions, to inform the public and to keep the hazard issue topical. Active opposition to management measures such as a rule

Table 10.7. Evaluation of floodplain management options (after Griffiths 1991).

Evaluative Category (Table 10.6)	Evaluative Factor (Table 10.6)	Units	Options (Table 10.5) 1	2	3	4	5
Physical	Future flexibility	-	Minimal constraints Minor cost to alter or reverse	As for Option 1	Low level of constraints Minor cost to alter or reverse	As for Option 3	Heavily constrained Extremely costly and difficult to alter or reverse
	Implementation	-	Relatively straight forward Restriction of urbanisation will be opposed. Normal land purchase/access problems with extension of stopbanks	Moderately difficult. Raising of floor levels and control of sites will be opposed.	Moderately difficult Similar problems to Option 2 with building line restrictions and elevation of sites Normal land purchase/acce ss problems with new groynes	Difficult. Re-zoning likely to be strongly opposed. Waterproofing technically demanding to design.	Very difficult. Land acquisition for new stopbanks problematic. Secondary flowpaths and insurance will attract strong opposition. Technical complications with outflow structures.
	Effectiveness	-	Moderately effective. Performance of gravel extraction ppolicy dependent on market demand. Results from technical advice programme likely to be variable.	As for Option 1.	Effective. Additional measures such as new groynes building line restrictions and elevation of sites increase reliability and total performance	Moderately effective. Upgrading of stopbanks re-zoning extension of building codes and waterproofing have performance uncertainties	Moderately effective New stopbanks increase effectiveness but this is offset by performance uncertainties with outflow controls, secondary flow paths and insurance
Economic	Net present value (Internal rate of return)[2] (0%)	$M	-0.98 (1.8)	-0.95 (2.4)	1.06 (14.8)	-0.07 (9.8)	-21.7 (-8.7)
Social	People affected	Person units	4500	4200	1050	900	300

[2] The internal rate of return (IRR) is simply the real rate of return on the investment. A generally accepted target figure is about 10%. IRR is directly related to net present value, but it is included here because it makes comparisons between options easier.

restricting subdivision can be defused to some degree by media campaigns involving promotions, talkback and so on. These should be handled by professionals because a plan can be lost, for example, by an ill considered series of commercials. The media are independent and relationships with the media must be managed objectively and neutrally over a sustained period bearing in mind the powerful support and influence the media can provide. A key element in achieving a good rapport is to provide enthusiastic, competent and sincere spokespersons.

Table 10.8. Consultation methods.

Consultation Method	OBJECTIVES			
	Giving information	Seeking information	Sharing information	Participatory decision-making
Direct mail	✓			
Media statements	✓			
Customer services	✓	✓		
Publications	✓	✓		
Polls/surveys/coupons	✓	✓		
Research		✓		
Hearings		✓		
Submissions	✓	✓		
Issues and Options papers	✓	✓		
Internet	✓	✓		
One-on-one meetings	✓	✓		
Hui on marae	✓	✓		
Pre-hearings/meetings	✓	✓	✓	
Seminars/conferences	✓	✓	✓	
Networking	✓	✓	✓	
Public meetings	✓	✓	✓	✓
Focus groups	✓	✓	✓	✓
Workshops	✓	✓	✓	✓
Liaison Committees	✓	✓	✓	✓
Consultative Committees	✓	✓	✓	✓
Council Committees	✓	✓	✓	✓
Direct Mail	✓	✓	✓	✓

Consultation

For plans prepared under the RM Act there is a requirement for formal consultation with the Minister for the Environment and affected ministers of the Crown, local authorities, and tangata whenua.

Case law provides the elements of effective consultation (see for example, Court of Appeal 1991). These include: (i) stating in proposal form the issue or concern on which you are to consult; (ii) not making a decision on the issue until everyone involved has had his or her say; (iii) allowing sufficient time to listen to everyone; (iv) providing enough information so that participants can give intelligent and useful responses; (v) carefully considering their ideas; (vi) being open to those

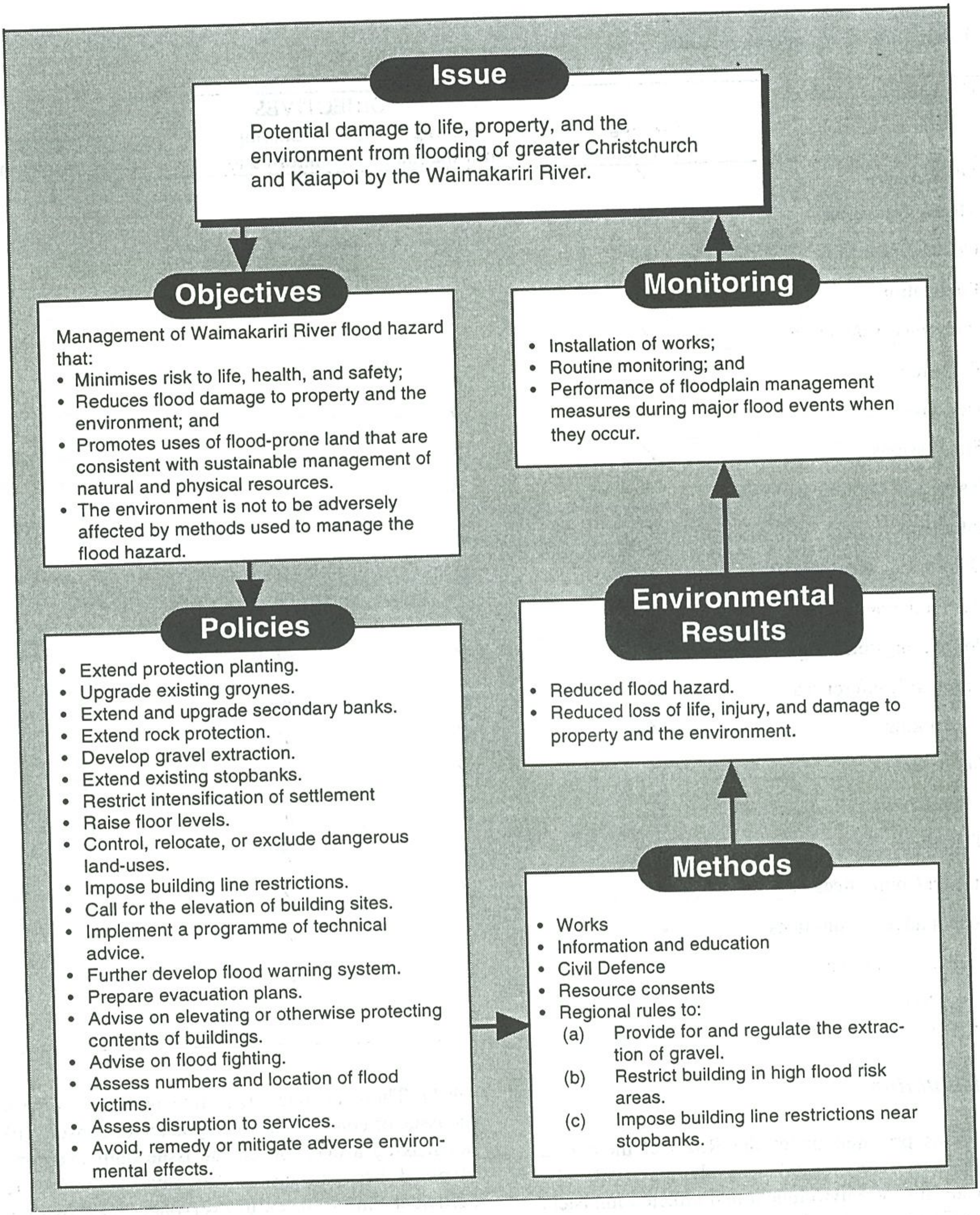

Figure 10.8. Diagrammatic summary of proposed Waimakariri River Floodplain Management Regional Plan (Canterbury Regional Council 1996).

ideas and being willing to start afresh if necessary; and (vii) being genuinely committed to the process of consultation.

The RM Act's requirements are a minimum. A hazard management plan requires consultation with a much wider range of affected parties, and this should precede formal consultation under the Act. Table 10.8 sets out various consultation methods; further details on processes and procedures are given in Canterbury Regional Council (1997).

Community Decision Making

As with communication and consultation with the public noted above, it is constructive to set up a community advisory committee to provide assistance and advice to the agency preparing a hazard plan. The committee should consist of nominees from key stakeholder groups representing, for example, residents of the affected community, environmental interests, development interests, industry and agricultural interests. Representatives from tangata whenua and local authority politicians should also be committee members. An independent chairperson is desirable along with a professional facilitator. The committee is a means of engendering public confidence or ownership in the planning process and for satisfying some contemporary expectations of accountability. It also provides a focus for media activity.

In the latter stages of plan development, opportunities must be provided for individuals to express their opinions of the proposals. Public meetings, phone-ins, opinion surveys, booths at public entertainments and the like can be used.

The main task of an advisory committee is to select an option that is technically defensible and practicable; and is suitable for, and affordable by, the affected community. Public notification of a proposed plan should not proceed until the advisory committee is satisfied with the content. Lastly, the agency team servicing the committee should be highly professional with appropriate planning, legal, environmental, social and technical expertise.

Formal Approvals

Where a hazard management plan takes the form of a regional plan, or part of a district plan, prepared under the RM Act there is a lengthy democratic process to make it operative. (Combined regional and district plans are another possibility.)Details are given in the First Schedule to the Act but the basic steps include public notification of the proposed plan, the receiving and hearing of submissions and further submissions on the document and the public notification of decisions on those submissions (with reasons). Appeals against decisions may be lodged to the Environment Court. After disposal of appeals by this Court or higher courts the proposed plan (possibly amended) can take final effect. Regional and district plans, and particularly any rules in them, have effect from the date of notification. However, implementation only becomes categorical as the final stages of approval are reached.

The main reason for this process is that these plans will contain policies and particularly rules which may seriously restrict the activities of people on a floodplain or in a droughty area. For example, there may be rules controlling building densities and locations or perhaps land-use. Rules are usually quite complex and the areas to which they apply must be defined at the scale of an individual lot, so that property owners can readily determine if and how a rule applies to them. For example, part of the rule for the control of land-use for building purposes in the Stopbank Zone (defined in detail on maps) for the Proposed Waimakariri River Floodplain Management Regional Plan (Canterbury Regional Council 1996, p28) reads:

Controlled activity

The replacement of buildings destroyed during or as the result of a flood is a controlled activity in the Stopbank Zone defined in ..., provided that the building or buildings concerned were lawfully established prior to being destroyed, and application for a resource consent for the replacement is made within 12 months of the flood event.

Matters over which the Council will reserve its control

When granting a resource consent, and in imposing any conditions, the Canterbury Regional Council will reserve its control to the degree of any increase *in potential flood damage owing to the replacement of the building or buildings concerned. In deciding this the Canterbury Regional Council will have regard to the following:*

(a) The safety of the occupants of the building or buildings concerned.
(b) Potential flood conditions at the site.
(c) Site topography and the location of the building on the site.
(d) The value of buildings and contents concerned.
(e) Other measures in place or to be taken to reduce potential effects of the proposed building or buildings, and any site development, on the movement of floodwaters.

Activities not affected

The following activities are not affected by the above rule:

(a) Extensions or alterations to existing buildings.
(b) The replacement of buildings destroyed other than during or as the result of a flood.
(c) Repairs to buildings damaged through any cause, but not destroyed.

And this is the simples of the rules in that Plan.

Finally, those affected must have an opportunity to formally challenge whatever is proposed.

Non-statutory hazard management plans may also be prepared and approved by local authorities. Appeals against provisions therein may be made by way of judicial review.

Implementation

Once a flood or drought hazard management plan has been approved or made operative it can be fully implemented, normally by a regional and/or district council. This involves putting in place a suite of hazard management measures which will be effective before, during and after a flood or drought event. Whatever the protection measure the implementation process usually involves five phases: (i) detailed design of the measure; (ii) operational planning; (iii) approvals and resource consents; (iv) funding; and (v) delivery. Implementation of a protection system should be carried out according to a schedule where the most important measures are installed first subject to physical, financial, social and other constraints. While these processes largely apply to organisational activity, of equal importance are actions by individuals such as taking out insurance, flood proofing a house or deepening a well. These need to be promoted. The five phases are now briefly discussed.

Design of Protection Measures

This phase involves creating concepts in detail for a specified protection measure in a form suitable for costing and construction or delivery. The form may range from detailed drawings for a stopbank or reservoir to regulations for tax relief.

Operational Planning

By this is meant plans, schedules or programmes for organising people and resources to put hazard management measures in place. It may involve an education programme or a district civil defence flood plan or ensuring compliance with a rule about water restriction in a regional or district plan. Operational plans are normally very detailed and with civil defence, for instance, which is primarily concerned with saving life, exercises involving simulated events are essential if the plans are to work when actually required. Another example concerns restoration of "lifelines" that is, services such as water, drainage, gas, electricity, telecommunications, broadcasting, transport and building, following an extreme event (Centre for Advanced Engineering 1991).

Approvals and Resource Consents

Once design and operational planning requirements are complete various approvals and resource consents will usually be needed to construct or deliver a protection measure. Land may have to be purchased and water permits and land-use, building and discharge consents obtained, for instance, before a water storage dam can be built.

Funding

As already noted, government grants and subsidies have officially ended. This leaves major hazard protection measures such as afforestation, channel improvements, and extensive stock agistment schemes to be funded by the affected community from property rates based on for example, capital value, land area or land value. The Rating Powers Act 1978 prescribes these rating matters. The general principle is that of the user paying in proportion to the benefit received from a particular hazard management measure or suite of management measures in a rating district. Rates in this category which are levied over a special section of the community are "separate rates". More indirect benefits, such as the avoidance of disruption of communications or education, may be funded by "general rates," levied on the whole community.

Delivery

This final stage of implementation involves actual construction or actioning of a protection measure. Detailed contract documents and tender specifications may have to be prepared and publicly advertised. Scheduling of physical actions, funding and payments, inspection and so on, all with corresponding performance measures may be required.

The output sought is a protection measure or system which should reduce flood or drought damage in the future. Paradoxically, despite all the investment in time, money and effort involved in installation the best possible outcome is that the measure will never be used. Like life insurance one hopes one's beneficiaries never collect, but of course they will eventually!

Monitoring and Review

Hazard management does not cease with the implementation of some management system prescribed by a hazard management plan for example (Figure 10.9). Plans are prepared because there are hazard issues to be resolved. It is only by monitoring the protection system's outcomes, and those environmental and societal changes which may affect it, that an assessment can be made of its suitability and effectiveness in resolving the issues and the need for any review and subsequent alterations (Stevens 1994). It is useful to prepare a monitoring strategy covering issues, objectives, indicators, information inventory and an implementation programme (Cooper 1996).

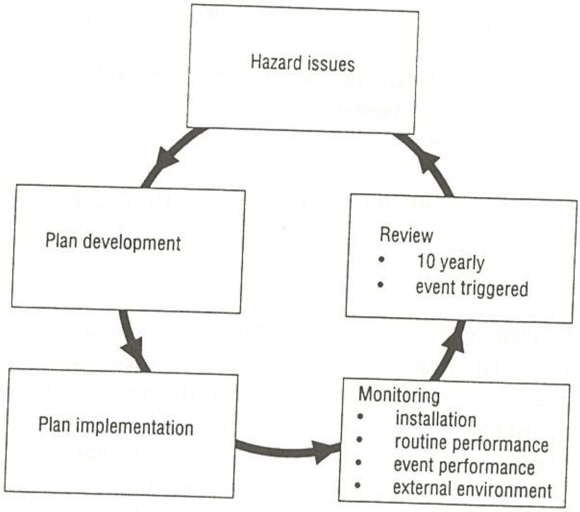

Fig. 10.9. Monitoring and review of hazard management.

Indicators

The basis of monitoring is the regular measurement of indicators or parameters from whose values and trends the performance of management responses can be evaluated as well as likely effects on their operation. Ideally the parameters should be simple, well defined, easily measurable, comprehensive and few in number. These requirements can be achieved readily enough for the monitoring of a flood or drought protection system itself but rarely so for external effects from factors such as new technology, research results, legislative action or changes in political leadership.

Monitoring Processes

Processes involving regular measurement of indicators, analysis and reporting of results need to

Table 10.9. Types of monitoring examples.

Type of monitoring	Example items	Indicators	Frequency
1. Installation of hazard management measures	Storage reservoir	Design and construction specifications	Installation period
2. Routine performance of hazard management measures	Public education programme on flood or drought hazard	Public opinion surveys	2 yearly
3. Event performance of hazard management measures	Fodder bank	Usage rate and benefit	During drought event
4. External environment	Growth of urbanisation on floodplain	Subdivision and building consents	Continuous

be established to cover four areas: (i) monitoring of the installation of hazard management measures; (ii) routine monitoring of the performance of these measures, where and when they are operative; (iii) event-based monitoring of how management measures are utilised and perform during a major flood or drought; and (iv) monitoring of the state of the external environment as far as it affects resolution of a hazard issue (Table 10.9).

Responsibility for monitoring of community projects will generally lie with the relevant regional and/or district council as part of their responsibilities under Section 35 of the RM Act.

Many aspects of monitoring are a never ending process and ought for reasons of objectivity and transparency to be carried out by a group who are independent of the promoters, managers and builders of hazard management systems.

Review

A review of the performance of a hazard management system needs to be carried out at regular intervals even if it has not had to go into action. For major systems a thorough-going review ought to be done every 10 years. The occurrence of a severe flood or drought, however, may well yield consequences that call for earlier review.

Where far reaching alterations are required it will probably be necessary to undertake the full public process as for the original development and, for example, formally notify a proposed plan change.

Future Directions

The philosophical approach to dealing with floods and droughts founded on the principles of risk management and sustainable management, has a sound theoretical basis, is supported by legislation and is underpinned by powerful analytical techniques and a wide range of proven and practicable protection measures.

But public knowledge and concern about hazards is at a low ebb. A market-oriented political climate with a focus on the short term and individuals looking out for themselves makes promotion of hazard management very difficult, given the many societal constraints that already work against the public recognising future risk and taking action to reduce potential losses. The main constraints are competing values of individuals and institutions, arguments over jurisdiction, the immediate costs of hazard protection measures whose benefits are long delayed (or may not be realised), and the general tendency to ignore the risks of low probability, high impact events.

For the above reasons progress with hazard management in New Zealand under the Resource

Management Act 1991 is slow or conspicuously absent. However the new Act must be given time to work: its implementation would be greatly assisted nevertheless by a national policy statement for hazard management, or at the very least non-statutory guidelines from central government.

Despite this, the *sine qua non* for action by an affected community is still an acceptance of their hazard problem and the leadership and political will to resolve it. The alternative is crisis management with traumatic and bitter experiences whose hard lessons are seldom learned.

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11
Floods and droughts: case studies

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Introduction

How do the science of flood and drought prediction, the engineering responses to floods and droughts, and the legal provisions for mitigating and responding to these extreme events translate into actual practice?

This chapter presents four case studies - two flood events and two droughts - to answer that question. The case studies cover comparatively recent major events for which substantial information is available, and which provide lessons for future management of hydrological extremes.

The four case studies are:

1. South Canterbury floods, 1986
2. Cyclone Bola floods, 1988
3. South Island hydro drought, 1992
4. Auckland water crisis, 1994.

Case study 1: South Canterbury floods, March 1986

This case study is valuable because detailed data were available on the causes of the flood damage and useful lessons were learned for future flood management.

Flooding of the Opihi, Tengawai, Pareora and Waihao rivers inland of Timaru in South Canterbury (Fig. 11.1) on 13 March 1986 was the worst since February 1868. Damage to property, roads, bridges and river control works exceeded $60 million (South Canterbury Catchment Board, 1987, p. iii).

Two thousand people were evacuated, and flooding affected Pleasant Point, Temuka, Orakipaoa and Milford Huts, Levels Plains and Seadown, the Washdyke industrial area, Pareora Valley and south to the Waihao Valley, Willowbridge and Morven areas. However, only one life was lost, probably because the flood peak occurred during the day.

Weather conditions

The March 1986 flood was caused by a weather pattern similar to those causing the smaller floods in 1945, 1951, 1961 and 1965 (Fig.11.2). Depressions in the north Tasman Sea and offshore from Canterbury, combined with the orographic effect of the Canterbury foothills, caused high intensity north-easterly rainfall for almost 24 hours from late on 12 March.

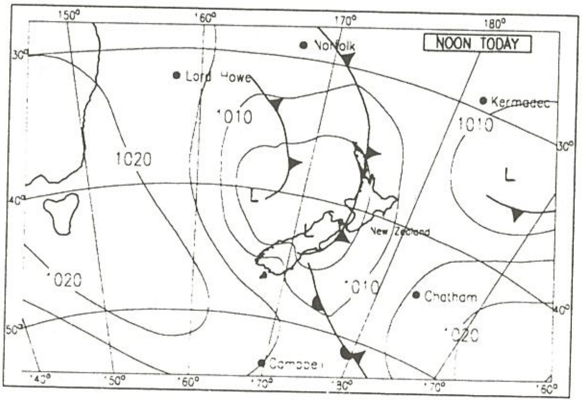

Figure 11.2. Weather map at noon, 12 March 1986.

Rainfall intensities for 2, 6, 12 and 24 hour intervals all exceeded 1:50 year intensities for Timaru and Kakahu Forest, with, for example,

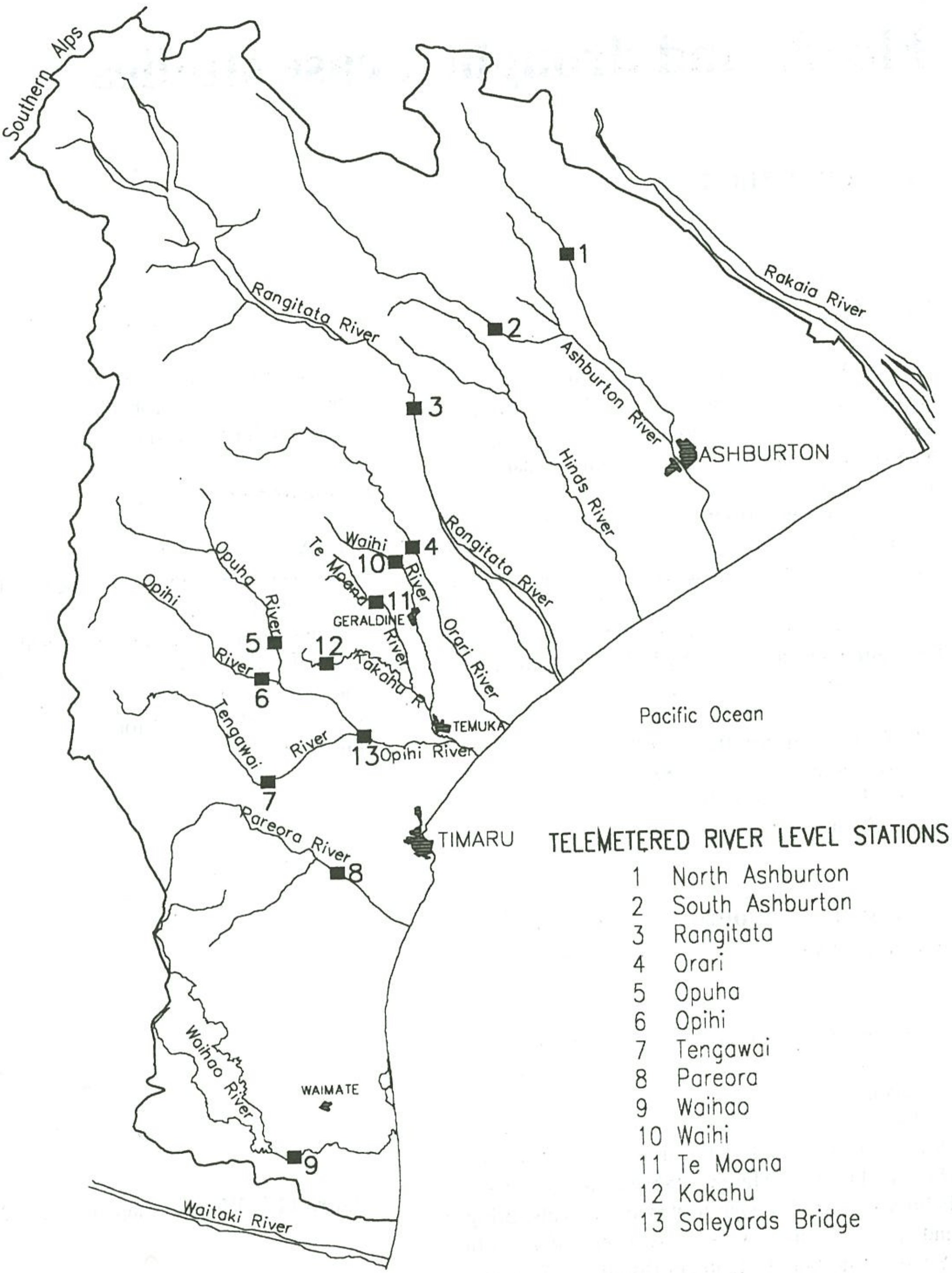

Figure 11.1. South Canterbury catchments and telemetered river level stations.

50mm falling in two hours at Kakahu Forest. Rainfall totals for the whole storm reached 250 mm in the Hunters Hills between 12-14 March.

Flood estimation

The former South Canterbury Catchment Board monitored river levels telemetered from 10 stations, but did not have telemetered raingauges for flood prediction. Three of the water level recording sites were washed away during the flood. River flow, normally gauged from bridges, could not be measured because of the high velocities, flood debris, the mobile riverbeds and damage to bridges caused by the flooding.

Flood hydrographs to estimate peak flows were constructed using one or more of these methods:

- rating curve extension,
- area-velocity estimation,
- slope-area calculations using the Manning equation,
- backwater curve analysis, or
- a modified Manning equation (Barnes, 1966).

Flood levels

Intense rainfall at the end of the storm produced some very large flood peaks. Gumbel analysis of 51 years of flow record for the Opihi River at Rockwood gave a return period of 200 to 300 years for its 1020 m^3/sec peak flow.

The ratio of peak discharge to mean annual flood was 6.75; Beable and McKerchar's (1982) regional flood study suggests a ratio of 4.0 for a 200 year flood in South Canterbury rivers.

Peak flows for the Opihi at Saleyards Bridge were estimated at 3440 m^3/sec and for the combined Opihi and Temuka rivers at Waipopo as 4400 m^3/sec. Figure 11.3 shows the portion of the flood peak which flowed outside the channel of the Opihi River at Saleyards Bridge.

Repair costs

The flood report (South Canterbury Catchment Board, 1987) estimated the repair costs for this flood (Table 11.1).

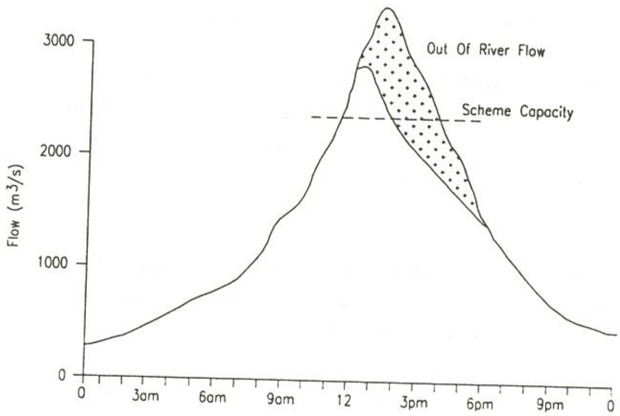

Figure 11.3. Flood hydrograph, Opihi river at Saleyards Bridge, 13 March 1986.

Performance of flood control works

Stopbanks and flood control works were generally effective in reducing the impact of the flooding, even though stopbanks were overtopped and breached on the Hinds, Waihi, Temuka, Opihi, Tengawai, Washdyke, Pareora, Waimate, and Waihao rivers. In valleys such as the Tengawai, Pareora and Waihao, floodwaters occupied the entire valley floor between the hills.

Table 11.1. Estimated costs of damage for the March 1986 South Canterbury floods (modified from South Canterbury Catchment Board 1987, p.54)

Type of damage	Estimated cost
Industrial and commercial property	~$20M
Houses and domestic property	~$10M
Estimated uninsured property	~$10M
Roads and bridges	$19M
Farm, stock and crop losses	$6.2M
Railways	$1M
Water and sewage schemes	$2.5M
Flood control works	$6.2M
TOTAL	~$74.9M

Stopbank designs usually include an allowance for freeboard (the distance between the design flood height and the top of the stopbank), to allow for factors such as local obstructions and flow alignment effects which are not accounted for when calculating flood levels. Thus, the actual flood capacity before overtopping occurs is greater than design capacity (Table 11.2).

Table 11.2. River works scheme performance, 12 March 1986 (summarized from South Canterbury Catchment Board 1987, ch.6).

River	Design flow (m^3/sec)	Scheme capacity (m^3/sec)	Flood flow (m^3/sec)
Hinds	164	230	260
Orari	1275	-	800
Waihi	145-176	180-200	200-300
Temuka	720	800-900	1100
Tengawai	500-1000	1100	1500-1650
Opihi to Tengawai R	1500	1800	1870
Opihi to Temuka R	2400	2900	3400
Opihi to mouth	3130	3700	4400
Washdyke	144	185	220
Pareora	400-500	900	1450
Waihao	710	530	1250

In spite of the breaches of flood control works, the South Canterbury Catchment Board (1987, p. 42-43) suggested that the river works prevented the flooding of 4000 hectares in the Ashburton catchment. In the Opihi catchment, flood protection works were credited with protecting 12 000 hectares from flooding and reducing the depth of floodwaters by 0.3-0.5 metres near the Tengawai confluence.

Damage to flood control works was caused mainly by lateral riverbank erosion, breaches of stopbanks, deep scour (up to 5 metres), blockage of fairways with trees, and scouring of grassed waterways. On the lower Opihi River, over the 30 km of river control works, the cost of repairing in-stream damage - including repair of training works, and vegetation and gravel clearance - averaged $18,900 (1986 dollars) per kilometre of stream length, and stopbank damage averaged $8,600 per kilometre.

Land damage

Land damage within individual catchments was assessed by catchment board staff using aerial photographs, and surveys and inspections of farms (Table 11.3).

Table 11.3. Summary of surveyed farmland damage (summarised from South Canterbury Catchment Board 1987, p.63).

Number of farms surveyed	257
Total farm area	211,413 ha
Total farm area flooded	10,674 ha
Number of slips/gullies	2,215
Total area of slips/gullies	485 ha
Total area of soil loss	1139 ha
Total area of gravel/silt deposition	1094 ha
Average depth of soil loss	235 mm
Average depth of gravel/silt deposition	315 mm

On steep lands with slopes greater than 20 degrees, land damage comprised slipping, slumps, and gully, streambank, and streambed erosion and deposition. Damage correlated strongly with rainfall totals. Old erosion scars were reactivated, fresh slips and gullies were initiated, and streambeds were degraded, commonly by one to two metres. Forested areas, as expected, were noticeably more stable than adjoining areas in pasture.

On downlands, the main type of land damage was from rilling or sheet wash on sloping cultivated paddocks. This could have been avoided by soil conservation practices such as reduced cultivation, contour cultivation, strip cropping, conservation tillage and maintaining drainage channels in grass.

The old and recent floodplains of the flats were subject to scour and deposition, with scour common in areas where river breakouts caused high flow velocities. Surveys showed that flooded cropped areas were three times more likely to suffer soil loss than pasture.

Lessons learned

Telemetered rainfall information would have given earlier warning of impending flooding, over the warning provided by telemetered river levels. Regional authorities need to ensure that flood warnings passed to radio stations, territorial authorities and Civil Defence are being passed on to the public and affected residents. In some cases during this flood, flood warnings were not being passed on to the public.

Flood response staff need to be deployed to isolated areas before access is lost, as locals may not be able to be contacted and reporting back of field conditions is vital for flood response.

Preparation of Civil Defence and territorial authority plans needs to involve regional authorities responsible for flood response, so that each organisation is aware of its role during a flood. For example, Civil Defence security arrangements prevented access by catchment board staff to damaged works for a period during this flood.

Local long term river flow data are extremely valuable for estimating flood frequency and thus for the design of flood protection works.

Depleted upper catchment areas and old erosion scars were a major source of sediment to the lower river.

Debris lines and areas of inundation need to be surveyed within about two weeks of the flood event; this requires a large commitment of personnel. This information, together with aerial photography taken during the event, is essential for mapping hazard areas for future land use planning, repair and upgrade of flood protection works, and estimation of peak flows.

Awareness of the devastation caused by major floods can quickly fade in the public memory, and short-term economies can start to take precedence over prudent risk management. Full reports on major floods, such as that by the South Canterbury Catchment Board (1987), including flood inundation maps, provide a permanent reminder of the risk and are valuable sources of informtaion for land use planning and flood mitigation.

Case study 2: Cyclone Bola

The Cyclone Bola storm of 5-10 March 1988 will remain in the memories of New Zealanders for decades to come. Although Bola affected the top half of the North Island, this case study is limited to the area of greatest devastation - from Gisborne to East Cape.

Cyclone Bola was the most destructive tropical cyclone to have reached New Zealand this century. While most of the flood damage was centred on the east coast of the North Island, there was considerable damage elsewhere, including severe wind damage to forests in Taranaki.

This storm showed how fragile the soils of the deforested erodible hill country of the East Coast can be under heavy rainfalls, and highlighted for many the unsustainability of some farming practices in that area. Government disaster relief following Bola exceeded $100 million (Table 11.4) (Parliamentary Commissioner for the Environment 1993).

Hydrology

During the first week of March 1988, Cyclone Bola moved south from Fiji to south of Kermadec Island. Then, blocked by an anticyclone to the south, it moved only slowly west across the top of the North Island before weakening as it moved south to Taranaki on 10 March. Bola brought a persistent easterly airflow to the upper North Island, which reached severe gale force (~100 km/hr) in the East Cape area during 7-9 March.

The damage caused by Cyclone Bola resulted not so much from the intensity of the rainfall as from the three day duration of the storm (Fig. 11.4). For Gisborne Airport, the return period for the three day rainfall of 300 mm was about 45 years, but the return period was more than 100 year further north for Tutamoe (705 mm), Tauwhareparae (900 mm) and Tokomaru Bay (843 mm) (East Cape Catchment Board 1988).

Analysis of 54 years data on flood peaks for the Waipaoa at Kanakanaia Bridge showed that the Bola flood had a return period of about 100 years, and was probably of similar frequency for the Hikuwai catchment at Tolaga Bay. At Te Karaka, the Waipaoa River rose over nine metres and stayed

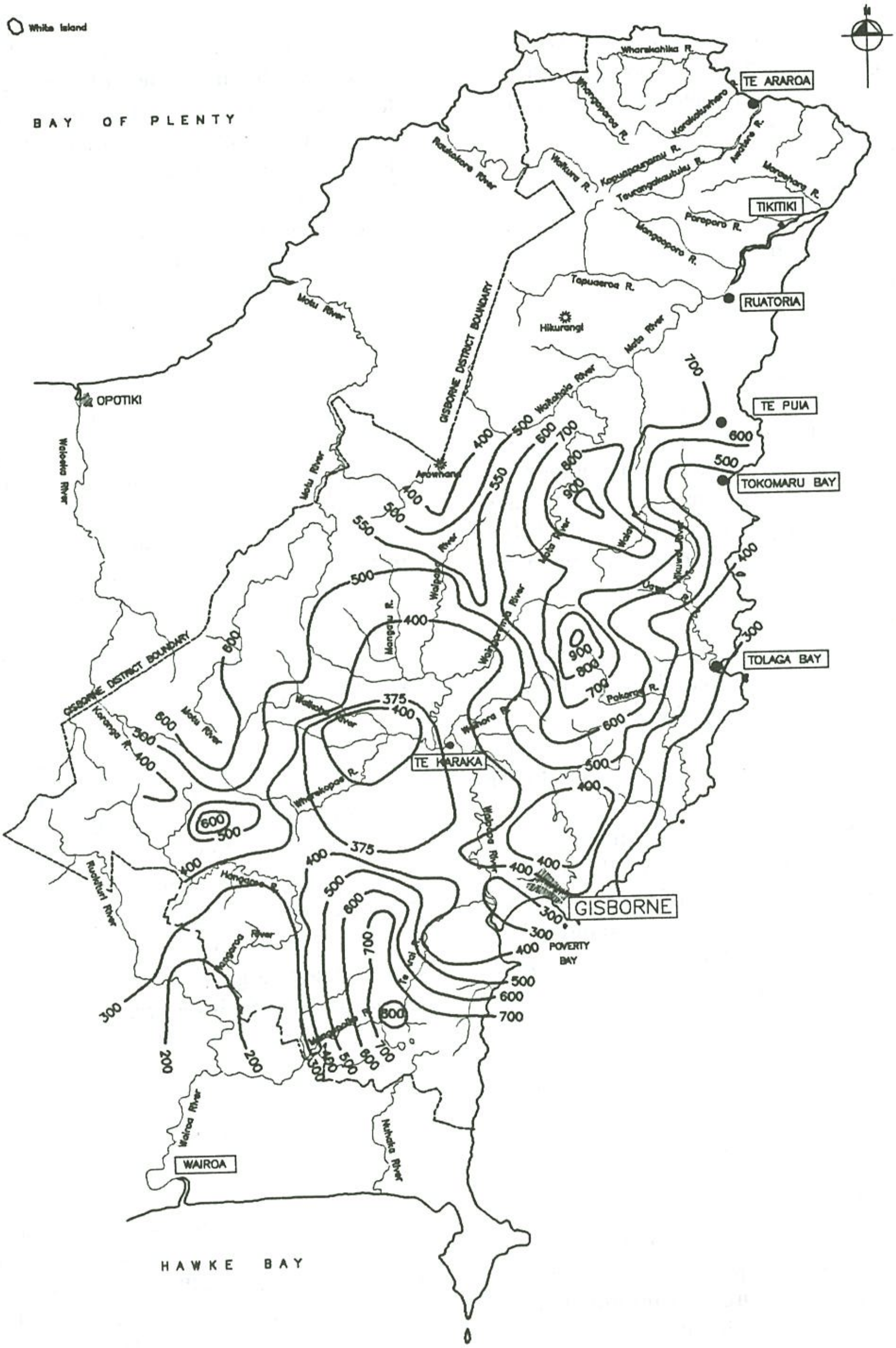

Figure 11.4. Rainfall totals (mm) for Cyclone Bola, Gisborne District.

at that level for 32 hours from midnight on 8 March, peaking at 5300 m^3/sec (Fig. 11.5).

Table 11.4. Government disaster relief, Cyclone Bola (Parliamentary Commissioner for the Environment 1993)

	Cost
Damage to catchment works	\$3.2M
Gisborne water supply	\$6.6M
Gisborne railway bridge	\$3.5M
Road repairs	\$34.3M
Farm Assistance Fund	\$50.0m
Disaster Recovery Employment Scheme	\$4.7M
Horticulture Salvage Scheme	\$0.75M
Civil Defence Disaster Recovery	\$3.3M
Mayoral Relief Fund	\$0.15M
TOTAL	\$111M

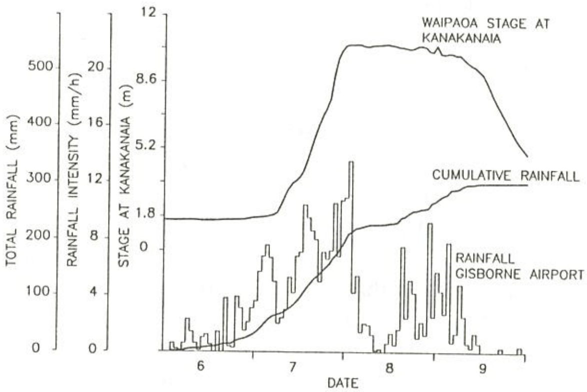

Figure 11.5. Rainfall and flood response for the Waipaoa River, 6-9 March 1988.

During this storm, local rivers discharged sediment equal to several times their mean annual sediment loads, largely consisting of mud and fine sand from the soft Tertiary siltstones and mudstones (Foster and Carter 1997). The mean annual sediment discharge for the Waipaoa River is 12.9×10^6 tonnes/year, which at 5840 tonnes/km^2 is the fifth highest specific sediment yield of any catchment in New Zealand (Griffiths and Glasby 1985). The suspended sediment load, estimated at 40×10^6 tonnes for the 6-day Bola event, was more than five times the mean annual load and resulted in the continental shelf off Poverty Bay being inundated with mud (Foster and Carter 1997).

Flood response

Routine flood warnings of the impending storm were telephoned to landowners on the Waipaoa, Waioeka/Otara, Taruheru and Waimata rivers on 6 March. Radio warnings were broadcast in the early afternoon of 7 March, and a civil defence emergency was declared by 9 pm that night.

Urban residents in low lying areas of the Waimata and Taruheru rivers were warned by 6.30 pm on 7 March that they should move furniture and appliances, as the Catchment Board expected Waimata River levels to exceed those of 1985, and this occurred at midnight.

The East Cape Catchment Board (1988) reported that flood hazard maps for Poverty Bay, and hydraulic modelling of flood overflows for the Waipaoa River, were helpful in warning Civil Defence where overflows would occur, such as at Mullooly Road, Waipaoa. The report noted however that some recently constructed buildings were flooded, which might otherwise have been avoided through better consultation with the Catchment Board when the planning or building consents were obtained.

The Waipaoa River Flood Control Scheme was begun in 1953, following disastrous flooding of the Poverty Bay flats in May 1948. It was designed to contain what was then considered to be the 100 year flood of 4400 m^3/sec at Kanakanaia.

The Bola flood was twenty percent larger, but was largely contained within the stopbanks. However, major damage occurred near the river mouth, where some 20 hectares of land and 300 m of stopbank were swept away, leaving the west abutment of the railway bridge in mid-river (Plate 11.1). Repairs to the scheme flood control works exceeded \$3 million, with a further \$2 million needed to repair the rail bridge.

The Waipaoa River overflowed its stopbanks at Mullooly Road, at Waituhi and at Ormond. The overflow near Ormond caused considerable damage to local orchards, but had little downstream effect on the levles of the Taruheru River in Gisborne City.

"Piping" occurred at the toe of a tributary bank at Ormond and around an irrigation pipe through the stopbank at Patutahi, and was difficult to contain; a house was evacuated at Patutahi because of the risk of bank collapse.

An economic review of the Waipaoa Flood Scheme (Harris 1988) noted that the scheme had provided a satisfactory economic result with an internal rate of return of 13% - without considering social impacts (such as relief from fear, uncertainty and upheaval), and at a time of poor agricultural and horticultural returns. However, Harris noted that afforestation and other conservation measures were needed in the upper catchment to avoid a reduction in the scheme's flood protection standard through ongoing deposition of silt in the Waipaoa River.

Inland of Gisborne, the Te Karaka Flood Scheme stopbanks were only three-quarters completed. Flood waters swept around the end of the uncompleted stopbank, causing extensive damage in low-lying parts of Te Karaka. Stopbanks without grass cover were severely eroded, and required rebuilding.

Roading damage

In Cook County alone, estimated damage to roads was $8.5 million and damage to bridges $1.25 million. Thirty to forty percent of the bridges required debris removal and repairs to their approaches. Adding roading and bridge damage in Waiapu, Waikohu counties and Gisborne City brought total immediate roading damage close to $20 million.

Further south at Wairoa, the State Highway bridge was destroyed by the Wairoa River. The township of Wairoa was split in two.

Water supply damage

Gisborne City's water supply from the Waingake/Mangapoike catchment, some 40 km southwest of Gisborne, was also badly affected. The major damage included serious blockage of the main water supply intake and landslide damage to pipelines, access roads and to the catchment area. Repairs cost some $11 million. The damage to the water supply catchment necessitated the immediate addition of coagulation and filtration systems, and prompted a search for potable groundwater from beneath the Poverty Bay flats.

Drain and other river damage

The East Cape Catchment Board managed 59 drainage districts and 10 river districts at the time of Cyclone Bola. Half the drainage districts suffered silt damage: in many districts, silt completely wiped out the crops. Clearing drains and outlets alone cost $0.3 million.

Floodways in some river districts were widened by two or three times by the force of the floodwaters. Considerable river stabilisation, planting and bridge protection works were needed after Bola.

Erosion

The most visible evidence of Cyclone Bola was the scarred hillsides of the East Cape. Half the area suffered 'very severe' to 'extreme' erosion. Old slip scars reopened, shallow slips were widespread, and gully erosion and deep-seated slumping were common. Satellite imagery indicated that 10-20 percent of the hill country had undergone severe landsliding (Trotter 1988).

Deep siltation of valley floors occurred, especially in the Hikuwai Valley. Observation showed, however, that forested land with trees more than 8-10 years old, and areas where pole planting and gully control soil conservation works had been carried out, had only limited erosion (East Cape Catchment Board 1988).

Government response

The magnitude of damage caused by Cyclone Bola (and perhaps its timing in the electoral cycle) provoked considerable government support for repairs.

In response to recommendations from the Primary Production Committee of Parliament, the government initiated two afforestation projects. The East Coast Project Conservation Forestry Scheme targetted severe to extreme eroding land within the

Class VII land-use category. Between 1989 and 1993, some 13 700 hectares of land were planted, costing around $10.8 million, two-thirds of which was government subsidy.

The East Coast Forestry Project of 1992 offered tendered grants for converting erosion prone land to forestry use. In 1993, the scheme was adjusted to encourage protection of indigenous vegetation and to give preference to the most severely eroding land. (Parliamentary Commissioner for the Environment 1993). The government also contributed to a contestable fund for on-farm soil conservation works for 1994.

In her 1993 report to Government, the Parliamentary Commissioner noted the poor progress in moving to more sustainable land use on the East Coast. She noted that only 5.5% of the at-risk land had changed to a more sustainable use, and recommended that at least 20 000 hectares should be planted between 1994 and 1999, to bring this total to 15%.

Between 1993 and 1995, the East Coast Forestry Project planted 7070 ha of forest, 39 percent of which was on the land most vulnerable to soil erosion. Between 1993 and 1996, the total new area planted in Gisborne District was about 21 000 ha.

The Parliamentary Commissioner (PCE 1993) also suggested that Gisborne District Council (which took over East Cape Catchment Board functions in 1989) should encourage forestry and soil conservation works, monitor land use change, complete its Vegetation Removal and Earthworks Regional Plan, and encourage the establishment of Landcare groups to increase awareness of sustainable land management.

The Gisborne District Council noted in response that some 195 000 hectares needed soil conservation work, and about half of this required a change in land use from pastoral farming to forestry.

By 1997, the Council was ready to notify a Combined Regional Land and District Plan. Rules regulate further land clearing and earthworks, but education and advocacy methods for land management are also implemented.

The $50 million provided by Government in the Farm Assistance Fund (Table 11.4) was intended to restore damaged farms and facilitate land-use and ownership change, by providing compensation for 60% of non-insurable losses caused by Cyclone Bola. A Ministry of Agriculture review of the effectiveness of the expenditure concluded that it did little to prevent a similar disaster occurring again. Many farmers used the money to reduce debt. The Minister noted that it may have been counterproductive, doing little to encourage more appropriate land use and risk management by farmers (Parliamentary Commissioner for the Environment 1993).

Case study 3: 1992 South Island hydro drought

New Zealanders will also long remember the 1992 hydroelectricity drought, as it dominated the news for several months, and resulted in calls for voluntary electricity savings and talk of 'brown-outs' in the cities between May and July.

This hydroelectricity shortage was the result of two factors: the low level of hydro storage relative to total hydro generation in New Zealand, and record low inflows to South Island hydro lakes from November 1991 to July 1992.

New Zealand hydroelectricity system

In 1992, most of New Zealand's electricity was provided by the Electricity Corporation of New Zealand (ECNZ), which has now been split up to encourage more competition in power generation. Three-quarters of New Zealand's electricity comes from hydro-generation, which supplies between 20 000 and 33 000 GigaWatt hours (GWh) per year, depending on rainfall. This compares with a current annual demand of around 32 000 GWh (Devine 1996).

Most of the hydro-generation is supplied from the South Island lakes on the Waitaki and Clutha rivers. Lakes Tekapo and Pukaki in the Waitaki Basin hold almost 66% of the total hydro storage in New Zealand (Electricity Shortage Review Committee 1992). Peak flows in these catchments occur in summer during snowmelt in the Southern Alps, while peak electricity demand, particularly in the North Island, occurs in July-August.

Because New Zealand's hydro storage amounts to only 15 percent of average annual station inflows, the North Island coal and gas-fired thermal power stations are used to meet peak demands, and to manage hydro lake levels when inflows are low. This low hydro storage capacity is a poor buffer when drought occurs.

1992 hydro lake inflows

Between November 1991 and March 1992, monthly inflows to South Island hydro storage were consistently below means for the previous sixty years (Table 11.5; Fig 11.6), although these low flows had a return period of less than 1 in 10 years (Devine 1996). This coincided with an El Nino weather pattern.

Table 11.5. South Island hydro lake inflows for 1992 (Electricity Shortage Review Committee 1992)

Month	% of average monthly inflow	Return period
January 1992	89%	1:3
February	92	1:3
March	74	1:6
April	59	1:12
May	48	1:18
June	50	>1:33
July	107	-

Cold temperatures in April and May 1992 throughout New Zealand increased normal electricity demand for those months by 5-6 percent. This was partly attributed to volcanic aerosols in the atmosphere from the Mt Pinatubo eruption. With continuing low inflows - even with all base-load thermal power stations generating - hydro storage continued to fall (Fig. 11.7).

Low inflows persisted through June until the first two weeks of July, when South Island inflows were above average for the first time. There were two further weeks of low inflows up to late July, and then rains finally broke the drought (Fig 11.7).

Electricity industry response

ECNZ alerted industry and the public in mid-May 1992 to the possible consequences of continuing low inflows to its hydro lakes. An Electricity Industry Committee was set up and after meeting on 2 June, called for 10 percent voluntary electricity savings.

ECNZ committed their emergency reserves: they began to draw down the storage of Lake Benmore, gas turbine stations were run at full load, and the Huntly thermal station was operated at overload. ECNZ had already advanced the commissioning of the new Clyde power station by six weeks.

ECNZ also reached an agreement with Comalco for the company to shut down a pot line at their aluminium smelter, that used electricity equivalent to five percent of national demand. The government passed special legislation (since repealed) to allow ECNZ to draw down Lake Pukaki below the levels allowed in its resource consents, although this was not needed.

Lessons learned

An Electricity Shortage Review Committee was set up by the government in September 1992. Their report (Electricity Shortage Review Committee 1992) analysed the drought and ECNZ's response, considered public submissions, and recommended changes to ECNZ's systems and practices. The report concluded that ECNZ had managed and operated the electricity generation system in an appropriate and professional way.

One major recommendation was that ECNZ change from a 1:20 to an interim 1:60 dry year security standard. This means that even if the worst inflow conditions of the last 60 years were repeated, there would be no need to ration electricity, if all thermal plant were operating. In a drier period, supply restrictions will occur. (Interestingly, the establishment of a wholesale electricity market and the splitting up of ECNZ since 1995 have moved decisions about security of supply - at least in theory - from generators to retail power companies.)

The difficulty of interpreting the severity of the 1992 event was highlighted by the huge variability in return period calculated for the inflow sequence, as shown in Table 11.6.

Statistical analysis shows the frequency distribution of minimum flows to be normally distributed rather than positively skewed. This led ECNZ to replace its traditional Log Pearson Type

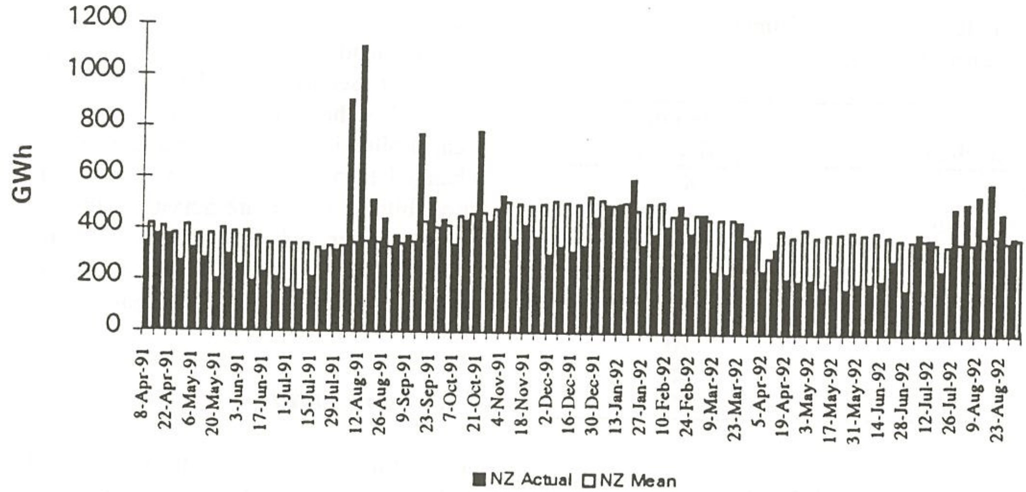

Figure 11.6. Total weekly inflows to South Island hydro lakes, 1991-92.

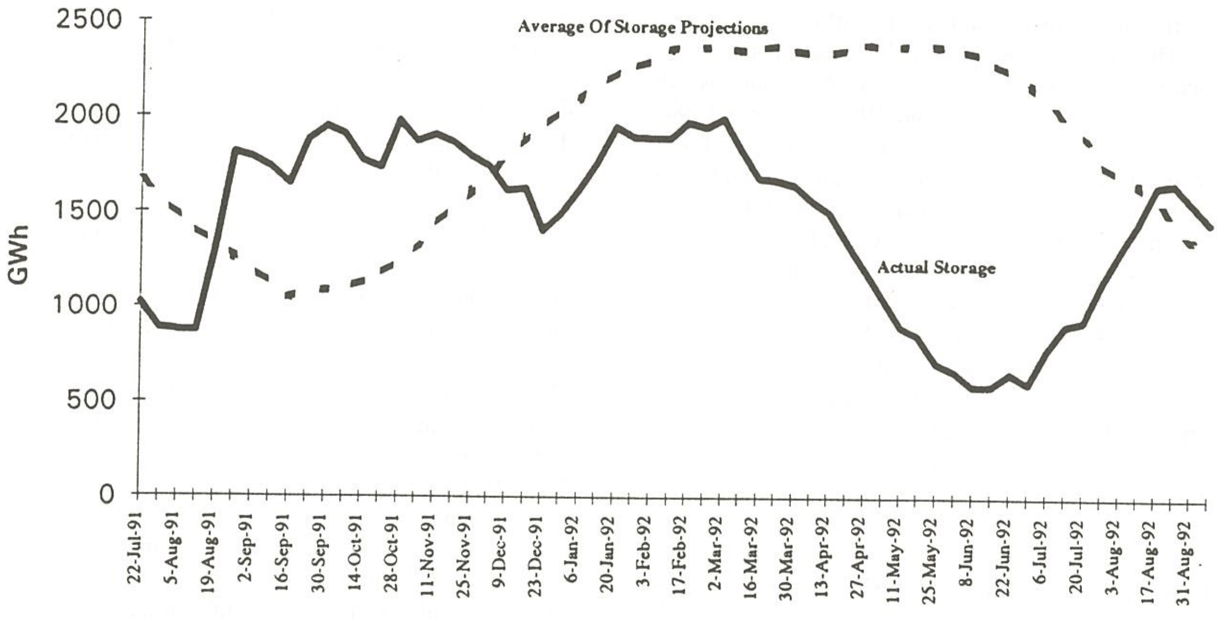

Figure 11.7. NZ hydroelectricity generation storage profiles, 1991-92.

III statistical analysis of inflows with the Gumbel method, which is a more conservative estimator of low flow frequency.

Following the 1992 drought, ECNZ also recognised that it had limited expertise to interpret the hydrological and climate information provided by its consultants. For example, Lake Tekapo generation potential was overestimated by 300 GWh because the lake level fell below the range for which the generation model had been calibrated (Electricity Shortage Review Committee 1992, p.53). ECNZ has since set up specialist advisory panels to provide expert advice on these matters, with significant reports required to be peer reviewed (Devine 1996).

Table 11.6. Return period estimates for the same inflow sequence (from Devine 1996).

Statistical method	Return period (yr)
Log Pearson	44
Log Pearson (adj)	41
Bobee	204
Log Normal	180
General EV	247
EV1	10
Gumbel	25
Jenkins	49

The main outcome of all ECNZ's soul searching following the 1992 drought was that the best predictor of future hydro inflows is still the distribution of historical recorded inflows.

The recent drought which received the most media attention was the 1994 Auckland water supply 'crisis'. Between mid-1992 and mid-1994, the water levels in Auckland's storage lakes dropped from 100 percent full (around 100 000 cubic metres) to a mere 31 percent (Fig 11.8).

The response, after considerable local government politicking over the drought, was a water conservation campaign and a proposal to pipe water to Auckland from the Waikato River. The 'crisis' had ended by December 1994, by which time lake storage had recovered to 93 percent full (Fig 11.8). The management and expansion of Auckland's bulk water supply has been the topic of lively political debate ever since.

Case study 4: Auckland's water supply system

Watercare Services Ltd supplies metropolitan Auckland's water from five dams in the Hunua Ranges (65.5% of total supply), five dams in the Waitakere Ranges (31.8%), and a wellfield at Onehunga (2.6%) (McPike 1995).

Auckland's average daily demand in 1994 had stabilised at 327 000 m^3/day (Fig. 11.9; Turner 1995). Residential uses accounted for 51%, industry 18%, and commercial 16%, leaving 15% unaccounted for (Heeringa 1994).

Auckland's water supply was operated to a 1:50 dry year security standard, i.e. a two percent probability that supply will not meet demand in any year. Following the 1994 drought, the standard was changed to a 1:200 security standard (0.5 percent probability). Watercare Services Ltd now operates a 'Savings Plan' which dictates the savings in water use required from users, based on the 'normal' lake storage available through the year (McPike 1995).

Weather conditions

The same El Nino conditions and Mt Pinatubo volcanic eruptions that contributed to the South Island hydro drought are also blamed for the Auckland water crisis. Persistent dry weather patterns - mainly anticyclones with cool, dry southwesterlies - began in 1991, the longest period of El Nino conditions since the mid-1910's. Statistical analysis of rainfalls attributed 43 percent of the variance to El Nino climatic conditions (Salinger 1995).

Log Pearson type III analysis of rainfalls at the Albert Park (Auckland City) and Moumoukai (Hunua Ranges) raingauges indicated that the 1992-94 event had a return period of 1:20 to 1:25 years. Analysis of total annual discharge for the Orere River in the Hunua Ranges gave a similar result (Cumming 1995). For durations of 18 months, the rainfall recorded at the Manganese Mine gauge, also in the Hunua Ranges, was the lowest in the 66 years since 1928 (A.McPike, pers.comm.).

Two-year rainfall at Albert Park during the 1992-94 drought was 1885 mm, compared with a mean two-year rainfall of 2502 mm for the period 1920-90. Analysis of annual rainfall totals for 1853-1995 at Albert Park, corrected for local changes in gauge location, suggest that the 1994 drought had a return period of 30 to 40 years (Fowler 1994). Drier periods than the year ending June 1994, in order of severity, were those ending December 1914, October 1913, May 1892 and May 1886 (Cumming 1995).

Inflows to Auckland's storage lakes during the 1994 event were 74 percent of the mean, and ranked as the lowest in 14 years of record (Freestone 1995).

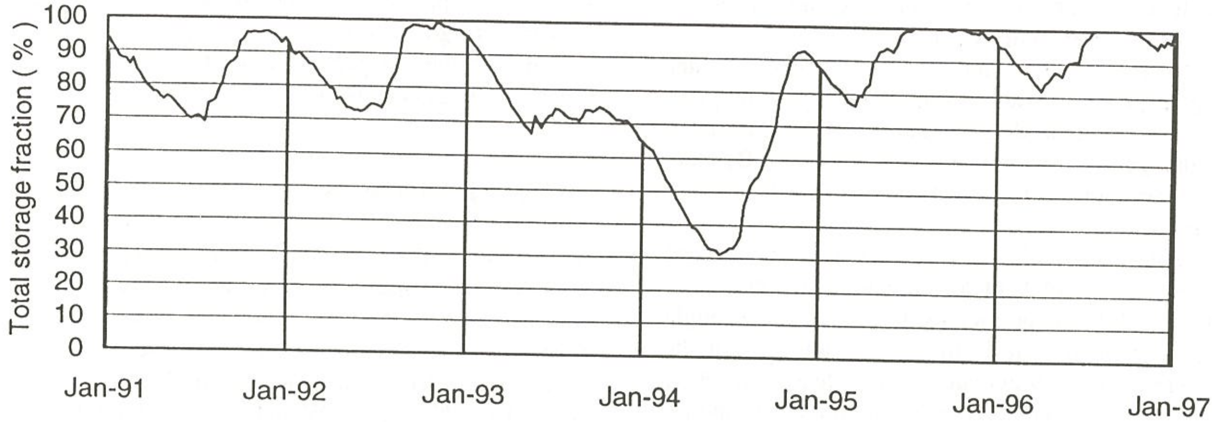

Figure 11.8. Auckland water storage (percent full), 1991-1996 (copyright Watercare Services Ltd).

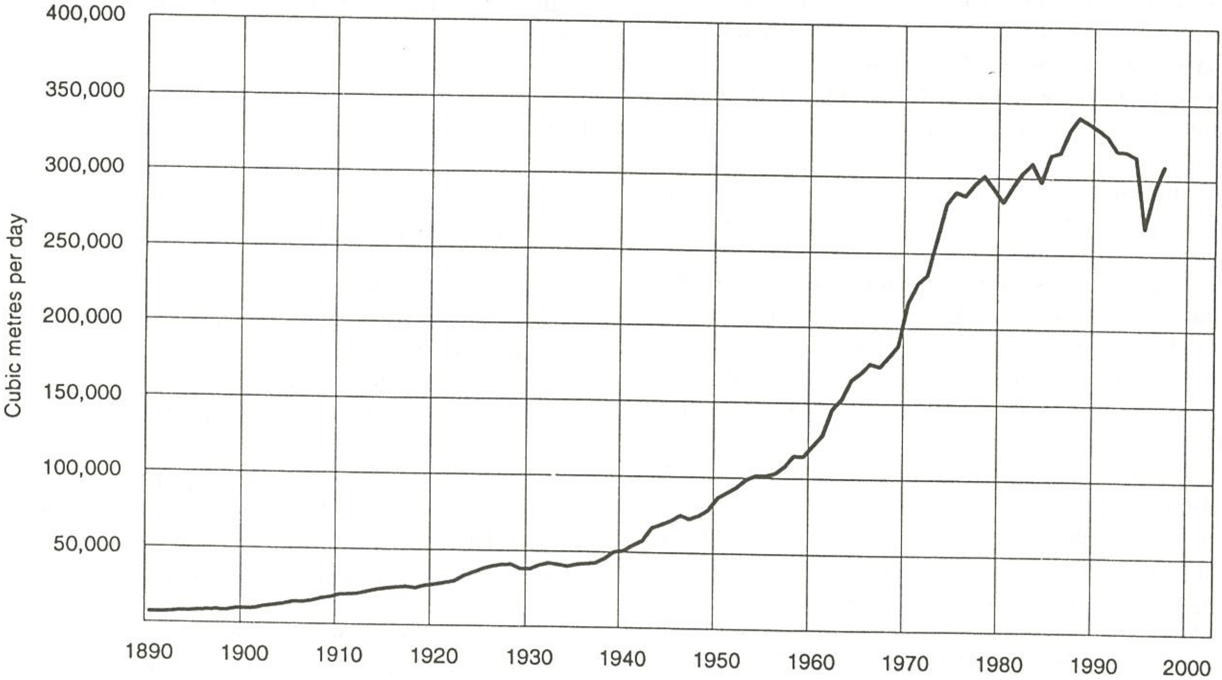

Figure 11.9. Trends in Auckland bulk water demand, 1890-2000 (copyright Watercare Services Ltd).

Response to the 'crisis'

When the normal winter rains did not come in the 1993 winter, Watercare warned Auckland's local authorities that, although a water supply crisis would not occur in the 1993/94 summer, restrictions would certainly be necessary by the 1994/95 summer if the winter rains were low again in 1994 (Heeringa 1994).

By November 1993, Watercare was warning that a drought more severe than 1:50 was likely, and predicted (accurately) that storage could fall below 40 percent after summer (Fig. 11.7).

In December, Watercare and council water engineers agreed on a drought management plan. Stage One, invoked in January 1994, was a media campaign to encourage water savings. By late February, sprinkler and odd-day hosing bans were enforced.

When storage levels fell to 36 percent in April 1994, Watercare held a workshop with engineers and local body politicians to prepare a drought management plan reflecting the seriousness of the situation. The Watercare plan, released in May 1994, recommended 16 percent domestic savings (10 percent for winter; 25 percent for summer), and a search for alternative water sources. Savings in usage were initially meagre. In June, the Auckland mayoral forum called for savings of 25 percent; the mayors considered a 16 percent target to be too modest, given the severity of the water shortage. By July, voluntary savings in usage were exceeding 28 percent.

In June, regional council civil defence staff announced that drastic measures would be taken if water storage levels fell to 15 percent: water would be available only from standpipes in the streets. During June and July, Watercare built an intake in the Wairoa River under the emergency provisions of the Resource Management Act to draw an additional 300 litres per second into the pipeline from the Hunua dams.

Investigations and negotiations began for installation by Christmas 1994 of a one-metre diameter pipeline to pump water from the Waikato River near Mercer to the Ardmore filter station. The pipeline was intended to supply an additional 120 000 m^3/day at an estimated construction cost of $65 million and annual operating cost of $2 million. This would cost ratepayers an average $15 extra per household per year. A private members bill was introduced to Parliament in July 1994 to bypass Resource Management Act consent procedures and expedite construction.

After storage lakes recovered to near normal levels by October 1994, the Waikato emergency pipeline proposal and the associated parliamentary bill were deferred.

In October 1995, Watercare decided to seek resource consents to build a $118 million treatment plant and pipeline from the Waikato River near Tuakau Bridge with a capacity of 80 000 m^3/day, intended to meet expected demand for 15 years at the 1:200 drought standard.

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The standard image of New Zealand is one of peaceful green pastures and sunny country towns. However, the New Zealand experience can be very different. Floods or droughts can affect virtually all parts of the country, from Northland down to Invercargill, in any year.

Floods and Droughts: the New Zealand experience aims to summarise the wealth of observation and analysis of floods and droughts in New Zealand. Chapters are contributed by twenty hydrological scientists and water resources professionals, who have worked on many different aspects of floods and droughts. Some chapters present observations of historically significant floods and droughts, and review different approaches to their analysis. Others consider the cause-and-effect relationships between floods and droughts, land use changes, instream uses such as ecosystem maintenance, erosion and sedimentation processes, and the behaviour of groundwater resources. A final pair of chapters focuses on approaches to management of floods and droughts that are being developed in this country, and discuss four specific case studies.

The book aims to be a reference text for water scientists, engineers, and resource managers whose work requires them to better understand and to manage floods and droughts. It is intended, too, as a source for senior undergraduate and postgraduate university students in engineering, resource management, geography, and related disciplines. While presenting the experiences of practitioners in New Zealand, the book should have value to water professionals in many other countries.

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