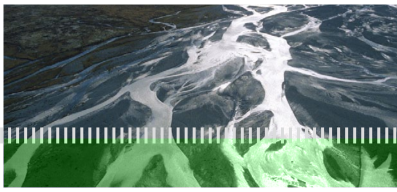
# **Chapter 8.** Water Resources

*Water resource impacts and adaptation under climate change*

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## Abstract

Water is critical for New Zealand's primary industries. Our ability to achieve export earnings from our land hinges on the relative abundance of water we have and on our ability to anticipate and control its availability. However, as the climate changes in the coming decades and century, the water resources on which the primary industries depend, will most probably also change.

Water resources vary naturally because of climate variability, such as the El Niño Southern Oscillation. Many water users in New Zealand are already well adapted to this variability. Anthropogenic climate change is anticipated to provide further changes in water resources, in addition to those that are familiar to water users.

While no effect of anthropogenic climate change has yet been detected in New Zealand's water cycle and resources, existing evidence internationally – and the mounting results from local modelling studies – indicate that effects are likely to begin within several decades' time. These effects will vary in both space and time. River flows will probably decline across the country and throughout the year, with the probable exception of Southern Alps-fed rivers which will likely increase during winter and spring. Alpine snow packs are expected to decline. Droughts are very likely to become more common, particularly in eastern regions, and floods more extreme. Higher evaporation rates would lead to greater water use, and rain-fed groundwater recharge will likely decline. Water quality is also likely decline for a myriad of reasons though very little research has been conducted on this front.

These changes would have impacts on water availability for irrigation, infrastructure, and the ability to balance competing needs for water. It is very plausible that these impacts could become severe in parts of New Zealand. However, many options exist, or are being developed to help stakeholders adapt, from the farm and forest to government. These include increases in water use efficiency and the augmentation of water supply for irrigation, reductions in nutrient loss and erosion, and the inclusion of climate change risks into operations from water storage to water allocation. Furthermore, as climate change is expected to manifest itself within the coming decades – well within planning horizons relating to water resources – it is prudent to begin the adaptation process now. Whatever portfolio of adaptation options is pursued, it would be best implemented by all stakeholders acting in concert and in tandem with other environmental and societal changes.

# Contents

# 1 Introduction

Water is critical to New Zealand's land-based primary sectors. It is a fundamental ingredient of photosynthesis which grows our crops that drive much of the country's economy. Compared with many other countries, New Zealand has abundant water, giving it a potential competitive advantage in an international market. This abundance is not uniform across New Zealand; some regions are wetter and drier than others. Some years are also wetter and drier than others, as climatic variability drives fluctuations in the abundance and quality of water resources. This leads to droughts and floods which have significant impacts for the primary sector. Knowing how much water we have, and how its abundance and quality changes over days, weeks, years or longer is of tremendous help for water users and water managers alike.

As the climate changes, so too will the availability of water resources. Some of these impacts may be beneficial, and some harmful. How and when these changes will come about, however, is not fully understood. This brings with it another challenge: we will have to manage water amid increasing uncertainty. In other words, we can no longer assume that water resource conditions of the past will prevail in the future (Kundzewicz et al. 2007; Milly et al. 2008).

Climate change and its associated water resource impacts are increasingly relevant for water resource managers. The framework for managing water resources in New Zealand is the Resource Management Act 1991 (RMA). With regard to climate change, a 2004 amendment of section 7 (s7) of the RMA added 'the effects of climate change' to the list of matters that people excising power under the RMA should 'have particular regard to'. In addition, the National Policy Statement for Freshwater Management 2011 (MfE 2011) requires freshwater management to have regard to the 'reasonably foreseeable impacts of climate change'. Decisions made today will leave a legacy in the future when climate change is expected to have tangible effects on our water resources. What these effects are, how likely they are, and what effects are 'reasonably foreseeable' may not be well understood, particularly by water users or water resource managers.

The dual scope of this chapter is to review existing knowledge relating to the potential impacts of climate change on water resources and their role in the land-based primary industries; and to identify potential adaptive responses. The review synthesises relevant and available New Zealand focussed peer-reviewed journal articles, book chapters, publicly available client reports, and conference proceedings, with a focus on the plausible and foreseeable impacts of climate change. This is then used to assess adaptation options, from tactical to transformational, which stakeholders of all types may use to cope with changing water resources.

# 2 New Zealand's water resources

Before we can examine how climate change may affect New Zealand's water resources, it is first important to understand what we already know about our water resources. How much water do we have, when and where do we have it, what quality is it, how is it used, and how is it managed? A more extensive review of New Zealand's freshwaters in general is available in Harding et al. (2004) and the chapters therein.

Much of our knowledge of our water resources stems from a number of extensive monitoring networks across the country operated by regional authorities: NIWA, GNS Science, as well as several other organisations. These networks record climatic conditions, soil moisture, river flow, lake and groundwater levels, and surface and groundwater quality. Together, they provide data on the state, fluctuations and trends of various components of the water resource system. Complementing these data are records kept by regional authorities on consented water allocation, and to a limited extent, the actual water use by consent holders.

## *2.1 Hydrology*

New Zealand's water resources are a product of the prevailing climate and the topographical, geological and ecological factors that modulate the water cycle. This section reviews what is known about the various elements of the cycle, beginning with a review of the more important features of the climate system (see Chapter 2 for a more detailed review). After falling, precipitation may be stored as snow, ice, or soil moisture. A fraction of the water will evaporate back into the atmosphere, while the remainder will make its way via rivers, wetlands, lakes and aquifers to the ocean. Near the coast, sea level conditions further modulate river flow, coastal lake discharge, and groundwater gradients.

### 2.1.1 *Climatic drivers*

As described more thoroughly in Chapter 2, New Zealand lies largely within the prevailing westerlies of the mid-latitude Southern Hemisphere (Salinger et al. 2004) and has a maritime climate. The weather follows the progression of travelling anticyclones, depressions and fronts. The mean annual precipitation across the country is about 610,000 million $m^3$ (Henderson et al. 2011), or a depth of 2.3 m spread uniformly across the country, though this varies substantially from region to region and between years.

The greatest amounts of precipitation fall along the west coast of the South Island, due to the combination of a prevailing airflow from the west and southwest and the orographic effects of the Southern Alps, while precipitation declines towards the east. The North Island and the north of the South Island exhibit winter precipitation maxima and summer minima (Figure 8.1). The east of the South Island exhibits an autumn maximum and summer or autumn minima. The south and west of the South Island exhibit autumn or spring maxima and winter minima.

Variations in precipitation from year to year are dominated by the El Niño Southern Oscillation (ENSO). During El Niño phases of ENSO, the east-west pattern in annual precipitation is generally accentuated, and is weakened during La Niña (Figure 8.2). El Niño conditions are more common during the positive phase of the Interdecadal Pacific Oscillation (IPO)[1], and La Niña conditions are more common during the negative phase (Salinger & Mullan 1999; See Chapter 2 Box 2.4). The IPO has been linked to fluctuations in some river flows and storages in New Zealand, particularly in the south and west of the country Westerlies are also accentuated during the negative phase of the Southern Annular Mode (SAM)[2] (Renwick & Thompson 2006), with warm and dry conditions in the South Island more common during the positive phase (Gillett et al. 2006).

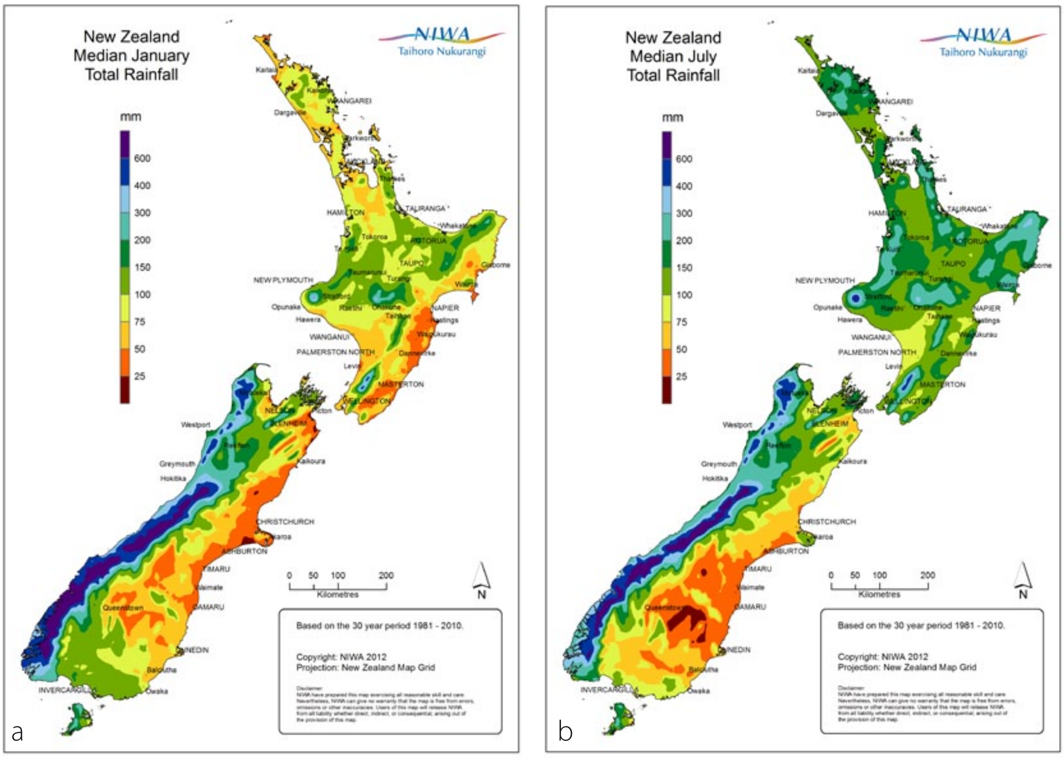


**Figure 8.1.** Median rainfall for New Zealand. (a) January. (b) July.

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[1]The IPO is a cyclical change in the linked circulation patterns of the ocean and atmosphere in the Pacific. A characteristic circulation pattern predominates for a 20–30 year period, and then the system changes to having a different characteristic circulation pattern. These patterns are known as phases of the IPO; the IPO was in a negative phase from 1945–77 and in a positive phase from 1978–99.

[2]The Southern Annular Mode is a cyclical change in atmospheric circulation patterns, centred on the South Pole. It flips back and forth between positive and negative phases, once every few weeks. It causes changes in atmospheric pressure and wind direction which affect weather patterns in the New Zealand.

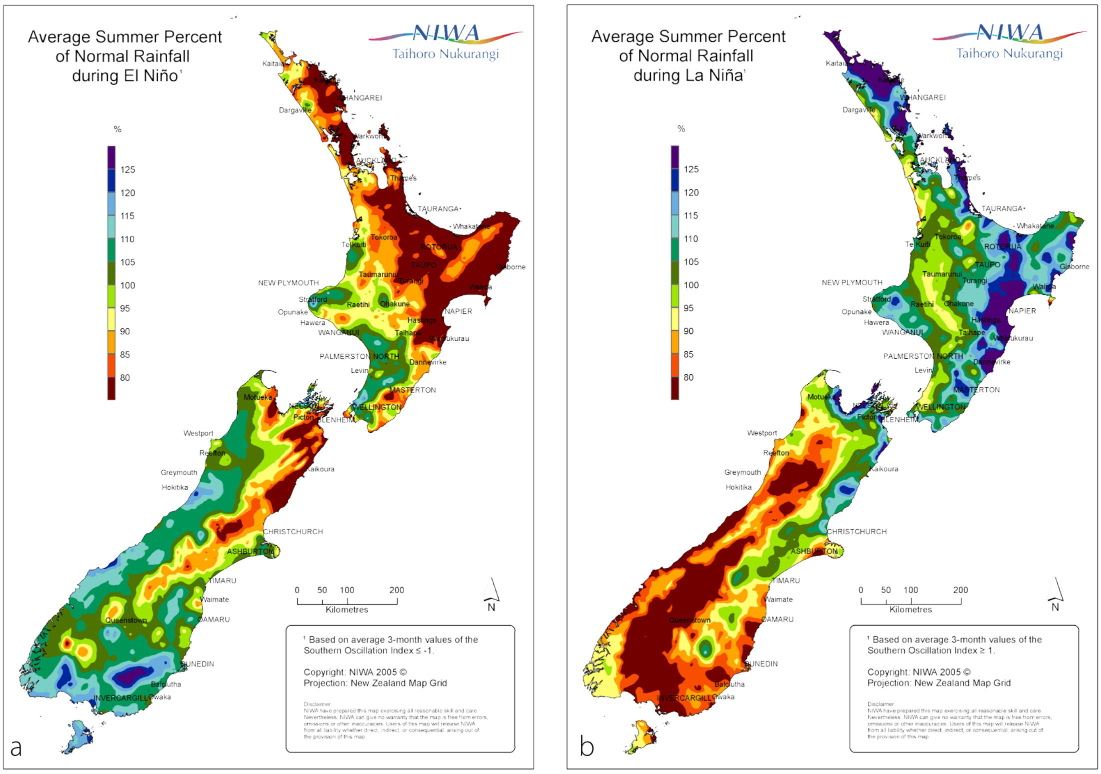


**Figure 8.2.** Effects of climatic drivers on summer rainfall in New Zealand. (a) El Niño. (b) La Niña.

### *2.1.2 Snowpack and glaciers*

Much of the South Island and small parts of the North Island are subject to seasonal snowfall. Glaciers and permanent snowfields line the Southern Alps, while only the North Island's tallest mountain (Mt Ruapehu) is glaciated. The long-term mass balance of glaciers and snowfields depends on temperature and precipitation, making them particularly useful indicators of climatic variability and change. Frozen water stored in glaciers and snowfields is an important component of the water balance of any downstream catchment. Seasonal snow packs serve as temporary storage of freshwater, much like a reservoir. As temperatures warm in the spring, the snow melts and feeds a pulse of water into rivers with sources at high altitude at the start of what is typically the irrigation season.

### *2.1.3 Evaporation*

Before rain and snow fall become river flow and groundwater, a significant portion of the water is evaporated back into the atmosphere – about 20% nationally (Henderson et al. 2011). The partition between evaporation and freshwater supply varies among years and locations. This depends on both the amount of water available for evaporation and the atmospheric conditions that control the evaporative demand; principally temperature, radiation and wind speed (and often referred to as the potential evapotranspiration [PET]). The PET varies from less than 460 mm/year in the mountains and high hills along the Southern Alps and the Central Plateau of the North Island to over 950 mm/year in Central Otago, and coastal areas of North Canterbury, Marlborough, Nelson, Hawkes Bay, Gisborne and Northland (Tait & Woods 2007). PET also varies seasonally and can easily reach about 5 mm/day in non-alpine regions during summer and drop down to about 1 mm/day in winter. While PET is typically smaller than total precipitation on an annual basis, the differences in the seasonality of the two often lead to summer soil moisture deficits in many areas of New Zealand.

### *2.1.4 Soil moisture*

Soil moisture is the most important component of the water cycle for primary production. For all of the crops grown in primary industries, be they pasture for grazing or forests for timber, the soil within the root zone serves as the source of water for plant uptake and photosynthesis. Soil moisture is naturally replenished by precipitation and, in certain circumstances, groundwater. Soil moisture dynamics are further moderated by plant cover and soil properties. When and where soil moisture conditions become drier than desirable, irrigation can be instrumental in maintaining and augmenting crop yields.

### *2.1.5 Drought*

Droughts are a normal feature of much of New Zealand, and can have a substantial impact on rural economies and livelihoods (Pearson & Henderson 2004) and the national economy (Buckle et al. 2002). Droughts have been associated with persistent dry weather patterns. For eastern and northern regions, these occur more often during the El Niño phase of ENSO (Salinger et al. 2004). This is because an El Niño often leads to more frequent than usual westerly winds, which are generally dry in these regions, bringing less moisture than usual to eastern and northern regions. These patterns do not necessarily hold in every El Niño event, as their strength is modified by other climate processes like SAM and local influences.

### *2.1.6 River flow and flooding*

Of the approximately 80% of the mean annual precipitation that reaches the coast, most does so via rivers (Henderson et al. 2011). The actual proportion varies greatly between regions, depending on climatic and catchment characteristics (e.g., geology, topography, land use). Snowmelt contributes to substantial springtime flow in rivers with alpine headwaters, and up to 24% of the annual inflows to the major South Island lakes (McKerchar et al. 1998).

The greatest source of inter-annual variability derives from ENSO, due to its effects on precipitation. The principal effect is a shift towards more frequent westerlies during El Niño, and more frequent easterlies during La Niña. Effects of the IPO have also been detected in river flow data: floods and low flows in the west and south of the South Island were higher in 1978–99 than in 1945–77 (McKerchar & Henderson 2003); in the Bay of Plenty region, there is an IPO effect on variability of flood size, but not on median flood size. During the period 1978–99, there was a marked absence of large floods in the region. A recent preliminary analysis suggests that, with the change of phase of the IPO in 1999, flows since 2000 have also been lower in the South Island (Woods 2011). Analysis of river flow data from 16 rivers in the South Island showed that statistics for floods, mean flows and low flows were lower in almost every case in 2000–09 than in 1978–99. However, not all the differences were statistically significant. Results for North Island rivers were more mixed, and did not display a consistent pattern of change.

Floods occur frequently in New Zealand and can have substantial impacts on communities, infrastructure, erosion, and land owners (Pearson & Henderson 2004). Flooding is typically associated with mid-latitude storms, thunderstorms or, in the northern parts of the country, ex-tropical cyclones. The frequency and magnitude of floods, which are generally derived from historical data, are important considerations in the design of culverts, bridges, dams and flood protection schemes.

### *2.1.7 Groundwater*

An estimated 614 x $10^9$ $m^3$ of water exists as groundwater within New Zealand (GNS Science 2011). The presence of groundwater depends on the geological environments and the availability of recharging water. Most of the country's aquifers are comprised of recent, relatively shallow, sedimentary or volcanic lithologies (White 2001). Approximately 70% of the country's groundwater underlies the Canterbury region, where the eastern plains consist of quaternary-age sedimentary deposits; the next largest proportions are in Waikato and the Bay of Plenty, with about 6% and 5% of national groundwater, respectively. Groundwater water is supplied by recharge from rivers and overlying soils and rock, and discharges to rivers, lakes, wetlands and the ocean, or is abstracted via wells.

Water levels in aquifers vary more slowly than surface water, being buffered from climatic drivers by the unsaturated zone of soil and rock between the water table and the ground surface. While seasonal patterns are readily observable among individual wells and aquifers, the variability of the national groundwater volume is only broadly related to climate (White & Reeves 2002). Large annual fluctuations in water level are seen in aquifers used for seasonal water takes. Because of the variations in substrate and flow path, groundwater ages can vary from days to millennia.

### *2.1.8 Lakes and wetlands*

Lakes and wetlands are minor features of New Zealand's landscape in general, with wetland cover having been reduced to about 10% of its extent in 1850 due to land use change (Sorrell et al. 2004). Lakes and wetlands serve as both sinks and sources of water, connected as they are to their surrounding surface and subsurface water bodies. As the loss of water from most lakes is mainly by river flow, many large lakes are managed for the purposes of hydropower generation. The greatest water loss from wetlands may be via evaporation (Campbell & Jackson 2004); even for the large, shallow Te Waihora/Lake Ellesmere, evaporation is estimated to account for 32% of total outflows (Horrell 2009).

### *2.1.9 Anthropogenic change*

In addition to these natural fluctuations in river flow, human-induced changes have also occurred. The substantial clearance of forest following the two waves of settlement – first by Polynesians and then Europeans – is likely to have increased mean river flows (Andrew & Dymond 2007), though no direct records of this are available. Experimental studies of land use change have demonstrated that forest clearance increases water yield while afforestation reduces yield (e.g., Fahey 1994; Farley et al. 2005), and further modelling studies have suggested it at larger scales (e.g., Woods et al. 2009). Damming of some rivers has also changed the nature of their downstream flow regimes, while groundwater abstraction has also been suggested as a possible cause of reduction in reducing the flow in the Selwyn River on the east of the South Island (McKerchar & Schmidt 2007). The drainage of much of the country's wetlands for farm land has also altered hydrological flows at local scales.

Against the background of significant natural fluctuations in climate, the effects of anthropogenic climate change on hydrology will be difficult to detect in many parts of New Zealand, and have not yet been detected. The projected changes in average annual precipitation of about 5% to 10% over 40 years are relatively small when compared to the year-to-year variability in rainfall, which is typically 15% to 20%. Such small changes are difficult to detect until long-term records have been collected, and so there will be a lag between the onset of the change, and its detection. For water resource managers, it is the combination of natural variability and the long term changes that are important.

International experience suggests that the hydrological effects of climate change are likely to manifest first in mountain catchments, where the hydrology of temperature-sensitive glaciers and snowfields is expected to change as the climate warms (see Section 3.1 for more detail). However, New Zealand has very few rivers whose flow regimes are completely dominated by the melting of snow and ice.

## *2.2 Erosion and sedimentation*

Erosion and sediment transport and deposition are a natural feature of any landscape. In New Zealand, with our particular geological and climatic settings and historical land use changes, erosion and sedimentation rates are highly variable in space and time (Hicks et al. 2004). High tectonic uplift rates in the Southern Alps mobilise substantial quantities of sediment towards both the east and west coasts. Within depositional areas, such as the Canterbury or Ruataniwha Plains, the active sediment loads and variable river flows contribute to often changing channel morphology. Where hard, erosion-resistant rocks pervade (e.g., Fiordland), even high rainfall rates are insufficient to generate substantial sediment loads. Where forest cover has been cleared, erosion and sediment supply are augmented, particularly within hill country. Towards the coast, fluvial sediment transport interacts with coastal processes in some places to create river mouth lagoons (hapua).

Erosion of channel beds and banks can undermine water resource infrastructure such as culverts and stopbanks, and reduce the usability of land. Sedimentation – the deposition of sediment in channels, lakes or reservoirs – can lower the efficacy of water intakes, storage dams, irrigation races and flood protection and drainage schemes. Both may interfere with transport corridors, affecting the ability to deliver products to the market.

## *2.3 Water quality*

There are a number of physical and chemical constituents of water that influence its suitability for use and life supporting capacity, in particular water temperature, the concentration of nitrogen (N), phosphorus (P), clarity and suspended solids. Water quality varies across the county, and depends on surrounding land use, climate, topography and geology (e.g., total phosphorus and nitrogen, Figure 8.3). Lowland streams and those surrounded by pasture or in urban areas typically have the lowest quality. Upland catchments with little or no agriculture typically have very high water quality.

Nitrogen and phosphorus help stimulate the growth of aquatic plants, including algae, which can be either suspended in the water column of lakes and rivers or attached to substrates (periphyton). Nutrient contamination results from point and non-point source discharges and is strongly associated with intensive land use. High nutrients can promote excessive ('nuisance') growth of plants that, in turn, can smother habitat, cause the growth of biotoxic algae (such as *Phoridium*, which is toxic to dogs), produce adverse fluctuations in dissolved oxygen and pH, and impede flows and block water intakes. An excess of plants in water bodies also has detrimental effects on aesthetics and human uses, causing changes to aquatic organisms, water colour, odour and the general physical nature of the environment. Lakes and wetlands are particularly vulnerable to changes in water quality as they act as nutrient sinks.

Visual water clarity and suspended solids are associated with ecosystem effects due to the attenuation of light in the water column in lakes, with effects on primary production and changes to animal behaviour. The settling of suspended solids also has the potential to smother the beds of rivers and downstream water bodies. This can have adverse effects on aquatic invertebrates, which form a key food source for fish and riverbed birds. Poor water clarity can limit use for human contact recreation.

In terms of surface water quality trends, both trend strength and direction vary across the country, and are linked to land use change. Ballantine et al. (2010), for example, found clarity is decreasing in rivers draining hill and lowland catchments and those dominated by pastoral and urban land-cover. Increasing trends in total phosphorous concentrations were found for rivers draining lowland catchments and those dominated by pastoral land-cover. Ballantine & Davies-Colley (2010) remarked that an upward trend in water temperature was approaching statistical significance. About one-third of groundwater quality monitoring wells show some level of human influence, with nitrate and/or sulphate concentrations above background levels (MfE 2007). In addition, from 1995 to 2008, twice as many wells had increasing nitrate concentrations as opposed to decreasing concentrations (Daughney & Randall 2009). These trends are strongly associated with agricultural land use change.

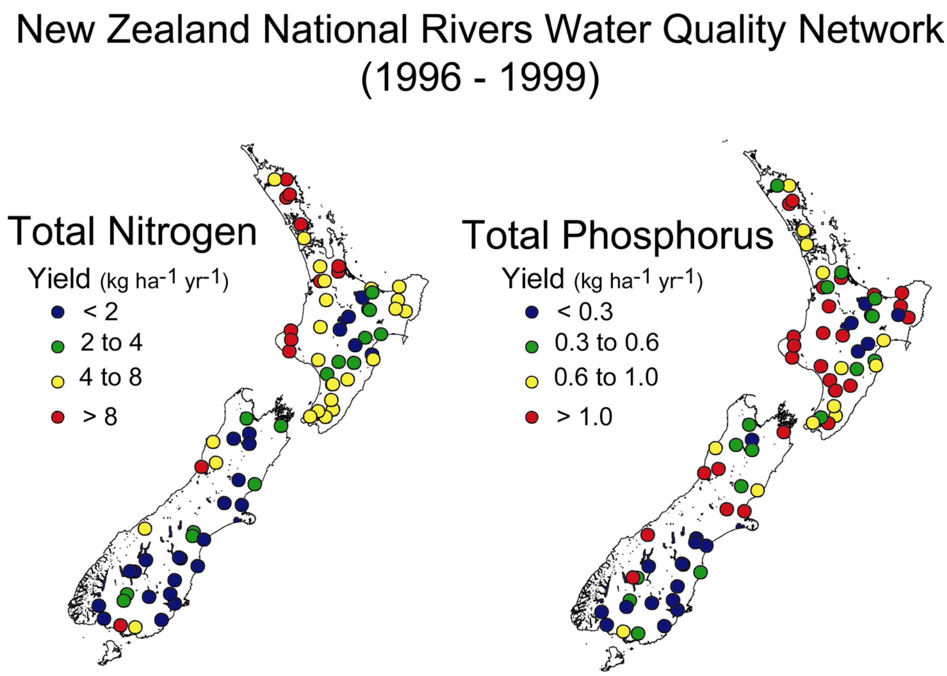


**Figure 8.3.** Yields of total nitrogen and total phosphorus for 77 sites on the National Rivers Water Quality Monitoring Network (1996–99). (after Elliott et al. 2005).

## 2.4 Primary sector water use

### 2.4.1 General water requirements

Water requirements for primary production depend on the needs of particular crops, the hydroclimatic conditions of the growing region, and on soil characteristics. Particularly important, are the summer soil moisture deficits in many areas of New Zealand.

For maximum pasture production in areas such as Canterbury with an annual rainfall of ~650 mm/year about a further 430 mm/year of effective irrigation is required over the average irrigation season (typically October to April). In dry years, 500–600 mm/year of effective irrigation may be required (Aqualinc Research Ltd 2009). The water requirements for most cereal and seed crops are lower than for pasture. This is because most crop growth occurs by the end of December. From then onwards cereal and seed crops are typically left to dry off and ripen, a process which is aided by the excess of PET over rainfall. Irrigation may be required in autumn to establish new crops, but water requirements are still less than for pasture that requires water over the entire irrigation season.

Apple and grape growers commonly practice regulated deficit irrigation to control excess vegetative growth; so for grapes, irrigation systems might be designed to apply only 25 mm/week, whereas pasture systems might be designed to apply up to 35 mm/week. The water requirement for seasonal frost-fighting may be more than that required for grape production.

Forests, as a general rule, transpire less water than pasture (Kelliher et al. 1993). The stomata in *Pinus radiata* needles control transpiration by closing when the humidity is low, thus limiting transpiration to ~3.5 mm/day in summer, whereas pasture may use 5–6 mm/day (Kelliher & Scotter 1992). However, forests do intercept rainfall and this may amount to 20% to 30% of annual rainfall in *Pinus radiata* (Fahey 1964; Fahey et al. 2001) and up to 40% in dense kanuka scrub (Rowe et al. 1999). This means that less rainfall reaches the soil under forest than under pasture, and so there may be less effective rainfall to contribute to transpiration, river flow and groundwater recharge. This is partly offset by the deeper roots of trees, enabling them to access a greater store of subsurface moisture.

Water requirements are further affected by the depth, texture, structure and composition of the soil – which control the soil's ability to retain moisture. Well-structured, deep clay soils may be able to produce high-yielding crops with little or minimal irrigation whereas on lighter, shallower or stony soils irrigation would normally be required to produce similar yields. The pine forests of the central North Island are renowned for their productivity, which is attributable to the deep friable ash soils allowing the roots to penetrate deeply and to draw upon greater reserves of soil moisture (Will & Stone 1967). In contrast, pasture in the same area may need to be irrigated because of its shallower rooting depth and the free draining nature of the soil.

### 2.4.2 Consented water use

The most thorough indicator of national water use, is currently the consent data for water takes kept by each regional authority and compiled most recently by Aqualinc Research Ltd (2010). These data are not measures of how much water is used, but are rather approximations of the amount of water that may be abstracted legally. Because of this, they need to be treated with much caution (see Section 2.4.3 below).

As of 2010, nearly 27,000 million $m^3$ of water was authorised to be abstracted from rivers and aquifers each year. Of this, 16,000 million $m^3$ is for the Manapouri hydropower scheme that takes water from the Waiau River and discharges it directly to the sea. The remaining 11,000 million $m^3$ is primarily consented for irrigation. Looking at the regional level, and excluding the Manapouri hydropower scheme, most of the water allocated for consumptive purposes is in Canterbury, at nearly half the total for New Zealand, followed by Otago (Figure 8.4). As a fraction of each region's annual freshwater supply, Canterbury's and Otago's allocations represent about 8.3% and 7.7% respectively. Cool and wet Southland and the West Coast represent 0.2% each, as does less-developed Gisborne. While abstraction does not occur steadily throughout the year, these values indicate regional differences in water allocation.

However, while only small fractions of the annually available water are consented for use, there are physical, economic, and regulatory impediments against using the remainder. Some catchments (and probably aquifers) are already over-allocated (e.g., in Canterbury), while others are approaching their sustainable limits.

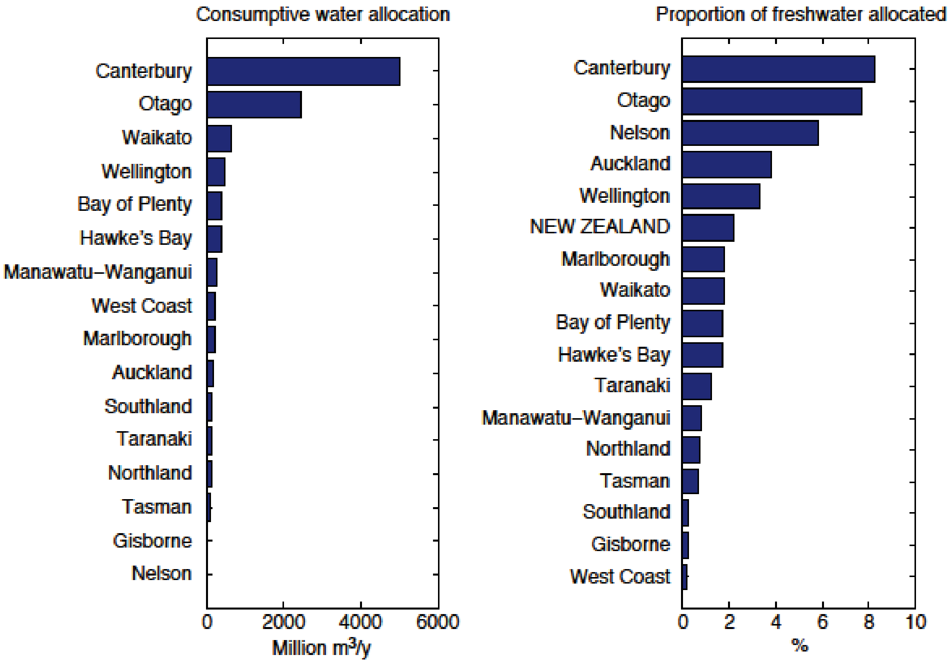


**Figure 8.4.** Consumptive annual regional water allocation, and annual water allocation relative to freshwater supply, excluding the Manapouri hydropower scheme (after Collins (2011a)).

About two-thirds of the consumptive water allocation (excluding Lake Manapouri) is from surface waters: rivers and lakes (Figure 8.5). About one-third comes from groundwater, and 5% from reservoirs, which are largely fed by rivers. Across New Zealand, the relative importance of each water source varies depending the relative abundance and importance of reliability of supply. In Otago, surface waters provide 84% of the allocated water supplies; in the Auckland region surface waters only provide 4%. In Hawke's Bay, groundwater accounts for 74% of consented water supplies, while in Otago and Taranaki the amount is 7%. In Auckland, reservoirs account for 74% of the consented water supplies, while in Waikato and Manawatu-Wanganui, the consented volume is 0%.

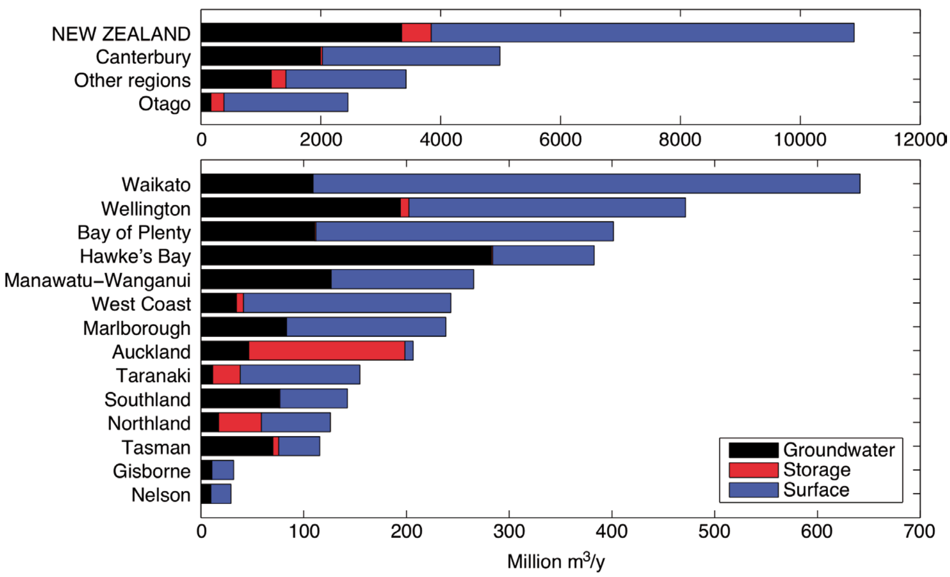


**Figure 8.5.** Consumptive annual regional water allocation according to water source, excluding the Manapouri hydropower scheme (after Collins (2011b)). Note the difference horizontal scales; 'other regions' in the top part of the figure represents all of the regions in the bottom part of the figure.

Over half of the annual consented water for consumptive uses (excluding Manapouri) was for irrigation (5800 million m$^3$/year), more than half of which is in Canterbury (3600 million m$^3$/year) (Figure 8.6); other consumptive uses include industry (2500 million m$^3$/year) and drinking water (1800 million m$^3$/year). Both Canterbury and

Otago allocated more water to irrigation than all other regions combined. Four-fifths of the national allocation of water for irrigation was used on pasture. Regionally, this proportion varies from 0% in Gisborne to 90% in Canterbury, with Canterbury and Otago dominating national figures. Most of the irrigation for horticulture occurs in the South Island, with Canterbury accounting for about a third of the national total. Stock water supply can also be an important use, making up about 5% of the allocation nationally.

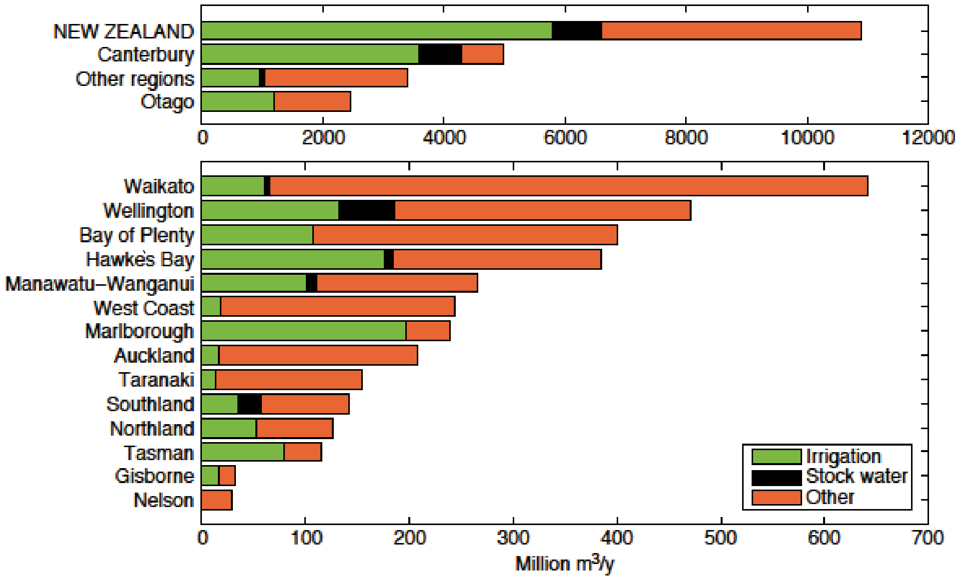


**Figure 8.6.** Consumptive annual regional water allocation by primary use, excluding the Manapouri hydropower scheme. The 'other' uses include industry and drinking water. Note the difference horizontal scales; 'other regions' in the top part of the figure represents all of the regions in the bottom part of the figure. Data from the Ministry for the Environment (L. Potter 2011, pers. comm., 6 July 2012)

In terms of the relatives uses of the allocated water, the largest fraction nationally and in many regions is associated with pasture (Figure 8.7). Notable exceptions to this are Marlborough, where most irrigation is consented for viticulture, and Hawke's Bay, where most is consented for horticulture.

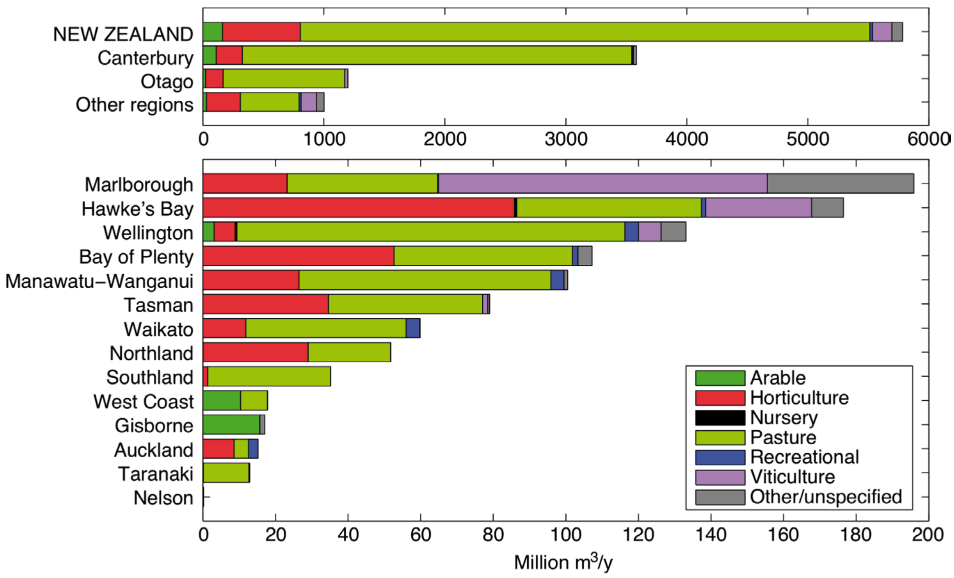


**Figure 8.7.** Consumptive annual regional water allocation to irrigation by specific use. Note the difference horizontal scales; 'other regions' in the top part of the figure represents all of the regions in the bottom part of the figure. Data from the Ministry for the Environment (L. Potter 2011, pers. comm., 6 July 2012).

While this section describes the amounts of water consented for use as of 2010, there have been significant changes over last 10 years. These include the irrigation of land previously thought to be unproductive (e.g., McKenzie Basin), and the expansion of dairying in Canterbury and Southland. There have also been changes among uses, most notably a shift from irrigation of arable land to pasture in Canterbury due to economic incentives, and a change towards more efficient spray irrigation systems. Demand for water continues to grow, and given that some catchments and aquifers are already over-allocated, alternative sources of water and/or storage will be necessary in the future.

### *2.4.3 Actual water use*

As for the actual quantities of water used, only estimates are currently available. This is because most water takes are not metered. Preliminary analysis, based on subsamples of consented water takes and including the Manapouri hydropower scheme, estimates the actual (versus consented) national use at 65% (Aqualinc Research Ltd 2010). Disregarding Southland, most of the remaining regions are estimated to use between 40% to 50% of their allocated water. A more recent report from Environment Canterbury (Tricker et al. 2012) estimates that 52% of the region's allocated water is actually abstracted, compared with a value of 57% estimated by Aqualinc Research Ltd (2010); though again this number is based on a subsample of existing consents. Much of this demand is for seasonal irrigation, with peak irrigation demand often coinciding with late summer low flows in rivers and streams. In the near future, as more water takes are measured and reported, as required by the Resource Management (Measurement and Reporting of Water Takes) Regulations 2010, more data will become available giving a more reliable estimate.

## *2.5 Water resource infrastructure*

Infrastructure plays a fundamental role in the control and use of New Zealand's water resources. This includes hydropower dams and associated canals and diversions, irrigation schemes, stock water races, drainage systems, and flood protection works.

The largest and most widespread infrastructure is associated with the hydropower industry, which between 1995 and 2010 used on average 32% New Zealand's total water resources. Some of this water is counted more than once as it includes water that flowed through more than one power station (Henderson et al. 2010). The structures include dams, canals and diversions. The largest system is in the McKenzie Basin where two large natural lakes are dammed, another is controlled, and four artificial lakes have been formed behind dams. Canals with hydropower stations connect the lakes, and the water flows through eight hydropower stations downstream. There are other major hydropower stations on: the Clutha River (two large stations); the Southern Waiau River (one very large station); the Waitaki (eight stations); the Tongariro Power scheme (two stations); and the Waikato River, that includes water diverted from the Whanganui River via the Tongariro Power Scheme, with ten hydropower stations.

Water used for irrigation is mainly abstracted from the many rivers flowing to the drier, eastern regions of New Zealand. The largest irrigation schemes are in Canterbury, with up to 34 $m^3/s$ being abstracted from the Rangitata River via the Rangitata Diversion Race to irrigate 64,000 ha via three separate schemes. In winter, the water is used to generate hydropower at Montalto and Highbank where the water discharges into the Rakaia River. Instream values are protected by a National Water Conservation Order. The Waitaki (24,000 ha, 27 $m^3/s$), Opuha (17,000 ha, 17 $m^3/s$), Rakaia (>6000 ha, 6 $m^3/s$), Waimakariri (>12,000 ha, 10.1 $m^3/s$), and Hurunui and Waiau Rivers (17,000 ha, 17 $m^3/s$, combined) all provide water for irrigation schemes in Canterbury.

Stock water races carry water to many of the drier parts of New Zealand. The races are generally small channels that convey water to almost every paddock on a farm, as is common across the Canterbury plains. Some stock water races have been enlarged to additionally convey water, e.g. the Waimakariri and Acton irrigation schemes. These water races add some limited habitat diversity to the dry plains and the often-leaky channels contribute to groundwater recharge. Only a small portion of the water (5% to 10%) is ultimately consumed by livestock, and there is increasing pressure to use pipes instead of canals in order to reduce losses, using the conserved water for irrigation or maintenance of environmental flows. In dry hilly areas there are many highly efficient community piped stock water schemes.

The principle driver for the historical loss of many of New Zealand's wetlands was the expansion of farm land using drainage. This land is generally very productive and today forms some of the prime dairy land in the country in regions such as Waikato, Northland and Manawatu-Wanganui. Three types of drainage are common: clay tile drains (or perforated plastic pipe these days), mole drains, and humping and hollowing. The first two types are normally placed 20–50 m apart and discharge into surface drains. Humping and hollowing is a process commonly carried out on the West Coast of the South Island where the land is 'dug' over by hydraulic excavators to break up the poorly structured top-soil and impervious iron pans to leave an artificial landscape with regular humps (ridges) 25–75 m apart with surface or tile drains in the hollows. The productivity of the Manawatu River flood plain and environs is maintained by 700 km of drains and 20 pumping stations. Other regional authorities have similar drainage infrastructure, such as on the Hauraki and Rangitaiki Plains. This drainage infrastructure is often aging, and will come under increasing pressure as sea levels rise, and further sedimentation of river channels occurs.

Many New Zealand rivers have levees or stop banks to confine flood waters for the protection of towns and productive flood plains. These will come under increasing pressure due to factors like sedimentation leading to loss of channel capacity (and in turn reducing flood protection), and sea-level rise causing water to become more backed up in lowland areas.

## *2.6 Water resource management*

Managing water resource use and water-related hazards requires a range of legal and regulatory instruments operating at both the national and regional levels. The overall framework for managing water resources is the Resource Management Act 1991 (RMA). Part 2 of the RMA promotes the sustainable management of resources; an amendment in 2004 to s7 required that decision makers have particular regard to the effects of climate change. The RMA provides for management at national, regional and local levels. Of these, the national and regional levels are most relevant to water resources.

### *2.6.1 National level*

For maters of national significance, the RMA provides for tools such as National Policy Statements and National Environmental Standards. In 2011, the National Policy Statement for Freshwater Management (NPSFM; MfE 2011) set out objectives and policies for regional authorities to manage water in an integrated and sustainable way while providing for economic growth. The NPSFM recognises the challenges in meeting competing needs for water, and that these challenges are likely to increase over time due to the impacts of climate change. In particular, the NPSFM sets out a number of policies for managing freshwater quality and quantity. With regard to water quantity, Policy B1 requires that in setting objectives and environmental flows, regard must be given to 'the reasonably foreseeable impacts of climate change' (MfE 2011, p 6 & 8).

Environmental flows are limits put in place to maintain in-stream values including ecological, tangata whenua and recreational values, and amenity and natural character (MfE 2008b). The more water required to maintain in-stream values, the less is available for out-of-stream uses. Defining these limits provides clarity for both environmental protection and resource use, and requires detailed knowledge of water resources and the needs of in-stream users.

### *2.6.2 Regional level*

In New Zealand responsibility for water resource management is largely delegated by government to 16 regional authorities, 12 of which are regional councils and four are unitary authorities. All but one regional authority is elected from the community at large; the exception is the Canterbury Regional Council where the government appointed commissioners in 2010.

The RMA requires regional authorities to carry out certain functions, specified in section (s)30 of the RMA. These include setting policies to achieve integrated resource management, the control of water use, and setting the rules for water allocation. Regional authorities' principal tools for managing water resources are regional policy statements and regional plans, and resource consents. Under s7 of the RMA, councils must have particular regard to certain matters, and as noted above these now include climate change. This suggests that regional authorities should be addressing climate change in their regional policy statements and regional plans.

Regional plans enable councils to be strategic in the setting of objectives for water resource use for their region as a whole, or for specific catchments (or aquifers) in the region. The planning process must consider potential use of resources and balance this with maintaining the natural value of resources, for instance how much water could be taken from a river to be used for irrigation versus what water needs to stay in the river to protect ecological or recreational values. In Tasman and Canterbury, regional plans also impose some limits on the extent and location of new forests due to the potential impacts forestry can have on river flow and downstream resource users.

Resource consents granted by regional authorities can authorise consent holders to take, use, dam or divert water through conditions which seek to avoid, remedy or mitigate the environmental effects of the activities. Under the RMA consents may be granted for up to 35 years, though councils have discretion to grant consents for shorter periods. Applicants for resource consents must undertake an Assessment of Environmental Effects (AEE), appropriate to the scale and significance of the activity. If abstraction limits have not been set in a regional plan, then they are set on a case-by-case basis within the consenting process.

It is more straightforward to manage surface water resources, which can be seen and measured more easily, than it is to manage groundwater, which are generally out of sight. It is often difficult to determine how much water there is in an aquifer, how much recharge occurs (when and from where), and the extent to which aquifers at different depths are interconnected. Accordingly, it is much more difficult to set sustainable allocation regimes for groundwater aquifers than it is for surface water bodies. Both surface water and groundwater allocation is also made more complex by hydraulic connections between stream flow and shallow riparian groundwater.

### *2.6.3 Recent trends in water resource management*

One notable recent move in water resource management is the development of 'collaborative' approaches taking place outside the RMA framework. Two examples of this are the Land and Water Forum (LAWF) at the national level and the Canterbury Water Management Strategy (CWMS) at the regional level.

The LAWF was formed in 2009, and brings together a range of industry groups, environmental and recreational NGOs, iwi, scientists, and other organisations to discuss matters relating to the management of land and water in New Zealand, with active observers from local and central government. The Forum's objective is to develop a shared vision through a stakeholder-led collaborative process. In its first report (Land and Water Forum 2010), the LAWF identified a set of outcomes and goals for freshwater management and recommended a number of policy changes to achieve them. It also noted the challenges that changing weather patterns bring to both drought-prone and wet regions. The second LAWF report (Land and Water Forum 2012) listed 38 recommendations on the two main topics of setting limits for water quality and quantity, and on using a collaborative approach to making plans and policies. Of relevance to climate change, recommendation 11 states that regional authorities should 'consider information uncertainty in setting objectives and limits' (Land and Water Forum 2012, p 23.)

At the regional level, the Canterbury Water Management Strategy (CWMS) (Environment Canterbury 2009) mandated that water resource management be developed in partnership with communities. It was put into a statutory context by the the Environment Canterbury (Temporary Commissioners and Improved Water Management) Act 2010 (sometimes called 'the ECan Act'). The CWMS outlines a governance structure to meet its targets, which involves splitting Canterbury into 10 water management zones and establishing a water management committee for each zone, plus a regional water management committee.

## 3 Water resources in a changing climate

Having reviewed the state of New Zealand resources under current climatic conditions, the state of knowledge of the potential impacts under future climate change is now reviewed. These potential impacts are both varied and rather uncertain. They are primarily based on water resource impact assessments that use scenario-based modelling to make science-based inferences about future conditions. They hinge on projections of temperature, precipitation and – in some instances – on sea-level rise. Understanding how climate change may affect our water resources is improved by understanding projections elsewhere in the world.

## 3.1 International evidence of hydrological change

While there are currently no studies that attribute historical hydrological change in New Zealand to anthropogenic climate change, there are many studies that do so internationally. There are two important reasons for this. First, there are more extensive monitoring networks elsewhere in the world with longer periods of record; and second, many other regions are more sensitive to anthropogenic climate change than New Zealand. Reviewing these observations can help determine the importance of hydrological change in a warming atmosphere, as well as identify those elements of the water cycle that are more liable to exhibit climate change-related trends.

Drawing from the most recent IPCC reviews (Kundzewicz et al. 2007; Bates et al. 2008), a range of trends have been identified. However, many studies have also failed to detect any trend or are unable to isolate the effects of climate change from other causal factors (e.g., land use change, reservoir construction). Most of the research has focussed on surface waters; of the studies that consider groundwater, no warming-related trends have been detected.

Warming-related trends that have been detected include the earlier occurrence of spring peak flow and an increase in winter baseflow in North America and northern Eurasia. Very dry areas have more than doubled in size globally since the 1970s due to a combination of ENSO and surface warming, while very wet areas declined by about 5% due to a combination of temperature and precipitation (Dai et al. 2004). In terms of floods, evidence of climate change is mixed. While Milly et al. (2002) identify an increase in frequency of large floods around the globe and attribute this to climate change, others argue that detection and attribution of flood frequency changes has been limited (e.g., Merz et al. 2012). Lake level alterations have also been tied to climate change, with both increases and decreases detected.

## 3.2 Water resource impact assessment

While data are fundamental to our understanding of historical and current water resources, anticipating how they may change requires modelling. Modelling can bring together existing scientific knowledge and make projections of future conditions based on prescribed scenarios of change. Such scenario-based modelling is already frequently used in water resource engineering and management analysis: for example in the assessment of land use change effects on flooding or water yield, or the effects of water abstraction on river and groundwater flow.

As with the sectoral chapters of this report, water resource impact assessments under climate change are typically the end product of a sequence of steps (See also Chapter 2, Section 4):

- The formulation and choice of emissions scenarios (e.g., Table 8.1).
- Global climate modelling using one or more models.
- The selection of climatic projections for specified time periods.
- The downscaling of Global Climate Model (GCM) results to regional or catchment scales.
- Use of the downscaled climatic information to drive one or more hydrological or water resource models to generate projections of the target variables.

**Table 8.1.** Emissions scenarios referred to in this chapter.

| ***Emissions scenario*** | ***Description*** |
|---|---|
| A1B | A middle-of-the-road emissions scenario based on a number of energy sources |
| A1F1 | A fossil fuel-intensive scenario |
| A2 | A high-end emissions scenario based on continually increasing populations and consumption |
| B2 | An intermediate-high emissions scenario with less growth than for the A2 scenario |

The hydrological or water resource models used in impact assessments are diverse. They may be conceptually, empirically, or physically based; they may vary in complexity from a few parameters to many tens of parameters; they represent different elements of the water resource system; and they are underpinned by different assumptions. Invariably, no single model simulates all aspects of potential interest, and so water resource models may be connected in sequence. An example is the work of Aqualinc Research Ltd (2008), which modelled responses in flow reliability in the lower Rangitata River basin following surface hydrological projections from Woods et al. (2008).

In the New Zealand impact assessments reviewed in this chapter, no single study considers all relevant aspects of the terrestrial water cycle together. Some focus solely on snow or consider river flow and groundwater. Of the models used, the physically based catchment hydrology model TopNet (Clark et al. 2008) provides the most complete representation of the water cycle. However, it also lacks thorough treatment of the groundwater system and so is coupled with other models.

Because of the computational effort involved in generating most hydrological projections, it was outside the scope of this chapter to create new hydrological and water resource projections. Instead, the projections presented here review the many individual studies carried out to date. They do not all relate specifically to the climate change scenarios described in Chapter 2, though they are sufficient to indicate the effects climate change is likely to have, at least where existing studies have been focussed. Therefore, this review describes the state of knowledge at the present time.

An important caveat when conducting impact assessments, or when interpreting their results, is that they are invariably somewhat uncertain. No projection of future conditions can be exact. These uncertainties accrue from the choice of the initial emission scenarios and global climate models, to the water resource models used to quantify the potential impacts. In some cases, studies offer a high degree of confidence in particular impacts (e.g., earlier snowmelt), while in other cases even the direction of hydrological change may be uncertain. However, while the models used are imperfect, if they are grounded in accepted science and used in targeted ways they can be useful in future engineering, agricultural and management decisions.

## *3.3 International projections of water resource change*

Just as New Zealand can learn from international reports of observed warming-related hydrological change, so too can we learn from international projections of hydrological change. Together, these studies can indicate what might happen in New Zealand, which elements of the water cycle to model and to monitor, and how to conduct water resource impact assessments. Because the number of these studies is continually increasing, the present chapter will summarise the review conducted by Kundzewicz et al. (2007).

### *3.3.1 Hydrology*

Projections of runoff and river flow vary across the globe and among climate models. While climate change scenarios from different climate models have resulted in very different projections in Australia, South America and Southern Africa, model results are in general agreement regarding an increase in runoff in high latitudes in North America and Eurasia during this century. Milly et al. (2005), for example, project increases of 10% to 40% by 2050 in these areas. Runoff is also projected to increase in the wet tropics, though with less certainty. Other regions are expected to experience decreases in runoff (e.g., the Mediterranean, southern Africa and western USA/northern Mexico). In rain-dominated catchments, studies have generally indicated that flow seasonality will increase, with higher flows in the peak flow season, and lower flows in the dry season or an extended dry season. The timing of the seasonality is typically unchanged. Projection certainty is particularly high in snow-dominated catchments, where more precipitation is likely to fall as rain; and snowmelt is projected to occur earlier and to be lower, with higher winter flows. This is more pronounced at lower elevations, and would increase drought risk in regions dependent on snow- and glacier-fed water resources.

Enrichment of the atmosphere by $CO_2$ has two potential and opposing effects on evaporation, and hence the water cycle. While higher concentrations of $CO_2$ allow plant stomata to close earlier, and so reduce transpiration loss, greater plant growth can lead to greater evapotranspiration as larger canopies both transpire more and intercept more precipitation. Incorporating these effects under a doubling of atmospheric $CO_2$ concentration produces an increase in global runoff of about 5% (Leipprand & Gerten 2006; Betts et al. 2007), which is typically much smaller than increases due to other environmental factors.

The global risk of both major floods and severe droughts is generally expected to increase through this century, though not in every case (Kundzewicz et al. 2007). Studies of lake and wetland water balances show both increases and decreases, which is not surprising given that lake level responds to multiple factors (inflow, precipitation, evaporation) that may complement or offset one another.

For groundwater, both recharge rates and levels are likely to change under climate change. Globally, groundwater recharge is expected to increase less than total runoff by 2050 (Döll & Flörke 2005), however the few case studies conducted so far show various effects depending on site-specific conditions, and large reductions in some regions (e.g., north-eastern Brazil, south-west Africa). Spring recharge will shift towards the winter and summer recharge will decline. In semi-arid and arid regions, where recharge critically depends on surface flow, heavier rainfalls and floods may augment recharge.

### *3.3.2 Water quality*

The effects of climate change on water quality will depend on local circumstances and the hydrological changes that come to pass. All else being equal, higher temperatures are likely to produce adverse changes in terms of human health, aquatic ecosystems, and water use, in part by fostering greater levels of nuisance algae. This would be exacerbated by greater variability in runoff, and particularly by lower flows. More intense rain would accelerate erosion causing turbidity and nutrient concentrations in rivers, lakes and reservoirs to rise; but could also dilute and flush contaminants downstream. In tidally influenced streams and rivers with decreased discharge, salinity will increase, as will groundwater in coastal aquifers due to salt water intrusion. The latter effects would be exacerbated by any reduction in groundwater recharge or sea-level rise. Perhaps the critical issue here, is how changes in water quality, in turn, affect aquatic ecosystems. Changes in river substrate, water temperatures, flow velocity, water depth, and water quality will all interact to alter the suitability of rivers for different organisms.

### *3.3.3 Erosion and sedimentation*

Changes in the water cycle will affect many geomorphic processes including erosion, slope stability, channel change, sediment transport and sedimentation. The exact direction of change will depend on the local hydrological and geomorphic conditions. All soil erosion studies have suggested that increased rainfall, particularly storm intensity, will lead to higher erosion, unless preventative measures are taken (Kundzewicz et al. 2007). Changes in erosion are also likely to stem from changes in the vegetation and ground litter cover, and from changes in the soil moisture and groundwater levels. Higher river flows and more intense floods would encourage sediment mobilisation and transport along rivers, possibly contributing to the undermining of channel banks, bridges and flood control works. Sedimentation of lower river reaches could affect the efficacy of infrastructure, particularly flood protection works and drainage schemes in low lying areas. This would be exacerbated by sea-level rise.

### *3.3.4 Water use and management*

Globally, water demand for agriculture is expected to increase to match rises in temperature and evaporative demand. This will be compounded by potential reductions in water supply and water quality and by general increases in water supply variability. This will put greater pressure on water resource management systems and the ability to balance competing demands for water, particularly irrigation and environmental protection.

Water resource management institutions have anticipated these changes, and many are actively incorporating climate change projections and risks into their planning and decision making. While this is a direct effect of projected climate change, it is in itself an adaptive response, and is discussed in more depth below.

## *3.4 Changes to New Zealand's water resources*

Potential changes to New Zealand's water resources may be broken down into effects on hydrology, water quality, erosion and sedimentation, water use, infrastructure, and management.

### 3.4.1 *Hydrology*

The projected impacts of climate change on our water resources begin with an assessment of the water cycle, based on the many water resource impact assessments conducted to date. This section first outlines the more salient conclusions about climate change discussed in Chapter 2, followed by step-by-step assessments along the water cycle. The study sites that inform this chapter are shown in Figure 8.8.

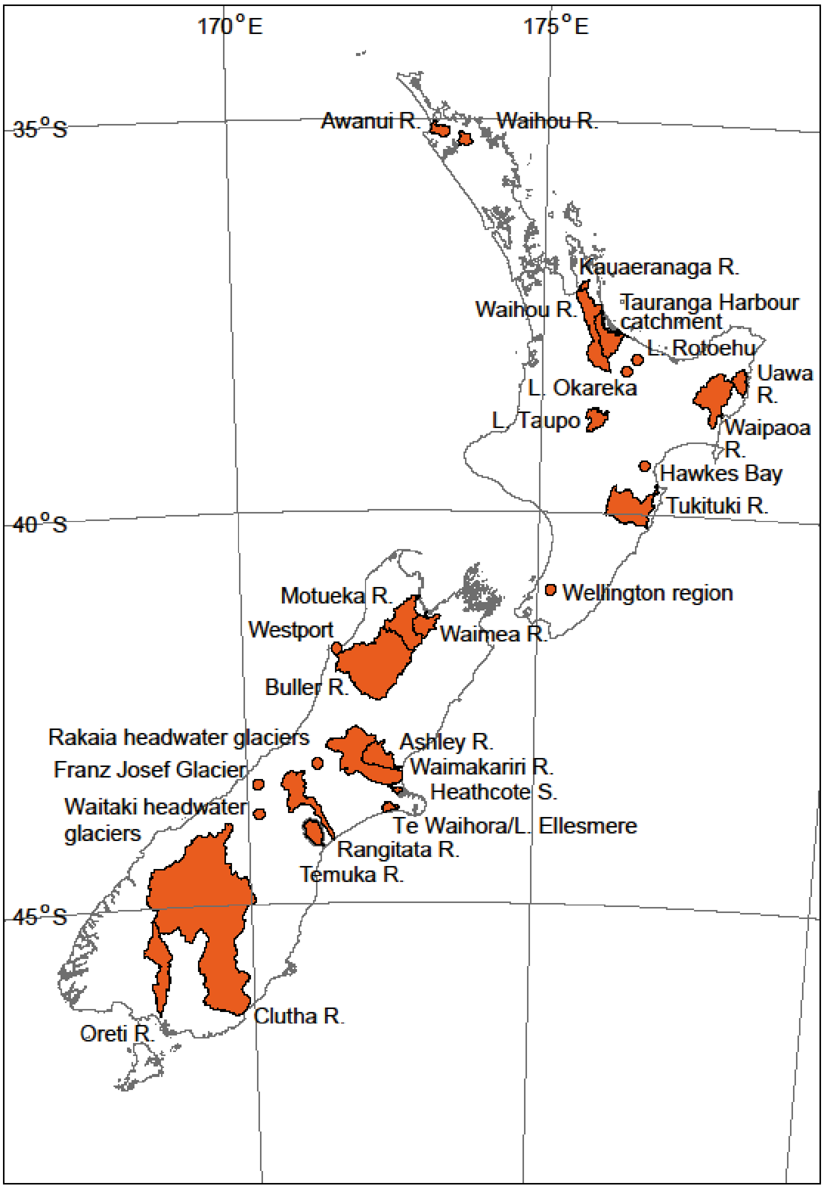


**Figure 8.8.** Coverage of site-specific water resource impact studies across New Zealand. The sites includes 18 river catchments, four lakes, two regions, one harbour catchment, one town, and multiple glaciated regions.

#### 3.4.1.1 *Climatic drivers*

As a precursor to the hydrological impacts assessment under climate change, the more salient aspects of Chapter 2 are briefly recapped here:

- Projected changes in climate will vary from region to region; more so for precipitation than for temperature.
- Projected temperatures based on 12 GCMs and several climate change scenarios indicate a likely increase in mean annual temperature across the country, with spring temperatures affected the least.
- Projections of annual precipitation indicate reductions in the north and east and increases in the south and west, with most of the change occurring during winter and spring.

- Precipitation is increasingly likely to fall as rain rather than snow, and extreme rainfall events are likely to become more extreme.
- With substantial variability among emissions scenarios as well as among the 12 GCMs used, projections of precipitation are less certain than for temperature.
- A regional breakdown of temperature and precipitation projections, along with plausible uncertainty ranges, is provided by (MfE 2008a).

#### *3.4.1.2 Snow pack and glaciers*

The projected changes in temperature and precipitation are likely to affect New Zealand's snow packs in two significant ways (Fitzharris 2004; Hendrikx & Hreinsson 2010; Poyck et al. 2011). While more precipitation is anticipated in the alpine regions, it is more likely to fall as rain rather than snow, and the snow that does fall will melt sooner. These changes are expected to occur by 2040. This would lead to a reduction in the areal extent of the seasonal snow pack, particularly for elevations below 1000 m. The results of two key studies on New Zealand snow pack completed to date are outlined in Table 8.2 (the exact projections are predicated on the climate change scenarios used to drive the modelling). The capacity of alpine regions to serve as temporary stores of water will decline, so more water will run off and replenish rivers in the winter and less in the spring (e.g., the Clutha River, Poyck et al. (2011)). This has important implications for river-derived abstractions and the use of reservoirs to store water between seasons.

In terms of impacts on New Zealand's glaciers (see Table 8.2), the Franz Josef glacier has received the most attention (Anderson et al. 2006; Anderson et al. 2008; Oelermans et al. 1998). Although different modelling approaches have been used, results were largely the same: despite higher precipitation tending to increase glacier mass, higher temperatures will more than compensate for this, resulting in a reduction of the Franz Josef glacier mass and extent over the course of this century. This applied to all scenarios considered. It is reasonable to expect this pattern to apply to other glaciers along the Southern Alps, though further research would be necessary. Based on 1990 projections of climate change, Chinn (2001) estimated a slight increase in river flow in the Rakaia, Rangitata and Clutha catchments as glacier mass in their headwaters declines over the first half of the century; and a modest increase in river flow in the Waitaki catchment.

**Table 8.2.** Studies of the effects of climate change on New Zealand snow packs.

| ***Study location*** | ***Key results*** | ***Reference*** |
|---|---|---|
| Nationwide | On average, at nearly all elevations, the 2040 and 2090 scenarios result in a decrease in snow as described by snow duration, fraction of precipitation that is snow, and mean maximum snow accumulation in each year | Hendrikx & Hreinsson (2010) |
| Alpine headwaters of eastern catchment in central-southern South Island | Rise of mean snowline by 120–270 m depending on scenario; mean annual snow accumulation reduced to as little as 30% in the east, 63% closer to the divide | Fitzharris (2004) |
| Waimakariri, Rakaia, Rangitata, Waitaki and Clutha catchment glaciers | Loss of mass from 2000–2050 based on indicative 1990 climate change projections | (Chinn 2001) |
| Franz Josef Glacier, West Coast | 5 km retreat and 38% mass loss by 2100 under mean climate change scenario; across all scenarios, 3.9–6.4 km retreat and 26-58% mass loss | Anderson et al. (2008) |
| Franz Josef Glacier, West Coast | Glacial retreat and continued reduction in mass over this century | Anderson et al. (2006) |
| Franz Josef Glacier, West Coast | Reduction in mass and extent during this century (exact details not reported) | Oerlemans et al. (1998) |

### *3.4.1.3 Evaporation*

Climate change could affect both evaporation and evaporative demand. Changes in evaporative demand were reported in several instances (Table 8.3) each time represented as potential evapotranspiration (PET). These results showed an increase in evaporative demand across Canterbury by 2040, and more so by 2090 (Woods et al. 2008; Zammit & Woods 2011a, b), in line with increases in temperature. A limitation of these results, and of most hydrological impact assessments, is that changes in evaporative demand reflect changes in temperature only. Changes in radiation and wind speed are known to have important effects (e.g., Kingston et al. 2009); Clark et al. 2011), but because less is known about how they may vary in the future, they are often left out of the calculations. Projected changes in evaporation in New Zealand have not been reported, even though they are often calculated as part of the hydrological modelling process.

For pasture sites across New Zealand, an additional study combined both evaporation and evaporative demand to examine the effects of climate change on difference between the two – the potential evaporation deficit (PED) (Mullan et al. 2005). PED is a measure of how much additional water could evaporate if available, and so indicates how much additional production could occur with sufficient irrigation. This study showed that in parts of New Zealand that are exposed to high PED, climate change will probably increase PED further over the coming decades, a finding similar to the results of Clark et al. (2011).

Increases in either evaporation or evaporative demand have two significant implications for water resources: the amount of freshwater available for abstraction diminishes, for both rivers and aquifers; and the amount of water that needs to be abstracted to irrigate a given area of land or to produce a given crop yield increases. Higher rates of evaporation also contribute to more frequent, more intense, or longer droughts. The impact of greater evaporative demand on agricultural water demand and irrigation efficiency is also discussed in Section 3.4.4 (below).

**Table 8.3.** New Zealand-based studies of the effects of climate change on evaporation.

| ***Study location*** | ***Key results*** | ***Reference*** |
|---|---|---|
| Nationwide | Annual average PED increases everywhere by the 2030s except for the west coast of the South Island; greater increases for the 2080s; drought risk substantially increases for eastern and northern parts of both islands; expansion of droughts into spring and autumn | Mullan et al. (2005) |
| Ashley River, Canterbury | PET increased by 75 mm/year in headwaters in 2040, 150 mm/year for plains; PET changes doubled for 2090 | Zammit & Woods (2011a) |
| Rangitata River, Canterbury | PET increases by up to 60 mm/year in 2040 for plains; small decreases in the headwaters | Woods et al. (2008) |
| Waimakariri River, Canterbury | PET increased by 60 mm/year in headwaters in 2040, 140 mm/year for plains; PET changes doubled for 2090 | Zammit & Woods (2011b) |

### *3.4.1.4 Soil moisture*

Climate change will affect soil moisture in two main ways: by changing the precipitation input, and altering the evaporative output. Although soil moisture is a central feature to physically based hydrological models, its changes are rarely documented. Only one study in New Zealand has considered soil moisture under a changing climate (Clark et al. 2011), showing that soil moisture conditions for pasture sites around the country are more likely be drier in the future (and as soon as the 2040), particularly in eastern regions that already experience more severe droughts. Changes in soil moisture, and the productive responses, are implicitly treated in the simulation modelling reported in Chapters 3–7. A smaller effect is possible in response to sea-level rise, as drainage of coastal soils declines due to a reduction in the hydraulic gradient and elevation of the water table.

### *3.4.1.5 Drought*

Two national assessments of drought under climate change have been carried out to date ( Mullan et al. 2005; Clark et al. 2011); both have discussed above in terms of evaporation and soil moisture. Although their methods differed, their conclusions about average changes are largely the same: regions that are already drought-prone are likely to experience more frequent and more severe droughts in the coming decades, and particularly so towards the end of this century. This applies most notably to eastern parts of Canterbury and Gisborne. The Clark et al. (2011) study explored a broader range of emissions scenarios and climate models. It identified a plausible upper-end drought scenario for New Zealand, with well over a doubling in current drought frequency for most of the North Island and east of the South Island.

#### *3.4.1.6 River flow and flooding*

Changes in evaporation and precipitation likely to alter the volume and variability of river flow. These changes will not be uniform across the country or across a region. Table 8.4 summarises the results of various studies that have looked at river flows, using a variety of methods (predominantly the catchment hydrology model 'TopNet' at various stages of its development). These provide a snapshot of what may happen with climate change, but they are by no means comprehensive. Alpine-fed rivers are expected to have higher flows by 2040, particularly during winter, though it is possible that summer flows will decrease (Chinn 2001; Woods et al. 2008; Poyck et al. 2011; Zammit & Woods 2011a,b). Other rivers, such as the Waimea River in Tasman (Zemansky et al. 2010), the Awanui River in Northland (Collins 2010), and the Waipaoa River in Gisborne (Collins 2012) are likely to have lower mean flows. These results indicate that the annual and seasonal supply of freshwater in the future may change – although depending on circumstances this could be for the better or for the worse. While we have a good understanding of the implications of climate change for about a dozen catchments around New Zealand, most of our catchments – including those of relevance to primary sectors – have not yet been studied in this regard.

Two pairs of studies listed in Table 8.4 usefully pertain to the same rivers – the Waipaoa in Gisborne (Gomez et al. 2009) (Collins 2012), and the Rangitata River in Canterbury (Mullan et al. 2001; Woods et al. 2008). While the first two studied different locations within the Waipaoa catchment and used different models, they both arrived at reasonably similar projections for mean annual flow. Gomez et al. (2009) projected a reduction near the coast of 13% by 2030 and 18% by 2080. (Collins 2012) projected a reduction further upstream of 14% in 2040 and 24% by 2090. The similarity of these results, after accounting for the difference of a decade and despite using different climate change projections and different hydrological models, gives added weight to the confidence of the two studies. The similarity in the seasonal trends projected by Mullan et al. (2001) and Woods et al. (2008) for the Rangitata River, are also consistent with each other, though their magnitudes are not identical.

Few studies have given particular attention to the issue of low flows. Extending the approach of Collins (2010), Collins (2012) projected only a slight decline in 7-day mean annual low flow (MALF) for the Waipaoa River in Gisborne for 2040 and 2090. However, uncertainties associated with the GCMs and emissions scenarios he used include both substantial increases and decreases. The middle-of-the-road projections for MALF are similar in magnitude to present day uncertainties in MALF. Another case study, of the Waimea River, Tasman, compared the 2058/59 water year to the 2000/01 water year – the driest year on record (Zemansky et al. 2010). The weather patterns under climate change were developed by taking the historical rainfall and temperature records and scaling them according to projected mean changes in climate; the temporal variability of the time-series were otherwise unchanged. They projected an increase in the number of low-flow days during the driest period of the year (February–April) from 18 days under historical conditions to 27 under the A1B scenario and 30 under the A2 scenario.

On the related issue of flow reliability, two studies from the Canterbury Plains show reductions as climate change progresses. The first study on the lower Rangitata River basin, Canterbury (Aqualinc Research Ltd 2008), projected a reduction in reliability of supply from both surface and groundwater sources due to lower flows and lower recharge. Similarly, Srinivasan et al. (2011) projected a reduction in the number of days that the Waimakariri Irrigation Scheme in Canterbury would meet demand, of 5% in 2040, and of 17% in 2090. While reliability of supply was not considered in the other catchment-based hydrological impact assessments, similar patterns can be inferred: with less snow base, less rain and lower flows in the drought-prone areas, within-season supply of water is also likely to drop.

At the other extreme, floods are generally expected to become more frequent and more extreme in coming decades (Gray et al. 2005; McMillan et al. 2010; MfE 2010; Li et al. 2011; Sturman et al. 2011), consistent with the expected increases in extreme rainfall events. This would be exacerbated in coastal areas due to sea-level rise. Changing storm tracks may also play a part: the North Island may experience more ex-tropical cyclones, such as

Cyclone Bola which caused severe damage around Hawke's Bay and the East Cape in 1988. Regional differences in temperature and storm track changes, as well as hydrological responsiveness of catchments, are likely to mean that the effects of climate change on flooding will vary among regions and among catchments, however no systematic assessment of these potential differences has yet been undertaken.

**Table 8.4.** Studies of the effects of climate change on river flow.

| *Study location* | *Key results* | *Reference* |
|---|---|---|
| Awanui River, Northland | Decrease in mean flow; little change in autumn; greatest decrease in winter and spring | Collins 2010) |
| Waihou River, Northland | 1-in-30 year summer flood increase by 40% for A2 and 100% for B2; 1-in-500 year flood increases from 900 $m^3/s$ to 1000-1500 $m^3/s$ | McMillan et al. (2010 |
| Kauaeranga River, Waikato | Increase in the 100-year ARI flood flow from 1150 $m^3/s$ to 1370 $m^3/s$ by 2050 and to 1550 $m^3/s$ by 2100, under the A1B scenario. For the 50-year ARI flood, the corresponding increases are from 1050 $m^3/s$ to 1250 and 1400 $m^3/s$ | Li et al. (2011) |
| Waihou River, Waikato | Increase in the 100-year ARI flood flow from 580 $m^3/s$ to 700 $m^3/s$ for 2050 under the A1F1 scenario, and to 780 $m^3/s$ in 2100 under the A1B scenario. For the 50-year ARI flood, the corresponding increases are from 480 $m^3/s$ to 550 and 630 $m^3/s$, both for the A1B scenario | Li et al. (2011) |
| Uawa River, East Cape | 1-in-30 year summer flood increase by 80% for A2 and 20% for B2; 1-in-500 year flood increases from 1800 $m^3/s$ to 2000-3100 $m^3/s$ for B2; 2900-4000 $m^3/s$ for A2 | McMillan et al. (2010) |
| Waipaoa River (at Kanakanaia), Gisborne | Mean flow to decrease in all seasons (2040 and 2090), with the least in summer and autumn and the most in winter and spring. MALF also exhibits a minor decrease. Uncertainty bounds encapsulate both increases and more pronounced decrease for most seasons | Collins (2012) |
| Waipaoa River (at Matawhero), Gisborne | Decrease in mean annual flow by 13% by 2030 and 18% by 2080 | Gomez et al. (2009) |
| Tukituki River, Hawkes Bay | 2050 summer and autumn flows 20-30% lower; winter flows 0-10% lower | Mullan et al. (2001) |
| Motueka River, Tasman | 2050 summer flows 20-30% lower, winter flows unchanged | Mullan et al. (2001) |
| Waimea River, Tasman | Little change in hill country; 23-27% decrease in flow and 50-76% increase in low-flow days during driest period in lowland plains | Zemansky et al. (2010) |
| Buller River and Westport, West Coast | Magnitude and direction of peak discharge change varied with storm characteristics and warming scenario: -15% to 82% change; township inundation from 2% AEP* storm increased from 4% to 13% in 2030s under low warming scenario, and to 79% in 2080s under higher warming scenario, partly due to sea-level rise | Gray et al. (2005) |
| Buller River, West Coast | Increase in peak flow and reduction in AEP for all projections; the AEP is doubled for the A1B scenario for the 2090s | Sturman et al. (2011) |
| Ashley River, Canterbury | Mean flows to change by -1% to+ 5% depending on location and projection period; monthly mean flows to increase for winter and autumn, and decrease or remain constant for summer and spring | Zammit & Woods (2011a) |
| Waimakariri River, Canterbury | Mean flows to increase by 7% to 10% depending on location and projection period; monthly mean flows to increase for winter and spring (up to 50% to 70 % for early spring), and slightly decrease or remain constant for summer and autumn | Zammit & Woods (2011b) |
| Heathcote Stream, Christchurch | Increases in flood peaks for the four projections considered; doubled for the 2090s A2 scenario | Sturman et al. (2011) |
| Rangitata River, Canterbury | Effects depend on climate model used: 2050 summer flows higher by 20% or unchanged, and winter flows unchanged or 20% lower | Mullan et al. (2001) |
| Rangitata River, Canterbury | Overall flow increase of 8%; small reductions in December and January flows; large increases in August, September and October | Woods et al. (2008) |
| Clutha River, Otago | Mean flow increases of 6% in 2040, 10% in 2090; increases in winter; little changed in summer; relative contribution from snowmelt decreases | Poyck et al. (2011) |
| Oreti River, Southland | Substantial differences between GCMs; 1-15% increase in long term flow; summer and autumn flows increase; winter flows decrease | Mullan et al. (2003) |

* AEP - Annual exceedance probability: the chance that a flood will occur at least once in any one year.

### 3.4.1.7 Groundwater

As the climate changes, aquifers will reflect the changes to the surface water systems that contribute to groundwater recharge. Drier soils would provide less recharge to aquifers, though by how much has not yet been studied. It is likely that the return flow from irrigation drainage would also decline. In New Zealand, what has been quantified is limited to only a few localised studies. In one case study along the Rangitata River in the Canterbury Plains (Aqualinc Research Ltd 2008), dry-land recharge was projected to decline by 10% by 2040, based on an IPCC Fourth Annual Report (AR4) projection (Table 8.5). This is consistent with the results of the studies by Mullan et al. (2005) and Clark et al. (2011), which imply that soil field capacity would be reached less often, with a corresponding reduction in soil drainage. In a second case, in the Wairoa Plains in Tasman District where groundwater recharge is controlled by the perennial Wairoa River, no change has been projected (Zemansky et al. 2010). A third example comes from Chapter 6 (Section 4.3.2.1), in which modelled groundwater recharge under irrigated grapes is projected to decrease. Groundwater levels, and any dependent spring-fed streams or gaining rivers (e.g., in the Canterbury Plains), would respond to changes in recharge accordingly, with implications for water allocation. In the case of the Zemansky et al. (2010), no effect was projected. Lastly, and in terms of coastal aquifers, as sea-level rises it is likely that the water table near the coast will increase and so the hydraulic gradient from land to sea will decrease. This would in turn affect the rate at which groundwater would flow to the coast.

**Table 8.5.** Studies of the effects of climate change on groundwater.

| Study location | Key results | Reference |
|---|---|---|
| Rangitata River, Canterbury | Groundwater recharge from unirrigated land declines by 10% for 2040 | Aqualinc Research Ltd (2008) |
| Wairoa Plains, Tasman district | Negligible effect on overall groundwater recharge and depth for a scenario extreme year projected into 2050–51 | Zemansky et al. (2010) |

### 3.4.1.8 Lakes and wetlands

In terms of climate change impacts on their water budget, very little attention has been given to lakes, and apparently none to wetlands. Renwick et al. (2010) conducted a hydrological assessment of Lake Ellesmere/Te Waihora for the 2040 and 2090 periods, and under three climate change scenarios. The main projected effect in this large shallow lake was higher evaporation (of between 6% and 129%, depending on the climate change scenario and forecast period considered) due to increased temperature, leading to lower average lake levels and reduced frequency of openings to the coast. However, as with the hydrological models discussed above, the PET model used was solely a function of temperature. Changes to inflows were assessed to be less consequential than changes in evaporation, although the report acknowledged a limitation in the model's available to quantify this effect. In relation to flood hazard, Opus International Consultants Limited (2008) assessed the effects of climate change on the level of Lake Taupo. Translating projected changes in precipitation directly to changes in lake inflow, they projected that the lake level for a 5-year return interval event would increase by 43 mm in 2030 and 98 mm in 2080; for a 100-year event, the increases would be 78 mm and 178 mm, respectively. These estimates, as noted by the authors, are probably over-estimates – as more sophisticated modelling capability or hydrological projections were not available. However, it must be noted that neither of these studies should be generalised to other lakes, or wetlands, elsewhere in New Zealand. As indicated by results of river flow simulations, the overall water balance of receiving water bodies may increase or decrease.

## 3.4.2 Erosion and sedimentation

Several studies have been conducted on the potential effects of climate change on fluvial erosion, and have focussed on North Island catchments. Their findings are generally inconclusive. For the Wellington and Hawke's Bay regions, and using projections from the IPCC Third Assessment Report, Schmidt & Glade (2003) project a decrease in landslide activity for the 2070–2099 period due to a reduction in the intensity of storms. Empirical modelling of sediment delivery to the Bay of Plenty projected a range of possible changes in annual sediment yield for the 2080s, depending on the precipitation projection: from a 25% reduction to 3% increase (Bell et al.

2006). Elliott et al. (2010) projected a 43% increase in sediment load to the Tauranga Harbour by 2051 under a more extreme climate change projection. Physically based modelling of sediment transport in the Waipaoa River (at Matawhero) in the Gisborne District also indicates a possible increase or decrease in mean annual suspended sediment discharge by about 1 Mt/year by 2030 and, depending on the climate change scenario, an increase of 1.9 Mt/year or decrease of 1 Mt/year (Gomez et al. 2009). In the context of the historical sediment load of 13.4 +/- 7.4 Mt/year, these changes would be difficult to detect. In addition, a study of the Manawatu region found that mean erosion rates and sediment yield would not be dramatically affected this century (Schierlitz 2008).

Sediment transport is also an issue for rivers and coastal lake outlets (e.g., Te Waihora/Lake Ellesmere) whose mouths open and close in response to both fluvial and coastal processes. As sea level rises, and as coastal sediment transport and wave dynamics shift, the dynamics of these openings will likely also change. This would affect the size and stability of river mouth lagoons (hapua), in turn affecting related flooding, water quality and mahinga kai (e.g., the Rakaia River mouth).

Any changes in erosion have important implication for water resources infrastructure, which are discussed in Section 3.4.5 (below). They may also affect other forms of infrastructure, in particular transport corridors. The undermining of roads, bridges and culverts by fluvial erosion may interrupt the delivery of goods to markets. How significant this effect may be, or where in New Zealand it may be important, are unstudied at this stage.

### *3.4.3 Water quality*

While trends have been detected in several water quality indicators (Section 2.3) and at least partially attributed to contemporary land use change, very little research has been completed to date on the possible effects of climate change on water quality. MWH (2010) provides a preliminary, and largely qualitative, assessment of water quality effects for a number of irrigation and stock water supply systems around New Zealand for the coming decades. Overall, they anticipate water quality will worsen and receiving water bodies will become more vulnerable due to changes in both river flow and temperature. Trolle et al. (2011) assess the implications of climate warming around 2100 for the water quality of three lakes (Okareka and Rotoehu in the Bay of Plenty, and Te Waihora/Lake Ellesmere in Canterbury). They conclude that the effect of projected warming by 2100 on total nitrogen, total phosphorus and chlorophyll ***a***, though changes in trophic status, is similar to that of a 25% to 50% increase in nutrient loading.

Changes in surface water quality will have particular bearing on aquatic ecosystems, though no additional studies shed light on the potential implications. Increasing water temperatures would lead to increased stress on aquatic biota through effects on dissolved oxygen and nitrate toxicity. Salmon and trout, in particular, are very sensitive to water temperature, and their distribution is very likely to contract with increasing water temperatures. These effects would, in turn, lead to pressure for more water to remain instream in order to buffer against the effects of higher temperatures and other degradation of the aquatic environment (e.g., channel bed sediment composition, channel morphology, nutrients).

In coastal groundwater or near-coastal surface waters, the issue of salinisation also becomes important. As the sea level rises, or as groundwater recharge drops, coastal salt water is able to migrate further into aquifers or coastal waterways. This occurs to varying extents depending on the hydraulic properties of the aquifers (Pattle Delamore Partners Ltd 2011) and land surface. This may make coastal wells less viable or even completely unviable. Coastal drainage systems used for summer irrigation, such as in the Wairarapa, may also be susceptible to water quality degradation in this way.

### *3.4.4 Water use*

As outlined above, climate change is projected to change the supply of water – both its magnitude and timing – as well as increasing evaporative demand. With higher evaporation rates, water demand will increase if production is to be maintained. If the hydrological changes led to a reduction in reliability of supply, then there will also be a greater requirement for water storage, both large scale and on-farm to maintain irrigation reliability.

Increases in water demands for irrigation are likely for dairying (Chapter 3, Section 4.3.3), broad acre cropping (Chapter 5, Sections 4.1.5 and 4.1.5.2), and horticulture (Chapter 6, Section 4.3.1.1), though his may be somewhat offset by more efficient irrigation systems (Chapter 5, Section 3.1.5.2). With higher temperatures, more water would also be necessary to reduce the risk of heat stress among stock (Chapter 3, Section 4.3.5). How much additional water would be sought is unknown. However, it must be appreciated, that additional water for these purposes may not be available due to needs such as protecting aquatic ecosystems or other instream values, the integrity of aquifer systems, or declines in water availability due to climate change.

The efficiency of irrigation schemes is also likely to decline as rates of evaporation increase. Compared with cool and calm conditions, warmer and windier conditions accelerate evaporation before water is able to reach plants' roots. More water would need to be abstracted to compensate for higher losses during the conveyance, storage and delivery of water to the crops. The extent to which this may occur under climate change has not yet been quantified.

### *3.4.5 Water resource infrastructure*

For irrigation schemes and stock water supplies in New Zealand, MWH (2010) have provided a nationwide assessment of potential impacts of climate change. Altered flow regimes may necessitate changes to the reservoir spillway capacity operation. Higher temperatures may foster greater growth of aquatic weeds, with implications for water conveyance. Screened intakes may become more clogged by sediment or organic matter, and depending on changes in the supply of this material, require changes in capacity or cleaning regimes. Mechanical devices, such as pumps and gates, may be affected by changes in sediment-induced damage or changes in the frequency of use, leading to altered lifespans and operation or maintenance costs. Pipe infrastructure is anticipated to be less vulnerable, while canal-based schemes may be prone to increased operation costs with sediment and weed accumulation. Overall, MWH (2010) estimate an average annual increase in operation and maintenance costs for irrigation schemes to be about NZ$20/ha this century, and NZ$5/ha for rural stock water supply schemes.

Other aspects of water infrastructure have received less attention, and are mentioned in previous sections. Anticipated changes in flood frequency would affect the design and maintenance of culverts on farms and managed forests, and of stopbanks; as well as of riparian protection works. Increased erosion or sedimentation would also have implications for flood protection, water intakes, and degradation of productive land. And sea-level rise would affect the drainage of water near the coast.

### *3.4.6 Water resource management*

The various climate-induced changes in water resources described above would, in turn, affect existing water resource management policies and practices. While no studies have considered this issue to date, it is possible to draw some reasonable conclusions at this time.

Much of our existing water-related infrastructure and management practices are based on analyses of historical information about river flows and lake and aquifer levels. We often assume that conditions in the future will resemble those in the past. For instance, calculations on the capacity of culverts, bridges and stopbanks to pass floods safely are predominantly based on analyses and predictions based on historical flood flows. Decisions on water allocation are based on historical flow records in rivers and streams, and levels in lakes, wetlands and aquifers. This will need to change to take better account of climate change.

In the first instance, a changing climate would mean that the amount of water available for allocation would be less certain than in the past. This brings with it a greater risk of over-allocation and the potential for the reliability of supply to decline for existing users. Environmental flow limits may be reached more often. The environment flow limits themselves may need to be re-evaluated as other environmental stressors (such as increased water temperatures) alter the relationships between ecosystem health and flow conditions. These problems would be further compounded by an increase in water demand, with the associated increase in demand for surface and groundwater takes and construction of water supply reservoirs. Balancing competing values is likely to become increasingly difficult.

River management costs, including those of associated infrastructure, will also increase in conjunction with changes in flooding and sediment transport.

All of these matters present substantial challenges for regional authorities charged with day-to-day water resource management, and with managing flood control and drainage schemes. Innovative approaches, such as fostering seasonal water storage, will be called for. It is not practicable that 16 regional authorities, some with very limited resources, drive the necessary changes individually. Ongoing government direction and guidance, such as the 2011 NPSFM, will be necessary.

## 4 Adapting to changing water resources

There are many ways in which water resource systems may be affected by climate change, as described above. These effects may operate in isolation (e.g., groundwater salinisation) or in tandem with one another (e.g., altered water availability, higher evaporation and changed seasonal flows in rivers). They will certainly differ in severity from one another and in different parts of the country. They will also impinge upon different land-based production systems in different ways. For example, forestry is likely to be the least vulnerable of the sectors considered here to changes in water resources (other than rainfall); while dairy farming may be the most vulnerable, given its frequent reliance on irrigation. There are also substantial differences in current knowledge about whether or how these effects may eventuate. However, despite these differences and uncertainties, it is highly likely that some form of adaptation will be warranted.

The relative significance of adaptation options would also vary with severity of the climate-change impacts. Small changes to water resources may only require the more efficient storage and use of existing water, while severe changes to climate may require a complete overhaul of the water-based production system. In keeping with Chapter 1, three levels of adaptation are described as follows:

> **Tactical adaptation** involves modifying existing water resource systems using current practices. Tactical adaptations require lower investment than other forms of adaptation, are already well understood, and in many instances are already being implemented. This will allow them to be implemented more readily and at shorter notice. However, they may not be sufficient to adapt to anything more than minor climate change.
>
> **Strategic adaptation** involves changing to another known water resource system, or making substantive changes to current system, where practices and technologies are well known. The cost of strategic adaptation is higher than for tactical, but it has a greater ability to respond to higher level of climate change.
>
> **Transformational adaptation** involves innovation to develop completely new water resource systems. Such adaptation is the least well understood, the highest risk, the most expensive, and the slowest to implement. It may become necessary only under severe climate change.

The adaptation options proposed here and summarised in Table 8.6 are identified as means of addressing the various water resource impacts reviewed above. They are grouped into the three levels of adaptation noted above, and many are discussed in more detail in preceding chapters. They apply to stakeholders ranging from the land owner and industry groups to regional and national governments. Many adaptations seek to balance water demand with changing water supply, but they may also seek to maintain an acceptable level of water quality. Many of the adaptations are also robust to uncertainties in climate change projections and hydrological impacts.

**Table 8.6.** Options to adapt to changing water resources in New Zealand.

| ***Tactical*** | ***Strategic*** | ***Transformational*** |
|---|---|---|
| • Identify thresholds for production systems<br>• Changing cropping and grazing calendars<br>• Changing crop varieties<br>• Conservation agriculture<br>• Improving soil nutrient management<br>• Greater irrigation<br>• Irrigation efficiency<br>• On-farm water storage<br>• Reduce erosion and freshwater contamination<br>• Avoiding salinisation of groundwater<br>• Changing stock numbers<br>• Review infrastructure in terms of climate change projections<br>• More efficient water resource management | • Changing crop species<br>• Developing new crop genotypes<br>• Precision agriculture<br>• Monitoring and forecasting programmes<br>• Expanding and improving access to irrigation<br>• Reduce the extent of taller vegetation in water-short areas<br>• Offset groundwater abstraction with artificial groundwater recharge<br>• Scheme committees and future asset management decisions<br>• Involvement in local and national water policy and planning processes<br>• Collaborative processes<br>• Incorporate climate change risks into resource and hazard management<br>• Incorporate climate change risks into new and existing infrastructure<br>• Research and development | • Improving crop uptake and conversion efficiency potentials<br>• Different land uses<br>• Re-evaluate the societal values behind water allocation<br>• Inter-regional water transfers<br>• Research and development |

## 4.1 Tactical adaptations

### 4.1.1 Identify thresholds for production systems

To better gauge the sensitivity of the production system to potential climate changes, it is valuable at an early stage to identify critical thresholds in water supply or the wider water resource system that lead to substantially more or less output. This could be a level of water supply reliability below which the uncertainty is too great to support a particular land use. It could perhaps be a level of water quality above which status quo discharges are curtailed. These thresholds would then be matched with the projections of water resource change, if available, to assess likelihood of a transgression. If projections are not available and are deemed important, then it is worthwhile to communicate this knowledge gap to industry groups, government and researchers so that the gaps may be filled.

### 4.1.2 Changing cropping and grazing calendars

As discussed in Chapter 5 (Section 4.1.1), changing the sowing and harvesting times is one of the easiest and most inexpensive adaptive measures available to broad acre farmers. Shifting grazing rotations is also an option for dairying (Chapter 3, Section 4.2.1). Shifting cropping and grazing calendars thus becomes a viable adaptation by aligning the growing periods of the crops with the shifting seasonality of water availability and evaporative demand. The benefits of this are illustrated in Chapter 5 (Section 4.1.5.1). While this may be beneficial everywhere in New Zealand, it may be most valuable in areas with snow-fed rivers that are used for irrigation (e.g., parts of Canterbury).

### 4.1.3 Changing crop varieties

Alternative crop varieties (Chapter 5, Section 4.1.2) also offer opportunities to adapt to changes in water resources. With different cropping date needs, they may offer another means of adjusting to seasonal shifts in the availability of water and higher evaporative demand.

### 4.1.4 Conservation agriculture

By leaving the previous season's crop residue on a field, conservation agriculture has a number of benefits within an adaptation portfolio (Chapter 5, Section 4.1.3). Among them are greater soil moisture retention in dry times, reduced water logging in wet times, and the reduction of erosion.

### 4.1.5 Improving soil nutrient management

Changes in the nutrient application to fields can help adaptation by increasing nutrient use efficiency (Chapter 5, Section 4.1.4). One of the potential benefits of this is the reduction of nutrient runoff from farms, and the subsequent pollution of receiving water bodies.

### 4.1.6 On-farm water storage

On-farm storage provides a means for irrigators to overcome, or partially overcome, times of water shortage. Small storage structures are already widely used in New Zealand with further expansion expected. Establishment typically has to undergo fewer legal hurdles than large, storage reservoirs and their operation is less subject to others' needs; but they are also more expensive per unit of water stored than their larger counterparts.

### 4.1.7 Greater irrigation and use of water storage

The use of increased irrigation is among the more obvious adaptation options available to farmers. Chapter 5 (Section 4.1.5.2) illustrates the benefits of various levels of supplemental irrigation for different broad acre crops and soils, while Chapter 6 (Section 4.3.1.1) examines the effects of irrigation in horticulture. One of the potential impediments for increasing reliance on irrigation, however, is that the water may not be available when it is needed due to reduced water supplies or increased competition with other water users. To overcome this it may be necessary to provide greater seasonal water storage, both within irrigation schemes and on-farm. This is already occurring in places such as Marlborough and Tasman, where beneficiary funded storage schemes have been built; and in South Canterbury, where about 16 million m3 of storage is being constructed alongside the Rangitata River to irrigate about 12,000 ha of land. A similar large-scale storage scheme is being promoted in the headwaters of the Tukituki River in Hawke's Bay to provide more reliable irrigation to the Ruataniwha Plains.

#### *4.1.8 Irrigation efficiency*

Shifting to more efficient irrigation systems, such as to centre-pivot from roto-rainer, supports greater crop or pasture yield, for a given volume of water (Chapter 5, Section 4.1.5.2). Reducing the leakage from water races and irrigating at times of low evaporative demand (i.e., under cool, windless conditions) can have similar benefits.

#### *4.1.9 Reduce erosion and freshwater contamination*

In areas where erosion may increase or water quality decrease, reducing the related degradation due to primary industry activities would benefit the receiving environment and help offset competition for water resources. Actions along these lines are well understood in New Zealand and already widely implemented, even if not universally so. This may be achieved by fencing rivers and streams (regardless of their depth, flow rate and intermittency), by planting riparian buffers, by limiting erosive practices on vulnerable soils and channels, by reducing nutrient and farm waste runoff, and even by widespread afforestation or reforestation. These activities are robust to climate change uncertainties because even under current conditions they can provide benefits to water resource users.

#### *4.1.10 Avoiding salinised groundwater wells*

Counteracting potential salinisation of coastal aquifers may be achieved by one of two solutions. Either alternative sources of water are used, perhaps by shifting to shallower aquifers, or the timing and rate of groundwater pumping is modulated to avoid abstraction of saline water.

#### *4.1.11 Change stock numbers*

One of the means of balancing water demand with supply, is to change stock numbers. Livestock require water for drinking as well as for irrigating pasture or feed. Reducing stock numbers in times of drought is a short-term adaptive strategy already in use in New Zealand. As the climate changes, adjusting stock numbers in concert with short-term fluctuations or longer-term trends is a viable adaptation option. The adjustment may be an increase or decrease, depending on climatic and hydrological circumstances within the planning horizon. The practical and financial viability of these changes need to be carefully considered for intensive (Chapter 3, Dairy) and extensive (Chapter 4, Sheep & Beef) systems.

#### *4.1.12 Review infrastructure in light of potential climate change impacts*

As MWH (2010) illustrate, climate change may lead to changes in which existing infrastructure is more vulnerable – or not managed as effectively as it could be. It would be valuable, therefore, to assess present day infrastructure in terms of potential climate change impacts. Is it robust to climate change projections over its design lifetime? This question is equivalent to the earlier adaptation of identifying thresholds in the production system, beyond which water resource change may bring significantly different outcomes. Any shortcomings identified following a review would assist in targeting subsequent adaptations.

#### *4.1.13 More efficient water resource management*

As competition for water resources intensifies, whether due to climate change or a myriad of other factors, more accurate and efficient water resource management may allow more water to be used for primary industries, all else being equal. This is not to say that other values are marginalised, but rather that instream and out-of-stream water needs are more accurately quantified, and that allocation limits are fine-tuned to these limits. In terms of water allocation for horticultural systems, this is already being implemented with the SPASMO model discussed in Chapter 6. Part of this process is the review of existing water take and discharge consents, to identify whether the limits are tailored to the actual needs and to identify what proportion of a catchment or aquifer system is allocated. And while fine-tuning the allocation of water is an option for water resource managers, engaging in water consent trading is an option for water users.

## 4.2 Strategic adaptations

### 4.2.1 Changing crop species

As discussed in Chapter 3 (Section 4.3.2) and Chapter 5 (Section 4.2.1), changing crop species is a more strategic means of growing crops in an altered climate. Doing so raises the opportunity to grow more water-conservative or drought-tolerant crops that yield greater economic output for a given volume of water or are more sustainable in an increasingly variable climate. However, as also as noted in Chapter 5, pressures for crop choice are likely to be more demand-driven than supply-driven, and so adapting crop choices to climate change can only occur if there is demand for the new crops.

### 4.2.2 Developing new crop types

Among the many potential benefits of novel crop genotypes, one is greater water use efficiency (Chapter 5, Section 4.2.2). Unlike tactical adaptation options, there is inherent uncertainty with this avenue of adaptatation, and new genotypes may not prove robust in all climatic conditions.

### 4.2.3 Precision agriculture

The application of irrigation can be made more effective, and thus water use more efficient, with knowledge when and where within a field water is needed. This is achieved through precision agriculture (Chapter 5, Section 4.2.3), which is already in use in a number of farms within New Zealand.

### 4.2.4 Monitoring and forecasting programmes

One possibility to adapt to increasing hydroclimatic variability, and to use existing water resources more efficiently, is to more actively monitor soil hydrological conditions as well as forecast near-future water supply and evaporative demand. This information can be used to better schedule irrigation during a week, or better select cropping decisions during a growing season. Chapter 5 (Section 4.2.4) discusses the potential benefits in more detail.

### 4.2.5 Expanding and improving access to irrigation

As noted in Chapter 5 (Section 4.2.5), the uncertainty surrounding future rainfall, greater rainfall variability, and the potential for more extreme droughts provides the greatest risks for broad acre cropping in New Zealand. If the tactical adaptation of augmenting existing supplies (Section 4.1.7) is insufficient, the strategic options of expanding irrigation opportunities become important. They include the development of new water storage and irrigation schemes of all sizes, inter-basin water transfers, water consent trading, and better conjunctive use of surface and ground waters. Developing new irrigation schemes is also a viable adaptation option for dairying (Chapter 3, Section 4.3.2) and horticulture.

### 4.2.6 Reduce the extent of taller vegetation in water-short areas

In addition to developing new sources of water for irrigation, it is also possible to alter existing land cover and uses so that greater water supplies are generated from the catchment. One possible approach in New Zealand would be to reduce the extent of forest or dense scrub cover in parts of the catchment upstream of the water take and groundwater well (Fahey 1994). Both Tasman District and Canterbury Region currently regulate the expansion of plantation forestry in a few water-sensitive catchments to help maintain instream values and the rights of downstream water users (Environment Canterbury 2011). However, with less vegetation cover comes the potential for greater erosion. Afforestation and reforestation are already identified as adaptation options where erosion is a concern.

### 4.2.7 Offset groundwater abstraction with managed groundwater recharge

Greater abstraction of water from aquifers may result in a decline in spring-fed river and stream flows. One plausible option to counteract this effect is to implement managed groundwater recharge schemes. These entail the artificial storage of water in infiltration basins during times of low water need and high supply, increasing the net recharge rate and helping to balance net groundwater depletion. A preliminary study of artificial groundwater recharge has been conducted for the Canterbury Plains (Williams 2011).

### *4.2.8 Scheme committees and future asset management decisions*

One intermediate means of adapting to climate change is to collaborate with fellow water users in the planning and management of water resource infrastructure and resources. Initiatives like irrigation schemes, water storage, or community water user groups will play an important role in water resource use in the future. As such, it is in the interests of individual water users to have their needs represented in, and accommodated by, the decision-making processes that bring these initiatives about. This would be valuable in the context of climate change because, even within a catchment, the nature of, and vulnerability to, climate change is likely to differ among farm types.

### *4.2.9 Involvement in local and national water policy and planning processes*

In a similar vein to the previous adaptation option, becoming involved in local and national water policy and planning processes is also advantageous for water users. By doing this, they can more effectively get their needs represented and accommodated by the emerging management decisions. Involvement can range from contributing as regional authorities draw up plans, on to more collaborative processes such as the Land and Water Forum.

### *4.2.10 Collaborative processes*

Current water resource planning under the RMA can be adversarial, involving expensive litigation in the Environment Court. Identifying institutional barriers and new ways of involving stakeholders in water resource planning are key strategic adaptation options. Examples of the latter include collaborative approaches being fostered under the national Land and Water Forum and the Canterbury Water Management Strategy (CWMS).

### *4.2.11 Incorporate climate change risks into resource and hazard management policies*

Of the adaptation options available to resource managers – both national and regional – developing policies and practices that reflect the realities and threats of climate change is the most important. Water resource planning will have to accommodate both greater uncertainty and shifting baselines (Kundzewicz et al. 2007). However, it is also very important to distinguish between natural climate variability (e.g., ENSO, IPO) and climate change. This will involve a change of mindset: from making decisions based on historical flow records to making projections about likely future changes. This will require local political buy-in, and perhaps further government direction.

Change will necessitate some different approaches to water resource management. These need to be both process- and outcome-driven. In terms of process, the current institutional arrangements are often adversarial, and lead to potentially expensive Court processes and a win/lose attitude. As already discussed, more collaborative approaches are now being fostered at a national level through the Land and Water Forum; and in Canterbury through the CWMS. Opportunities exist to promote collaborative approaches elsewhere in the country. Opportunities also exist to make current institutional arrangements more flexible to allow for more rapid responses to changing circumstances.

In terms of outcomes, some greater flexibility may also be desirable. As the climate warms, irrigation will become increasingly important on the one hand, but less reliable on the other. This can be overcome by medium- or large-scale storage systems; and possibly by methods such as using surface water for aquifer recharge. Regional plans will need provisions for greater flexibility in seasonal water allocation to allow storage to be replenished.

Alternative approaches also exist. For example, allocation limits may be set and updated every 10 years or so (or when important information comes to light), based on the most reliable climate change projections and environmental flow needs; a buffer of unallocatable water could be maintained in the event of shortages outside historically expected patterns; or water allocation and use could be adjusted on shorter time-scales as observations or projections indicate. All these approaches would require some legislative change.

Another possible approach would be to grant shorter consents for A block allocation[3] (e.g., 15–20 years) and

[3]A and B block allocations constrain abstraction depending on the river flow at a given time. Once flows drop to an upper threshold, B block takes must cease but A block takes may continue. Once flows drop to a lower threshold, A block takes must also cease. As a result, A block allocations are more reliable than B block but are also more susceptible to climate change.

longer for B block (e.g., 25+ years in eastern regions). This would allow the more sensitive B block allocations to be reassessed should environmental limits or flow reliability become increasingly compromised, while still giving long-term certainty for users of A block allocations. This provides a trade-off between longevity of supply and reliability of supply. In terms of setting environmental flows, the only option at present is probably to set aside an additional buffer such as a higher minimum flow and/or lower allocation cap. The most robust solution will depend heavily on the planning horizons, the flexibility of the water users, and the certainty of the science, and would require concerted assessment and re-assessment by scientists and planners.

In the case of river engineering, for example, managers have several options available to them. One is to use the best available projections of flooding change to alter design specifications for river works in advance of climate change (e.g., MfE 2010). A problem with this approach, is that even the best projections will be uncertain. Another option is to reduce the vulnerability of property and infrastructure within the floodplain by relocation or rezoning infrastructure. This approach has the benefit of reducing the costs of flooding if or when it occurs, but can be very expensive to implement and may run into strong local opposition. A third option is to manage river protection schemes adaptively, only implementing improvements when observational evidence signals it necessary (e.g., Williman 2010). While this may avoid mal-adaptation, this approach increases the risks of flooding before evidence of a climate change effect is statistically significant.

#### *4.2.12 Incorporate climate change risks into new and existing infrastructure*

In instances where water resource infrastructure may be adversely affected by climate change, addressing these risks in the design and maintenance would be a prudent adaptation option. This may entail re-sizing reservoirs or on-farm dams, repositioning water intakes, or simply budgeting for greater maintenance costs. To what extent these risks should be included depend on the expected lifetime of the infrastructure and the associated projected risks over that time.

#### *4.2.13 Research and development*

Should climate change to an extent that stretches our existing capacity, not only will strategic adaptation decisions need to be made, but research and development will also increase in importance. Research and development would be valuable in supporting other adaptation actions, in discovering new options, and in further refining how the water resources are and may change. In this way, more advanced science can support more successful adaptation.

## *4.3 Transformational adaptations*

### *4.3.1 Improving crop uptake and conversion efficiency potentials*

The development of crop genotypes with higher uptake and conversion efficiency of water has been mooted by several researchers and may benefit dairying (Chapter 3, Section 4.4.1) and broad acre cropping (Chapter 5, Section 4.3.2.1) among other sectors. One line of research lies in the transfer of the C4 biochemical pathway into C3 plants.

### *4.3.2 Different land uses*

If competition for scarce water resources becomes too costly, various irrigation-dependent activities may cease to be economically viable (Chapter 5, Section 4.3.3). In this case, a shift in land uses may be a necessary response.

### *4.3.3 Re-evaluate the societal values behind water allocation*

Should severe climate change occur, and New Zealand water resources become greatly disrupted, it will probably become necessary to re-evaluate the societal drivers behind water allocation decisions (Miller et al. 1997). Just as the Land and Water Forum and the Canterbury Water Management Strategy are developing consensus-based visions of water management in today's climate, the process may need to be revisited as the climate change and priorities shift.

### 4.3.4 Inter-regional water transfers

Should the economic benefits of irrigated agriculture become sufficiently high, it may become worthwhile to examine the transfer of water across large topographic barriers, from wet to dry regions. This already takes place on small scales, including the transfer of water from the Waikato to Auckland city.

### 4.3.5 Research and development

As previously raised in the context of strategic adaptation, research and development will be of particular importance in underpinning adaptation as climate change becomes more severe. The more severe the change, the greater the need to move away from historical norms, for which we have already developed suitable practices. This requires new solutions, and these require research.

## 4.4 How to identify the right adaptation portfolio

Identifying the most suitable adaptation pathway for any one stakeholder or group of stakeholders will not be an easy task. There is no 'one-size-fits-all' approach and no silver bullet. The best adaptive pathway will probably be a portfolio of staged responses that address different material threats (both within the water resource system and outside), different levels of risk, and does so at different times. It is also highly likely that multiple stakeholders adapting in concert will yield benefits greater than would be possible separately.

The selection process must be one of risk management, incorporating a range of benefits and costs – economic, environmental, social and cultural. Benefits and costs will differ over time, among catchments and among sectors. In most cases, adaptations would yield benefits even in the absence of climate change; such interventions are termed 'no regrets' interventions. Examples of these include greater resource use efficiency and greater water storage. Under conditions of high uncertainty, these robust options are particularly favourable (Wilby & Dessai 2010), even if they are not optimal. In addition, as more data come to hand, and the science of climate change and water resource response advances, uncertainty in the benefits and costs will decline.

In order to assist stakeholders in the selection process, the following series of questions is offered as a means to guide and prioritise decision-making. This applies as much to land owners and industry groups as to regional and national governments.

- How does climate change affect water resources in your area and for your sector? Think about current water resources and any thresholds for instance, soil moisture levels.
- Of these potential impacts, which affect your particular operation now and into the future? Think about your production system, inputs into your system (e.g. feed), getting your produce to market, as well as any benefits and advantages from any changes in management now.
- How do these impacts compare to impacts outside the water resources sphere? Can these impacts be managed as part of your other business as usual activities, for instance regular maintenance on stock water systems or decision making processes e.g. a regional water plan?
- What adaptation options are relevant to water resource impacts? Look at current good practice and discuss with industry representatives. Are there good examples overseas that can adopted for use in New Zealand?
- Are there 'win-win' adaptation options which have benefits now? One example is increasing irrigation efficiency or training staff in best practice?
- Are adverse impacts likely to occur within the planning horizons of existing activities? Are you thinking of investing in water storage or stock water systems, flood or drainage management? Are rainfall or flow estimates factoring in the changing climate, or are they based on historical data?
- What are the potential costs and benefits of acting compared to not acting? Does it matter when you act?

## 4.5 Evaluating the costs and benefits of adaptation options

Choosing whether and when to implement an adaptive response to climate change is driven by the benefits and costs that may be anticipated. While adaptation may alleviate adverse water resource impacts, all adaptation involves various degrees of cost. Given the current level of knowledge, it is not possible to evaluate the expected benefits and costs of different adaptation options in quantitative terms. Even the relative costs cannot currently be estimated.

Despite these limitations, the array of adaptive responses to water resource change is diverse and extensive. Whether they are tactical, strategic or transformational, there are many options to choose from in order to build a robust adaptation portfolio. This is particularly true when stakeholders adapt in concert.

## 5 Knowledge gaps

While the New Zealand research community at large has a good understanding of hydrology and water resources at the present time, our knowledge of the potential impacts of climate change is substantially poorer. Our knowledge of climate change impacts across the country is patchy, in that we have reasonable understanding of some aspects of the water resource system (e.g., river flow) in certain catchments, but little or no understanding in many others. For some elements of the water resource system, such as groundwater, only a few studies have been conducted, but they offer no regional or nationwide indication of the potential effects. Many of the potential impacts described above are only qualitative (e.g., water quality) as very little focussed research on these issues has been conducted in New Zealand.

In order to guide future research, and to better inform adaptation choices, current knowledge gaps are listed in Table 8.7. This report prioritises them in terms of both their potential utility and current feasibility of implementation.

**Table 8.7.** Prioritised knowledge gaps pertaining to water resource impacts.

| *Priority* | *Knowledge gap* |
|---|---|
| High | . National impacts on river flow at the seasonal scale<br>. Changes to groundwater recharge for important aquifer systems<br>. Effects on low flows and reliability for abstraction<br>. Hydrological and ecological effects of altered water supply and resource use<br>. Economic, social and environmental implications of water-related adaptation choices<br>. How water resource management policies could be changed to accommodate climate change risks and uncertainties<br>. Understanding the hydrological and water resource variability and changes of the past in more detail |
| Medium | . Changes to groundwater flow and levels<br>. Identification of bores vulnerable to coastal salinisation<br>. Effects on spring-fed streams and ephemeral rivers<br>. Comprehensive hydrological assessments of catchments of high significance (e.g., Waikato, Waitaki)<br>. Erosion and sediment yield in representative catchments around the country<br>. Protocol for testing the emergence of climate change trends among hydrological observations<br>. Preliminary studies of the effects on aquatic habitat vulnerability and environmental flows<br>. Indicative assessments of flooding changes in more regions around the country<br>. Preliminary studies of the design and operation of water storage needed to offset effects of climate change<br>. Preliminary assessments of the potential role of groundwater in offsetting reductions in surface water reliability<br>. Comparisons of climate change impacts with other drivers of change: Interdecadal Pacific Oscillation (IPO), ENSO, land use change, economic growth<br>. Economic, environmental and social costs and benefits of implementing water resource-related adaptations<br>. Identification of land uses that are better suited to the prevailing water resource projections including uncertainties<br>. Understanding climatic, social and economic drivers of water use<br>. Water balance studies of lakes and wetlands<br>. Effects of climate change relative to climatic variability and other sources of change (e.g., increase in demand)<br>. Effects on surface water quality, particularly water temperature |
| Low | . Effects on evaporation from irrigation races, dams and reservoirs<br>. Effects on whole irrigation system efficiency<br>. Division of the country into regions of coherent hydrological responses<br>. Impacts on irrigation efficiency due to changes in evaporative demand |

## 6 Summary

This chapter has synthesised existing studies on the impacts of climate change on New Zealand's water resources as they pertain to land-based production sectors. In terms of what could be known, this knowledge is far from complete. The knowledge gaps are greater or smaller in size depending on location and the water resource element in question. However, just as uncertainties remain, it is also possible to outline plausible future scenarios for the county's water resources, and offer guidance on how different stakeholders – from land owners to government – should be involved in the collective adaptation process.

Based on this review, the foreseeable implications of climate change for water resources, along with an assessment of uncertainty, are as follows:

- Hydrological and water resource conditions of the past cannot be assumed to prevail in the future.
- Snow packs are very likely to decline in volume, shifting a portion of the annual runoff from spring to winter.
- Evaporation rates and evaporative demand will probably increase, though the magnitude of change is highly uncertain due to limited modelling.
- Higher evaporation would translate to reduced average river flows and aquifer levels, and greater irrigation demand.
- River flows will reflect changes to the amount, timing and state (liquid or frozen) of precipitation, and the amount and timing of evaporation. Seasonal flows will typically remain steady or diminish, with the key exception that alpine-fed runoff is likely to increase in winter and spring.
- Little is known about effects on groundwater, but land-based recharge is more likely to decline than increase. River-fed recharge may change little or not at all.
- Little is known about effects on lake hydrology, and nothing about implications for wetlands. Their water balance will reflect the combined effects of local precipitation and evaporation as well as catchment inflows.
- Droughts are most likely to become more severe in most regions, particularly in eastern regions where drought is already severe at times.
- Flooding is likely to become more intense due to higher storm intensities, but absolute amounts are highly uncertain.
- Erosion rates may increase, though there is appreciable uncertainty and variability. Some of the projected changes are within the range of natural variability, suggesting that detecting them would be difficult.
- The effects on freshwater quality have largely gone unstudied. Temperatures will most likely increase. It is reasonable to expect water quality in lakes and rivers to remain steady or decline.
- With changes in river flow regimes and intensity of storms, it is likely that environmental flow limits will be met more or less frequently, depending the changes in local hydrological conditions.
- With higher evaporative demand, irrigation efficiencies will most likely decline, assuming no other changes in irrigation technology.
- With less reliable water supplies and greater evaporative demand, water demand for irrigation will most likely increase. The extent will vary among crops, soil types and catchments, and must be put into the context of other pressures controlling water demand such as agricultural expansion, conversion and development of large scale and on farm, storage.
- Infrastructure such as bridges, culverts, roads and stop banks are likely to be more susceptible to damage during intense storms.
- Drainage infrastructure will come under increased pressure from channel sedimentation and rising sea levels.
- Water-related infrastructure is more likely to incur greater operation and/or maintenance costs due to changes in use, sedimentation and water quality.

Depending of the severity of future climate change, some or all of these effects may warrant amelioration by way of adaptation. Adaptation options identified in this chapter may be summarised as follows:

- Increased water use efficiency, including better matching the amount and timing of water supply and demand.
- Short- and medium-term projections of water supply and demand.
- Increased erosion control and nutrient retention.
- Increased water supply, from either alternative sources or inter-seasonal water storage, particularly in eastern regions.
- Incorporation of climate change risks into water resource policies and plans, particularly those governing water allocation.
- Incorporation of climate change risks into infrastructure maintenance, operation and design.
- Adjustment of crop choices and stocking densities in tandem with medium- to long-term changes in water supply.
- More attentive observation of climate change impacts and attribution.

It is important that current knowledge gaps are steadily filled, balancing the need to know with the feasibility and cost of doing so. It is also important that adaptations to water resource change do not occur in isolation from other features of climate, environmental and societal change. They must occur in tandem, and t all stakeholders must adapt in concert.

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