Chapter 37

Impacts of hydro-dams, irrigation schemes and river control works

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INTRODUCTION

Many New Zealand rivers are modified by large water projects. Water is used for irrigation, water supply and industrial purposes throughout New Zealand, but the amounts of water abstracted are often relatively small (less than 1% of New Zealand's total water resources; Statistics New Zealand 2000). Large-scale abstraction and storage of water for irrigation or water supply occurs primarily in drier parts of the country, or close to larger cities and industrial areas. In contrast, hydro-electric power schemes use 16–33% of New Zealand's total water resources (Statistics New Zealand 2000), but generally allow water to be returned to the same river system.

Water storage is often a key feature of large water projects. Storage can be "online", where water is held back within the river channel by a dam, or "off-stream", where water is diverted to a reservoir away from the river channel. The effects of large water projects depend to a great extent on the type and volume of storage involved. Online storage requires the construction of large dams and interferes with many natural processes within the river channel. In contrast, off-stream schemes might be expected to have more benign effects on the environment, but such schemes are uncommon due to the difficulty in locating suitable water storage areas away from the river channel and the costs of transferring water out of the river channel.

Other large projects associated with river systems include flood protection and river control works. Here floodwaters and channel movement are confined to a restricted area to protect the surrounding land from flooding and erosion. Such projects have been instrumental in providing sufficient security for the development of land within river floodplains and have resulted in significant economic benefits to New Zealand. However, confinement of rivers can have negative effects on the ecological functioning of river systems, reducing the amount of available habitat and also altering natural geomorphic processes.

This chapter reviews the history of the development of large water projects in New Zealand, comments on current trends in project development and summarises the effects of large water projects on flow regimes, lake levels, sediment movement and water quality. Changes to the life-supporting capacity of habitats affected by large water projects are also examined, along with their effects on cultural, aesthetic and recreational values that are cherished by many New Zealanders. We also provide a short summary of how the impacts of large water projects are managed within the context of the Resource Management Act (RMA).

HISTORY OF LARGE WATER PROJECT DEVELOPMENT

Hydroelectric development

The hydroelectric potential of New Zealand rivers was recognised in the early 1900s. At first various small schemes were operated by private companies or local bodies, then the growing demand for electricity led to the construction of the first government power scheme at Lake Coleridge, which was completed in 1914 (Table 37.1). Development continued throughout the country, with Mangahao and Tuai supplying power to the lower North Island, Arapuni supplying Auckland, and Waitaki supplying various parts of the South Island. After a delay in construction activities through World War II, further stations were constructed on the Waikato, Clutha, Waitaki and Waiau rivers. Much of the Tongariro Power Development occurred during the 1970s, with diversion of water

Table 37.1 Moderate and large (>10MW) hydroelectric power schemes (as of 2003).

Name	First operated	Installed capacity (MW)
Karipiro	1947	90
Arapuni	1929-46	197
Waipapa	1961	51
Maraetai	1953-62	360
Whakamaru	1956	100
Atiamuri	1958	84
Ohakuri	1961	112
Aratiatia	1964	84
Tokaanu	1973	240
Rangipo	1983	120
Kaitawa	1949	37
Tuai	1929-39	52
Piripaua	1943	44
Mangahao	1925	19
Matahina	1967	72
Patea	1984	31
Lloyd Mandeno	–	16
Ruahihi	1983	20
Wheao	1980	26
Cobb	1944-55	32
Branch	1983	11
Lake Coleridge	1915-29	45
Highbank	1945	25
Tekapo A	1951	25
Tekapo B	1977	160
Ohau A	1979	264
Ohau B	1983	212
Ohau C	1985	212
Benmore	1965	540
Aviemore	1968	220
Waitaki	1935-49	105
Paerau	–	10
Clyde	1992	432
Roxburgh	1956-61	320
Manapouri	1969-71	680
Waipori 2	--	54

from the Whanganui and Rangitikei headwaters into the Rangipo and Tokaanu power stations; this also resulted in increased generating capacity of the stations on the Waikato River downstream. The major development in the 1980s was the complex system of canals connecting the waters of Lakes Tekapo, Pukaki and Ohau in the upper Waitaki River. The last major development was the Clyde Dam on the Clutha River, which was completed in 1992 (Table 37.1).

Irrigation development

Prior to 1950, the majority of irrigation schemes were developed and financed solely by the government. Almost 100,000 hectares of land were irrigated by these schemes, the majority of which were dependent on mining rights to water in Central Otago, or the development of the Rangitata diversion race in mid Canterbury (MAF 2001). Between 1950 and 1980, problems with the use of existing schemes by farmers became evident. Future schemes needed prior commitment by farmers to ensure that benefits from the schemes were maximised, and it was recognised that the beneficiaries of schemes should contribute to the costs. Large areas of land were irrigated through this period. From 1980 onwards, the development of large community irrigation schemes slowed due to the removal of subsidies and loans to farmers and the tight financial conditions that faced farming during the late 1980s and early 1990s. However, with very dry summers in 1982 and again in 1984–85, there was rapid growth of irrigation on the Canterbury Plains, as individual farmers sank deep groundwater wells (deeper than 30 m) and used spray irrigation for crops and pasture. Central government no longer funded community irrigation schemes and local body reform and the implementation of the Resource Management Act virtually halted communal irrigation schemes (MAF 2001). Two notable exceptions to this were an 11,000-hectare development in the Waimakariri area and the 16,000-hectare Opihi augmentation scheme in South Canterbury. By 2002, around 500,000 hectares of land were under irrigation, largely in Canterbury, Otago and Hawkes Bay (Table 37.2).

Table 37.2 The area of land irrigated for agriculture in 2000 (from Hegarty *et al.* 2002)

Region	Area irrigated	% of total area
Northland	4,040	0.8
Auckland	6,500	1.3
Waikato/King Country	4,500	0.9
Bay of Plenty	9,341	1.8
Gisborne	5,000	1.0
Hawkes Bay	23,242	4.6
Taranaki	2,000	0.4
Manawatu/Wanganui	8,000	1.6
Wellington/Wairarapa	9,273	1.8
Tasman	7,920	1.6
Marlborough	12,087	2.4
Westland	0	0
Canterbury	347,022	68.6
Otago	65,090	12.9
Southland	1,500	0.3
TOTAL	505,514	100

Flood protection and river control works

The importance of flood protection and drainage works became evident as soon as European settlers attempted to develop river floodplains for agriculture. River Boards were set up in some regions as early as 1868, with the River Boards Act being passed by the central government in 1884. Numerous amendments and new acts followed, however most of the Boards dealt with only small parts of river systems. In some cases one Board would control one side of a river, while another Board would control the other side. To overcome this problem, Catchment Boards were set up under the Soil Conservation and Rivers Control Act 1941. Each Catchment Board exercised control over one or more large catchments and was involved with catchment-wide river control planning. Under the Resource Management Act 1991, regional and unitary councils are responsible for the avoidance or mitigation of natural hazards such as flooding. Throughout the country over 650,000 hectares of floodplains have been protected from flooding (Williman and Smart 1987).

CURRENT TRENDS IN PROJECT DEVELOPMENT

Low rainfall in the catchments of the southern hydro-lakes during 1992, 2001 and again in 2003, resulted in electricity crises involving substantial increases in the spot price of electricity, widespread calls for power savings by consumers, and subsequent calls for increased generation capacity. Knowledge that the Maui gas fields will run out earlier than originally expected has also prompted reviews of New Zealand's future electricity generation. The Kyoto Protocol's focus on reducing emissions of greenhouse gases will also encourage further moves to develop renewable sources of energy.

Several new hydroelectric schemes have been proposed. The largest is Meridian Energy's "Project Aqua" on the lower Waitaki River. This project is projected to cost around $1.2 billion and will involve the construction of a 60-km canal between Kurow and State Highway 1, with approximately 70% of the river flow being diverted down the canal. The balance of the water is to remain in the existing river bed. Six power stations along the canal, each generating up to 90 MW of power, are proposed.

Brown (2002) reports that up to 400,000 hectares of land are currently under consideration for communal irrigation schemes. Market forces are expected to result in at least a 28% increase (144,000 ha) in area irrigated by 2010, with the majority of the increase predicted to be in Canterbury (57,000 ha increase) and Otago (36,000 ha increase) (Hegarty *et al.* 2002). Substantial increases in the amount of irrigated land are also expected in Waikato, Hawkes Bay, Wairarapa and Marlborough (Hegarty *et al.* 2002). Meridian Energy has proposed that Project Aqua be linked with several new irrigation schemes in North Otago, potentially irrigating up to 39,000 ha of land that is not currently irrigated. Integration of hydro-power and irrigation projects will probably become more common, as there are often mutual benefits in joint development.

EFFECTS OF LARGE WATER PROJECTS

Downstream flow regimes

Large water projects have caused dramatic changes to the flow regimes of many New Zealand rivers. The diversion of water to Doubtful Sound as part of the Manapouri Power Scheme, for example, has substantially reduced flows in the Waiau River downstream of Lake Manapouri, while diversion of water from the headwaters of the Whanganui and Rangitikei rivers, as part of the Tongariro Power Development, has increased flows in the Waikato River. Water storage reservoirs tend to attenuate flood peaks and change the annual distribution of flows by storing water at one time and releasing it at another. Flows in the Waitaki River, for example, are highly moderated by the presence of control structures on Lakes Tekapo and Pukaki. These lakes are capable of absorbing large floods and generally augment flows in winter when they would naturally be at their lowest (Waugh and Payne 2003). Fluctuations in the spot price of electricity mean that generation generally peaks for a few hours during weekday mornings and again in the late afternoon when demand is highest. If storage is available, water is held back during weekends and at night. These fluctuations in demand and generation result in substantial fluctuations in flow over short periods. Further details of the effects of large water projects on flow regimes are given in Chapter 7.

Lake levels upstream

Fluctuating water levels are a feature of all lakes and are controlled by a combination of factors, including catchment size, topography, climate, lake size and the characteristics of the lake outlet. In natural lakes, levels generally fluctuate by less than 5 m, while the levels of storage lakes controlled by large water projects tend to fluctuate more widely (Mark 1987; Fig. 37.1). For example, Lake Hawea historically fluctuated by around 3 m prior to control, and then by over 20 m after the lake was controlled (Mark 1987). Such large fluctuations in lake level are no longer considered acceptable, and the normal operating range is now restricted to 8 m (Freestone and Payne 2000).

Fluctuations in lake levels can have a variety of effects. High lake levels can cause erosion of shorelines, the inundation and mortality of terrestrial vegetation around the shore, and a decrease in available light to littoral and

Figure 37.1 The Cobb Reservoir after a prolonged period of dry weather. Photo: Roger Young

benthic aquatic plant communities (James *et al.* 2002). Low lake levels can also increase rates of lake shore erosion and expose littoral communities to freezing, dessication and wave action (James *et al.* 2002). The ecology of lakes, and the effects of level fluctuations, is discussed further in Chapters 23, 24 and 25.

Storage dams also have the potential to increase the risk of flooding for communities upstream. For example, the presence of the Roxburgh Dam, and sediment deposited in the upper reaches of Lake Roxburgh, appear to have increased the risk of flooding in the town of Alexandra just upstream (Mackay *et al.* 2000). To address this problem, the level of the lake is lowered prior to floods and increased water velocities are used to flush sediment further down the lake. Some sediment is also carried downstream past the dam. This flushing program and the practice of drawing down the lake in advance of a flood has combined to reduce flood levels at Alexandra by approximately 1.7 m (Mackay *et al.* 2000).

Morphologic effects

The largest New Zealand rivers move millions of tons of sediment to the sea each year (see Chapter 12). Changes brought about by large water projects can significantly modify sediment transport, and hence river geomorphology (Fig. 37.2). The size of river sediment ranges from suspended clay particles that remain in the water column, to larger substrate materials that move along the riverbed. The finer the particles, the further they travel after being entrained into the river flow. In a flood, entrained clay particles may travel through the river system and out to sea, whereas gravel may only be transported from one river bar to the next. Thus, water projects can have both local and remote morphological effects.

The total sediment load carried by a river is often evaluated in terms of the suspended load and the bed load. At a specified location and flow there is an upper limit to the bed load that a river can transport. Scour and erosion can take place when the actual bed load is below the local transport capacity. Deposition occurs if the transport capacity is exceeded. Suspended load can be deposited in backwaters, on floodplains or within voids between bed particles. The types and rates of sediment erosion and re-deposition determine the morphology of a river system. Rivers can be single thread, meandering, braided or a sequence of steps and pools. Morphology is relatively stable when the long-term supply of sediment to a river is matched by a river's ability to transport sediment, but water projects can alter the balance between sediment supply and transport capacity and bring about serious morphological changes. More details about sediment transport in rivers can be found in Chapter 12.

Dams can result in improved water clarity downstream, as their reservoirs trap most of the sediment that previously passed through. Sediment trapping can cause adverse effects both upstream and downstream. Sediment deposition within the reservoir can reduce the intended storage volume and may raise the riverbed upstream. For example, the Waihopai Dam in Marlborough has trapped 10 million cubic metres of sediment since its construction in 1926 and increased bed levels upstream by up to 25 m. Downstream of a dam the combination of clear water and modified flow patterns can increase erosion and lower the river bed. Lowering of the river bed may endanger the structural stability of the dam, undermine banks and bridges and lower groundwater levels. Changes to the channel will eventually cease when the downstream river slope becomes flatter or when the bed becomes armoured with stones large enough to resist erosion. Figure 37.3 shows bridge piles that have been exposed as a result of falling bed levels in the Waikato River. Parts of this river are degrading because sediment supplies from upstream are trapped behind dams, and sediment starvation allows

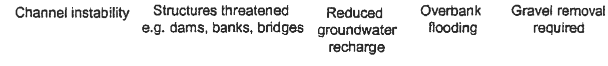

Figure 37.2 Conceptual diagram of the potential effects of large water projects on river morphology

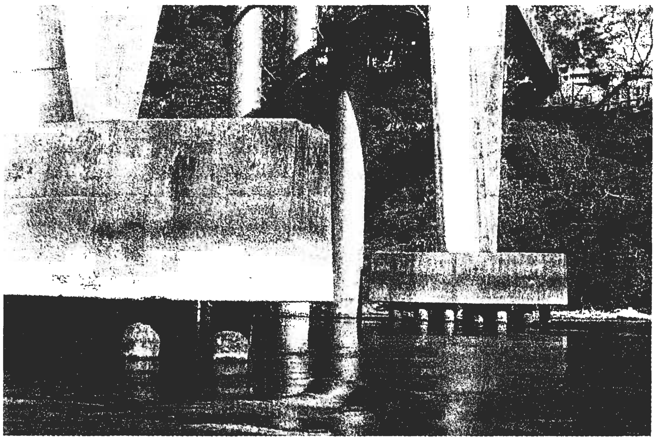

Figure 37.3 Piles exposed beneath the piers of the Claudelands Rail Bridge on the Waikato River, Hamilton.
Photo: Graeme Smart

the river to scour and transport material from the bed and banks downstream of the dams, producing the effects shown in Figure 37.3.

Water diversion intakes can also affect the sediment regime of a river. If too much water is taken, the flows downstream of an intake may not be sufficient to move incoming sediment and sediment deposition will occur, raising the bed level. Channel instability and over-bank flooding may also occur. Sediment may also be diverted along with the water, causing problems. This occurred at the Poutu Intake of the Tongariro Power Development in the late 1980s, when 42,000 tons of sediment per year were diverted from the Tongariro River and had to be excavated from canals.

Islands within river systems are particularly susceptible to changes associated with flow regulation. For example, changes in sediment dynamics may cause island growth, migration or erosion. Some low-lying islands may be drowned when river depths increase. Conversely, if flows and depths are reduced, previously inaccessible islands may be easily accessed by the public and by introduced predators. This is a particular concern for local iwi, since many riverine islands are waahi tapu or offer sanctuary to rare species (MfE 1998).

Effects on coastal erosion

Where a dam intercepts the natural export of sediment to the ocean, severe effects can be seen in the coastal zone, as beaches may be depleted and coastal erosion accelerated. Concerns have been raised about the effects of sediment trapping by the large dams on the Clutha and Waitaki rivers, since both rivers historically contributed significant amounts of sand and gravel to the Otago and South Canterbury coasts. The potential yield of sand and gravel from Clutha River tributaries to the coast has been reduced by 95% since the Roxburgh and Clyde dams have been in place (Hicks *et al.* 2000). However, the effects of this reduction on rates of coastal erosion are not clear. Rates of coastal erosion north of the Waitaki River mouth appeared to increase immediately after the construction of the Waitaki Dam, but have now returned to pre-dam levels (Hicks *et al.* 2002).

Geomorphic effects of flood control schemes

By protecting land from inundation, flood control schemes prevent flood flows from covering parts of their original floodplain. Floodwaters and their associated sediment load are concentrated into a channel or floodway. Not only is sediment that would have been deposited on the floodplains conveyed further downstream, but also the concentrated flows have a greater ability to erode and transport sediment. Local degradation and downstream sediment accumulation can occur. Narrowing of braided rivers sometimes has the opposite effect and causes rapid aggradation in the riverbed between the floodbanks. Because of this process, reaches of the North Ashburton River are now perched above their original floodplain. Substantial aggradation of riverbeds between floodbanks decreases the level of flood protection offered by the banks, while substantial degradation has the potential to undermine the foundations of the floodbanks, thus requiring expensive bank protection works. Riverbed levels also influence the rate of recharge to surrounding aquifers. For example, a 0.5 m drop in the lower Motueka riverbed is predicted to reduce summer recharge of the Motueka Plains aquifer by 24% (Basher 2003). Changes in the roughness of channel banks, such as occur when replacing scrub-covered banks with grass or rock, can also bring about large changes in the sediment-transporting characteristics of a river channel (Yu and Smart 2003).

Effects on water quality

Effects of storage on water quality

Storage of water in reservoirs often results in changes to the physical and chemical characteristics and temperature of the water released downstream (Table 37.3). The changes depend on a variety of factors, including the residence time (i.e., the average length of time taken for water to pass through the reservoir), the position of the reservoir within the catchment (i.e., in the headwaters or lower reaches), whether the water within the reservoir becomes stratified and anoxic, and the level of the reservoir outlet (surface or deep).

Generally, the longer the residence time, the greater the potential effects of water storage. As mentioned above, most of the suspended sediment washed into a deep reservoir will be trapped within the reservoir. Therefore water released downstream will generally be clearer, with

Table 37.3 Changes in downstream water quality associated with water storage

Parameter	Change	Comments
Suspended solids	Reduced	Most marked effects in large deep lakes. Sediment may be re-suspended by wind in shallow lakes.
Water clarity	Increased	Dense blooms of phytoplankton in lakes may reduce clarity at times Release of iron and manganese in some reservoirs may reduce water clarity downstream
Organic matter	Reduced	However, high quality organic material is often released from reservoirs
Water temperature	Reduced daily temperature fluctuations Increased summer daily mean temperatures in headwater reservoirs Seasonal buffering of temperatures in large lowland reservoirs Delayed seasonal minima and maxima	
Dissolved oxygen	Reduced	Depends on the degree of stratification
Phosphorus, Iron and Manganese	Increased	Particularly if bottom waters of reservoir are anoxic
Nutrients	Increased	Especially after inundation of fertile soils by a new reservoir

lower concentration of suspended sediment. The classic examples of this in New Zealand are the Roxburgh and Clyde Dams, which intercept much of the sediment from the Kawarau and Shotover rivers upstream. As well as geomorphic effects, the changes in water clarity and suspended sediment concentration can have marked effects on the ecology of river systems downstream.

Organic matter (e.g., leaves, wood and other detritus) can also be trapped within reservoirs, altering the composition and delivery of material to downstream reaches. Organic matter from upstream is often a key food source for many riverine organisms (Fisher and Likens 1973; Chapter 13). The interception of organic matter may interfere with the natural longitudinal changes in river ecosystems and the productivity of downstream reaches (Vannote *et al.* 1980). Ward and Stanford (1983) proposed the Serial Discontinuity Concept, which suggested that natural and artificial lakes "reset" many abiotic and biotic conditions below impoundments (Fig. 37.4). The downstream or upstream shift of a particular abiotic or biotic parameter caused by impoundment is defined as the discontinuity distance, while the magnitude of change is referred to as the parameter intensity (Fig. 37.4). The construction of a dam might be expected to reduce biodiversity in the downstream river, for example, and maximum biodiversity may not return to pre-impoundment levels for many kilometres downstream.

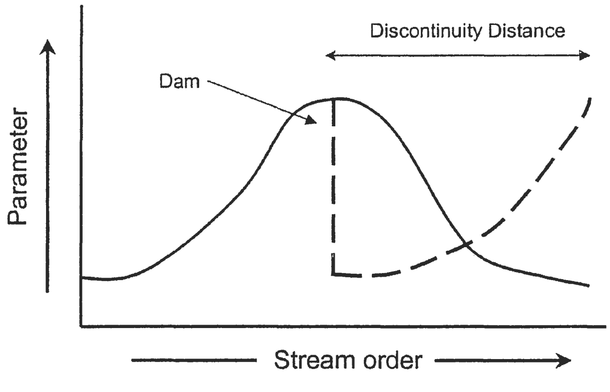

Figure 37.4 Conceptual diagram of the effect of dams in resetting biotic and abiotic parameters compared to a natural river system (redrawn from Ward and Stanford 1983)

A reservoir near the headwaters of a river catchment is predicted to have markedly different effects than one in the lower reaches (Ward and Stanford 1983). For example,

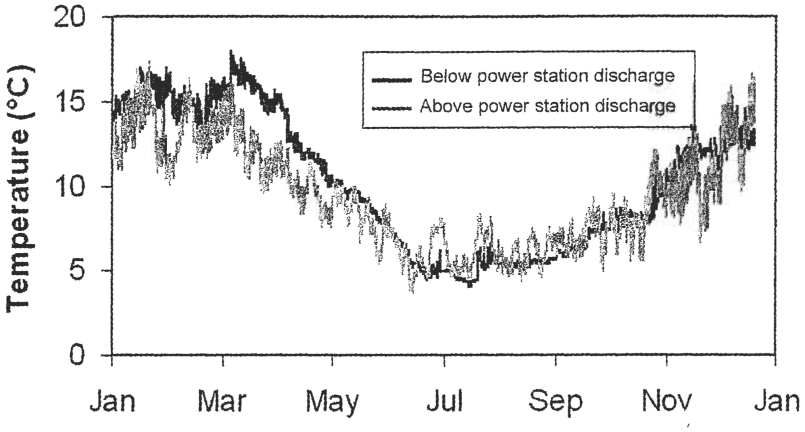

Figure 37.5 Changes in the annual water temperature regime as a result of storage in the headwaters of a river catchment (Takaka River, Golden Bay).

the water temperature of forested headwater streams is generally cool throughout the year due to shading by overhanging riparian vegetation and the buffering influence of groundwater contributions (Poole and Berman 2001). A dam in the headwaters of a river may allow more solar heating of the water, especially during summer. The Cobb Power Scheme in Golden Bay dams the headwaters of the Cobb River and water released from the dam is up to 4°C warmer than riverine water from a neighbouring catchment during summer, but very similar during winter (Young *et al.* 2000; Fig. 37.5).

In contrast, a large-volume reservoir in the lower reaches of a river will act as a thermal buffer. Water released will often be cooler in the summer, and warmer in the winter, than would have been expected naturally. Historically, the Green River in Utah, U.S.A., had extremely variable flow, sediment concentrations and temperature, and evolved a unique assemblage of native fish species adapted to these extreme conditions. The construction of the Flaming Gorge Dam resulted in major changes to the thermal regime of the river downstream, with much cooler temperatures in the summer and slightly warmer temperatures in the winter. This effect is exacerbated, as the water released downstream is from deep in the reservoir. Many of the native fish species that relied on warm summer temperatures as cues for spawning have been displaced downstream. Introduced cold-water species, such as rainbow trout, now flourish downstream of the dam (Filbert and Hawkins 1995). Such dramatic changes in thermal regimes have not been documented in New Zealand hydro dams. However, significant buffering of temperatures is expected to occur below large natural and hydro lakes.

Dissolved oxygen concentrations in water bodies are controlled by the balance between the supply of oxygen from the atmosphere and photosynthetic inputs, and the consumption of oxygen by biological and chemical oxidation processes. Oxygen exchange with the atmosphere is reduced in deep reservoirs, relative to rivers, and may result in the deeper parts of reservoirs becoming anoxic, especially if the water column becomes thermally stratified. In addition, organic matter will tend to sink to the bottom of reservoirs, where it eventually decomposes, increasing the demand for dissolved oxygen. Water released from the deeper parts of reservoirs may be depleted in dissolved oxygen, with direct effects on biota downstream. However, exchange with the atmosphere will eventually bring oxygen back to equilibrium concentrations. This may happen very quickly if water is passed through turbines, resulting in turbulent mixing of water and air.

The concentration of dissolved oxygen near the bottom of a reservoir also influences the concentrations of phosphorus, iron and manganese in the water (Wetzel 1983). As the concentration of dissolved oxygen declines near the sediment surface, the release of phosphorus, iron and manganese increases markedly. The change in redox conditions, caused by low oxygen concentrations, results in the reduction of insoluble iron and manganese hydroxides to more soluble forms, and the mobilization of adsorbed phosphorus. Dissolved iron and manganese will precipitate out of solution once oxygen concentrations increase. Therefore, iron and manganese flocs are sometimes seen on substrates downstream of power station discharges (Young *et al.* 2000). Increases in phosphorus concentrations may stimulate periphyton growth downstream if the availability of phosphorus limits their growth.

Water passing through or over dams may become supersaturated with gases. The pressure inside the turbines may be sufficient to force large quantities of gas to dissolve into solution. Alternatively, water plunging over a spillway will contain air bubbles that may be carried to a considerable depth, where the water pressure is great enough to force the gas into solution. If fish respire water that is supersaturated with gases, the excess gas may come out of solution in their blood as bubbles, resulting in "gas-bubble disease", which resembles the "bends" experienced by some divers. These bubbles lodge in various parts of the body and can cause injury or death. Major fish kills have resulted from this super-saturation below several dams overseas (Backman *et al.* 2002). To our knowledge, mortality due to gas supersaturation has not been documented in New Zealand.

Effects of diversion on water quality

Diversion of water from one catchment to another also results in the diversion of sediment, nutrients and organic matter. Therefore, any benefits or problems resulting from this material may also be transferred between catchments. Nutrient availability often determines phytoplankton production around parts of New Zealand's coast. Therefore, the productivity of some coastal areas around river mouths may depend on the supply of nutrients and organic matter from adjacent rivers, and could be affected if this supply is diverted elsewhere. This concern has been raised in relation to the Manapouri Power Scheme's diversion of Waiau River water to Doubtful Sound, and the potential effect on the ecology of the Southland coast.

Diversion of water also reduces the ability of a river to dilute wastes. This is particularly a problem with irrigation schemes, where the diverted water allows more intensive agriculture in the surrounding catchment. Runoff from this irrigated land then makes its way back into the river and is usually highly enriched with nutrients and other contaminants. The effects of diversion are essentially doubled, since the reduced flow of the river is less able to dilute these elevated levels of contaminants in the runoff.

Reductions in flow may also alter dissolved oxygen and temperature dynamics in rivers. Lower, more stable flows and slower velocities tend to allow higher biomasses of periphyton to accumulate. Assuming that more biomass means more photosynthesis, the amount of oxygen released during daylight and taken up at night by periphyton mats will also be increased. Under low flow conditions, this increased flux of oxygen will be dissolved in a smaller volume of water, potentially resulting in larger daily fluctuations in dissolved oxygen concentration if the amount of exchange of oxygen through the river surface is not altered. The thermal buffering effect of a large water volume will also be reduced at lower flows, potentially leading to larger daily fluctuations in water temperature.

Ecological effects

New lake formation

The impoundment of rivers and creation of artificial lakes causes dynamic shifts in pelagic and benthic communities in these new water bodies. Over time the community composition changes, with a reduction in lotic (running water) species and an increase in lentic (still water) ones. The formation of Lake Dunstan in Central Otago in 1992 resulted in the flooding of surrounding river terraces, which caused significant changes in energy transfer within the new lake, as terrestrial vegetation and organic material associated with the land decomposed. During the early years of the lake, the benthic fauna was dominated by chironomids and oligochaetes. However, as this source of enrichment dissipated, and aquatic macrophytes invaded, the community changed to one dominated by snails and caddisflies (Strickland *et al.* 2000). New reservoirs will usually be invaded within a few years by aquatic macrophytes. Lake Dunstan had not been completely filled when *Elodea canadensis*, *Myriophyllum* spp. and *Lagarosiphon major* were observed in the lake. By 1998, six years after the dam have been completed, a stable community of 16 aquatic plant species had formed throughout the lake. *Lagarosiphon* dominated in the 2–4 m zone (Strickland *et al.* 2000).

Not surprisingly, the formation of a new lake will create habitat for aquatic birds. Eight years after Lake Dunstan was filled, 25 species occurred around the lake, compared with 14 recorded prior to lake formation. New colonisers included the New Zealand scaup, Canada geese, Black swans, Australian coots, and Black and Little shags. Lake-level fluctuations resulting from changes in hydro-electric power generation have positive and negative effects on bird communities. These are discussed in more detail in Chapter 26. The most important impacts are on nesting activities of species such as grebes, coots, pukeko and black swans, which construct floating nests or nest close to the shoreline. Feeding can also be affected, as the raising and lowering of lake levels may reduce the availability of aquatic plants and benthic invertebrates as food, or alternatively make terrestrial food that was previously flooded available (Sanders 1996). However, these effects vary markedly with the lake morphology and riparian vegetation of the lake deltas.

Planktonic communities in artificial lake outlets

Regulated lake outlets frequently receive significant inputs of planktonic material from lakes upstream. Phyto- and zooplankton biomass in outlet rivers may be greatly elevated, depending on the type of impoundment and season. If surface water is released, it will contain plankton representative of lake surface waters, whereas hypolimnetic (deep-release) lakes may be devoid of plankton or have communities representative of the lake pelagic zone. Plankton biomass in outlet rivers decreases dramatically downstream, as material is either deposited on the riverbed or consumed by abundant benthic communities associated with the outlet (Monaghan *et al.* 2001; Fig. 37.6).

Benthic algae

Benthic algae or periphyton may proliferate after river regulation. Lake outlets generally provide an ideal habitat for algae, with reduced flood intensities, a moderate supply of nutrients from the lake, and high water clarity, allowing plenty of light for photosynthesis on the river bed (Young 1998). Furthermore, water temperatures are often buffered, and the stable "armoured" river beds that are characteristic of many regulated lake outlets provide an ideal substrate for periphyton attachment.

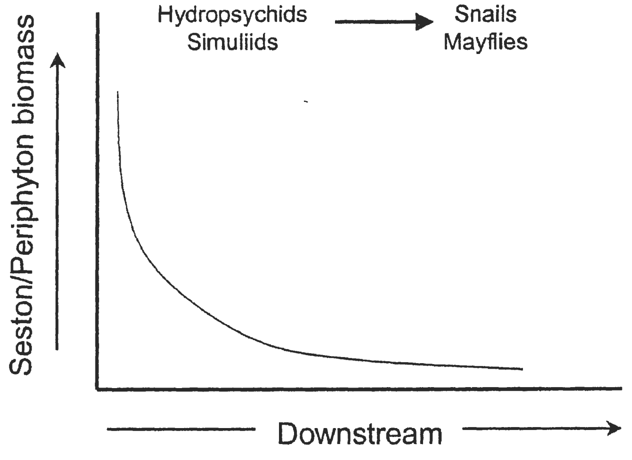

Figure 37.6 Model of the characteristic decline in seston downstream from the lake, and changing benthic community.

Diversion of water may also increase periphyton biomass downstream. Reductions in flow reduce the velocities and associated shear stresses on algal mats, allowing thick mats to accumulate. For more details on periphyton and factors controlling periphyton growth see Chapter 15.

Benthic invertebrates

Considerable research has been done on the response of benthic invertebrate communities to river impoundment (Fig. 37.7). Again, responses vary with the type of outlet. In general, outlets releasing surface water have communities with relatively low species richness, but exceptionally high densities and biomass. Production studies of lake outlet species have recorded high productivity, which is a response to the availability of plentiful, high-quality food (i.e., lake plankton), relatively stable flow conditions and substrate, and buffered water temperatures, moderated by the upstream presence of a lake. These high densities of invertebrates can occur for some distance downstream in extremely large outlet rivers, however more frequently this response is relatively localised (e.g., 500 m to 1 km downstream). These low-diversity outlet communities are frequently similar to those found in natural lake outlets where similar physical conditions occur. The communities are usually dominated by filter-feeding species such as Simuliidae, and the net-spinning Hydropsychidae (Harding 1994). Densities as high as 10,000/m^2 have been recorded, and these are usually highest at the lake outlet, declining rapidly downstream. The plentiful food supply in these habitats has been shown to facilitate the co-existence of conspecifics, which might be expected to occur only under certain circumstances. Harding (1997) showed that two species of the Hydropsychid *Aoteapsyche* were able to co-exist on the same boulders in a lake outlet. One species, a more aggressive, territorially-dominant caddis *Aoteapsyche raruraru* occupied the high-quality food sites on the tops and sides of stones, while its conspecific *Aoteapsyche colonica* was restricted to the undersides of stones, where presumably there was less food. Both simulids and hydropsychids have been shown to aggressively defend territory against other members of their species. However, the abundant food in lake outlets seems to suppress this competition in some species.

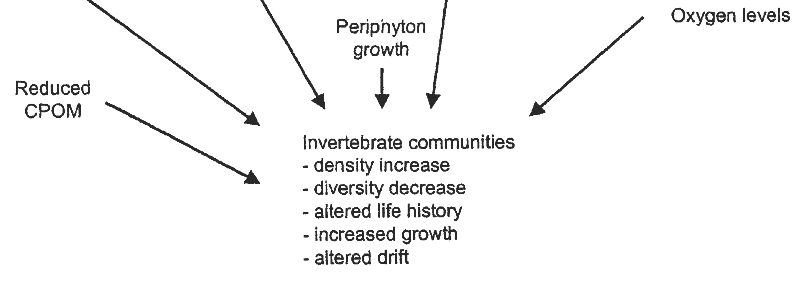

Figure 37.7 Conceptual diagram of the potential effects of river regulation on downstream benthic communities.

Benthic communities downstream of deep-release dams appear to be markedly different to those downstream of surface-release outlets. In these conditions, relatively little planktonic food may be released into the river, while water quality may be poor, with low dissolved oxygen, high concentrations of iron and manganese, and cool water temperatures. In extreme cases, these outlets may be devoid of benthic invertebrates or have communities almost entirely dominated by a few taxa. For example, Lake Waitaki has a deep-release outlet and 87% of the invertebrate community just downstream is a single net-spinning caddis species, *Aoteapsyche raruraru* (Harding 1994; Fig. 37.8).

As discussed earlier, the Serial Discontinuity Concept (Ward and Stanford 1983) predicts downstream changes in abiotic, and hence biotic, communities. As we have already seen, lake outlet communities are affected by several unique conditions created by the presence of the lakes (Harding 1992). The presence of a lake may enhance conditions for some

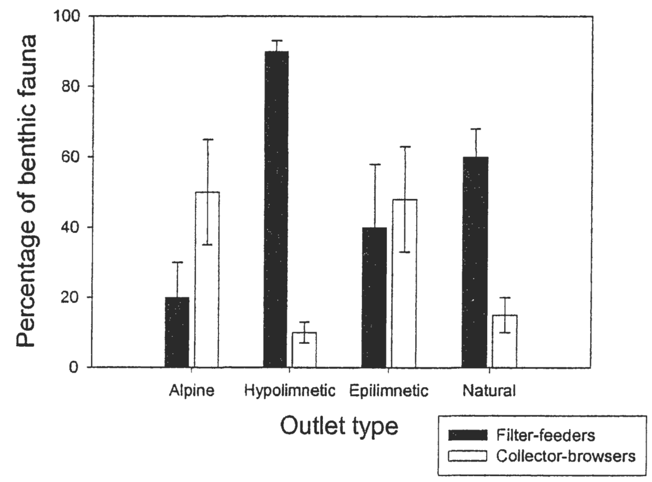

Figure 37.8 Relative importance of filter-feeders and collector-browsers in different lake outlet types (after Harding 1994). Alpine outlets were >1000 m asl, and Natural outlets <500 m asl.

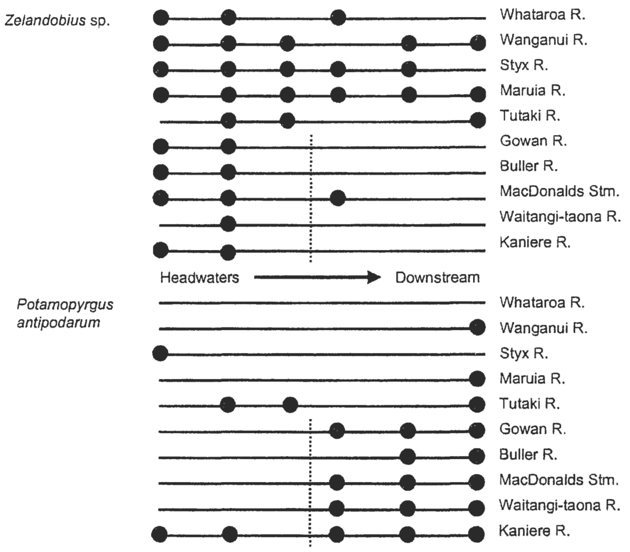

Figure 37.9 Discontinuities in the distribution of the stonefly *Zelandobius* spp. and the snail *Potamopyrgus antipodarum* down a river continuum due to the presence of an impoundment (Harding 1992). Dashed line indicates a lake or impoundment within the river system. Solid circles indicate sites at which species were present.

species, while creating unsuitable conditions for others (Fig. 37.9).

Regular fluctuations in flow resulting from changes in electricity demand may have detrimental effects on benthic invertebrates, particularly along the varial zone—the edges of river channels that are exposed to repeated wetting and drying. The effects are expected to be greatest in rivers with gently sloping margins, resulting in large areas of riverbed being repeatedly inundated and exposed. Despite the potential importance of this effect on benthic invertebrates, there have been surprisingly few studies of it conducted in New Zealand. Irvine and Henriques (1984) found that invertebrate drift densities increased in response to flow changes in the Hawea River, while Irvine (1985) reported similar increases in drift and eventual depletion of the benthos after repeated fluctuations in experimental channels in the lower Waitaki River. More recently, a survey of fish-stranding on the lower Waitaki River reported lower invertebrate densities in areas that are regularly exposed during the fluctuating flow cycle compared with areas that were exposed only during an extreme low flow trial (Strickland *et al.* 2002).

Fish

Large water projects have had major impacts on fish communities in New Zealand. As well as indirect effects on water quality and food supplies, large water projects can directly affect fish migration, habitat availability, and juvenile survival, and can increase competitive interactions among species. Transfer of water between catchments also provides the opportunity for some species to colonise areas where they would not have occurred naturally.

Many of New Zealand's native fish species are diadromous, requiring access to the sea for part of their life cycle (see Chapter 17). Sports fish, like salmon and sea-run trout, also require access to and from the sea at times during their life cycle. Impoundments can thus severely disrupt migration and alter the distribution of species within and between catchments. With no recruitment of juveniles, eel populations upstream of dams will eventually disappear, although this may take many years. For example, eels currently found in the Cobb Reservoir are remnants from before dam construction in 1955 (Young *et al.* 2000). New Zealand's only sockeye salmon population in the Waitaki River initially benefited from hydro-power development, with Lake Benmore providing productive feeding grounds. However, the construction of dams on the Ohau River cut access between Lake Benmore and spawning streams at the head of Lake Ohau. Spawning runs of this fish have been reduced from over 18,000 in the late 1970s to fewer than 100 fish, which may be insufficient to maintain wild stocks (Graynoth 1995). The construction of the Waitaki Dam in 1934 on the Waitaki River and the Roxburgh Dam in 1956 on the Clutha River had similar dramatic effects for the large chinook salmon populations that once migrated from the sea up to the spawning tributaries and productive lakes in the upper part of these catchments.

Fish passes have been constructed on many New Zealand dams to allow upstream passage (Fig. 37.10). A few have been relatively successful for some species

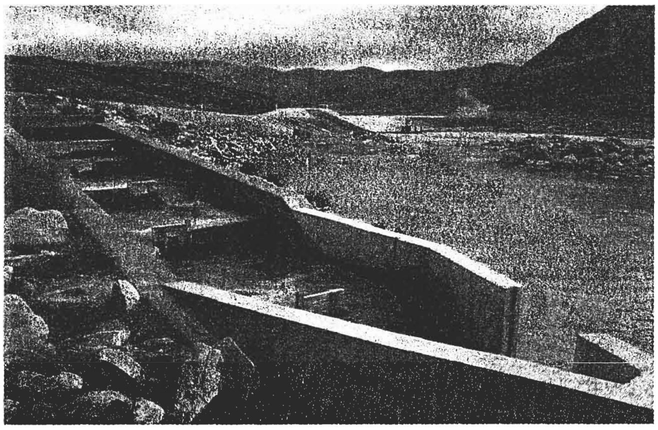

Figure 37.10 The Ohau River fish pass near the outlet of Lake Ohau. Photo: Jon Harding

(e.g., the eel pass at the Patea Dam, the new vertical slot fish pass at the Mararoa Weir, Manapouri Control Structure), while most have been failures (e.g., the fish ladder on Waitaki Dam). In rivers with multiple dams (e.g., Waikato, Waitaki, Clutha, Rangitaiki) it appears to be more efficient to capture juvenile eels and manually transfer them upstream past dams (Boubee *et al.* 2001). However, downstream passage also needs to be considered if the aim is to provide future brood stock, rather than just maintain an eel fishery (Boubee *et al.* 2001). Many large eels suffocate on intake screens, or are killed as they pass through turbines. Nevertheless, some fish survive downstream passage. The sea-run quinnat salmon fishery in the lower Clutha River, for example, appears to be dependent on successful downstream migration of juveniles from landlocked populations in Lakes Wakitipu and Wanaka (James and Dungey 2000). Juvenile fish migrating downstream are also susceptible to being diverted into irrigation race intakes and may eventually end up stranded on irrigated pastures.

Diversion of flow by large water projects reduces the wetted width of residual river channels, and the depth and velocity of the water in that channel. Changes in wetted width reduce the total area of available habitat, while changes in depth and velocity affect the suitability of specific locations for particular species. Available habitat for species that prefer fast and/or deep water (e.g., adult salmonids, torrentfish, bluegill bullies) will be most affected by flow reductions. Fish, such as trout and koaro, that depend on drifting invertebrates for a large proportion of their energy intake are particularly susceptible to reductions in water velocity, since the rate of their food delivery directly depends on water velocity. Flow reductions may also make sections of rivers too shallow for fish migration, a particular problem for chinook salmon attempting to migrate up the shallow braids of Canterbury rivers.

Rapid flow fluctuations resulting from changes in electricity demand will also affect the amount of available habitat. The depth and velocity at a particular location may provide ideal habitat at one flow, but be too shallow or slow during the low-flow phase of the cycle and/or too fast during high flows. Mobile fish species may be able to deal with these flow fluctuations by moving laterally in response to changes in flow. However, their food resources (invertebrates) are not so well equipped and may be exposed during low flows or dislodged by high flows. Stranding may also occur, particularly of juvenile fish and species that tend to hide in river gravels (Almodovar and Nicola 1999).

An example of the complex effects of impoundment on fish populations is reported in Allibone (1999). The formation of Lake Mahinerangi on the Waipori River in Otago resulted in a previously diadromous population of koaro becoming landlocked. The change to lake rearing of juveniles, and decreased migration distance, allowed greater recruitment of koaro into the tributaries of the lake. This increase in koaro abundance has been linked with displacement of two species of non-migratory galaxiids from tributaries of the lake (McDowall and Allibone 1994). There now appears to be a dominance hierarchy in lake tributaries—brown trout are the most dominant species, but are only found downstream of waterfalls. Koaro are the next most dominant and can ascend waterfalls and displace non-migratory galaxiid populations further upstream (Allibone 1999).

Tunnels or water races built to transfer water from one catchment to another also act as conduits for fish to move between catchments. Such movement allows species to invade areas where they would not have occurred naturally. In several locations, aggressive species like brown trout and koaro appear to have wiped out non-migratory galaxiid populations, which would otherwise have been protected by downstream barriers (McDowall and Allibone 1994). Fish movement between catchments also allows interbreeding of closely related species, such as the various non-migratory Otago galaxiids, which almost never co-exist naturally (Esa *et al.* 2000).

Ecological effects of river control schemes and river confinement

The ecological importance of interactions between rivers and their floodplains has become more widely recognised over the last few decades (Bayley 1995). When floodplains are inundated, the habitats and food resources of the flood plains become available to riverine biota, potentially enhancing the biodiversity and productivity of river systems. For example, a large unconstrained floodplain in the upper reaches of the Taieri River is a major source of organic matter for the river downstream

(Young and Huryn 1997). During periods when the floodplain is inundated, fish move out of the river channel to exploit the abundant food resources on the floodplain. Stable isotope analyses of invertebrates and fish in this reach of the river indicate that the floodplain is the primary contributor of carbon and nitrogen to the riverine food web (Huryn *et al.* 2002). River control schemes break the connection between rivers and their floodplains by containing floodwaters within a narrow zone inside the floodbanks (Fig. 37.11). The importance of this break in ecological connectivity will largely depend on the geomorphology of the river system, since inundation has to occur regularly and for sustained periods to accrue significant ecological benefits. Therefore, the ecological effects of river control schemes are likely to be greatest in rivers with low-gradient floodplains and prolonged floods, but minimal in rivers with steep gradients and flashy hydrographs.

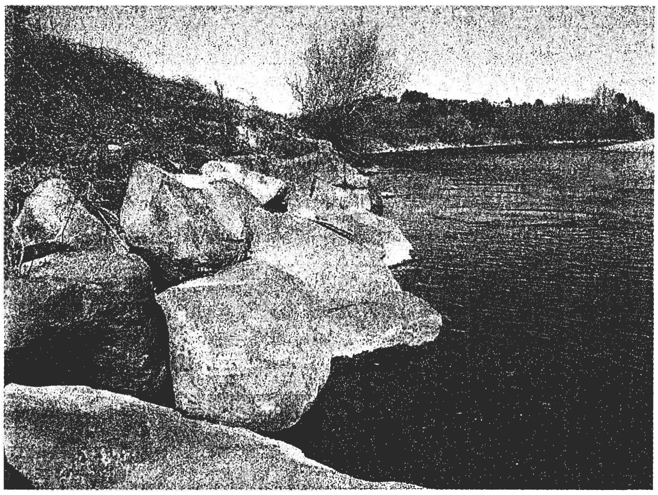

Figure 37.11 Bank control works confine the lower Motueka River to a single narrow channel.
Photo: Roger Young

Effects on people

People value waterways for a variety of reasons. A river may have important cultural values (mauri, mahinga kai, waahi tapu), be important for recreation (fishing, whitebaiting, kayaking, rafting, swimming, jet boating), and/or make a major contribution to the aesthetics of the surrounding landscape (MfE 1998). Large water projects have the potential to degrade these values if safeguards are not put in place. For example, flow regulation changes the seasonal pattern of flows, the strength of the connection between the mountains and the sea, and the ability of a river to carry sediment and dilute contaminants. All these changes will affect the mauri or life-essence of a river. Diversions resulting in the mixing of water from one catchment with another will also desecrate the mauri of rivers (MfE 1998). River-mouth blockages associated with reduced flows, along with dams themselves, can adversely affect the passage of mahinga kai species between spawning and rearing areas. Many waahi tapu are located near rivers and lakes, and can be inundated by storage dams, or overgrown with weeds due to reductions in flood frequency caused by river control upstream. Kai Tahu considers that an estimated 90% of waahi tapu sites adjacent to Lake Hawea, Lake Dunstan and Lake Roxburgh have been lost because they were sited next to the river and are now drowned under the hydro-electricity lakes (Contact Energy 2001).

Many of New Zealand's large water projects have improved public access and created reservoirs, which are recreational assets for anglers, swimmers and boat owners. The network of lakes in the Waitaki Valley, for example, attracts numerous holidaymakers every summer. However, these improvements in recreational facilities have often been offset by the loss of recreational activities using the flowing waters inundated by reservoirs. For example, rapids on the Kawarau River that were popular for rafting and kayaking have been inundated by Lake Dunstan (Egarr and Egarr 1981). Changes in flow regime may also influence the quality of the recreational experience on some waterways. Reductions in water depth may expose debris, such as logs and rocks, posing serious risks for swimmers and paddlers. The safety of some swimming holes/jumping sites that require deep water may also be affected by reduced flows. Changes in water quality as a result of large water projects may also affect people's enjoyment of an area. An interesting example is the Tekapo River, where water clarity has increased now that turbid glacial water is diverted down the hydro-electric canals. While this increase in clarity and reduction in flow fluctuation has improved the trout fishery in the Tekapo River, local iwi are concerned that the stabilised flows have benefited salmonids and thus increased predation and competitive pressures on native fish species (MfE 1998).

Aesthetic values are determined by the landscape's physical and natural properties, coupled with the cultural values of the person experiencing the landscape (MfE 1998). Large water projects may affect the physical properties of a river by directly altering flow variability, water colour and clarity, hydraulics (width, depth and velocity), and the amount of riverbed exposed during low flows. Indirect physical changes associated with large water projects include modifications to riverbed vegetation and channel type (braided versus single thread) caused by changes in the sediment supply or flooding frequency. The extent of physical effects on aesthetic values will depend on the channel shape, with the most apparent effects on single-thread rivers with gently shelving margins. Very large changes in flow are required to change the wetted area of a river with near-vertical banks, while braided rivers are naturally dominated by exposed gravel banks, so additional exposed areas are less conspicuous (MfE 1998). Other perceptual qualities of a river may also be affected by large water projects. Artificial structures, like dams and canals, will reduce the natural character associated with a river, while reductions in flow may influence the sound, smell and overall mood of a river. The wild and scenic properties of a large, raw, untamed river will be degraded by flow regulation and reduction (Godman 1989). Chapter 8 provides further discussion on "riverscapes".

MANAGEMENT OF IMPACTS

Conflicts between the needs of ecosystems and human needs for freshwater resources are becoming increasing common throughout the world (Poff *et al.* 2003). In New Zealand debate has intensified recently with the increasing demand for development of large water projects related to hydro-power and/or irrigation. Partly in response to these demands, Fish and Game New Zealand and other environmental agencies have applied for water conservation orders on several major river systems to recognize and sustain the outstanding values associated with these systems. The continuing development of regional water plans by regional councils has also heightened the level of interest in freshwater management.

With the introduction of the Resource Management Act (1991), consents for the majority of existing large water projects expired in 2001. The act requires that any effects of resource use should be avoided, remedied or mitigated. Therefore, substantial amounts of consultation and assessment of environmental effects have been required as a part of consent renewal. This has allowed many different groups to express their opinions on the pros and cons of specific schemes, some of which were developed at a time when little consideration was given to any associated ecological, social and cultural impacts. Consents that have been renewed have often included conditions to mitigate observed effects. A good example is the Manapouri Power Scheme, which initially involved the diversion of almost all of the Lake Manapouri inflow (mean 343 m^3/s) to Doubtful Sound via the Manapouri power station. For much of the time only a small flow (0.29 m^3/s) was released past the Mararoa Weir through the existing fish pass. Not surprisingly, this flow provided little in-stream habitat for aquatic life in the reach downstream, until flows were augmented by tributaries. After much consultation, new resource consents were granted for the scheme in 1996, and included conditions requiring a minimum discharge past the weir of 16 m^3/s over summer and 12 m^3/s over winter. The trout population has increased dramatically since the initiation of these minimum flow requirements (Fig. 37.12), although most of the change has resulted from increases in the number of small and medium-sized fish (Moss 2001). The consent also included conditions requiring monthly flow releases over summer for recreational purposes, and installation of an effective fish pass on the weir. Groups such as the Waiau Working Party and the Guardians of Lakes Manapouri and Te Anau have been instrumental in the consultative process that led to decisions on the management of the Manapouri Power Scheme (Sutton 2002).

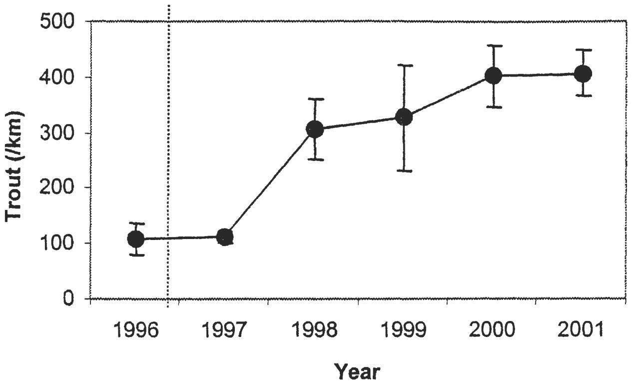

Figure 37.12 Trout abundance in four reaches of the Waiau River downstream of the Mararoa Weir. Minimum flow releases from the Mararoa Weir began in December 1996 (Dotted line). Data from Moss (2001).

We are not aware of any existing large water projects in New Zealand that have failed, or are likely to fail to renew their consents. Nevertheless, this is a possibility and will become more likely as projects approach their life expectancy. Decommissioning of large water projects is becoming relatively common overseas, particularly in the United States, where more than 500 dams have been removed to achieve specified ecological goals (Poff *et al.* 2003). Dam removal is expensive, with both monetary and environmental costs. However, these costs are undoubtedly low compared with the potential costs of dam failure, as was demonstrated by the failure of the partially completed Opuha Dam in February 1997. The only dam removals in New Zealand have been of defunct water supply dams such as the Brook Reservoir near Nelson and the Wainuiomata River near Wellington.

Large water projects will continue to be proposed and involve considerable debate on the benefits and costs of such schemes. The Resource Management Act provides a framework encouraging consultation between developers, resource managers and other interested parties, and mechanisms for addressing adverse effects. The RMA also provides for the development of statutory Water Management Plans or Regional Plans, where issues of water allocation between competing demands, water use priority, instream flow requirements, a minimum flow regime, flow sharing rules, and a cap on the total abstractive allocation can all be dealt with on a catchment or regional basis. Future advances in scientific understanding and model development may allow improved prediction of the impacts of projects, allowing the costs and benefits of schemes to be more accurately assessed prior to their construction. Striking the balance between costs and benefits is very important, since New Zealand's economy is highly dependant on the use of our water resources, while most New Zealanders want to ensure that the integrity of our freshwater ecosystems and recreational amenities remain intact for future generations to enjoy.

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