Water quality in New Zealand:
Understanding the science

March 2012

Parliamentary Commissioner for the Environment
Te Kaitiaki Taiao a Te Whare Pāremata

Acknowledgements

The Parliamentary Commissioner for the Environment would like to express her gratitude to those who assisted with the research and preparation of this report, with special thanks to her staff who worked so tirelessly to bring it to completion.

Photography

Cover: Erin Currie

This report and other publications by the Parliamentary Commissioner for the Environment are available at: **www.pce.parliament.nz**

Contents

Commissioner's overview

When Parliament appointed me to the position of Environment Commissioner five years ago, I came into the job knowing a great deal about some environmental matters and relatively little about others. Water quality was one area in which I had to work rapidly to come up to speed. I clearly recall an evening with Professor David Hamilton from the University of Waikato when he patiently did his best to give me a rapid grounding in the basic science.

In 2010 I had the rewarding experience of speaking about water quality science to Members of Parliament. A request from several MPs for more led to developing greater expertise within my office on water quality and eventually to this report.

The aim of this report is to provide a guide to water quality science covering those aspects which are most useful for the many New Zealanders who are engaged in, and concerned about, this high profile environmental issue. Water quality science is indeed complicated, much is unknown, and the devil often really is in the detail.

There is effectively no limit to the different aspects of water quality that could be covered, so this report is not intended as a complete reference on the subject. Its scope is confined to fresh water – in rivers and streams, lakes, wetlands, estuaries, and aquifers – and to the three main water pollutants of greatest concern in New Zealand. These three are pathogens, sediment, and nutrients.

Pathogens are invisible microbes that cause disease and obviously deserve being labelled pollutants. But sediment and nutrients are only water pollutants by virtue of being in the wrong place. They belong on the land, not in water.

Too much soil and rock washed off land become destructive sediment in water. Nutrients, specifically phosphorus and nitrogen, should also stay on the land helping plants grow there rather than in water. We want fertile land not fertile water.

In a 2011 interview, the incoming President of Federated Farmers, Bruce Wills, was described as keen to have a frank science-based discussion with the nation about dairy pollution. *"If we've got a dirty river let's understand why it's dirty and what science can tell us about fixing it…"* [1]

I strongly agree with Mr Wills. He has put his finger squarely on the value that science can provide – understanding cause-effect relationships. And because water quality is an issue of such widespread public concern, this understanding must also be widespread.

In this report we have sought to go beyond providing lists of sources of water pollutants and their damaging effects. The aim is more ambitious – to explain as simply as possible why a particular pollutant causes certain effects – and therefore lay a basis for how well a particular intervention might improve or protect water quality.

I was interested to learn, for example, about a key difference between nitrate and phosphate – the main forms in which the nutrients nitrogen and phosphorus occur as water pollutants. Nitrate is very soluble in water, but phosphate most often is not. One intervention aimed at preventing nutrients from moving off land into water is a *riparian strip* – a fenced margin along banks covered with plants that will take up nitrogen and phosphorus as they grow. In general, riparian strips are much better at reducing phosphate than nitrate because nitrate can elude the roots of the plants and travel through groundwater directly into the waterway.

Concerns over the impacts of nutrients on water quality have grown over recent years, but we should not delude ourselves that all has been well in the past. Decades of burning of forested hills to create pasture for sheep farming is largely responsible for the widespread erosion that continues to carry sediment into our rivers and lakes. And while dairy cows are the greatest source of nitrate in many of our catchments, sediment from erosion is the greatest source of phosphate. While on the subject of phosphate, city dwellers concerned about water quality should be aware they can do their bit by switching to phosphate-free detergents and laundry powder.

It is a truism that to be effective, water quality policy and action must be based on science. But what does that actually mean? I think it means the following:

- Measuring the different parameters of water quality
- Understanding the causes of change in those parameters
- Designing interventions that are likely to be effective
- Measuring the effectiveness of those interventions

In 1911, there was an outbreak of typhoid among workers in flax mills in the Manawatū. The cause was deemed to be the rancid water coming out of the mills, but it was actually the sewage from the town of Feilding. While this mistake is not one we would make today, we are still capable of wrongly linking cause and effect. And once that is done, we cannot design interventions that will be effective.

We need, however, to know when more science is *not* needed. A call for more science to be done can sometimes be a way of delaying difficult decisions. There is, for example, no need for more scientific data or modelling to establish the link between the land use change that has taken place in the Waituna catchment in Southland and the dire state of the Waituna Lagoon; there simply is no other explanation.

Scientists themselves are not always the best people to advise when more science is required – their basic motivation quite rightly is to continue to explore and gather new data.

While science is necessary for policy, it is not sufficient. Science does not tell us how to make trade-offs, and trade-offs will almost certainly be needed. It is very unlikely that we can have our cake and eat it too. Even if technical fixes were to become available for dealing with all our water quality problems, they would still cost a great deal of money.

As the writing of this report draws to a close, I am aware that my own knowledge of the science of water quality has increased hugely since my presentation to Members of Parliament in 2010. There is no end to the complexity, but the state of our rivers, lakes, wetlands, estuaries, and aquifers is of great importance to this clean green country of ours. Increasing our understanding is a worthwhile investment and will pay dividends for our children and grandchildren.

Dr Jan Wright
Parliamentary Commissioner for the Environment

1 Introduction

Water sculpted New Zealand. Over millennia, water and ice literally moved mountains, moulding the land. Mountains rose, but water ground them down. But for the power of water, the Southern Alps would today be five times the height of Aoraki Mount Cook. Water eroded peaks, carved valleys, and flushed rock downstream.

Stones and silt washing down from the hills filled in valley floors, expanded plains, and built up beaches. Floodwater flushed away sediment, leaving water clean and clear most of the time. Nutrients also washed down, fertilising the lowlands. Productive and habitable, these are the places where most people now live and grow food.

Stony-bedded streams predominated, providing cracks and crevices for fish and other creatures to shelter, breed and feed, and for native plants to find root. The forest-cloaked land shaded the water's edge. Clean, clear, and cool fresh water, abundant in food, greeted arriving Māori.

Today's reality is very different – and different for entirely understandable reasons. For the last century and a half, a great range of economic enterprises have changed most of the land and the water that flows through it.

Over the years there has been much progress in controlling pollutants entering water. Many practices that were acceptable in the past would be inconceivable now. Nevertheless, in the last decade, public concern about water quality has become very high and for good reason.

This report is aimed at increasing understanding of the cause-effect relationships that determine the quality of fresh water – in rivers and streams, in lakes, in wetlands, in groundwater and aquifers, and the catchments within which they sit. Estuaries also feature since this is where fresh water meets the sea.

The focus is on the three main pollutants of fresh water in New Zealand – pathogens, sediment, and nutrients. Pathogens make people and animals sick. Sediment makes clear water murky and blankets stony riverbeds with mud and silt. Excess nutrients (nitrogen and phosphorus) can lead to rampant weed growth, algal blooms, and oxygen depletion.

There are other pollutants in water, of course, including heavy metals, toxic chemicals and pesticides. Much, but not all, is a legacy of past industry. But from a national perspective, the big three are pathogens, sediment, and nutrients.

A knowledge of the science of water quality provides a basis for understanding where the pollutants come from, how they get into water, and what they do to the water. Relying on perceptions can be very misleading. For example, water that is stained brown from naturally occurring tannins appears polluted, but clear water polluted with pathogens appears clean when it is not.

A knowledge of the science of water quality also provides a basis for understanding how effective different ways of improving water quality might be. To a considerable extent, pollutants that get into water from the end of a pipe have been dealt with although there is still some way to go – the pollutants are easy to measure and the responsibility is clear. In contrast, diffuse sources by their very nature come from wide areas and are therefore much more troublesome; the sediment that is washed into lakes and the nitrate that seeps into groundwater are the most intractable.

1.1 Purpose of the report

The Parliamentary Commissioner for the Environment is an independent Officer of Parliament, with functions and powers granted by the Environment Act 1986. Her role allows a unique opportunity to provide Members of Parliament with independent advice in their consideration of matters that may have impacts on the quality of the environment.

Water quality is a subject of high public concern and vigorous debate. However, the science of water quality is very complex, and much of the information available required to fully understand it is highly technical. This report is an educative one, written with the intent of providing an accessible guide to the science, in order to support informed debate and decision-making.

This report has been produced pursuant to s16(1)(f) of the Environment Act 1986.

1.2 Structure of the report

The remainder of this report is structured as follows:

- Chapter 2 outlines the history of water quality in New Zealand in order to provide the wider context in which this report is placed, including how the concerns around water quality have changed over time
- Chapters 3, 4, and 5 cover the three main pollutants in turn – pathogens, sediment, and nutrients. The sources of each pollutant, the impacts each has on water quality, and how they are measured are described
- Chapter 6 explores the reasons why some water bodies are more vulnerable to the impact of pollution than others. The greater the natural vulnerability of a body of fresh water, the greater the impact of human activities
- Chapter 7 describes methods that are being used to protect and improve water quality
- Chapter 8 is a case study of the Manawatū River, using it to illustrate much of what is covered in earlier chapters
- Chapter 9 begins with a summary of the main points and then presents a series of questions that can be used for considering particular water quality problems

1.3 What the report does not cover

This report is about understanding the science of water quality. It is not an analysis of water policy or water management. And unlike previous investigations, the Commissioner does not make specific recommendations.

The report is written at a high level, and every effort has been made to ensure that it is sufficiently accurate for its purpose. The following aspects are therefore not discussed in any detail:

- Pollutants other than pathogens, sediment, and nutrients
- An analysis of what values might be placed on fresh water, including Māori spiritual values
- Water scarcity and allocation including water storage for irrigation, except to note that taking water out of a river increases its vulnerability to pollution
- The state of the water in any water body, except in the case study of the Manawatū
- Standards, guidelines, limits, and targets for water quality
- Governance, legislation, policy or regulation

Source: Wanganui District Council

Figure 1.1: Canoeing the Whanganui river

2 The story of water quality in New Zealand

This is the story of how pathogens, sediment, and nutrients have affected New Zealand fresh water, and how society has responded over the years. A range of other pollutants like heavy metals have also polluted water, but this chapter focuses on the three pollutants that were, and are, the most significant and widespread.

Since European settlement, each of these three pollutants has taken a turn at dominating public concern for water quality. In the late nineteenth century, pathogens were the scourge of early New Zealand towns. By the early twentieth century, sediment rose to the fore after decades of deforestation accelerated erosion and worsened flooding. And later that century, nutrients from factories, towns, and farms emerged as the latest challenge alongside the legacy of erosion.

2.1 Settlement of New Zealand

For Māori, water is a *taonga* – a treasure. Māori identify themselves in terms of their rivers and mountains, along with their ancestors. For instance, someone from Ngāti Porou might say *"Ko Waiapu tōku awa"* – The Waiapu is my river. Whanganui iwi identify themselves so strongly with their river that they say:

E rere kau mai te Awanui
Mai i te Kahui Maunga ki Tangaroa
Ko au te awa, ko te awa ko au

(The Great River flows
From the Mountains to the Sea
I am the River, and the River is me)[2]

Rivers provided routes through the mountains, and freshwater food including tuna, kākahi, and kōura (eels, mussels, and crayfish), as well as edible plants. Māori living or travelling away from the coast relied heavily on these resources. Given the importance of fresh water as a source of food, it is not surprising that Māori still have a particularly strong aversion to sewage pollution.

Early Māori burnt very large areas of forest, mainly to encourage edible plants and to make travel easier. This increased natural erosion, affecting rivers and lakes, especially in places like the South Island high country, where forest failed to regenerate.[3]

European settlers had a very different relationship to water than Māori and feared rivers for their power. They did not understand how quickly New Zealand rivers could rise after heavy rainfall, and drowning became known as 'the New Zealand death'.

Europeans set out to 'tame' the land, leading to widespread impacts on water quality.

2.2 Town sewage causes disease and death

Town populations in the new colony grew rapidly, and so did their sewage. Urban streams soon became polluted by human and animal waste containing pathogens that caused disease and death.

In 1862, one out of every three people living in the gold rush boom town of Cromwell was infected by typhoid. Two years later Dunedin's mortality rate matched the unhealthiest English towns due to poor sanitation. The Otago Daily Times wrote:

> *Dunedin is allowed to remain a city which invites pestilence; every sanitary precaution is neglected; its streets and the surroundings of its dwelling houses reek with impurity and filth – its inhabitants imbibe poison in the water they drink…*[4]

Sewage washed into the grounds of Parliament in the 1860s and no well, tank or stream in crowded parts of Wellington was safe to drink.[5] In Auckland, the channelled stream running down Queen Street was described as *"a pestiferous ditch, the receptacle of every imaginable filth, bubbling in the noonday sun"*.[6]

In response, two laws – the Public Health Act 1872 and the Municipal Corporations Act 1876 – led to the creation of town sewage and water supply systems. Collecting 'night soil' for disposal replaced backyard cesspits. Eventually underground sewers replaced open drains and flushing toilets replaced backyard privies.

Early responses were far from perfect. In Auckland in the 1890s human waste collected from cesspools and privies was emptied just above the city's clean water source at Western Springs.

Unsurprisingly, separating waste water from drinking water led to dramatic health improvements in cities and towns. Today, typhoid no longer haunts our cities, but pathogens from town sewage systems and untreated animal effluent continue to cause illness.

Source: Otago Witness 1906

Figure 2.1: The Dunedin Drainage Board lays sewage pipes in 1906.

2.3 Deforestation leads to erosion and flooding

European settlers deforested vast areas, particularly in the North Island, in a quest for minerals, timber, and pasture. Over time this caused severe and widespread erosion, sedimentation, and flooding.

Mining took off following the Otago gold rush in the 1860s. Digging, crushing rock, and sluicing created a lot of sediment. The effects on erosion and water quality were immediate and severe, but localised. Later, vast quantities of toxic sediment containing cyanide were dumped into the Ōhinemuri River, authorised by the Mining Act 1891.[7]

Coal mining initially had little impact on water quality compared with mining for gold and other metals. Acid mine drainage became more significant as large opencast coal mines on the West Coast of the South Island expanded in the 1990s.[8]

As early as 1840, timber was exported to England and Australia. Extensive areas of kauri in the north fell to giant saws, and lowland forests of rimu, kahikatea, mataī, and tōtara followed.

However, by the end of the nineteenth century, pasture for livestock became the primary pressure on forests. Tussocks had already been burned off much of the South Island high country to create grazing for great flocks of Merino sheep. In 1882, the *Dunedin* departed for England carrying the first shipment of frozen meat. With the ability to sell far more meat than the population of young colony could consume, pasture became more valuable than timber. Forests were burned and grass seed scattered among the stumps. With the advent of refrigeration, freezing works and dairy factories proliferated.

Source: Tyree Collection, Alexander Turnbull Library, Wellington

Figure 2.2: Sluicing to separate gold from gravel washed large amounts of sediment into rivers. Gold mining on the Rocky River, near Collingwood in Golden Bay.

From the early twentieth century, the government drained massive areas of lowland wetlands for conversion into pasture, passing enabling legislation and carrying out the works. It took 25 years to drain the 36,000 hectares of wetlands on the Hauraki Plains.[9] The light, odourless kahikatea wood cleared from the swamps was turned into butter and cheese boxes.

'Breaking in' hill country blocks granted to returning soldiers led to further erosion, but often failed to create productive farmland. Governments continued to subsidise the clearance of erosion-prone land until the 1980s.

By the 1930s, the lowland forests and swamps that had once absorbed floodwaters were largely gone. Rivers in flood spilled across land, lives and homes were lost, and soils were washed away or buried in mud. The risk of further flooding increased as sediment built up in rivers.

Source: Northwood Collection, Alexander Turnbull Library, Wellington

Figure 2.3: Two settlers sow grass seed among the stumps of cut-over forest in Northland.

Concern at the damage from flooding spurred authorities into action. The Soil Conservation and Rivers Control Act 1941 led to the creation of 17 catchment boards across the country, the forerunner of today's regional councils. Reforesting steep slopes, removing stock, and controlling deer and possums all helped conserve soil. Constructing stopbanks, straightening and deepening river channels, and planting river banks helped control rivers.

The historical legacy of deforestation, erosion, and sediment has irreversibly changed most catchments. The struggle to keep the soil on the hills and the water in the rivers is far from over.

Source: Bloomfield Collection, Alexander Turnbull Library, Wellington

Figure 2.4: The Mōhaka River in flood, 1938. Floods in Hawke's Bay in the 1930s buried floodplains in silt, destroyed bridges, and killed 21 workers at a railway camp.

2.4 Factories, towns, and farms raise nutrient levels

In the years following the Second World War, New Zealand's economy grew rapidly and the pressure on fresh water from factories, towns, and farms increased. The nutrients nitrogen and phosphorus became new pollutants of concern.

Factory wastes had been a problem since European settlement. Milling flax, scouring wool, and tanning hides produced large volumes of pungent, nutrient-rich wastewater, and rivers were a convenient method of disposal.

Freezing works and other animal processing plants discharged wool, fat, blood, and guts into water, sometimes resulting in mats of bacteria called 'sewage fungus'. Sewage fungus uses up dissolved oxygen as it grows, and in severe cases, these bacterial mats led to oxygen levels so low that significant fish kills occurred.

Town sewage schemes led to great gains in public health, but the outfall had to be put somewhere and rivers were often convenient. While the treatment of sewage gradually improved, some urban streams were turned into industrial sewers. Heavy metals, acids, oils, and other poisons accumulated in streams like Lower Hutt's Waiwhetū Stream.

Three early attempts at passing a law to control water pollution had been unsuccessful, but in 1953 the Waters Pollution Act created the Pollution Advisory Council to regulate end-of-pipe discharges into water.[10]

On farms, effluent containing pathogens and rich in nutrients was routinely washed from dairy sheds into the closest streams. Basic two-pond treatment systems were introduced in 1972. Increasingly, effluent is now discharged onto land rather than into water, recycling the nutrients.

Grass grew faster on hill country farms if phosphorus was added to that naturally present in the soil. In 1949 aerial topdressing of superphosphate fertiliser took place for the first time in the Wairarapa, providing a new occupation for some who had been pilots in the Second World War. Phosphate clings to soil, so erosion from the deforested hills then began to take even more phosphorus along with sediment into rivers and streams.

In 1982, a plant making the nitrogen fertiliser urea was opened in Taranaki using natural gas from the Kapuni gas field. Before a ready supply of urea became available, nitrogen was usually added to soil by growing clover and other legumes.[11] Together with irrigation, urea has enabled the grass growing season to be extended well beyond the spring and autumn flushes of the traditional pasture of ryegrass and clover. This is largely why dairy farming has been able to intensify and expand into new parts of the country.[12]

Source: Bloomfield Collection, Alexander Turnbull Library, Wellington

Figure 2.5: Whakatū freezing works near Hastings in the 1920s-30s. Blood and guts from freezing works contained nutrients that created 'sewage fungus', depleting oxygen and killing fish.

2.5 Recent developments

In 1991 the 'sustainable management' of fresh water was assigned to the new regional councils under the Resource Management Act. End-of-pipe (point) sources of water pollution, which require resource consents, became increasingly tightly controlled, and much has been invested in upgrading wastewater treatment.[13] Diffuse sources of water pollutants are a much greater challenge.

In 2002, public concern about water quality rose rapidly in response to the 'Dirty Dairying' campaign run by Fish and Game New Zealand. The following year the Dairying and Clean Streams Accord was signed by the country's major dairy company and central and regional government agencies. The Accord sets voluntary targets, such as excluding dairy cattle from 90 percent of streams, rivers, and lakes by 2012.

A large amount of public money has been allocated to clean up iconic and vulnerable lakes and rivers in recent years. In 2004, $81 million was assigned to the protection of Lake Taupō; in 2008, $144 and $210 million was assigned for the Rotorua lakes and the Waikato River respectively.[14] In 2011, $11.6 million allocated to clean up Te Waihora/Lake Ellesmere also included contributions from the local iwi and the dairy industry.

In 2008, the Minister for the Environment established a Land and Water Forum based on a collaborative governance model used in Sweden and Finland. The Forum contains representatives of "*iwi, agricultural, industrial, urban, and environmental organisations with interests in water management*".[15] In 2011, the Government released a National Policy Statement (NPS) for Freshwater Management to guide regional and district council decision making.

3 Pathogens

The word pathogen has its origin in two Greek words – *pathos* meaning suffering, and *gene* meaning to give birth. Pathogens are invisible microbes – bacteria, viruses, and so on – that cause disease.

Significant outbreaks of typhoid, the waterborne killer of colonial times, have not occurred for many years in New Zealand. But 20,000–30,000 people still get gastrointestinal illness from pathogens in polluted water every year.[16] Skin infections are also common.

A water sample from the nearest river will almost certainly contain the *Campylobacter* bacteria, which can cause diarrhoea and vomiting.[17] *Cryptosporidia* and *Giardia,* protozoa that also cause gastroenteritis, are common too.

This chapter is focused on the pathogens in water that come from faecal sources. Cyanobacteria, also known as blue-green algae, are not pathogens – but some can produce lethal toxins that are much more dangerous than most pathogens. Cyanobacterial abundance is related more to nutrients than to faecal sources, so they are discussed in Chapter 5.

This chapter describes how pathogens get into fresh water, the impact they have on human and animal health, and how they are measured.

3.1 How pathogens get into water

The main sources of pathogens in fresh water are human sewage and animal manure.

Most human waste in New Zealand is treated by municipal sewage treatment systems before being discharged into water. One aim is to reduce the number of pathogens in the wastewater, but the extent and effectiveness of sewage treatment varies. Storm overflows, broken sewer pipes, and poorly located and maintained septic tank systems mean some sewage gets into water without being treated at all.

When livestock manure gets into water, pathogens get into water. Some manure is deposited directly into water – cattle and deer are attracted to water. According to one study, dairy cows are over 50 times more likely to defecate straight into water, when given the opportunity.[18]

Around 15 percent of dairy cow effluent is deposited in the shed during milking. Traditionally this effluent was run through two-pond treatment systems and eventually discharged into water; these systems removed most of the solids, but pathogens often survived the process.

Today, many dairy farmers irrigate shed effluent back onto land, though pathogens can still be washed into water if the storage pond overflows, the effluent irrigator breaks down, or the receiving land is too wet for the effluent to soak in.

But the bulk of livestock manure is deposited directly onto pasture. Whenever it rains, some manure gets washed off land into streams, rivers, and lakes. Additional sources of pathogens, such as Canada geese, dogs, and ducks, are insignificant nationally, but can be important locally.[19]

Source: United States Department of Agriculture

Figure 3.1: Common faecal bacteria, *Escherichia coli*

3.2 What pathogens do in water

The potential for pathogens in water to make people sick should not be underestimated. In 1984, when a sewer overflowed close to the water supply intake in Queenstown, 3,500 people came down with gastroenteritis and most of the town's pupils were absent from school.[20]

Eating food from water contaminated with pathogens can make people sick too. Pathogens can remain on the moist surfaces of foods like watercress if the food is not washed properly. Filter-feeding shellfish such as pipi and mussels grown in polluted waters can be particularly risky to eat. Since 2009, the public have been advised to avoid collecting shellfish in the Tauranga and Waihī estuaries due to regular contamination with norovirus, which causes vomiting.[21]

Animals also get sick from polluted water. While sick animals are more likely to directly infect each other, contaminated water can spread disease on to healthy herds and flocks downstream. *Salmonella*, a well known cause of food poisoning in humans, is an emerging problem for livestock. Recent outbreaks have caused diarrhoea, loss of milk production, miscarriage, and deaths.[22]

Some waterborne diseases readily jump from animals to people. *Leptospirosis*, known as 'dairy farm fever', is a typical example. It is often caught directly from infected animals by farmers and meat workers, but can also be transmitted in water.[23]

Source: Wiki Commons

Figure 3.2: A sign warns of pathogen risk from freezing works effluent (2004)

3.3 Measuring pathogens in water

There are two commonly used ways of measuring pathogens in fresh water. Both are measured in units of the number of live bacteria per 100 millilitres of water.

1. *Faecal coliform (FC)* bacteria counts measure sewage and manure contamination in water. This measure can give a false impression of health risk because coliforms of plant (not faecal) origin can grow when water samples are tested.

2. *Escherichia coli (E. coli)* bacteria live in the guts of mammals and birds, so any sewage or manure contains many millions of these bacteria. Most *E. coli* strains are not harmful.[24] However, high levels of *E. coli* indicate the presence of faecal material in the water, and therefore other pathogens too. So the level of *E. coli* in a water sample indicates how likely the water is to cause disease. Water is only deemed safe for drinking if there are no *E. coli* present. When *E. coli* counts in rivers and lakes are detected above 550 per 100 millilitres, health authorities put up signs stating 'Swimming or collecting shellfish is not recommended'.[25]

4 Sediment

Forests store up water for gradual distributions; and they prevent the vegetable mould they form from being washed away. Consequently it follows that when the bush is cut down, not only do the streams tend to disappear with it, but the rain, when it comes, carries the fertile soil from the hillsides down into the valleys.[26]

Sediment – particles of soil and rock eroded from the land and washed or blown by the wind into rivers and lakes – is a widespread and serious water quality pollutant in New Zealand. This is not new – the quote above is from 1909.

The problem is not sediment *per se*. Erosion is a natural process – it is geology in action. Even a pristine headwater in a national park turns brown in flood. The startling blue of Lake Tekapo is due to very fine suspended sediment known as 'glacial flour'. Native ecosystems have had plenty of time to adapt to these conditions.[27]

The problem is that accelerated erosion produces too much sediment. Removing most of the original forest cover of New Zealand exposed soil to the elements and greatly accelerated the natural process.

Particles of sediment range in size from fine particles of clay to boulders.[28] Smaller particles of silt and clay tend to float in the water as 'suspended sediment'. In calm water, they gradually settle to the bottom forming soft layers of 'deposited sediment'. Waves, winds, and floods can stir up deposited sediment, filling the water with suspended sediment again.

Sediment is also a major source of phosphorus because phosphate sticks to the surface of soil particles carried into water. Phosphorus is one of the two problem nutrients discussed in Chapter 5.

This chapter describes what causes excess sediment in water, the impacts it has, and how sediment is measured.

4.1 How sediment gets into water

Erosion and sedimentation are continual processes that slowly redistribute vast volumes of material in this geologically young country.

The highest natural rates of erosion occur on the South Island's West Coast, with its high rainfall, steep slopes, uplift on the alpine fault and erodible soils. Short, steep rivers wash most of this sediment straight out to sea.

In contrast, the wide alluvial plains of Canterbury were made from alpine sand and gravel deposited by the Waimakariri, Rakaia, and other braided rivers. Doubtless the notorious nor'wester winds also played a role.

Before people arrived in New Zealand, it was almost completely forested from shore to snowline. Under cover of trees, ferns, tussocks, and other vegetation, the land could cope with heavy rain.[29] But human activities have changed the landscape completely. The greatest rates of erosion in the country are found on the North Island's East Cape, in areas where steep, erosion-prone land has been cleared of native forests.

Pasture produces two to five times more sediment than an equivalent area of forest.[30] Animals can break down banks putting soil directly into streams. Overgrazing leaves soil exposed and sheep tracks along hillsides create channels for water to carry away soil into rivers, lakes, and wetlands.

Other land uses can also produce large amounts of sediment in waterways. Losses of soil from production forests are lower than from pasture for most of the forest rotation. But when the trees are harvested and replanted, erosion rates go up 10 to 100 fold.[31] Opencast mining, urban development, and road building can all put sediment into water.

Overall, every year more than 200 million tonnes of sediment washes down New Zealand rivers into the sea.[32] This soil is lost forever.

Source: Peter Scott

Figure 4.1: Bare hillsides erode while their neighbours hold firm under a canopy of plantation pine, Hawke's Bay.

4.2 What too much sediment does in water

Sediment makes clear water murky (or turbid), smothers aquatic life, alters water flows, and exacerbates flooding.

Murky water

Sediment in flowing water can damage the native plants that grow on stones and gravels – effectively acting like sandpaper, abrading and scouring them away. Suspended sediment can also damage the gills and delicate body parts of invertebrates and native fish like īnanga (one of the five whitebait species).[33]

Sediment can also have a major impact by reducing visibility. Native freshwater plants need light and most cannot grow in murky water; while creatures that hunt their food by sight, such as trout and kōura, can find it harder to catch food.

Swimming in murky water is not appealing and can be dangerous, as logs and other hazards underwater are not easily seen.

Source: David Peacock

Figure 4.2: The Waipāoa River sends a plume of sediment-laden water into Poverty Bay.

A blanket of mud and silt

The greatest impact of sediment on water quality comes from its ability to smother the beds of rivers, streams, and lakes.

The spaces among the stones and gravels on the beds of streams, rivers, and lakes are an important habitat for aquatic plants, invertebrates, and fish.[34] Many animals use these spaces – that can stretch down many metres – for shelter, feeding, and spawning. When water flow is slow enough, the sediment settles out, and this bottom habitat can become choked and buried under a layer of mud and silt.

This blanket of mud and silt can directly kill native plants and animals. And when the plants disappear, so too can the invertebrates and fish that rely on them. A thick layer of silt also provides a foothold for exotic weeds.

This problem can be particularly severe in estuaries. When a river mixes with seawater, the increasing saltiness leads to more sedimentation in the estuary or just offshore.[35] Saltmarsh plants like cordgrass and mangroves accelerate this by trapping sediment.

The Kaipara Harbour is the biggest estuary in the Southern Hemisphere, and where most of the snapper on the west coast of the North Island originate. Sediment from the catchment threatens to overwhelm horse mussel beds and seagrass meadows, which are nursery grounds for snapper.[36]

Changing water flows

When sediment builds up, it changes water flows and reduces the capacity of waterways. The impact of excess sediment goes well beyond water quality.

For instance, silt from urban development, pastoral land, forest areas, and quarries has long accumulated in the Tauranga estuary. Navigation channels are increasingly shallow, fish habitats and shellfish beds have been buried, and the port must be regularly dredged.[37]

Layers of silt can make rivers, lakes and estuaries more vulnerable to flooding because they are shallower. Flooding along Northland's Awanui River in 2007 was made considerably worse by a build-up of silt in the flood channel.[38]

Figure 4.3: Most New Zealand rivers are naturally stony-bottomed. Native plants and animals that have adapted to that environment, like this torrentfish, can be killed by sediment.

4.3 Measuring sediment in water

There are various methods used for measuring both sediment that is suspended in water and sediment that has settled on river and lake beds.

Suspended sediment can be measured directly (in grams of sediment per litre of water), or inferred by measuring the murkiness of the water or its opposite, the clarity of the water.

- Murkiness can be measured by the amount of light scattered when a beam of light is passed through water. The technical term for murkiness is turbidity. The unit of measurement is 'nephelometric turbidity units' (NTU)[39]
- Clarity can be measured by the distance through water before a standard black disk can no longer be seen. Sometimes a 'Secchi disk' is used to measure clarity. A Secchi disk has alternate black and white segments and is lowered into the water until it can no longer be seen

Deposits of sediment on river, lake, or estuary beds can be assessed by:

- Measuring changes in the percentage of silt and clay in sediments
- Surveying the elevation and shape of the bed

5 Nutrients

Like people, plants need certain nutrients in order to grow. Gardeners are familiar with NPK fertilisers that contain the three essential elements of nitrogen, phosphorus and potassium.[40] Too much of the first two of these – nitrogen and phosphorus together – are the cause of the algal blooms and other unwanted plant growth in waterways that has become such a concern today.[41]

Both nutrients occur in different chemical forms. The two common forms of nitrogen in water are nitrate and ammonia, whereas phosphorus mainly exists as phosphate.[42]

This chapter describes how phosphorus and nitrogen get into the water, what the impacts are, and how they are measured.

5.1 How nutrients get into water

What nitrogen and phosphorus have in common is that they are both needed for plants to grow – they are both essential nutrients. But there is much they do not have in common.

Both common forms of nitrogen – nitrate and ammonia – are highly soluble in water. In contrast, phosphorus in the form of phosphate usually clings to soil and sediment.[43] This difference affects how the two nutrients get into water, what happens to them in water, and, as discussed in Chapter 7, how they can be prevented from getting into water.

The biggest source of nitrogen in New Zealand's waterways is urine from farm animals.[44] Urine contains urea which is rich in nitrogen. Urine thus acts as a nitrogen fertiliser, but urine patches in paddocks can be too much of a good thing – the grass cannot grow fast enough to take up all the nitrogen, particularly in winter. The soluble excess nitrogen seeps down into groundwater or washes off the paddock into streams. Wasted nitrogen fertiliser is a much smaller source of nitrogen in fresh water than urine.[45]

Because phosphate usually clings to soil particles, the main way in which phosphorus gets into water is when soil is washed in and becomes sediment.[46] Much of the phosphorus in rivers and lakes is a legacy of erosion caused by forest clearance and fertilising for sheep farming. Most New Zealand soils are naturally low in phosphorus, but when washed into water add to the cumulative effect of decades of erosion and topdressing with superphosphate.

Sewage and animal effluent are rich in both nitrogen and phosphorus. Many smaller sewage plants have limited treatment capability, leaving behind much of the nitrogen and phosphorus. Some sewers overflow at times and septic tanks can be poorly located and maintained. Household detergents are also a source of phosphorus. Animal effluent comes from dairy sheds, piggeries, freezing works, mole and tile drains, and from animals with access to waterways. Manure can also wash off paddocks in heavy rain.

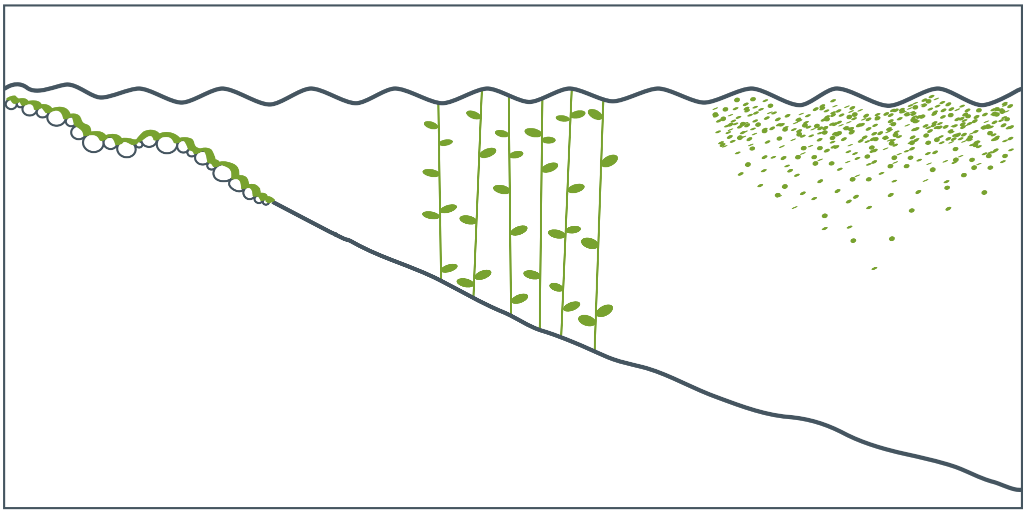
Wastewater from dairy factories, freezing works, and pulp and paper plants can be significant point sources of phosphorus in particular.[47]

Although point sources of nitrogen and phosphorus can be very significant at specific places and times, they are much less significant at a national level than the diffuse sources. The great majority of the nitrogen that gets into fresh water comes from animal urine. The amount of phosphorus that gets into fresh water with sediment far outweighs inputs from point sources.

5.2 What too many nutrients do in water

Both common forms of nitrogen in water – nitrate and ammonia – cause problems. Very high levels of nitrate can make groundwater unsafe to drink.[48] Nitrate can also kill sensitive organisms like young trout and salmon.[49] Ammonia is highly toxic to fish and other creatures that live in water, so direct discharge of ammonia-rich wastes such as raw sewage or dairy shed effluent can be particularly damaging. But the main impact of too much nitrogen and phosphorus is the ‘overfertilisation’ of aquatic plants, leading to excessive plant growth, algal blooms and the depletion of oxygen dissolved in the water.

Too many nutrients cause excessive growth of three kinds of aquatic plants – large plants visible to the naked eye called *macrophytes*, and two kinds of tiny plants called *periphyton* and *phytoplankton*.



Periphyton Macrophytes Phytoplankton

Figure 5.1: Excessive growth of three types of plants degrades water quality. All three must receive sunlight in order to photosynthesise. Periphyton tend to grow in shallow water; because they form films on submerged stones they must be close to the water surface. Macrophytes grow in deeper water – they are rooted to the bottom and reach up towards the sunlight. Phytoplankton float and so can thrive in deep water.

Periphyton are tiny plants that grow on surfaces under the water. Growing in millions, they form the film or slime covering stones and wood in streams, and can also grow on, smother, and kill larger plants. Excessive growth of periphyton can carpet the bottom of lakes and rivers, degrading swimming and fishing spots and driving away creatures that need to spawn, feed, and shelter on the bed.[50]

Macrophytes generally root into the bottom and send stems and leaves up towards the light. Some macrophytes emerge above the water, like rushes in a wetland; others have leaves floating on the surface, like a pond-lily; and still others are entirely submerged, waving in the current. Native plants are generally adapted to low nutrients, low sunlight, and low sediment.[51] In contrast, invasive exotic weeds, like hornwort, respond prolifically to excess nutrients, crowding out natives, fouling pipes, and clogging lakes and streams.

Phytoplankton differ from periphyton in one key way – they float freely in the water, rather than being attached to surfaces under the water. The term comes from the Greek word *planktos*, meaning to wander.

Both periphyton and phytoplankton come in two forms:[52]

- Algae that photosynthesise, growing in the same way as most plants on land by using sunlight and carbon dioxide
- Cyanobacteria or 'blue-green algae'.[53] Strictly speaking, cyanobacteria are bacteria, but are usually classified as plants because they also grow using a form of photosynthesis

As nutrient levels increase, periphyton generally multiply first followed by macrophytes, which can shade out the periphyton. Very high nutrient levels then lead to blooms of phytoplankton – known as algal blooms.

Algal blooms

In slow moving water containing high levels of nutrients, algae can rapidly multiply forming algal blooms. This is most likely to occur in summer when the water is warmest and there is plenty of sunlight.

Generally the term 'algal bloom' refers to an extremely rapid increase of phytoplankton. In such a bloom a litre of water can contain millions of algal cells and the water is often discoloured a vivid green, brown, or red. Some cyanobacteria produce poisonous toxins that reach dangerous levels during a bloom, with the danger often persisting for days after the bloom is over.[54]

Food gathered from toxin-tainted water can be dangerous and cooking does not destroy the toxins. Filter-feeding shellfish in estuaries, like scallops and mussels, accumulate algae toxins as well as pathogens. Other wild foods, such as eels, can also become poisonous when they live in waters infested with algae.[55]

Colonies of periphyton can also increase very rapidly, forming a dense slimy mat trailing long tendrils and carpeting submerged stones and wood. 'Didymo' ('rock snot') is a type of introduced periphyton that can smother an entire river bed. It was first recorded in the Lower Waiau River in the South Island in 2004, and is currently confined to the South Island – where it is now found in over 150 rivers and lakes. Like other nuisance species of periphyton, the severity of a didymo outbreak depends on the 'flow regime' of the river, and the amounts of nitrogen and phosphorus present.[56]

Source: Dr. Max Gibbs, NIWA

Figure 5.2: One of the most polluted lakes in the country is Lake Horowhenua. This shallow dune lake on the Manawatū coast is in an area of intensive horticulture. Cyanobacteria regularly bloom in Lake Horowhenua in late summer. Algae toxins at the edge of the lake have been measured at up to 36 milligrams per litre – 3,000 times greater than the recommended action level of 0.012 milligrams per litre.[57]

Box 5.1: Nutrient limitation

An excess of nitrogen or phosphorus *alone* will not lead to exorbitant growth of algae and aquatic weeds. There needs to be enough of both nutrients, in the right ratio. If a river or lake has plenty of nitrogen to fuel unwanted plant growth but not enough phosphorus, it is said to be *phosphorus-limited*. Conversely, water with plenty of phosphorus but not enough nitrogen is *nitrogen-limited*.[58]

The concept of nutrient limitation is fundamental when it comes to considering how to keep nitrogen and phosphorus out of water. In theory, if a water body is phosphorus-limited, then there is less need to control inputs of nitrogen. However, in many situations controlling one nutrient may be insufficient because:

- The limiting nutrient in a water body can be different at different times[59]
- The limiting nutrient can be different in different parts of the same water body[60]
- Cyanobacteria may bloom even in nitrogen-limited waters[61]

Oxygen depletion

Fish and other animals that live in rivers and lakes need oxygen to breathe, but excessive plant growth in water can sometimes cause oxygen levels to plummet below that needed to sustain life.

When plants photosynthesise they produce oxygen. When they respire they consume oxygen. Oxygen is also consumed when plants die and are broken down by bacteria. The problem is that plants only produce oxygen during the day because photosynthesis requires sunlight, but the processes that consume oxygen – respiration and decomposition – occur day and night.

The result is that excessive plant growth can lead to dramatic drops in oxygen levels at night, leaving fish and other aquatic creatures unable to breathe.

Box 5.2: 'Stratification' and oxygen depletion of lakes

In summer, many New Zealand lakes 'stratify' into two distinct layers, a warm upper layer and a cold lower layer. The two layers do not mix because the warm layer is lighter than the cold layer.

Bacteria in the bottom layer use up oxygen in the water as they break down dead plant and animal matter. And because this layer is isolated from the surface and from the warmer upper waters where plants are photosynthesising, the oxygen cannot be replaced. This lack of oxygen can kill invertebrates and fish directly, but also affects the lake by greatly increasing the release of phosphorus from the sediment into the water of the bottom layer.[62]

In autumn, the top layer cools, the wind stirs up the water, and the lake waters mix again. The phosphorus released from the sediment is mixed throughout the lake, ready to fuel algal blooms the next summer.

5.3 Measuring nutrients in water

There are many ways of measuring nutrients and their impacts in water. Some are presented below, including three measures that go beyond just measuring nutrients to capture the overall health of fresh water.

Indicators of nutrient status

Both nitrogen and phosphorus can be measured as totals or just in their dissolved forms.

Dissolved inorganic nitrogen (DIN)

DIN includes nitrate, ammonia, and other forms of inorganic nitrogen. It is nitrogen available for plant growth.

Total nitrogen (TN)

TN is the total amount of nitrogen present in water. It includes nitrogen from dead plants and animals as well as DIN. When dead plants and animals decay, they release nitrogen into the water, so it becomes available for plant growth.

Dissolved reactive phosphorus (DRP)

DRP is the amount of phosphorus that has dissolved in water and is therefore readily available for plant growth.

Total phosphorus (TP)

TP is the total amount of phosphorus present in water. It includes the phosphate that is stuck to sediment as well as DRP. TP is a particularly important measure for lakes, because over time phosphate that is stuck to sediment can be released and become available for plant growth.

Indicators of ecosystem 'health'

Dissolved oxygen (DO)

The amount of dissolved oxygen gas in water is usually reported as a percentage of the maximum possible concentration – 'saturation'.[63] Trout begin to be affected when saturation drops below 80 percent; many native fish and invertebrates are affected below 50 percent, and killed if oxygen depletion persists for long.[64]

Trophic Level Index (TLI)

The nutrient (trophic) status of a lake is often assessed using the TLI – a composite index that amalgamates measures of nitrogen, phosphorus, chlorophyll and the clarity of the water. A low TLI value (2 or less) indicates the lake has low levels of nutrients and plant growth, as would be expected of many New Zealand lakes in their natural state. A high TLI (4 or above) indicates the lake is enriched with nutrients and likely to experience growth of macrophytes and algae.

Macroinvertebrate Community Index (MCI)

The MCI is an ecological index that measures the variety of insects, worms, snails, and so on, that are present in a stream or river. An MCI score of less than 80 indicates poor ecological health while a score of 120 or more indicates excellent ecological health.

Figure 5.3: Algae health risk warning, Manawatū-Wanganui region

6 Natural vulnerability to water pollution

The previous three chapters have described the three types of pollutants that are of most concern in New Zealand – what they are, where they come from, and the impacts they can have on fresh water. But how serious those impacts are depends to a large extent on the characteristics or vulnerability of the specific water body where the pollutants end up; that is, the nature of the 'receiving environment'. The greater the *natural* vulnerability of a body of fresh water, the greater the impact of human activities.

Lakes, rivers and streams, wetlands, estuaries, and aquifers are different receiving environments. Moreover, a shallow warm lake is a different receiving environment from a deep cold lake. A river that meanders on a winding course to the sea is a different receiving environment from a river that flows swiftly straight to the sea.

On a larger scale, some catchments are naturally more sensitive than others. How much it rains, how steep or flat the terrain is, and the types of soil and rock present all influence how vulnerable a catchment is to water pollution. And within a catchment, all lakes, rivers and streams, wetlands, estuaries, and aquifers are linked to others, and the impacts of water pollution in them are linked too. This is why water pollution is best understood at the catchment level.

This chapter describes how the vulnerability of fresh water to pathogens, sediment, and nutrients is affected by a variety of *natural* (not human) factors. These factors and their influence on the vulnerability of lakes, rivers and streams, wetlands, and aquifers to pollutants are explained in the following sections.

6.1 Lakes are especially vulnerable

By their very nature, lakes are generally more vulnerable than rivers. Lakes act like sinks, accumulating the pollutants that come down a catchment. Sediment and phosphate, in particular, become trapped. Lakes – especially small, shallow, warm ones – also provide ideal conditions for weeds and algae to grow.

Weeds (macrophytes) can readily grow in sediment that has built up in shallower parts of lakes. The nutrients that so usefully fertilised the plants on land accumulate and fertilise the water weeds. And because lakes are wide open to sunlight, there is plenty of warmth and light for photosynthesis.

Algae (periphyton and phytoplankton) growing on surfaces or floating in the water also grow more prolifically in response to light and warmth as nutrients and sediment accumulate in lakes.

Lack of oxygen can be a major issue in lakes. In lakes with high nutrient levels, excessive plant growth can lead to wild fluctuations in oxygen levels, including the dramatic overnight drops that can kill invertebrates and fish. Warm shallow lakes are most vulnerable to these fluctuations.

Lake stratification (described in Box 5.2) sometimes leads to oxygen depletion in lakes.

Source: Dr. Rohan Wells, NIWA

Figure 6.1: Hornwort forms a dense bed in Rotorua's Kaituna River. A former aquarium plant gone wild, hornwort can spread from a single fragment, thrives in full sunlight or shade, and can even grow under ice. Hornwort readily blocks drains and fills shallow lakes, wiping out native water plants and preventing fishing or boating.

Source: Waikato Regional Council

Figure 6.2: Lake Rotongaro, a small shallow lake near Huntly in the Waikato, hit the headlines in the summer of 2005 when nine cattle died from drinking its toxic waters during an algal bloom.[65]

6.2 Rivers and streams have varying vulnerability

How much water there is in a river or stream, how fast it moves, and whether its flow is constant or fluctuates up and down are key factors in how vulnerable it is to the effects of pollutants. The 'flow regime' is the most important thing that determines the vulnerability of most rivers and streams to excess periphyton growth:[66]

- Taking water out of rivers for irrigation and other purposes reduces flows and dilution, which makes these rivers more vulnerable
- Small and stable flows increase vulnerability by allowing sediment, periphyton, and macrophytes to build up. In comparison, larger and more variable flows can carry sediment and weeds away – as well as diluting any nutrients – and therefore reduce vulnerability
- Floods are the extreme examples of high, variable flows. Floods can scour out not just sediment, but also weeds rooted in the sediment and periphyton clinging to the rocks. However, floods will wash yet more soil off the land into water, adding more sediment and the phosphorus bound to it

Rivers and streams are usually most vulnerable to nutrients in summer. Algae and weeds generally grow more prolifically in summer because:

- Less rainfall results in lower flows, fewer flushing flows, and higher concentrations of nutrients
- More sunlight results in more photosynthesis and warms the water

Many natural factors in catchments can also affect the vulnerability of rivers and streams. For example, a catchment with exposed steep slopes, silty or sandy soils, and subject to sudden downpours of rain will erode, readily putting sediment into rivers and streams. A flatter catchment with stony or gravelly soils is vulnerable to nitrogen leaching into groundwater and thence into rivers and streams.

Source: GNS Science

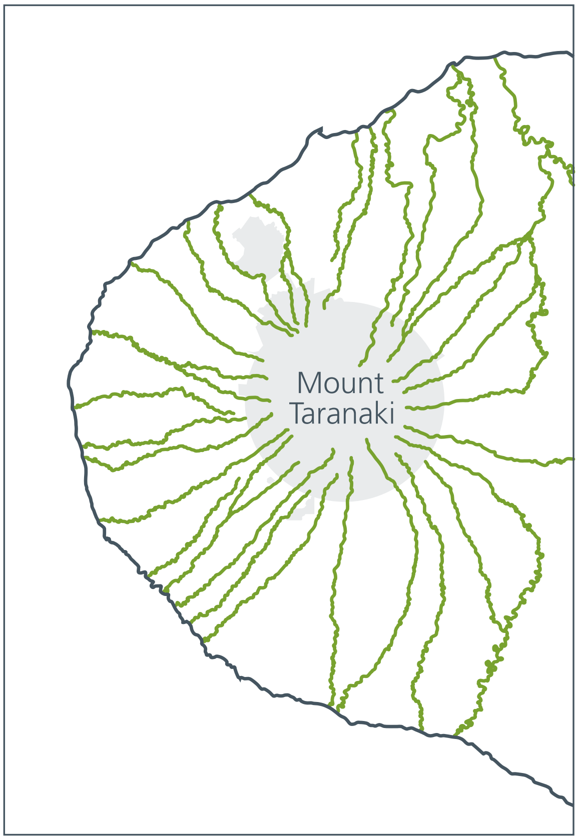
Figure 6.3: The headwaters of the Waimakariri River – meaning 'frigid water' in Māori. Of the rivers crossing the Canterbury Plains, some, like the Waipara, come from the seaward hills, and are relatively small and warm. But others, like the Waimakariri, are fed by melting snow in the Southern Alps, which makes them big, cold, and prone to powerful spring floods. The Waimakariri is thus much less vulnerable to water pollution than the Waipara.

Source: Hawke's Bay Regional Council

Figure 6.4: The Tukituki River begins in the rugged Ruahine Range. When the river slows down on the Ruataniwha Plains around Waipukurau, the river drops the sediment it carries, and mats of algae form in the meandering shallow bends. The Tukituki River rarely floods, as heavy rain is rare in its headwaters, so periphyton can readily build up.

Source: Waikato Regional Council

Figure 6.5: The Waipā River, a tributary of the Waikato, flows through relatively soft, erodable land and is particularly susceptible to sediment pollution. The photograph shows the effect of a large flood in 1998.



Source: Taranaki Regional Council

Figure 6.6: Regular heavy rains on Mount Taranaki feed more than 300 short and straight streams, which run quickly across the volcanic ring plain to the sea. Because these west Taranaki streams are so well flushed, they are much less vulnerable to algal blooms than long, dry-country east coast rivers.

Source: Mark Brimblecombe

Figure 6.7: Sediment can sometimes make a river so murky that there is not enough light for plants to grow. Hill rivers of the western North Island, such as the Whanganui, flow through landscapes of relatively soft rock. These hills are easily eroded, and so these rivers carry a lot of sediment. Sediment makes the Whanganui River so murky and muddy that weeds and algae cannot grow. So, while the Whanganui is susceptible to sediment pollution, nutrient pollution has very little effect.[67]

6.3 Wetlands and estuaries have some resilience

Wetlands differ in their vulnerability to pollutants. There are two aspects to this vulnerability: how likely pollutants are to get into the wetland, and how big an impact pollutants have if they do get in.

Alpine wetlands – tarns and bogs – generally receive all their water from rainfall, and so there is no easy pathway for pollutants to get into the wetland. The ecology of these wetlands is attuned to very low levels of nutrient, so their plants, insects, and fish, often rare or endangered, are likely to rapidly disappear if their habitats are polluted.

Lowland wetlands – swamps and marshes – receive water from streams, rivers or lakes as well as rainfall. Because they receive nutrients from the wider catchment, the ecology of these wetlands is naturally attuned to higher nutrient levels. Consequently, the plants and animals in swamps and marshes can be resilient to nutrient pollution, but only up to a point. As nutrient levels increase, introduced weeds and animals can start to out-compete the natives. And if nutrient levels get high enough, native plants can be smothered by algae, 'flipping' the wetland from resilient to polluted, sometimes irreversibly.

Like lowland wetlands, **estuaries** are also vulnerable to pollutants. Estuaries trap sediment.[68] When a stream or river reaches an estuary and the water gets saltier, the particles of sediment carried by the flowing water clump together and settle. Sediment is also trapped in the roots of salt-marsh plants like mangroves. Plants and animals that live in estuaries are used to sedimentation, so estuaries can be quite resilient to sediment pollution. But too much sediment can change the flows, bury estuary life, and even fill in the estuary.

While tidal flushing removes nutrients from estuaries, it also brings in phosphorus, for seawater naturally contains moderate amounts of phosphate. Consequently estuaries with large, shallow mudflats, such as Manukau Harbour, have suffered frequent algal blooms and nuisance seaweed growths.[69]

Source: Environment Southland

Figure 6.8: The Waituna coastal lagoon in Southland is part of the internationally recognised Awarua Wetland. For many years native seagrass beds have kept the water clear despite growing nutrient pollution. But this protection has now reached its limits. The nutrient concentration has risen too high and periphyton are coating the seagrass, killing it. The water has become murky and overtaken by algal blooms.

Source: Dr. Mal Green, NIWA

Figure 6.9: Thick sediment lost from the surrounding hills fills Auckland's Mangemangeroa estuary.

6.4 Aquifers can trap and accumulate nitrate

Aquifers are, in effect, underground lakes that are fed by water soaking through the ground. Like lakes, aquifers are relatively still and contained, so nitrate and pathogens accumulate – although any pathogens will die off over time.[70] But unlike lakes, aquifers have no light, so weeds and algae cannot grow.

When nitrate concentrations in aquifers rise to critical levels, the water becomes unsafe to drink. How vulnerable an aquifer is to dissolved pollutants depends on how accessible it is to water from the surface. Some aquifers are naturally protected from nitrate and pollutants leaching down from the surface by layers of impermeable silt or clay, but others are not.[71]

Source: P. Smith

Figure 6.10: In the vegetable-growing area of Pukekohe south of Auckland, shallow groundwater is undrinkable in many places because of high nitrate levels from decades of fertiliser use. But cleaner water can be taken from the deep Kaawa aquifer in the same area. The water in this aquifer is protected from pollution by water-resistant ground layers that lie above it.

6.5 Summarising vulnerability

The effect of pollution on the quality of water varies greatly. On the one hand, there is the amount and type of pollutant. On the other is the 'receiving environment' – a host of natural factors that influence the impact of the pollutant on water quality.

The list of factors presented in this chapter – and summarised below – is not comprehensive and some factors will appear so obvious as to be scarcely worth mentioning. Nevertheless, it is important and useful to develop a 'feel' for interactions between the three main water pollutants and their receiving environments, since a major direction of current policy development is based on distinguishing between catchments that are 'sensitive' and catchments that are not.

Box 6.1: Factors that affect vulnerability

Flow characteristics

Volume

Flow regime

Physical factors

Source or sink

Depth

Light

Temperature

Catchment characteristics

Soil and rock type

Terrain

Position in the catchment

Ecological factors

Natural nutrient levels

Resilient or sensitive ecosystem

This chapter has described how the impacts of water pollutants are influenced by the vulnerability of the receiving environment. The next chapter describes some of the ways that water quality can be improved and protected.

7 Protecting and improving water quality

There are many ways to help protect and improve water quality. But there is no single solution that will work on everything, everywhere.

What helps reduce one type of pollutant in water may or may not reduce another. What kills bacteria may not kill hardier pathogens like viruses and will have no impact on sediment. What helps stop phosphorus getting into water may not reduce nitrogen.

Pollutants that come from **end-of-pipe sources** (point sources) are the easiest to manage – though treatment can be costly. The type and amount of each pollutant is easy to measure, and its origin (and who is responsible) is easy to identify.

Pollutants that come from **diffuse sources** (non-point sources) are much more difficult to manage. Diffuse pollution often comes from a large number of small sources, but the term also covers the pollution that comes from an eroding river bank or seepage of soluble pollutants into groundwater. Diffuse pollution is thus much more of a challenge than end-of-pipe pollution.

Improving water quality by dealing with **trapped pollutants** that are already in water is perhaps the greatest challenge and likely to be very expensive.

This chapter describes methods to improve water quality for each pollution source:

- End-of-pipe sources including factories, sewage treatment plants, and dairy sheds
- Diffuse sources such as eroding slopes and grazing stock
- Trapped pollutants, like sediment laden with phosphorus that has accumulated in a lake

7.1 Reducing end-of-pipe pollution

There are three general ways to reduce end-of-pipe pollution.

1. Avoiding creating the pollution in the first place
2. Treating wastewater to lessen its impact on fresh water
3. Discharging wastewater into the ocean or spraying it on to land

Reducing pollutants going into pipes

Taking steps to avoid creating pollution in the first place is almost so obvious that its value can be underestimated. An example is that about a quarter of phosphorus from the wastewater that comes out of cities could be removed by switching to phosphorus-free detergents.[72]

End-of-pipe industrial discharges have changed greatly over the years, particularly since the enactment of the Resource Management Act in 1991. One successful example of achievement through technology change is the Fonterra dairy factory on the Waitoa River in the Hauraki district. Virtually all discharges of phosphate have been eliminated by changing cleaning practices, changing the kinds of products being made, and improving the wastewater treatment system.[73]

Treating sewage and manure

New Zealand has more than 300 sewage treatment plants treating sewage and other waste water from both domestic and industrial sources. But many town wastewater systems carry out only primary or secondary treatment, which may be inadequate for reducing pollutants.[74]

The impact of wastewater could be reduced by introducing treatment where there is none, and by increasing the effectiveness of existing sewage treatment by adding further treatment steps (see Box 7.1).

Improved treatment of sewage can make a big difference. Between 1960 and the 1990s, the population of Auckland doubled and so did its sewage. The city responded by adding secondary and tertiary treatment (bioreactor systems and an ultraviolet light disinfection step) to the Māngere sewage treatment plant. The discharge now contains less nutrients and fewer viruses than before the upgrade. As a result, shellfish in the Manukau estuary are once again edible.[75]

Box 7.1: Treating wastewater

Primary treatment	Solids are removed by settling out in large tanks.
Secondary treatment	Organic content is broken down in contact with air, e.g. in oxidation ponds or artificial wetlands.
Tertiary treatments	Particular pollutants are removed, such as: • Killing pathogens with ultraviolet light or chlorine • Removing nitrogen using bacteria • Removing phosphate by chemical precipitation • Removing nutrients by growing and harvesting algae

Washing down dairy sheds after milking generates large amounts of effluent – a mix of wastewater, manure, and urine. Practices that reduce the amount of water used, like scraping the solid manure up before hosing the shed down, reduce the amount of effluent produced. Effluent from piggeries is less well-recognised, but a piggery can generate very large quantities of effluent.[76]

Some dairy farms still use 'two-pond' systems for treating effluent from dairy sheds. In these systems, the first pond settles the solids out and the second pond exposes the wastewater to air and light, similar to primary and secondary sewage treatment. However, these systems perform inconsistently and are generally poor at removing pathogens (especially viruses) and nutrients (especially nitrogen). Most dairy farms now spray this effluent onto land as described below.

Discharging wastewater onto land

Often, discharging wastewater into fresh water can be avoided altogether.

Spraying wastewater onto land has many advantages: solids are trapped by the soil structure; nutrients are taken up by plants or retained in soil, reducing the need for fertiliser;[77] bacteria break down organic matter, and light and drying out kills pathogens; and water is recycled.

Spraying dairy shed effluent onto land is now common practice on many New Zealand dairy farms. But it must be done well to be effective; for instance, effluent should not be sprayed onto waterlogged soil. This means that farms must have appropriately sized storage ponds so they can delay spraying until conditions are right.

Coastal towns and cities have long discharged treated sewage and wastewater into the ocean, and there have been significant improvements to these systems. Away from the coast, an increasing number of towns and cities are spraying treated sewage and wastewater onto land.

Before 1995, Taupō discharged its treated effluent directly into the Waikato River. Now it is sprayed onto pasture in summer, so that the growing grass is fertilised by the nutrients and any residual pathogens dry out and die. The grass is harvested and sold as hay and silage.

Source: Taranaki Regional Council

Figure 7.1: Many dairy farms in New Zealand now dispose of their shed effluent by spraying it onto land, reducing the need for fertiliser.

7.2 Reducing diffuse pollution

There are two ways to reduce diffuse pollution:

1. Dealing with the causes of diffuse pollution
2. Preventing diffuse pollution from getting into water

Dealing with the causes of diffuse pollution

Nearly all sediment in fresh water is the result of erosion. Erosion on vulnerable land can be prevented by avoiding overgrazing and maintaining vegetation cover. If the land has already been cleared, planting trees or allowing gullies to revert to native scrub will reduce erosion and sediment in streams.

Avoiding using excess fertiliser can reduce nutrient pollution in water. The optimal amount of fertiliser to apply to farmland can be identified using nutrient budgeting, ideally leading to less fertiliser with no decrease in land productivity.

Reducing stock numbers is an obvious way to reduce pollution from urine – the major source of nitrogen pollution – and manure. But changing the way stock is managed, without reducing stock numbers, can reduce nutrient inputs into water.

Keeping stock on heavy soils in winter increases the chance of the soil becoming waterlogged and pugged. Pugging damages soil structure, makes soil waterlogged and kills grass so it does not take up nutrients. Pathogens, sediment, and nutrients are all more likely to get into water from such damaged soils.

Source: NZ Landcare Trust

Figure 7.2: Poplars are used for reducing erosion on hill farms. A poplar will sprout from a pole hammered into the ground. Poplars grow rapidly, have extensive root networks, and do not kill off the grass around them.

Moving stock into less vulnerable paddocks or onto stand-off pads can reduce the risk of pugging and nutrient loss. Recent trials have shown that restricting the time cows spend grazing on the pasture to only eight hours per day can halve the nitrogen lost to water.[78]

An even more effective, albeit more expensive, solution is to build 'wintering barns'. These are buildings that are large enough to easily house cows for periods of time over the wetter months. Grated floors allow the urine and manure to be readily collected and sprayed onto land as a fertiliser.

Preventing diffuse pollutants from getting into water

Fencing off streams and bridging crossings to keep stock out of water is the first step in preventing diffuse pollution on farms. These actions prevent stock from directly urinating and defecating into water, reducing inputs of pathogens and nutrients. Fencing and bridging also prevent stock from breaking down banks, thus reducing the sediment entering the water.

Establishing a buffer zone of vegetation (a riparian strip) between a fence and a stream is the next step. The word 'riparian' comes from the Latin word *ripa*, meaning 'river bank'. Ideally a riparian strip is about 5 metres wide and covered with a range of plants, including dense ground cover and trees. These plants take up nutrients from runoff as they grow.[79] Trees stabilise banks with their root systems. Trees also shade narrow streams reducing light and heat, thus hindering the growth of algae and water weeds.

Riparian strips can trap sediment. And because phosphorus sticks to sediment, riparian strips can also prevent phosphorus from getting into water. A well-designed riparian strip with actively growing dense ground cover will typically reduce the phosphorus that would otherwise get into the water by about 60 percent.[80] Even a riparian strip as simple as an area of rank grass and a single wire electric fence will remove some phosphorus.

Riparian strips that will be effective at reducing the nitrogen that gets into water are more expensive to establish and maintain. The bulk of the nitrogen getting into water is dissolved in water draining off the surface and through the ground. Only the dissolved nitrogen that flows through the root zone of the plants can be taken up. Therefore, well-designed riparian strips that have deep-rooted plants are most effective for nitrogen removal and typically will remove about 40 percent of the nitrogen in the water that flows through them.[81]

Preventing nitrogen pollution of water is an especially hard problem. However, solutions may be emerging. In some climates, 'nitrification inhibitors' can slow down the movement of nitrogen through soil, giving plants more chance to use it. Nitrification inhibitors could significantly reduce the amount of nitrate getting into fresh water, especially in the South Island.[82]

Wetlands work in a similar way to riparian strips to remove pollutants. They trap sediment, and wetland plants take up nutrients. And they can be very effective, removing up to half the nitrogen and phosphorus flowing into them.[83]

Therefore, preserving and restoring wetlands is a good way to improve water quality. This is a case where prevention is clearly better than cure – it is better to preserve a wetland rather than seek to replace it at great cost in the future.

Source: Taranaki Regional Council

Figure 7.3: Riparian strips along a Taranaki stream. These buffers protect the banks and the fields behind them, filter out pollutants and shade the water. At one study site, where local dairy farmers have fenced and planted along half the stream's length since 2003, sediment, phosphorus, and *E. coli* have all declined markedly.[84]

7.3 Dealing with trapped pollutants

Once sediment and nutrients are trapped in water they may stay there for a very long time. Nitrogen entering an aquifer will remain there for decades or more because water flow through aquifers is extremely slow.

Sediment in lakes, slow rivers, and estuaries is essentially there forever. The phosphorus it contains can gradually dissolve from the sediment back into the water to feed weeds and algae for many years into the future.

When and where it is possible to reduce the impact of trapped pollutants, doing so is difficult and expensive. For example, considerable investment has been, and is being, made in removing nutrients from some of the Te Arawa lakes in the Rotorua district, including the following:[85]

- An artificial floating wetland the size of a rugby field and costing nearly $1 million dollars has been constructed for Lake Rotorua
- A 'diversion wall' costing $10 million dollars has been built across Lake Rotoiti to prevent pollution flowing into it from Lake Rotorua. The wall ensures that the outflow from Lake Rotorua passes quickly into the Kaituna River, rather than mixing with the Lake Rotoiti water as it did previously
- In Lakes Ōkaro and Okareka, sediment has been capped with a thin layer of material that blocks phosphate from escaping. But it is expensive and not a permanent solution, as new sediment will settle on the cap and start the phosphorus cycling again

Introducing fish to eat unwanted plants is one alternative, but obviously must be done cautiously. In Lake Ōmāpere in Northland, blooms of cyanobacteria were controlled with silver carp between 1988 and 1992. Later, when the lake was re-infested by weeds, grass carp were used to eradicate them too. On both occasions a retaining wall prevented the fish escaping into the wild.[86]

The following chapter provides the opportunity to explore water quality in a real world setting with a case study of the Manawatū river.

8

A case study: The Manawatū River

In late 2009 the front page of the *Dominion Post* provocatively declared the Manawatū *"Our River of Shame"*. The river suddenly became infamous as *"one of the most polluted in the Western world"*.[87]

This chapter uses the Manawatū to illustrate many of the aspects of water quality science discussed in this report. The effects of pollutants on water quality in this catchment are well understood after many years of research. The chapter begins with a description of the nature and history of the catchment, then covers the three main pollutants of pathogens, sediment, and nutrients. It ends by considering whether the river deserves its 'shameful' reputation.

8.1 The catchment of the Manawatū

The Manawatū River is the only river that carves its way from one side of New Zealand's mountainous spine to the other. The upper river forms in the east of the lower North Island, but instead of heading to the Pacific Ocean, it punches through the main divide at the Manawatū Gorge and heads west to the Tasman Sea. About 5 percent of the North Island lies in the Manawatū catchment.

The nature of the river changes as it flows down from the mountains to the sea. Headwater streams arise in native forest, and are small and fast flowing. They are well shaded with stony beds and a mix of waterfalls, rapids, and pools along their length. There are healthy populations of native fish and invertebrates, and low levels of water weeds and algae.

The river and its tributaries then flow through rolling hill country farmland dotted with small rural towns. Sheep and beef farms dominate, with some dairying and pine plantations. The river here is wider, slower, and less shaded than in the headwaters, and some of the land is steep with easily erodable soils.

In its lower reaches, from Palmerston North down, the river is unshaded and shallow, and winds slowly along a meandering course. Extensive engineering works have drained wetlands and penned the river in behind stopbanks. Little native vegetation remains in the lower catchment; the land has been converted to agriculture, including dairying, sheep and beef farming, cropping, and market gardening.

A large shallow estuary at the river mouth near Foxton is home to thousands of migratory birds in the summer and is recognised as an internationally important wetland.[88] The shallow mudflats develop nuisance seaweed growths when nutrient levels are high.[89]

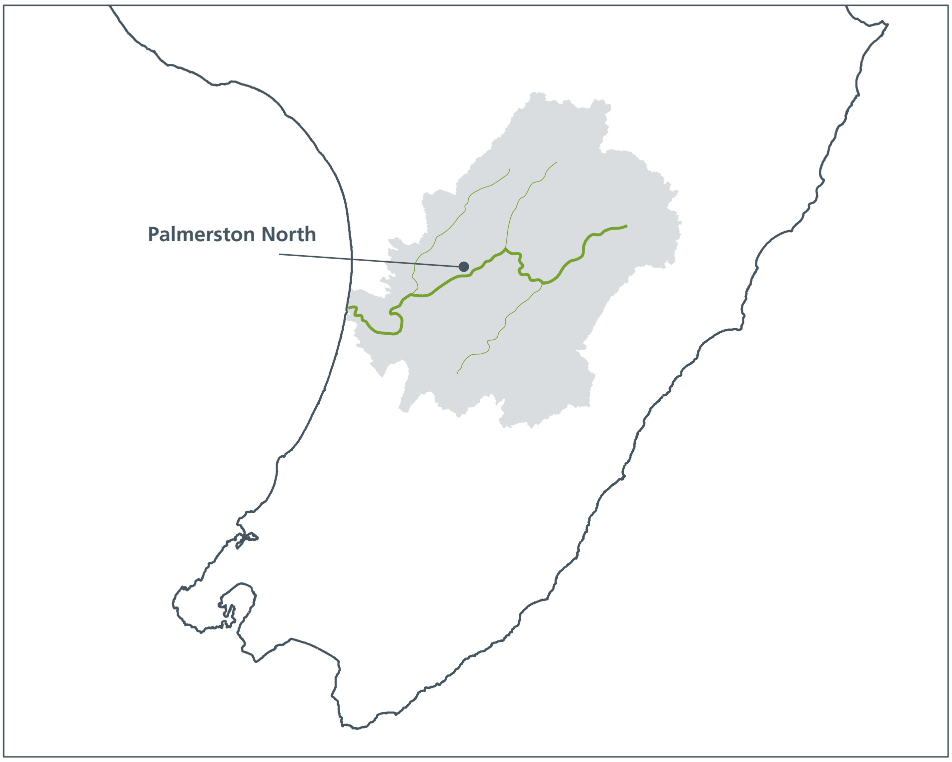


Figure 8.1: The Manawatū River catchment.

8.2 Water quality in the past

The first European settlers arrived on the lower river in the mid-1800s. From as early as the 1850s, they began to convert the catchment into sheep farms, first along the river itself and then across the wider catchment. Over time, virtually all of the wetlands were drained. Around 80 percent of the original forests were felled, exposing the highly erodable hill soils and letting sunlight into streams and rivers. By the early 1900s, sediment building up in the Foxton estuary had made the river unnavigable.[90]

Late in the nineteenth century, towns and factories sprang up along the river and its tributaries, using water as a convenient way to get rid of wastes. Flax milling became a major industry around Foxton and Opiki.

For many years 'gross' pollution such as fat, blood, wool, and raw sewage entered the river from numerous freezing works and towns. Downstream, mats of 'sewage fungus' – growths of algae and bacteria – often formed, depleting dissolved oxygen and occasionally killing large numbers of trout. In the 1970s and 1980s this 'sewage fungus' spurred successful efforts to treat raw sewage, dairy shed effluent, and other organic wastes.

> *Half a mile below the freezing works the water (at low flow) was very turbid and yellow coloured. There was a very strong smell and pieces of fat were seen on the water surface…The riverbed stones had a thick covering of sewage fungus.*[91]

Source: Louis John Daroux Collection, Alexander Turnbull Library, Wellington

Figure 8.2: Flax harvesting on the Manawatū River, circa 1900-1910. 'Retting', the waste from flax mills, was rotten, acidic, very smelly, and poisonous to fish.[92]

8.3 Water quality today

> *It's not the dairy farmers, Palmerston North city, Horowhenua district or the industrial users, it's a combination of those compounding on top of each other.*[93]

The Manawatū River faces a number of water quality challenges today. The legacy of the past, combined with today's pollutants, interplay with the various natural vulnerabilities of the catchment. In some places and at some times, indicators show water quality can be particularly poor.[94]

All three key pollutants, from many sources, contribute to the situation. This section looks at pathogens, sediment, and nutrients in turn, describing where they come from, their effects in vulnerable parts of the river, and some of the actions being taken to reduce them.

Source: Horizons Regional Council

Figure 8.3: In the Manawatū Gorge the river is fast, deep, and shaded, making it less vulnerable to algae.

Pathogens

Levels of pathogens in parts of the catchment often exceed standards for swimming and drinking.

In large part this is due to rain washing manure into the river, while in many places animals are still able to defecate directly into the water. This is changing: more than a quarter of dairy farms in the wider Manawatū-Wanganui region have completely fenced off their waterways.[95] Virtually all the catchment's dairy farms now dispose of shed effluent onto land.[96] All these changes require investment of money and time.

In some small towns, sewage treatment plants lack disinfection systems and are significant sources of pathogens. Some towns have upgraded their sewage systems in recent years at substantial cost.

Sediment

In an average year, nearly 4 million tonnes of soil and rock is lost off land and washes down the Manawatū.[97]

Murky water and sediment blanketing the riverbed deprives plants, invertebrates, and fish of their habitat. As a result, native fish such as kōaro, banded kōkopu, and redfin bully are missing from high-erosion parts of the catchment where they would otherwise be expected to occur.[98]

Steep hill country farmland is the major source: two thirds of all the sediment in the river system comes from the cleared hills east of the Manawatū Gorge.[99] Increasingly, farms on vulnerable land have developed 'whole farm plans' to reduce accelerated erosion, and consequently reduce the amount of phosphorus bound to sediment that enters the rivers of the catchment.[100]

Source: GNS Science

Figure 8.4: Silt-laden floodwaters of the Pohangina River destroy a bridge and drown surrounding farmland, 2004. Sediment also increases the damage done by flooding. In the lower Manawatū and its tributary the Ōroua, sediment deposits are raising the level of the channel, reducing the ability of the rivers to deal with the next high flow.

Nutrients

Many parts of the Manawatū River suffer from excessively high levels of nitrogen and phosphorus. In summer, black, slimy mats of cyanobacteria are common in many tributaries and the main river from Dannevirke to Palmerston North. Sometimes these growths produce algae toxins, making the water dangerous for swimming and fishing.[101] High nutrient levels have also led to many streams being choked with weeds.[102]

Algae growths reduce habitat for fish and invertebrates, and can cause severe oxygen depletion. Dissolved oxygen at levels less than 40 percent of what a healthy river would contain have been recorded in the Manawatū River – low enough to kill aquatic life.[103]

End-of-pipe sources of nutrients in the catchment include 18 sewage treatment plant discharges, two dairy factories, a freezing works, a fellmongery, and a brewery.[104]

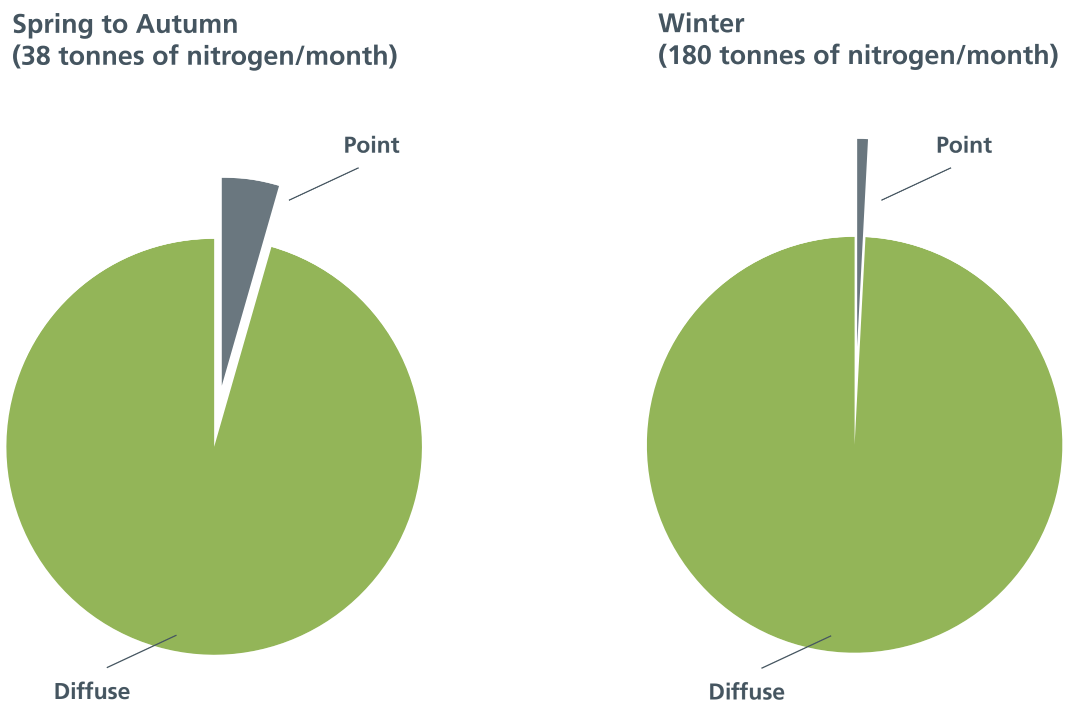
Diffuse sources of nitrogen are dominated by leaching and runoff of urine, manure, and fertiliser from sheep/beef and dairy farmland. Dairy farmers report that almost all their farms now have nutrient budgets, and increasingly many have nutrient management plans.[105]

For phosphorus, diffuse sources include soil erosion from hill country sheep and beef farms, and run-off from lower catchment farms.

Box 8.1: Is nitrogen or phosphorus the limiting nutrient in the Manawatū catchment?

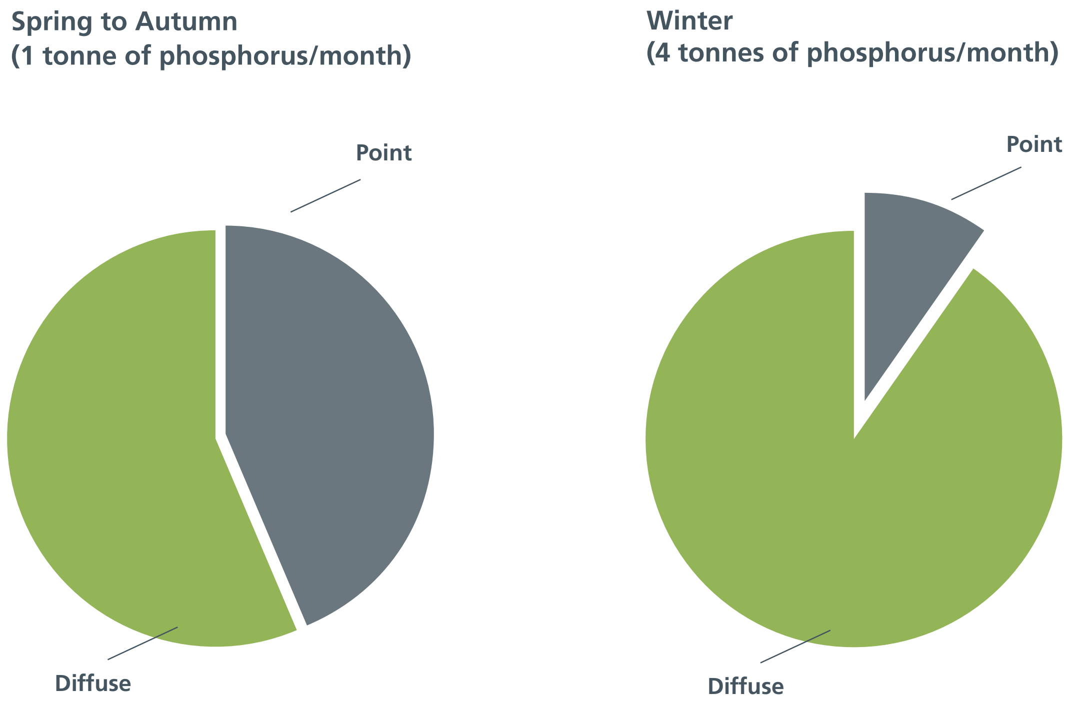
There is no definitive answer to this question. In the same location, the relative amounts of nitrogen and phosphorus can change substantially over the course of a day. At a time when a lack of phosphorus appears to be the factor controlling algae growth in the Mangatainoka, a lack of nitrogen may be limiting algae growth in the upper Manawatū or the Foxton estuary. Frequently, nutrients are not limiting algae growth at all. Under these conditions the only thing preventing accumulation of algae mats may be periodic floods that scour them away.[106]

Figure 8.5: Sources of nitrogen in the Upper Manawatū River at different times of the year.[107]



Diffuse sources of nitrogen – particularly nitrogen leached from animal urine – are the most important sources of nitrogen into the Upper Manawatū River throughout the year. Much more nitrogen is lost in winter because grass is not growing and taking up nitrogen, and there is more rain to wash nitrogen into the river.

Figure 8.6: Sources of phosphorus in the Upper Manawatū River at different times of the year.[108]



Point sources of phosphorus in the Upper Manawatū River are very significant for a good portion of the year; about half the phosphorus entering the river from spring to autumn comes from point sources. While amounts of phosphorus from point sources remain fairly constant throughout the year, in winter rain washes more soil and manure containing phosphorus into the river.

8.4 The worst river in the Western world?

The study that sparked recent headlines found that sometimes parts of the Manawatū River were in exceptionally poor condition. In that study, a relatively new indicator of water quality was calculated using samples from different parts of the river over a two-year period. This indicator used changes in the dissolved oxygen concentration over 24 hours to measure the rate of photosynthesis from unwanted plant and algae growth.

Although a high level of dissolved oxygen is an indicator of good water quality, an extremely high level caused by rapidly growing weeds and algae is an indicator of poor water quality. As described in Chapter 5, a very high oxygen concentration driven by photosynthesis during daylight will plunge to a very low level at night, threatening fish and other creatures that rely on oxygen.[109]

The highest measurement of photosynthesis from unwanted plant and algae growth in the study was 107 in a sample taken from the river north of the Manawatū Gorge.[110] The following night, dissolved oxygen levels at the site dropped to below half that of a healthy river as plant and animal respiration used oxygen up.[111]

The photosynthesis measure was compared with samples from 295 other rivers – 145 in New Zealand and 150 in other countries. The next highest measurement of 59 was from an urban stream in Germany.[112] Any reading above 7 is considered to indicate a river in 'poor' condition, with excess levels of nutrients and plant growth.[113]

But at other times the same site on the Manawatū was in a healthy state, with normal levels of nutrients, photosynthesis and dissolved oxygen; and other sites on the river never reached 'poor' condition. This is to be expected; plant and algae growth changes throughout the year and between years, responding to changes in flow conditions, light and warmth, and nutrient inputs.

Do these results mean that the Manawatū River is the worst in the western world? Dr Roger Young from the Cawthron Institute, the scientist who led the development of the method, summed up the findings this way:

> *Measurements of [photosynthesis and respiration] from the lower Manawatu are higher than has been seen in any other sites around the world where this measurement has been conducted. However, only a tiny fraction of the world's rivers have been tested using this approach and it is likely that other rivers would have higher measurements if they were tested. [The Cawthron Institute's] research DOES NOT indicate that the Manawatu River is the worst in the western world. Nevertheless, our results do indicate that the Manawatu River is very unhealthy. Other indicators of river health such as nutrient concentrations, water clarity, faecal bacteria and stream invertebrates also indicate the poor status of the Manawatu River.*[114]

Behind the headlines, the Horizons Regional Council has developed a new combined regional policy statement and plan – known as the 'One Plan' – to guide the management of the catchment and improve water quality. And a wide range of community and industry interests have formed the Manawatū River Leaders' Forum with a common objective to *"improve the Manawatū River… such that it sustains fish species, and is suitable for contact recreation…"*[115]

In conclusion

Water quality is far from a new problem in New Zealand, although its nature and extent have changed over the years. Since the arrival of Europeans, economic activities and pressure from settlement on land have had a variety of impacts on the quality of the water in our rivers and streams, lakes, wetlands, estuaries, and aquifers.

9.1 Revisiting the three big pollutants

The three major types of pollutants that are of current concern are pathogens, sediment, and nutrients.

Pathogens – invisible microbes that affect the health of people and animals – are obviously pollutants. The public are particularly aware of water-borne pathogens in summer when river flows are low and the public are warned against swimming and fishing in some places. However, they cause relatively little damage to the natural environment.

Sediment is very different. It is only a pollutant by virtue of where it is – in water rather than on land. The main source of sediment – erosion – is a natural process; indeed erosion has shaped the landscape of New Zealand over millennia. But the loss of forests and other vegetation that held soil on land has led to an acceleration of this natural process – geology 'on speed'. Despite this speeding up in geological time, sediment builds up very slowly in human time, and because of this goes largely unnoticed. Who can remember when muddy streams ran clean and clear over stones?

During the twentieth century, New Zealanders became well aware of the loss of soil due to erosion and the damage done by flooding rivers. The country's 'water managers' – the catchment boards – were responsible for managing water and soil, but not pathogens or nutrients. Two aspects of the erosion-sediment problem were not widely appreciated at that time. One was the damage done to aquatic life in the rivers by sediment destroying the habitat of fish and other creatures. The other was that the sediment was carrying phosphorus into the water.

Nutrients are the focus of most concern today. The rapid growth of unwanted algae and water weeds is tangible evidence of a problem. To attribute this problem entirely to dairying is unfair and inaccurate. There are two nutrients that collectively cause the problem – nitrogen and phosphorus. The largest source of nitrogen is urine from livestock; but the largest source of phosphorus is the sediment from ongoing erosion – a legacy of forest clearance and topdressing.

The two nutrients get into water by largely different routes. Nitrogen occurs in forms that are highly soluble in water and so can travel via groundwater as well as across surfaces. This makes it particularly elusive – preventing it getting into water is a major challenge. Most phosphorus, on the other hand, gets into water with soil and if the soil can be stopped from getting into water, so will the phosphorus. Once in water, however, much of the phosphorus is locked up in sediment and can be there for a very long time.

Excess nutrients can have dramatic effects on water bodies. Nitrogen and phosphorus stimulate plant growth, leading to algal blooms (sometimes toxic), oxygen depletion, and ecological damage. Ammonia can kill fish, and elevated nitrate levels can make aquifers undrinkable.

9.2 Vulnerability matters

It is not only the characteristics of the pollutants which are important when considering the factors which influence water quality. The vulnerability – the natural characteristics of the water body where the pollutants end up – has a great influence on the impact of the pollutants.

Thus lakes, rivers and streams, wetlands, estuaries, and aquifers are all different in terms of vulnerability. Lakes are generally more vulnerable than rivers because they accumulate pollutants, and small shallow warm lakes are particularly vulnerable. The most important factor determining the vulnerability of a river or stream is its ‘flow regime’ – how much water there is, how fast it moves, and how its flow fluctuates.

Lowland wetlands have some resilience as they are naturally attuned to higher nutrient levels, but can ‘flip’ into a degraded state. Estuaries are prone to sedimentation. Once nitrate gets into an aquifer, it will stay there for a very long time.

Scaling up to the larger level, some catchments are naturally more vulnerable than others. Factors such as topography and soil type influence how sensitive a catchment is to water pollution. And within a catchment the lakes, rivers, streams, wetlands, estuaries, and aquifers are all linked, and so is the water quality. Consequently, water quality is usually best understood at the catchment level.

9.3 Protecting and improving water quality

There is a large menu of interventions that will help protect and improve water quality, but there is no magic bullet.

Pollutants that come from end-of-pipe sources are generally the easiest to reduce, though still require considerable investment of money and time. Over the years, there have been great advances in reducing end-of-pipe pollution from industry, from towns and cities, and from farms.

Diffuse sources of pollutants are much more difficult to control.

Sediment carrying phosphorus continues to get into water in many parts of the country. Significantly slowing the widespread erosion – much of it originating in the historic clearance of forest on marginal land – would require the strategic planting of many millions of trees.

Ways of reducing nutrients from animal effluent finding their way into water are exercising the minds of many scientists. Bridging stream crossings, fencing streams, and planting riparian strips are all well-established methods that make a difference. Keeping stock off waterlogged paddocks in cold wet months is key, because only actively growing grass will take up nutrients.

Once pollutants are trapped in water bodies, options for getting them out are very limited and likely to be very expensive.

9.4 Thinking through water quality problems

Water quality science is complex and often confusing. This final section of the report presents a way of thinking through the science of water quality problems. It involves working through a set of four inter-related questions:

- What are the pollutants?
- How do the pollutants get into water?
- Where do the pollutants end up?
- What can be done about it?

These questions are listed in Box 9.1 below along with some detailed questions to provide more guidance.

Box 9.1: Thinking through the science of water quality problems

What What are the pollutants?	Pathogens? Sediment? Nutrients? Nitrogen or phosphorus or both?
How How do the pollutants get into the water?	What are the sources (end-of-pipe or diffuse) and their relative importance? By what routes do they get from their sources to the water?
Where Where do the pollutants end up?	River or stream, lake, wetland, estuary, aquifer? How does the water body relate to the rest of the catchment? What are the factors that make the water more or less vulnerable to the impacts of the pollutants? Do some of these factors depend on the time of the year?
Interventions What can be done about it?	Can the pollutants be reduced at their sources? Can the routes by which they get into water be blocked? What are the most effective options?

This approach can also be represented in the diagram shown in Figure 9.1.

Figure 9.1: Thinking through the science of water quality problems.

9.5 Illustrating the approach

This four-question approach can be readily illustrated with a hypothetical example.

Imagine a river flowing through hill country out into flatter plains. The river has long been a favourite destination for swimming, fishing and boating, but now slimy trailing mats of periphyton carpet the rocks in summer. So what is causing this and what can be done about it?

What are the pollutants?

The periphyton growth is fuelled by excess nitrogen and phosphorus. Testing samples of water shows that phosphorus is the limiting nutrient, meaning that reducing phosphorus inputs should reduce the growth of periphyton.

How do the pollutants get into the water?

The higher steeper parts of the catchment are scarred with erosion – a consequence of burning forest to create pasture for sheep in the 1920s. Sediment has settled (and continues to settle) in some of the river bends, and over time some of the phosphorus it contains dissolves out and becomes available for plant growth.

Upstream of some of the swimming spots is a pipe discharging wastewater from a town treatment plant.

There are several dairy farms above the swimming spots. All are spraying their shed effluent onto land, though doing it under the right conditions is sometimes a challenge. In a few places, stock have direct access to water and heavy rainfall sometimes washes manure into the river and its tributaries.

Where do the pollutants end up?

The obvious answer is in the river, but this question is aimed at thinking about how vulnerable the river is.

The river is fairly wide and unshaded. In places, particularly above large flat rocks on the riverbed, it is shallow and relatively warm. In winter, high flows from winter storms scour the periphyton off the rocks and wash some of the sediment downstream. But in summer, the volume of water in the river falls, the flow rate slows, and the periphyton returns.

Interventions?

What can be done about the causes of this water quality problem?

Erodible land in the hills can be planted – most effectively with poplars that will grow from poles hammered into the ground and develop extensive root systems that will hold soil. The clearance of any remaining native vegetation in gullies should cease.

One option for the town wastewater is building bigger storage tanks and not discharging into the river when flows are low. Another is spraying the wastewater onto land possibly fertilising a forest.

Stock should be restricted from direct access to water though this is much more important for cattle than sheep. Because the limiting nutrient is phosphorus, relatively simple riparian strips of an area of rank grass between an electric fence and the river should have a significant effect.

The relative size of the different sources of phosphorus and the effectiveness of the different interventions need to be key considerations.

9.6 A final comment

The questions listed above are questions of science. After these come the 'decision-making' questions – the 'what should we do' questions. They are beyond the scope of this report. But without first understanding the cause-effect relationships uncovered by scientists, we cannot make sensible decisions about what to do.

The first chapter of this report begins with a description of fresh water in New Zealand as it once was. Clear clean cool streams full of life flowing through forests still exist in remote parts of the country. It is not realistic to return all our fresh water to this pristine state. But nor can we afford not to act. The quality of our fresh water is one of the biggest environmental challenges that we face in this clean green country of ours.

Glossary

Many of the definitions in this Glossary have been adapted from those given in Harding et al., 2004.

Aerobic	A condition of water where the oxygen level is high enough to support oxygen-using bacteria.
Algae	A class of simple aquatic plants, including microscopic species known as *periphyton* and *phytoplankton*. Larger algae like seaweeds and charophytes are known as *macrophytes*. Almost all algae can use *photosynthesis* but are dependent on *nutrients* including *nitrogen* and *phosphorus*.
Algal bloom	Dense growths of microscopic *algae* or *cyanobacteria* in response to high nutrient levels and warm temperatures. Often makes water discoloured and *turbid*, sometimes including scum on the surface of the water.
Ammonia	A highly soluble *nitrogen* compound, chemical formula NH_3, characteristically found in manure, sewage and *anaerobic* conditions.
Anaerobic	A condition of water where the oxygen level is too low to support any kind of oxygen-breathing life.
Anoxic	Without any oxygen.
Aquifer	A geological layer of sand, gravel, or fractured rock that contains groundwater. Confined aquifers are underneath impermeable layers of silt or clay (aquitards) so they do not receive water and dissolved pollutants from land directly overlying them. Unconfined aquifers lack aquitards, so pollutants can leach directly into them.
Benthic	Living on the bottom of a water body.
Biochemical oxygen demand (BOD)	The amount of dissolved oxygen needed by micro-organisms to break down organic matter in the water. It is a measure of organic pollution, usually from wastewater.
Blue-green algae	See *Cyanobacteria.*

Campylobacter	A type of bacteria living in the guts of humans and animals, which may cause gastroenteritis.
Catchment	A catchment is the area of land feeding a river system. All the *precipitation* within the catchment combines and flows down to form a single interconnected network of water bodies, including streams, rivers, lakes, wetlands, and *aquifers*.
Chlorophyll	A pigment used by plants, *algae,* and *cyanobacteria* to harvest energy from light as part of photosynthesis.
Cryptosporidium	A type of *protozoan* pathogen, living in the guts of humans and animals.
Cyanobacteria	A group of bacteria that can use *photosynthesis*, like true *algae*. Some species are *periphyton* and others are *phytoplankton*. Unlike freshwater *algae*, some species of cyanobacteria produce toxins and some are able to extract *nitrogen* directly from the air.
Denitrification	A bacterial process removing *nitrate* from soil, air, or water, requiring *anaerobic* conditions and usually forming *nitrogen* gas.
Deposited sediment	Layers of fine sand, silt, and clay that have settled on the bottom of a waterway.
Diffuse source pollutants	Pollutants that do not come from a single *end-of-pipe* source, but from many small sources or from a wide area of *leaching, runoff*, erosion, etc.
End-of-pipe pollutants	Pollutants from local, stationary sources such as factories or mines, which discharge wastewater through pipes or channels.
Escherichia coli (*abbr.* E. coli)	A type of bacteria that live in the guts of humans and other animals. Although usually harmless themselves, high levels of *E. coli* indicate that other pathogens are present.
Flow regime	Typical behaviour of a stream or river, including how much water it carries, how fast it flows, how often it floods, and how big its flood peaks are.
Gastroenteritis	General term for gut disease involving inflammation of the stomach and intestines.

Giardia	A type of *protozoan* pathogen, living in the guts of humans and animals. Notoriously associated with trampers and possums, occasionally found in poorly treated drinking water supplies.
Hypoxic	Of water with low levels of oxygen, low enough to kill fish.
Invertebrates	Types of animals without a backbone, such as insects, worms, and snails.
Leaching	Process by which pollutants in and on soil are dissolved by rain or irrigation water and carried down into groundwater.
Leptospirosis	An infectious bacterial disease of rats, dogs, pigs, and other animals, which can be transmitted to humans.
Macrophytes	Large water plants and *algae* that are visible to the naked eye, as opposed to the microscopic periphyton and phytoplankton.
Mole-and-tile drainage	Drainage systems to remove excess water from heavy clay soils, formed by tunnelling through the soil (mole drains) or by laying down pipework (tile drains).
Nitrate	A highly soluble compound of *nitrogen* and oxygen with the chemical formula NO_3^-.
Nitrification	A process, usually bacterial, forming *nitrate* from other forms of nitrogen.
Nitrogen	A chemical element, symbol N. Common forms of nitrogen in water include *ammonia* and *nitrate*. 'Nitrogen gas' N_2 also makes up about 78 percent of the Earth's atmosphere. All life needs nitrogen for molecules such as proteins and DNA.
Non-point source pollution	*Diffuse* source pollution.
NTU	'Nephelometric turbidity units'; arbitrary units in which *turbidity* is measured.
Nutrient	A substance, element or compound that organisms need to live and grow.
Nutrient budget	A calculation comparing nutrients brought onto a farm in fertiliser, feed, and new stock, with nutrients lost in produce, leaching, runoff, and into the atmosphere as gas.

Nutrient management plan	A written plan that documents how the major plant nutrients on a farm will be managed to maximise production or productivity while minimising any adverse effects.
Organic matter	Any solid, liquid, or gaseous substance that contains carbon. It is generally taken to mean substances that have been produced by a plant or animal.
Pathogens	Disease-causing micro-organisms, including many bacteria, *protozoa*, and viruses.
Periphyton	Microscopic *algae, cyanobacteria*, and bacteria living in fresh water but attached to objects such as submerged rocks, wood, or *macrophytes*.
Phosphorus	A chemical element, symbol P. The most common form of phosphorus is (ortho)phosphate PO_4^{3-}, which is only slightly soluble in water. Phosphates are constituents of bone and of molecules like DNA.
Photosynthesis	A biochemical process by which green plants and some other organisms use sunlight to help them make *organic matter* from carbon dioxide gas. Photosynthesis generally involves the green pigment *chlorophyll*. Oxygen is generated as a by-product.
Phytoplankton	Microscopic *algae* and *cyanobacteria* drifting or floating in water.
Plankton	Organisms drifting or floating in water, including some *algae*, some *cyanobacteria*, waterborne *pathogens,* and microscopic *invertebrates*.
Point source pollution	*End-of-pipe* pollution.
Precipitation	Water deposited on the ground; dew, rain, snow, etc.
Protozoa	A class of simple, one-celled micro-organisms that do not *photosynthesize*, instead preying on bacteria, algae and other microscopic organisms. They include pathogens like *Giardia* and *Cryptosporidia.*
Respiration	The process whereby animals, plants, algae, and some bacteria use oxygen to break down carbohydrates to generate energy. Respiration reduces dissolved oxygen.

Riparian	Relating to the banks of a river or wetland; a riparian strip is a buffer zone covered with plants and trees between surrounding land and a waterway.
Run-off	Water moving overland, carrying fine *sediment* and dissolved pollutants.
Salmonella	A family of bacterial pathogens that live in the guts of humans and other animals. In humans they can cause diarrhoea and vomiting; in cattle and sheep the symptoms are similar but often fatal.
Sediment	Material transported by the water. Sediment is generally inorganic material, but can include organic material such as plant fragments, and dead algae.
Sedimentation	Settling or depositing of sediment within waterways.
Sewage fungus	A form of *periphyton* made up of masses of bacteria, growing in water polluted by *organic matter.*
Stand-off pad	A specially designed area that cows can be moved to during wet periods to prevent them damaging wet or waterlogged soils.
Stratification	Formation of two distinct layers within a lake over summer; a bright, warm upper layer or 'epilimnion' and a denser, cooler lower layer or 'hypolimnion'.
Suspended sediment	Particles of silt, clay, or *organic matter* floating in water.
Trophic level, TLI	[See Box G.1 below]
Turbidity	Murkiness or cloudiness of water due to *suspended sediment* and/or other material, including *phytoplankton.*
Typhoid	A disease affecting people only, caused by the bacteria *Salmonella enterica* Typhi, transmitted in food or water. Typhoid causes fever, *gastroenteritis,* and potentially death.

Washload	*Suspended sediment* carried by a stream or river.
Watershed	The boundary dividing one *catchment* from its neighbours.
Wintering barn	A wintering barn is a covered area in which cows can be kept during colder and wetter parts of the year. The cows can be fed and housed in the barn – and their effluent collected, but they are also free to move out onto pasture to feed.

Box G.1 The trophic level of a lake or river describes the amount of biological activity (productivity), such as plant growth, that is happening in the water. The trophic level can be measured using the TLI, which combines information on the clarity of the lake and the amounts of nitrogen, phosphorus, and chlorophyll (and thus plant growth) in the lake.

Increasing degree of *eutrophication* ↓

Trophic Level	TLI	Lake condition
Microtrophic	1	Clear, very low in nutrients, very slow-growing plants, few algae.
Oligotrophic	2	Low in nutrients, usually clear and blue, slow plant growth, may support periphyton.
Mesotrophic	3	Moderately clear and with moderate nutrient levels, usually blue-green, supporting plant growth, typically macrophytes.
Eutrophic	4	Increasingly green and turbid, with high nutrient levels supporting rapid macrophyte or phytoplankton growth that sometimes leads to oxygen depletion.
Supertrophic	5	Very high nutrient levels, usually with poor water clarity, often with severe oxygen depletion, probably no macrophytes, may be dominated by bacteria.

Notes

1 Morgan, 2011a.
2 See for example Whanganui Iwi and The Crown, 2011.
3 McWethy et al., 2010.
4 Otago Daily Times, 1862, p.4.
5 Dann, 2010.
6 New Zealand Herald, 1870.
7 By 1910, parts of the river were no longer deep enough for boats to navigate, and adjacent farms were regularly flooded; Allibone et al., 2001.
8 Acid mine drainage occurs when sulphur-containing minerals are exposed to air and rain, which converts them to sulphuric acid. Some coal seams have a high sulphur content, as do some metal-rich ores.
9 Hauraki District Council, 1997.
10 The three bills were 1912, 1937, and 1949. The Pollution Advisory Council was subsequently renamed the Water Pollution Control Council. The functions of this council were taken over by the Water Resources Council in 1972, and then by the National Water and Soil Conservation Authority in 1983.
11 Legumes are a large family of plants – including clover, peas, lucerne and gorse – that effectively make their own fertiliser; special colonies of bacteria in their roots ‘fix’ nitrogen directly from the air. However, legumes do not fix nitrogen if there is already a good source of available nitrogen in the soil, such as urea fertiliser.
12 Along with the increased use of supplementary feeds such as maize.
13 The 2003 upgrade of Auckland’s Māngere Wastewater Treatment Plant alone cost some $460 million; Fitzmaurice, 2009.
14 Half the Rotorua Lakes Restoration Fund is from local government and half from central government. Fifty-five percent of the Lake Taupō Protection Fund is from central government and 45 percent from central government. All of the Waikato River clean up fund is from central government as part of the Waikato River deed of settlement between the Crown and Waikato-Tainui.
15 Land and Water Forum, 2010.
16 Ball, 2007.
17 Till et al., 2008.
18 Davies-Colley et al., 2004. Similarly, wallowing by deer in streams increases levels of pathogens – and sediment – in the water, and levels of pathogens can increase 10-fold downstream of deer farms; Collins et al., 2007.
19 Spurr and Coleman, 2005; Moriarty and Gilpin, 2009.
20 Otago Polytechnic, 2002.
21 Toi Te Ora, 2011; Scholes et al., 2009.
22 Clark et al., 2004; Teague, 2011.
23 OSH, 2001.
24 Some strains of *E. coli* can cause serious disease. These are called verotoxic strains. In 2011, 42 people died in a foodborne outbreak of verotoxic *E. coli* in Germany.
25 *Enteroccocus* is another gut bacterium that is used similarly to *E. coli* as an indicator of health risk in salt water, and has been used as an indicator of fresh water quality in the past.
26 Grossman, 1909, p. 7.
27 Although most of New Zealand’s lakes, rivers, and streams naturally have high water clarity, there are exceptions to this. For example, many streams on the South Island’s West Coast are naturally stained brown with tannins.

28 Larger particles of sediment are so big and heavy that even fast rivers cannot lift them up; they tend to roll along the bottom, from which they get the name 'bedload'. These gravels and boulders have relatively little impact on water quality.

29 Nonetheless, exceptional storms (like Cyclone Bola) may cause substantial erosion irrespective of forest cover, because of New Zealand's steep topography.

30 Hicks et al., 2004; Blaschke et al., 2008.

31 Around 70 percent of the sediment that comes from a plantation forest is produced over the harvest phase. Hicks et al., 2004.

32 New Zealand's rates of sediment loss are disproportionately high internationally. We produce 1 percent of the world's sediment inputs to the ocean, despite having less than 0.2 percent of the land area. Hicks et al., 2004.

33 In large amounts, suspended sediment can be enough to kill fish outright. Rowe et al., 2002.

34 This area – known as the hyporheic zone – is the interface between the surface water in a river or lake, and the deeper groundwater beneath. Many bacteria, invertebrates, and fish make use of the hyporheic zone.

35 This occurs because salt causes the sediment particles to clump together. Because the sediment particles are bigger, they sink faster, which leads to faster sedimentation.

36 Morrison et al., 2009.

37 Lawrie, 2006; Hume et al., 2010.

38 Blaschke et al., 2008.

39 Turbidity in rivers generally ranges from 2–50 NTU but can be in the thousands during floods. Suggested guideline levels are 4.1 NTU for upland rivers and 5.6 NTU for lowland rivers. Lakes and estuaries are generally less turbid than rivers. See ANZECC, 2000.

40 The element needed in the greatest amount by plants is carbon, but plants obtain this from carbon dioxide in the air during photosynthesis.

41 Plants require trace amounts of numerous other nutrients as well, but in New Zealand waters these are generally in concentrations that do not limit plant growth.

42 Nitrate is NO_3^- and phosphate is PO_4^{3-}. Ammonia is NH_3, but when dissolved in water partly becomes ammonium NH_4^+. Another chemical form of nitrogen that is important environmentally is the potent greenhouse gas nitrous oxide (N_2O).

43 In most soils, metal ions including iron, aluminium, calcium, and magnesium bind tightly to phosphate. If there is more phosphate than these metal ions can hold, the excess is lost to water. Additionally, in the absence of oxygen, iron minerals in soils and sediments undergo chemical changes which mean they can no longer hold phosphate. See Cuttle, 2008 for a fuller discussion.
This is why phosphorus is released from sediments on the bottom of a stratified lake when it runs out of oxygen.

44 Urine patches have long been understood to be the major route for nitrogen loss from pasture – for example Wilcock, 1986; Ledgard, 2009.
At a national level, pasture is the principal source of nitrogen to water; see Elliott et al. 2005, Parfitt et al. 2008, Unwin et al. 2010, Abell et al. 2011.

45 The risk of nitrogen runoff from applying too much fertiliser is greatest in intensive horticulture and when growing winter forage crops. Menneer et al., 2004; Clothier et al., 2007; Monaghan et al., 2007.

46 At a national level, phosphorus entering water is largely due to erosion; see Elliott et al. 2005, Unwin et al. 2010.
During erosion, soil, manure and fertiliser particles containing phosphate, as well as dissolved phosphate, are carried by runoff into surface water. See Parfitt et al. 2007, Cuttle 2008, McDowell et al. 2008, Zarour 2009.

47 Hickey and Rutherford 1986; Elliott et al., 2005.

48 For example, decades of horticulture around Pukekohe has left levels of nitrate in some shallow groundwater in breach of the Drinking Water Standards – see Environment Waikato, 2008.

49 Hickey and Martin, 2009.

50 Biggs, 2000.

51 For instance, in shaded, stony streams, mosses and liverworts were predominant. Increases in sunlight and sediment mean exotic plants now dominate and are readily fueled by excess nutrients. De Winton and Schwartz, 2004; Collier and McColl, 1990.

52 A third type of periphyton, 'sewage sludge', is not a plant at all, but rather globs of bacteria fed by excess nutrients.

53 The prefix 'cyano' is derived from a Greek word meaning dark blue. However, cyanobacteria are not all 'blue-green'; different species are a range of different colours. Perhaps the best known cyanobacteria are the green *Spirulina*, used as a nutritional supplement.

54 These algal blooms in freshwater are generally cyanobacteria, unlike the 'red tide' blooms that can occur in the sea.

55 Gibbs, 2009; Wood et al., 2010.

56 Didymo is particularly invasive and can thrive even in low nutrient levels. Larned et al., 2007.

57 Turner et al., 2005.

58 Larned et al., 2011. Unless levels of both nutrients are very high, a nitrogen-to-phosphorus ratio of more than 15:1 over the long term indicates a lake or river is likely to be phosphorus-limited, while less than 7:1 indicates it is probably nitrogen-limited. However, different types of plants have different nutrient requirements.

59 For example, in the Waituna Lagoon; Robertson et al., 2011.

60 For example, in the Manawatū River; McArthur et al., 2010a.

61 Many species of cyanobacteria have a major advantage over true algae; they can obtain their nitrogen needs directly from the air, potentially allowing them to form algal blooms even in nitrogen-limited waters. Schallenberg, 2004.

62 In the absence of oxygen, iron minerals in sediments undergo chemical changes which mean they can no longer hold phosphate. Hamilton et al., 2004.

63 Water at different temperatures can hold different amounts of dissolved oxygen. Colder water can hold more oxygen than warmer water.

64 Wilcock et al., 2011.

65 Environment Waikato, 2005.

66 Biggs, 2000.

67 Horizons, 2003.

68 If there is no estuary to trap sediment, a river is free to carry its pollutant load out into coastal waters. Sheltered bays like the Firth of Thames can be badly affected by plumes of riverborne pollutants, which can coat the seabed with sediment, feed algal blooms, and spread microbes – see Hauraki Gulf Forum, 2011. Sometimes vulnerability lies beyond the river mouth.

69 Fitzmaurice, 2009.

70 Sometimes pathogens in an aquifer can cause problems. In Canterbury, the 70 metre deep 'town well' in Dunsandel has had to be treated since 2009 when it tested high for *E. coli*; Selwyn District Council, 2011.

71 Aquifers that are protected from surface waters by impermeable layers are known as *confined* aquifers, while ones that have permeable caps that water can pass through are termed *unconfined*.

72 Hamill, 2009.

73 Vant, 1999, 2011; Fonterra, pers. comm., 2011.

74 Water NZ, 2011, p.11. However, this report notes: "It is difficult to obtain information on the performance of wastewater services because it is not aggregated and published."
75 Fitzmaurice, 2009; Robinson, 2011.
76 Ryan, 1998.
77 However, dairy shed effluent is not a well balanced fertiliser, being very high in potassium. It is best used on a dedicated 'effluent block', supporting crops such as maize that need plenty of potassium.
78 Christensen et al., 2012.
79 Plants in a riparian strip will be more effective at taking up nutrients if they are growing rapidly. Cutting plants and trees back to keep them growing fast is one aspect of good management of riparian strips.
80 Wilcock, Monaghan et al., 2010.
81 Wilcock, Monaghan et al., 2010.
82 Nitrification inhibitors are more effective when soil temperatures are low. PGGRC, 2012 conclude "[Nitrification inhibitor] DCD application decreased N leaching from urine patches by around 40% and in grazed pasture by 21%." See also Clough et al., 2011.
83 Wilcock, Monaghan et al., 2010.
84 Shearman and Wilcock, 2011.
85 Environment Bay of Plenty, 2010.
86 New Zealand Waterways Restoration, 2012; see also Gear and Hofstra, 2011.
87 Morgan and Burns 2009.
88 The Manawatū estuary is one of six New Zealand wetlands protected under the international Ramsar Convention.
89 Zeldis, 2009.
90 Manawatu Estuary Trust, 2010.
91 'Pollution in the Manawatu and Oroua rivers', a Ministry of Works report cited in Gilliland, 2009.
92 Coard, 2010.
93 Greg Carlyon, former Regulatory Manager, Horizons Regional Council, quoted in Morgan, 2011b.
94 McArthur, 2009.
95 Sanson and Baxter, 2011.
96 However, there have been issues with effluent spreading operations that do not comply with consent conditions, or that do not have sufficient effluent storage capacity. See Russell, 2009.
97 Schierlitz et al., 2006.
98 Joy, 2009.
99 Manawatū River Leaders Accord, 2011.
100 Schierlitz et al., 2006.
101 Ausseil and Clark, 2007; Wood and Young, 2011.
102 McArthur et al., 2010b.
103 Young, 2010.
104 Manawatū River Leaders Accord, 2011. When the water warms up in summer and flow in the Manawatū is particularly low, Palmerston North treats its sewage discharge to remove phosphate, but the smaller towns do not currently have this tertiary treatment capability.
105 MAF, 2011.
106 McArthur et al., 2010a.

107 Inputs of nitrogen are expressed as tonnes of dissolved inorganic nitrogen (DIN) per month. Spring to autumn covers October to May, winter covers June to September. Average monthly inputs have been calculated by assuming inputs are constant over each time period. Data from Ledein et al., 2007.

108 Inputs of phosphorus are expressed as tonnes of dissolved reactive phosphorus (DRP) per month. Monthly inputs were calculated using the same method as for nitrogen. Data from Ledein et al., 2007.

109 How low dissolved oxygen levels drop in a river, and how long they stay low, are the critical factors determining invertebrate and fish survival. To kill fish, dissolved oxygen levels need to be very low (10-30%) for some time – generally a period of days; Landman et al., 2005.

110 The unit of measurement is grams of oxygen (O_2) per square metre per day.

111 The daily fluctuations in dissolved oxygen recorded in the Manawatū River as a result of photosynthesis and respiration are not likely to cause significant fish kills. Significant fish kills in the river in the past were the result of large point-source inputs of organic material that fuelled algal blooms and bacterial breakdown that dropped dissolved oxygen levels to low levels for long periods at a time.

112 Data from Young et al., 2008. A more recent literature search by the report's authors found an additional 277 sites where the method has been used. The levels of photosynthesis and respiration measured in the Manawatū are still the highest on record; Young, 2011.

113 Wilcock et al., 2011.

114 Young, 2011.

115 Manawatū River Leaders' Forum, 2011.

References

Abell, J.M. et al. 2011. Relationships between land use and nitrogen and phosphorus in New Zealand lakes. *Marine and Freshwater Research* 62: 162-175.

Allibone, R. et al. 2001. *Ecology of the Ohinemuri River: Historical changes and current status.* Report CFR00201/A to Ngāti Koi Trust. National Institute of Water and Atmospheric Research Ltd. (NIWA).

Australian and New Zealand Environment and Conservation Council (ANZECC). 2000. *Australian and New Zealand guidelines for marine and fresh water quality.* Canberra: ANZECC with ARMCANZ.

Ausseil, O. and Clark, M. 2007. *Recommended water quality standards for the Manawatū-Wanganui region: Technical report to support policy development.* Horizons Regional Council.

Ball, A. 2007. *Estimation of the burden of water-borne disease in New Zealand: Preliminary report.* Report by Institute of Environmental Science and Research Ltd. (ESR). Ministry of Health.

Biggs, B.J. 2000. *New Zealand periphyton guideline: Detecting, monitoring and managing enrichment of streams.* Report from NIWA. Ministry for the Environment (MfE).

Blaschke, P. et al. 2008. *Quantification of the flood and erosion reduction benefits, and costs, of climate change mitigation measures in New Zealand.* Blaschke and Rutherford Environmental Consultants. MfE.

Christensen, C.L. et al. 2012. *Three years of duration-controlled grazing: What have we found?* 25th annual Fertilizer and Lime Research Centre workshop, Massey University.

Clark, R.G. et al. 2004. Salmonella Brandenburg – Emergence of a new strain affecting stock and humans in the South Island of New Zealand. *New Zealand Veterinary Journal* 52(1): 26-36.

Clothier, B. et al. 2007. *Farm strategies for contaminant management*. Report to Horizons Regional Council. Sustainable Land Use Research Initiative, AgResearch.

Clough, T.J. et al. 2011. *Incorporation of the nitrification inhibitor DCD into New Zealand's 2009 national inventory.* Report by AgResearch. Ministry of Agriculture and Forestry (MAF).

Coard, P. 2010. *Foxton 1888–1988 – Flax town.* Horowhenua Library Trust. http://horowhenua.kete.net.nz/site/topics/show/2376-foxton-1888-1988-flax-town, dated 13 December 2010.

Collier, K.J. and McColl, R.B.S. 1990. Assessing the natural value of New Zealand rivers. *In:* P.J. Boon et al. (eds.) 1992, *River conservation and management*. Chichester, UK: Wiley: Chapter 13.

Collins, R. et al. 2007. Best management practices to mitigate faecal contamination by livestock of New Zealand waters. *New Zealand Journal of Agricultural Research* 50(2): 267-278.

Cuttle, S.P. 2008. Impacts of pastoral grazing on soil quality. *In:* R.W. McDowell (ed.), *Environmental impacts of pasture-based farming*. Wallingford, UK: CABI International: Chapter 2.

Dann, C. 2010. Sewage, water and waste – Dirt and disease. In: *Te Ara – The Encyclopedia of New Zealand*, http://www.teara.govt.nz/, dated 26 November 2010.

Davies-Colley R.J. et al. 2004. Water quality impact of a dairy cow herd crossing a stream. *New Zealand Journal of Marine and Freshwater Research* 38: 569-576.

De Winton, M. and Schwartz, A.-M. 2004. Littoral algal and macrophyte communities. *In:* Harding et al. 2004: Chapter 24.

Elliott, A.H. et al. 2005. Estimation of nutrient sources and transport for New Zealand using the hybrid mechanistic-statistical model SPARROW. *Journal of Hydrology (NZ)* 44(1): 1-27.

Environment Bay of Plenty. 2010. *State of the Rotorua/Te Arawa lakes 2009–2010*.

Environment Waikato. 2005. *Cattle die from drinking contaminated lake water.* 22 February 2005.

Environment Waikato. 2008. *The condition of rural water and soil in the Waikato region: Risks and opportunities*.

Fitzmaurice, J.R. 2009. *History of Auckland wastewater and Mangere wastewater treatment plant.* 3rd Australasian Engineering Heritage Conference, Dunedin, November 2009.

Gear, I. and Hofstra, D. 2011. *Assessment of the environmental effects: The efficiency of caged grass carp (Ctenopharyngodon idella) at removing the aquatic weed hornwort (Ceratophyllum demersum) in Lake Karapiro.* NIWA report HAM2011-104. MAF.

Gibbs, M.M. 2009. *Proposed One Plan – Section 42A report of Mr Max Martin Gibbs.* Horizons Regional Council.

Gilliland, B.W. 2009. *Proposed One Plan – Section 42A report of Mr Barry William Gilliland.* Horizons Regional Council.

Grossman, J.P. 1909. *The evils of deforestation*. Auckland: Brett Printing and Publishing Co.

Hamill, K. 2009. *Phosphorus and laundry detergent: A case to control at source (revised).* Presentation to Surface Water Information Group at MfE. Opus International Consultants.

Hamilton, D. et al. 2004. Physical and chemical characteristics of lake water. *In:* Harding et al. 2004: Chapter 21.

Harding, J. et al. (eds.) 2004. *Freshwaters of New Zealand*. New Zealand Hydrological Society Inc. and New Zealand Limnological Society Inc.

Hauraki District Council. 1997. *The operative District Plan of the Hauraki District Council.* p. 1.1.

Hauraki Gulf Forum. 2011. *State of our gulf: Tikapa Moana – Hauraki Gulf state of the environment report 2011*.

Hickey, C. and Martin, M. 2009. *A review of nitrate toxicity to freshwater aquatic species.* NIWA report HAM-2009-099. Environment Canterbury.

Hickey, C.W. and Rutherford, K.C. 1986. Agricultural point source discharges and their effect on rivers. *New Zealand Agricultural Science* 20(2): 104-110.

Hicks, M. et al. 2004. Stream sediment load and organic matter. *In:* Harding et al. 2004: Chapter 12.

Horizons. 2003. *Whanganui catchment strategy: Updated action plan September 2003.* Horizons Regional Council.

Hume, T.M. et al. 2010. *Tauranga Harbour sediment study: Assessment of predictions for management.* Report HAM2009-139 for Environment Bay of Plenty. NIWA.

Joy, M. 2009. *Proposed One Plan – Evidence of Dr Mike Joy.* On behalf of Fish and Game, and Forest and Bird: Horizons Regional Council.

Land and Water Forum. 2010. *Report of the Land and Water Forum: A fresh start for fresh water.*

Landman, M.J. et al. 2005. Relative sensitivities of common freshwater fish and invertebrates to acute hypoxia. *New Zealand Journal of Marine and Freshwater Research*, 39: 1061-1067.

Larned, S. et al. 2007. *Ecological studies of Didymosphenia geminata in New Zealand, 2006-2007*. Report CHC2007-070 for MAF Biodiversity New Zealand. NIWA.

Larned, S. et al. 2011. *Nutrient limitation in New Zealand lakes, rivers and estuaries.* Discussion paper prepared for Land and Water Forum.

Lawrie, A. 2006. *Tauranga Harbour integrated management strategy.* Environmental publication 2006/09. Environment Bay of Plenty.

Ledein, E. et al. 2007. *Identifying point source and non-point source contributions to nutrient loadings in water ways in three catchments in the Manawatū-Wanganui region: Technical report to support policy development.* Horizons Regional Council.

Ledgard, S.F. 2009. *Proposed One Plan – Section 42A report of Dr Stewart Francis Ledgard.* Horizons Regional Council.

MAF. 2011. *The dairying and clean streams accord: Snapshot of progress 2010/2011.*

Manawatu Estuary Trust 2010. *A history of the estuary and its surrounds*. http://www.massey.ac.nz/~grapson/metrust/history.php [Accessed 1 March 2012].

Manawatū River Leaders' Accord. 2011. *Ours: The Manawatū River Leaders Accord action plan.*

McArthur, K.J. 2009. *Proposed One Plan – Section 42A report of Mrs Kathryn Jane McArthur.* Horizons Regional Council.

McArthur, K.J. et al. 2010a. Understanding variations in the limiting nitrogen and phosphorus status of rivers in the Manawatu-Wanganui Region, New Zealand. *Journal of Hydrology (NZ)* 49(1): 15-33.

McArthur, K.J. et al. 2010b. *End of hearing report on behalf of Horizons Regional Council.* In the matter of hearings on submissions concerning the Proposed One Plan.

McDowell, R.W. et al. 2008. *A commentary on agricultural sources, transport and impact of phosphorus in surface waters: Knowledge gaps and frequently asked questions*. Report for unitary authorities. AgResearch.

McWethy, D.B. et al. 2010. Rapid landscape transformation in South Island, New Zealand, following initial Polynesian settlement. *Proceedings of the National Academy of Sciences* 107(50): 21343–21348.

Menneer, J.C. et al. 2004. *Land use impacts on nitrogen and phosphorus losses and management options for intervention.* Report from AgResearch. Bay of Plenty Regional Council.

Monaghan, R.M. et al. 2007. Linkages between land management activities and water quality in an intensively farmed catchment in southern New Zealand. *Agriculture, Ecosystems and Environment* 118: 211-222.

Morgan, J. 2011a. *It's time for some friendly persuasion.* Dominion Post: 14 July.

Morgan, J. 2011b. *River health waits on brave leaders.* Dominion Post: 20 October.

Morgan, J. and Burns, K. 2009. *Manawatu River among worst in the West.* Dominion Post: 26 November.

Moriarty, E. and Gilpin, B. 2009. *Faecal source tracking in the Avon River, Christchurch, March–May 2009.* ESR report R09/67. Environment Canterbury.

Morrison, M.A. et al. 2009. A review of land-based effects on coastal fisheries and supporting biodiversity in New Zealand. New Zealand aquatic environment and biodiversity report No. 37, NIWA. Ministry of Fisheries.

New Zealand Herald 1870. *Spectemur agendo*. Editorial, March 16.

New Zealand Waterways Restoration Ltd. 2012. *Lake Omapere (Northland) restoration.* http://www.nzwaterways.com/Case-Studies/Lakes/Lake-Omapere/ [Accessed 21 February 2012].

Occupational Safety and Health Service (OSH). 2001. *Guidelines for the control of occupationally acquired leptospirosis*. Accident Compensation Corporation and Department of Labour.

Otago Daily Times. 1862. *Inveniam viam aut faciam*. June 9: p. 4.

Otago Polytechnic, 2002. Otago Polytechnic Water Assessors Course. Based on an article by A.L. Thorstensen in *New Zealand Local Government* magazine, February 1985.

Parfitt, R. et al. 2007. *Best practice phosphorus losses from agricultural land*. Report LC0708/012 for Horizons Regional Council. Landcare Research.

Parfitt, R. et al. 2008. Nitrogen inputs and outputs for New Zealand at national and regional scales: Past, present and future scenarios. *Journal of the Royal Society of New Zealand* 38(2): 71-87.

Pastoral Greenhouse Gas Research Consortium (PGGRC). 2012. *Trials show benefits of nitrification inhibitors across New Zealand.* 24 February.

Robertson, B. et al. 2011. *Interim recommendations to reduce the risk of Waituna Lagoon flipping to an algal-dominated state.* Lagoon Technical Group. Environment Southland.

Robinson, E. 2011. *Project Manukau and the Manukau Harbour.* Presentation for Watercare Services, Auckland, http://www.arc.govt.nz/ [Accessed November 2011].

Rowe, D.K. et al. 2002. *Lethal turbidity levels for common freshwater fish and invertebrates in Auckland streams.* Report ARC02283 to Auckland Regional Council. NIWA.

Russell, A.F. 2009. *Proposed One Plan – Section 42A report of Ms Alison Frances Russell.* Horizons Regional Council.

Ryan, P. 1998. *Effects of biologically active discharges into aquatic ecosystems: Review of treatment systems and standards.* Report by Ryan Environmental to Department of Conservation.

Sanson, R. and Baxter, W. 2011. *Stock exclusion survey.* Technical paper 2011/102 prepared by AsureQuality Ltd. MAF.

Schallenberg, M. 2004. Primary production in the open water. *In:* Harding *et al.* 2004: Chapter 22.

Schierlitz, C. et al. 2006. *Erosion/sedimentation in the Manawatū catchment associated with scenarios of whole farm plans.* Report 0607/028 for Horizons Regional Council. Landcare Research.

Scholes, P. et al. 2009. *Microbiological quality of shellfish in estuarine areas: Joint agency research report 2009.* Bay of Plenty Regional Council and others.

Selwyn District Council. 2011. *Dunsandel community water supply contamination*. Notices on http://www.selwyn.govt.nz/services/water-sewage/dunsandel-community-water-supply-contamination, updated 25 August 2011. [Accessed 6 March 2012.]

Shearman, D.W. and Wilcock, R.J. 2011. Water quality gains from riparian enhancement – Waiokura. *In:* L. Currie and C. Christensen (eds.), *Adding to the knowledge base for the nutrient manager*. Occasional report No. 24, Fertilizer and Lime Research Centre. Massey University.

Spurr, E.B. and Coleman, J.D. 2005. Review of Canada goose population trends, damage, and control in New Zealand. *Landcare Research Science Series No. 30*. Manaaki Whenua Press.

Teague, B. 2011. Salmonella typhimurium outbreaks in dairy herds. *Proceedings of the Society of Dairy Cattle Veterinarians of the New Zealand Veterinary Association Annual Conference*: 7.19.1–7.19.6.

Till, D. et al. 2008. Large-scale freshwater microbiological study: Rationale, results and risks. *Journal of Water and Health* 06.4: 443-460.

Toi Te Ora. 2011. *Bay of Plenty recreational water health warnings*. http://www.toiteorapublichealth.govt.nz/health_warnings. [Accessed 6 March 2012.]

Turner, N. et al. 2005. *Review of non-commercial wild food in New Zealand.* Report from ESR. New Zealand Food Safety Authority.

Unwin, M. et al. 2010. *Modelling water quality in New Zealand rivers from catchment-scale physical, hydrological and land-cover descriptors using random forest models*. Report CHC2010-037 to MfE. NIWA.

Vant, W. 1999. *Sources of the nitrogen and phosphorus in several major rivers in the Waikato region.* Technical report 1999/10. Environment Waikato.

Vant, W. 2011. *Water quality of the Hauraki rivers and southern Firth of Thames, 2000–09.* Technical report 2011/06. Waikato Regional Council.

Water NZ, 2011. *Future face of urban water services in New Zealand*. New Zealand Water and Wastes Association.

Whanganui Iwi and The Crown. 2011. *Record of understanding in relation to Whanganui River settlement.* 13 October.

Wilcock, R. 1986. Agricultural run-off: A source of water pollution in New Zealand? *New Zealand Agricultural Science* 20: 98-103.

Wilcock, R. et al. with R. Monaghan et al. 2010. Unpublished response by NIWA and AgResearch to questions posed by the Parliamentary Commissioner for the Environment.

Wilcock, R. et al. 2011. *Continuous measurement & interpretation of dissolved oxygen data in rivers.* Report from NIWA. Horizons Regional Council.

Wood, S. and Young, R. 2011. *Benthic cyanobacteria and toxin production in the Manawatu-Wanganui region.* Report No.1979 for Horizons Regional Council. Cawthron Institute.

Wood, S.A. et al. 2010. *New Zealand guidelines for cyanobacteria in recreational fresh water: Interim guidelines.* Ministry of Health and MfE.

Young, R.G. 2010. *Proposed One Plan – Revised section 42A report of Dr Roger Graeme Young.* Horizons Regional Council.

Young, R. 2011. *Manawatu River health*. Cawthron Institute.

Young, R.G. et al. 2008. Organic matter breakdown and ecosystem metabolism: Functional indicators for assessing river ecosystem health. *Journal of the North American Benthological Society* 27(3): 605-625.

Zarour, H.I.S. 2009. *Proposed One Plan – Section 42A report of Mr. Hisham Ibrahim Sabri Zarour*. Horizons Regional Council.

Zeldis, J.R. 2009. Proposed One Plan – Section 42A report of Dr John R. Zeldis. Horizons Regional Council.