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Water quality of Lake Taupō and its catchment to 2020

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Prepared by:
Bill Vant and John Hadfield

For:
Waikato Regional Council
Private Bag 3038
Waikato Mail Centre
HAMILTON 3240

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Drs Roland Stenger and Piet Verburg Date September 2022

Approved for release by:
Tracey May Date July 2023

Disclaimer

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Executive summary

The water quality of Lake Taupō has been studied since the 1930s. The lakewater is generally clear and blue, reflecting the low concentrations of freely floating plant cells (“phytoplankton”) and the nutrients nitrogen (N) and phosphorus (P) which support their growth. During 2000–11 a statutory plan was developed to protect the lake’s excellent water quality. This involved managing the current inputs of N to the lake from the surrounding catchment; at the same time the inputs of P have been closely monitored.

Waikato Regional Council has routinely monitored the water quality of the lake at a deep-water site since 1994 (with the field and laboratory work being undertaken by NIWA). The survey results confirm the excellent quality of the lakewater, with low concentrations of N, P and chlorophyll. During 2016–20 most of the requirements of the National Policy Statement for Freshwater Management (NPS-FM) for “Band A” (=”oligotrophic”) lakes were met—although dissolved oxygen concentrations in the deeper waters only met the requirements for Band B lakes. The generally more stringent Waikato Regional Plan (WRP) requirements for the lake were also met—with the exception that an average total N of 70 mg/m^3 was exceeded. (When the WRP standards were set it was recognized that the standards might not be met for several decades.)

There was an increase in total N concentrations in the lakewater from 2010, with the annual average peaking at 119 mg/m^3 in 2013; this was followed by a decrease through to 2020 (annual average 71 mg/m^3). No obvious explanation for these changes is apparent (and the changes are not seen in a contemporaneous, independent record of total N in the water flowing out of the lake). Apart from the changes in total N, lakewater quality has been largely stable since 1994. The concentrations of certain forms of N and P in the lakewater suggest that phytoplankton growth in the water is now dependent on the availability of both N and P; and while the concentrations of either or both nutrients remain low, phytoplankton levels are likely to do so as well.

The water quality of 14 rivers and streams flowing into the lake is also routinely monitored. In general, the water quality of these streams is good-to-excellent; often it is in Band A of the relevant NPS-FM attributes. Dissolved reactive P concentrations are an exception, however, probably reflecting the naturally high concentrations found in cold-water springs in the Taupō catchment (and elsewhere on the Central Volcanic Plateau).

Nitrogen concentrations in several streams in catchments where pasture is the dominant landcover have increased markedly since the 1970s. Phosphorus concentrations, however, have shown little change. On average, the combined load of river-borne nitrogen entering the lake from the catchment was estimated to have increased by about 5–7% over the past 20 years. Some of the increase has occurred in streams draining catchments where pine forest is currently the dominant landcover, but where records show that pasture was present in the past (1950s). This is likely to reflect the often slow movement of water through the land and into the inflowing streams, such that the load of N from historic farming has taken an appreciable time to reach the stream waters.

Mean residence time, MRT (or “water age”), during summer has been routinely determined in 11 streams draining areas in the northern and western part of the lake’s catchment where pasture is present. Four streams in the northern area have MRTs in the range 40–80 years; the other streams—in the western part of the catchment—have ages in the range 10–25 years. Nitrogen concentrations in these streams—particularly those with longer MRTs—have continued to increase, consistent with earlier predictions of a “nitrogen load to come”.

Groundwater is the primary link for the transport of nitrogen from land-use to the lake, either as direct seepage or indirectly via typically baseflow dominated streams. Most of the rain falling in the Taupo catchment percolates through the soils and can take many years before re-emerging and thus may reflect activities that occurred in the past. Much of the investigation of groundwater in the Taupō catchment has thus focused on the load of nitrogen that is still migrating to the lake, and the processes that can remove it from the water on the way. Research has progressively shown that conditions favourable to denitrification are widespread in catchment groundwater and described the mechanisms involved. This focus was signalled early on as important to estimate nitrogen load projections more confidently for management.

Groundwater quality is routinely monitored in a network of 34 wells in the Taupo catchment. Median nitrate-N concentrations are typically low (≈70% < 2 g/m^3) and the two highest (9.75 and 23 g/m^3) are impacted by point sources. Deeper and older groundwater has little nitrate, and it is not detected where conditions are anaerobic. Slight-to-moderate trends in nitrate concentration have been found at many wells, with decreases slightly outweighing increases.

Numerical modelling estimations of the nitrogen load to come have progressively considered the improved understanding of denitrification in the catchment. Despite remaining uncertainties, simulation of the potential eventual load to the lake indicates it is likely to be substantially less than early worst case predictions.

The water quality rules for the Taupō catchment in the Waikato Regional Plan (WRP, see chapter 3.10) aim to protect the water quality of the lake by (1) capping all sources of manageable nitrogen from the catchment at their 2001 levels, and (2) offsetting much of the load of nitrogen which is still in transit to the lake by reducing some of the manageable sources. A public fund has been used to purchase the rights to discharge about 20% of the nitrogen entering the lake from manageable sources. This has meant that some 6675 ha of pasture, or about 12% of the area of pasture in the Taupō catchment in the year 2000, has now been planted in forest. In due course the load of nitrogen delivered from this land is expected to fall. This will help offset the load from historic activities still travelling through the groundwater, which as noted, is now considered likely to be substantially smaller than initial conservative predictions.

1 Introduction

Lake Taupō is New Zealand's largest lake (area 620 km^2; average depth 98 m). It is highly valued for many reasons, foremost among which is its excellent water quality. Only a few of the New Zealand lakes for which Livingston et al. (1986) collated information have similarly-high water quality (with the other excellent lakes including Lake Waikaremoana in the North Island, and several large upland lakes in the South Island, e.g. Lakes Coleridge, Hawea, Wakatipu and Wanaka). In Lake Taupō, concentrations of the plant nutrients nitrogen (N) and phosphorus (P) are low, and so too are concentrations of the microscopic, freely floating plants called phytoplankton whose growth they support. As a result, the water is clear and blue. Lakes with higher nutrient concentrations typically support higher levels of phytoplankton, meaning their water is typically greener and less clear.[1]

Most of the nutrients found in a lake enter it via surface waterways or groundwater, and therefore reflect the intensity of land-use in the catchment. Many of the lakes in the lowland areas of the Waikato region that are intensively used for agriculture are nutrient-enriched, and thus support scums and blooms of nuisance phytoplankton (Hamilton et al. 2010). Early signs of land-use intensification in the Taupō catchment in the late 1990s therefore posed a threat to the lake's near-pristine water quality.

In many lakes in the northern hemisphere, it is the availability of phosphorus that controls phytoplankton growth. Levels of nitrogen, by contrast, are often much higher than those required by phytoplankton. In many New Zealand lakes, however, large excesses of nitrogen have historically been uncommon—although this is changing as pastoral agriculture continues to intensify—and the ratio of nitrogen to phosphorus in the lakewater approximated that required for balanced phytoplankton growth (White 1983, Pridmore 1987). In addition, phosphorus concentrations are relatively high in many of the lakes of the central volcanic plateau, due to the dissolution of phosphorus from the pumice deposits (Timperley 1983). Phytoplankton growth may therefore be partly limited by the availability of nitrogen in these lakes. Furthermore, studies of the phytoplankton in Lake Taupō showed that their growth could indeed be N-limited at times, such that the experimental addition of nitrogen increased their abundance (White and Payne 1977; White et al. 1986; Hall et al. 2002).

Historically, the catchment of Lake Taupō was mostly covered in tussock grassland and native forest (Leathwick et al. 1995). Since 1840, however, much of the tussock has been replaced with pine plantations and pasture (Fig. 1). Concern about the erosion of pumice soils following development of the Taupō catchment in the 1960s led to the introduction of the "Lake Taupō Catchment Control Scheme" (Waikato Valley Authority 1973). From 1976 many streams and erosion-prone hillsides were fenced to exclude stock, and in some cases riparian areas were planted with native wetland species.

Reducing nutrient runoff from farmland also became an important objective of the scheme. Removal of substantial amounts of nitrogen has been observed in protected riparian areas of the Tutaeuaua Stream in the north-west part of the catchment, while nitrogen removal by plants living in the channel of the Whangamata Stream has also occurred (Vincent and Downes 1980; and see later). Even so, concentrations of nitrogen in several of the streams flowing into the lake have increased over the past 30 years (Vant 2018).

[1] In particular, nutrient and phytoplankton concentrations are higher, and the water is greener and less clear in the Waikato River hydrolakes, downstream of Lake Taupō (Bates 2021).

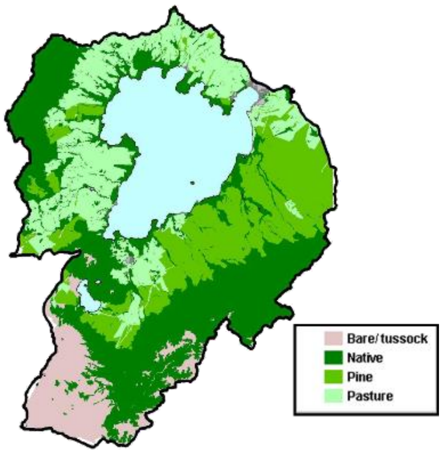

Figure 1: Landcover in the catchment of Lake Taupō, 1996—shortly before the WRP 3.10 process began.

Towards the end of the twentieth century, the potential for converting existing areas of sheep and beef pasture in the Taupō catchment to more-intensive dairying was identified (Ministry of Agriculture 1997). The Waikato Regional Council became concerned about the effects on lakewater quality of the increases in the loads of nutrients that this would be likely to cause. In 2005 it formally notified its intention to vary the Waikato Regional Plan (WRP) so that nitrogen loads from the catchment could be managed to ensure that the lake's water quality was protected. The variation to the Plan was eventually confirmed by the Environment Court in 2011.[2]

Section 3.10 of the Plan aims to ensure that by 2080 the water quality of Lake Taupō will be as good as it was around the turn of the century (namely in the 5-year period 1999–2003), based on the results of the water quality monitoring undertaken then.[3] It aims to do this by:

- capping all sources of manageable nitrogen from the catchment at their 2001 levels, and
- offsetting much of the load of nitrogen which is still in transit to the lake by reducing some of the manageable sources.

Much of the rain falling on the Taupō catchment percolates through the soil and spends time underground as groundwater—in some cases for many years—before finally entering the lake, either directly or via the inflowing streams. The groundwater therefore contains some of the nitrogen leached from historic land use practices, but which has not yet entered the lake. This "legacy" nitrogen has been widely described as the "nitrogen load to come". When the variation to the plan was developed it was anticipated that, despite capping, the loads of nitrogen entering the lake in its inflows would continue to increase substantially until the offsetting began to take effect. It was expected that it would take several decades or more before the full effects of intervention would be seen in the lake.

While loads of nitrogen were regarded as being of greater importance to the current condition of the lake, phosphorus is also important. The Plan therefore requires that the amount of phosphorus entering the lake be closely watched. It aims to manage the nitrogen and to monitor the phosphorus.

[2] The OECD has reviewed the development and implementation of WRP 3.10 (OECD 2015). It described the Plan as "a bold policy experiment [that] is globally unique: it is the only trading programme or market where diffuse sources of pollution operate under a cap".

[3] Burns et al. (1999) showed how the water quality of New Zealand lakes could be assessed using records of total nitrogen and total phosphorus, together with chlorophyll *a* and Secchi disc depth. WRC's analysis of the record of near-surface (0–10 m depth) water quality during 1999–2003 at its deep-water site in Lake Taupō showed that the average concentrations of total nitrogen and total phosphorus were 70.3 and 5.6 mg/m^3, respectively; the average concentration of chlorophyll *a* was 1.2 mg/m^3; and the average Secchi disc depth was 14.6 m (WRC document #984015; see also document #1280800, paragraph 4.11). These measures became the water quality objectives for the lake in the WRP.

1.1 The nitrogen cycle in the Taupō catchment

There are several pathways by which nitrogen can enter the Lake Taupō catchment, including atmospheric deposition (e.g. via rainfall), nitrogen fixation by clover and other plants,[4] and additions of fertilizer. These can be regarded as "inflows" of nitrogen to the system. Similarly, there are several pathways by which nitrogen can leave the system or be otherwise made semi-permanently unavailable to it. These can be regarded as "outflows" of nitrogen and include transport out of the lake down the Waikato River, burial in lake bottom sediments, export of agricultural produce outside the catchment and the return of nitrogen to the atmosphere by the process of "denitrification".

A fundamental principle of ecology is that matter, including atoms of nitrogen, is neither created nor destroyed within ecosystems. Even so, nitrogen in each chemical form, such as the nitrate ion (NO_3^-), can be transformed to different forms by various chemical and ecological processes. For example, plants like phytoplankton and grasses can convert the nitrogen present in the nitrate ion into nitrogen contained within large, complex proteins and other molecules (e.g. the photosynthetic pigment chlorophyll *a*, $C_{55}H_{72}O_5N_4Mg$); this process is called "biosynthesis". Conversely, certain bacteria can convert the nitrogen present in the nitrate ion into nitrogen gas, N_2, the simplest form of naturally occurring nitrogen; this process is called "denitrification".

The nitrogen cycle of the Lake Taupō catchment thus involves the transport of nitrogen into and out of the catchment, together with the various processes of chemical transformation of individual nitrogen atoms. Denitrification reduces the amount of nitrogen present in the water, thereby "attenuating" the nitrogen load that it carries. Attenuation also occurs when nitrogen is transformed from forms that are readily useable by aquatic organisms to other aquatic forms that are much less useable, and thus are effectively unavailable for further biosynthesis. Figure 2 is a simple summary of the key concepts and processes of the nitrogen cycle in the Lake Taupō catchment.

1.2 Nitrogen budget for Lake Taupō

Loads of nitrogen and phosphorus in the Taupō catchment were measured in a major study during 1976–79 (Schouten et al. 1981). Nitrogen and phosphorus concentrations in the rivers and streams flowing into the lake were measured at 69 sites. Stream flows were measured continuously at 18 of these sites and were regularly gauged or estimated at many others. This included the nitrogen load carried by "foreign" water that had been diverted to the lake from outside its natural catchment via the Tongariro Power Development (TPD). Nitrogen levels in rainfall collected near the lake were measured in 1981–83 (Timperley et al. 1985) and again in 2004–05 (Vant and Gibbs 2006). Elliott et al. (1999) and Elliott and Stroud (2001) used this information to develop detailed numerical models of the Taupō catchment that could be used to explore how alternative activities would be likely to affect the loads of nutrients entering the lake.

In 2008 the Environment Court asked eight experts to provide it with an agreed statement of the sources of nitrogen entering the lake then. Table 1 summarizes the nitrogen budget determined by the group. The loads from rainfall, undeveloped and pine land and the TPD were regarded as being at or close to background levels, such that they were essentially un-manageable; together these totaled about 820 t/yr, or about 60% of the combined load. The remaining 540 t/yr (40%) came from land that had been developed for pastoral farming (510

[4] Including certain phytoplankton in the lake itself.

t/yr) and from urban runoff and wastewater (30 t/yr); these were regarded as being manageable loads, and therefore became the focus of the plan to protect the water quality of the lake.[5]

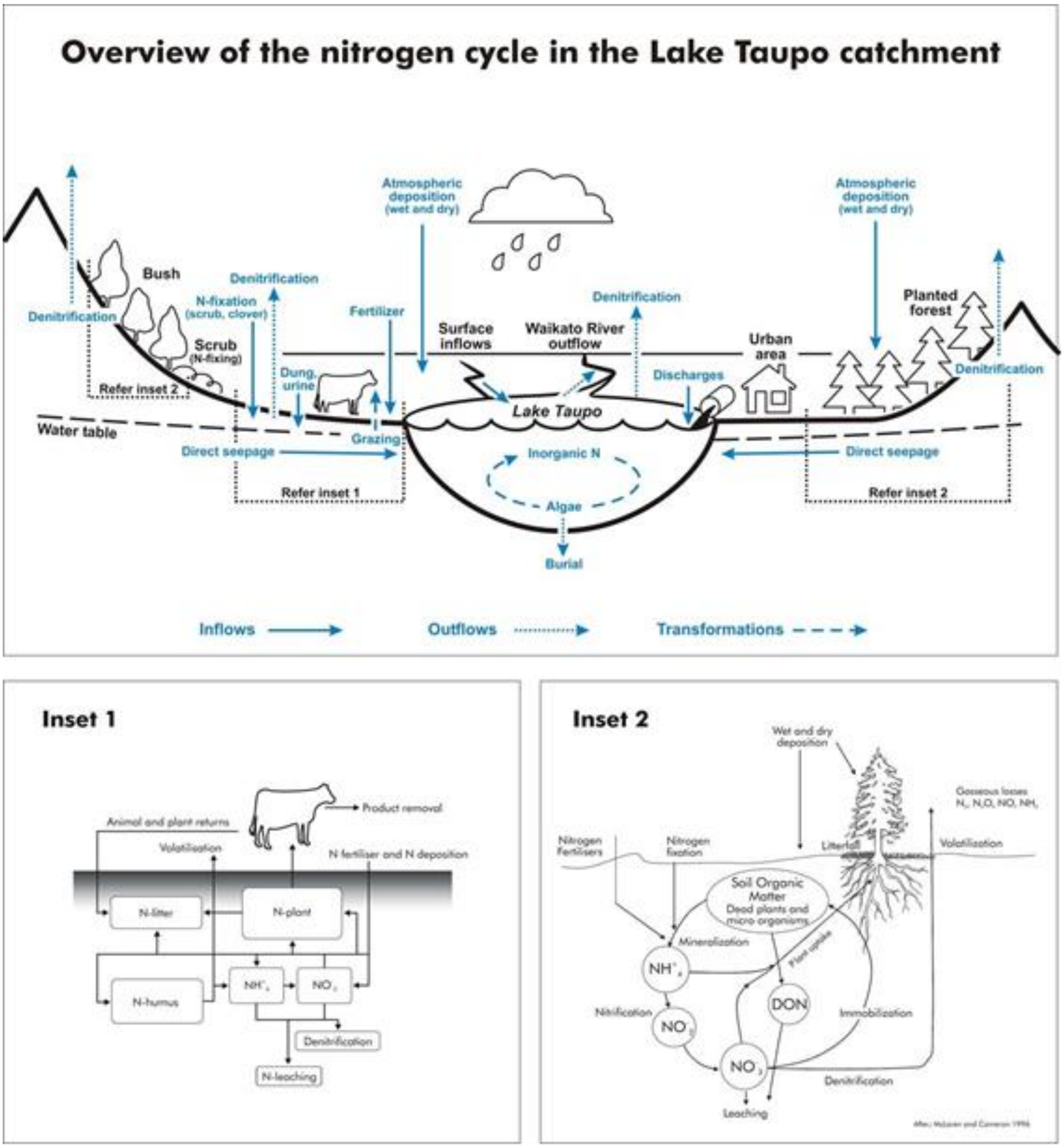

Figure 2: The nitrogen cycle in the Lake Taupō catchment.

Table 1: Nitrogen loads entering Lake Taupō, 2008. Based on an expert statement prepared for the Environment Court. Values are rounded. See WRC document #1493280 for details.

Source	Load (t/yr)
Rainfall on the lake	270
Undeveloped land	310
Pine and scrub	150
Pasture	510
Urban runoff and wastewater	30
Tongariro Power Development	90
Sum	**1360**

[5] By way of comparison, the Court was also told that the "nitrogen load to come" mentioned above was expected to be of the order of 160–230 t/yr (see section 5).

2 Water quality of Lake Taupō

2.1 State and trend

In the 1930s the family doctor in Taupō town was John Armstrong. He was interested in the water quality of Lake Taupō and made the first recorded measurements of the lake's water clarity and temperature—including in the cooler, deep waters (Armstrong 1935). During 1955–56 Hilary Jolly travelled north from the University of Otago to study the limnology of several North Island lakes, including Lake Taupō. She published the first comprehensive information on the water quality of Lake Taupō, describing its temperature, dissolved oxygen, water clarity and the concentrations of dissolved forms of nitrogen and phosphorus (Jolly 1968). Between 1974 and 1992 the Department of Scientific and Industrial Research (DSIR) operated a freshwater research laboratory at Taupō. Over this period many studies of the lake's limnology were published (e.g. Vincent 1983, White et al. 1980, 1986); Howard-Williams et al. (1994) summarized these studies. When the DSIR laboratory closed in the early 1990s the Waikato Regional Council assumed the responsibility for monitoring the water quality of the lake.

The Council has operated a water quality monitoring programme at Lake Taupō since 1994. The field work and laboratory analyses are done under contract by NIWA Hamilton. A deep-water site near the middle of the lake (Fig. 3) is visited roughly every three weeks, and water samples are collected, and field measurements made. Profiles of temperature, dissolved oxygen and chlorophyll are measured throughout the 150-m deep water column on each visit, and water samples are collected from the 0–10 m layer using an integrating tube. Secchi disc depth is also measured. On a single occasion in both autumn and spring each year water samples are also collected at 10-m intervals throughout the water column. Sensitive and accurate analytical methods are used to determine concentrations of chlorophyll *a* and of various forms of nitrogen, phosphorus and carbon in all samples. Full details of the results of the water quality monitoring are described in NIWA's annual reports to the council (e.g. Verburg and Albert 2019).

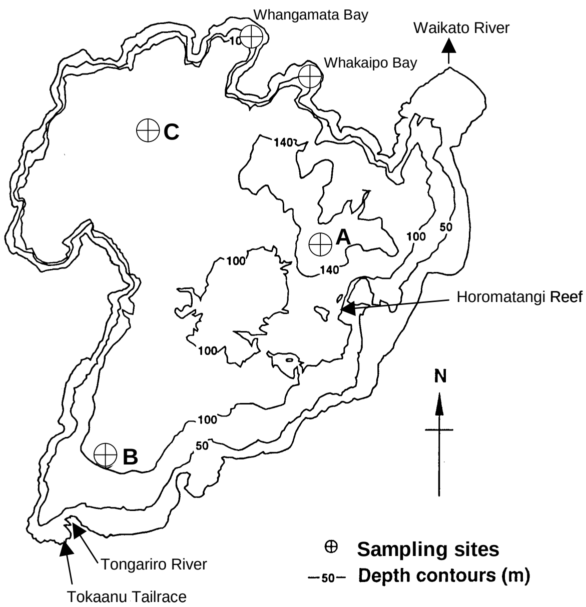

Figure 3: Location of the long-term, deep-water monitoring site at Lake Taupō ("Site A"), sampled for WRC during 1994–2020 (from Verburg and Albert 2019). Contour lines show water depths, generally at 50-m intervals. Two additional deep-water sites (B and C) were sampled during 2002–04, while near-shore sites in Whangamata and Whakaipo Bays were sampled during 2007–09, with similar results in each case to those at Site A (see Gibbs 2005, 2010).

In common with many deep lakes in temperate regions, Lake Taupō experiences regular annual cycles in water temperature and dissolved oxygen concentrations that affect the whole water column. These are illustrated below by reference to the profiles that were measured at Site A during 2017–18.

Figure 4 shows contour plots derived from profiles of temperature and dissolved oxygen that were measured in 2017–18 (28 profiles were recorded during the 17-month period shown). The upper plot shows that the deeper water (>60 m depth) remained cool (c. 11°C) throughout the year. During October-to-June, however, the shallower waters (<60 m) warmed-up, reaching temperatures as high as 22°C at the surface in February.[6] This thermal stratification weakened and broke down during the winter months, with the temperature being largely uniform (11–12°C) throughout the water column during July-to-September.

During the period of thermal stratification in the summer the deeper waters were isolated such that there was no opportunity for oxygen gas from the atmosphere to dissolve in them. Microbial respiration in these deeper waters therefore meant that the concentration of dissolved oxygen slowly declined from the summer onwards, reaching minimum values of 6–7 g/m^3 in the deepest water (150 m) during April-to-June, before increasing when the water column mixed later in the winter (Fig. 4, lower plot).

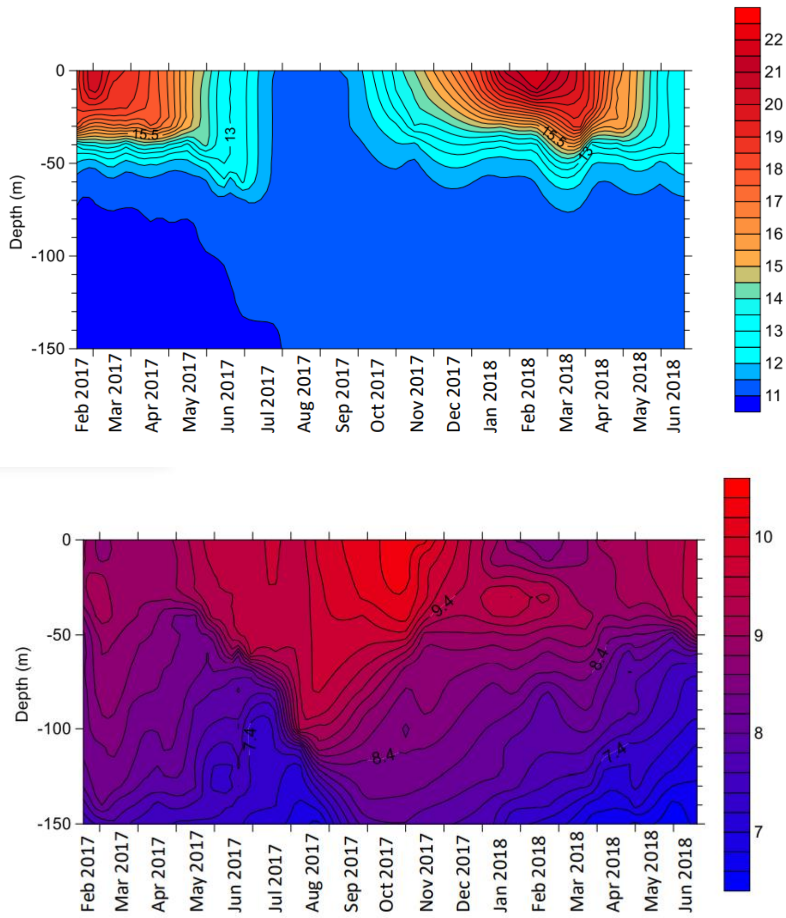

Figure 4: Contour plots of temperature (upper plot; °C) and dissolved oxygen (lower plot; g/m^3) at the deep-water monitoring site at Lake Taupō during 2017–18 (from Verburg and Albert 2019).

[6] Being less dense than the cooler, deeper waters, this upper layer resisted vertical mixing until its temperature declined during the following winter. This is described as "stable thermal stratification".

The other water quality results that are of special interest are those from the samples collected from the 0–10 m deep "near-surface" layer of water in the lake, particularly the concentrations of total nitrogen, total phosphorus and chlorophyll *a*, and the measurements of Secchi disc depth. Figure 5 shows the variation in monthly-average results for these variables during 1994–2020.

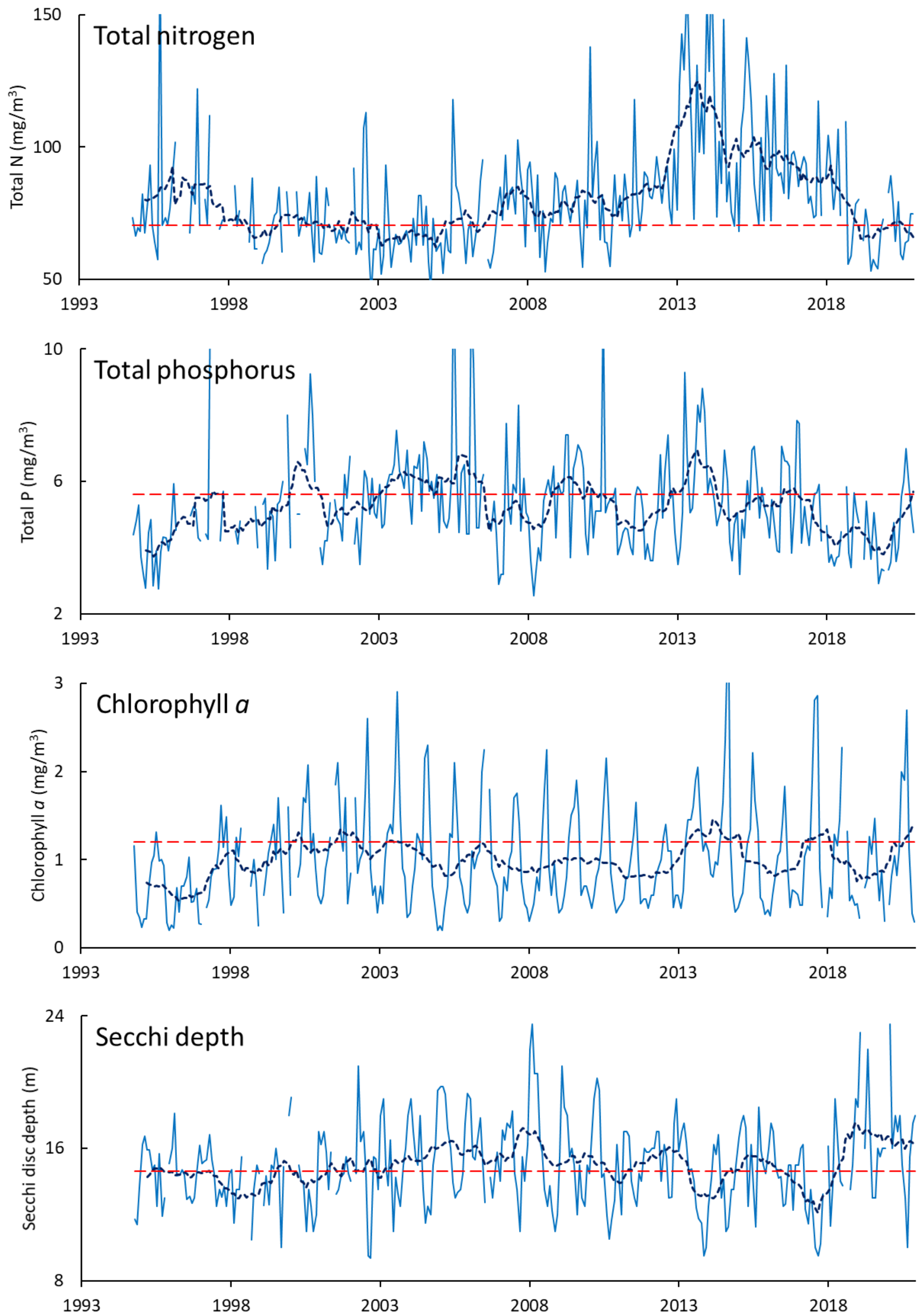

Figure 5: Monthly-average water quality in the near-surface layer (0–10 m) of Lake Taupō, 1994–2020. The dashed blue line is the 12-month running average, while the dashed red line is the WRP water quality objective.

Notwithstanding the often marked month-to-month variability in water quality, several general features were apparent, as follows (Fig. 5):

- there was a marked seasonal pattern in chlorophyll *a*, with annual maxima occurring each winter and low values during summer—reflecting the greater availability of dissolved nutrients in winter following annual mixing of the water column, as is also seen in other lakes in the volcanic area of the Central North Island: see McColl (1972);
- this was reflected in an inverse pattern in water clarity, with the lakewaters being clearest during summer when chlorophyll *a* concentration is low (see also Fig. 6); and
- there was an increase in total N concentrations in the lakewater from 2010, with the annual average peaking at 119 mg/m^3 in 2013; this was followed by a decrease through to 2020 (annual average 71 mg/m^3). No simple explanation for these changes has thus far been proposed (and see the information in Appendix 1 which further compounds this puzzle).

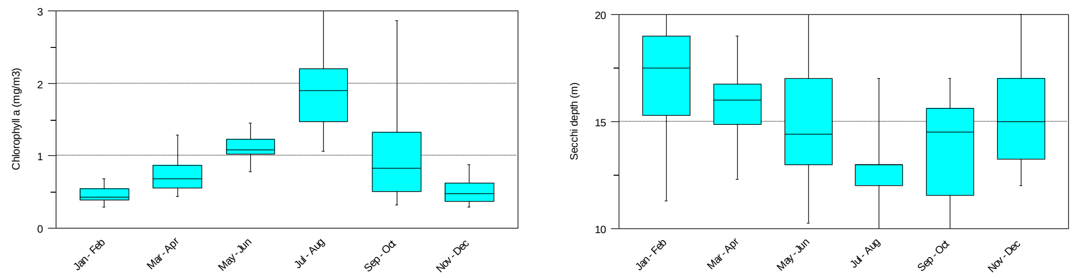

Figure 6: Seasonal box and whisker plots of chlorophyll *a* and Secchi disc depth in Lake Taupō, 2016–20. The boxes span the inter-quartile range, with the lines in the middle being the median value for each 2-month period; the whiskers encompass the remaining results.

Table 2 summarizes the state of water quality in Lake Taupō during 2016–20. As noted above, section 3.10 of the Waikato Regional Plan (WRP) contains long-term objectives for the water quality of the lake (to be met by 2080); these are shown in Table 2. The objectives for total phosphorus, chlorophyll *a* and Secchi disc depth were all met during 2016–20 (see also the red dashed lines in Fig. 5). However, the average concentration of total nitrogen was about 18% higher than the WRP objective (although the average concentration during 2019–20, namely 69 mg/m^3, did meet the long-term objective).

Table 2 also shows the water quality requirements for lakes in the National Policy Statement for Freshwater Management 2020 (NPS-FM). It lists the requirements for "Band A" lakes, where "lake ecological communities are healthy and resilient, similar to natural reference conditions". These correspond to New Zealand lakes that Burns et al. (1999) characterized as being "oligotrophic" (or better); similarly, Band B lakes are "mesotrophic" in their classification. During 2016–20 Lake Taupō was well-within the Band A requirements for total nitrogen, total phosphorus, chlorophyll *a*, ammoniacal-nitrogen and *E. coli*. However, it only met Band B requirements for dissolved oxygen in the bottom and mid-hypolimnetic waters.

Table 2: Water quality of Lake Taupō, 2016–20. ***E. coli*** **results are from WRC's monthly monitoring at the lake outlet; all other results are from a deepwater site in the middle of the lake ("Site A", 150 m deep; 85 sampling visits at roughly 3-week intervals). Total nitrogen, total phosphorus and chlorophyll** ***a*** **results are for an integrated sample collected from the 0–10 m deep layer; ammonia and dissolved oxygen results are from measurements at 10-m intervals throughout the water column (ammonia and pH determined twice per year). The water quality standards shown are from the Waikato Regional Plan (WRP, chapter 3.10) and for Band A of the National Policy Statement for Freshwater Management (NPS-FM). Results that did not meet these standards are shown in bold red type.**

Attribute	L Taupō, 2016–20	WRP 3.10	NPS-FM, Band A
Total nitrogen, average, mg/m³	**82.8**	≤70.3	–
Total nitrogen (stratified), median, mg/m³	80.4	–	≤160
Total phosphorus, average, mg/m³	4.8	≤5.6	–
Total phosphorus, median, mg/m³	4.7	–	≤10
Phytoplankton, average chlorophyll *a*, mg/m³	1.0	≤1.2	–
Phytoplankton, median chlorophyll *a*, mg/m³	0.8	–	≤2
Phytoplankton, maximum chlorophyll *a*, mg/m³	3.7	–	≤10
Secchi disc depth, average, m	15.1	≥14.6	–
Ammoniacal-nitrogen* (pH-adjusted), median, mg/m³	<1	–	≤30
Ammoniacal-nitrogen* (pH-adjusted), maximum, mg/m³	6	–	≤50
Dissolved oxygen†, lake bottom, minimum, mg/L	**4.5**	–	≥7.5
Dissolved oxygen†, mid-hypolimnion, minimum, mg/L	**5.0**	–	≥7.5
E. coli ,median, cfu/100 mL	5	–	≤130
E. coli ,95-percentile, cfu/100 mL	20	–	≤540

*The NPS-FM uses units of mg/L for ammoniacal-nitrogen in lakes (and rivers); for consistency with the other attributes described here, these have been converted to mg/m³ (noting that 1 mg/L = 1000 mg/m³)

†The dissolved oxygen "bottom" result is from 150 m depth, the "mid-hypolimnion" result is from 100 m; Band B of the NPS-FM requires minimum dissolved oxygen concentrations of ≥2.0 mg/L in bottom waters and ≥5.0 mg/L in mid-hypolimnion waters.

The water quality of Lake Taupō during 2016–20 was thus generally excellent. Concentrations of the nutrients nitrogen and phosphorus were low, and so were the concentrations of microscopic phytoplankton whose growth they supported (as indicated by the concentration of chlorophyll *a*). As a result, the water was clear and blue; in addition, the bottom waters of the lake were mostly well-oxygenated. Furthermore, although blooms of potentially harmful cyanobacteria have occasionally been observed in the lake (e.g. in March 2003), thus far these have not been common.

The long-term records for mid-lake water quality shown in Figure 5 were also examined for trends over time.[7] Table 3 summarizes the results of the trend analyses conducted for two periods. These were (1) the near-complete WRC record (calendar years 1995 to 2020), and (2) the past 20 years (2001–20), the period since the possibility of controlling land use in the catchment was first raised with the community. The following changes in water quality over time were found (Table 3):

- as noted above, total nitrogen concentration has increased overall—by about 0.8% per year since 1995, and by about 1.3% per year during 2001–20;[8]
- total phosphorus concentration has not increased (and in fact it decreased at a rate of about –0.8% per year during 2001–20);
- chlorophyll *a* concentration has neither increased nor decreased; and

[7] Trends were analysed to determine the seasonal Kendall slope estimator and the associated slope direction probability (using I Jowett's TimeTrends software). Vant (2018) described the use of this approach in detail (noting that adjustment of the observed water quality for variations in stream flow described in that report is not relevant to these records from the lake).

[8] Note that this conclusion applies to the (non-monotonic) records considered as a whole. And it is not inconsistent with the earlier description of total N concentrations peaking around 2013 before decreasing through to 2020. Other methods of trend analysis such as simple linear regression gave similar results.

- Secchi disc depth has increased (i.e. improved) slightly (0.2% per year) since 1995, but did not show a trend during 2001–20.

The increase in total nitrogen concentration seen in the lake since 2001 (Fig. 5, Table 3) is consistent with the Regional Plan's expectation of a "nitrogen load to come". However, the information in Appendix 1 casts some doubt on this apparent increase in total nitrogen as there has been no corresponding increase in the concentration in the water flowing out of the lake.

Table 3: Trends in water quality in Lake Taupō. Results are shown for the WRC record since 1995 (see Fig. 5), and for the past 20 years, 2001–2020, since the rules in WRP 3.10 were initiated. Values are trend slopes (% per year) and, in brackets, probabilities that slopes are different from zero (%). Trends that are very likely to have occurred (slope probability >95%) are shown in bold type—deteriorations in red, improvements in blue.

	1995–2020	2001–2020
Total nitrogen	**0.8 (>99)**	**1.3 (>99)**
Total phosphorus	0.0 (50)	**–0.8 (>99)**
Chlorophyll *a*	0.2 (91)	–0.4 (93)
Secchi depth	**0.2 (99)**	0.0 (50)

2.2 Forms of nitrogen in the lakewater

The water samples collected in the Council's monitoring programme are analysed for several different chemical and biochemical forms of both nitrogen and phosphorus. These include nitrate plus nitrite-nitrogen[9] and ammoniacal-nitrogen; together these comprise "dissolved inorganic nitrogen" (DIN). Organic nitrogen, which is nitrogen that has been incorporated into biological tissue is also present. It is convenient to distinguish between (1) dissolved forms of organic nitrogen which are collectively called "dissolved organic nitrogen", DON, and (2) "particulate nitrogen", PN (i.e. nitrogen that is present in particles that are retained on a laboratory filter; in Lake Taupō these particles are mostly biological, either living plankton, or dead and decaying cells or tissues). The concentration of "total" nitrogen in a water sample is equivalent to the sum of DON, PN and DIN. Similarly, the total phosphorus concentration is equivalent to the sum of dissolved organic phosphorus (DOP), particulate phosphorus (PP) and dissolved reactive phosphorus (DRP).[10]

Hall et al. (2005) conducted experiments which showed that the DON present in water from Lake Taupō is largely biologically inert or "refractory" and cannot be used by phytoplankton to support their growth. Instead, it is the DIN in the lake that supports phytoplankton growth. The DON present in the water presumably results from the breakdown of biological "detritus" (i.e. dead and dying plants and animals), and is itself relatively resistant to breakdown to simpler forms in the medium-term.

Figure 7 shows the relative importance of the different forms of nitrogen in the samples collected from the 0–10 m layer. On average, DON, PN and DIN accounted for about 69%, 28% and 3% of the total N in the 0–10 m layer during 1995–2020. This means that much of the nitrogen present in the lake is not suitable for supporting phytoplankton growth; conversely the DIN that does support this growth is often present at very low concentrations (such that sensitive and accurate analytical methods are needed to reliably detect it).

[9] Referred to simply as "nitrate" in this report—recognizing that concentrations of nitrite are typically very low in well-oxygenated natural waters; nitrate plus nitrite-nitrogen is abbreviated as "NNN" in the WRC database and "TON" (total oxidized nitrogen) elsewhere.

[10] In practice, since 2000 total dissolved N (TDN) and total dissolved P (TDP) have been measured, such that TN = TDN + PN, TP = TDP + PP, DON = TDN – DIN and DOP = TDP – DRP (see Verburg and Albert 2019 for details).

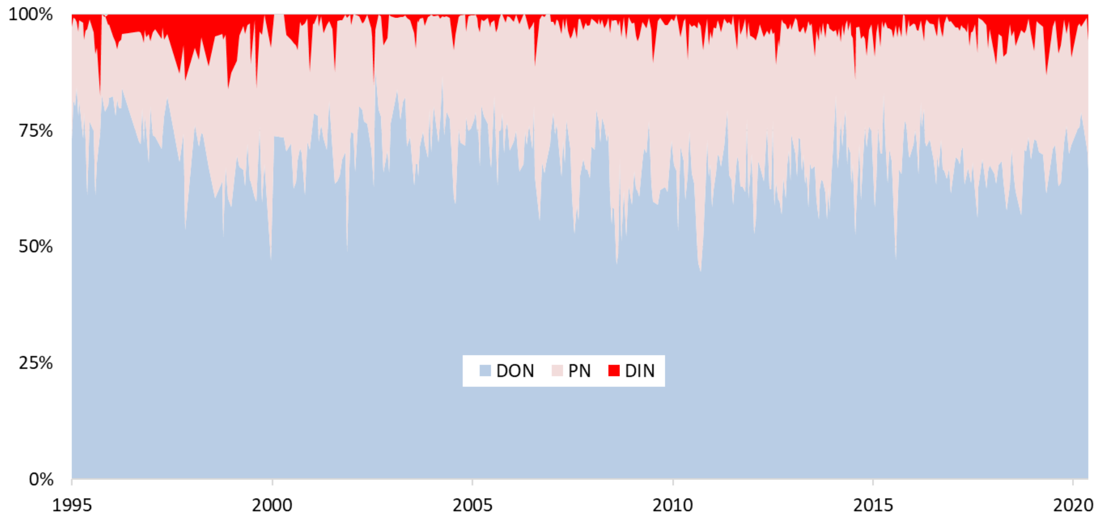

Figure 7: Forms of nitrogen present in the near-surface layer (0–10 m) in Lake Taupō, 1995–2020. Values are percentages of the total nitrogen concentration. "DON", dissolved organic nitrogen; "PN", particulate nitrogen; "DIN", dissolved inorganic nitrogen.

By contrast, in most cases much (50–90%) of the river-borne nitrogen entering the lake is present as DIN (see Appendix 2). When it reaches the lake it is rapidly taken-up by phytoplankton and converted to organic forms (see Fig. 2).

White et al. (1985) investigated the demand for plant nutrients in assemblages of phytoplankton found in 12 North Island lakes and concluded that assessments of the relative importance of nitrogen and phosphorus to plant growth needed to take account of the presence of refractory forms of these nutrients. They concluded that where concentrations of DON and DOP were relatively-large—as in Lake Taupō—assessments that simply considered the relative availability of total nitrogen (TN) and total phosphorus (TP) as the ratio TN/TP were likely to be flawed. They instead proposed that the concentrations of the dissolved organic forms of these nutrients should be discounted, and the ratio (TN – DON)/(TP – DOP) be used instead. They considered that where this ratio was greater than 15 (by weight), then potential P-limitation of phytoplankton growth was likely, and where it was less than 7 then potential N-limitation was likely (see also Pridmore 1987). Intermediate values of the ratio could correspond to co-limitation by both nitrogen and phosphorus.

Figure 8 shows how the ratio (TN – DON)/(TP – DOP) has varied since 1994 in the near-surface waters of Lake Taupō. Note that values of the ratio were relatively low around 2002 when Hall et al. (2002) found that the availability of nitrogen limited growth in water samples collected from the lake (see earlier). Furthermore, during 2010–18 when the concentration of total N was elevated (Fig. 5), the value of the ratio increased, but both the total N concentration and the ratio have fallen since then. Over much of the past 25 years, co-limitation of phytoplankton growth by both N and P appears to have been common.

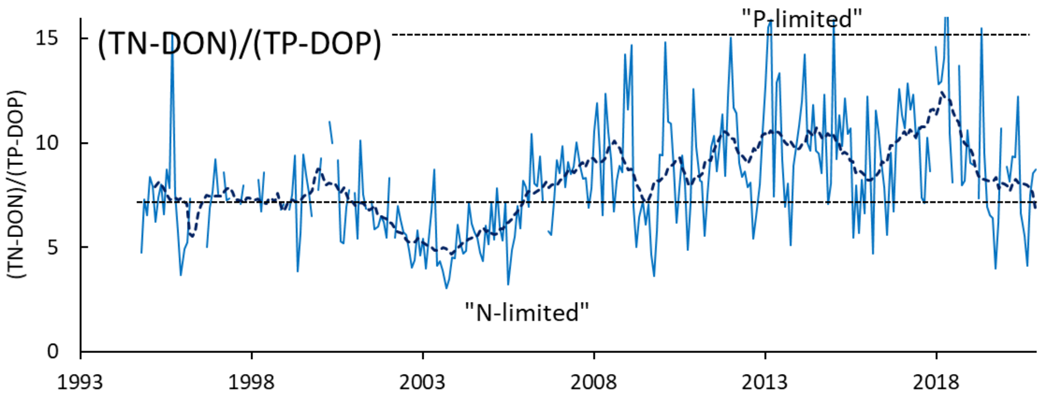

Figure 8: Ratios of forms of nitrogen and phosphorus in the near-surface layer of Lake Taupō, 1994–2020. "TN", "TP", total nitrogen and total phosphorus; "DON", "DOP", dissolved organic nitrogen and phosphorus. The dashed lines indicate values of the ratios (by weight) at which phytoplankton growth in the lake may become more-or-less limited by one or other nutrient; between these lines nitrogen and phosphorus are regarded as being "co-limiting" (While et al. 1985; Pridmore 1987).

3 Water quality of surface inflows to Lake Taupō

3.1 State and trend

The National Policy Statement for Freshwater Management 2020 also includes numeric objectives for New Zealand rivers. These objectives aim to protect the suitability of freshwaters for ecological and human health. Several of the water quality attributes for rivers are compulsory including (1) suspended fine sediment as indicated by median visual water clarity, (2) minimum daily dissolved oxygen concentration in summer (November-to-April), (3) median and maximum ammoniacal-nitrogen concentrations (both adjusted for pH), (4) median nitrate, 95-percentile nitrate, and (5) median and 95-percentile DRP. The 2019 consultation draft of the Policy Statement also included (6) median and 95-percentile DIN (i.e. ammoniacal-nitrogen plus nitrate-nitrogen). All these attributes are relevant to ecosystem health. In addition, the NPS-FM specified several measures of *E. coli* concentrations including median and 95-percentile *E. coli* concentrations. These are relevant to human health.

For each water quality measure, a range of "attribute bands" is given; these are generally labelled "A", "B", "C" and "D".[11] Band C is generally the minimum acceptable state, with the boundary between Bands C and D being termed the "National Bottom Line". For the nitrate and ammoniacal-nitrogen attributes, however, the national bottom line is the boundary between Bands B and C.

Table 4 shows the summary statistics for several key measures of water quality at the 14 routinely monitored stream sites in the Taupō catchment during the 5-year period 2016–20. While the NPS-FM often refers to "annual" statistics, a monitoring period substantially longer than a year will provide more robust results, particularly for 95-percentile and maximum values.[12] In general the water quality of these streams was good; often it was excellent. Most of the results in Table 4 are in Band A for the relevant water quality attribute; and some of those that are not—especially the results for dissolved reactive phosphorus—are largely the result of natural hydrological and geochemical processes that occur in this volcanic catchment (Timperley 1983).

[11] With a fifth band "E" for *E. coli*.

[12] Indeed for some attributes (e.g. visual water clarity and *E. coli*) the NPS-FM specifies a 5-year period of record.

Table 4: Water quality of 14 surface water inflows to Lake Taupō, 2016–20.# The "National bottom lines" from the NPS-FM are also shown. Results are graded according to the NPS-FM as follows: blue, Band A; green, Band B; yellow, Band C; red (orange for *E. coli*), Band D. "PS", power station; "Whg", Whangamata; "y_{BD}", horizontal water clarity; "DO", dissolved oxygen (November-to-April); "NH4", ammoniacal-nitrogen (adjusted to pH 8); "NNN", nitrate and nitrite-nitrogen; "DRP", dissolved reactive phosphorus; "DIN", dissolved inorganic nitrogen; "med", median; "max", maximum; "95%", 95-percentile; "nd", no data. Note that to be consistent with other material in this report, the units for the concentrations of the various forms of N and P are mg/m³ rather than the g/m³ used for these attributes in the NPS-FM.

Site	med-y_{BD} (m)	minDO (g/m³)	medNH4 (mg/m³)	maxNH4 (mg/m³)	medNNN (mg/m³)	95%NNN (mg/m³)	medDRP (mg/m³)	95%DRP (mg/m³)	medDIN§ (mg/m³)	95%DIN§ (mg/m³)	med*Ecoli* (/100mL)	95%*Ecoli* (/100mL)
Hinemaiaia atSH1	2.3	9.2	3	9	106	147	23	32	111	152	23	179
Kuratau at SH41	2.6	8.6	2	10	220	486	2	3	225	491	12	127
Kuratau at Te Rae St	nd	5.9	3	12	650	973	5	16	665	988	50	276
Mapara at off Mapara Rd	1.2	8.6	3	11	740	837	119	149	950	846	90	665
Omori at Omori (TDC site #1)	nd	nd	20	40	1255	1980	10	20	1270	2005	nd	nd
Tauranga-Taupō at SH1	3.0	8.4	2	6	61	90	12	16	66	95	21	100
Tokaanu at off SH41 Turangi	nd	7.7	2	6	460	560	74	81	465	565	12	123
Tokaanu PS tailrace	nd	8.6	3	46	3	13	2	5	9	24	5	47
Tongariro at Turangi (NIWA)	3.1	9.4	2	14	55	116	13	17	59	120	23	574
Waihaha at SH32	3.1	9.4	2	11	92	140	16	26	97	145	16	93
Waitahanui at Blake Rd	2.7	9.6	3	7	400	458	40	44	405	463	23	98
Whangamata Stream at Whg Rd	nd	9.1	3	13	1420	1736	65	95	1438	1745	100	1000
Whanganui at Lake Taupō	nd	8.4	2	14	360	535	8	16	365	540	50	368
Whareroa at Lake Taupō	nd	8.9	3	7	690	1010	18	24	702	1015	155	564
National bottom line	1.3*	4.0	240	400	2400	3500	–	–	(1000)	(2050)	130†	1200†

#Omori Stream monitored by Taupō District Council; Tongariro River monitored by NIWA.

*for suspended sediment class 1 (which all of the streams are)

§not currently an NPS-FM attribute (see text)

†for Band C (poorest state that is still suitable for swimming)

Eleven of the inflowing streams where water quality is currently monitored were included in a DSIR study of 26 inflows in the 1970s (White and Downes 1977).[13] Table 5 shows the average concentrations of DIN and DRP measured at sites that were monitored in both 1973–74 and 2016–20. The streams can be broadly separated into two groups—"forested" and "pasture"—reflecting the dominant landcover in their catchments. Note, however that the "forested" streams are all in the eastern and southern part of the Taupō catchment while the "pasture" streams are in the western and northern part—and that the geology of these areas also differs (Morgenstern 2007a, see his Fig. 4). This means that the differences described here may not simply be related to landcover as these labels might imply.

Several conclusions can be drawn from this information, as follows:

- DRP concentrations did not usually show marked differences between forested and pasture streams;[14] furthermore, concentrations were generally lower during 2016–20 than in 1973–74 (possibly reflecting differences in the laboratory methods used in the two periods)
- DIN concentrations by contrast were generally substantially higher in pasture streams than in forested streams (see also Fig. 9), and
- DIN concentrations in all streams were higher during 2016–20 than in 1973–74 (see also Fig. 9); they were particularly high in the pasture streams

It is therefore clear that nitrogen concentrations in several of the inflows to Lake Taupō have increased substantially over the past 4–5 decades. Phosphorus concentrations, however, have shown little change.

Table 5: Average concentrations (mg/m³) of DIN and DRP in 11 streams flowing into Lake Taupō in two periods. Results for 1973–74 from White and Downes (1977).

Stream†	Dissolved inorganic N		Dissolved reactive P	
	1973–74	2016–20	1973–74	2016–20
Forested				
Hinemaiaia (5)	68	105	38	24
Tauranga-Taupō (8)	57	65	21	12
Tongariro (11)	23	61	22	13
Waihaha (26)	97	104	25	17
Waitahanui (4)	142	411	76	40
Pasture				
Kuratau (18)	298	664	14	6
Omori (17)	507	1310	29	13
Tokaanu (14)	219	469	46	73
Whangamata (32a)	331	1425	85	67
Whanganui (23a)	224	374	14	9
Whareroa (21a)	331	741	85	18

†Numbers in brackets are the sub-catchment numbers in White and Downes (1977); MT Downes (pers. comm.) clarified the sites' precise locations.

[13] The locations of the 11 sites currently sampled are either at or are reasonably close to the locations that were sampled during 1973–74. Some other inflows are currently sampled at locations that are some distance from the location sampled in the 1970s (e.g. Mapara Stream), and these inflows are not considered here.

[14] Instead, Vant and Smith (2004) found DRP concentrations in streams in this catchment varied with the age of the water: see their Fig. 3. The results suggested that where water is stored underground for many years the amount of phosphorus dissolved from volcanic deposits increases—thereby accounting for the long-standing observation that DRP concentrations tend to be high in coldwater springs on the Central Volcanic Plateau (e.g. Timperley 1983).

Routine monthly monitoring of the water quality of rivers and streams in the catchment of Lake Taupō began between 1989 (Tongariro River, NIWA) and 1993 (seven WRC sites), with monitoring beginning at a further four WRC sites around 2001.[15] Changes in the water quality at these sites during 1993–2017 were determined by Vant (2018).[16] Those results have now been updated to cover the period to the end of 2020. Full results are shown in Appendix 3, while Table 6 lists the trend slopes for eight important variables.

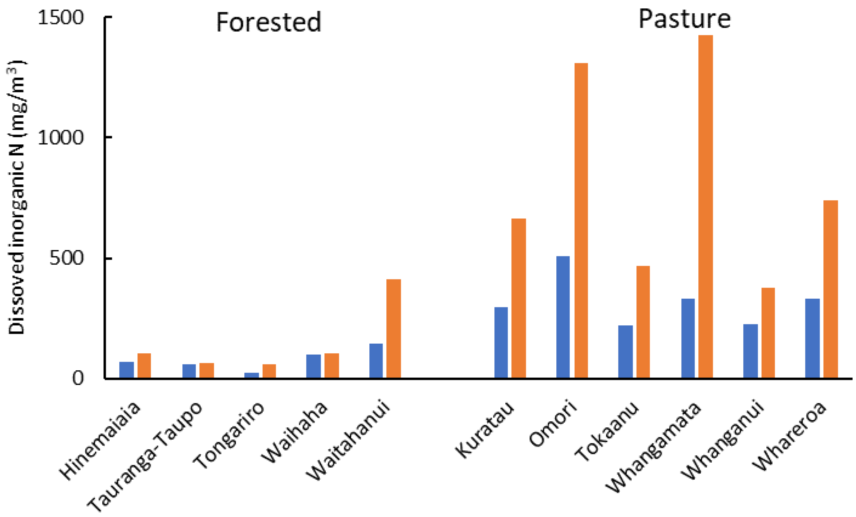

Figure 9: Average concentrations of dissolved inorganic nitrogen during 1973–74 (blue) and 2016–20 (orange) in five forested and six pasture streams in the catchment of Lake Taupō.

Table 6: Slopes (i.e. rates of change, % per year) of very likely trends (slope direction probability >95%) in flow-adjusted water quality at 12 inflows to Lake Taupō during 1991–2020. Important improvements ("Imp") are shown in bold blue type; important deteriorations ("Det") are bold red underlined; "nvl", not very likely (trend slope probability <95%). Updated from Vant (2018).

	Temperature	**Dissolved oxygen**	**Turbidity**	**Visual clarity**	**Total nitrogen**	**Ammonia**	**Total phosphorus**	***Escherichia coli***
Hinemaiaia	nvl	–0.1	0.7	–0.7	**1.6**	nvl	–0.7	nvl
Kuratau (upper)	0.6	–0.1	nvl	nvl	**2.5**	nvl	–0.9	–
Kuratau (lakeside)[1]	0.3	–0.1	**1.2**	–	**1.4**	nvl	**–1.3**	nvl
Mapara	0.2	nvl	nvl	nvl	0.6	**–1.6**	**–1.0**	nvl
Tauranga–Taupō	0.5	–0.2	**1.1**	–0.6	**1.0**	nvl	–0.9	–
Tokaanu	0.1	–0.2	**2.1**	–	0.9	nvl	–0.1	–
Tokaanu PS	0.4	0.1	**1.4**	–	nvl	nvl	**–1.4**	–
Tongariro (NIWA)	0.2	0.0	nvl	**1.0**	0.7	nvl	nvl	nvl
Waihaha	0.7	nvl	0.9	**–1.5**	0.4	nvl	nvl	nvl
Waitahanui	0.1	–0.1	**1.7**	–0.9	**1.4**	nvl	–0.6	**–3.4**
Whanganui	nvl	–0.2	nvl	–	–0.9	nvl	**–1.3**	nvl
Whareroa	–0.4	–0.1	**1.1**	–	0.3	nvl	–0.9	nvl
Imp – Det	0 – 0	0 – 0	0 – 6	1 – 1	0 – 5	1 – 0	4– 0	1 – 0

[1]Not flow-adjusted (see Vant 2018)

[15] WRC's ongoing monitoring programme for the water quality of rivers and streams was described by Tulagi and Salu (2021).

[16] Vant (2018) described very likely trends where the absolute value of the rate of change exceeded 1% per year as being "important". We have adopted this convention here also.

Water temperature increased at nine of the sites at an average rate of about 0.4°C/decade (range 0.1–0.8°C/decade). Turbidity also increased at several sites, with the average rate of change being about 1% per year. Concentrations of total nitrogen also generally increased at an average rate of about 1% per year. Figure 10 shows the total nitrogen records at three of the sites where concentrations have increased. By contrast, concentrations of total phosphorus generally decreased—although changes in laboratory methods during 2004–12 have meant that the reliability of the records is uncertain; at this stage the trend results for total phosphorus should be regarded as being provisional.

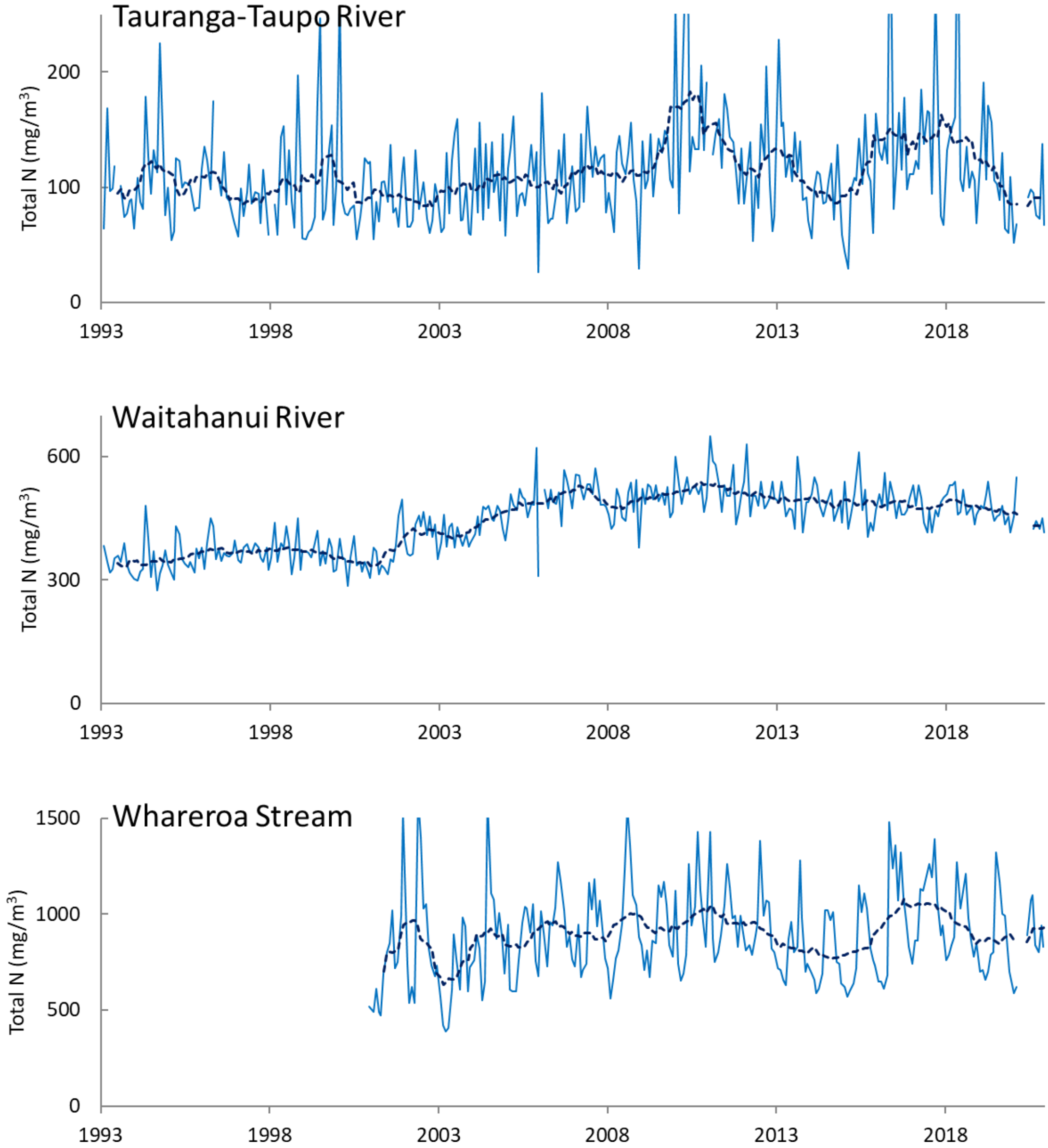

Figure 10: Monthly total nitrogen concentrations in three inflows to Lake Taupō, 1993–2020. Dashed blue line is the 12-month running average. Trend results for these records are shown in Tables 6 and 7.

3.2 Estimated changes in river-borne nutrient loads since 2001

The previous section described changes in the water quality of several of the inflows to Lake Taupō, including the changes in concentrations of total nitrogen and total phosphorus. This section describes what changes like these are likely to mean for the combined loads of nutrients entering the lake via the surface inflows. Unfortunately, river flows were only measured on 4–5 of the inflows which have records of nutrient concentrations.[17] This means that nutrient loads could not be determined for all the monitored inflows.[18] Instead, the loads that had been calculated previously for each inflow (Elliott et al. 1999) were used to determine the load-weighted average rate of change in the nutrient concentrations during 2001–20 in the inflows as a whole. These averages should provide an approximate indication of the overall changes in the combined loads carried by the important inflows in the catchment since 2001.

Table 7 shows the modelled loads of nutrients carried by 13 inflows to the lake during the 1990s (Elliott et al. 1999). The trend results (slopes and slope probabilities) for the records of total nitrogen and total phosphorus concentrations in these inflows during 2001–20 are also shown.[19] The records used were as follows:

- all those described in the previous section, apart from the Upper Kuratau site (as this river's load is better determined from the record at the downstream site near the river mouth)
- the Omori Stream (using Taupō District Council's quarterly record), and

Table 7: Percentage contributions of 13 inflows to the modelled N and P loads to Lake Taupō (Elliott et al. 1999). Changes in total nitrogen and total phosphorus concentrations in the inflows during, 2001–20 are also shown: values are trend slopes (% per year) and, in brackets, probabilities that slopes are different from zero (%); trends that are very likely to have occurred (slope probability >95%) are shown in bold type, with decreases in blue and increases in red. Except where noted, samples were collected monthly, and records were flow-adjusted. The average concentrations (units mg/m^3) of total N and total P during 2001–20 are also shown.

	Load N (%)	Load P (%)	Total N slope	Total P slope	Av_[Total N]	Av_[Total P]
Tokaanu PS	27.5	19.1	0.6 (87)	**−1.4 (>99)**	120	15
Tongariro (NIWA)	11.3	10.6	**0.7 (99)**	**0.3 (97)**	90	23
Kuratau (lakeside)[1]	8.8	7.0	**1.4 (>99)**	**−1.3 (>99)**	740	16
Waihaha	6.9	5.1	0.2 (74)	−0.1 (68)	180	25
Tauranga-Taupō	6.0	6.3	**0.9 (99)**	**−1.3 (>99)**	120	19
Waitahanui	5.4	17.1	**0.6 (>99)**	**−0.7 (>99)**	480	48
Hinemaiaia	3.4	3.1	**2.4 (>99)**	**−0.7 (>99)**	150	36
Whareroa	3.4	2.1	**0.4 (99)**	**−1.0 (>99)**	900	38
Tokaanu Stm[1]	2.9	2.2	**0.8 (>99)**	**−0.2 (>99)**	470	79
Whanganui	2.5	2.6	**−0.9 (>99)**	**−1.4 (>99)**	470	18
Whangamata[2]	1.1	2.1	**0.6 (99)**	<0.1 (60)	1560	76
Omori[1, 2] (TDC)	1.1	0.6	**1.1 (99)**	0 (50)[3]	1380	–
Mapara	0.1	0.2	**0.3 (>99)**	**−1.4 (>99)**	960	160

[1]Not flow-adjusted
[2]Quarterly
[3]Result is for DRP

[17] Flows were continuously recorded at or near the water quality sites at the Tokaanu Power Station, the Tongariro and Tauranga-Taupo Rivers and the Whareroa Stream. In addition spot gaugings of the flow of the Whangamata Stream were done 4–9 times per year during 2001–20.

[18] Furthermore, some of the records contained considerable gaps, with between 72 and 237 results being available for the individual inflows during 2001–20.

[19] The records for a 14th inflow (Waimarino River) were also considered in previous analyses (e.g. Vant 2013). However, recent results (post-2011) from this site are not available.

- WRC/NIWA's record for the Whangamata Stream;[20] in this case the monitoring frequency has varied from five times per year (NIWA 2001–08) to monthly (WRC 2008–20), with flows being gauged 4–9 times per year, so quarterly-average results were calculated, and these were used in the trend analyses.

As was also apparent from Table 6, increasing trends in total nitrogen concentrations (i.e. positive slopes) and decreasing trends in total phosphorus concentrations were common (Table 7).[21] The outflow from the Tokaanu Power Station was the single largest input of nitrogen to the lake in the 1990s (27% of the combined total), despite the relatively-low nitrogen concentrations in the water there (Table 7). An increasing trend in nitrogen was found in this inflow during 2001–20, but it was weak (slope probability 87%).

Conversely, in the 1990s the Hinemaiaia River contributed only a modest load of nitrogen (3.4% of the total), but the increasing trend observed there since then was both strong (slope probability 99%) and relatively large (2.4% per year). Finally, even though concentrations of both nitrogen and phosphorus were high in the Mapara Stream, it contributed only small nutrient loads to the lake, so that the observed changes in the water quality of this stream are of little consequence.

Between them, the 13 inflows contributed most of the river-borne load of nitrogen (80%) and phosphorus (78%) entering the lake during the 1990s (Table 7). Changes in these inflows since then should therefore provide a reasonable indication of how the overall catchment loads of nutrients entering the lake have changed. The changes in the combined loads carried by these inflows since 2001 were estimated as follows:

- lower bound: set trend slopes for the 13 inflows that were "not very likely" (i.e. slope probability <95%) equal to zero, and calculate the load-weighted average rate of change in nutrient concentration, and
- upper bound: use all 13 trend slopes regardless of slope probability to calculate the load-weighted average rate of change in nutrient concentrations.

The combined load of river-borne nitrogen entering Lake Taupō was thus calculated to have increased by between 0.5% per year and 0.7% per year during 2001–20. The combined load of phosphorus, by contrast, decreased by about –0.8% per year (although the reliability of most of the records used to determine this is uncertain: see above).

There is not enough data available for us to reliably determine the combined load of river-borne nitrogen entering Lake Taupō at specific times during 2001–20. However, the weighted-average change in the concentrations of nitrogen in the 13 inflows does provide a basis for estimating the average change in the annual loads of river-borne nitrogen carried into the lake over this period. From Table 1, the river-borne load of nitrogen entering the lake at the start of the century was about 1060 t/yr. An average trend slope of between 0.5% per year and 0.7% per year suggests that the average value of the annual loads during 2001–20 was between 55 and 77 t/yr greater than the load at the start of the century (i.e. 1060 t/yr). While these estimates indicate an increase in the combined load that entered the lake during the period, the concentration time series (Fig. 10) suggest that the load did not steadily increase, but rather there were several periods of both increases and decreases. The overall effect of these has been a net increase of about 5–7% in the river-borne load of nitrogen entering the lake.

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[20] At the "top" site at Whangamata Road, 2–3 km upstream of the stream mouth (where the "bottom" site is located: see below).

[21] Interestingly however, an <u>increasing</u> trend in total phosphorus was found at NIWA's site on the Tongariro River where a different laboratory is used to analyse the water samples and the total phosphorus records have not been compromised by changes in methods.

The overall increases in nitrogen observed in the Tauranga-Taupō, Waitahanui and Hinemaiaia Rivers were somewhat unexpected, given their catchments are dominated by bush and plantation forests (Table 5). Between them, these inflows accounted for about one-third (30–40%) of the combined increase in nitrogen load from the 13 inflows that occurred during 2001–20. Wildland Consultants (2013) examined aerial photos from 1958–65 of the eastern part of the Taupō catchment, including much of these three river catchments. The area covered by the photos was about 987 km^2, or about 34% of the entire lake catchment. Of this, some 182 km^2 (19%) was found to have been in pasture at the time the photos were taken.

Examination of the recent landcover (LCDB3) of Taupō catchment showed that about 456 km^2 of the area covered by the historic aerial photos was covered by pine plantation in 2008. Of this 456 km^2, about 140 km^2 (31%) was in pasture during 1958–65.[22] So in this reasonably-large (c. 1000 km^2) part of the Taupō catchment, about one-third of today's pine forest is planted on land that was in pasture in 1958–65.

During 2001 to 2007 the total nitrogen concentration in the Waitahanui River increased steadily (Fig. 10)—from an average of 360 mg/m^3 before 2001 to an average of 490 mg/m^3 after 2007, an increase of about 36% over the seven years. At low flow in March 2012 a water sample was collected from the Waitahanui River and analysed for tritium. It was found to have an estimated mean residence time (i.e. water age) of 38 years.[23] This suggests that nitrogen leached from pasture prior to the planting of the pine plantations may still have been present as recently as 2007 or later.[24] Since then there has been a gradual reduction in the concentrations in the river (Fig. 10; and see Appendix 3 which shows that both total N and nitrate declined during 2011–20). Nitrogen concentrations in the Tauranga-Taupo River have also tended to decrease since about 2010 (Fig. 10; Appendix 3, particularly the results for nitrate). This may indicate that pasture-derived nitrogen has also been washing out of this catchment during recent years.

That is, even parts of the Taupō catchment that have been in forestry for several decades may have been affected by nitrogen leaching from earlier land use, with nitrogen concentrations having continued to increase over time until about a decade ago before finally beginning to decrease (i.e. there have been loads of legacy nitrogen from areas of the catchment in addition to those in current/recent pasture).

3.3 Water age in surface inflows to Lake Taupō

As noted in the Introduction, rain falling on the Taupō catchment can percolate through the soil and into underground aquifers from where it can travel slowly towards a nearby stream and thence into the lake. How large the aquifers are, and the time taken for the water to move through them are largely determined by the geology of the area (see section 4). In 2002 WRC began a programme of determining the average age or "mean residence time" of the water flowing into Lake Taupō in 11 streams draining areas of pasture in the Taupō catchment (Fig. 11).[25] Since then water samples have been collected from the streams during summer low flow at 5-year intervals. Samples are analysed for tritium concentrations by GNS Science, and modelling is used to estimate the mean residence time of the water in each stream.

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[22] WRC document #2715002

[23] GNS Science Letter Report 2012/25LR: see WRC document #2286709.

[24] Also note that Table 5 shows that the average DIN concentration during 2016–20, namely 411 mg/m^3, was nearly three times that observed during 1973–74 (142 mg/m^3), with the current value being substantially higher than those in the other "forested" streams (61–105 mg/m^3).

[25] Areas of pasture covered between 13% and 88% (average 54%) of each stream's catchment.

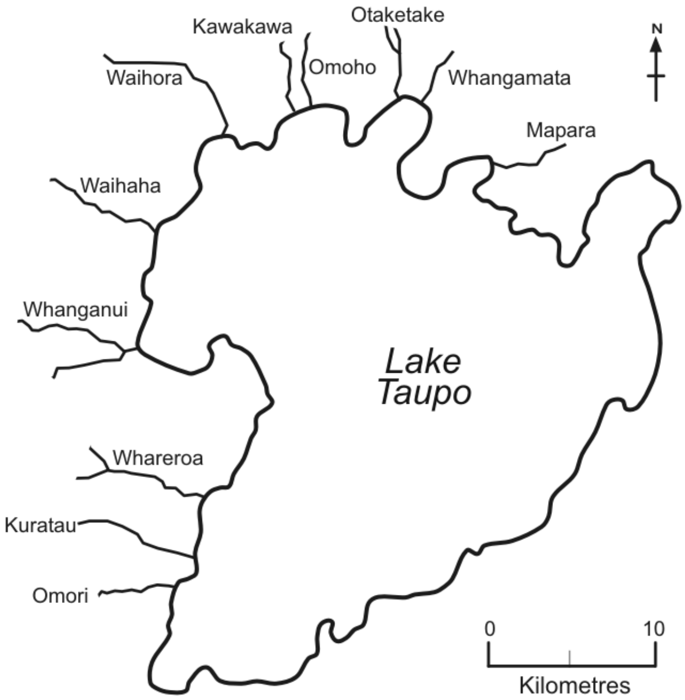

Figure 11: Location of 11 streams in the northern and western areas of the Lake Taupō catchment where samples were collected for tritium analysis during 2002–17. Apart from Omori, all samples were collected where the streams enter the lake.[26]

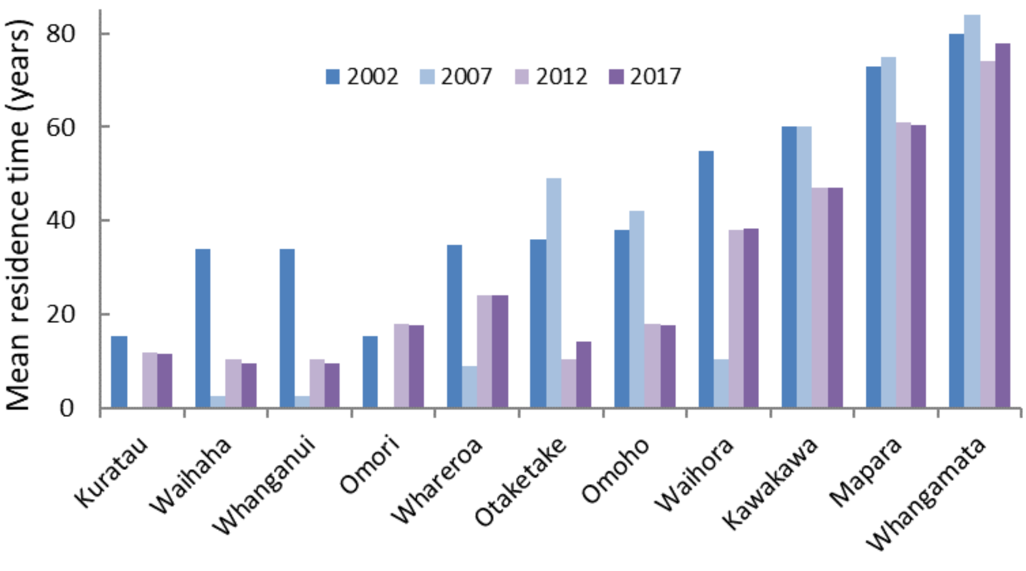

Figure 12: Modelled mean residence times of baseflow samples collected from 11 streams in the Taupō catchment at 5-yearly intervals during 2002–17.

[26] The tritium site for the Whangamata Stream, namely the "bottom site", is thus 2–3 km downstream of the location where the long-term multi-agency record of water quality has been collected (the "top site"). The tritium sites for the Mapara Stream and Waihaha River are also some distance downstream of WRC's routine water quality sites on those inflows (as in Table 4). Finally, the tritium site on the Omori Stream is Taupō District Council's "Site 1", upstream of the area where wastewater is spray-irrigated to the nearby land.

Figure 12 shows the estimates of mean residence time determined for each stream during 2002–17. In several cases the estimated residence times have varied markedly over time. Indeed, only the results for the Kawakawa, Mapara and Whangamata Streams have been reasonably consistent between samplings. Most of the variability at the other locations has resulted from changes made to the modelling procedures used to estimate the residence times in particular environments. The most recent estimates—for 2017—are thus regarded as being the most reliable.

In 2017, seven streams (Kuratau, Waihaha, Whanganui, Omori, Whareroa, Otaketake and Omoho) had mean residence times in the range 10–25 years. The other four (Waihora, Kawakawa, Mapara and Whangamata) had longer mean residence times, in the range 40–80 years. These four are all located in the northern part of the Taupō catchment—where the geology is dominated by thick layers of Taupō and Oruanui ignimbrites (Morgenstern 2007a: see his Fig. 4). These porous formations have a large capacity to store groundwater. Apart from Otaketake and Omoho, the remaining streams are all located in the western part of the Taupō catchment—where the geology is dominated by less porous Whakamaru ignimbrites and andesite and basalt.[27]

Vant and Smith (2004) used the residence time estimates for the samples collected in 2002 in a simple model to predict the load of legacy nitrogen (or the "load to come") from the 11 streams. They found that by the time the loads carried by them stabilized at some point in the future, their combined input to the lake could be 20–80% larger than in 2002. Their estimates of the size of the load to come were subsequently refined—and reduced—using the lower mean residence times determined in the three subsequent surveys (Morgenstern 2007a and authors' unpublished results).

In 2007, four expert witnesses to the Environment Court hearings on the proposed changes to the Waikato Regional Plan agreed that the combined load of nitrogen to come from the 11 monitored streams was of the order of 21 t/yr, with the load to come from all streams in pasture catchments being about 50 t/yr.[28] However, this river-borne contribution was considered to be the minor fraction (c. 20–30%) of the nitrogen load to come from areas of pasture, with much of the load being likely to enter the lake via direct seepage of groundwater through the lakebed.[29]

The tritium results for the samples collected from the 2017 survey were analysed using a "binary mixing model" which envisages two distinct pathways through each of the aquifers and into the streams, namely a younger, shallower pathway and an older, deeper pathway.[30] Both pathways have their own mean residence times, and the results for 2017 in Figure 12 are the combined values for each stream.

This improved model of water movement through the aquifers and into the stream channels is consistent with the long-term water quality and flow records for the Whangamata Stream (Fig. 13). Monitoring of nitrate concentrations and flows in this stream began during 1973–76 and has continued over the following five decades. Flows have gradually increased and decreased over this period with a period of roughly one-to-two decades between consecutive peaks/troughs. During low flow periods, flows average about 0.03–0.04 m^3/s, increasing to about 0.2 m^3/s during periods of high flow. These changes in flow appear to broadly reflect long-term patterns in rainfall in the area (B Jenkins, WRC, unpublished results).

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[27] The geology of the largely pine and bush-covered eastern part of the catchment (Fig. 1)—including the catchment of the Waitahanui River (see above)—is also dominated by volcanic ignimbrites (Taupō, Oruanui and Whakamaru), together with sedimentary greywacke in some of the upper catchment areas.

[28] Statement of agreed matters between technical experts for the appellants (W Silvester and P White) and respondent (J Hadfield and W Vant). WRC document #1418479.

[29] The experts estimated this groundwater-borne load to come to be of the order of 110–180 t/yr. Note, however, that the current (2022) understanding is that the load to come via direct seepage of groundwater is likely to be "substantially smaller" than this: see later.

[30] GNS Science Letter Report 2017/218LR: see WRC document #11427871.

There are also decadal-scale variations in the timeseries of nitrate concentrations.[31] Decadal-minima in nitrate concentrations occurred around 1986, 2003, 2016 and 2020, corresponding broadly to the lower flows occurring at each of those times (Fig. 13). And in each decade the highest nitrate concentrations occurred when flows were high.

The deeper, older water present in the aquifer is likely to contain lower nitrogen concentrations because much of it fell as rain before the land was cleared for farming, while the shallower, newer water is likely to contain higher nitrate concentrations. So, the changes apparent in Fig. 13 are consistent with the older, low-N water supplying the 0.03–0.04 m^3/s of baseflow, with the younger, high-N water topping this up during wetter periods. Superimposed on these cycles is a trend of slowly increasing nitrate concentrations which is the delayed response to the development of the catchment that has occurred since about the 1950s (Ward 1956).

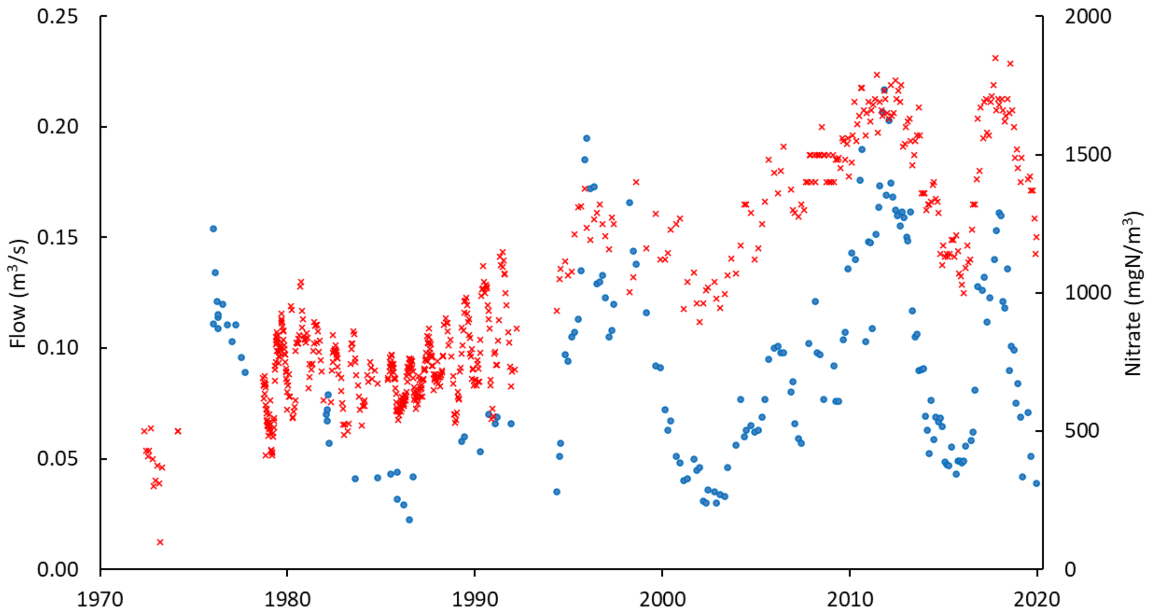

Figure 13: Monthly flow (blue dots) and nitrate (red crosses), Whangamata Stream at Whangamata Rd ("top site"), 1973–2020. Results are from Ministry of Works and Development (unpublished), DSIR (unpublished), Howard-Williams and Pickmere (2010) and WRC.

[31] Nitrate concentrations also varied seasonally in the 1980s—particularly at the "bottom" site further downstream (results not shown)—as uptake by the plants that grew vigorously in the then unshaded stream channel removed nitrate from the water (Vincent and Downes 1980). This in-stream uptake later reduced markedly as the channel became progressively shaded by the riparian vegetation that was established from 1976 to reduce erosion of the stream banks (Howard-Williams and Pickmere 2010).

4 Groundwater in the Taupō catchment

Groundwater is a key pathway for the transport of nutrients derived from land-use activities to the lake. Investigation of groundwater resources in the Taupō catchment by WRC commenced in 2000 with an initial survey of groundwater quality reported in 2001 (Hadfield et al. 2001). A groundwater quality network was established in the northern and western sub-catchments, being the areas of principal land-use development (see Fig. 1). Investigations have focused predominantly on the transport and fate of nitrogen given its importance as the limiting nutrient for eutrophication in the lake (see section 2). Also, phosphorus is readily adsorbed onto soils and is therefore relatively less mobile. Groundwater quality state and trends are reported here along with some related influences including land-use impacts, lags in contaminant transport and attenuation processes which mitigate effects.

Hydrogeologic setting

Lake Taupō is a large lake (620 km^2) formed in a caldera largely shaped by a massive eruption about 26,500 years ago. Geology is dominated by young (< 0.4 Ma), locally derived, rhyolitic pyroclastics. The sequence in the western catchment is relatively simple, principally comprising surficial Oruanui ignimbrite overlying a large thickness of Whakamaru ignimbrite. The latter is sufficiently welded in places to have moderate vertical fracture development and to form impressive cliffs along the lakefront.

In the north, to the east of Kawakawa Bay faulting is common and there is a more complex sequence of ignimbrites, fall deposits, localised lava extrusions and lacustrine sediments (Wilson, 2000, Hadfield et al. 2001). The unwelded Oruanui ignimbrite overlies this broad grouping of 'rhyolite pyroclastics'.

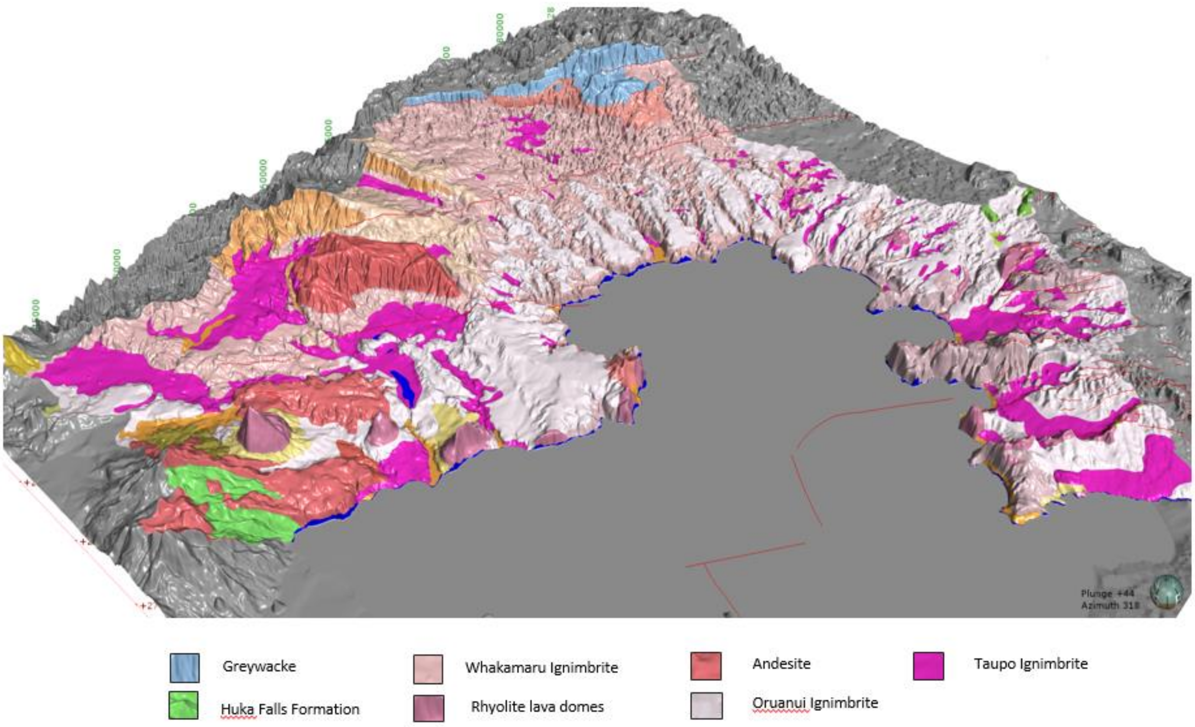

Figure 14: Geology and topography of the northern and western Lake Taupō catchments.

Occasional paleosols punctuate these formations marking periods of cessation in volcanic activity and may act as aquitards. The youngest unwelded Taupō Ignimbrite forms localised and surficial deposits which are often unsaturated. The distribution of geological formations in the western and northern catchments is illustrated in Figure 14.[32]

The lake acts as a sink for groundwater, which is recharged from rainfall in the catchment. Groundwater flow is essentially consistent with topography, although more subdued. The piezometric surface presented in Figure 15 is from surveys of more than 130 wells in 2001 and 2007. A recharge regime exists generally in the area. This is evident by depths from ground surface to static groundwater levels typically increasing with well depth and streams gaining from groundwater and being baseflow dominated. Well yields and aquifer transmissivities are modest, with median hydraulic conductivities for the Whakamaru Ignimbrite, Oruanui Ignimbrite and 'rhyolitic pyroclastic' grouping being about 0.01, 0.93 and 0.28 m/day, respectively. The unwelded ignimbrites in the north have greater capacity to store groundwater than the welded Whakamaru Ignimbrite in the west (Hadfield et al. 2007, Morgenstern 2007b).

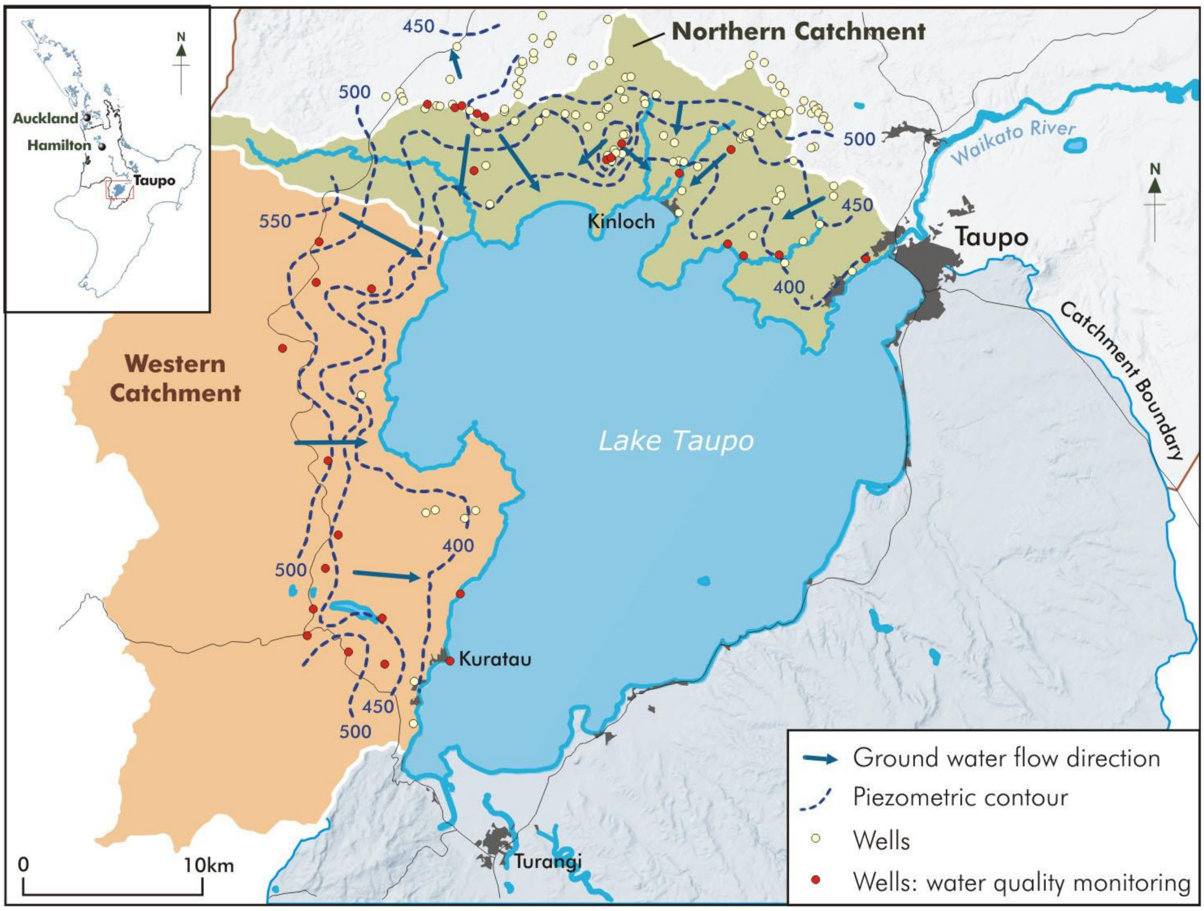

Figure 15: Groundwater contours and flow directions

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[32] These formations are also represented in three dimensions at https://data.gns.cri.nz/ebof/graphics.jsp.

4.1 Groundwater quality state and trend

The groundwater quality monitoring network in the Taupō catchment is described in Appendix 4. This section reports the monitoring results for the period 2003–20. Initial analysis was undertaken using an automated spreadsheet from GNS. This allowed outliers to be identified and obvious anomalies to be examined. These occasionally led to corrections relating to data entry. It is noted that there are various gaps in individual monitoring records and sometimes changes also in analyses methods and associated detection limits. Methods were aggregated where appropriate and detection limits maintained. Trend analysis was carried out using R scripts obtained from the LandWaterPeople (LWP) trends library in 2021 described by Snelder and Frazer (2019). These tools for water quality analysis require the plyr, NADA and gam packages. Left censored (below detection) data are replaced by imputed values based on non-censored data.

The results for the major ions in the 34 wells are shown as milli-equivalent ratios in the Piper trilinear diagram in Figure 16 (based on software from Winston 2020). This shows the type and general character of the groundwaters. The monitored groundwaters are predominantly of bicarbonate type in respect to anions and tending toward sodium type for cations. The overall water character is of mixed or bicarbonate types. This reflects the hydrogeologic setting which is dominated by rhyolitic or acid volcanic formation aquifers.

There are two notable outliers in the distribution distinguished as green squares. These both reflect point source influences. The more central well (68_320) has been investigated and was shown to be influenced by discharge from a nearby woolshed (Hadfield and Barkle 2004). The other monitoring well (72_1076), is located down-gradient of a farm airfield with the anomalously high calcium and sulphate concentrations presumed to relate to fertiliser loading.

The state of groundwater quality in the Lake Taupō catchment is represented by median values for ten of the key parameters for the period 2016–20, as listed in Table 8. Note that nitrate concentrations strongly correlated with chloride and moderately with conductivity, potassium and magnesium, which also reflect land-use effects.

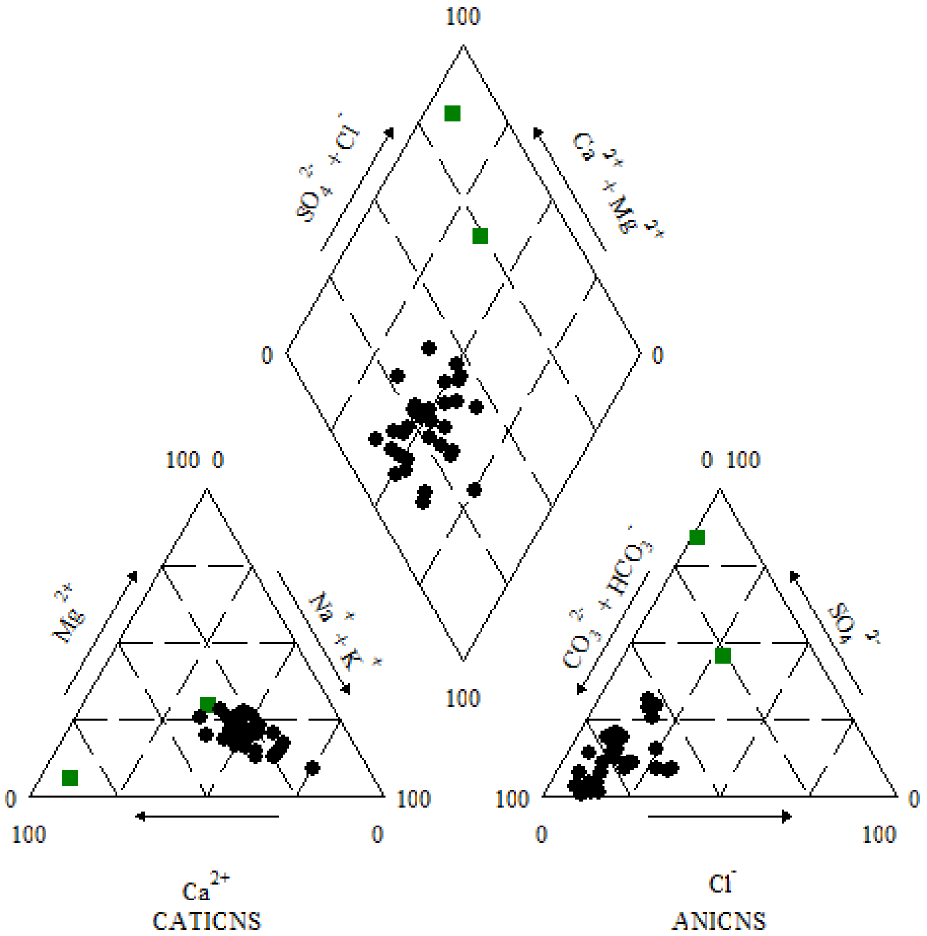

Figure 16: Median values of major ion concentrations in 34 groundwater monitoring wells in the Taupō catchment, 2016–20.

The trends in 15 key determinands in the monitoring wells during 2003–20 are summarized in Figure 17. It is apparent that the trends are mixed with the most obvious predominant increases being for alkalinity and sodium. Of more importance for nutrient management is that there are slightly more significant decreases in nitrate concentration than increases.

The magnitude of the trends in nitrate are shown in Figure 18. This shows that the majority (≈70%) of significant trends are gradual, being less than 0.1 g/m^3/yr. The highest rate for both increases and decreases are both related to point source impacts from woolsheds. They have both resulted in substantial exceedances of the drinking water standards. In 2005, nitrate concentrations at well 68_320 reached 35.8 g/m^3, which is three times higher the maximum acceptable value for drinking waters.

Table 8: Median values for key parameters in 34 groundwater wells in the Taupō catchment, 2016–20 (units: g/m³, pH units and mS/m). The redox status of each monitoring well is also shown, with green being aerobic, red anaerobic, yellow mixed and grey indeterminate (see text for further details). "Cond", electrical conductivity, "NA", not assessed, because left-censored results dominated (>80% of results).

Well	Ca	Cl	Cond[1]	HCO_3	K	Mg	Na	NO_3-N	pH	SO_4
68_301	5.45	3.7	11.7	39.7	1.54	3.6	12	2.3	6.9	9.25
68_317	6.9	6.75	14.6	35.4	3.2	3.35	14.4	4.1	6.8	12.95
68_320	20	20.5	35.7	32.3	3.35	10.35	22	9.75	6.6	45
72_1005	6.7	2.9	11.8	32.9	1.81	3	10.6	4.6	6.8	3.6
72_1006	3.1	2.8	6.4	34.2	1.43	1.82	7.2	0.07	6.7	0.9
72_1007	4.7	6.7	13.3	39.7	1.48	2.5	16.3	0.12	6.65	16.45
72_1008	4.9	4.1	10.1	26.8	5.3	2.6	8.9	2	6.8	12.3
72_1010	6.9	5	12.8	47.6	0.79	3.1	14.9	1.46	6.9	9.3
72_1011	5	4.8	12.2	43.9	1.56	2.9	14.9	2.4	6.8	7.3
72_1012	2.3	3.7	5.6	21.5	3.3	0.83	5.2	0.11	6.3	2.6
72_1068	76	2.8	45.7	35.4	4.6	3.1	5.8	1.94	6.2	168
72_1069	3.4	3.75	12.25	42.7	26	1.16	3.7	0.88	6.4	9.95
72_1070	7.5	2.2	9.8	47.6	4.3	2.4	8.7	1.01	6.6	3.5
72_1071	4.5	2.7	7.7	36.6	1.75	2.1	7.6	0.59	6.4	1.6
72_1072	5.8	3.8	9.6	52.5	3.1	2.1	9.3	0.07	6.9	0.25
72_1073	4.65	3	7.5	32.9	2.5	1.83	7.9	1.51	6.6	1.35
72_1075	4.9	5.6	8.9	36.6	1.6	2.3	8.8	0.46	6.7	3.6
72_1076	25	17	36.6	53.7	30	7.6	10.5	23	6	6.3
72_1078	5.2	4.1	9.1	46.4	2.1	2.6	7	NA	6.7	2.1
72_1079	2.8	3.7	6.3	23.9	4.1	0.93	6	0.31	6.3	2.9
72_1080	2.4	3.2	7.1	36.6	3.1	1.09	6.3	NA	6.5	0.5
72_1081	3.3	4.4	8.6	40.3	3.7	1.01	7.4	0.31	6.5	0.6
72_1082	4.9	6.6	8.7	25.6	3.8	1.57	7.4	1.6	6.6	2.8
72_1083	7.7	4	9.9	40.3	2.2	3	6.6	0.92	6.6	6.5
72_1084	5.5	3.1	8.3	32.9	2.5	2.1	7.4	1.57	6.7	2.4
72_1086	3	3.7	5.5	15.4	3.1	0.91	4.8	1.1	6.3	3.1
72_1087	3.9	2.8	7.05	24.3	3.1	1.01	6.75	1.05	6.8	5.55
72_1089	9.8	3.9	15.75	56.1	4.7	3.95	12.9	3.7	6.75	11.9
72_356	4.9	3.8	9.9	36.6	2.2	2.4	10.6	2	6.6	5.1
72_392	7.7	6.4	14.9	34.2	2.8	3.7	14.3	4.1	7	14.7
72_431	4.95	3.9	9	34.2	1.54	2.8	8.2	1.64	6.9	4.5
72_513	5.6	2.5	8.55	46.4	1.12	2.95	7.3	0.07	7.25	1.4
72_514	7.5	3.4	14.2	70.8	1.27	4.8	14.8	0.06	7.8	9.7
72_6637	7.4	7.35	11.55	24.3	6.5	2.25	8.7	5.1	6.3	2.55

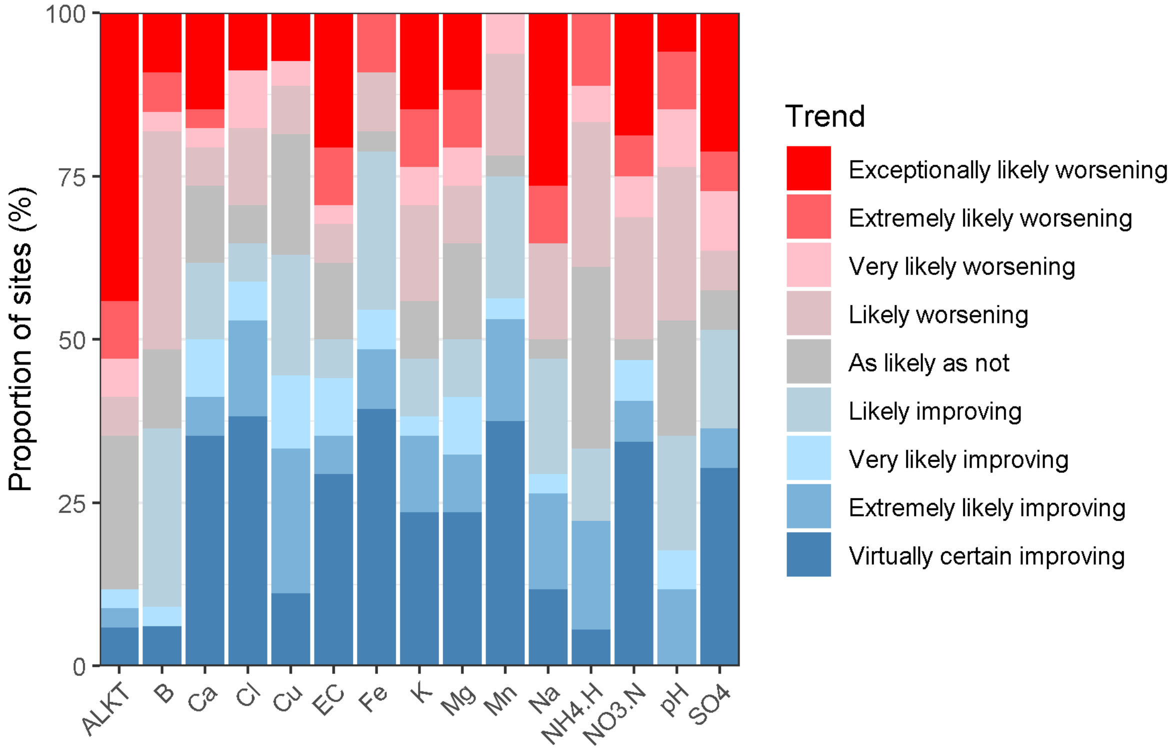

Figure 17: Trends in groundwater quality in 34 wells in the Taupō catchment, 2003–20.

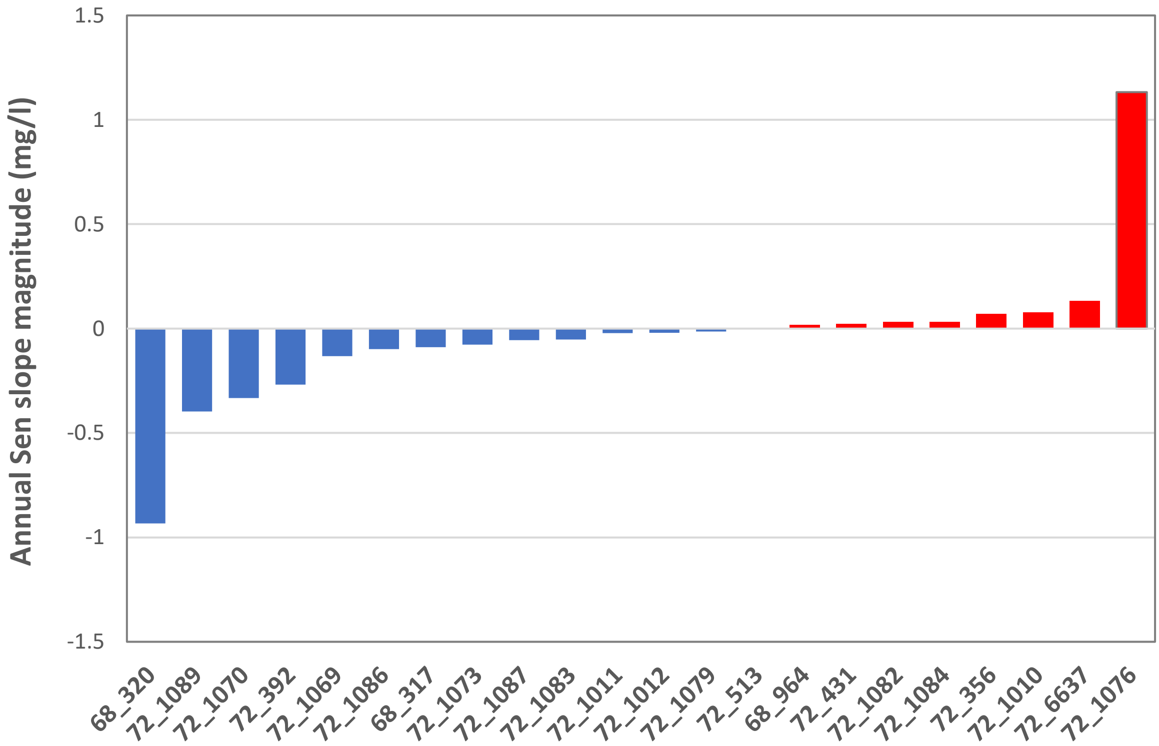

Figure 18: Magnitudes of trends in nitrate change for trends of 95% confidence

The spatial distribution of the state and trends in nitrate concentrations in the groundwater wells is shown in Figure 19. There are no obvious spatial trends apparent in this distribution. With the exception of the two anomalously high, point source influenced wells, concentrations are relatively low compared to those in areas of the Waikato region which are influenced by intensive dairy and market gardening activities (Hadfield 2022).

Although there are land-use impacts apparent, monitoring to date shows that nitrate concentration trends are mixed and not increasing overall. There are more significant decreases than increases represented in the monitoring dataset. Apart from the sites influenced by point sources, the trends are gradual. The rates of change tend to be greatest associated with the highest concentrations. Unsurprisingly, no change is expected at anaerobic sites unless there is a change in redox conditions.

Nitrate concentration variation with the depth of the groundwater wells is shown in Figure 20. The total depth provides a broad indication of the sampled groundwater depth. Typically, there is a wedge-shaped distribution in Waikato groundwaters showing higher nitrate concentrations and a larger range are more prevalent in shallower wells. The distribution in Figure 20 is consistent with this wedge shape, although strongly influenced by one point source influenced site. Low nitrate concentrations may also occur at shallow depth, depending on factors such as redox conditions and land-use. The redox status of each well is also shown, based on the following criteria:

Aerobic:	NO_3-N > 1 g/m^3 and NH_4, dissolved Fe and dissolved Mn all non-detect
Anaerobic:	Two of NH_4, dissolved Fe and dissolved Mn detected and NO_3-N non-detect
Mixed:	NO_3 -N > 1 g/m^3 and two of NH_4, dissolved Fe and dissolved Mn detected
Indeterminate:	Criteria above are not met

The wells with anaerobic groundwater are essentially devoid of nitrate (Fig. 20). It is apparent that the mixed category can have high nitrate concentrations. These monitoring wells are typically screened across more than one redox condition (Hadfield 2021). Indeterminate category wells are yet to show definitive land-use effects and may represent wells with old groundwater or situations where there are no significant land-use effects. Almost half the network monitors wells with aerobic conditions with anaerobic and indeterminate redox categories at six wells (17.6%) and five wells being of mixed category. This representation provides one view of the larger groundwater environment discussed further below.

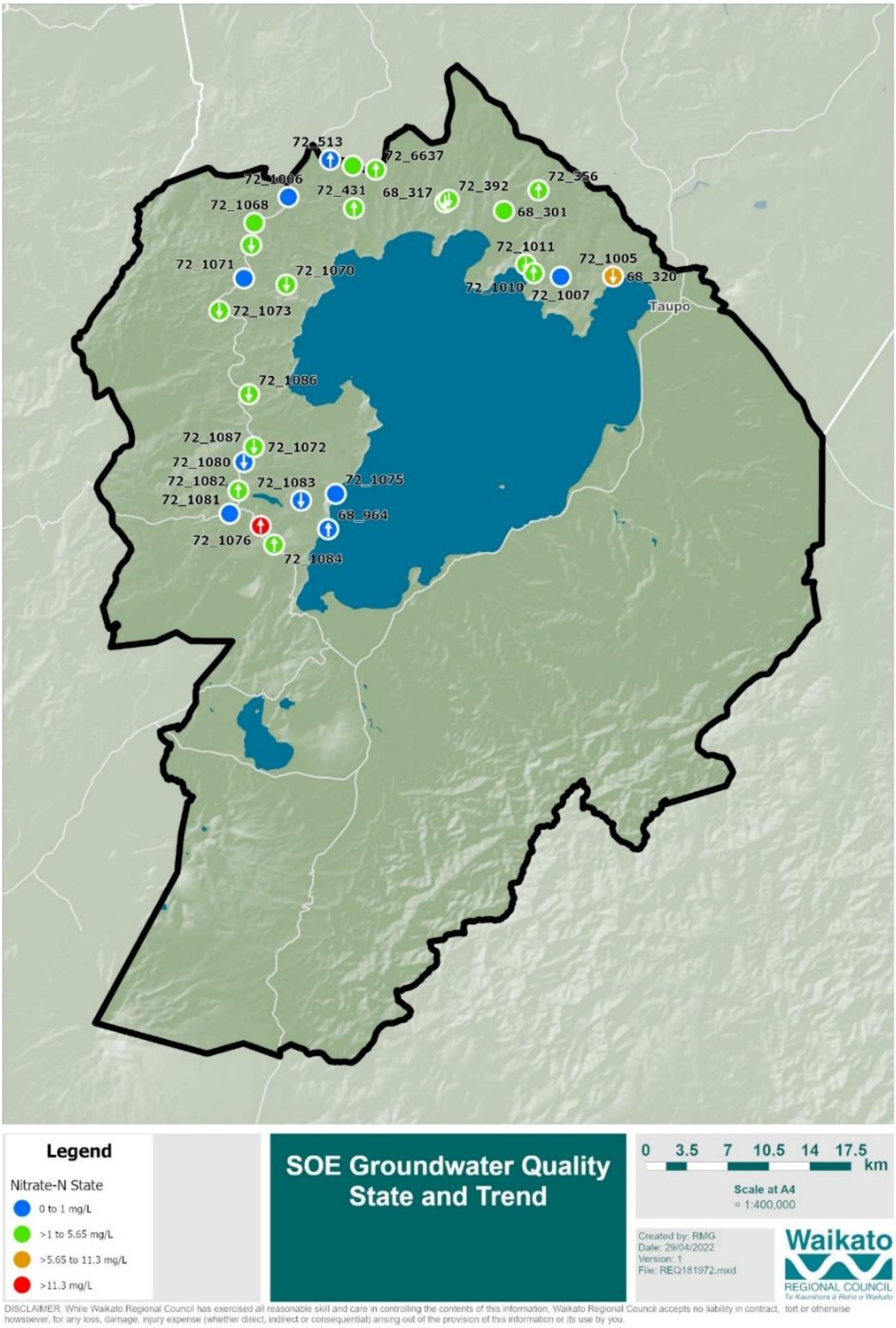

Figure 19: State and trend of nitrate concentrations in groundwater wells in the Taupō catchment.

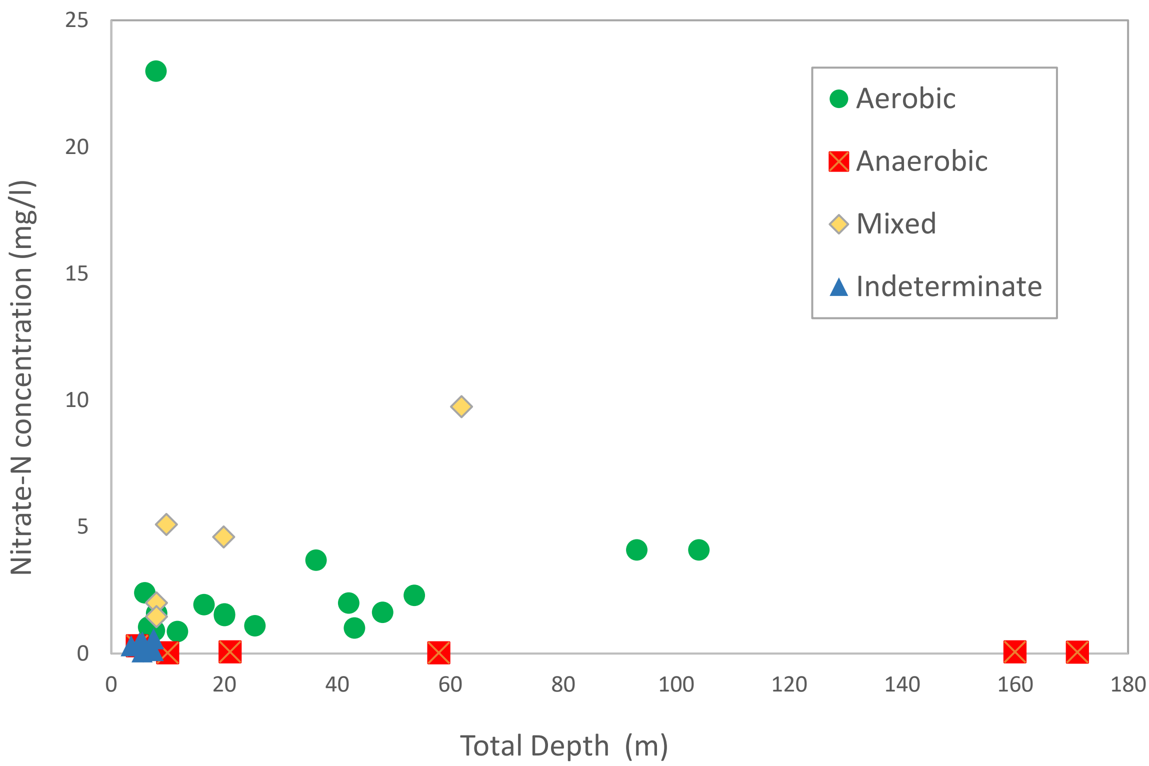

Figure 20: Median nitrate concentrations during 2016-20 versus total well depth for monitoring network wells; the redox status of each well is shown.

4.2 Groundwater fate and transport: age and lags

Groundwater age has been estimated by analysing tritium isotopes and atmospheric trace gases (CFC and SF_6). This included initial analyses of 25 samples in the northern and western catchments (Hadfield et al. 2007). MRTs have been estimated for 14 of the current groundwater quality monitoring network wells. These are shown in red in Figure 21, with nitrate concentrations from 2020. The remaining 11 points are from the earlier survey.

The plot does show a typical wedge shape narrowing with age as the agricultural influence diminishes. Younger groundwaters may have a range of nitrate concentrations dependent on factors including redox conditions and site specific, land-use intensity.

Water samples comprise a mixture, rather than a discrete age dependent on the relative contribution of flow paths. It is therefore useful to also estimate the fraction of water recharged since farming was established in the Taupō area (% young fraction), beginning in the mid-1950s. The potential future nitrogen concentration, when ambient groundwater has been flushed out, may be simply estimated as an increase inversely proportional to the % young fraction (Morgenstern et al. 2007). This assumes little ambient nitrogen concentration and consistent land-use.

Figure 22 shows measured nitrate concentrations during 2007–20 for the 14 available current monitoring network sites with groundwater age estimates. The potential equilibrium concentrations are also shown. These were calculated from the 2007 results divided by the proportion of young, land-use affected water. Although the available data is limited, it is evident that there are common divergences in magnitude and direction from nitrate concentration trend projections. Although the general spatial distribution of land-use impacted sites is similar, the temporal variations are important for predicting future mass nitrogen flux to the lake.

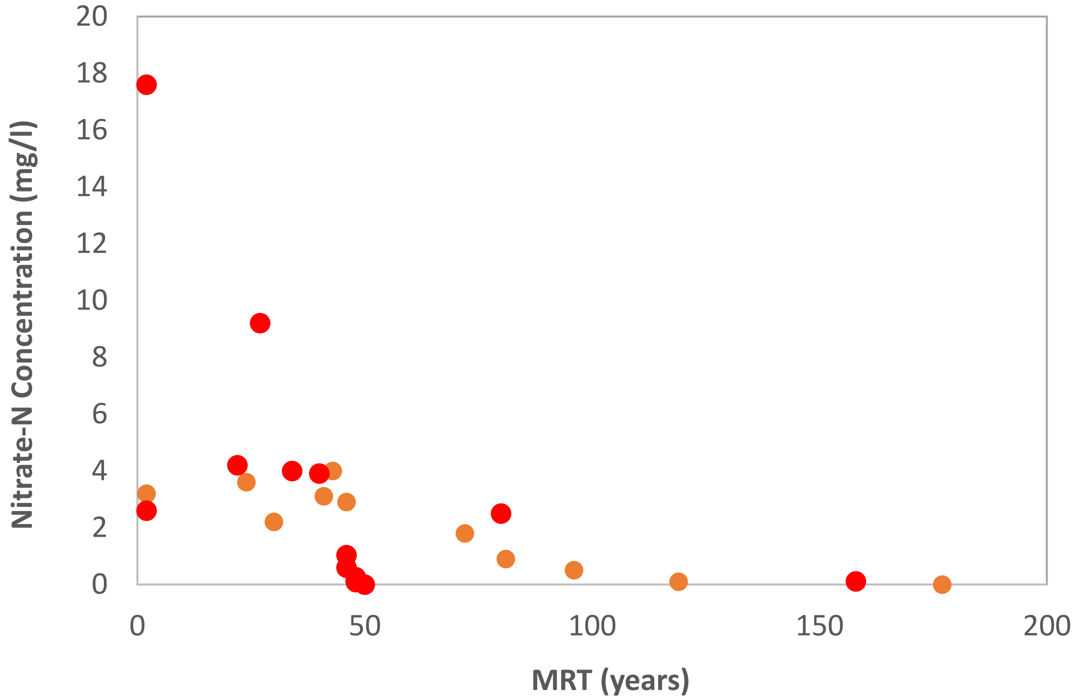

Figure 21: Nitrate concentration and groundwater age in groundwater wells in the Taupō catchment. Sites shown in red are from the current groundwater quality monitoring network; sites in orange are from the earlier survey.

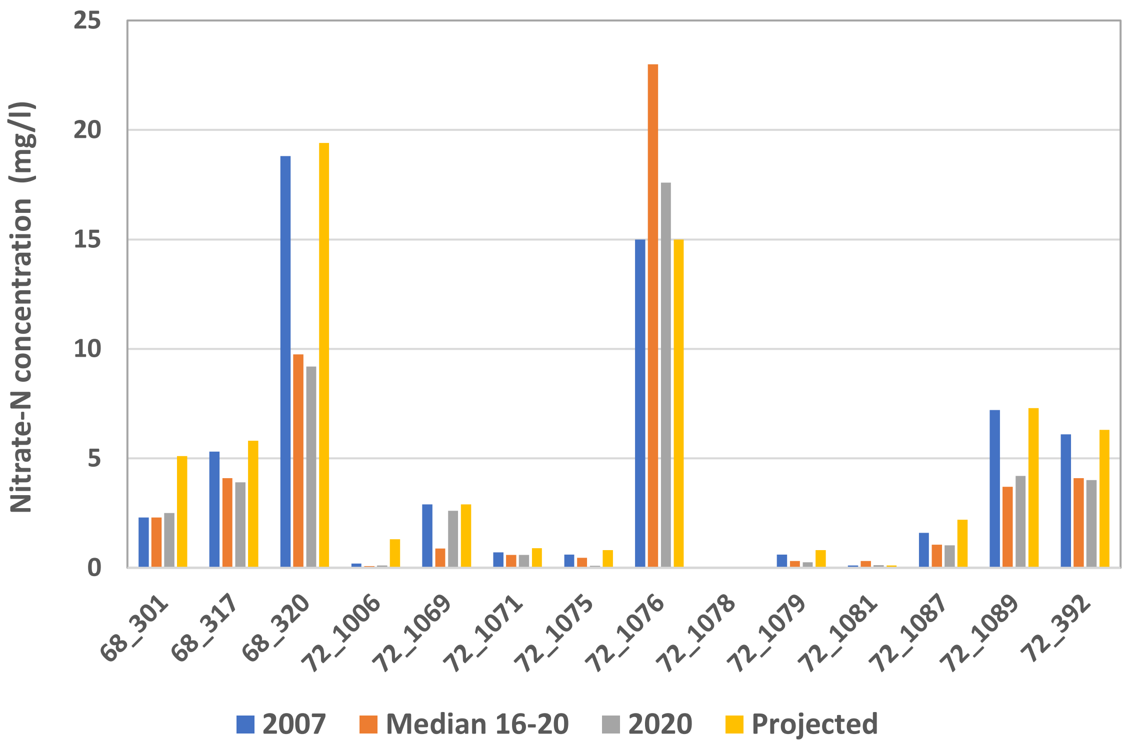

Figure 22: Nitrate concentrations during 2007–20 in 14 groundwater wells where water age has been estimated. Projected concentrations are also shown: see text. The percent young fractions in order of appearance from the left are 45, 91, 97, 15, 100, 77, 72, 100, 67, 71, 71, 76, 98 and 97. Two of the wells (72_1078 and 72_1081) have anaerobic groundwater and well 68_320 has a mixed redox category.

It is generally inferred from groundwater age analysis that groundwater quality has not yet reached equilibrium with land-use. This is the conceptual basis for further increases in nitrogen load being expected as old pristine groundwater is progressively replaced by younger land-use impacted water. The extent of this is uncertain, however, and observed temporal trends suggest this is not as large as early worst-case scenarios predicted. The area of greatest potential for additional load to come is the northern area east of the Waihora sub-catchment where streams are underfit and some 70% of flow to the lake is via direct seepage of groundwater. The attenuation of nitrogen and mass flux transport are described below.

Morgenstern (2007b) compared other groundwater quality determinand concentrations with the 25 age estimates available in 2007. A positive correlation was found between DRP and groundwater age indicating it is of geogenic origin. There was no indication of any breakthrough from more recent fertiliser use. Higher concentrations of sulphate and potassium were found in younger waters, indicating anthropogenic effects.

4.3 Nitrogen attenuation in groundwater

Denitrification is a key nitrate attenuation process, where nitrogen leached into groundwater can be reduced to gaseous forms. The distribution of redox conditions within the lake catchment is fundamentally important for attenuation during transport. Denitrification is a microbially mediated process requiring an electron donor and anaerobic conditions (Korom 1992). There has been considerable investigation of both the distribution of favourable conditions for, and processes involved in, denitrification in the Taupō catchment. Evidence to the Environment Court in 2008 indicated that the extent of denitrification was an area of uncertainty that had the potential to substantially influence the estimation of nitrogen input to the lake from groundwater. More recent investigations have shown anaerobic conditions in the Taupō catchment are more prevalent with greater potential for attenuation through denitrification.

Shallow drilling of boreholes in the Taupō catchment has been carried out to obtain soil cores to identify redox conditions in the soil profile using the Childs' test (Childs 1981). A colour changing reagent (dipyridil in an ammonium acetate solution) applied to the cores showed where iron was present in the reduced (ferrous) form, thereby indicating anaerobic conditions. The shallowest groundwater in the Lake Taupo catchment is typically oxic (Clague et al., 2013). Figure 23 shows the depth from the water table to the first redox change to anaerobic conditions. These redoxyclines occurred at a depth of less than five metres at nearly 60% of the sites investigated (range <1 to >20 m). Note that nitrate is not detected in groundwater samples obtained from piezometers specifically isolated to anaerobic zones. Similar investigations in other parts of the Waikato region (e.g. Hauraki and Hamilton Basin) have also shown redox chemistry results consistent with Childs' testing indications.

Laboratory analysis of retrieved core samples showed low sulphide and low carbon content apart from sections of paleosols. Further testing using a ferrous fractionation method, where progressively aggressive extractions were carried out using anaerobically stored core, showed that the exchangeable ferrous ion concentration distribution was consistent with the Childs' testing undertaken in the field (Hadfield and Korom 2012).

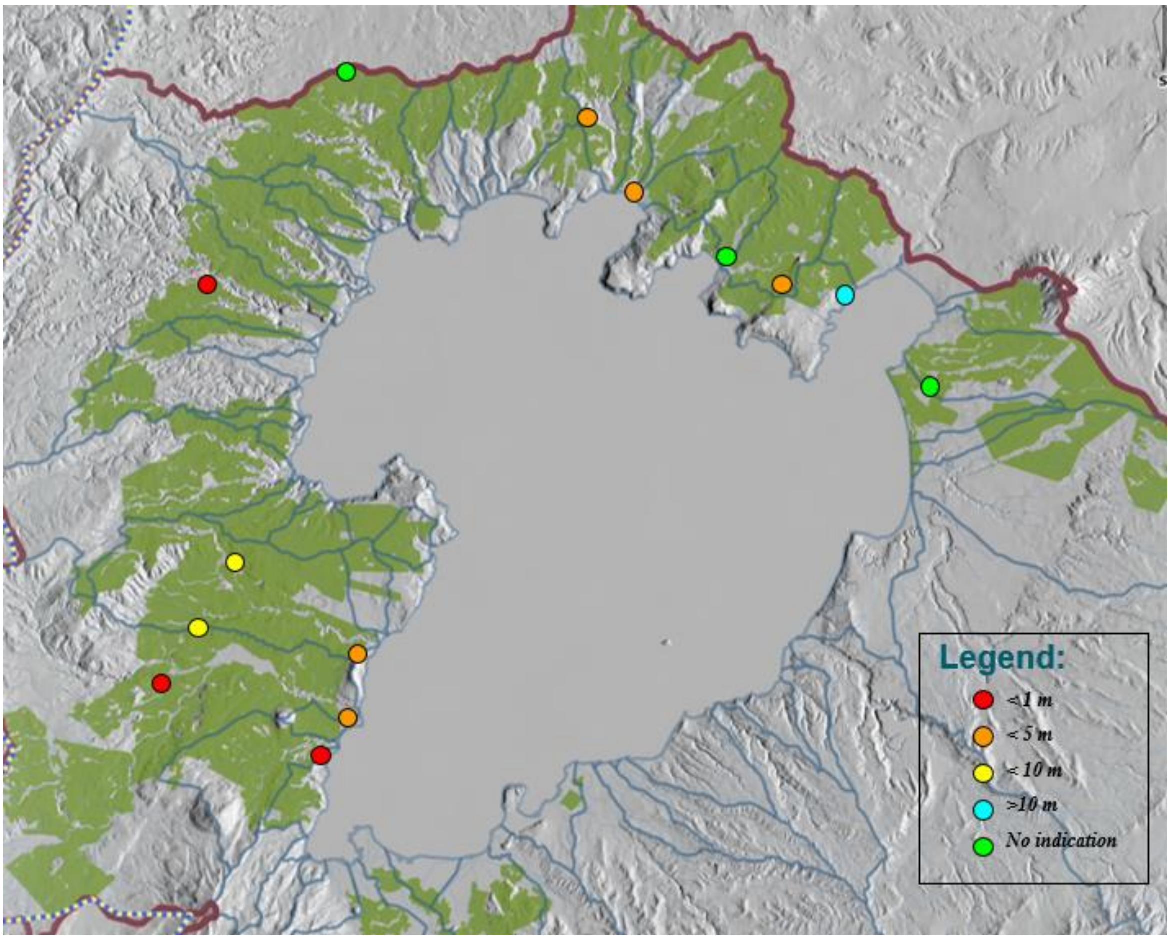

Figure 23: Depths from the water table to anaerobic conditions in 14 boreholes in the Taupō catchment (green shading indicates areas of pastoral development)

A series of "push-pull" tracer tests were carried out at 14 of the study sites to see whether nitrate injected into the anaerobic zones would actually be attenuated. Denitrification at various rates was confirmed relative to a conservative bromide tracer (Hadfield and Korom 2012). In-situ mesocosms were also used to enable longer term geochemical modelling to determine electron donor contributions. Denitrification in Oruanui Ignimbrite at a site in the Tutaeuaua sub-catchment was indicated by both accelerated reduction of nitrate relative to bromide and isotopic fractionation. Both ferrous iron and to a lesser extent organic carbon were shown to contribute as electron donors. This indicated that while organic carbon in paleosols is important, denitrification may be more widespread with both autotrophic and heterotrophic denitrification occurring in the Lake Taupō catchment (Korom et al. 2016).

The above work showed where attenuation of nitrate would occur. Importantly also for modelling, it showed where nitrogen would not be transported with groundwater flow. Martindale at al. (2019) went a step further and looked for evidence of where denitrification was actively occurring. This involved calculating the concentration of excess N_2 gas to quantify the extent of denitrification under natural flow conditions. Measurement of two noble gases (neon and argon) enabled differentiation of the excess N_2 gas produced via denitrification from atmospherically derived dissolved N_2 gas. This method was applied to ten shallow piezometers in the Lake Taupō catchment, in combination with other denitrification proxies ($\delta^{18}O$ and $\delta^{15}N$ isotopes of nitrate), identification of microbial denitrifying genes and redox conditions. Results showed eight of the ten sites had measurable excess N_2, indicating that denitrification had occurred there. While only based on the Ne/Ar ratio, Stenger et al (2018) had already reported excess N_2 results from the Lake Taupo catchment (insignificant amounts present in the shallow oxic groundwater, but concentrations between 1.7 and 4.8 mg N/L in the underlying anoxic groundwater).

Extensive investigation has also occurred at an intensively instrumented Waihora hillslope study site in the Tautaeuaua catchment (Barkle et al. 2011, Stenger et al. 2018). This examined small scale biogeochemical and hydrological controls on denitrification at a well field consisting of 11 multilevel well clusters. A field monitoring system to directly measure fluxes through the vadose zone was also installed involving automated equilibrium tension lysimeters. Vertical redox gradients and denitrification potentials were detected at 7 of the 11 sites.

Palaeosols were identified as electron donors for denitrification in laboratory experiments (Clague et al., 2013). Enhanced groundwater dissolved organic carbon (DOC) concentrations occurred where resident electron donors were present. DOC concentrations were lower where anoxic and nitrate-depleted groundwater was found, along with an absence of resident electron donors. This implied that up-gradient nitrate reduction had occurred. Tritium-based age dating indicated oxic conditions at the site were restricted to very young groundwater (MRT ≤ 3 yr). Anoxic groundwater was also sufficiently young (3–25 yr MRT) to have received leachate from agricultural land-use activities (Stenger et al., 2018).

4.4 Modelling the fate and transport of nitrogen in groundwater

Numerical modelling of groundwater flow and nitrogen transport has been undertaken in the Taupō catchment using three separate model domains. The western catchment has been modelled by GNS using a sequence of models. The first was a single layer, finite element model using FEFLOW software (Hong 2005). This model simulated conservative (non-reactive) nitrogen transport and included six streams. Subsequent modelling switched to Modflow and MT3D software, comprised 16 layers and included additional transient transport calibration using tritium (Gusyev et al. 2013). Nitrogen transport was again assumed to be conservative.

The most recent western catchment modelling used a stochastic approach with Modflow and MT3D (Hemmings 2021). Other modelling is deterministic and hence there is uncertainty inherent in modelling assumptions. With denitrification included in this recent modelling most wells were predicted to reach equilibrium concentrations within 150 years, with a median of 38 years and interquartile range of 18 to 84 years. The median predicted equilibrium nitrate concentration for all wells was 0.99 g/m^3 with an interquartile range of 0.35 to 2.53 g/m^3. The median time for equilibrium nitrogen discharge to the lake was predicted to be 65 years with an interquartile range of 52 to 84 years. The predicted median mass flux of nitrogen to the lake was 309 t/yr with an interquartile range of 174 to 503 t/yr. Predicted quantities were greater if denitrification was ignored.

The northern catchment was modelled using Modflow and MT3D in three layers to simulate steady state flow and transient (time variant) nitrogen transport (Hadfield 2007). Flow calibration indicated groundwater velocities in the range of about 0.02 to 1.5 m/day with highest rates in simulated fractured ignimbrite and porous media in the vicinity of Kinloch. Groundwater travel time to the lake was over 100 years along some flow-paths. Under ambient conditions before agricultural development roughly 65 t of nitrogen were estimated to discharge to the lake annually from the northern catchment, with some 3,500 t of nitrogen being stored in the groundwater system.[33]

[33] Representation of fractured ignimbrite in the west of the model domain by lower porosity formation had the effect of reducing the capacity of the groundwater system to store nitrogen. This meant that nitrogen flux to the lake increased more quickly.

Land use effects at the time were simulated by modelling estimated farm-influenced nitrogen loading for a period of 35 years. Conservative nitrogen transport was assumed, given the limited knowledge of denitrification rates in the catchment at that stage. The discharge of nitrogen from groundwater after 35 years was roughly 175 t/yr, at which time some 10,000 t of nitrogen was estimated to be stored in the groundwater system. Extended model simulation indicated equilibrium annual nitrogen flux of roughly 300 t would occur after some 250 years. The mass of nitrogen stored in the northern groundwater modelled at that stage would be some 18,000 t. It was predicted that roughly half the total manageable nitrogen load of about 235 t would be still to come. Given about 30 per cent of groundwater discharge to the lake from the northern catchment is via streams, the contribution still to come from direct groundwater seepage was therefore estimated to be roughly 90 t. This assumed no attenuation and was therefore a worst-case, given some denitrification (≈20%) was at that stage expected.

Modelling of a proposed policy initiative to reduce the manageable nitrogen load was carried out by reducing all the estimated manageable land-use loading by 20% after 35 years of simulation. Differentiating nitrogen input to the model before and after the 20% reduction as separate contaminants provided insight into transport, as trends varied throughout the domain. Rather than introduce denitrification into this model, attenuation was subsequently considered by discounting nitrogen mass flux contributions to the lake from parts of the domain. This was based on the observation that where anaerobic conditions conducive to denitrification occurred, no nitrate was detected. For example, very simplistically removing the nitrogen contribution of the deepest model layer and part of the middle layer had the effect of reducing the equilibrium annual nitrogen flux to the lake to about 185 t, with mass flux approaching a quasi-equilibrium after about 80 years (Hadfield and Korom 2012).

The eastern lake catchment was modelled by Bou (2007) using a FEFLOW finite element model involving steady state flow and transient transport. The model was described as illustrative rather than predictive given surface flows were not sufficiently included. Nitrogen transport was simulated as a conservative solute with mass flux to the lake predicted to roughly double in 20 years.

There is now improved information on nitrogen fate and transport in the lake catchment for modelling, including more detailed estimates of leaching from Overseer. Denitrification mechanisms and distribution, in particular, are better understood than in 2007 when an upper limit assumed no attenuation (to accommodate appellants). Interpolation between sites and scaling up for modelling, however, remain challenging aspects. Efforts to find pragmatic spatial predictors for redox change (e.g. geological) have made little progress. There is generally increasing recognition of the relative importance of shallow groundwater pathways for streamflow, which is often derived from a veneer of the total groundwater storage (Berghuijs and Kirchner 2017). This is also likely to be accentuated in nitrogen flux to the lake via direct groundwater seepage given typically reduced redox conditions at depth.

In summary, considerable investigation into the likely extent of denitrification in the Lake Taupō catchment, signalled to the Environment Court (2008) as very uncertain, indicates that substantially greater nitrogen attenuation is likely. This suggests the nitrogen load still to enter the lake via direct groundwater seepage and indirectly via steams is considerably less than earlier predicted.

5 Implementation of Waikato Regional Plan Section 3.10

As outlined in the Introduction, during the period 2005–11 the Waikato Regional Council and the Environment Court varied the Waikato Regional Plan so the Council could control the amount of nitrogen entering Lake Taupō from its catchment. The new section 3.10 of the Plan introduced rules that capped manageable sources of nitrogen at their 2001 levels. It also provided for the establishment of an $80-million public fund that could be used to purchase the rights to discharge nitrogen in the catchment so these could be retired, and thus in effect be removed from the nitrogen budget for the lake (Fig. 2, Table 1). This would offset some of the load of nitrogen which is still in transit to the lake (i.e. the "nitrogen load to come"). Central, regional and local government all contributed to the fund, and together with the local iwi, represented by the Tuwharetoa Maori Trust Board, oversaw the operation of the Lake Taupō Protection Trust.

The Council began by "bench-marking" the load of nitrogen discharged during 2001–05 from all the farms in the catchment, using an on-farm nutrient management model (Overseer). This established the "nitrogen discharge allowance" (NDA) for each property. By the end of 2012, Council staff had completed the process of benchmarking and advised the Trust that the combined nitrogen discharge from all the farms considered was about 850 t/yr.[34,35] The NDAs of each of the bench-marked properties in the catchment are shown in Figure 24, with the average NDA being about 17 kg/ha/yr. By 2013, some 80 consents to farm had been issued by the Council, taking account of each farm's NDA.

During 2008–15 the Trust purchased NDAs totalling 170 t/yr,[36] or 20% of the combined NDAs from the farms in the catchment.[37] As a result, 6675 ha of farmland have been permanently converted to forestry—with the areas and adjusted-NDAs being noted on the relevant farms' consents. This has meant about 12% of the land area that was in pasture before the Plan was developed (Fig. 1) is now covered in forest.

In due course, the former areas of pasture now in forestry should discharge less nitrogen, with the load of nitrogen actually delivered to the lake from them falling by perhaps half that of the retired NDAs (= 170 t/yr of "Overseer" or unattenuated nitrogen). Furthermore, as described above (section 4), the load of nitrogen stored in groundwater in the catchment and which is still to enter the lake via the inflowing streams and by the direct seepage of groundwater is now considered likely to be substantially smaller than was predicted in 2007.[38] As a result, the combined load of nitrogen entering the lake in the future may well be similar to that estimated in 2008 (see Table 1).

[34] Monthly report from WRC to Lake Taupō Protection Trust, December 2012. WRC doc #2528594.

[35] Note that this load (850 t/yr) is larger than the corresponding value in Table 1, namely 510 t/yr. This is because Overseer determines the amount of nitrogen escaping from the root zone of an area of pasture, and not the amount of nitrogen that finally enters the lake from it. As noted above (Introduction), some of the nitrogen leaving the root zone is "attenuated" by being lost to the atmosphere as it travels to the lake, so the load of "Overseer-nitrogen" is always larger than that of "delivered-nitrogen".

[36] See Lake Taupō Protection Trust's report for the year ending 30 June 2021 at LTPT-Chairs-Report-YE-2021.pdf (waikatoregion.govt.nz). And see Barns and Young (2013) for a comprehensive review of the development and operation of the market in NDAs.

[37] NDAs totalling an additional 17 t/yr have also been traded privately within the catchment.

[38] In 2007 the nitrogen load to come via both the inflowing streams and the direct seepage of groundwater was predicted to be 160 to 230 t/yr: see WRC document #1418479.

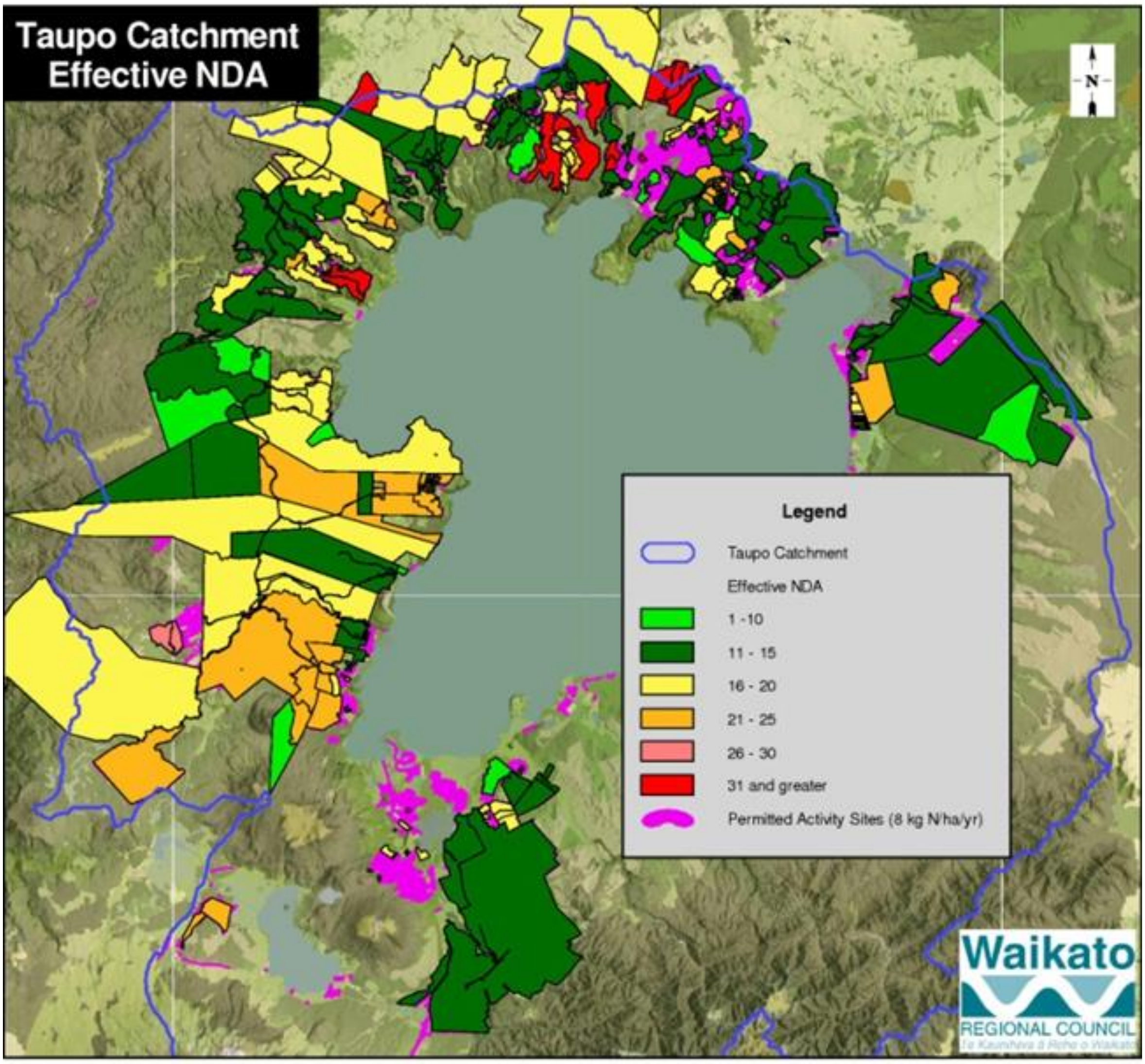

Figure 24: Nitrogen discharge allowances (kg N/ha/yr) of bench-marked properties containing pasture in the Lake Taupō catchment (determined using Overseer v5.4.3).

6 Summary and conclusions

The water quality of Lake Taupō has been studied since the 1930s. The lakewater is generally clear and blue, reflecting the low concentrations of freely floating plant cells (“phytoplankton”) and the nutrients nitrogen (N) and phosphorus (P) which support their growth. During 2000–11 a statutory plan was developed to protect the lake’s excellent water quality. This involved managing the current inputs of N to the lake from the surrounding catchment; at the same time the inputs of P have been closely monitored.

Waikato Regional Council has routinely monitored the water quality of the lake at a deep-water site since 1994 (with the field and laboratory work being undertaken by NIWA). The survey results confirm the excellent quality of the lakewater, with low concentrations of N, P and chlorophyll. During 2016–20 most of the requirements of the National Policy Statement for Freshwater Management (NPS-FM) for “Band A” (=”oligotrophic”) lakes were met—although dissolved oxygen concentrations in the deeper waters only met the requirements for Band B lakes. The generally more stringent Waikato Regional Plan (WRP) requirements for the lake were also met—with the exception that an average total N of 70 mg/m^3 was exceeded. (When the WRP standards were set it was recognized that the standards might not be met for several decades.)

There was an increase in total N concentrations in the lakewater from 2010, with the annual average peaking at 119 mg/m^3 in 2013; this was followed by a decrease through to 2020 (annual average 71 mg/m^3). No obvious explanation for these changes is apparent (and the changes are not seen in a contemporaneous, independent record of total N in the water flowing out of the lake). Apart from the changes in total N, lakewater quality has been largely stable since 1994. The concentrations of certain forms of N and P in the lakewater suggest that phytoplankton growth in the water is now dependent on the availability of both N and P. And while the concentrations of either or both nutrients remain low, phytoplankton levels are likely to do so as well.

The water quality of 14 rivers and streams flowing into the lake is also routinely monitored. In general, the water quality of these streams is good or better; often it is in Band A of the relevant NPS-FM attributes. Dissolved reactive P concentrations are an exception, however, probably reflecting the naturally high concentrations found in cold-water springs in the Taupō catchment (and elsewhere on the Central Volcanic Plateau).

Nitrogen concentrations in several streams in catchments where pasture is the dominant landcover have increased markedly since the 1970s. Phosphorus concentrations, however, have shown little change. On average, the combined load of river-borne nitrogen entering the lake from the catchment was estimated to have increased by about 5–7% over the past 20 years. Some of the increase has occurred in streams draining catchments where pine forest is currently the dominant landcover, but where records show that pasture was present in the past (1950s). This is likely to reflect the often slow movement of water through the land and into the inflowing streams, such that the load of N from historic farming has taken an appreciable time to reach the stream waters.

Mean residence time, MRT (or “water age”), during summer has been routinely determined in 11 streams draining areas in the northern and western part of the lake’s catchment where pasture is present. Four streams in the northern area have MRTs in the range 40–80 years; the other streams—in the western part of the catchment—have ages in the range 10–25 years. Nitrogen concentrations in these streams—particularly those with longer MRTs—have continued to increase, consistent with earlier predictions of a “nitrogen load to come”.

Groundwater is the primary link for the transport of nitrogen from land-use to the lake, either as direct seepage or indirectly via typically baseflow dominated streams. Most of the rain falling in the Taupo catchment percolates through the soils and can take many years before re-emerging and thus may reflect activities that occurred in the past. Much of the investigation of groundwater in the Taupō catchment has thus focused on the load of nitrogen that is still migrating to the lake, and the processes that can remove it from the water on the way. Research has progressively shown that conditions favourable to denitrification are widespread in catchment groundwater and described the mechanisms involved. This focus was signalled early on as important to estimate nitrogen load projections more confidently for management.

Groundwater quality is routinely monitored in a network of 34 wells in the Taupo catchment. Median nitrate-N concentrations are typically low (≈70% < 2 g/m^3) and the two highest (9.75 and 23 g/m^3) are impacted by point sources. Deeper and older groundwater has little nitrate, and it is not detected where conditions are anaerobic. Slight-to-moderate trends in nitrate concentration have been found at many wells, with decreases slightly outweighing increases.

Numerical modelling estimations of the nitrogen load to come have progressively considered the improved understanding of denitrification in the catchment. Despite remaining uncertainties, simulation of the potential eventual load to the lake indicates it is likely to be substantially less than early worst case predictions.

The water quality rules for the Taupō catchment in the Waikato Regional Plan (WRP, see chapter 3.10) aim to protect the water quality of the lake by (1) capping all sources of manageable nitrogen from the catchment at their 2001 levels, and (2) offsetting much of the load of nitrogen which is still in transit to the lake by reducing some of the manageable sources. A public fund has been used to purchase the rights to discharge about 20% of the nitrogen entering the lake from manageable sources. This has meant that some 6675 ha of pasture, or about 12% of the area of pasture in the Taupō catchment in the year 2000, has now been planted in forest. In due course the load of nitrogen delivered from this land is expected to fall. This will help offset the load from historic activities still travelling through the groundwater, which as noted, is now considered likely to be substantially smaller than initial conservative predictions.

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Appendix 1: Contrasting records of total nitrogen in the lake and its outflow

At the same time as the water quality of Lake Taupō and its inflowing streams has been routinely monitored since the mid-1990s, the water quality of the outflow from the lake—the Waikato River—has been monitored by NIWA as part of its "National Rivers Water Quality Network" (from 1989). This means there are records of lake and outflow water quality covering nearly three decades which may be compared with one another.

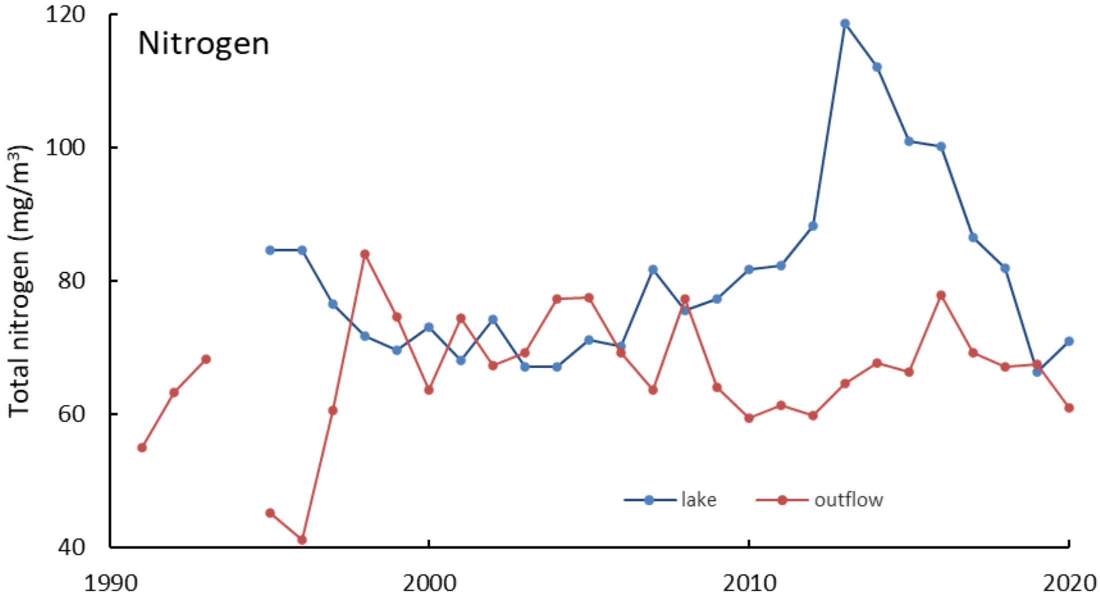
Although the samples collected from the lake and its outflow have been analysed by the same laboratory, namely NIWA Hamilton, somewhat different methods have been used for some variables. In particular, total nitrogen and total phosphorus concentrations in the samples from the lake have been determined by separately-analysing various different fractions—noting that the fractions analysed have changed over time—and combining the resulting values (see section 2). By contrast, the samples from the outlet are analysed by using strong reagents to "digest" all the different components present into simple inorganic forms of nitrogen and phosphorus, and then determining the concentrations of these.

Figure A1 shows the annual average concentrations of total nitrogen and total phosphorus in samples collected from the 0–10 m surface layer of the lake and from its outflow during 1991–2020. And Table A1 shows the average concentrations during the last two decades—periods for which all the records are complete or nearly-so. The average total phosphorus concentration in the lake during 2001–10 was 8% higher than in the outflow (with the difference just being statistically significant: t-test, $p \approx 5\%$). More strikingly, the total nitrogen concentration in the lake during 2011–20 was 40% higher than in the outflow, and the difference was highly significant ($p = 0.01\%$).

It is difficult to account for these differences, especially the difference in total nitrogen concentrations during the past decade, and particularly during 2009–2018 when the annual average concentrations in the lake were consistently higher than in the outflow (Fig. A1). A hypothesis could be advanced that during this period a larger proportion of settling nitrogen was recycled from the lakebed to the overlying water (Fig. 2). But what processes may have caused this, and why the recycled nitrogen then disappeared from the 0–10 m layer—either by resettling or by denitrification—before the water left the lake via the outflow is not-at-all clear. More work would be needed to clarify this.

Table A 1: Decadal-average concentrations (mg/m^3) of total nitrogen and total phosphorus in Lake Taupō and its outflow during 2001–20.

	Total nitrogen		Total phosphorus	
	Lake	**Outflow**	**Lake**	**Outflow**
2001–10	74	70	5.5	5.1
2011–20	93	66	5.2	5.0



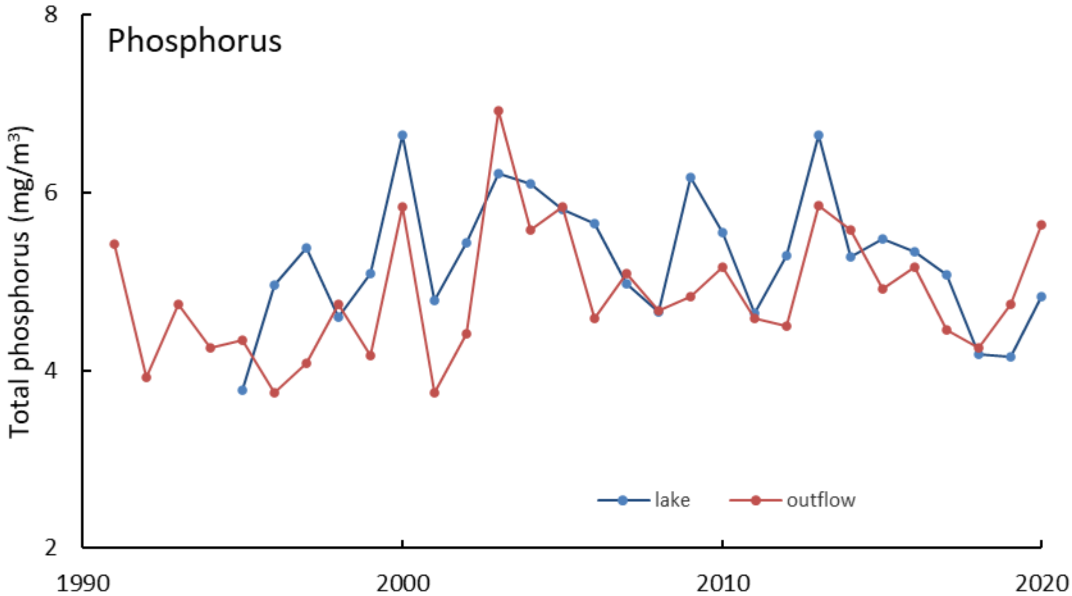


Figure A. 1: Annual average total nitrogen and total phosphorus concentrations in Lake Taupō (10-m tube results, blue lines) and its outlet (Waikato River at Reids Farm, data from NIWA, red lines), 1991–2020.

Appendix 2: Forms of nitrogen in 13 inflows to Lake Taupō

The water quality of 13 rivers and streams flowing into Lake Taupō is monitored routinely (see section 3). The streams, and the average concentrations of total nitrogen determined during 2016–20, are listed in Table 7. Figure A2 shows how the proportion of nitrogen that was present as DIN in each stream tended to increase as the concentration of total nitrogen increased: the more nitrogen was present, the larger the proportion of it that was DIN. On average, apart from the Tokaanu Power Station tailrace, DIN represented between 51% and 93% of the total N in these inflows. In the Tokaanu tailrace samples DIN averaged 11% of the total nitrogen, presumably because algae in the lake upstream (Lake Rotoaira) use much of the DIN that is present there, converting it to organic forms before the water is entrained into the Power Station.

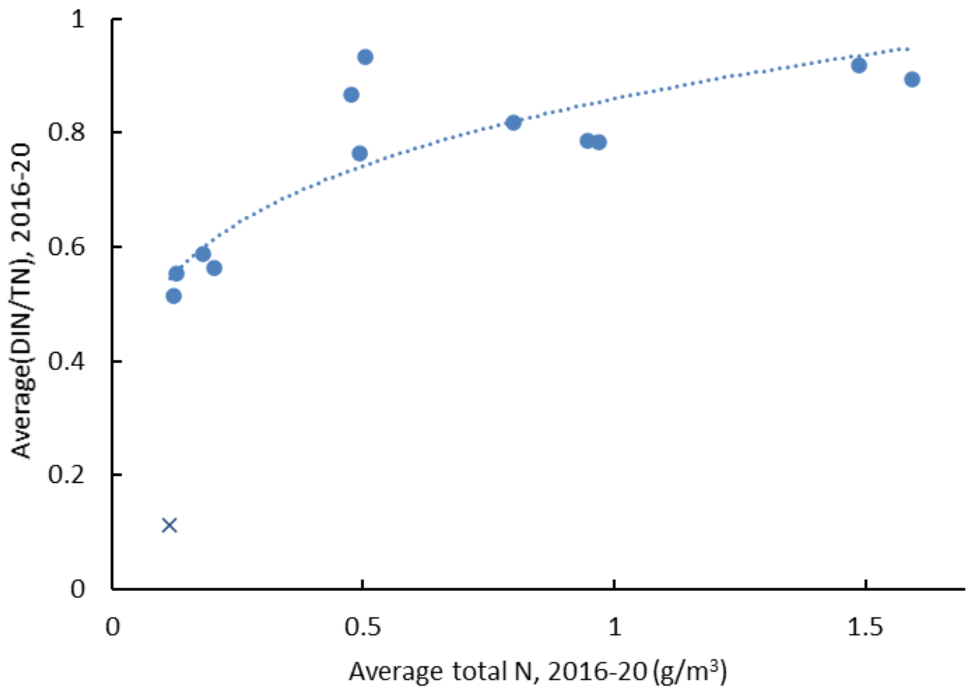


Figure A. 2: Ratio of DIN to total N (DIN/TN) versus average total N in 13 inflows to Lake Taupō, 2016–20. The cross is the result for the Tokaanu Power Station tailrace (i.e. the outflow from Lake Rotoaira).

Appendix 3: Trends in water quality in 12 inflows to Lake Taupō.

This shows the trend slopes (% per year) and, in brackets, slope direction probabilities (%) for monthly records of flow-adjusted water quality variables at 12 inflows to Lake Taupō. Results are shown for 1993–2020 (28-year record) and for 2011–20 (10-year record). Important improvements (see text) are shown in bold blue type; important deteriorations are bold red underlined. Note that site names have been abbreviated. Note that the *E. coli* and enterococci records generally contained considerably fewer results than those for the other variables. Results for total phosphorus are provisional. Updated from Vant (2018).

	Temperature	Dissolved oxygen	Conductivity	Turbidity	Visual clarity	Total nitrogen	Nitrate–N	Ammonia	Total phosphorus	Dissolved reactive P	*Escherichia coli*	Enterococci
1993–2020												
Hinemaiaia	0.1 (79)	−0.1 (99)	0.1 (92)	0.7 (99)	−0.7 (99)	**1.6 (99)**	0.8 (99)	0.0 (50)	−0.7 (99)	−0.9 (99)	−0.9 (69)	**3.8 (99)**
Kuratau (upper)	0.6 (99)	−0.1 (99)	0.1 (99)	0.4 (95)	−0.3 (85)	**2.5 (99)**	**2.6 (99)**	0.0 (50)	−0.9 (99)	0.0 (50)	–	–
Kuratau (lakeside)	0.3 (99)	−0.1 (99)	0.0 (50)	**1.2 (99)**	–	**1.4 (99)**	**1.7 (99)**	0.0 (50)	**−1.3 (99)**	**−1.8 (99)**	1.6 (89)	0.8 (87)
Mapara	0.2 (99)	0.0 (78)	0.5 (99)	−0.3 (94)	−0.1 (74)	0.6 (99)	0.8 (99)	**−1.6 (99)**	**−1.0 (99)**	−0.6 (99)	0.7 (73)	0.9 (78)
Tauranga–Taupō	0.5 (99)	−0.2 (99)	−0.2 (99)	**1.1 (99)**	−0.6 (99)	**1.0 (99)**	0.4 (99)	0.0 (50)	−0.9 (99)	**−1.2 (99)**	–	–
Tokaanu	0.1 (99)	−0.2 (99)	0.2 (99)	**2.1 (99)**	–	0.9 (99)	**1.0 (99)**	0.0 (50)	−0.1 (96)	−0.1 (89)	–	–
Tokaanu PS	0.4 (99)	0.1 (96)	−0.1 (88)	**1.4 (99)**	–	0.6 (87)	0.3 (71)	0.0 (50)	**−1.4 (99)**	**−2.0 (99)**	–	–
Tongariro	0.2 (99)	0.0 (99)	0.0 (66)	0.0 (53)	**1.0 (99)**	0.7 (99)	**1.0 (99)**	0.6 (93)	0.1 (87)	0.3 (99)	0.8 (75)	–
Waihaha	0.7 (99)	0.0 (94)	0.1 (99)	0.9 (99)	**−1.5 (99)**	0.4 (99)	−0.6 (99)	0.0 (50)	0.1 (67)	−0.6 (99)	1.2 (82)	2.0 (91)
Waitahanui	0.1 (98)	−0.1 (99)	0.4 (99)	**1.7 (99)**	−0.9 (99)	**1.4 (99)**	**1.3 (99)**	0.0 (50)	−0.6 (99)	−0.7 (99)	**−3.4 (95)**	0.9 (80)
Whanganui	0.2 (82)	−0.2 (99)	−0.2 (96)	0.7 (93)	–	−0.9 (99)	**−1.1 (99)**	0.0 (50)	**−1.3 (99)**	**−2.4 (99)**	0.5 (58)	0.7 (61)
Whareroa	−0.4 (99)	−0.1 (99)	−0.1 (99)	**1.1 (98)**	–	0.3 (99)	0.5 (99)	0.0 (50)	−0.9 (99)	**−1.1 (99)**	0.6 (64)	−0.5 (52)
2011–2020												
Hinemaiaia	−0.2 (72)	0.1 (74)	0.1 (64)	−2.0 (93)	**2.7 (99)**	**2.5 (99)**	**4.0 (99)**	0.0 (50)	0.1 (57)	**−1.3 (99)**	**7.3 (99)**	**7.8 (99)**
Kuratau (upper)	0.5 (89)	0.0 (53)	−0.5 (99)	−1.5 (89)	**2.8 (99)**	1.7 (88)	2.4 (87)	0.0 (50)	2.6 (88)	0.0 (50)	**12.8 (99)**	**13.7 (99)**
Kuratau (lakeside)	0.0 (50)	−0.1 (80)	0.2 (74)	1.3 (94)	–	−0.4 (79)	0.0 (50)	0.0 (50)	0.0 (50)	0.0 (50)	**9.7 (99)**	**8.3 (99)**
Mapara	0.3 (87)	0.1 (66)	0.3 (99)	0.9 (84)	**−2.7 (99)**	−0.7 (99)	−0.7 (99)	**1.6 (98)**	−0.1 (71)	−0.9 (99)	**12.6 (99)**	**7.8 (99)**
Tauranga–Taupō	0.9 (97)	−0.1 (82)	0.0 (54)	−0.4 (56)	1.4 (94)	−1.3 (88)	**−2.5 (99)**	0.0 (50)	**1.7 (99)**	0.2 (76)	**8.2 (99)**	**11.3 (99)**
Tokaanu	−0.1 (93)	−0.2 (95)	0.2 (99)	−3.3 (86)	–	0.0 (50)	0.0 (50)	0.0 (50)	0.6 (99)	−0.8 (99)	**10.9 (99)**	3.9 (89)
Tokaanu PS	0.9 (90)	−0.2 (76)	0.4 (96)	−1.9 (93)	–	1.2 (86)	**4.5 (95)**	0.0 (50)	0.5 (74)	0.0 (50)	**11.6 (99)**	**14.5 (99)**
Tongariro	1.3 (95)	0.0 (59)	**1.5 (99)**	0.0 (51)	0.2 (64)	0.3 (76)	−2.6 (92)	**5.4 (99)**	0.5 (87)	−0.6 (94)	**7.7 (99)**	–
Waihaha	0.4 (71)	0.1 (69)	−0.3 (97)	−0.3 (64)	1.6 (93)	−0.2 (58)	**−3.3 (99)**	0.0 (50)	−0.5 (73)	**−2.6 (99)**	**10.9 (99)**	3.9 (90)
Waitahanui	−0.1 (60)	0.0 (50)	0.2 (99)	1.6 (80)	**1.5 (96)**	**−1.3 (99)**	−0.9 (99)	0.0 (50)	0.1 (63)	**−1.3 (99)**	0.5 (67)	1.4 (63)
Whanganui	−0.5 (74)	0.1 (68)	0.2 (79)	0.7 (72)	–	**1.5 (97)**	1.0 (95)	0.0 (50)	1.2 (86)	−1.2 (85)	**9.6 (99)**	4.4 (87)
Whareroa	−0.5 (78)	0.1 (75)	0 (64)	**2.3 (99)**	–	−0.2 (81)	−0.5 (91)	0.0 (50)	0.8 (98)	−0.2 (64)	**7.9 (99)**	**6.0 (98)**

Appendix 4: Groundwater quality monitoring in the Taupō catchment

A monitoring network of 36 wells, including one National Groundwater Monitoring Programme (NGMP) well, was established after an initial survey of groundwater quality at 44 wells. The network was intended to represent a broad range of groundwater characteristics rather than investigate the impacts on quality of specific point source discharges. Some point source impacts have been detected, however.

Initial monitoring, predominantly from 2002, was undertaken quarterly. This was reduced to six-monthly in 2009. This continued until 2020 when a subset of 19 wells was again sampled quarterly with the remainder reducing to annual monitoring. Recently the Tuwharetoa Maori Trust Board has undertaken the monitoring.

The dataset used in this report comprises analyses from a total of 34 wells. Reliance in large part on private existing, rather than dedicated, wells means there may be uncontrolled changes. Monitoring at one of the initial sites (72_383) was discontinued and another (72_1009) was replaced by monitoring well 72_6637. There are also two school wells in the catchment which are monitored biennially and one NGMP well (68_964) monitored quarterly. Information about the wells is presented in Table A2, and their locations are shown in Figure 15.

Sampling procedures

Sampling for this report was carried out by WRC's Environmental Monitoring team using a range of in-situ pumps and introduced pumping equipment, predominantly submersibles. Three annular volumes are flushed prior to sampling to remove stagnant water and field parameters are checked during this process to ensure equilibrium has been reached. There are very minor exceptions where lower volume or low-flow purging has been used. Sampling procedures have largely followed the national protocol for state of the environment groundwater sampling in New Zealand introduced by the Ministry for the Environment (2006). A notable exception was that pH continued to be analysed only in a controlled laboratory environment until 2017. Before 2006 conductivity, temperature and inconsistent dissolved oxygen (DO) measurements were taken in the field. The DO results were often considered unreliable due to in-situ pumping effects.

More recently protocols have been adjusted to adhere to the National Environmental Monitoring Standards (NEMS) for groundwater quality introduced in 2019. This includes sensor calibration and field stabilization criteria for sample collection. The following pre-sampling criteria apply to field determinands: temperature ± 0.2°C, conductivity ± 5% if <= 100 uS/cm and ± 3% if > 100 uS/cm, pH ± 0.1 pH units and dissolved oxygen ± 0.3 g/m^3.

Collected samples are kept cool (≈4°C) and transported to Hill Laboratories in Hamilton for analysis (IANZ-accredited). Microbial samples are delivered within 24 hours. NGMP samples are sent to the Geological and Nuclear Sciences (GNS) laboratory at Wairakei.

Table A 2: Monitoring well information (including NGMP well 68_964).

Well	Easting	Northing	Well Depth (m)	Casing depth (m)	Lithology	Confinement	Water age (y MRT)	Land-use
68_301	1855521	5718798	53.6	49	Rhyolitic pyroclastic	Leaky	80	Dry stock
68_317	1850484	5719524	104	71	Rhyolitic pyroclastic	Unknown	40	Dairy
68_320	1864824	5713191	62	46	Oruanui Ignimbrite	Unconfined	30	Motor camp
68_964	1840522	5691618	5	2	Sand	Unconfined	1	urban
72_1005	1864821	5713198	19.9	10.9	Unwelded Ignimbrite	Unconfined		Motor camp
72_1006	1837116	5719976	5.43	2.43	Unwelded Ignimbrite	Semi-confined	76	Dry stock
72_1007	1860347	5713181	7.4	1.7	Taupo Ignimbrite	Unconfined		Dry stock
72_1008	1842613	5722653	8	2	Oruanui Ignimbrite	Unconfined	15.5	Dry stock
72_1010	1858043	5713480	8	2.3	Taupo Ignimbrite	Unconfined		Dry stock
72_1011	1857370	5714209	5.88	2.3	Taupo Ignimbrite	Unconfined	50	Dry stock
72_1012	1833318	5697353	5.65	0.63	Unwelded Ignimbrite	Unconfined		Dry stock
72_1068	1834199	5717775	16.4	6.4	Unwelded Ignimbrite	Unconfined		Drystock - airstrip
72_1069	1833951	5715883	11.7	2.7	Oruanui Ignimbrite	Unconfined	4	Dry stock
72_1070	1836950	5712508	43	27	Oruanui Ignimbrite	Unconfined		Dry stock
72_1071	1833334	5713048	7.5	1.5	Oruanui Ignimbrite	Unconfined	5	Reserve
72_1072	1834190	5698624	21	14.5	Oruanui Ignimbrite	Confined	62	Dry stock
72_1073	1831222	5710274	20	8	Whakamaru Ignimbrite	Unconfined		Dry stock
72_1075	1841138	5694653	5.5	0.5	Sand	Unconfined		Reserve
72_1076	1834748	5691889	7.9	1.9	Unwelded Ignimbrite	Perched	1	Sheep
72_1078	1833321	5697360	58	6.7	Whakamaru Ignimbrite	Confined	12	Sheep
72_1079	1833324	5697361	3.5	1.5	Oruanui Ignimbrite	Unconfined	1	Sheep
72_1080	1833317	5697354	10	6	Ignimbrite	Semi confined		Sheep
72_1081	1832115	5692948	4.6	0.45	Sand	Unconfined	1	Reserve
72_1082	1832842	5694923	7.98	1.99	Taupo Ignimbrite	Unconfined		Agriculture
72_1083	1838192	5694070	7.58	2.58	Taupo Ignimbrite	Unconfined		Dry stock
72_1084	1835911	5690310	20	10.9	Unwelded Ignimbrite	Unconfined		Sheep

Well	Easting	Northing	Well Depth (m)	Casing depth (m)	Lithology	Confinement	Water age (y MRT)	Land-use
72_1086	1833754	5703147	25.4	19.35	Whakamaru Ignimbrite	Unconfined		Sheep
72_1087	1834175	5698626	6.6	0.6	Taupō Ignimbrite	Unconfined	3	Dry stock
72_1089	1833951	5715871	36.2	na	Oruanui Ignimbrite	Confined	22	Dry stock
72_356	1858456	5720549	42	37	Rhyolitic pyroclastic	Confined		Lifestyle
72_392	1850808	5719734	93	19.2	Rhyolitic pyroclastic	Leaky	34	Dry stock
72_431	1842718	5719019	48	45.7	Whakamaru Ignimbrite	Confined		Dry stock
72_513	1840692	5723164	160	97.5	Ignimbrite	Confined		Dry stock
72_514	1842617	5722651	171	78	Ignimbrite	Confined		Dry stock
72_6637	1844584	5722311	9.75	5.75	Unwelded Ignimbrite	Unconfined		Dry stock

Data suite and analysis

The ion charge balance error is routinely calculated for samples at the laboratory. Charge balance errors over the standard 5% threshold are reviewed, attributed and may uncommonly require re-analysis. Quality assurance checks are also made before all the water quality data from field measurements and laboratory analysis is stored in the council's water quality archiving database (Wiski). More recently this has involved automated comparison with expected determinand ranges.

The current SOE determinands along with their associated methods and detection limits are listed below (Table A3). The SOE state and trend analysis in this report, however, has been carried out using 15 selected determinands. These comprise the major ions, pH, electrical conductivity, nitrate, ammonium-N, iron, manganese and boron (except the last two for the NGMP well). Although there are more determinands measured in the current routine SOE suite, many do not have sufficient records for trend analysis.

The groundwater quality programme has recently been transitioning from a predominance of total analysis to also include a greater number of field-filtered dissolved determinands. Total analysis is required for comparison with the drinking water standards to determine potability. Dissolved concentrations, however, better reflect likely migration from an environmental perspective. Dissolved iron and manganese have been routinely analysed since 2008. The dissolved fraction of several other major ions has been added since 2017, although these records are insufficient to report here.

Dissolved reactive phosphorus has been analysed on an occasional basis. This is due to the slow concentration changes expected, reflecting long residence times required for the dissolution from minerals in formation (Scott and Wong 2016). It has now, however, been routinely included since 2014 given an interest in providing nationally consistent reporting.

Apart from the SOE state and trend analysis there are numerous other parameters that have been analysed and are covered in respect to potability in regional groundwater quality SOE reporting (Hadfield 2022). These include pesticide analysis of over a hundred compounds, which are analysed from selected wells on a much less frequent basis. Similarly, *E. coli* is not measured routinely. Some other specific investigations are briefly reported including specific studies of parameters of concern including arsenic, glyphosate and recently a much wider group of emerging contaminants.

Impacts on use – potability

This section describes groundwater quality impacts in respect to potable and other uses by comparison with relevant standards and guidelines. These relate to microbial, inorganic and organic contaminants, and there are also aesthetic guidelines relating to nuisance rather than health concerns. The current maximum acceptable values (MAVs) of determinands of health significance are listed in the Ministry of Health Drinking-water Standards (Ministry of Health 2018). Some determinands are currently being reviewed by Tuamata Arowai. It is noted that there are no National Objectives Framework (NOF) bands established for groundwater quality under the National Policy Statement for Freshwater Management.

The five inorganic determinands monitored routinely which have MAVs of health significance are arsenic, boron, copper, manganese and nitrate. Table A4 presents the percentage of wells in the Taupō network which have exceeded the relevant MAVs at least once in the last five years to 2020. The percentage of five-year median concentrations exceeding the MAVs are also shown. The MAVs apply to total rather than dissolved fractions.

Table A 3: Groundwater quality analysis methods and detection limits

Determinand	Analysis Method	Detection Limits
Alkalinity Total	Potentiometric autotitration to pH 4.5. APHA 2320B.	1.0 mg/l-CACO3
Ammonium-N	Colorimetry,Phenolhypochlorite. FIA. APHA Method 4500	0.01 mg/l-N
Arsenic Total	ICP-MS after HNO3 digestion	0.0011 mg/l
Boron Dissolved	Filtered, ICP-MS	0.005 mg/l
Boron Total Recoverable	ICP-MS after HNO3 digestion. APHA 3125B.	0.0053 mg/l
Calcium Dissolved	Filtered, ICP-MS	0.05 mg/l
Calcium Total	ICP-MS after HNO3 digestion. APHA 3215 B.	0.053 mg/l
Chloride Dissolved	Filtered sample, Ion chromotography. APHA 4110B.	0.5 mg/l
Copper Total Recoverable	ICP-MS after HNO3 digestion. APHA 3125B.	0.00053 mg/l
Dissolved Reactive Phosphorus	Molybdenum blue colorimetry. Flow injection analyser. APHA 4500-P G	0.004 mg/l-P
Conductivity at 25 DegC	Measured in lab by meter @ 25"C. APHA Method 2510B	0.1 mS/m @25°C
Iron Dissolved	Filtered, ICP-MS	0.02 mg/l
Iron Total Recoverable	ICP-MS after HNO3 digestion. APHA 3125B.	0.021 mg/l
pH	Measured in lab by meter. APHA Method 4500-H+ B.	0.1 pH units
Potassium Dissolved	Filtered, ICP-MS	0.05 mg/l
Potassium Total	ICP-MS after HNO3 digestion. APHA 3215 B.	0.053 mg/l
Magnesium Dissolved	Filtered, ICP-MS	0.02 mg/l
Magnesium Total	ICP-MS after HNO3 digestion. APHA 3215 B.	0.021 mg/l
Manganese Dissolved	Filtered, ICP-MS	0.0005 mg/l
Manganese Total Recoverable	ICP-MS after HNO3 digestion. APHA 3125B.	0.00053 mg/l
Nitrate-N	Ion Chromotography. APHA 4110B	0.05 mg/l-N
Sodium Dissolved	Filtered, ICP-MS	0.02 mg/l
Sodium Total	ICP-MS after HNO3 digestion. APHA 3215 B.	0.021 mg/l
Sulphate Dissolved	Filtered sample.Ion chromotography APHA 4110B	0.5 mg/l
Zinc Total	ICP-MS after HNO3 digestion. APHA 3125B/US EPA 200.8	0.0011 mg/l
Calculated parameters:		
Hardness Total	Calculation from Ca and Mg. APHA 2340B.	1.0 mg/l-CACO3
Total Dissolved Solids	Calculated from Electrical Conductivity	2.0 mg/l
Free Carbon Dioxide	Calculation from alkalinity and pH (APHA 4500 CO2D)	1.0 mg/l-CO2
Field measurements:		
Conductivity at 25 DegC	Field Meter	mS/m @25°C
Dissolved Oxygen	Field Meter	mg/l
% Dissolved Oxygen	Field Meter	% Sat
pH	Field Meter	pH
Water Temperature	Field Meter	°C

Table A 4: Percentage of Taupō network wells with groundwater which exceeded MAVs during 2016–20.

Determinand	As	B	Cu	Mn	NO_3-N
MAV (g/m^3)	0.01	1.4	2	0.4	11.3
At least one exceedance	20.59	0.00	2.94	23.53	5.88
Median exceedance	12.50	0.00	0.00	8.82	2.94

It is evident that health related exceedances are more prevalent for arsenic and manganese, which are more likely in anaerobic conditions than for nitrate which is of anthropogenic origin and occurs in aerobic conditions. Arsenic is more likely to occur in volcanic settings such as Taupō (Piper and Kim 2006).

Exceedances of aesthetic guidelines (MoH 2018) from routine network monitoring are summarised in Table A5. The guidelines generally relate to taste or staining nuisance issues. Median concentrations at monitoring wells only exceeded aesthetic guidelines for three determinands, namely pH, manganese and iron (Table A5). All but three wells have median pH levels which are more acid than the guideline range and are therefore considered to have high plumbosolvency or tendency to corrode metal piping. Higher than guideline iron and manganese concentrations, which typically occur together, are considered likely to lead to nuisance staining and sometimes taste issues. The other very minor occurrences relate to point source contamination. The occasional exceedances for sulphate and hardness occurred at site 72_1068 associated with point source effects from an airstrip. Similarly, the ammonium-N exceedance at well 68_320 is another point source (woolshed) influenced site. The occasional copper exceedances at one well 72_392 are likely to relate to pipework.

Table A 5: Percentage of Taupō network wells with groundwater which exceeded aesthetic guidelines (GV) during 2016–20.

Determinand	GV (mg/l)	At least one exceedance	Median exceedance	
NH_4-N	1.5	2.94	0.00	
Cl	250	0.00	0.00	
Cu	1	2.94	0.00	
Hardness	200[1]	2.94	0.00	
Fe	0.2	61.76	20.59	
Mn	0.04[2]	61.76	38.24	
pH	7 – 8.5	97.06	91.18	
Na	200	0.00	0.00	
SO_4	250	2.94	0.00	
TDS	1000	0.00	0.00	

[1]scaling threshold; taste threshold is 100 to 300 g/m^3
[2] staining threshold; taste threshold at 0.1 g/m^3