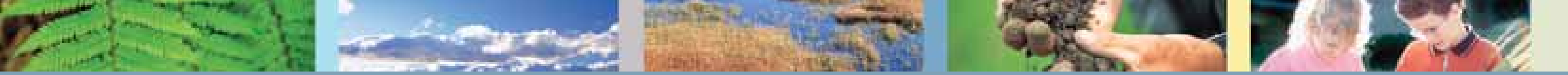

Lake water quality and ecology in the Wellington region

State and trends

Quality for Life

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REGIONAL COUNCIL
Te Pane Matua Taiao

Lake water quality and ecology in the Wellington region

State and trends

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GW/EMI-T-12/139
ISBN: 978-1-927217-04-7 (print)
ISBN: 978-1-927217-05-4 (online)

February 2012

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The report may be cited as:

Perrie, A and Milne, JR. 2012. *Lake water quality and ecology in the Wellington region: State and trends*. Greater Wellington Regional Council, Publication No. GW/EMI-T-12/139, Wellington.

Main cover photo: Lake Wairarapa

Executive summary

Greater Wellington monitors water quality and ecological condition in selected lakes in the Wellington region. Up until recently, water quality has only been monitored in Lake Wairarapa. Monitoring in this lake commenced in 1994 and incorporated four principal sampling sites. In August 2009, water quality monitoring programmes were established for two additional lakes, Waitawa (Kapiti Coast) and Onoke (South Wairarapa). Monitoring of Lake Waitawa was restricted to a year-long investigation while monitoring of Lake Onoke is ongoing. Baseline assessments of ecological condition – based on submerged plant community condition – were also undertaken during 2011 in three lakes: Kohangapiripiri, Kohangatera (collectively known as the Parangarahu Lakes) and Pounui.

This report summarises the current condition of these six lakes mainly in terms of nationally recognised indicators; the Trophic Level Index (TLI) for those lakes with sufficient water quality data (Lakes Wairarapa, Onoke and Waitawa) and the Lake Submerged Plant Index (LakeSPI) (Parangarahu Lakes and Lake Pounui). The current condition of these lakes was also compared against national water quality and ecological condition data sets. Drivers of lake water quality and ecological condition were also examined where appropriate. Only the water quality data record for Lake Wairarapa was of sufficient length to enable formal trend assessment.

Based on regular water quality monitoring, Lakes Wairarapa, Onoke and Waitawa can all be considered to be in a degraded state with typically elevated concentrations of nutrients and phytoplankton biomass, and poor water clarity. Application of the TLI results in all three lakes being classed as supertrophic. However, TLI scores for both Lakes Wairarapa and Onoke are significantly influenced by re-suspension of lakebed sediments (which in turn adversely affect Secchi depth and concentrations of total phosphorus) and potentially both lakes would be more appropriately classified as being in a eutrophic to supertrophic condition. Examination of temporal trends in Lake Wairarapa water quality data indicated that, overall, this lake has remained in a relatively stable, yet poor, state since 1994.

Comparison of the TLI scores from Lakes Onoke, Wairarapa and Waitawa with those from other lakes across New Zealand indicates that all three lakes are typically in a poorer state than other similar lake types. Lake Waitawa has particularly poor water quality and on several occasions recorded concentrations of potentially toxic cyanobacteria above guideline levels for recreational use. Lake Waitawa was also stratified for a significant part of the year and this resulted in the lake bottom becoming anoxic for several months; this anoxia is potentially impacting on aquatic fauna in the lake and also, at times, resulting in a release of dissolved nutrients from lakebed sediments.

Based on LakeSPI assessments undertaken by NIWA in March 2011, Lakes Pounui and Kohangapiripiri can be classified as having ‘high’ ecological values and Lake Kohangatera as having ‘excellent’ ecological values. All three lakes support higher than average ecological values when compared to other lakes across New Zealand, with the Parangarahu Lakes considered an outstanding national example of lowland lake systems.

Water quality in Lakes Onoke, Wairarapa and Waitawa is affected by the large component of agricultural land use in their catchments; this includes intensive farming around much of the margins of all three lakes. These lakes also receive inputs from urban land use and, indirectly, discharges of treated municipal wastewater. As yet, the relative contributions from external sources of nutrients are not well understood in any of these lakes. Similarly, the role of internal nutrient cycling – a potentially significant factor for all three lakes – has not been quantified. Investigations into nutrient inputs is a high priority, particularly for Lakes Wairarapa and Onoke given that further land use intensification is expected in the Wairarapa Valley. In contrast, Lakes Kohangapiripiri, Kohangatera and Pounui are located in catchments that are still dominated by indigenous forest land cover. Introduction of invasive aquatic weeds is the principal ongoing threat to the high ecological values of these lakes.

Greater Wellington's lake monitoring programmes and investigations summarised within this report have greatly improved our knowledge of lakes in the region. However, a number of limitations and knowledge gaps exist and there is a need to review the existing lake monitoring programme to address these. Recommendations for future monitoring and investigations are listed in Section 9.1.

Contents

1. Introduction

There are a variety of lakes in the Wellington region, which provide a range of biodiversity, water supply, recreational, aesthetic and food resource values. Lake Wairarapa is the largest and most well known of the region's lakes. It is also the only lake that Greater Wellington Regional Council (Greater Wellington) routinely monitors for physico-chemical and microbiological water quality. However, over the last few years, assessments of lake condition have extended to Lake Waitawa on the Kapiti Coast, the Parangarahu Lakes (Lakes Kohangapiripiri and Kohangatera) on Wellington's south coast, and Lake Pounui and Lake Onoke in south Wairarapa.

This report provides a comprehensive assessment of the results of Greater Wellington's water quality and ecological monitoring of lakes in the Wellington region. Some of this monitoring forms part of Greater Wellington's larger programme of state of the environment monitoring, a specific requirement of regional councils under Section 35(2)(a) of the Resource Management Act (RMA) 1991.

1.1 Report purpose

This technical report is one of eight covering air, land and water resources prepared with the primary purpose of informing the review of Greater Wellington's five regional plans. These plans were established to sustainably manage the region's natural resources, including fresh and coastal waters. The review of the regional plans follows the recently completed review of the overarching Regional Policy Statement (RPS) for the Wellington region (GWRC 2010).

The focus of the eight technical reports is on providing an up-to-date analysis of monitoring information on state and trends in resource health as opposed to assessing the effectiveness of specific policies in the existing RPS (WRC 1995) or regional plans. Policy effectiveness reports were prepared in 2006 following the release of Greater Wellington's last formal State of the Environment (SoE) report, *Measuring up* (GWRC 2005).

The last technical report supporting SoE reporting on lake condition in the Wellington region was prepared by Perrie (2005)[1]. This report focussed solely on state and trends in the water quality of Lake Wairarapa.

1.2 Report scope

The report focuses on the period 2006 to 2010 to classify the current state of water quality in Lake Wairarapa; the full data record (1994–2010) is used to assess temporal trends. In the case of the other lakes, the information presented is limited to one-off or fixed-term assessments. In terms of Lake Onoke, a coastal barrier-bar type lake, the quality of its substrate and associated benthic fauna are reported separately under Greater Wellington's coastal water quality and ecology monitoring programme (see Oliver & Milne 2012).

[1] Greater Wellington also prepares annual summary reports documenting SoE monitoring results obtained in the last financial year. Refer to Perrie and Cockeram (2010) for the most recent annual freshwater quality monitoring report.

1.3 Report outline

The report comprises eleven sections:

- Section 2 provides a brief overview of the region's lakes and Greater Wellington's lake monitoring network, sampling methods and water quality and ecological indicators.
- Section 3 presents an analysis of the water quality of Lake Wairarapa, including both current state and temporal trends. One-off phytoplankton sampling results are also presented.
- Section 4 summarises the results of water quality monitoring undertaken in Lake Onoke over August 2009 to July 2011 inclusive. Phytoplankton results from limited sampling are also presented.
- Section 5 summarises the results of water quality and phytoplankton monitoring undertaken in Lake Waitawa over August 2009 to July 2010 inclusive.
- Section 6 summarises the results of ecological assessments of the Parangarahu Lakes made in March 2011. One-off water quality sampling results are also presented.
- Section 7 presents the results of an ecological assessment of Lake Pounui in March 2011. One-off water quality and phytoplankton sampling results are also summarised.
- Section 8 discusses the main findings from Sections 3 to 7 and places these in a national context. The principal impacts on lake condition are briefly discussed and monitoring limitations and knowledge gaps are also outlined.
- Section 9 presents conclusions and recommendations.

2. Overview of lake monitoring in the Wellington region

2.1 Background

There are approximately 110 lakes[2] over one hectare in area in the Wellington region (and many more that are smaller). Of these, only 14 are greater than 10 ha in area, with the two largest being Lake Wairarapa (7,850 ha) and Lake Onoke (622 ha). Several other lakes are closely associated with these, including Lake Pounui (46 ha), Pounui Lagoon (42 ha) and the numerous wetland/lagoon/lake systems situated around the eastern and northern ends of Lake Wairarapa (eg, Boggy Pond (58 ha), Matthews Lagoon (37 ha), Barton's Lagoon (11ha)). Other lakes in the Wellington region include the Parangarahu Lakes (Kohangapiripiri (11 ha) and Kohangatera (21 ha)) at Pencarrow Head and Lake Waitawa (16 ha) and Lake Waiorongomai (6 ha) that form part of the cluster of small dune lake/wetland systems located just north of Otaki on the border between the Wellington and Manawatu-Wanganui regions (Snelder 2006).

Man-made lakes, reservoirs and ponds are also a significant feature of the regional landscape. Approximately 30% of the region's 110 lakes over 1 ha in area are considered to be man-made; these include several well known water bodies such as Henley Lake (12 ha) and Kaurarau Dam (7 ha) in the Masterton District, the Karori Reservoirs in Wellington (2-3 ha) and the Whitby Lakes in Porirua (2 ha).

Up until recently, Greater Wellington has only routinely monitored water quality in one lake in the region, Lake Wairarapa. Monitoring in this lake commenced in 1994 and incorporated four principal sampling sites[3]. In August 2009, water quality monitoring programmes were established for two additional lakes, Waitawa and Onoke. Monitoring of Lake Waitawa was restricted to a year-long investigation while monitoring of Lake Onoke is ongoing. Baseline assessments of ecological condition – based on submerged plant community condition (ie, LakeSPI, outlined later in this section) – were also carried out in three additional lakes during March 2011: Kohangapiripiri, Kohangatera and Pounui (Figure 2.1).

The six lakes discussed in this report (Lakes Kohangapiripiri, Kohangatera, Onoke, Pounui, Wairarapa and Waitawa) can be classified as shallow coastal lakes[4]. These types of lakes are considered to differ naturally from larger deeper lakes located at higher elevations in several ways; they tend to be more productive, warmer and can have photic zones that extend to the lake bottom.

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[2] In this sense, a 'lake' includes any open body of water such as some wetlands, ponds, lagoons, dams and reservoirs, and this is based on data available through the Freshwater Ecosystems of New Zealand (FENZ) geodatabase (Snelder 2006). Areas of lakes discussed in this report have been measured in Arcview GIS. Areas for lakes, dams and reservoirs that are not discussed further are based on values provided in the FENZ geodatabase (Snelder 2006); in some cases the 'lake area' presented may also include extensive 'wetland' areas.

[3] Historically, the Lake Wairarapa monitoring programme also included the collection of water samples from two lagoon/wetland systems adjacent to Lake Wairarapa: Boggy Pond (1994–1999) and Matthew's Lagoon (1997–1999). Monitoring results from these sites are reported in Stansfield (1999).

[4] Based on the criteria used in Drake et al. (2011); <10 m deep and located within 25 km from the coast. Lakes Onoke, Kohangapiripiri and Kohangatera are located on the coast, while Lakes Pounui, Wairarapa and Waitawa are situated around 7 km, 12 km and 4 km inland from the coast, respectively.

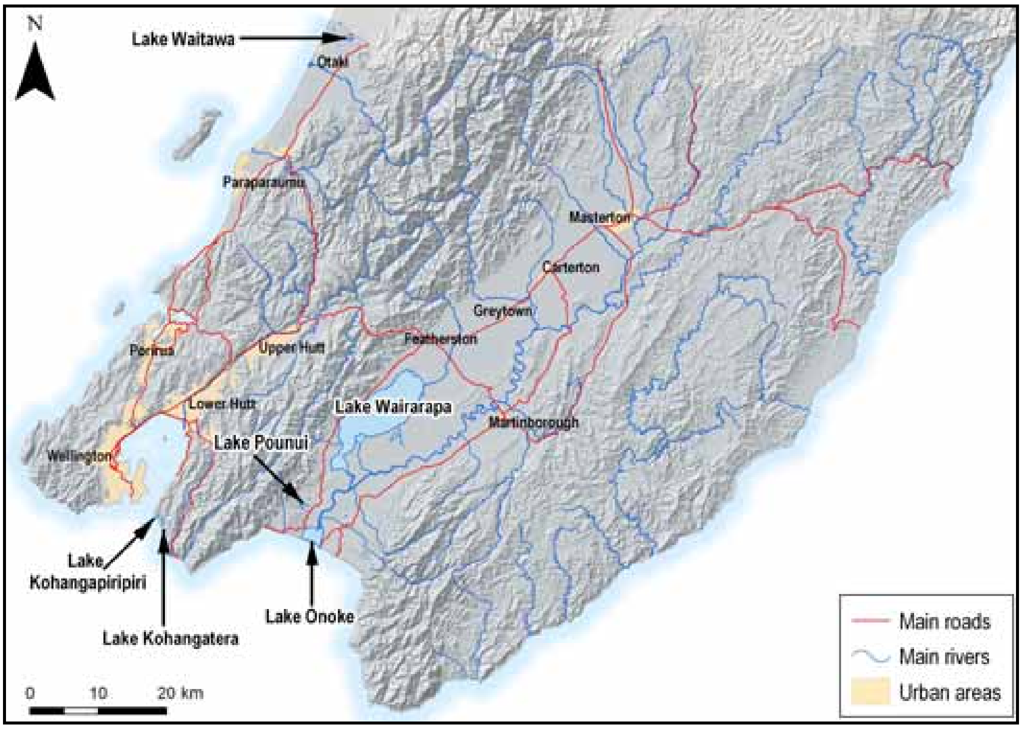

Figure 2.1: Map of the Wellington region featuring the six lakes discussed in this report

Shallow coastal lakes are less likely to stratify and re-suspension of lake-bottom sediments, caused by wind disturbance, is known to be an important driver of water quality and ecosystem processes (Burns et al. 2000, Drake et al. 2011). Close proximity to the coast can also mean that in some cases the water quality of these lakes can be influenced by the sea (eg, by tidal movement of saline water, storm surges and/or salt inputs from sea spray). Due to their lowland location, the catchments of shallow coastal lakes are typically highly modified and commonly impacted by land use changes; this can result in alterations to the natural hydrological regime, increased inputs of sediment, nutrients and other contaminants, and widespread habitat loss and degradation (Drake et al. 2011; Robertson & Stevens 2007; Kirk & Lauder 2000).

2.2 Monitoring and reporting protocol

Two types of lake monitoring have been undertaken in the region:

- Occasional to regular analysis of surface water samples for a variety of physico-chemical and bacteriological variables (eg, total and dissolved nutrients, dissolved oxygen, secchi depth, etc.) in Lakes Onoke, Wairarapa and Waitawa; and

- Baseline assessments of ecological condition based on surveys of the submerged aquatic plant communities in Lakes Kohangatera, Kohangapiripiri and Pounui.

These monitoring approaches, along with analysis and data interpretation techniques, are briefly outlined in Sections 2.2.1 and 2.2.2. Phytoplankton samples were also collected from all lakes (although only regularly from Lake Waitawa), with the main focus put on identifying the potentially toxic cyanobacteria species present and the potential health risk posed to recreational users (refer Section 2.2.3). Further details on sampling methodology and approaches to analyses that are specific to each individual lake are presented in later sections.

2.2.1 Water quality

For Lakes Onoke, Wairarapa and Waitawa, reporting and interpretation of lake condition focuses mainly on a comparison of physico-chemical water quality data against a national dataset and application of the trophic level index (TLI). Nutrient limitation of phytoplankton growth was also investigated in these lakes.

(a) Comparison with national values

Where applicable, water quality results are compared against national median values reported in Verburg et al. (2010) and summarised in Table 2.1. Because the values presented in Verburg et al. (2010) encompass a wide range of lake types (eg, large deep alpine lakes, shallow coastal lakes, etc.) and the lakes featured in this report are classified as shallow coastal lakes, comparisons are also made against the average coastal lake condition presented in Drake et al. (2011). Drake et al. (2011) undertook a nationwide assessment of shallow coastal lakes (*n*=45), albeit of limited sampling effort in regards to water quality[5], and reported a mean TLI of 4.3 (eutrophic). A median TLI of 3.9 (mesotrophic) was subsequently calculated from their appended data for use in this report.

Note that comparison with national values is only to provide some general 'national context'. Some of the lakes discussed in this report are quite unique. For example, while Lake Onoke is a shallow coastal lake it is also a barrier-bar type lake and as such, ideally, its condition should only be compared against other similar coastal barrier-bar lakes.

Table 2.1: National median values for selected water quality variables categorised by dominant lake catchment land cover, taken from Verburg et al. (2010). The number of lakes in each land cover category is shown in brackets. Note: the total number of lakes used to generate median values differs between variables.

Variable	Dominant land cover[1]	
	Native (49)	Pasture (50)
Conductivity (µS/cm)	228	192
pH	7.5	7.7
Secchi depth (m)	6.4	2
Turbidity (NTU)	0.8	3.2
Total nitrogen (mg/L)	0.149	0.7734
Ammoniacal nitrogen (mg/L)	0.006	0.013
Total phosphorus (mg/L)	0.007	0.0368
Dissolved reactive phosphorus (mg/L)	0.002	0.0025
Chlorophyll *a* (mg/m^3)	1.6	8.8
TLI	3.0 (mesotrophic)	4.9 (eutrophic)

[1]Dominant lake catchment land cover was determined by the largest percentage of land cover within a catchment (Verburg et al. 2010), although the authors note that land cover/uses that are not dominant can also have a significant impact on lakes water quality.

[5] Trophic state was inferred from one-off water quality sampling.

(b) Trophic level index (TLI)

Burns et al. (2000) developed a trophic level index (TLI) for assessing the water quality status of New Zealand lakes. The TLI is calculated using four key variables of lake water quality (chlorophyll *a*, Secchi depth, total phosphorus and total nitrogen) and is based on the following four regression equations:

1. TLc = 2.22 + 2.54 log(Chlorophyll *a*)
2. $\text{TLs} = 5.10 + 2.27\log\left(\dfrac{1}{\text{Secchi depth}} - \dfrac{1}{40}\right)$
3. TLp = 0.218 + 2.92 log(Total phosphorus)
4. TLn = -3.61 + 3.01 log(Total nitrogen)

An overall TLI score is calculated by averaging the four individual TL equation results. Lake water quality is then assigned an overall trophic level status according to its average score (Table 2.2) (see Burns et al. 2000 for full details).

Table 2.2: Classification of lake trophic status using the TLI (after Burns et al. (2000)) and nutrient enrichment descriptions described in Burns et al. (1999)

Trophic status	TLI	Chlorophyll *a* (mg/m^3)	Secchi depth (m)	Total phosphorus (mg/L)	Total nitrogen (mg/L)
Ultra-microtrophic (practically pure)	0.0–1.0	0.13–0.33	33–25	0.00084–0.0018	0.016–0.034
Microtrophic (very low)	1.0–2.0	0.33–0.82	25–15	0.0018–0.0041	0.034–0.073
Oligotrophic (low)	2.0–3.0	0.82–2.0	15–7.0	0.0041–0.009	0.073–0.157
Mesotrophic (medium)	3.0–4.0	2.0–5.0	7.0–2.8	0.0090–0.0200	0.157–0.337
Eutrophic (high)	4.0–5.0	5.0–12	2.8–1.1	0.0200–0.0430	0.337–0.725
Supertrophic (very high)	5.0–6.0	12–31	1.1–0.4	0.0430–0.0960	0.725–1.558
Hypertrophic (extremely high)	>6.0	>31	<0.4	>0.09600	>1.558

It is important to note that the TLs equation used in Burns et al. (2000) has since been updated (Burns et al. 2009) because the original equation was based on a dataset that also included humic stained lakes (Hamill 2011). However, the original equation has been used in this report to better facilitate comparisons with earlier Greater Wellington reports (Perrie 2005) and with a recent national lake water quality report (Verburg et al. 2010) which also used the earlier equation. Moreover, application of the Burns et al. (2005) equation results in negligible difference in the calculated TLI score. The updated TLs equation from Burns et al. (2005) is:

$$\text{TLs} = 5.10 + 2.60\log\left(\frac{1}{\text{Secchi depth}} - \frac{1}{40}\right)$$

Burns et al. (2000) recommend that at least two years of monthly monitoring is undertaken to provide an adequate baseline of current lake status. Therefore some caution is required when interpreting the TLI scores in this report as sampling regimes and/or current data records do not meet this requirement. In all cases, the TLI scores were calculated based on the mean value for each of the key variables over the reporting period examined. The exceptions were the calculation of TLI scores based on the one-off water quality samples collected at the three lakes that have no regular water quality monitoring data (Lakes Kohangapiripiri, Kohangatera and Pounui). Extreme care must be taken when interpreting these values, although when comparing between lakes, Drake et al. (2011) has previously found a strong correlation between TLI scores that have generated for a lake from a one-off sample with those that have been generated from long-term data records.

(c) Nutrient limitation

Phytoplankton growth can in some situations be limited by the availability of nitrogen or phosphorus. Determining which nutrient is limiting, if limitation occurs, can help with lake water quality management decisions. Examining the ratio of total nitrogen to total phosphorus is one such way of inferring which nutrient may potentially limit phytoplankton growth. Ratios greater than 15 may indicate phosphorus-limited conditions and ratios less than seven may indicate nitrogen-limited conditions. Ratios between seven and 15 are considered inconclusive (Sorrell 2006). Nutrient ratios should be interpreted carefully and can only be used to infer the possible limiting nutrient; nutrient enhancement bioassays are required to confirm the limiting nutrient. Furthermore, not all nutrients are readily available for phytoplankton growth, different phytoplankton species have different nutrient requirements (Verburg et al. 2010) and in some situations, concentrations of both nutrients may result in unlimited or co-limited conditions. Other factors, such as water clarity, may also play an important role in limiting phytoplankton growth.

(d) General data processing, analysis and presentation

During data processing, concentrations of any water variables reported by the laboratory as less than the analytical detection limit were replaced by values one half of the detection limit. These ‘halved values’ were then used in the calculation of summary statistics, TLI scores and any other data interpretation.

Only the Lake Wairarapa water quality dataset is of sufficient length to enable temporal trend analysis. The methods used in this analysis are outlined in Section 3.2.2.

Extensive use of box-and-whisker plots (box plots) is made in this report to graphically summarise the median and range of concentrations measured for various water quality variables and, where applicable, compare these between sampling sites. All plots were generated in Sigmaplot (v11.0), with the whiskers (error bars) above and below the box (interquartile range) set at the 90th and 10th percentiles respectively (Figure 2.2).

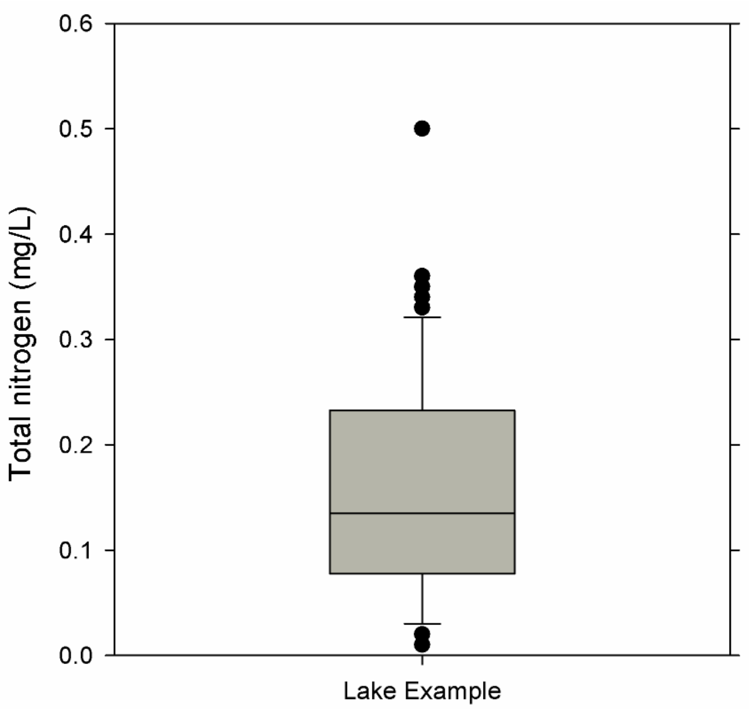

Figure 2.2: An example of a box-plot showing the various summary statistics;

- the lower and upper boundaries of the box represent the lower (25%) and upper (75%) quartiles of the data respectively – a minimum of 3 data points are needed to generate the box
- the horizontal line inside the box represents the median value
- the 'whiskers' extending below and above the box represent the 10^{th} and 90^{th} percentile values respectively
- the black dots represent outliers

2.2.2 Assessment of submerged aquatic plant communities

Submerged aquatic plant communities were assessed in Lakes Pounui, Kohangapiripiri and Kohangatera following the nationally accepted LakeSPI (Submerged Plant Index) methodology. LakeSPI, developed by Clayton and Edwards (2006), is an index of ecological condition based on key features of macrophyte community structure and composition. Application of the LakeSPI method involves scuba divers assessing 11 metrics over a 2 m wide transect from the shore to the deepest vegetation limit at several sites which are representative of the lake. Metrics include measures of diversity from the presence of key of plant communities, the depth of vegetation growth, and the extent that invasive weeds are represented.

These metrics are condensed into three indices expressed as a percentage of expected pristine state:

- A native condition index (ie, the diversity and quality of the indigenous flora);
- An invasive condition index (ie, the degree of impact by invasive weed species); and
- An overall LakeSPI index that synthesises components of both the native condition and invasive condition indices to provide an overall indication of lake ecological condition.

The LakeSPI index is used to place the lake vegetation into one of five categories of lake condition (Table 2.3). Table 2.4 presents the most recently completed national picture of current lake condition based on LakeSPI survey results undertaken since 2005 (taken from Verburg et al. 2010).

Table 2.3: Classification of lake ecological condition using the LakeSPI index (from Verburg et al. 2010)

Lake ecological condition	LakeSPI index (% of expected pristine state)
Non-vegetated	0
Poor	>0–20
Moderate	>20–50
High	>50–75
Excellent	>75

Table 2.4: Ecological condition (LakeSPI score) categorised by dominant lake catchment land cover for lakes assessed across New Zealand since 2005, taken from Verburg et al. (2010)

Dominant land cover	Ecological condition				
	Excellent	High	Moderate	Poor	Non-vegetated
	> 75%	50–75%	20–50%	>0-20%	0%
Alpine	1				
Exotic	6	6	10	1	2
Native	8	11	18	14	4
Pastoral	8	7	18	6	27
Urban		1			1
Not determined		3	1		2
No. of lakes	23	28	47	21	36
Total %	15	18	30	14	23

2.2.3 Phytoplankton

In lakes where phytoplankton data were available, the potential health risk to recreational users from the presence of potentially toxic cyanobacteria was investigated following protocols in the interim national cyanobacteria guidelines for recreational fresh waters (MfE/MoH 2009). This involves calculating a 'biovolume' for any potentially toxic cyanobacteria species present and then comparing the total biovolume to the alert level framework outlined in Table 2.5 (see MfE/MoH 2009 for full details).

Table 2.5: Biovolume alert level framework used to assess the health risk to recreational users from potentially toxic phytoplankton species (from MfE/MoH 2009). Interpretation of the guidelines in terms of the risk to human health is also presented.

Alert level	Biovolume (mm^3/L)	Risk to human health
Surveillance (green mode)	≤0.5 mm^3/L	Low risk
Alert (amber mode)	0.5 to <1.8 mm^3/L	Increased risk
Action (red mode)	≥1.8 mm^3/L	High risk

3. Lake Wairarapa

This section provides an overview of Lake Wairarapa, including its values and catchment land use. Lake monitoring implemented to date is then outlined, followed by a summary of the current state of water quality in the lake, based on data collected over 2006–2010. Temporal trends in water quality are also examined, utilising the entire data record available (1994–2010).

3.1 Introduction

Lake Wairarapa is the largest lake in the Wellington region (~7,850 ha) and it is the only lake that has had its water quality routinely monitored to date. It is typically very shallow – only around 2.5 m at its deepest point – and is considered to be isothermal (ie, does not thermally stratify). The lake is situated towards the bottom end of the Ruamahanga River catchment, south of Featherston township (Figure 3.1).

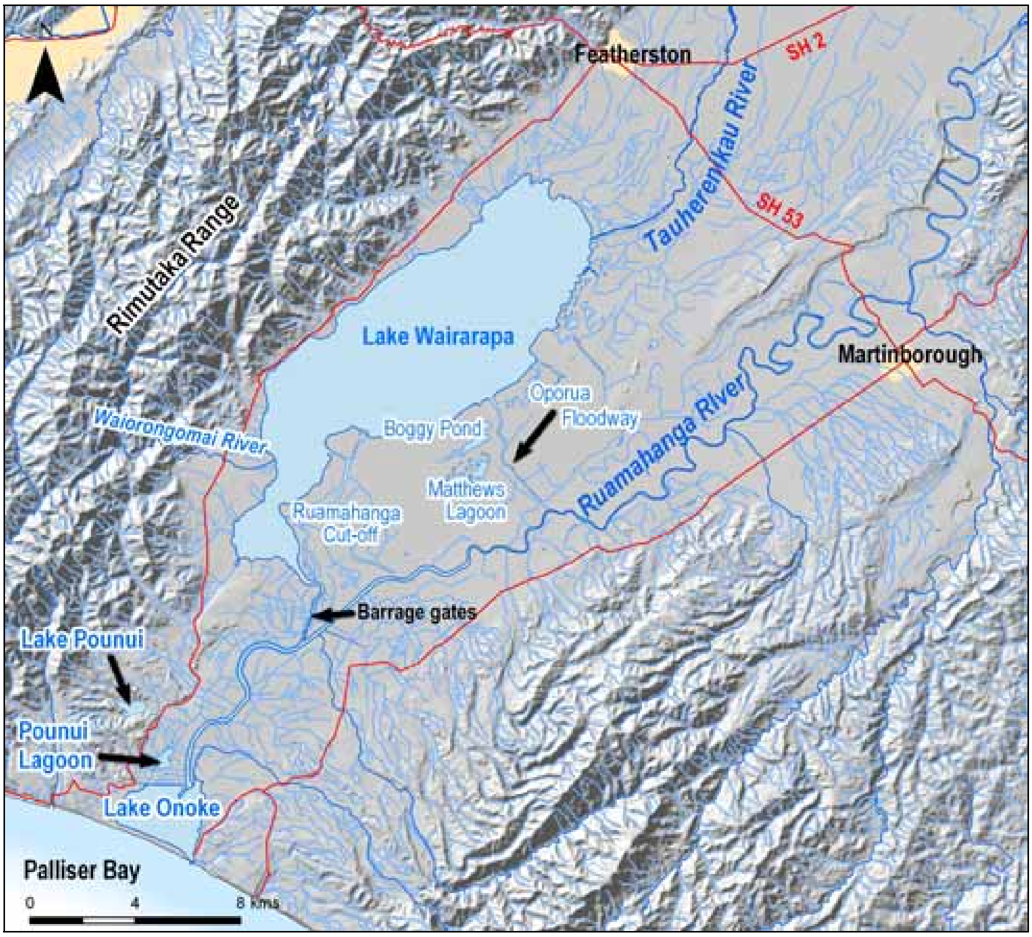

Figure 3.1: Lake Wairarapa and key features

Lake Wairarapa, along with the lower Ruamahanga River, Lake Onoke and associated wetlands, has been significantly modified through flood protection and drainage activities carried out under the Lower Wairarapa Valley Development Scheme (LWVDS) (Airey et al. 2000; Armstrong 2004). The most significant changes carried out under the LWVDS took place in the 1960s and 1970s and included the diversion of the Ruamahanga River from its direct course into Lake Wairarapa, across the Kumenga Peninsula directly into Lake

Onoke, the separation of Pounui Lagoon from Lake Onoke and the drainage of over 1,200 ha of wetlands (Airey et al. 2000). Barrage gates were also installed at the outlet of Lake Wairarapa to regulate lake water levels. The LWVDS is considered to have had major socio-economic benefits in terms of flood protection and development of land for agricultural use. However, it is also considered to have had significant negative impacts on the wetland, lake, river and stream ecosystems that have been highly modified through the works carried out under the scheme (Armstrong 2004).

There is limited understanding around the relative importance of some of the lake's inflows and outflows and the overall water balance of the lake is not well understood (Thompson 2010). The main surface inflow into the lake is the Tauherenikau River (mean flow 9.2 m^3/s, Gordon 2009), although there are numerous small streams and spring systems (Figure 3.1), some of which are associated with extensive drainage and water race systems. At times, flood flows from the Ruamahanga River can enter the lake via the Oporua Floodway; while this is generally limited to a few occasions each year, it may be a significant vector for nutrient and sediment inputs (Stansfield 1999). Completion of the Wairarapa Valley groundwater resource investigation indicated that when compared to other inflows, the input of groundwater into the lake was relatively minor (Gyopari & McAlister 2010). Further investigations attempting to more accurately quantify the groundwater contribution are ongoing.

Lake Wairarapa's outlet is situated at its southern end where lake water 'discharges' into the lower reaches of the Ruamahanga River. However, whether a discharge into the river occurs depends on many factors including the status of the barrage gates (open or closed) and water movement through the gates (flow commonly occurs in both directions, driven by the movement of tidal water in the lower river system – under some conditions (eg, a blocked Lake Onoke mouth), backflow of water through the barrage gates and into Lake Wairarapa may be significant).

The condition of water quality in Lake Wairarapa was last reported by Perrie (2005). As with earlier reports (eg, Stansfield 1999), Perrie (2005) concluded that for the 1994 to 2005 period there had been little or no change in water quality; overall the water quality of the lake was poor and the lake was in a supertrophic state.

3.1.1 Values

Lake Wairarapa is part of the largest wetland complex in the southern North Island. It is considered to be of both national and international importance due to its significant cultural, ecological, recreational and natural character values (Airey et al. 2000). A National Water Conservation Order was placed on Lake Wairarapa in 1989 recognising the high ecological values of the area (Robertson 1991).

Historically, Lake Wairarapa and the surrounding wetlands were an important source of mahinga kai and even today the area still has significant traditional and spiritual values and is considered a taonga (Airey et al. 2000). Due to the high diversity of wetland habitats present in and around Lake Wairarapa the lake and its margins provide significant habitat for a wide variety of plant, fish and bird species, including regionally rare and nationally threatened species (Ogle 1990; Hicks 1993; Airey et al. 2000; McEwan 2010; Perrie 2010). However, over the last 20 years concern has been growing over the current status of populations for some of these species (eg, eels and black flounder), and in some instances local extinction of some plant species (eg, *Leptinella dioica*) is thought to have occurred (Ogle 1990; Hicks 1993; Airey et al. 2000; McEwan 2010).

The lake and its surrounding wetlands are used for many recreational activities including hunting, fishing, motor boating, yachting, windsurfing, kayaking, camping, picnicking, walking, and nature studies (Airey et al. 2000). Lake Wairarapa also acts as an important reservoir for flood waters in the Ruamahanga River which can enter the lake via the Oporua Floodway and backflow through the barrage gates (Blakemore 1998).

The high ecological values associated with Lake Wairarapa and several adjacent wetlands (eg, Matthews Lagoon, Boggy Pond, Tauherenikau Delta, etc.) are recognised in Greater Wellington's Regional Freshwater Plan (RFP, WRC 1999) with the lake listed in Appendix 2 as having a high degree of natural character, in Appendix 3 (along with several lake tributaries such as the Tauherenikau River) as providing habitat for nationally threatened indigenous fish and in Appendix 5 as a water body with regionally important amenity and recreation values (power boating and duck shooting). Several lake tributaries are also listed in Appendix 4 as having important trout habitat.

The lake is also listed in Greater Wellington's proposed Regional Policy Statement (pRPS, GWRC 2010) as having a significant indigenous ecosystem, specifically habitat for six or more migratory indigenous fish species and habitat for threatened indigenous fish species. Numerous lake tributaries are also identified in the pRPS as significant indigenous ecosystems (habitat for indigenous and threatened fish species and/or high macroinvertebrate community health).

3.1.2 Catchment land cover and land use

Table 3.1 presents a breakdown of Lake Wairarapa's catchment land cover and land use. A breakdown for the potential catchment that may drain into the lake under flood conditions (ie, via the Oporua Floodway or backflow through the barrage gates) is also provided for comparison[6].

Pastoral land cover makes up just over 50% of the lake's current catchment area and is generally located to the north and east of the lake. Indigenous forest and scrub makes up around 44% of the catchment and is largely associated with the Rimutaka Range to the west of the lake (Figure 3.2).

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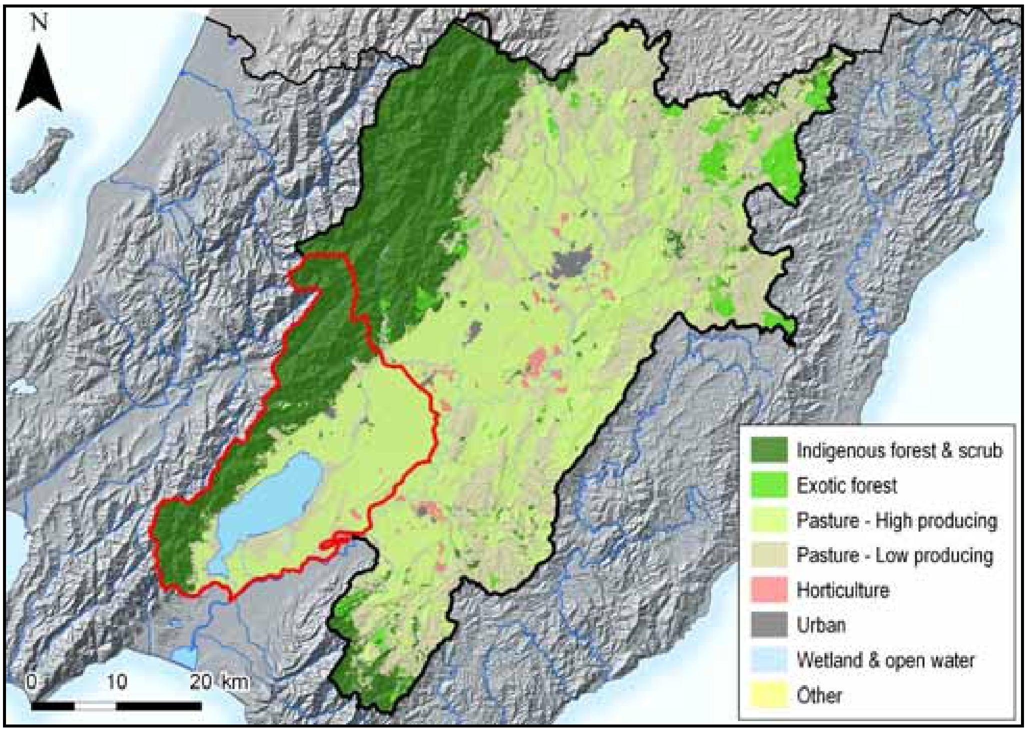
[6] The diversion of the Ruamahanga River so that it bypasses Lake Wairarapa reduced the lake's catchment area by around 80% (Figure 3.2). However, in some situations – notably flood flows entering the lake via the Oporua Floodway or backflow through the barrage gates – Lake Wairarapa can still receive water from the Ruamahanga River. On such occasions (generally once or twice each year in the case of flood events), water quality in the lake may be influenced by land use activities spanning much of the larger 'pre-diversion' catchment.

Table 3.1: Area and percentage of major land cover and land use types in the current and former (pre-diversion) catchments of Lake Wairarapa, derived from aerial photographs taken in 2008 (Source: LUCAS – MfE 2010)

Land cover	Existing catchment		'Pre-diversion' catchment	
	Area (ha)	% of catchment	Area (ha)	% of catchment
Indigenous forest & scrub	25,103	43.9	80,684	26.7
Exotic forest	54	0.1	12,020	4.0
Horticulture	136	0.2	3,099	1.0
Pasture – high producing	24,043	42.0	116,389	38.5
Pasture – low producing	6,857	12.0	85,609	28.3
Urban	226	0.4	2,282	0.8
Wetland & open water	490	0.9	1,740	0.6
Other	335	0.6	566	0.2
Total	57,245		302,390	



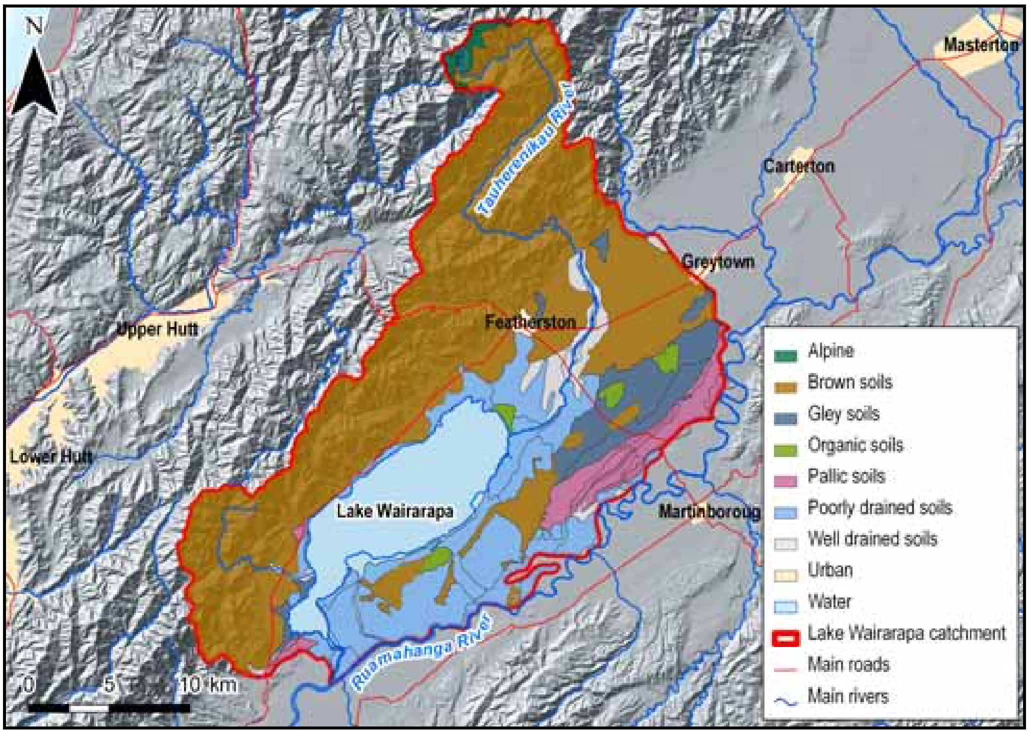
(Source: LUCAS – MfE 2010)

Figure 3.2: Major land cover and land use types within Lake Wairarapa's catchment. The red line indicates the lake's current catchment while the black line outlines the lake's former (pre-Ruamahanga River diversion) catchment.

Up-to-date information detailing specific land uses in the catchment is unavailable. Based on Agribase (2001), dairying and sheep and beef farming occupy around 20% and 35% of the existing catchment respectively. Farming typically occurs up to and along the entire lake margin (or adjacent wetlands) and includes a significant amount of dairying on the eastern and northern edges of the lake. Based on Statistics NZ data, the number of dairy cows in the South Wairarapa district increased from 35,466 in 2002/03 to 37,577 in 2009/10 (Sorensen 2012); some of this increase will have occurred within the Lake Wairarapa catchment. Based on information received from Fonterra in September 2011, along with a cross-check of stock numbers recorded during

Greater Wellington dairyshed effluent inspections in 2011, there are in the order of 19,000 dairy cows in the catchment.

Most of the farming in the vicinity of the lake takes place on poorly drained soils (Figure 3.3) and would not have been possible without the construction of extensive artificial drainage (eg, the Battersea Drainage Scheme and pump drainage schemes such as Te Hopai (refer Figure 3.4, Section 3.1.3) to lower the underlying groundwater table.



(Source: New Zealand Land Resource Inventory)

Figure 3.3: Soils of in the vicinity of Lake Wairarapa

3.1.3 Significant consented activities

There are a range of consented activities in the Lake Wairarapa catchment (Figure 3.4). The most significant point source discharge is treated municipal wastewater from the township of Featherston; this discharge enters the lake indirectly via Donald and Abbotts creeks. Other significant consented wastewater discharges in the catchment are applied to land and include piggery wastewater from the Windy Farm piggery (supporting approximately 550 pigs) and dairyshed washdown water from 48 dairy farms.

There are ten consented water takes that take water directly from the lake (this has increased from five in 2000) and 459 L/s is allocated across these ten takes (Thompson 2010). Numerous other consented water takes occur from the lake's many tributaries and from groundwater within the lake's catchment.

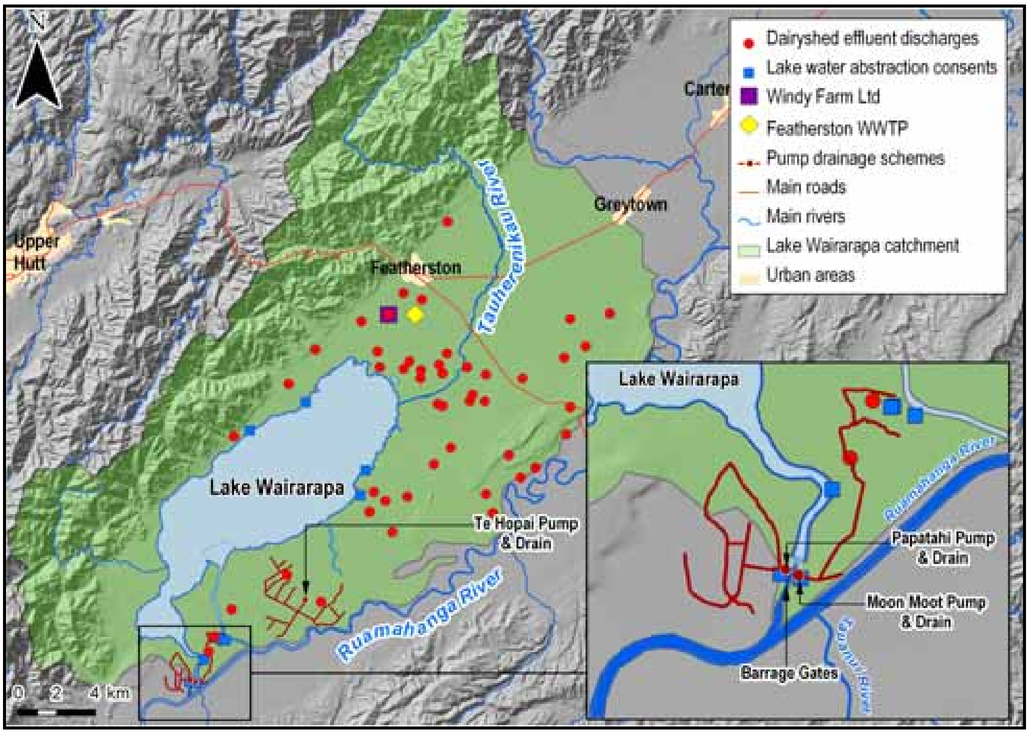


Figure 3.4: Major consented discharges in the Lake Wairarapa catchment, along with the location of consented water takes from the lake and the location of major pump drainage schemes

Operation of the Geoffrey Blundell Barrage (barrage gates) located at the southern end of Lake Wairarapa is also a consented activity (water permit for damming and diversion of water). The barrage comprises six gates that can be manipulated individually, or together, to control – to the extent possible – water levels in Lake Wairarapa. Consent conditions detail the water level management based on the regime outlined in Policy 6.1.12 of Greater Wellington's RFP (WRC 1999). This policy aligns with the National Water Conservation Order that declares that the wildlife habitat created in part as a consequence of natural fluctuations of water levels is an outstanding feature of Lake Wairarapa. Outside of times when the lake and rivers are in flood, or the mouth of Lake Onoke is blocked, the barrage is operated to maintain the water levels stipulated in the RFP and to provide fish passage by facilitating automatic daily openings of two of the six gates (the lateral gates) for one hour.

3.2 Monitoring protocol, sites and variables

Water samples have been collected from four sites located in the northern two-thirds of Lake Wairarapa since 1994 (Figure 3.5, Appendix 1). The rationale for site selection is outlined in Berry (1993).

Sampling is attempted on a quarterly basis, but in practice this rarely occurs because strong winds common in south Wairarapa often prevent safe access to sampling sites. As a result, sampling has occurred intermittently since the monitoring programme began in 1994, with the number of samples collected each year ranging from none to four (mean = 2.6 sampling occasions per year). Consequently sampling is biased towards calmer weather conditions.

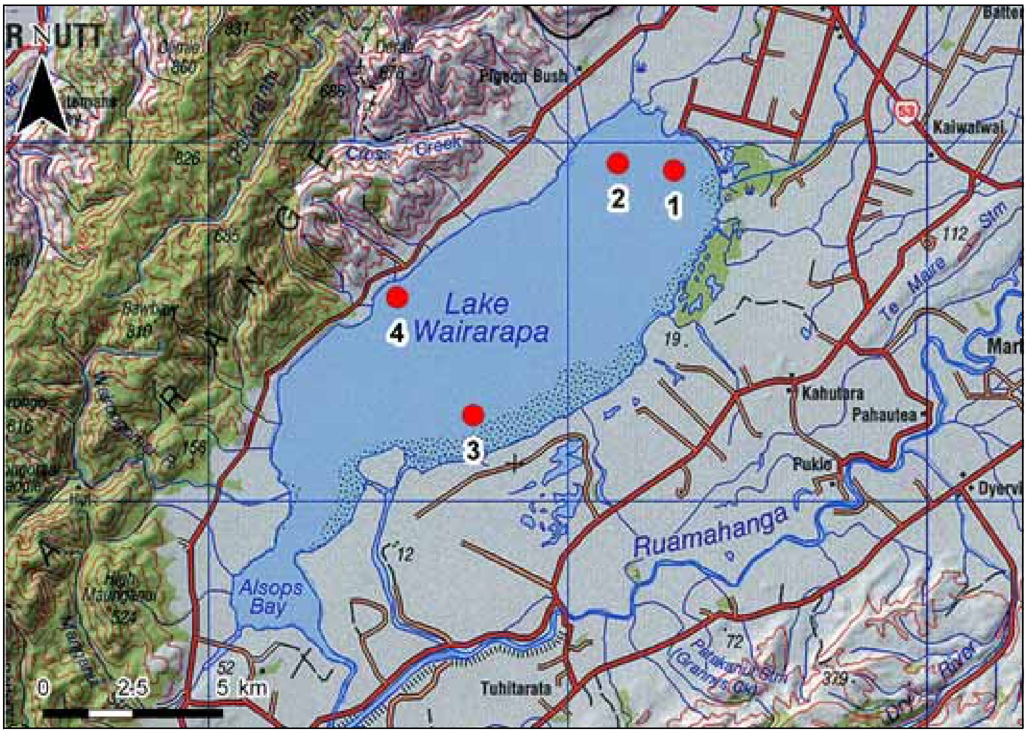


Figure 3.5: Location of water quality sampling sites on Lake Wairarapa

Water quality is assessed by measuring a range of physico-chemical and microbiological variables: dissolved oxygen, 5-day biochemical oxygen demand, water temperature, pH, conductivity, Secchi disc, turbidity, total and volatile suspended solids, faecal indicator bacteria, dissolved and total nutrients, and chlorophyll *a*.

Biological sampling is not currently undertaken in Lake Wairarapa, although one phytoplankton sample was collected in May 2008 when a phytoplankton bloom was evident.

Sampling methodology and the full list of variables monitored (both current and historic), along with information on laboratory analytical methods and detection limits can be found in Appendix 1.

3.2.1 Monitoring objectives

According to Berry (1993), specific objectives of the Lake Wairarapa monitoring programme were to:

1. Pursue the maintenance of a high quality of water entering the lake; and

2. Maintain and enhance the natural diversity of the water qualities and hence habitats in different water bodies within the lake.

Berry (1993) also states that the monitoring sites were selected to assess the suitability of lake water quality for the following values: recreational use (Site 1), bird populations (Sites 3 and 4) and general lake status (Site 2). In more recent times, the emphasis has been on the reporting of overall lake condition in accordance with nationally used indicators (eg, Perrie (2005)).

3.2.2 Approach to analysis

(a) State of water quality

To provide an overview of current lake water quality, physico-chemical and biological water quality results were summarised by pooling data collected from all four sampling sites for the period 2006 to 2010 (inclusive). This period included fourteen separate sampling occasions, three per year except in 2007 (two sampling occasions).

The current state of water quality was assessed by calculating a TLI score for the period 2006 to 2010 (inclusive). The TLI score was generated from mean values for each of the key variables (total nitrogen, total phosphorus chlorophyll *a* and Secchi depth,) using data pooled from all sites to provide an overall indication of the state of the whole lake. TLI scores were also calculated on an individual site basis to examine spatial variation (see Section 2.2.1 for further details on the calculation and application of the TLI).

As sampling is restricted to 2 to 4 times per year, to better examine relationships between selected water quality variables and seasonality, wind disturbance and conductivity, the entire available data record was used (eg, 1994 to 2010 where available). As outlined in Section 2.2.1, any values that were reported by the laboratory as below the analytical detection limit were replaced with one half the value of the detection limit.

(b) Temporal trends

An initial screening process for each water quality variable indicated that datasets for some variables were unsuitable to analyse for temporal trends due to a high proportion (>30%) of results being below the laboratory's analytical detection limit (*E. coli*, nitrite nitrogen and ammoniacal nitrogen) and/or because a change in analytical laboratory in August 2007 resulted in a significant change in the detection limit (5-day biochemical oxygen demand). Carrying out trend analyses in either of these cases would produce results of limited reliability and could lead to the detection of 'false trends' (Scarsbrook & McBride 2007; Ballantine & Booker 2011; Hamill 2011).

For the remaining variables that were deemed suitable for trend analysis, any value below the detection limit was replaced with one half the value of the detection limit before performing the analyses. It is worth noting that several variables had variable detection limits throughout the reporting period (irrespective of the laboratory used): chlorophyll *a*, faecal coliforms and volatile suspended solids.

Trends were assessed using the entire available time period (1994 to 2010 for most variables) for all suitable variables at each of the individual sampling sites but also using data pooled across all four sites to help increase the overall sensitivity of the trend tests. Analysis was carried out using LakeWatch software (Version 2.0) which incorporates protocols from Burns et al. (2000). This involves removing seasonal effects (deseasonalising) in the data (accomplished by plotting the data as a function of month with no regard to the year of collection) and fitting a polynomial curve to the data which allows for the deseasonalised residuals to be calculated. The observed values and the deseasonalised residuals are then plotted against time and straight line plots are fitted using ordinary least squares regression. A trend was considered statistically significant if the p-value was <0.05. The slope of the regression line was used to indicate the change per year and the percent annual change (PAC) was calculated by dividing the change per year by the mean value of the variable for the reporting period analysed. Following a similar approach by Scarsbrook (2006) for interpreting trends in water quality data, a PAC value of >1% was used to signify potentially 'meaningful' trends.

Given that sediment disturbance by wind-induced turbulence is considered to be a stronger process controlling lake water quality than seasonality in some shallow lakes (Burns et al. 2000), TLI variables were also 'deweathered' before carrying out trend analysis. This was undertaken following the method in Burns et al. (2000) and involved examining the relationship between the TLI variables and non-volatile suspended solids[7] (which increase in concentration with increasing wind-induced disturbance) to calculate residual values (ie, any effects of weather were removed). Trend analysis was then carried out following the steps above using these residual values.

Preliminary analysis of the monitoring data indicated that conductivity (in this case a surrogate for salinity) may also be a strong factor controlling some water quality variables. Where this was found to be the case a similar process to the calculation of deweathered values was undertaken. Variables were plotted against conductivity to examine the relationship and to calculate residual values (ie, any effects of conductivity were removed). Trend analysis was then carried out following the steps above using these residual values.

Trends in TLI scores were examined by calculating a mean TLI score (based on the mean value of each of the four TLI variables from data pooled for all sites) for each year and plotting a straight line using ordinary least squares regression. A trend was considered statistically significant if the p-value was <0.05.

3.3 Water quality

Table 3.2 presents a summary of the current water quality of Lake Wairarapa, with data pooled from the four sampling sites, based on 14 sampling occasions during the period 2006 to 2010. Figure 3.6 summarises the range of concentrations for selected variables (data pooled from all four sites), with these reported against national median values for lakes in catchments dominated by indigenous forest and pastoral land cover (Verburg et al. 2010).

[7] Non-volatile suspended solids are those solids that are not lost on ignition of total suspended solids; they give a rough approximation of the amount of inorganic matter present in the solid fraction of the water sample.

Table 3.2: Summary of physico-chemical and microbiological water quality in Lake Wairarapa, based on 14 sampling occasions during 2006 to 2010 (data pooled from all four sites). National median values for lakes in catchments dominated by pastoral land cover are also presented (taken from Verburg et al. 2010). D.L. = detection limit.

Variable	National median values	Median	Minimum	Maximum	% *n* <D.L.
Water temperature (°C)	—	13.1	7.7	17.7	—
Dissolved oxygen (% saturation)	—	98.6	92.5	117	—
Dissolved oxygen (mg/L)	—	10.4	8.2	13.8	—
pH	7.7	7.5	6.7	7.9	—
Conductivity (µS/cm)	192	774	136	3,200	—
Secchi depth (m)	2.0	0.24	0.09	1.23	—
Turbidity (NTU)	3.2	51.5	3.2	220	0
Total suspended solids (mg/L)	—	48.5	10	230	0
Volatile suspended solids (mg/L)	—	5.5	<2.0	24	16
Total nitrogen (mg/L)	0.773	0.52	0.07	1.48	0
Nitrite nitrogen (mg/L)	—	0.001	<0.002	0.004	75
Nitrite-nitrate nitrogen (mg/L)	—	0.053	<0.002	0.943	32
Ammoniacal nitrogen (mg/L)	0.013	0.016	<0.01	0.320	38
Total phosphorus (mg/L)	0.037	0.080	0.030	0.290	0
Dissolved reactive phosphorus (mg/L)	0.003	0.005	<0.004	0.029	33
5-day biochemical oxygen demand (mg/L)	—	0.40	0.24	4.2	34
Chlorophyll *a* (mg/m^3)	8.8	5.95	<1.90	31	18
E. coli (cfu/100 mL)	—	10	<1	150	16
Faecal coliforms (cfu/100 mL)	—	11	<1	190	11

Relative to national median values for lakes located in catchments dominated by pastoral land cover, the median total phosphorus concentration was higher, while the median water clarity (Secchi depth) and median total nitrogen and chlorophyll *a* concentrations were lower. The lower water clarity is probably primarily due to suspended sediment arising from wind disturbance rather than high phytoplankton biomass; this is supported by the very low median volatile suspended solids concentration (Table 3.2), indicating that the majority of the suspended sediment is of inorganic origin. Similarly, the high total phosphorus concentrations are also probably due to suspended sediment arising from wind disturbance (the effects of wind disturbance are examined further in Section 3.3.2).

Measurements of conductivity ranged from 136 to3,200 µS/cm over the reporting period and the median value of 774 µS/cm is well above national medians for lakes situated in catchments dominated by pastoral or indigenous forest land cover (Figure 3.6). No conductivity measurements were recorded above ANZECC (2000) trigger levels that may cause a loss in production to sensitive stock types (~4,478 µS/cm[8]). Elevated conductivities are a clear indication that despite being located approximately 12 km from the coast, Lake

[8] The ANZECC (2000) trigger levels for tolerance of various livestock types are for concentrations of total dissolved solids. As per recommendations in ANZECC (2000), concentrations of total dissolved solids were approximated from measurements of conductivity using the following equation: Total dissolved solids (mg/L) = 0.67 x conductivity (µS/cm).

Wairarapa is still influenced, at least at times, by a backflow of saline water from Lake Onoke and/or the tidal regime of Lake Onoke and the lower Ruamahanga River. The tidal effect is also evident in changes in stage height recorded at the southern end of Lake Wairarapa at the barrage gates (eg, Figure 3.7), although this depends on a variety of factors including whether or not the barrage gates are open, whether Lake Onoke's mouth is open and potentially also lake levels (in both Onoke and Wairarapa) and flow conditions in the lower Ruamahanga River.

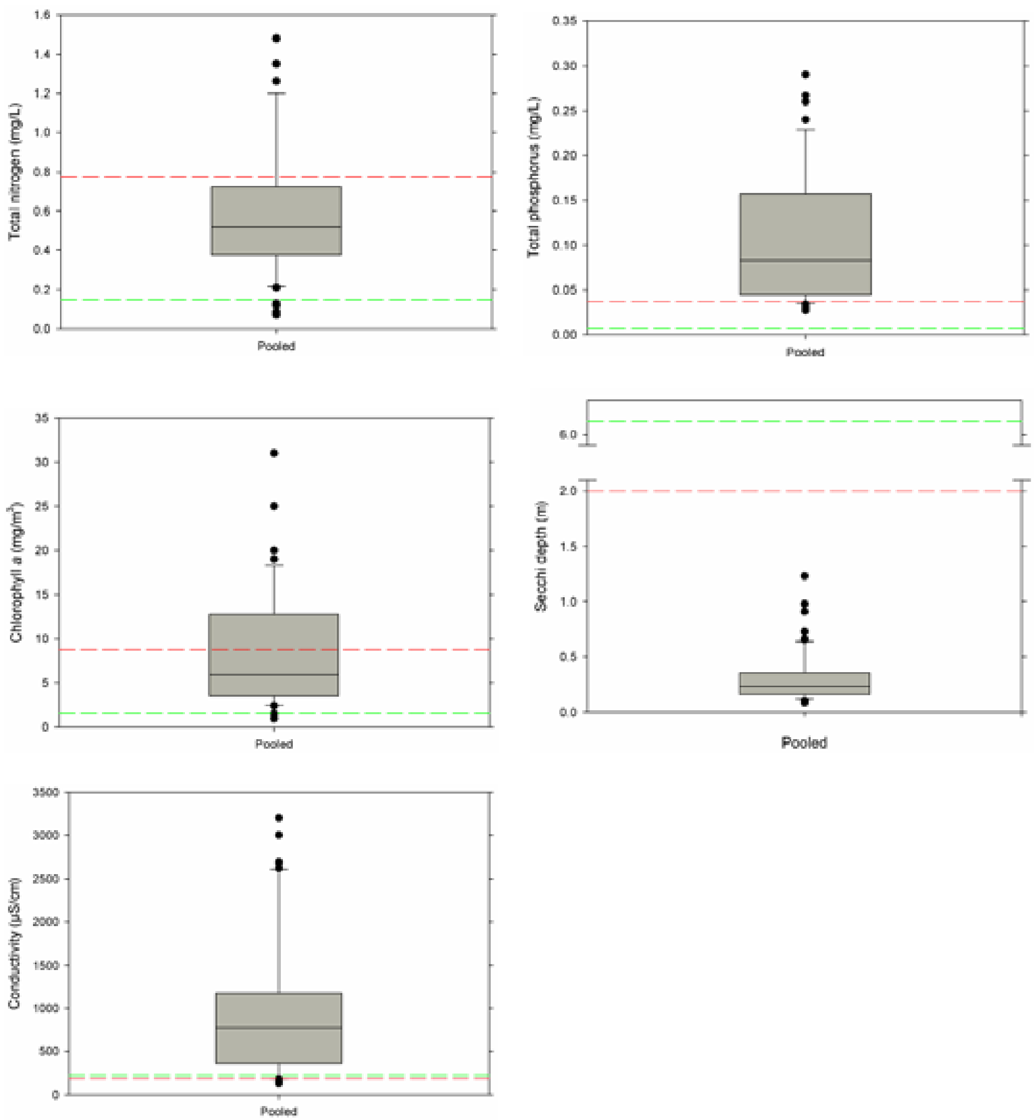


Figure 3.6: Box plots for selected water quality variables, based on data pooled for all four monitoring sites for the period 2006 to 2010. Horizontal dashed lines indicate national median values (taken from Verburg et al. 2010) for lakes in catchments dominated by indigenous forest (green) and pastoral (red) land cover.

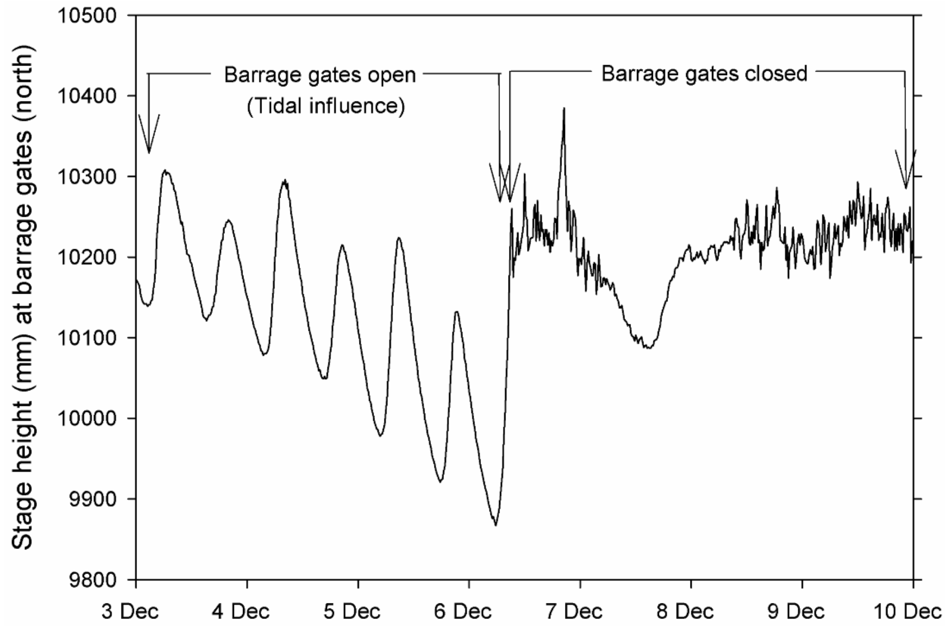


Figure 3.7: Continuous stage height measurements from the recorder located at the northern side of the barrage gates, 3 December 2009 to 10 December 2009. The status of the barrage gates (ie, open or closed) is also presented.

The median *E. coli* concentration recorded over the five-year reporting period was well below the ANZECC (2000) and MfE/MoH (2003) guidelines for both stock water drinking and for recreational use (Figure 3.8). On only one occasion did one site (Site 1) record a count greater than 100 cfu/100mL. However, it is important to note that the four sampling sites are located well away from any potential sources of likely faecal contamination (eg, stream inputs); most recreational use and water takes are likely to occur around the lake edge where faecal indicator counts may be higher.

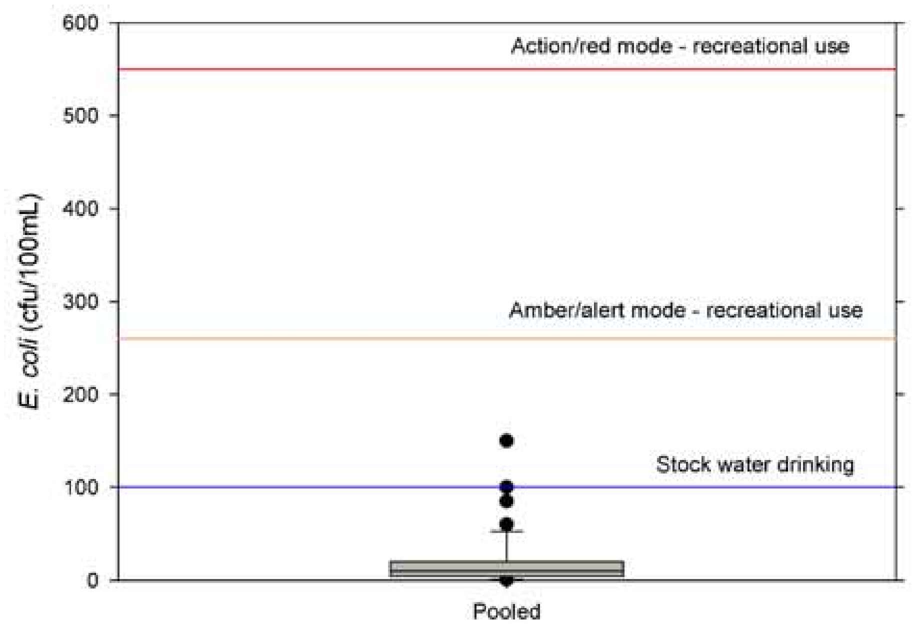


Figure 3.8: Concentrations of *E. coli*, based on pooled data collected between 2006 and 2010. The horizontal dashed lines indicate ANZECC (2000) and MfE/MoH (2003) guidelines for stock drinking water and contact recreation, respectively.

3.3.1 Trophic state

Based on the period 2006 to 2010 (n=14), Lake Wairarapa has an overall TLI score of 5.4 and is classed as supertrophic (Table 3.3). TL values for both chlorophyll *a* and total nitrogen were indicative of a lower trophic state (eutrophic) when compared to TL values for total phosphorus and Secchi depth (hypertrophic). A closer look at the TLI scores for each sampling site indicated there was no statistically significant difference between sites (Repeated measures ANOVA on ranked data, p=0.29), with median TLI scores ranging from 5.2 to 5.5 (Figure 3.9).

Table 3.3: Lake Wairarapa mean total nitrogen, total phosphorus, Secchi depth (water clarity) and chlorophyll *a* values for years 2006 to 2010 along with the overall means and TL values for the five-year reporting period. All values presented are based on data pooled from the four sampling sites.

Year	*n*	Total nitrogen (mg/L)	Total phosphorus (mg/L)	Secchi depth (m)	Chlorophyll *a* (mg/m^3)
2006	3	0.811	0.129	0.22	6.4
2007	2	0.412	0.090	0.55	3.6
2008	3	0.582	0.106	0.37	12.5
2009	3	0.678	0.143	0.20	10.8
2010	3	0.432	0.060	0.28	7.7
Overall mean (2006–2010)	14	0.595	0.106	0.30	8.5
TL value		4.7 (eutrophic)	6.1 (hypertrophic)	6.3 (hypertrophic)	4.6 (eutrophic)
TLI score	5.4 (supertrophic)				

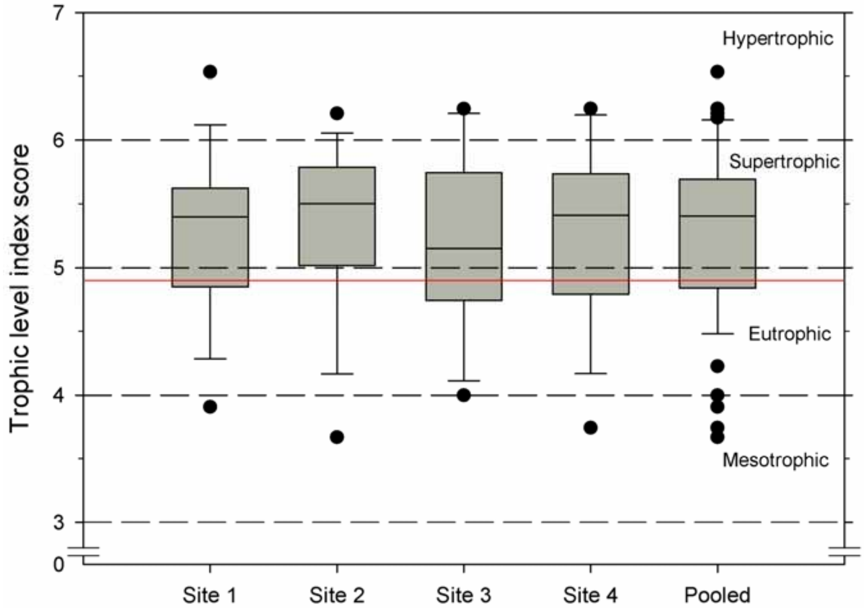


Figure 3.9: Box plots summarising TLI scores for each Lake Wairarapa sampling site and for all sites pooled, based on 14 sampling occasions between 2006 and 2010. The horizontal red line indicates the national median TLI score for lakes in catchments dominated by pastoral land cover (taken from Verburg et al. 2010). Note the scale break on the *y*-axis.

(a) Nutrient limitation

Calculation of total nitrogen and total phosphorus ratios, based on all sampling occasions, results in median ratio values of around five or less for all four sampling sites, with ratios below seven on 71% of sampling occasions (Figure 3.10). This suggests that nitrogen may be the limiting nutrient, if nutrient limitation of phytoplankton growth occurs. There is also some indication of seasonal changes in nutrient limitation. For example, ratios for all samples collected between December and February are below 7. This is not observed during the other seasons (Figure 3.10).

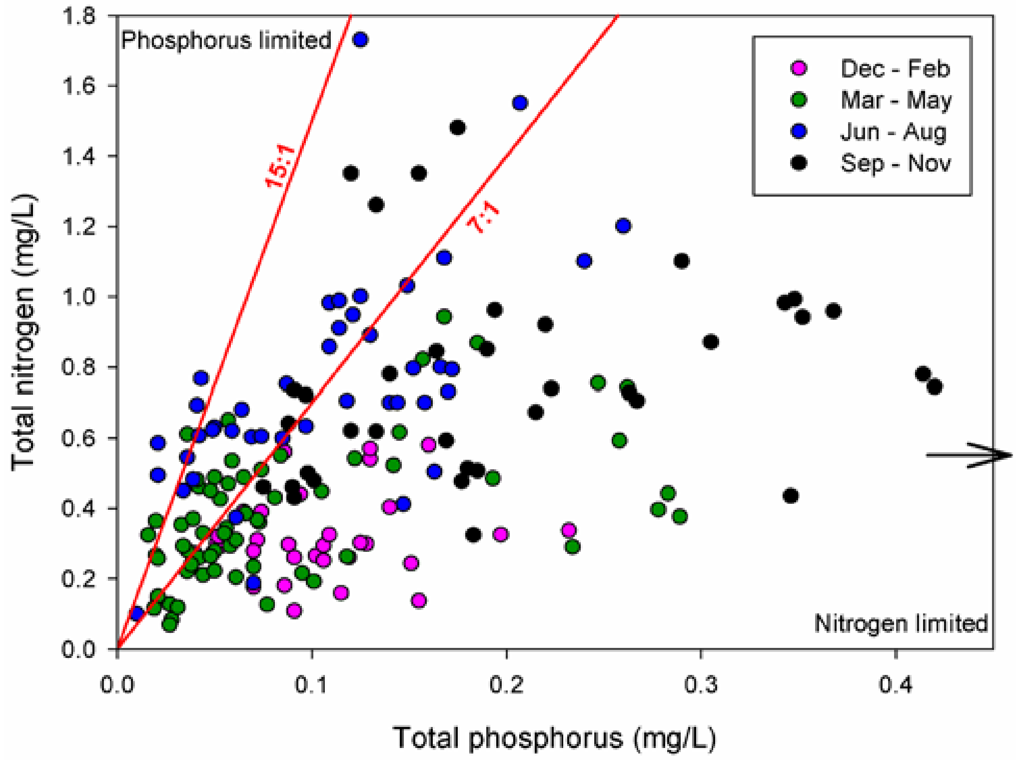


Figure 3.10: Plot of total phosphorus against total nitrogen, based on data from all sampling occasions across all four Lake Wairarapa sampling sites, coloured according to season. The red lines indicate thresholds for potential phosphorus limited (15:1) and nitrogen limited (7:1) conditions for phytoplankton growth. Values between the red lines are inconclusive. The arrow indicates the presence of three values off the scale of the graph.

Plots of chlorophyll *a* concentrations (an indicator of phytoplankton biomass) against dissolved nutrient concentrations also suggest that at times phytoplankton growth may be nitrogen limited. When chlorophyll *a* concentrations are very high (ie, high phytoplankton biomass), concentrations of dissolved inorganic nitrogen are typically low indicating that the available nitrogen is being used up by phytoplankton growth. This relationship is not observed with dissolved reactive phosphorus (Figure 3.11). However, it is important to remember that this analysis is not unequivocal and further targeted investigations would be required to determine if and when nutrient limitation of phytoplankton growth occurs.

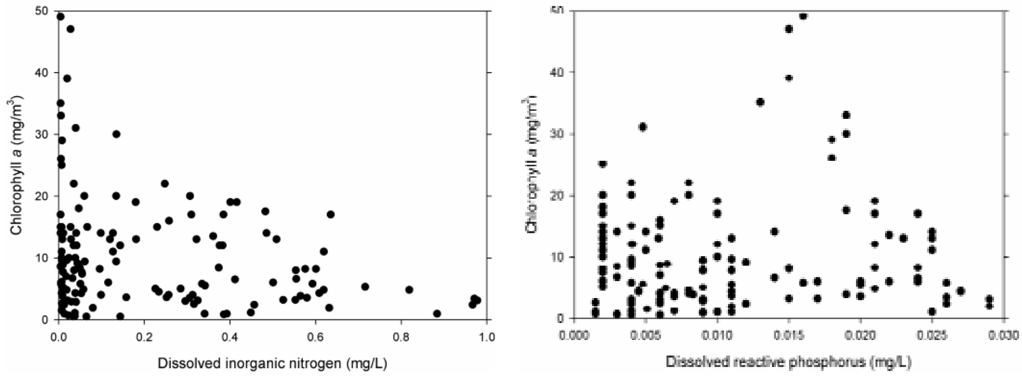


Figure 3.11: Concentrations of chlorophyll *a* against concentrations of dissolved inorganic nitrogen (left) and dissolved reactive phosphorus, based on data pooled from all four Lake Wairarapa sampling sites over the entire monitoring record (1994–2010)

(b) Phytoplankton

Eleven taxa were identified in a one-off water sample collected in May 2008 from Site 2 (Table 3.4); on this occasion the lake water was green in appearance and surface scums of phytoplankton were visible at all four sampling sites (Figure 3.12). One potentially toxic cyanobacteria species was identified in the sample: *Anabaena lemmermannii*.

Calculation of a cell biovolume (based on a count of 12,000 *Anabaena lemmermannii* cells) and application of the alert level framework for assessing risk to recreational users following protocols in MfE/MoH (2009) results in a biovolume of 1.392 mm^3/L. This value falls into the alert (amber) mode of the framework and indicates a potential health risk to recreational users. Under such situations, the framework recommends increasing the frequency of sampling and the number of sampling sites.

Table 3.4: Phytoplankton taxa identified in a one-off water sample collected from Lake Wairarapa in May 2008. Cell counts are also presented.

Taxa	Cell count (cells/mL)
Anabaena lemmermannii	12,000
cf. *Quadricoccus sp*.	110,000
Cryptomonas sp.	10
Cyclotella sp.	10
Dictyosphaerium sp.	210
Monoraphidium spp.	140
Oocystis sp.	290
Romeria sp.	370
Small unicells (<5µm)	13,000
Thalassiosira sp.	10
Unknown filamentous algae	6,700

Figure 3.12: Phytoplankton scum visible on the northern shore of Lake Wairarapa in May 2008. Phytoplankton scums were also visible on the lake's surface at each of the four sampling sites.

3.3.2 Effect of wind disturbance on water quality

Following recommendations in Burns et al. (2000), the effects of sediment disturbance on the water quality of Lake Wairarapa were investigated by plotting selected variables against non-volatile suspended solids (NVSS)[9] (a surrogate for wind disturbance) using the entire monitoring data record (1994–2010).

All four TLI variables showed a general deterioration with increasing concentrations of NVSS (Figure 3.13) indicating that wind disturbance is potentially a strong driver of water quality in Lake Wairarapa. Both Secchi depth and concentrations of total phosphorus showed moderately strong linear relationships with NVSS, decreasing and increasing with increasing NVSS concentrations, respectively. Concentrations of total nitrogen and chlorophyll *a* also increased with increasing concentrations of NVSS, although there was far more variability in these relationships.

Given the strong relationship between water quality and wind disturbance, along with the bias of sampling occasions towards calm weather conditions (ie, when it is safe to sample), it is likely that the Lake Wairarapa monitoring programme to date is indicating better water quality then is actually the case. Windy and turbulent lake conditions are common place in the lower Wairarapa Valley and it is likely that sampling during these conditions would result in poorer water quality being observed than is currently being measured (at least in terms of water clarity and concentrations of total phosphorus).

[9] NVSS were calculated by subtracting the volatile suspended solids concentration from the total suspended solid concentration.

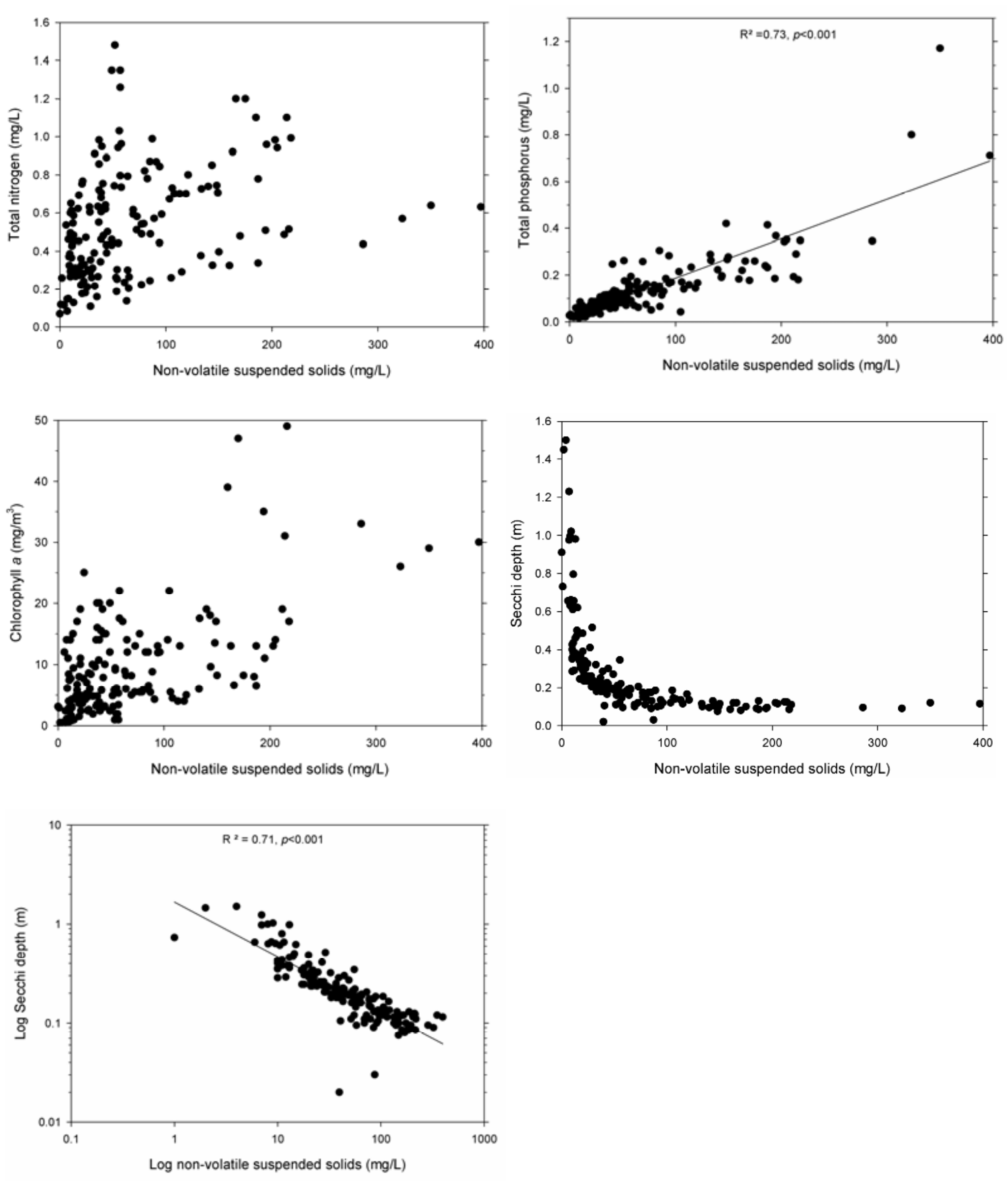


Figure 3.13: Selected variables plotted against non-volatile suspended solid (NVSS) concentrations, based on data pooled from all four sampling sites over the entire monitoring period (1994–2010). A linear regression line has been fitted where appropriate. Both actual and log transformed data are presented to demonstrate the relationship between Secchi depth and NVSS.

3.3.3 Effect of conductivity on lake water quality

The effects of saline inputs on water quality in Lake Wairarapa were investigated by plotting measurements of the four TLI variables against conductivity (as a surrogate for salinity) for the entire monitoring data record (1994–2010 where available). Figure 3.14 indicates that all four TLI variables show a general improvement as conductivity increases. Secchi depth shows the strongest relationship, with measurements generally increasing with increasing conductivity. The relationships between conductivity and concentrations of total nitrogen, total phosphorus and chlorophyll *a* are less clear but they all tend to decrease as conductivity increases.

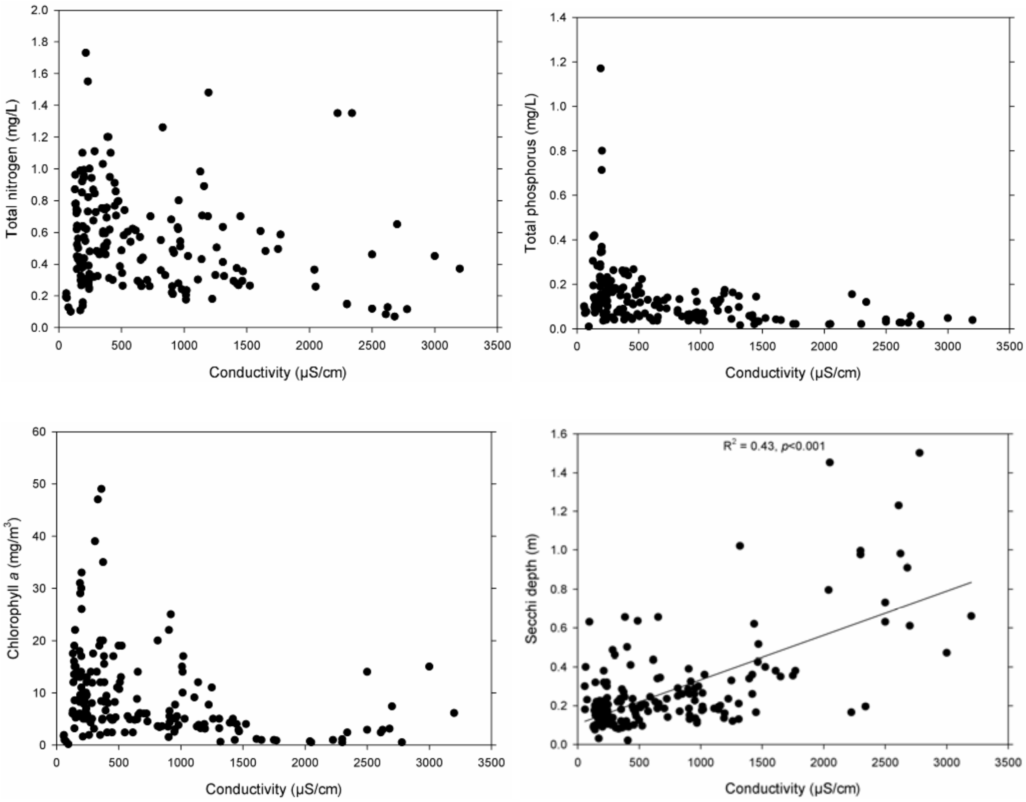


Figure 3.14: Plots of TLI variables against measurements of conductivity, based on data pooled from all four Lake Wairarapa sampling sites across the entire monitoring data record (1994–2010 where available). A linear regression line has been fitted where appropriate.

The effect of conductivity on the different TLI water quality variables can clearly be seen if sampling occasions are split by whether or not they coincided with elevated measurements of conductivity[10] (Figure 3.15). All variables showed a statistically significant improvement when sampling coincided with a conductivity measurement above upper quartile (Mann-Whitney Rank Sum Test, $p \leq 0.002$). In the case of chlorophyll *a* and total phosphorus, this improvement would result in the classification of a lower trophic category. A significant improvement can also be seen in overall TLI scores (Figure 3.16, Mann-Whitney Rank Sum Test, $p<0.001$) with a median score of 5.6 and 5.0 based on sampling occasions that coincide with a conductivity less than or greater than 989 µS/cm, respectively. Overall, the analysis indicates that water quality in Lake Wairarapa tends to be better when there is a stronger saline influence (as indicated by higher conductivity measurements), suggesting that the saline inputs often have a 'diluting' effect.

[10] In this case elevated measurements of conductivity were considered to be values over the upper quartile (75th percentile) value (989 µS/cm) for the entire monitoring record.

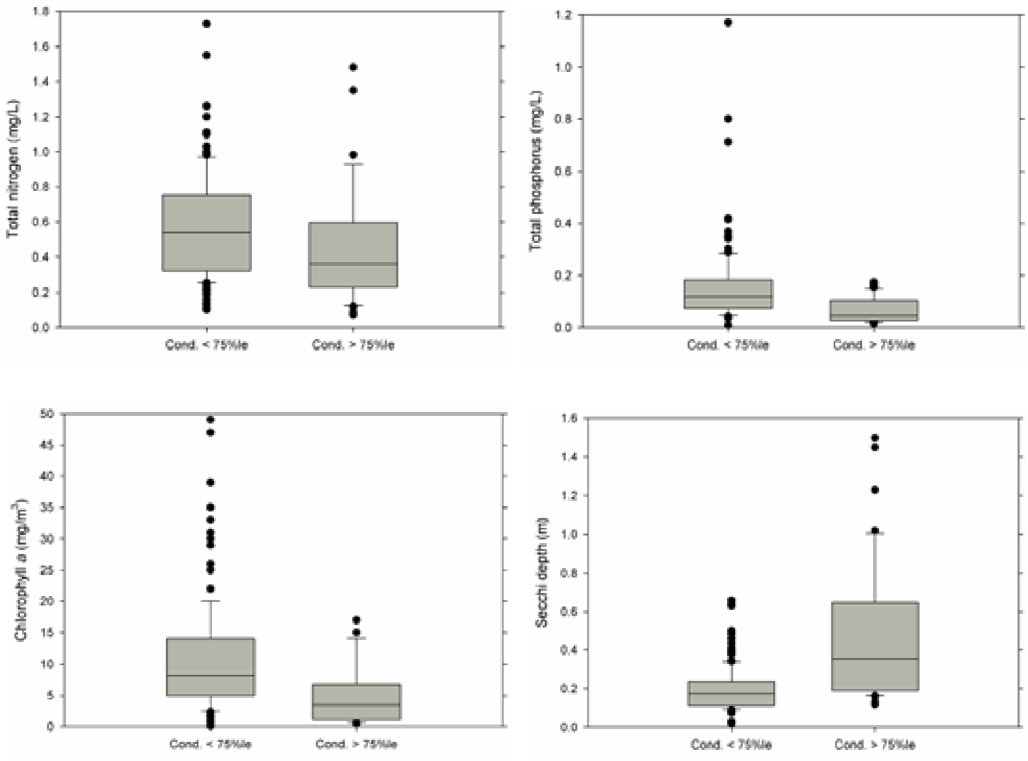


Figure 3.15: Box plots summarising the range of results for the four TLI variables for sampling occasions that coincided with conductivity values below (*n*=135) or above (*n*=45) the 75th percentile conductivity value (989 µS/cm), based on data pooled from all four Lake Wairarapa sampling sites over the entire monitoring record

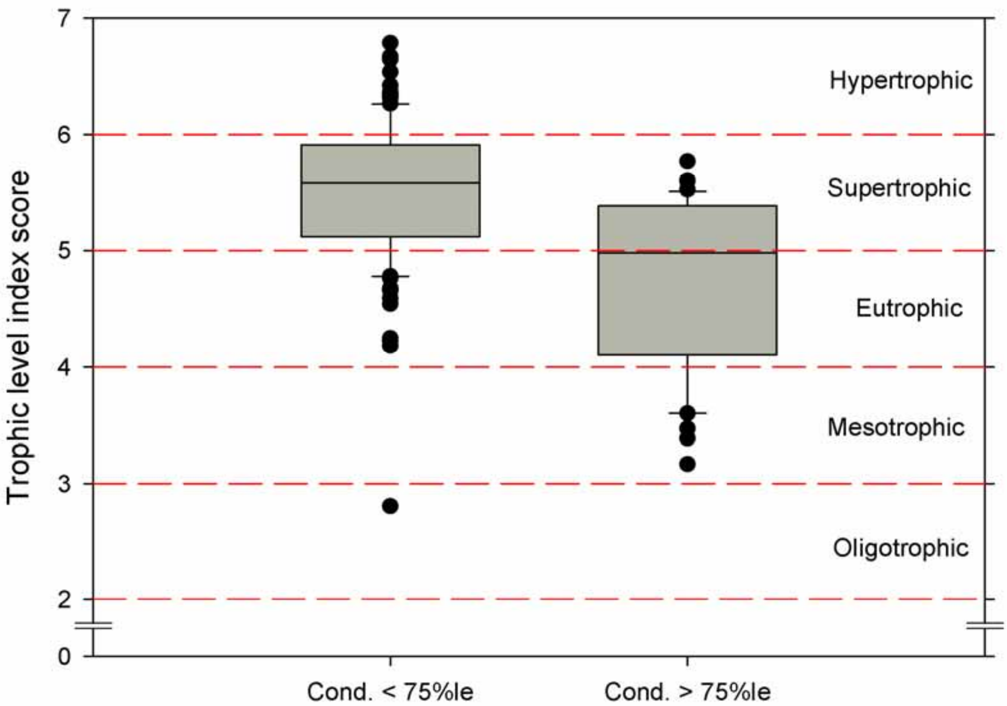


Figure 3.16: Box plots summarising the range of TLI scores for sampling occasions below and above the 75th percentile conductivity value (989 µS/cm), based on pooled data from all four Lake Wairarapa sampling sites (1994–2010)

3.3.4 Spatial patterns in lake water quality

Spatial patterns in water quality were examined by comparing results from selected variables between sampling sites. The entire monitoring data record (1994–2010 where available) was used in this analysis to increase statistical sensitivity. In general, results from the four sampling sites were moderately to highly correlated (eg, Figure 3.17, Pearson's Product Correlation, $p<0.05$ for all variables across all sites except faecal coliforms and *E. coli,* see Table A2.2, Appendix 2 for details), although statistically significant differences (Repeated measures ANOVA on ranked data, $p<0.05$) were found between some sampling sites for some variables including Secchi depth (Sites 1 and 4), turbidity (Sites 1 and 2, 3 and 4), total phosphorus (Sites 1 and 4), conductivity (Sites 1 and 4, 1 and 3, 2 and 4), pH (Sites 1 and 2, 1 and 3, 1 and 4, 2 and 3) and water temperature (Sites 2 and 3).

In most cases the observed differences between median values for the sites and variables mentioned above were generally quite small and unlikely to be having much influence over spatial variation in water quality/lake condition. For example, the difference between median values in water temperature at Sites 2 and 3 was only 0.5^{o}C (median 13.2^{o}C and 13.7^{o}C respectively).

The most marked differences in water quality between sites were found between median values for conductivity and total phosphorus at Sites 1 and 4 (Figure 3.18). The difference in median conductivity values observed between Site 1 and Site 4 (333 µS/cm and 488 µS/cm, for Sites 1 and 4 respectively) indicates that at certain times there is a conductivity gradient in the lake, with conductivity typically higher at the southern end of the lake near its outlet. A closer look at individual sampling occasions shows that the difference in conductivity between Site 1 and Site 4 can be over 1,000 µS/cm. However, there are also a number of sampling occasions when measurements of conductivity are comparable between these sites (as well as the other sites) and even one occasion where the north to south conductivity gradient is reversed.

The median total phosphorus concentration at Site 1 (0.08 mg/L) at the northern end of the lake is about two thirds of that recorded at Site 4 (0.121 mg/L) at the southern end. Site 1 also had slightly better water clarity (both higher Secchi depth and lower turbidity) which may further indicate overall better water quality at this site compared to the other three sampling sites. Morton (1995) and Stansfield (1996; 1999) have previously reported slightly better water quality at this site. However, similar to the 2006–2010 period examined in Section 4.3.1, there is no significant difference between sites for TLI scores calculated for the entire monitoring record (Repeated measures ANOVA on ranked data, $p=0.66$). This suggests that despite these slight differences, overall, the better water quality observed at Site 1 is fairly insignificant.

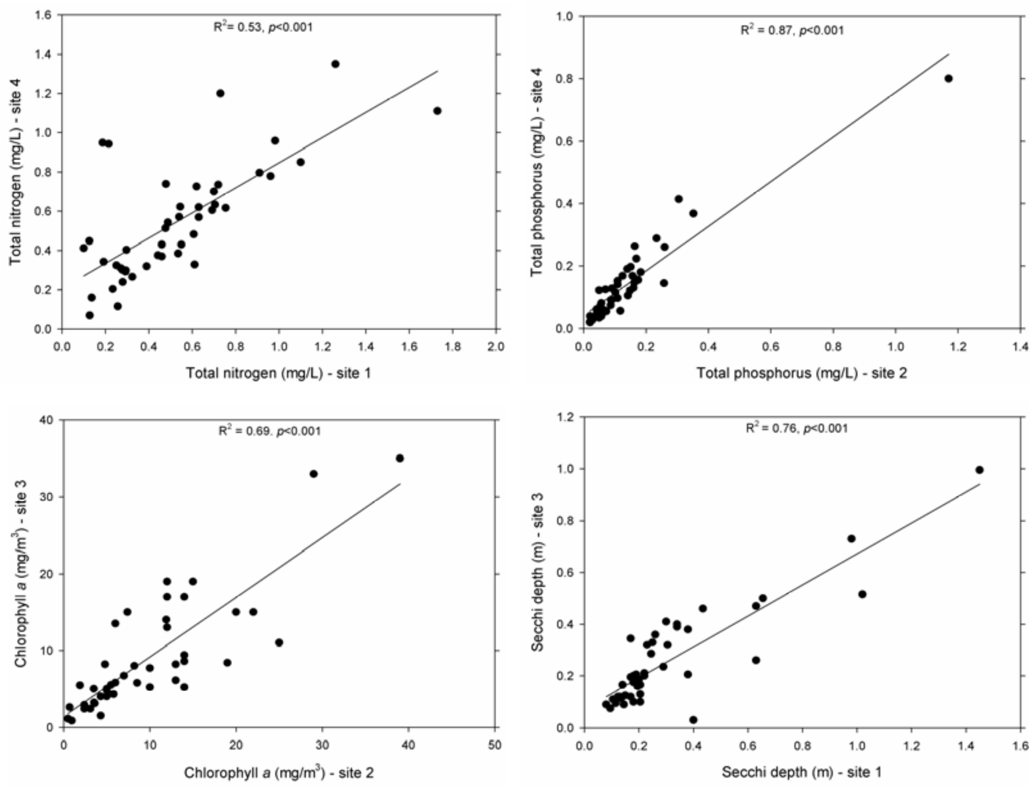


Figure 3.17: Example plots showing relatively strong relationships in TLI variable concentrations between sampling sites, based on the entire monitoring data record for each site (1994–2010). Linear regression lines have been fitted to help visualise these relationships.

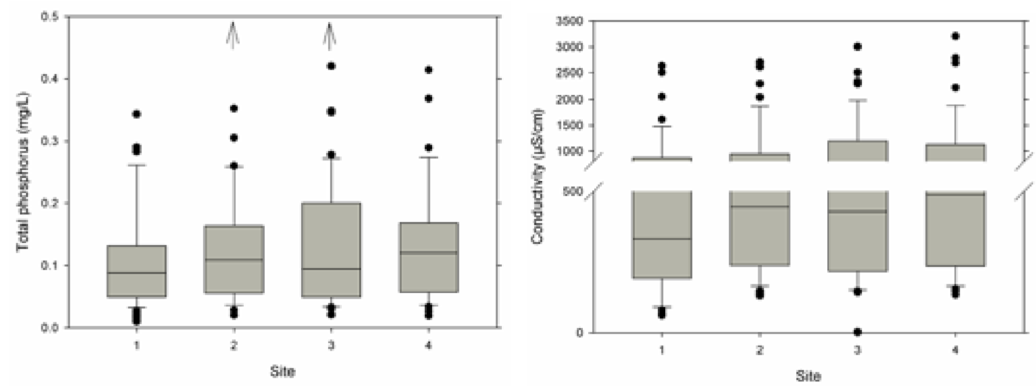


Figure 3.18: Box plots summarising differences in total phosphorus (left) and conductivity (right) concentrations between the four sampling sites, based on the entire monitoring data record (1994–2010). Arrows indicate where additional outliers are not shown. Note the *y*-axis break on the conductivity plot.

3.3.5 Seasonal patterns in lake water quality

Seasonal patterns in selected variables were examined by grouping sampling occasions into the following ‘seasons’: December to February, March to May, June to August, and September to November (Figure 3.19). While some care must be taken when interpreting seasonal trends due the wide scatter of the data and also the irregular sampling frequency (ie, not all seasons have been sampled the same number of times), several potential seasonal patterns are apparent:

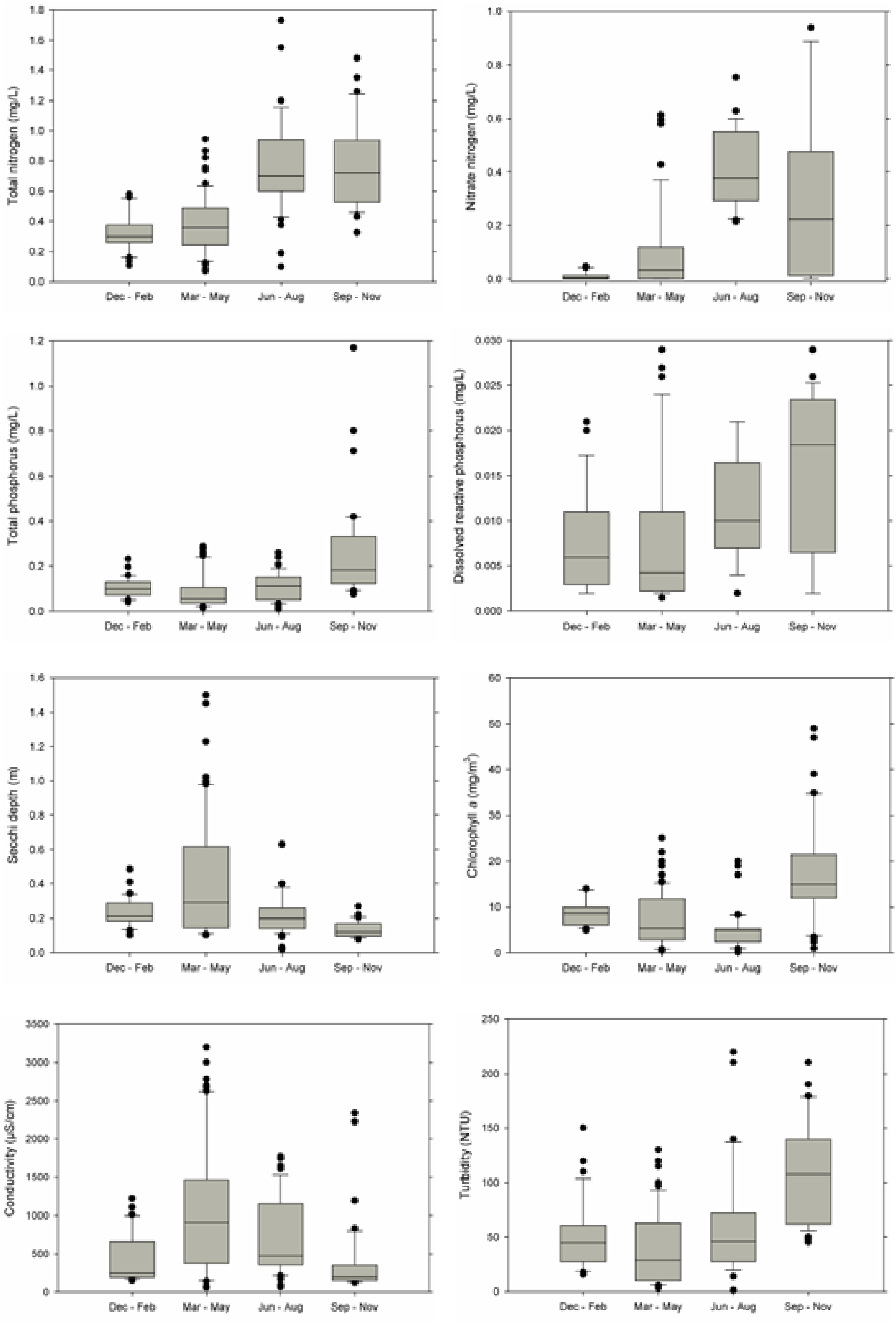


Figure 3.19: Lake Wairarapa box plots summarising the range of measured values for selected water quality variables, based on data pooled from all four sites for the entire monitoring record (1994–2010 where available). Sampling occasions have been grouped according to the following seasons: December to February (summer), March to May (autumn), June to August (winter) and September to November (spring).

- Concentrations of total nitrogen and nitrate nitrogen are higher during winter and spring (June to November), while concentrations of total phosphorus, dissolved reactive phosphorus and chlorophyll *a* are all highest in spring (September to November);

- Water clarity, as indicated by high Secchi depth measurements and low turbidity measurements, is highest during autumn (March to May) and lowest during spring; and

- There is some indication that elevated conductivity measurements are more likely to occur in autumn.

Not all of these patterns are easy to explain but seasonal winds are likely to be a factor behind some; although there is no clear evidence of variation in wind intensities among seasons, analysis of Greater Wellington's wind data collected from the barrage gates indicates that there are fewer calm days in spring (especially compared with autumn and winter). In the case of soluble inorganic nitrogen – present principally in the form of nitrate nitrogen – the peak concentrations in the lake are observed during winter and are probably due to the winter 'flush' from agricultural soils in the catchment. Lower denitrification rates as well as limited uptake by phytoplankton (ie, minimal phytoplankton growth) in winter may also be influencing the observed seasonal trends in nitrogen. This is discussed further in Section 3.4.

3.3.6 Temporal trends in water quality

Potentially meaningful trends (ie, statistically significant ($p<0.05$) with a PAC >1%) in deseasonalised data pooled across the four sampling sites over the period 1994–2010 are summarised in Table 3.5. Full trend analysis results, including results for each individual sampling site, are provided in Tables A2.3–A3.8, Appendix 2.

Table 3.5: Summary of potentially meaningful trends (ie, statistically significant ($p<0.05$) with PAC >1%) in deseasonalised data, based on data pooled from the four Lake Wairarapa sampling sites for the entire monitoring record (1994 to 2010 where available)

Variable	Period analysed (*n*)	*p*-value	Mean	Rate of change (units/year)	Annual change (%)
Conductivity (µS/cm)	1994–2010 (45)	<0.01	719.5	36.9	5.1
Secchi depth (m)	1994–2010 (45)	<0.01	0.27	0.01	3.7
Volatile suspended solids (mg/L)	1995–2010 (41)	<0.01	11.1	-0.7	-5.9
Total suspended solids (mg/L)	1995–2010 (41)	0.02	83.9	-3.52	-4.2
Dissolved reactive phosphorus (mg/L)	1998–2010 (35)	<0.01	0.0107	-0.0006	-5.1

Five potentially meaningful trends were present in the deseasonalised data (Table 3.5) and except in the case of total suspended solids (p=0.06), these trends were also statistically significant in the raw data. Statistically significant trends were also detected in deseasonalised data for water temperature and pH but these were not considered meaningful (eg, PAC <1%, see Appendix 2)

An increasing trend in Secchi depth (Figure 3.20), along with decreasing trends in concentrations of volatile suspended solids, total suspended solids and dissolved reactive phosphorus are all indicative of improving water quality. Concentrations of total phosphorus also appeared to be decreasing (-0.003 mg/L/year or -2.5%) although this was just outside statistical significance (p=0.07, Appendix 2). It is possible that some of the observed 'improvements' may be related to sampling conditions (wind in particular) as no significant trends were evident in selected key variables (total nitrogen, total phosphorus and chlorophyll *a*) after 'deweathering' of data was undertaken (see Appendix 2). Similarly, correcting Secchi depth for conductivity resulted in no significant trend in water clarity, suggesting that the improving trend in water clarity observed in both the raw and deseasonalised data may be related to the increasing trend in conductivity (and/or wind at the time of sampling).

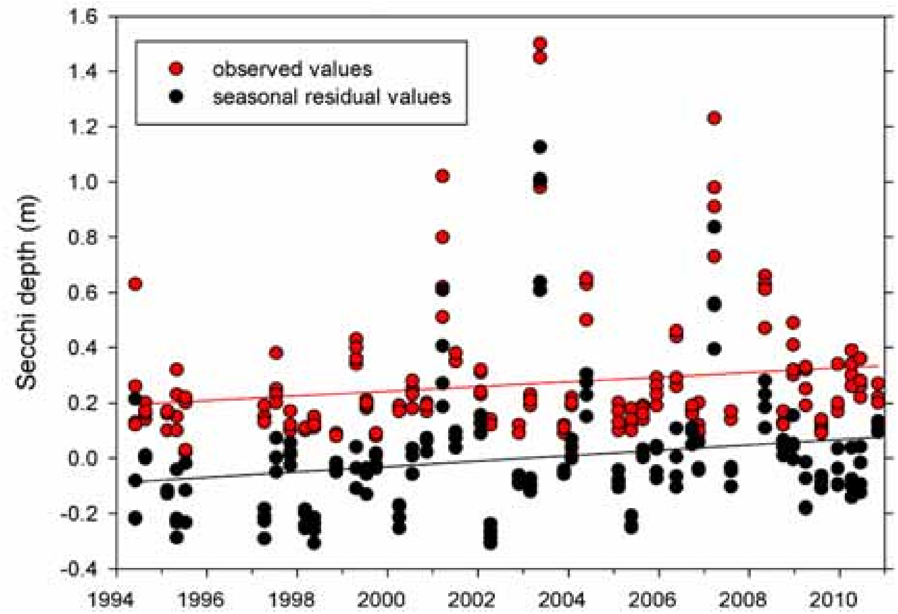


Figure 3.20: Observed Secchi depth measurements and deseasonalised residual values, based on data pooled from all four sampling sites over the period 1994 to 2010. The solid lines represent the overall trends.

An increase in conductivity of 36.8 µS/cm per year (Figure 3.21) neither represents an improvement nor a degradation in water quality. However, this increase is of interest given its apparent influence on some water quality variables and its potential impact on the lake's ecology.

The trends presented in Table 3.5 were typically not evident (p<0.05 and PAC >1%) when sites were analysed on an individual site by site basis except in the case of volatile suspended solids (all sites) and conductivity (Site 1). Trends in Secchi depth and conductivity were just outside statistical significance at Sites 2 and 3 (p=0.05 to 0.08) (Appendix 2).

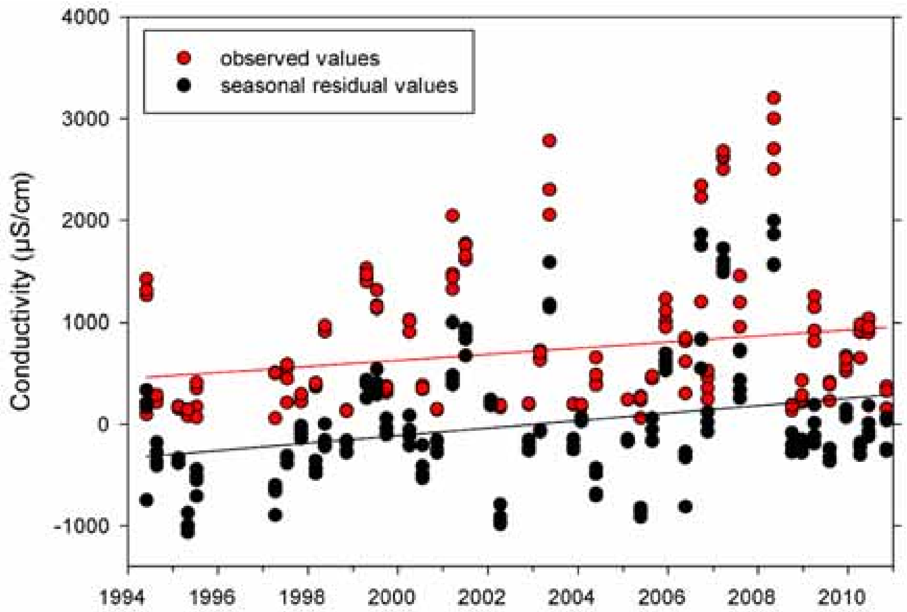


Figure 3.21: Observed conductivity values and deseasonalised residual values, based on data pooled from all four sampling sites over the period 1994 to 2010. The solid lines represent the overall trends.

Mean TLI scores for each year are presented in Figure 3.22. While fitting of a linear regression line indicated a slight decline in TLI score over the period 1994 to 2010 it was not statistically significant (p=0.6) and overall, based on the monitoring undertaken to date, it can be concluded that lake water quality has not changed significantly since monitoring began.

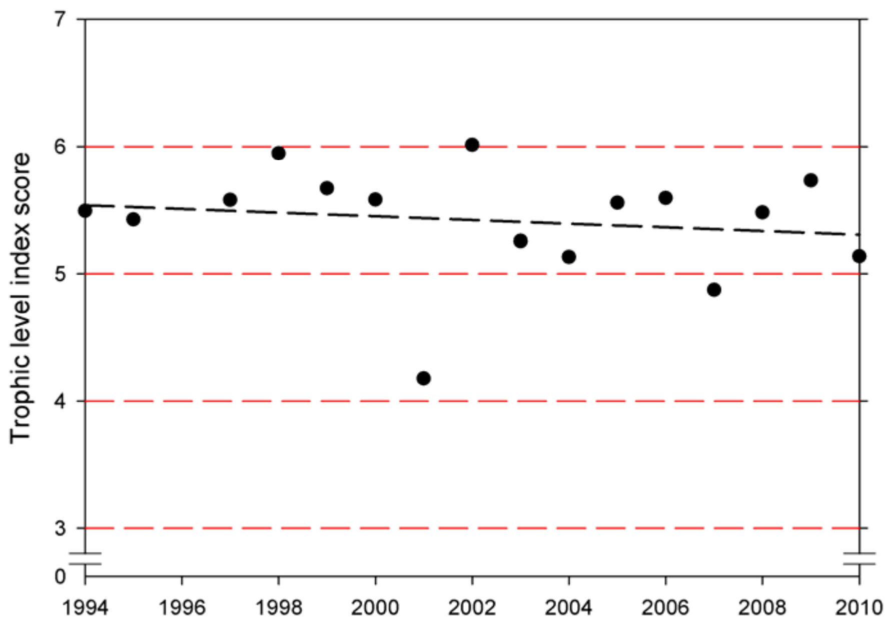


Figure 3.22: Mean TLI score for each year for the period 1994 to 2010*, based on data pooled from all four sampling sites on Lake Wairarapa. The black dashed line represents the (non-significant) trend and the horizontal dashed red lines indicate the different trophic level classes.

*Note that the low TLI score for 2001 was generated from just two sampling occasions and on both of these occasions concentrations of total phosphorus and chlorophyll *a* were lower, and measurements of Secchi depth higher (ie, clearer water), than was typically recorded during sampling occasions in other years.

3.4 Discussion

Despite several limitations with the current monitoring programme – discussed later in this section – monitoring to date clearly shows that Lake Wairarapa is in poor condition. The key characteristics and drivers of the lake's water quality are revisited here, followed by a brief discussion of some of the nutrient sources contributing to the lake's poor water quality.

3.4.1 Water quality characteristics and drivers

Lake Wairarapa has degraded water quality, characterised by elevated concentrations of nutrients and algal biomass and poor water clarity. Application of the TLI for monitoring data collected over 2006–2010 results in the lake being classed as supertrophic, indicative of 'very high' nutrient enrichment. Lake Wairarapa can be considered to be in a poorer than average condition when compared to other similar lakes in New Zealand (ie, lakes in pastoral catchments and other shallow coastal lakes). However, this classification (supertrophic) is heavily influenced by low water clarity and high total phosphorus concentrations which are, in turn, both adversely affected by wind suspension of bottom sediments in this shallow lake. Trophic state is traditionally used as a measure of lake productivity, and for this purpose the trophic state of Lake Wairarapa may be better defined simply in terms of its mean chlorophyll *a* and total nitrogen concentrations – which both indicate a eutrophic state. Overall then, it may be more appropriate to classify Lake Wairarapa as being eutrophic/supertrophic (K. Hamill pers. comm. 2011[11]).

The current poor state of water quality is similar to that which has been reported previously with both Stansfield (1999)[12] and Perrie (2005) classifying the lake as supertrophic. While there is some indication of improvements in aspects of water quality (eg, water clarity and dissolved reactive phosphorus), these are generally small and in terms of overall water quality and lake condition, as measured by the TLI, there has been little change since monitoring began in 1994.

Seasonal patterns in water quality are evident, with concentrations of total nitrogen highest in the winter months. This is most likely due to the increased 'flushing' of agricultural land that occurs during these wetter months (discussed further in Section 3.4.2), as well as potentially less uptake by phytoplankton and lower rates of denitrification. In contrast, concentrations of total phosphorus tend to peak with non-volatile suspended solid concentrations in spring and early summer, coinciding with increased sediment re-suspension that can be attributed to the more frequent occurrence of windy days at these times of the year.

Alongside wind, which is known to be a strong driver of water quality in shallow lakes (Burns et al. 2000), the monitoring data indicate that salinity (as indicated by conductivity) also influences some aspects of water quality in Lake Wairarapa. Water clarity was shown to be better and concentrations

[11] Keith Hamill, Principal Environmental Scientist, OPUS International Consultants Ltd.

[12] Stansfield (1999) actually classed the lake as ranging from eutrophic (based on concentrations of total nitrogen and chlorophyll *a*) to hypertrophic (based on concentrations of total phosphorus and measurements of Secchi depth) but the average of these two trophic states can be considered supertrophic.

of total nitrogen, total phosphorus and chlorophyll *a* lower at higher conductivity concentrations, suggesting that inputs of saline water are having a 'diluting' effect on lake water quality. A conductivity gradient is also apparent within the lake, with conductivity concentrations generally higher at the two southern sites. This is to be expected given the closer proximity of these sites to Lake Onoke and subsequent increased likelihood of exposure to saline backflow into the lake (refer Section 4.1). The freshwater discharge from the Tauherenikau River is also potentially influencing the lake's conductivity gradient, resulting in lower conductivity concentrations at the two northern monitoring sites.

Movement of saline water into Lake Wairarapa is considered a natural phenomenon and there are historic records for plants in the lake that are typical of brackish conditions (Ogle et al. 1990). However, since the installation of the barrage gates in 1974 the movement of saline water into the lake was thought to have been largely removed and this has been implicated in the local extinction of several plants that prefer brackish water (Ogle et al. 1990). While saline water is clearly still entering the lake, with the monitoring record only starting in 1994, it is not known how inputs today compare with the natural conditions that existed prior to the implementation of the Lower Valley Development Scheme. The regular presence of several fish species (yellowbelly flounder, yelloweye mullet and kahawai (pers. obs.)) at the southern end of the lake that are generally considered to be marine species (McDowall 2000) may be an indication that saline or brackish conditions are still relatively common.

Further work is required to better understand the frequency and spatial extent of saline water movement into Lake Wairarapa. Salinity is clearly influencing the lake's water quality and, with monitoring over 1994 to 2010 indicating an increasing trend in conductivity concentrations, could also have significant ecological implications (ie, potential negative impacts on stenohaline[13] species and favourable impacts on saltwater tolerant/dependant species). An increasing trend in conductivity could also have implications for lake water users (ie, water takes for irrigation and stock water).

The phytoplankton bloom observed in May 2008 (*Anabaena lemmermannii*, a toxin-producing species of cyanobacteria) is the first reported to date since routine water quality monitoring commenced in 1994. Anecdotally, phytoplankton blooms have not been considered a significant issue in Lake Wairarapa due to the highly turbid nature of the lake. However, chlorophyll *a* concentrations generally indicate an elevated phytoplankton biomass and concentrations that fall within the supertrophic range (12 to 31 mg/m^3) are not uncommon in the data record. This means that while not often visible as an obvious 'nuisance' or a discolouration of the lake water, phytoplankton biomass in Lake Wairarapa can at times still be high. Furthermore, given that monitoring is limited to a few times a year blooms may be missed (eg, Figure 3.23).

[13] Plants and animals that cannot tolerate variations in salinity.

Figure 3.23: *Hydrodictyon reticulatum* (water net) washed up on the northern shore of Lake Wairarapa on a non-water sampling occasion in December 2007 (left), close up (right)

Based on nutrient ratios and relationships between dissolved nutrients and chlorophyll *a*, nitrogen is the nutrient most likely to be limiting phytoplankton growth, if nutrient limitation occurs. However, this analysis is not unequivocal and targeted investigations would be required to confirm this. Additionally, other factors, such as high suspended sediment concentrations (eg, poor water clarity), may also play a significant role in limiting phytoplankton growth in Lake Wairarapa.

3.4.2 Nutrient sources

The poor water quality reported for Lake Wairarapa is unsurprising given that agricultural land uses occupy over half of the lake's catchment. This includes intensive beef and sheep farming and dairying which border the majority of the lake's margin (or the margins of the wetlands adjacent to the lake). The observed peaks in nitrogen concentrations that occur in winter are likely linked to the agricultural land use, as conditions during winter, such as wetter soils and a high groundwater table, promote the 'flushing' of nitrogen from the soil into the underlying groundwater and, ultimately, the lake via tributary streams and drains.

While diffuse nutrient inputs from agricultural land are most likely the principal source of nutrient inputs to the lake, there are multiple pathways by which this occurs and the relative importance of each is not well understood. Regular monitoring of physico-chemical water quality currently occurs in only two of the lake's main tributaries (the Tauherenikau River and the Waiorongomai River), both of which are typically reported as having excellent water quality (Perrie & Cockeram 2010; Perrie et al. 2012). This suggests that smaller tributaries, groundwater inputs, flood flow inputs and, potentially, backflow through the barrage gates at the southern end of the lake, may be important sources of nutrients.

Elevated concentrations of nutrients have certainly been recorded in some of the smaller tributaries and artificially constructed drains that discharge into the lake along its northern and eastern shores (eg, Morton 1995; Tidswell & Sorensen 2010). With poorly drained Recent Soils dominating the soil profile immediately north and east of the lake (refer Figure 3.3), it likely these streams and drains receive considerable farm runoff and subsurface seepage during the winter months. This has been demonstrated by Hughes and Gyopari (2011) for the Otukura Stream which, along with Battersea Drain, probably receives a significant proportion of its winter flow from the underlying groundwater (Gyopari & McAlister 2010).

In addition, stock grazing the margins can be expected to be contributing directly to the lake's nutrient load, particularly in terms of urine patches from dairy cows[14]. In some areas, stock have been able to directly access the lake and defecate in the water (Figure 3.24). Stock access to tributary streams, drains and water races is particularly common and, in the case of Otukura Stream and Battersea Drain, has resulted in slumping of stream banks and siltation of the streambed (Watts 2007).

(Source: Geoff Ewington, Greater Wellington)

Figure 3.24: Stock grazing around the northern shore (Lake Domain) of Lake Wairarapa in June 2009. Stock are no longer grazed at the Lake Domain although stock access to other parts of the lake still occurs.

There are other sources of nutrients to the lake that also need to be quantified such as treated wastewater from Featherston, which discharges into Donald's Creek, a tributary of Abbott's Creek, approximately 4 km upstream of its confluence with Lake Wairarapa. Milne (2009) demonstrated that this discharge is having a measurable impact on water quality in Donald's Creek

[14] Urine is the main source of nitrate leaching in grazed dairy pasture (eg, Ledgard et al. 2005, Di et al. 2002) – dairy cow urine deposits the equivalent of 800–1,000kg N/ha in each urine patch (Borrie & Webb 2006). In contrast sheep urine contains around 300–500 kg N/ha per urine patch.

and, based on median effluent flows and nutrient concentrations, conservatively estimated the discharge contributes in the order of 5 tonnes/yr and 1.25 tonnes/yr of total nitrogen and total phosphorus to the creek respectively (Milne 2009)[15]. By way of comparison, mean total nitrogen and total phosphorus loads entering Lake Wairarapa from the Tauherenikau River are estimated to be in the order of 14.7 and 1.5 tonnes/yr respectively[16]. While these load estimates are coarse and the disproportionately higher nutrient loads during flood events are not accounted for, they do suggest that, relative to the largest riverine input to the lake (estimated by Thompson (in prep) to account for around 20% of the surface water input during low flows), the Featherston WWTP is not an insignificant source of nutrients to the lake, particularly during low to moderate flows.

Flood waters from the Ruamahanga River can also enter Lake Wairarapa via the Oporua Floodway (including overland flow) and/or backflow through the barrage gates. While this only occurs a few times a year, it is potentially a significant pathway for nutrients, sediments and other contaminants to enter the lake (for example, a number of studies (eg, Sharpley 2008) have demonstrated that most (up to 80%) of the total phosphorus that enters waterways does so in heavy rainfall periods and storm events). Much of the sediment (and associated nutrients) in the flood waters entering Lake Wairarapa can be expected to drop out of the water column due to reduced water velocity; thus the lake acts as a reservoir for not only floodwater but also sediments and nutrients (Morton 1995). It is unclear whether the lake has become even more of a repository for nutrients and sediments since the diversion of the Ruamahanga River but certainly the ability of the lake to 'flush' itself will have reduced[17].

The likely store of nutrients in the lakebed sediments has important implications for the lake's water quality. Even if nutrient inputs entering the lake are reduced, there is potentially a significant store within the lakebed, which is recycled through wind-induced sediment re-suspension. Concentrations of total phosphorus and, to a lesser extent, total nitrogen, both demonstrate positive relationships with wind disturbance (inferred from non-volatile suspended solid concentrations), indicating that re-suspension of lakebed sediments may be an important source of nutrients within the lake; moreover, this suggests that some historical nutrient inputs may be having a lasting impact on lake water quality.

In order to help direct remedial action to improve the water quality of Lake Wairarapa, a water and nutrient balance needs to be developed to determine the relative contributions of nutrients from both surface and groundwater inputs, as well as from internal nutrient cycling. There is also a need to investigate reducing direct nutrient inputs from existing farming activities on the lake's margins.

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[15] Limited flow data were available for the discharge and Donald's Creek, preventing accurate quantification of nutrient loads (Milne 2009).

[16] Estimation is based on an assumed a mean flow of 3,668 L/s (ie, 60% of the mean flow recorded at Tauherenikau River at the Gorge to account for groundwater losses at the mouth, see Thompson (in prep)) and mean nutrient concentrations recorded from five years of monthly water sampling in the Tauherenikau River at Websters (July 2006 to June 2011 inclusive).

[17] An investigation into changes in the morphology of Lake Wairarapa by Trodahl (2010) indicated that in the two decades post the Lower Wairarapa Valley Development Scheme, the rate of 'infilling' increased by ten-fold along the eastern shore of Lake Wairarapa. However, this was accompanied by deepening of some other parts of the lake.

3.4.3 Monitoring limitations

Monitoring of water quality in Lake Wairarapa needs to be reviewed. Sampling is currently limited to a maximum of four occasions per year; while this is probably adequate to characterise the lake's overall condition (state), it is insufficient to characterise seasonal trends and reduces the ability to detect meaningful changes in water quality over an appropriate timeframe for SoE reporting and management response (5 years). Monthly sampling is generally recommended for statistically sensitive and robust trend detection over five-year timeframes (eg, Scarsbrook & McBride 2007) and is the frequency proposed by Davies-Colley et al. (2011) to monitor water quality state and trends at the national lake scale.

Monthly sampling should also extend to monthly phytoplankton species identification and cell counts to help improve our understanding of the lake's phytoplankton population dynamics, in particular the occurrence of potentially toxic cyanobacteria blooms such as that recorded in May 2008. Cyanobacteria blooms pose a potential health risk to recreational users of the lake and the interim national cyanobacteria guidelines in MfE/MoH (2009) highlight the need to monitor their status at regular intervals. Improved understanding of potential nutrient limitation in relation to phytoplankton growth would also be helpful.

The high variability, along with at times the poor precision (eg, <13mg/m^3), of the analytical detection limit for determining concentrations of chlorophyll *a* has limited interpretation of chlorophyll *a* results to date. Given the importance of chlorophyll *a* in lake water quality monitoring, there is a need to investigate the potential for achieving consistent and reliably lower analytical detection limits.

The current four sampling sites are all located in the northern two-thirds of the lake and may not represent water quality across the entire lake (ie, the southern end). The potential for a sampling site located in the southern part of the lake should be investigated (especially since the southern end of the lake will be more strongly influenced by backflow events of saline water from Lake Onoke). Rationalisation of the existing monitoring sites should also be undertaken as the only site to show any meaningful variation in water quality to date is Site 1 (marginally better water clarity and lower concentrations of total phosphorus compared with the other three sites); as suggested by both Morton (1995) and Stansfield (1999), this is likely to be due to its relatively close proximity to the Tauherenikau River inflow (~1.2 km east). Overall, all four sites are highly correlated and have the same TLI classification, suggesting that continued monitoring at all four sites probably isn't necessary.

It is recognised that sampling Lake Wairarapa in relatively calm weather conditions introduces a bias into the sampling results, resulting in potentially more favourable results for wind-influenced aspects of water quality such as water clarity[18]. However, this bias is common to most lake monitoring in New Zealand (Davies-Colley et al. 2011) and is to a certain extent impossible to

[18] Although sampling is avoided in windy conditions for safety reasons, strong winds will probably leave lakebed sediments in suspension for some time after winds have dissipated – therefore the current sampling methods are still able to pick up the effects of wind to some degree.

eliminate (sampling in very windy conditions is unsafe). In any case monthly sampling should result in the collection of water samples over a greater range of wind intensities than present since sampling in some of the windier months of the year will be unavoidable at this sampling frequency. Continuous turbidity measurements from the lake would also greatly improve our current understanding of the effects of wind on lake water quality and assist with future ‘de-weathering’ of data.

4. Lake Onoke

This section opens with an overview of Lake Onoke before presenting the water quality results from an on-going monitoring programme for the two-year period August 2009 to July 2011. Information on the benthic health of the lake is reported in Oliver and Milne (2012).

4.1 Introduction

Lake Onoke is approximately 622 ha in size and is the second largest lake in the Wellington region. It is located at the very bottom of the Ruamahanga River catchment on the southern Wairarapa coast and drains to Palliser Bay through an opening via a sand spit at the south-eastern end of the lake (Figure 4.1). The main inflow to the lake is the Ruamahanga River which drains a large and predominantly agricultural catchment encompassing the entire Wairarapa Valley. Several smaller tributaries also flow directly into the lake, notably the Turanganui River and Pounui Stream (via Pounui Lagoon).

Figure 4.1: Lake Onoke and key features. The red dots indicate Greater Wellington's two water quality monitoring sites – only Site 1 has been sampled regularly to date.

Lake Onoke is around 5–6 m deep at its deepest point but the majority of the lake is shallow (<1 m); depth varies depending on the tidal cycle, how the lake mouth is functioning (eg, open, semi-blocked, blocked) and flow conditions in the Ruamahanga River. The deepest parts of the lake are around the 'river channel' (ie, from where the Ruamahanga River discharges into the lake and through to the lake opening to the sea) and also parallel to the spit, especially at the eastern end of the lake. At times when the lake level is low, low tides commonly expose extensive mud flats in the central part of the lake.

The lake is typically tidal as long as the mouth remains open. However, under southerly conditions and low river flows the lake mouth regularly closes (on average nine times per year[19]) and at such times the lake height can rise to such a level that water can backflow up the Ruamahanga River into Lake Wairarapa (Robertson 1991). Historically the lake mouth would stay closed for a significant period of time and could result in extensive flooding of the lower Wairarapa Valley. Today lake levels are managed by Greater Wellington's Flood Protection Department and the lake mouth is typically opened within days to weeks of closure to minimise flood risk.

Lake Onoke is classified as a type of coastal lake called a 'barrier-bar lake'. These types of coastal lakes are more commonly found along the east and south coasts of the South Island (Robertson & Stevens 2007). These types of systems are – at least when in a natural state – more often closed off to sea than open to it and the water is typically fresh or brackish (Kjerfve 1994). They typically have high ecological values due to the wide variety of different habitats present but are considered highly vulnerable to land use activities in their catchments that result in changes to the natural hydrological regime and increased inputs of sediment, nutrients and other contaminants (Kirk & Lauder 2000). Habitat loss through reclamation and degradation is also a widespread problem in these systems (Robertson & Stevens 2007). This is particularly the case for Lake Onoke, which along with the lower Ruamahanga River and Lake Wairarapa, has been extensively modified through the implementation of the Lower Wairarapa Valley Development Scheme (refer Section 3.1).

Little was known about the current status of the lake in terms of water quality and ecosystem health, but the lake's location at the bottom of a large and predominantly agricultural catchment puts it at high risk from nutrient enrichment, sedimentation, and habitat degradation. A 'vulnerability assessment' completed for Greater Wellington by Robertson and Stevens (2007) considered that the regular blocking of the lake mouth meant that the lake has a high natural susceptibility to issues associated with eutrophication compared to an estuary, but that this susceptibility is reduced by the regular manual opening of the mouth by Greater Wellington's Flood Protection Department. Limited one-off water sampling undertaken by Drake et al. (2011) in 2007 indicated that the lake was in a eutrophic state. It was also one of just five of the 45 shallow coastal lakes that they sampled where they caught five native fish species; most lakes had a lower diversity of native species.

In response to a recommendation made in the vulnerability assessment (Robertson & Stevens 2007), Greater Wellington's Environmental Monitoring and Investigation Department commenced a water quality monitoring programme in the lake in August 2009. A benthic ecological assessment followed in January 2010 (see Oliver & Milne 2012).

4.1.1 Values

Together with Lake Wairarapa, Lake Onoke is part of the largest wetland complex in the southern North Island, which is considered to be of both national and international importance due to its significant ecological, recreational and natural

[19] Greater Wellington unpublished data.

character values. It also has traditional and spiritual values and is considered a taonga (Airey et al. 2000). Historically, Lake Onoke was an important source of mahinga kai, especially in regards to tuna (eels) which could congregate in large numbers if a blocked lake mouth coincided with their downstream spawning migrations. However, eels are reportedly not as numerous as they used to be in Lake Onoke and the wider Ruamahanga River catchment (Airey et al. 2000) and Hicks (1993) considered the eel fishery in the region to be in crisis.

Due to the high diversity of wetland habitats present in and around the lake it provides significant habitat for a wide variety of plant, fish and bird species, including both regionally rare and threatened species. However, as with the eels mentioned above, there is some growing concern around the status of many of these populations (Hicks 1993; Airey et al. 2000; McEwan 2010).

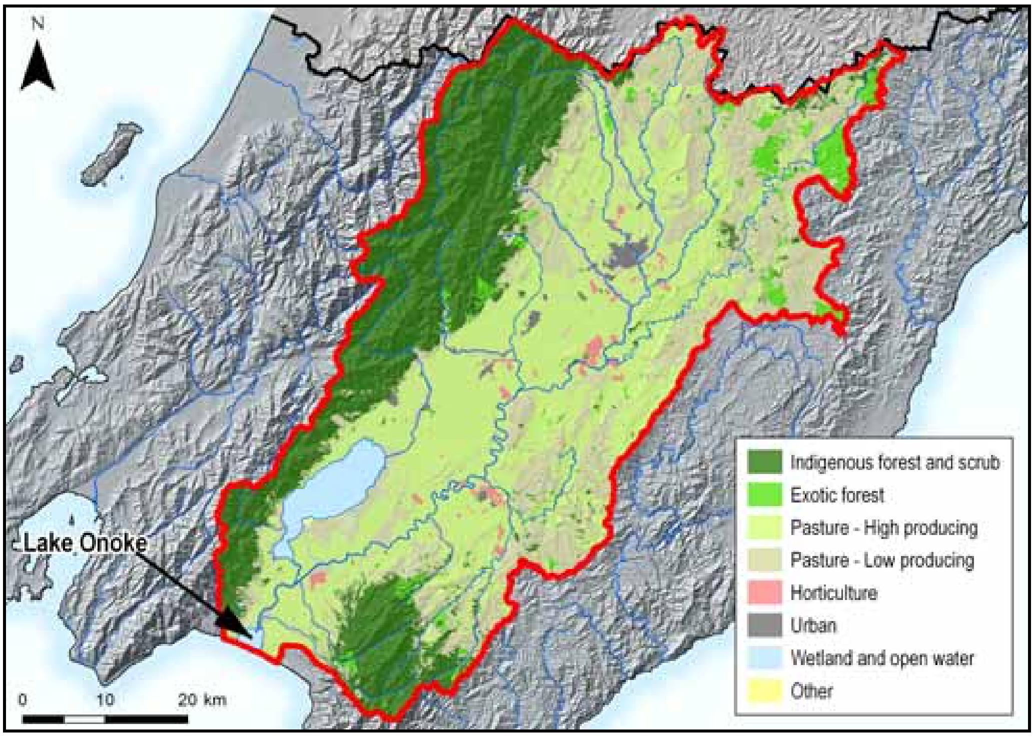
Lake Onoke is listed in Appendix 2 of Greater Wellington's Regional Coastal Plan (WRC 2000) as an area of significant conservation value. Values mentioned specifically include a breeding ground for threatened bird species and marine fish (including *Galaxias* spp.) and rare and vulnerable native plant species. The high conservation values are not limited to the lake itself and include the surrounding area such as the Lake Onoke Spit which, for example, is considered to be of high botanical value (Airey et al. 2000).

Lake Onoke falls within the coastal marine area (WRC 2000) and as such it is not mentioned in Greater Wellington's Regional Freshwater Plan (RFP, WRC 1999) or proposed Regional Policy Statement (pRPS, GWRC 2010) as having significant native freshwater fish values other than as a spawning area for inanga (pRPS). However, the Ruamahanga River and other tributaries of the lake are mentioned and given that the fish faunas of these catchments are largely made up of predominantly diadromous species that must migrate through Lake Onoke twice to complete aspects of their lifecycles, the importance of the lake can not be underestimated. Furthermore, Hicks (1993), McEwan (2010) and Drake et al. (2011) have all recorded a diverse native fish community in Lake Onoke comprising a mixture of both saltwater and freshwater species such as kahawai, yellowbelly flounder, estuarine triplefin, shortfin eels, common bullies and inanga.

Lake Onoke and its surrounds are also used for many recreational activities including hunting, fishing, motor boating, yachting, windsurfing, kayaking, camping, picnicking, walking, and nature studies (Airey et al. 2000; Robertson & Stevens 2007). The recreational whitebait fishery is also considered to be regionally significant (Hicks 1993; pers. obs.).

4.1.2 Catchment land cover and land use

As previously outlined, Lake Onoke is situated at the bottom of the Ruamahanga River catchment, the largest catchment in the Wellington region (Figure 4.2). Land cover in the catchment is predominantly pastoral (~64%, Table 4.1) of which the majority is sheep and/or beef farming (Agribase 2001). Dairying accounts for approximately 9% of the lake's catchment area (Agribase 2001) and based on a combination of information supplied by Fonterra in September 2011 and data collected during Greater Wellington's 2010/11 dairyshed effluent inspections, there are 169 dairy farms in the catchment and around 69,000 dairy cows.



(Source: LUCAS – MfE 2010)

Figure 4.2: Major land cover and land use types within Lake Onoke's catchment (outlined in red)

Table 4.1: Area and percentage of major land cover and land use types in the Lake Onoke catchment, derived from aerial photographs taken in 2008
(Source: LUCAS – MfE 2010)

Land cover	Area (ha)	%
Indigenous forest & scrub	93,842	27.5
Exotic forest	12,747	3.7
Horticulture	3,405	1.0
Pasture – high producing	127,042	37.2
Pasture – low producing	91,647	26.8
Urban	2,293	0.7
Wetland & open water	9,796	2.9
Other	971	0.3
Total	341,744	100

While the area of urban land cover is relatively minor (<1%), all five major towns in the catchment (Masterton, Carterton, Greytown, Martinborough and Featherston) discharge stormwater and treated wastewater into rivers or streams that eventually drain into Lake Onoke. Indigenous forest and scrub make up just 27% of the catchment land cover. Land use around the lake's margins includes a mixture of dairying, sheep and beef farming and the Lake Ferry township (located on the eastern margin).

4.1.3 Significant consented activities

In draining the entire Wairarapa Valley, there is a very large range and number of consented activities that occur in Lake Onoke's catchment, including discharges of treated municipal wastewater, urban stormwater, and dairy and piggery effluent. In closer proximity to the lake, the principal consent is for the discharge of treated wastewater to land from Lake Ferry township[20] (although the area of land used to discharge the treated wastewater actually drains to Palliser Bay). There are also several consented wastewater discharges to land for dairyshed washdown water for farms located immediately north of the lake (and west of the Ruamahanga River). There are no consented water abstractions from the lake although there are a large number of water abstractions (surface and groundwater) from the wider catchment.

4.1.4 Other significant activities

The mouth of Lake Onoke regularly blocks (on average nine times per year) and is manually opened by Greater Wellington's Flood Protection Department to minimise the flood risk to surrounding land. The opening of the lake is currently a permitted activity under Rule 30 of the Regional Coastal Plan (WRC 1999).

The Lake Onoke Pump Drainage Scheme, which drains predominantly dairying land located to the north of Lake Onoke (and west of the Ruamahanga River), discharges into the north-western side of the lake.

4.2 Monitoring protocol, sites and variables

Water samples were collected on 20 occasions (approximately monthly[21]) during the August 2009 to July 2011 reporting period from one site (Site 1) located at the north end of Lake Onoke at the point where the Ruamahanga River enters the lake (refer Figure 4.1). On three occasions water samples were collected from an additional site (Site 2) located on the western margins of the lake. All sampling was undertaken at or within two hours following low tide to minimise any influence from the incoming tide. Water quality was assessed by measuring a range of physico-chemical and microbiological variables: dissolved oxygen, water temperature, pH, conductivity, Secchi depth, turbidity, faecal indicator bacteria, dissolved and total nutrients, and chlorophyll *a*.

Biological sampling is not currently routinely undertaken in Lake Onoke, although a one-off benthic ecological assessment has been made (see Oliver & Milne 2011) and phytoplankton samples were collected from both monitoring sites on two occasions (20 November 2009 and 22 March 2011) to allow for the identification of phytoplankton species and an estimate of relative species abundance.

Further details on monitoring site locations, along with water quality sampling and analytical methodology, can be found in Appendix 1.

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20 Prior to December 2007 and the implementation of the Lake Ferry Wastewater Treatment Plant, all wastewater from the township was treated through individual septic tanks.

21 Due to resource constraints the times between sampling occasions was sometimes up to eight weeks and some sampling occasions were also closer together than four weeks to target some sampling around when the lake mouth was blocked.

4.2.1 Approach to analysis

To provide an overview of current lake water quality, physico-chemical and bacteriological water quality results were summarised for all sampling occasions from Site 1 (maximum n=20). However, where applicable, data collected from Site 2 were also referred to. The current state of water quality was assessed by calculating a TLI score using all available data for the two year reporting period (August 2009 to July 2011). The TLI score was generated from the mean values for each of the key variables (chlorophyll *a*, Secchi depth, total nitrogen and total phosphorus), using the Burns et al. (2000) equations outlined in Section 2.2.1.

Some care must be taken when interpreting the water quality results as all sampling was undertaken from the lake's edge and so the results may not be representative of the lake as a whole – for example, some variables such as Secchi depth may be affected by the re-suspension of sediments that is more likely to occur around the shallower lake edge.

4.3 Water quality

Table 4.2 presents a summary of selected water quality results from Site 1 for the period August 2009 to July 2011 inclusive (selected results from Site 2 are provided in Appendix 2). Figure 4.3 summarises the range of concentrations for the four TLI variables over this same period. During this period, water samples were collected on 13 occasions when the lake mouth was open, although on three of these occasions the lake mouth had been recently blocked and had only been open for up to four days. The remaining seven sampling occasions all occurred when the lake mouth was blocked and had been so for at least four days preceding sampling and in one case around three weeks.

Relative to national median values for lakes located in catchments dominated by pastoral land cover, the median concentrations of chlorophyll *a*[22], total nitrogen and, to a lesser extent, total phosphorus were all lower. The median Secchi depth value indicated much lower water clarity than the national median value for lakes located in pastoral catchments (Figure 4.3) reported by Verburg et al. (2010). Similar to Lake Wairarapa, the poor water clarity is probably primarily due to re-suspended sediment from the lakebed or Ruamahanga River rather than high phytoplankton biomass since Table 4.2 indicates the majority of the suspended sediment is inorganic – as opposed to organic.

Measurements of conductivity varied from 70 to 7,856 µS/cm (Table 4.2) and there is some indication that higher conductivities were recorded at times when the lake mouth was blocked and the lake level was higher (Figure 4.4). An initial assessment in August 2009 showed that conductivity varies across the lake, with measurements typically lowest around the river inflow channel and highest at the southern end of the lake parallel to the spit (Figure 4.5). At times when the lake mouth is blocked, more saline water may be re-circulated from the southern end of the lake back up to where the Ruamahanga River enters the lake; this may result in the observed higher conductivity measurements.

[22] The majority (65%) of chlorophyll *a* concentrations were below the limit of detection and while this may indicate that phytoplankton biomass is typically low (ie, below detection), on four occasions the limit of detection was higher than the expected <3 mg/m^3 and ranged from <4 mg/m^3 to <15 mg/m^3. Therefore, some care is required when interpreting the chlorophyll *a* results.

Table 4.2: Summary of water quality in Lake Onoke, based on monthly sampling at Site 1 on 20 occasions over August 2009 to July 2011. National median values for lakes in catchments dominated by pastoral land cover are also listed (taken from Verburg et al. 2010). D.L.=detection limit.

Variable	National median	Median	Min	Max	*n*	*n* <D.L.
Water temperature (°C)	—	14.2	6.7	23.6	20	—
Dissolved oxygen (% saturation)	—	96.7	79.5	132	19	—
Dissolved oxygen (mg/L)	—	10.3	7.91	12.2	19	—
pH	—	7.4	5.9	8.8	20	—
Conductivity (µS/cm)	192	1,438	70	7,856	20	—
Secchi depth (m)	2.0	0.40	0.11	>1.00[1]	18	—
Turbidity (NTU)	3.2	17.9	3	350	20	0
Volatile suspended solids (mg/L)	—	2.1	<2.0	31	20	9
Total suspended solids (mg/L)	—	16.0	<2.0	440	20	1
Total phosphorus (mg/L)	0.037	0.035	0.016	0.340	20	0
Dissolved reactive phosphorus (mg/L)	0.003	0.014	<0.004	0.024	20	2
Total nitrogen (mg/L)	0.773	0.475	<0.300	1.430	20	2
Nitrite-nitrate nitrogen (mg/L)	—	0.167	<0.002	0.920	20	2
Nitrite nitrogen (mg/L)	—	0.003	<0.002	0.005	20	7
Ammoniacal nitrogen (mg/L)	0.013	0.013	<0.010	0.039	20	8
Chlorophyll *a* (mg/m^3)	8.8	2.5	<3.0	19	20	13
E. coli (cfu/100mL)	—	150	<10	1,700	17	1
Enterococci (cfu/100mL)	—	49	<10	1,300	17	1
Faecal coliforms (cfu/100mL)	—	150	<10	1,700	17	1

[1] When this maximum Secchi disc measurement was recorded the disc was visible on the lake bottom.

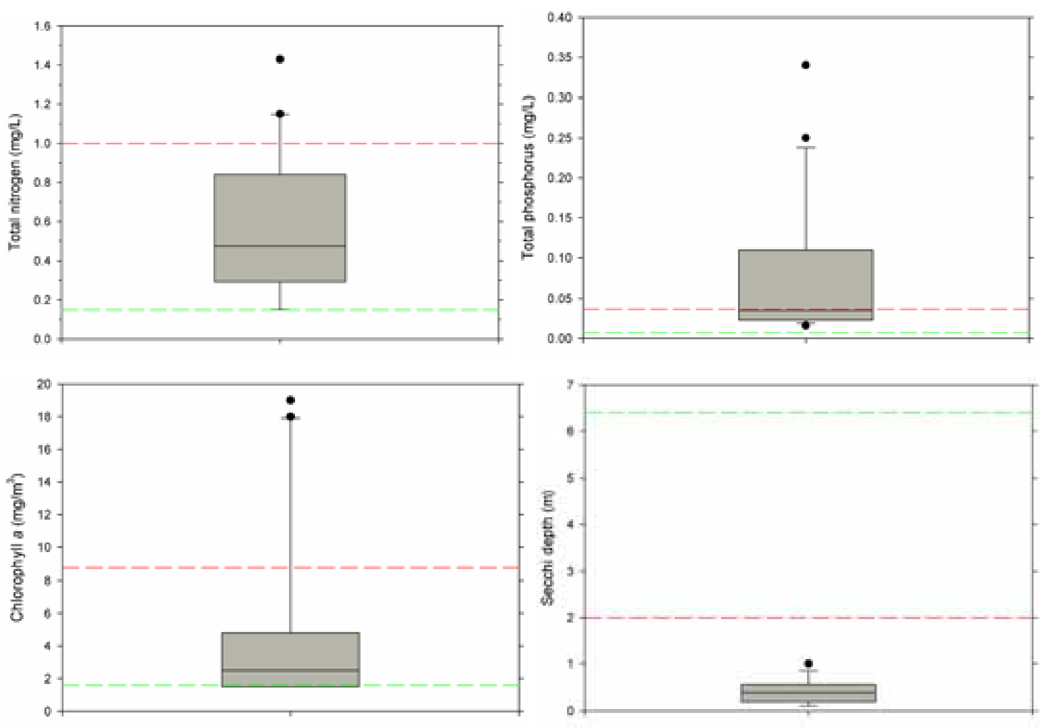

Figure 4.3: Box plots for the TLI variables, based on 20 sampling occasions between August 2009 to July 2011. The horizontal dashed lines indicate national median values (taken from Verburg et al. 2010) for lakes in catchments dominated by indigenous forest (green) and pastoral (red) land cover.

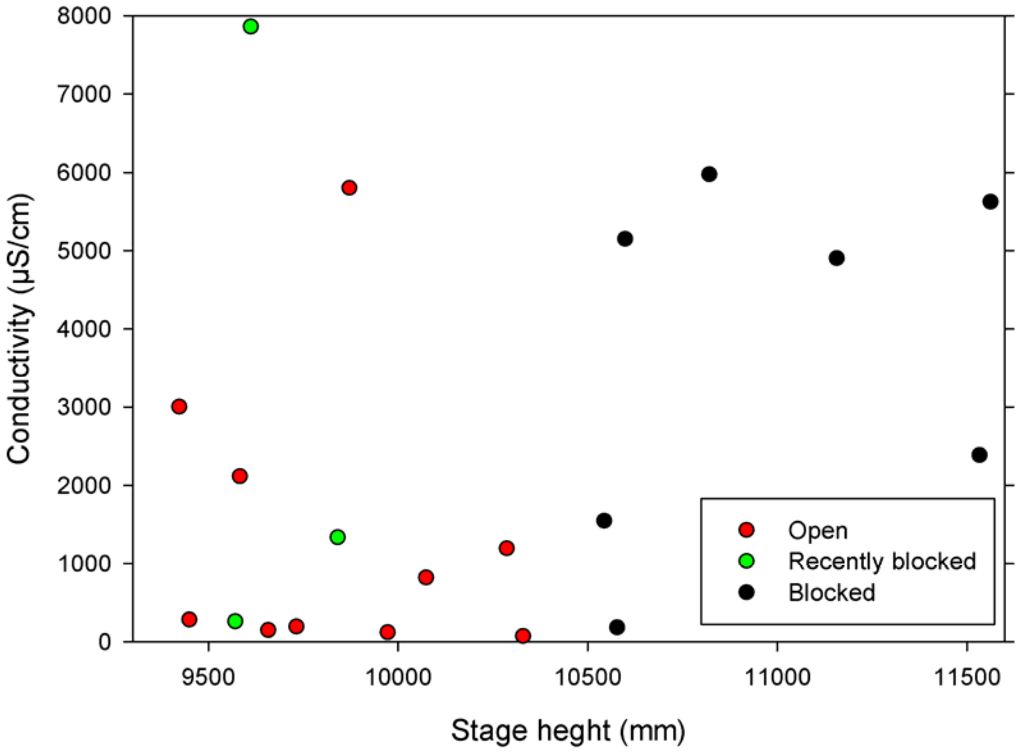

Figure 4.4: Scatter plot of lake level (stage height recorded at Lake Ferry) against measurements of conductivity. The status of the lake mouth (ie, open, recently blocked or blocked) is also shown.

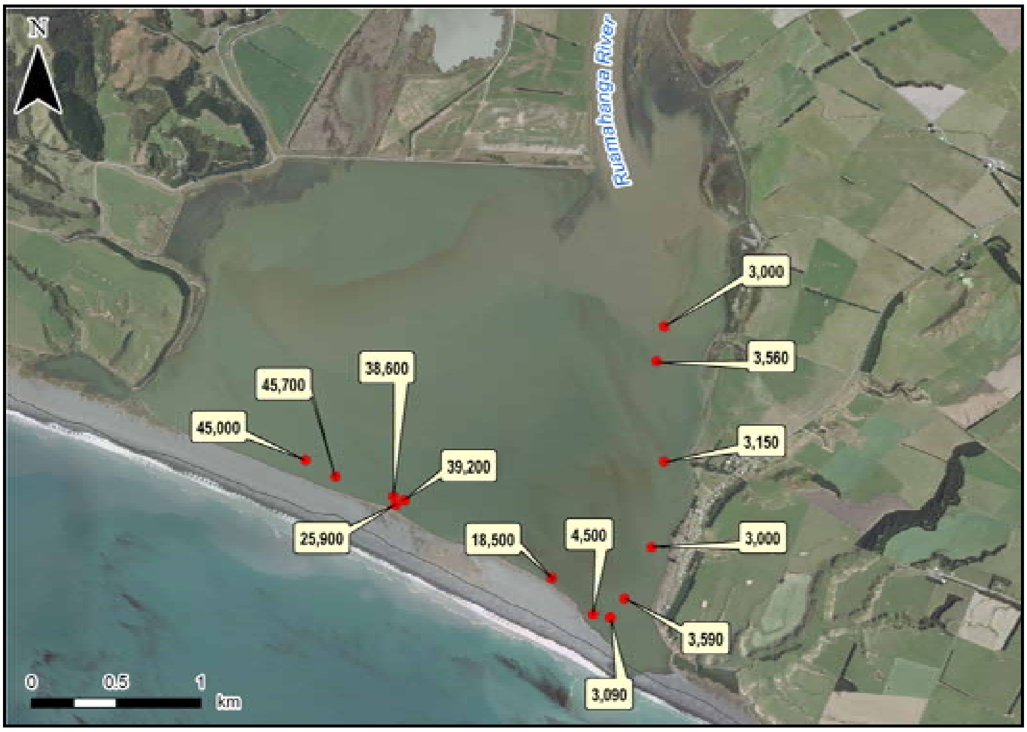

Figure 4.5: One-off conductivity values (µS/cm) measured at various locations in Lake Onoke on 28 August 2009, illustrating how conductivity varies spatially across the lake. The lake mouth was open at the time of this survey.

The prevailing flow conditions in the Ruamahanga River also appear to have an influence over measurements of conductivity recorded at Site 1 (Figure 4.6), with lower conductivities generally occurring at higher flows (ie, greater dilution of saline water).

Similar to the spatial variation in conductivity concentrations indicated in Figure 4.5, limited sampling at Site 2 on the western side of the lake has also shown that other aspects of water quality may vary spatially. For example, Site 2 tends to have higher suspended solid concentrations than Site 1 (see Table A2.1, Appendix 2).

E. coli counts ranged from <10 to 1,700 cfu/100mL, with a median value of 180 cfu/100mL. Four *E. coli* results exceeded the MfE/MoH (2003) 'action' recreational water quality guideline of 550 cfu/100mL; exceedances generally coincided with high river flows (illustrated later in Section 4.3.5).[23]

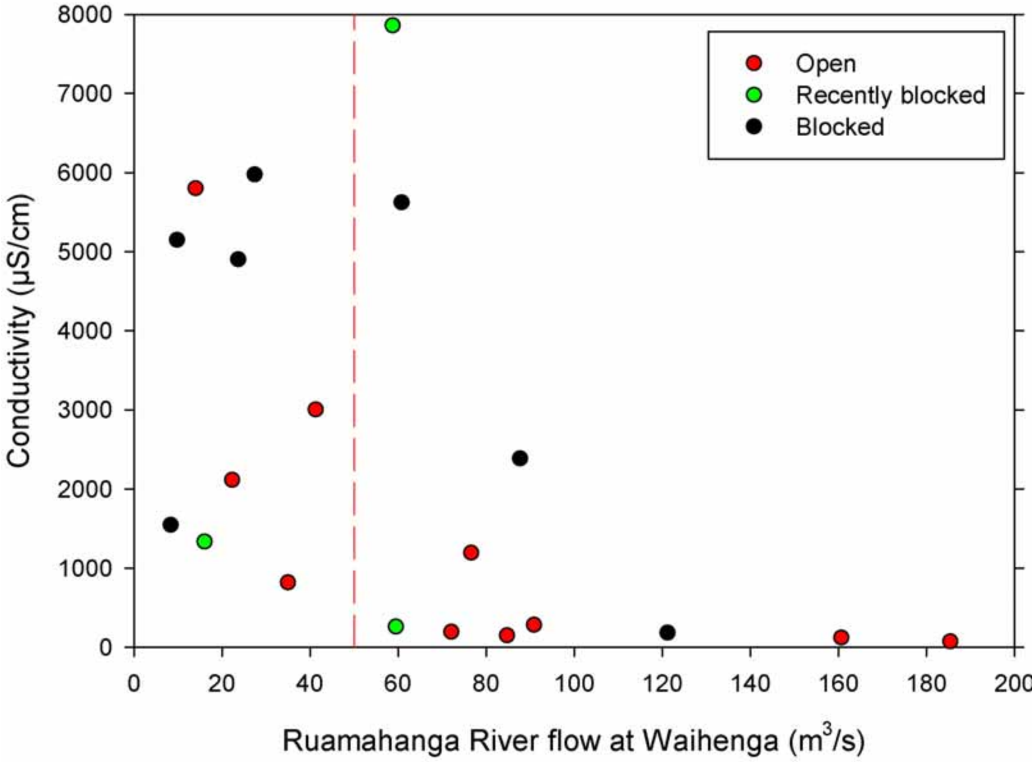

Figure 4.6: Flow recorded in the Ruamahanga River at Waihenga against conductivity measurements recorded at Site 1 in Lake Onoke. The status of the lake mouth (ie, open, recently blocked or blocked), along with the median flow of the Ruamahanga River at Waihenga (dashed vertical red line (50 m^3/s), Gordon (2009)), are also shown.

[23] *E. coli* is the preferred microbiological indicator in brackish waters (MfE/MoH 2003) but water samples were also tested for enterococci; enterococci counts ranged from <10 to 1,300 cfu/100mL.

4.3.1 Trophic state

Application of the TLI for the period August 2009 to July 2011 resulted in a score of 5.1 which classes Lake Onoke as supertrophic (Table 4.3). Similar to what was observed in Lake Wairarapa (refer Section 3.3.1), the TL values for chlorophyll *a* and total nitrogen indicate lower/better trophic categories (mesotrophic/eutrophic and eutrophic respectively) than the TL values for total phosphorus and Secchi depth (supertrophic).

Table 4.3: Mean values for the four key variables used in the calculation of the TLI as well as the individual TL scores and an overall TLI value for Lake Onoke, based on 20 sampling occasions at Site 1 over August 2009 to July 2011 inclusive

	Total nitrogen (mg/L)	Total phosphorus (mg/L)	Chlorophyll *a* (mg/m^3)	Secchi depth (m)
n	20	20	20	18
Mean	0.721	0.076	5.0	0.43
TL value	4.7 (eutrophic)	5.7 (supertrophic)	4.0 (eutrophic)	5.9 (supertrophic)
TLI score	5.1 (supertrophic)			

Both Secchi depth (water clarity) and concentrations of total phosphorus appear to be strongly influenced by suspended sediment concentrations (see Section 4.3.3) and given that the low water clarity is primarily due to suspended sediment rather than high phytoplankton biomass, the TL values for chlorophyll *a* and total nitrogen may better reflect the lake's true trophic state (ie, eutrophic). Certainly if the overall TLI score is calculated excluding Secchi depth (as done by Verburg et al. (2010))[24] and which might be justified here given that lake edge sampling may not accurately reflect actual water clarity), the resulting TLI is within the eutrophic range (4.8).

(a) Nutrient limitation

Potential nutrient limitation of phytoplankton growth was inferred by plotting concentrations of total nitrogen against total phosphorus (Figure 4.7). Calculation of total nitrogen and total phosphorus ratios, based on all sampling occasions (August 2009 to July 2011), results in a median ratio of 9.6, which is within the range considered inconclusive in determining the potential limiting nutrient. Plots of chlorophyll *a* versus dissolved nutrient concentrations were also inconclusive in determining the limiting nutrient as concentrations of both dissolved inorganic nitrogen and dissolved reactive phosphorus were typically low when concentrations of chlorophyll *a* were measured above the detection limit (Figure 4.8). Further monitoring, including targeted nutrient investigations, is required before any conclusions about nutrient limitation can be made.

[24] In their case Secchi depth was excluded because measurements were not available for all lakes that were being reported on rather than a decision being made that sampling methodology ruled the measurement unsuitable for inclusion in the TLI calculation.

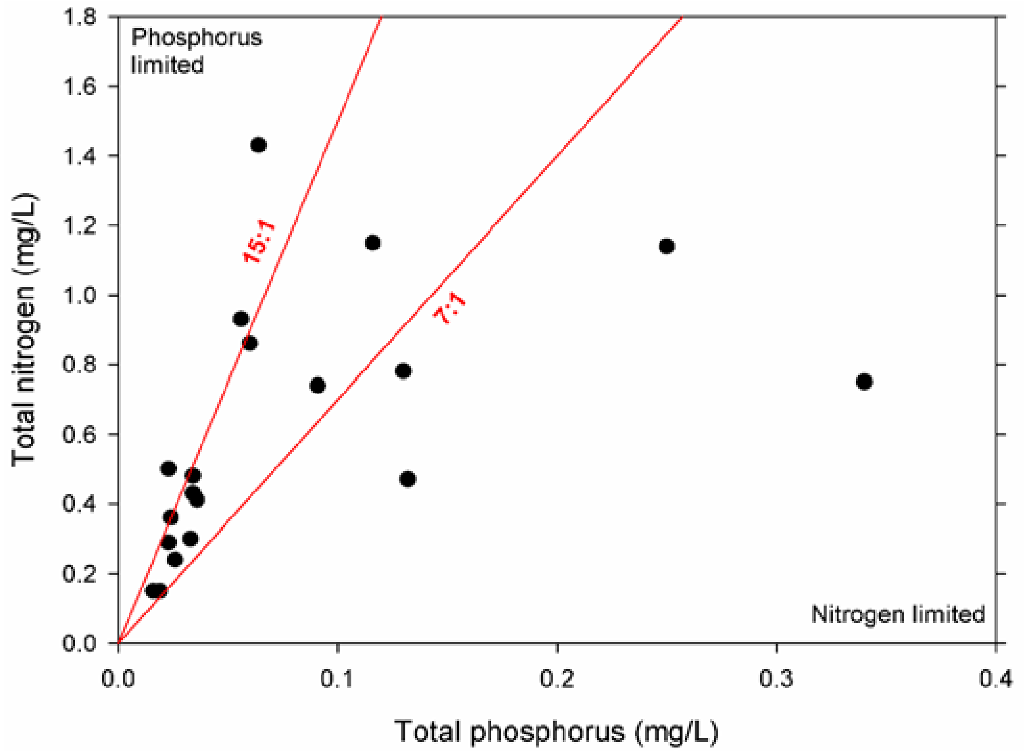

Figure 4.7: Plot of Lake Onoke total phosphorus against total nitrogen concentrations, based on data collected from Site 1 over August 2009 to July 2011. The red lines indicate thresholds for potential phosphorus limited (15:1) and nitrogen limited (7:1) conditions for phytoplankton growth. Values between the red lines are inconclusive.

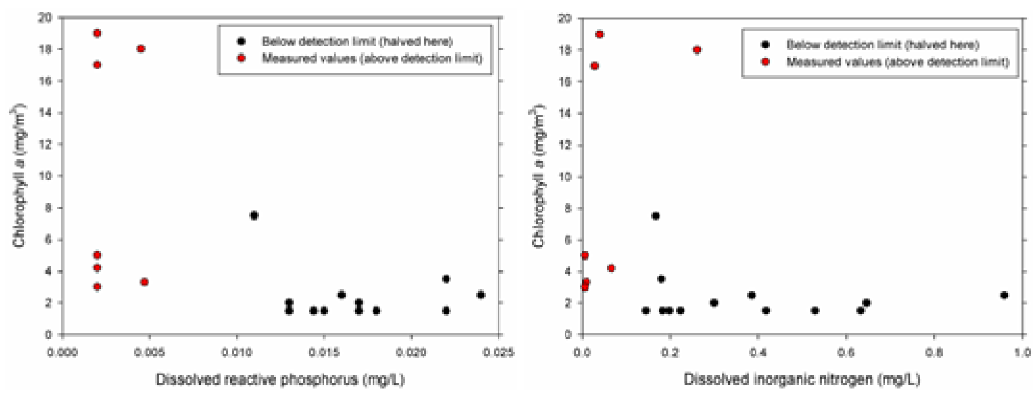

Figure 4.8: Concentrations of chlorophyll *a* against concentrations of dissolved reactive phosphorus (left) and dissolved inorganic nitrogen, based on data collected from Site 1 in Lake Onoke over August 2009 to July 2011

(b) Phytoplankton

Phytoplankton taxa identified in the samples collected from both sites 1 and 2 in November 2009 and March 2011 are presented in Tables A3.1–A3.2 (Appendix 3). The majority of species were found at both sites and the most abundant taxa were typically the same between sites. The majority of taxa identified on both sampling occasions were generally of freshwater origin, although a few marine or brackish species were present (eg, 'small chain forming diatoms', *Chaetoceros* sp., *Skeletonema* sp. and *Melosira* sp.) (D. List pers. comm. 2010[25]).

Potentially toxic species of cyanobacteria were identified in the samples collected from Site 2 (*Anabaena sp.* and *Aphanocapsa sp.)* in November 2009 and from Site 1 in March 2011 *(Phormidium* sp.). However, on both occasions these species were present in very low numbers (see Appendix 3) and were unlikely to represent any significant risk to recreational users of the lake.

4.3.2 Effect of the lake mouth blocking on water quality

Figure 4.9 shows plots of the TLI variables over time along with the status of the lake mouth (open, recently blocked or blocked). No clear patterns are obvious between key variables and whether the lake mouth is open or blocked, although there may be some indication of higher chlorophyll *a* concentrations being recorded when the lake mouth is blocked or shortly after it has been blocked. It is likely that the duration for which the lake mouth is blocked is a more important driver of lake water quality rather than just whether the lake mouth is open or blocked and further monitoring is required to better examine how the status of the lake mouth (open or closed) affects water quality.

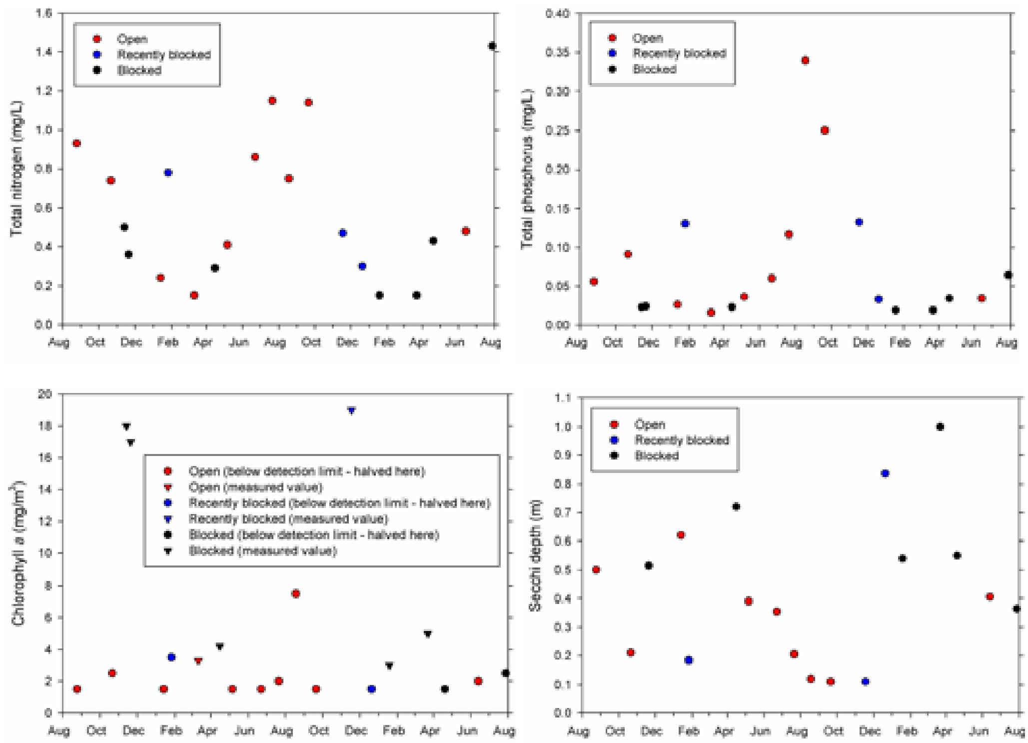

Figure 4.9: Plots of TLI variables over the period August 2009 to July 2011 with the status of the lake mouth (open, recently blocked, blocked) indicated

[25] Daniel List, Freshwater Technician, Cawthron Institute.

4.3.3 Effect of wind disturbance on water quality

Concentrations of non-volatile suspended solids (NVSS) – a surrogate for wind driven re-suspension of lakebed sediments – show a strong relationship with two of the TLI variables: Secchi depth and total phosphorus (Figure 4.10). This indicates that regular re-suspension of lakebed sediments by wind may be a key driver of water quality in Lake Onoke. However, unlike in Lake Wairarapa where wind induced re-suspension of lakebed sediments is likely to be the only cause of the elevated NVSS concentrations (ie, there are no other significant sources evident), in Lake Onoke, the situation appears more complex. This is because of apparent interactions between suspended sediment (eg, water clarity) and salinity (see Section 4.3.4) and also because elevated concentrations of suspended sediment enter the lake from the Ruamahanga River during high flow conditions (see Section 4.3.5).

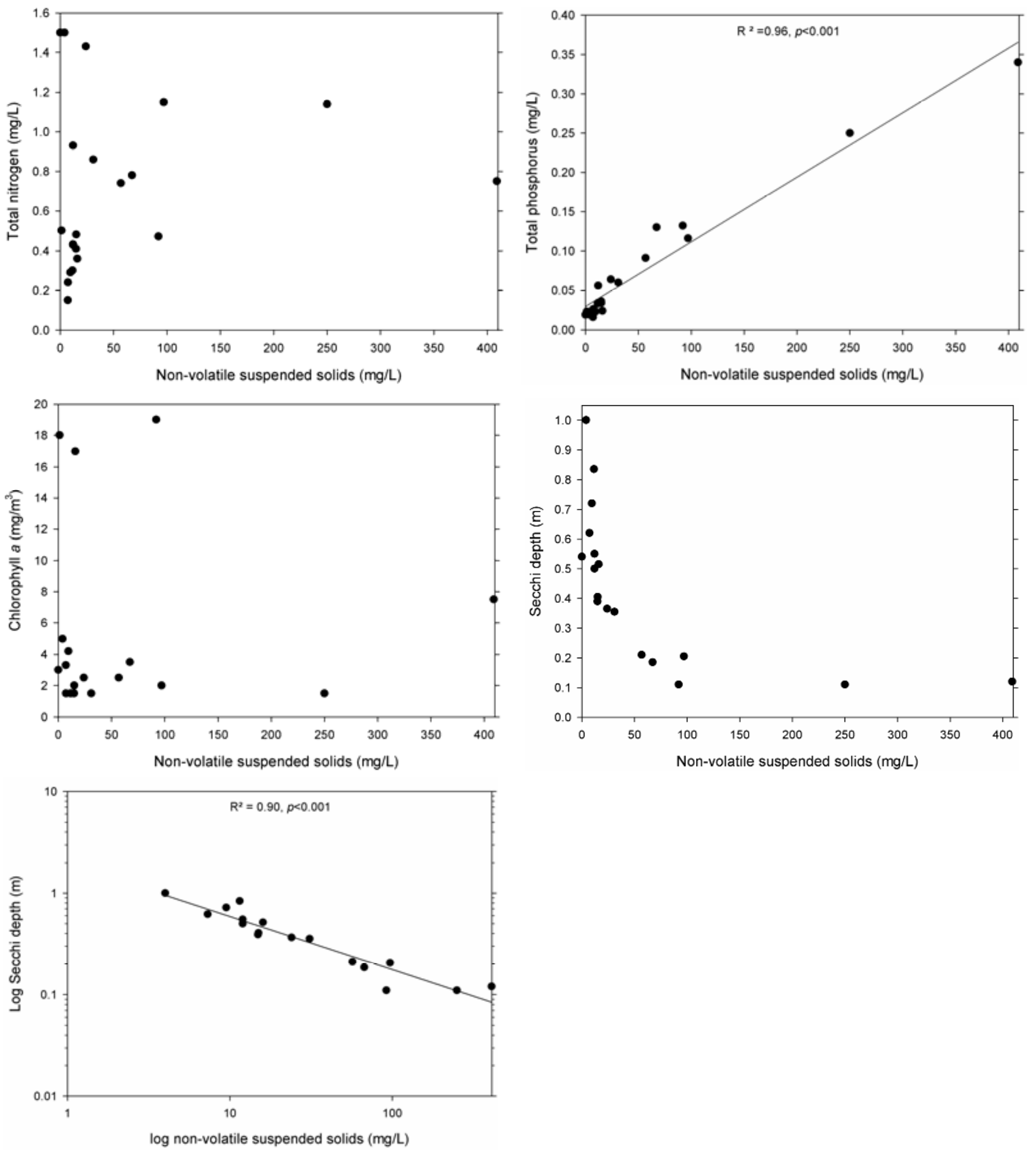

Figure 4.10: Selected variables plotted against non-volatile suspended solid (NVSS) concentrations, based on data collected from Site 1 over August 2009 to July 2011. A linear regression line has been fitted where appropriate. Both actual and log transformed data are presented to demonstrate the relationship between Secchi depth and NVSS.

4.3.4 Effect of conductivity on water quality

Conductivity measurements can be used as a surrogate for the amount of saline water in the lake, with higher measurements indicating higher salinity and therefore greater potential for dilution of river-derived contaminants. Several water quality variables showed relationships with conductivity, with these relationships generally indicative of improving water quality (Figure 4.11). Measurements of Secchi depth showed a moderately strong positive linear relationship (ie, clarity measurements were better when the conductivity was higher) and while relationships with both total nitrogen and total phosphorus were less clear, lower concentrations were typically recorded when measurements of conductivity were higher. Concentrations of chlorophyll *a* did not appear to be related to lake conductivity.

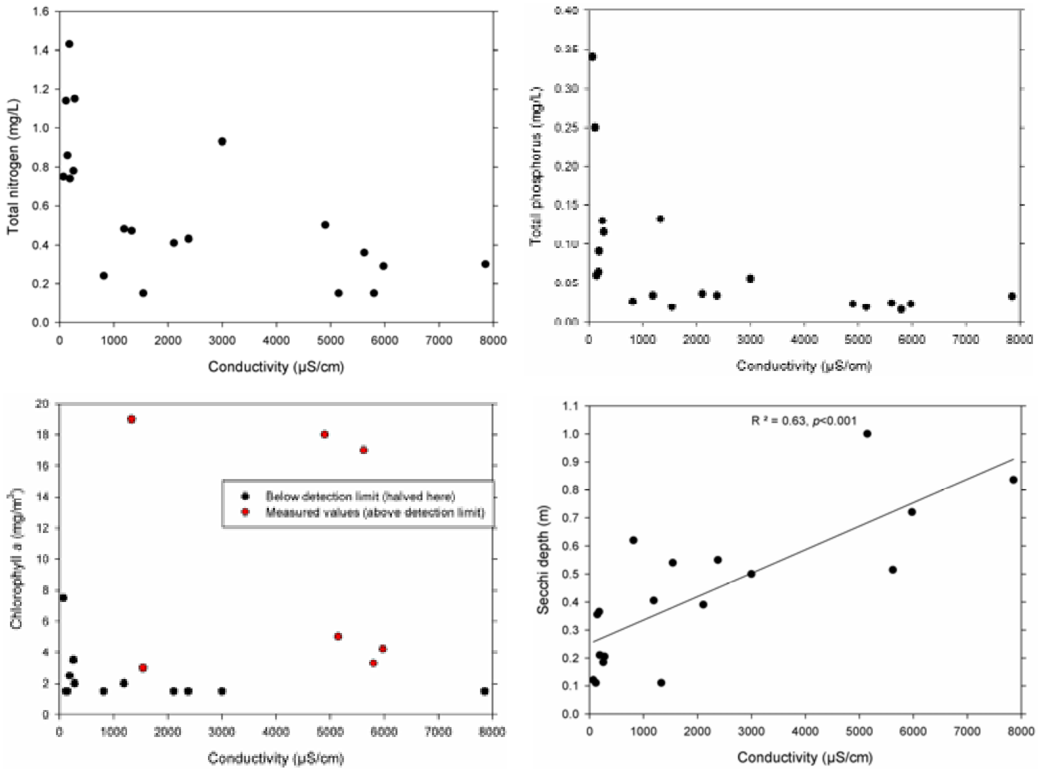

Figure 4.11: Selected variables plotted against conductivity, based on data collected from Site 1 over August 2009 to July 2011. A linear regression line has been fitted where appropriate.

4.3.5 Effect of Ruamahanga River flow on water quality

Relationships between selected lake water quality variables and flow in the Ruamahanga River (as measured by the flow recorder located at Waihenga[26]) are shown in Figure 4.12. Concentrations of total nitrogen, total phosphorus and suspended solids (illustrated here as NVSS) all tended to be higher at higher river flows, while measurements of Secchi depth tended to be lower. *E. coli* counts were also higher at higher river flows. Interpretation of any potential relationships between flow and chlorophyll *a* are difficult given the high number of chlorophyll *a* values reported below the detection limit; however, values above the detection limit all occurred at flows below or just above the median flow (Figure 4.14).

[26] The Ruamahanga River flow recorder at Waihenga is located approximately 45 km upstream of Lake Onoke.

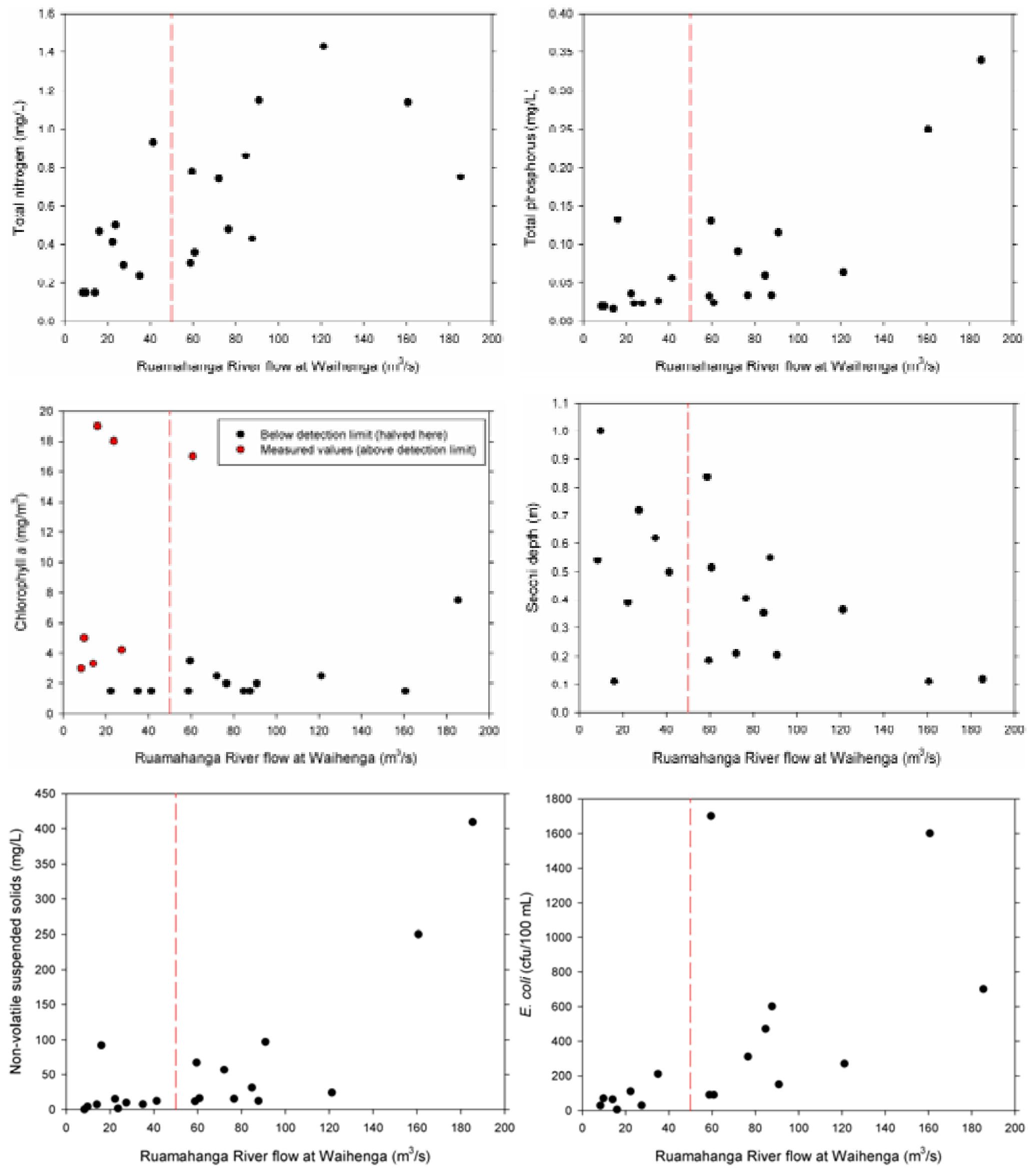

Figure 4.12: Plots of selected lake water quality variables against flow recorded in the Ruamahanga River at Waihenga, based on data collected over August 2009 to July 2011. The vertical dashed red line represents the median flow for the Ruamahanga River at Waihenga (50 m³/s, Gordon 2009).

4.4 Discussion

Monitoring of Lake Onoke over the period August 2009 to July 2011 has shown that water quality is degraded; water clarity is low, concentrations of nutrients are typically elevated and, at times, phytoplankton biomass is high. Application of the TLI classes the lake as supertrophic, indicative of 'very high' nutrient enrichment. Based on this classification, Lake Onoke can be considered to be in a poorer than average condition when compared to other 'similar' lakes in New Zealand (ie, lakes in pastoral catchments and other shallow coastal lakes). However, given that Lake Onoke is an example of a relatively unique lake type (eg, coastal barrier-bar lake similar only to Lakes Ellesmere, Forsyth, Waituna and perhaps Waihola in the South Island), apart from providing some 'national context', comparisons against national lake water quality data sets (such as those presented in Verburg et al. (2010) and Drake et al. (2011)) may be of limited value.

As was observed for Lake Wairarapa (Section 3.3.1), the TLI score for Lake Onoke is heavily influenced by the very low Secchi depth (water clarity) measurements and relatively high concentrations of total phosphorus. Given that the elevated concentrations of total phosphorus and poor water clarity are principally driven by suspended sediment (ie, the poor water clarity is not the result of high phytoplankton biomass), and that the mean concentrations for the other two key TLI variables (total nitrogen and chlorophyll *a*) are indicative of a lower trophic state, Lake Onoke may be better described as being in an eutrophic to supertrophic condition.

Considerable caution must be taken in applying this trophic classification to the whole of Lake Onoke. The site monitored to date is located at the point where the Ruamahanga River discharges into the lake (ie, in an area of higher flushing). Monitoring elsewhere on the lake, albeit limited, shows that some aspects of water quality are likely to vary spatially across the lake; in particular, water quality may be poorer on the western side of the lake where less flushing appears to occur. Monitoring at a site more representative of this part of the lake is recommended.

Flow conditions in the Ruamahanga River at the time of sampling strongly influence water quality in the lake. Water quality typically deteriorates with an increase in river flow, reflecting both the location of the monitoring site near the mouth of the Ruamahanga River and the increased flushing of nutrients and sediments that occurs within the large upstream agricultural catchment during periods of sustained rainfall. Analysis of nutrient concentrations at Greater Wellington's SoE monitoring sites on the Ruamahanga River has also shown a deterioration of water quality (ie, higher concentrations of both phosphorus and nitrogen) at higher flows (Ausseil 2011). The influence of the Ruamahanga River outflow on water quality in other parts of the lake (ie, the western side) is not known but is likely to decrease to some extent with distance from the river mouth (at least when the lake mouth is open). Similarly little is known about the potential for internal cycling of nutrients within the lakebed sediments, although Milne (2010) reported moderately elevated concentrations of phosphorus in surface lakebed sediment samples collected from sites in the centre and western portions of the lake.

Water quality in some coastal lakes has been shown to be strongly influenced by whether the lake mouth is open or closed[27], with a deterioration of water quality typically occurring when the mouth is closed (Schallenberg et al. 2010; Hamill 2011). Insufficient monitoring has been carried out in Lake Onoke to date to assess the effects of lake mouth blocking on the water quality, although there is some indication that concentrations of chlorophyll *a* are higher when the lake mouth is blocked or has been recently blocked. Overall, as noted by Robertson and Stevens (2007) the lake's susceptibility to eutrophication issues, such as elevated phytoplankton biomass, is reduced by the regular manual

[27] Schallenberg et al. (2010) found that water quality in Waituna Lagoon improved rapidly within days of a blocked barrier being opened. However, in contrast, they found that the water quality of Lake Ellesmere responded only weakly to opening and closing events.

opening of the mouth by Greater Wellington's Flood Protection Department. Historical records dating from the 1970s indicate that the lake mouth blocks on average nine times per year for an average of just over six days. Issues associated with eutrophication are likely to increase when the mouth is blocked for extended periods of time, such as in February 2008 when the mouth was blocked for around 41 days[28].

Although sampling was standardised to within two hours of a low ebb tide, there was considerable variability in salinity concentrations at Site 1, some of which could not be explained by closure of the lake mouth[29]. This variability appears to have a strong influence on the lake; water quality generally improves with increasing salinity, suggesting there is a 'dilution' effect arising from a greater proportion of typically 'cleaner and clearer' saline water at the sampling site.

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28 Greater Wellington unpublished data.

29 At times when the lake mouth is blocked, a backflow of more saline water could be occurring from other 'saltier' parts of the lake. A blocked lake mouth is known to result in a backflow of saline water as far up as Lake Wairarapa (Robertson 1991). However, a blocked lake mouth did not coincide with all observations of high conductivities, indicating, at times, other potential causes such as differences in tidal height and/or flow in the Ruamahanga River.

5. Lake Waitawa

This section focuses on Lake Waitawa, a small lake on the Kapiti Coast. A brief overview of the lake's catchment and values is presented followed by an assessment of the lake's water quality, based on a year-long investigation over August 2009 to July 2010.

5.1 Introduction

Lake Waitawa is a small (~16 ha), shallow (typically ≤ 7m deep) dune lake situated just north of Otaki near the edge of Greater Wellington's regional boundary. It is part of a group of highly modified small dune lake/wetland systems found in this area. The lake is fed by several small streams/wetlands that run into its eastern arms although these generally have limited or no flow. Little is known about groundwater inputs into the lake but they are potentially a significant source of water. The lake outflow is located in the western arm of the lake and eventually discharges into the Waitohu Stream (Figure 5.1).

Figure 5.1: Lake Waitawa and key features. The red line indicates the lake's catchment and the black line represents the boundary between the Wellington and Manawatu-Wanganui regions. Sampling sites are indicated by the red dots.

Little was known about the current state of water quality in Lake Waitawa prior to the year-long investigation described in this section, although anecdotally it was considered poor, with a history of algal blooms and nuisance growths of macrophytes. One-off water quality sampling in 2007 by Drake et al. (2011) classed the lake as supertrophic and of the 45 shallow coastal lakes assessed across New Zealand, Lake Waitawa had the eighth highest (ie, eighth worst) TLI score. Limited sampling undertaken by Wood et al. (2006) in 2003 confirmed the presence of high concentrations of cyanobacteria toxins in the lake.

5.1.1 Values

Lake Waitawa has high recreational use and a range of activities are commonly carried out on the lake including swimming, boating and kayaking. Regular users of the lake include visitors to the Forest Lakes Camp and Conference Centre which is situated on the lake edge, along with a water skiing lodge and Waka Ama (out rigger canoe) club (KCDC 2006; Gabites 2009). The lake is also popular for coarse fishing (Gabites 2009) and is one of four water bodies designated as a coarse fishery in the Wellington region. Lake Waitawa is listed in Appendix Five of Greater Wellington's existing Regional Freshwater Plan (RFP, WRC 1999) as a water body with regionally important recreational values. However, under Policy 5.2.4 it is excluded from requiring management of water quality for contact recreation purposes.

The lake, as part of the Waitohu Stream catchment, is also listed in the existing RFP (WRC 1999) as a water body with nationally threatened indigenous fish recorded in the catchment, and in the proposed Regional Policy Statement (GWRC 2010) as a significant indigenous ecosystem. However, based on recent fish surveys undertaken within the lake, the fish fauna is dominated by introduced species (Hicks et al. 2006; Cahill et al. 2010) and it is unlikely that the lake itself has high indigenous fish values.

5.1.2 Catchment land cover and land use

Lake Waitawa's catchment is approximately 278 ha in area and is dominated by pastoral land cover (~94%); this includes intensive farming practices such as a dairy farm that borders the northern edge of the lake[30]. Indigenous forest and scrub cover make up an insignificant proportion of catchment, as does urban land cover (Table 5.1). Some of the lake margin is still bordered by flax swamp, although this has been reduced in extent (KCDC 2006).

Table 5.1: Area and percentage of major land cover and land use types in the Lake Waitawa catchment, derived from aerial photographs taken in 2008
(Source: LUCAS – MfE 2010)

Land cover	Area (ha)	Catchment (%)
Indigenous forest	5.7	2.0
Horticulture	0.3	0.1
Pasture – low producing	26.7	9.6
Pasture – high producing	234.8	84.5
Urban	3.1	1.1
Other	7.3	2.6
Total	278.0	100

5.1.3 Significant consented activities

The principal consented discharge activity in the vicinity of the lake is the discharge of up to 15,340 L/day of treated wastewater from the Forest Lakes Camp and Conference Centre to a wetland that adjoins the lake's southern arm. This discharge, which is treated via a multi-cell oxidation pond, principally

30 The dairy farm that is located on the northern edge of Lake Waitawa is consented to run up to 400 cows, although the effective farmed area is not all within the Lake Waitawa catchment boundary.

occurs over the October to April period when the camp and conference centre are at their highest occupancy (118–300 people).

There is one permit in the catchment authorising the discharge of dairyshed washdown water to land just to the north of the lake.

5.2 Monitoring protocol, sites and variables

Water samples were collected on 11 occasions during August 2009 to July 2010 inclusive (every four to six weeks) from one sampling site[31] located at the deepest part of the lake (Figure 5.1, Appendix 1). Water quality was assessed by measuring a range of physico-chemical, microbiological and biological variables: dissolved oxygen, water temperature, pH, conductivity, Secchi depth, turbidity, faecal indicator bacteria, dissolved and total nutrients, and chlorophyll *a*. Although water samples were collected from the lake's surface, water temperature and dissolved oxygen measurements were also recorded at a series of depths to assess whether the lake stratifies[32].

Water samples were also collected on each sampling occasion for analysis of phytoplankton species richness and abundance.

Details of sampling and analytical methodology, along with the full list of variables monitored, are provided in Appendix 1.

5.2.1 Approach to analysis

To provide an overview of current lake water quality, physico-chemical and bacteriological water quality results were summarised for all sampling occasions (n=11) over the period August 2009 to July 2010. The current state of water quality was assessed by calculating a TLI score generated from the mean values over this period for each of the key variables (chlorophyll *a*, Secchi depth, total nitrogen and total phosphorus) using the Burns et al. (2000) equations outlined in Section 2.2.1.

The potential health risk to recreational users from the presence of potentially toxic cyanobacteria was assessed following protocols in the interim national cyanobacteria guidelines for recreational fresh waters (MfE/MoH, see Section 2.2.3).

5.3 Water quality

Physico-chemical and biological water quality results for the period August 2009 to July 2010 are summarised in Table 5.2. Over this period the water depth at the time of sampling ranged from 6.40 m (October 2009) to 6.95 m (June 2010).

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[31] Water samples were originally collected at two sites. However, results from both sites for the first three sampling occasions (August, September and October 2009) were similar and it was considered unnecessary to continue monitoring both sites.

[32] Water temperature and dissolved oxygen depth profiles were limited to a depth of 4 m in August and September 2009 because of the type of field meter used on those sampling occasions. From October 2009 onwards, water temperature and dissolved oxygen depth profiles were carried out to a depth of at least 6 m.

Table 5.2: Summary of water quality in Lake Waitawa, based on 11 sampling occasions over August 2009 to July 2010. National median values for lakes in catchments dominated by pastoral land cover are also listed (taken from Verburg et al. 2010). D.L. = detection limit.

Variable	National median	Median	Minimum	Maximum	*n*<D.L.
Water temperature (°C)	—	15.7	10.2	22.6	—
Dissolved oxygen (% saturation)	—	74.6	35.1	164	—
Dissolved oxygen (mg/L)	—	7.42	3.31	16.6	—
pH	7.7	7.26	6.62	9.46	—
Secchi depth (m)	2.0	1.58	1.01	2.72	—
Turbidity (NTU)	3.2	2.4	1.15	10	—
Conductivity (µS/cm)	192	234	221	248	—
Total nitrogen (mg/L)	0.773	1.5	1.1	2.1	0
Nitrite-nitrogen (mg/L)	—	0.012	0.007	0.018	0
Nitrate-nitrogen (mg/L)	—	0.059	0.009	0.660	0
Nitrite-nitrate nitrogen (mg/L)	—	0.071	0.019	0.680	0
Ammoniacal nitrogen (mg/L)	0.013	0.10	<0.01	0.63	1
Dissolved reactive phosphorus (mg/L)	0.003	0.110	0.011	0.200	0
Total phosphorus (mg/L)	0.037	0.151	0.082	0.300	0
Chlorophyll *a* (mg/m³)	8.8	16	5.7	80	0
E. coli (cfu/100mL)	—	4	<1	16	1

Figure 5.2 compares the range of measurements for the four TLI variables against national median values for lakes in catchments dominated by pastoral land cover (Verburg et al. 2010). The median concentrations of both total nitrogen and chlorophyll *a* were almost twice that of the national median for lakes in pastoral catchments and the median total phosphorus concentration was over four times that of the national median. The median Secchi depth value was also lower than the national median value for lakes in pastoral catchments (Figure 5.2); while this poor clarity is likely due, at times, to high phytoplankton biomass, the lake water has a brown humic colour and this is also likely to influence measurements of water clarity (Figure 5.3). As with the concentrations of total nutrients, the median concentrations of ammoniacal nitrogen and dissolved reactive phosphorus were also significantly higher (one and two orders of magnitude greater respectively) than the national median values for lakes located in pastoral catchments (Table 5.2).

Concentrations of many of the variables monitored showed significant variation over the reporting period (eg, Figure 5.4). The observed variation may be due to seasonal changes, biological activity, periods of stratification, or most likely a combination of these factors.

A median *E. coli* concentration of 4 cfu/100mL was recorded over the monitoring period and results from all sampling occasions were well below the MfE/MoH (2003) surveillance (safe level) guideline of 260 cfu/100ml; the highest *E. coli* count was just 16 cfu/100mL. While this indicates that the lake is suitable for contact recreation from a microbiological point of view, it is prone to toxic algal blooms and this affects the lake's suitability for contact recreation. This is discussed further in Section 5.3.1.

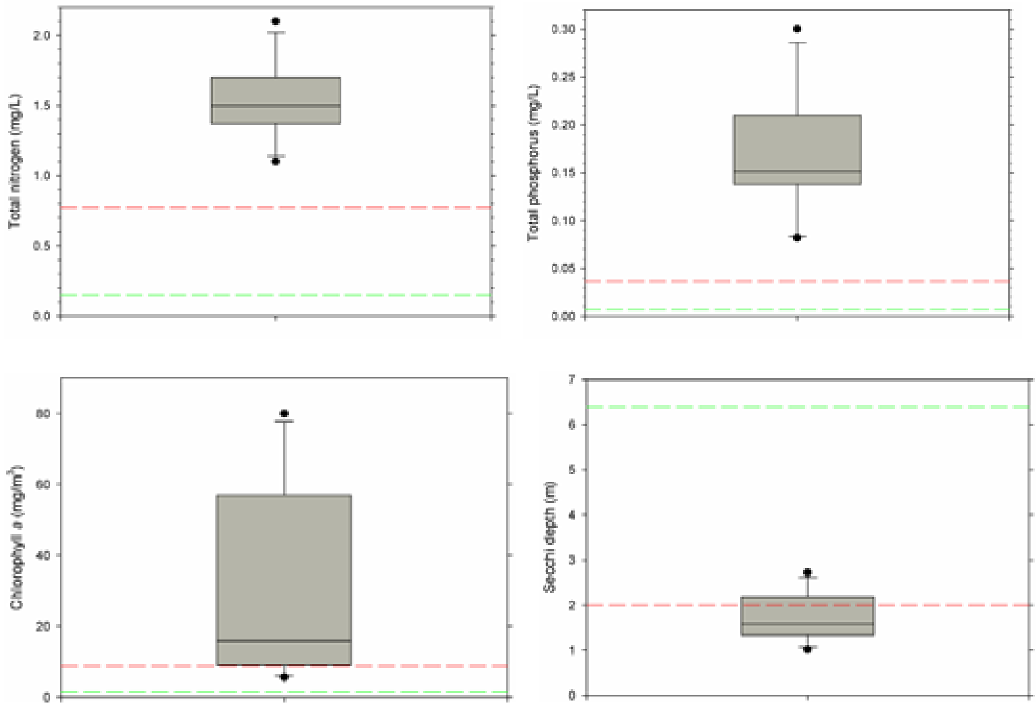

Figure 5.2: Box plots for TLI variables, based on water samples collected from Lake Waitawa over August 2008 to July 2009 (*n*=11). The horizontal dashed lines indicate national median values (taken from Verburg et al. 2010) for lakes in catchments dominated by indigenous forest (green) and pastoral (red) land cover.

Figure 5.3: Humic-stained water of Lake Waitawa which influences measurements of water clarity

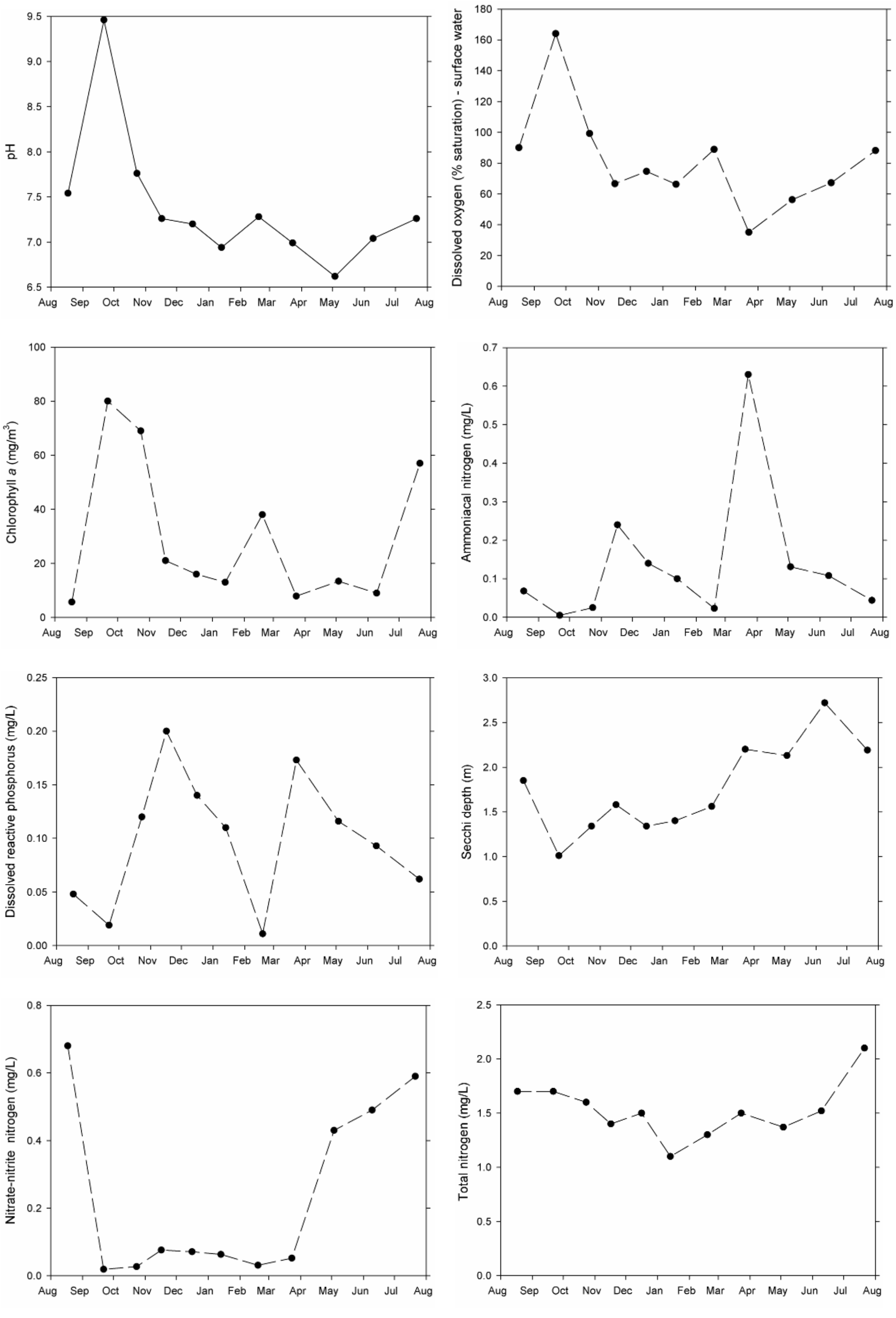

Figure 5.4: Variation in measurements of selected water quality variables, based on 11 sampling occasions of Lake Waitawa's surface waters, August 2009 to July 2010

5.3.1 Trophic state

Application of the TLI resulted in a score of 5.8 (Table 5.3), indicating Lake Waitawa is supertrophic. This places the lake in a poorer state than other New Zealand lakes situated in catchments dominated by pastoral land cover (based on the Verburg et al. (2010) national median TLI score of 4.9 (eutrophic)) and when compared with shallow coastal lakes (average condition mesotrophic/ eutrophic as reported in Drake et al. (2011)).

Individual TL scores for total nitrogen, total phosphorus and chlorophyll *a* all indicate a hypertrophic state (although in the case of both total nitrogen and chlorophyll *a*, the TL scores are on the border between the supertrophic and hypertrophic categories). The TL value for Secchi depth (water clarity) indicates a better trophic state (eutrophic) than the other TLI variables.

Table 5.3: Mean values for each of the four key variables used to calculate individual TL scores and an overall TLI score, based on 11 sampling occasions of Lake Waitawa over August 2009 to July 2010

	Total nitrogen (mg/L)	Total phosphorus (mg/L)	Secchi depth (m)	Chlorophyll *a* (mg/m^3)
Mean	1.53	0.17	1.76	30
TL value	6.0 (hypertrophic)	6.7 (hypertrophic)	4.5 (eutrophic)	6.0 (hypertrophic)
TLI score	5.8 (supertrophic)			

(a) Nutrient limitation

Potential nutrient limitation of phytoplankton growth was inferred by plotting concentrations of total nitrogen against total phosphorus (Figure 5.5). Calculation of total nitrogen and total phosphorus ratios, based on all sampling occasions, results in a median ratio of 9.1, which is within the range considered inconclusive in determining the potential limiting nutrient. Comparison of chlorophyll *a* concentrations with concentrations of dissolved nutrients were also inconclusive (Figure 5.6). Further monitoring, including targeted nutrient investigations, will be required to determine if nutrient limitation of phytoplankton growth occurs.

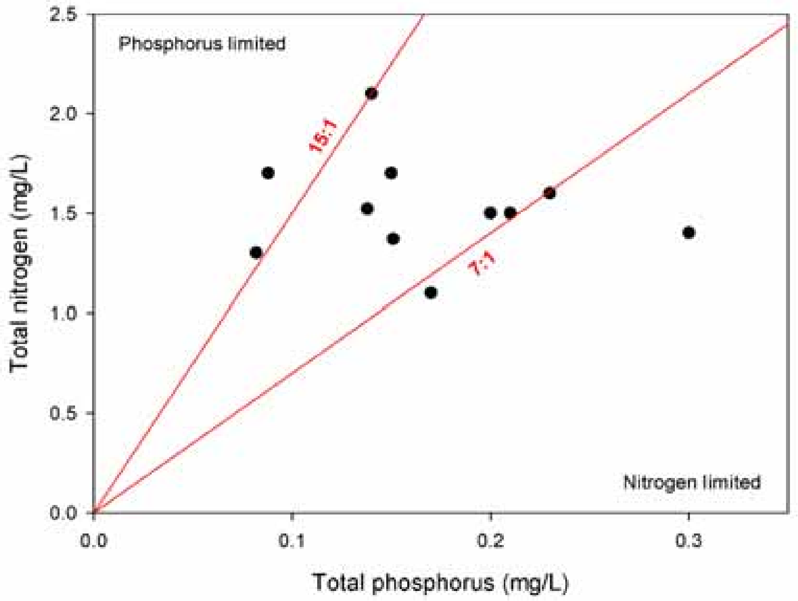

Figure 5.5: Plot of total phosphorus against total nitrogen, based on all data collected over August 2009 to July 2010. The red lines indicate thresholds for potential phosphorus limited (15:1) and nitrogen limited (7:1) conditions for phytoplankton growth. Values between the red lines are inconclusive.

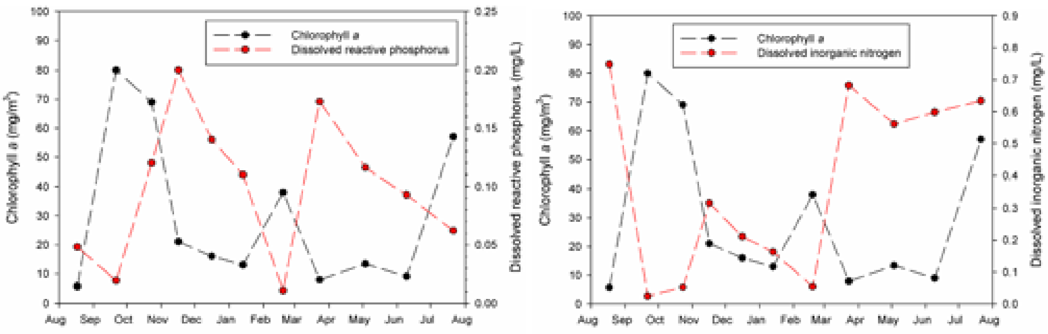

Figure 5.6: Concentrations of chlorophyll *a* alongside concentrations of dissolved reactive phosphorus (left) and nitrite-nitrate nitrogen (right), based on 11 sampling occasions in Lake Waitawa over August 2009 to July 2010

(b) Phytoplankton

In the nine samples in which all phytoplankton taxa were identified[33], the number of phytoplankton taxa ranged from two (October 2009) to 27 (May 2010), with a median of 14 (see Table A3.3, Appendix 3). The highest diversity of species was generally observed in the winter months (eg, May and June 2010).

Potentially toxic cyanobacteria species were recorded on every sampling occasion and four taxa were identified: *Anabaena*, *Aphanocapsa*, *Microcystis* and *Pseudanabaena*. *Anabaena* species were recorded most frequently (all sampling occasions), followed by *Microcystis* species (four occasions) and *Aphanocapsa* and *Pseudanabaena* species (two occasions each). When Anabaena were identified to species level (seven out of 11 occasions), *Anabaena circinalis* was the species present on six occasions and *Anabaena flos-aquae f. flos-aquae* on the other occasion. One dinoflagellate taxon known to cause taste and odour problems (*Ceratium sp.*) was also recorded on four occasions.

Cell counts and biovolumes for the potentially toxic phytoplankton species are summarised in Table 5.4. On all sampling occasions, *Anabaena* species made up the majority of the total biovolume. The highest biovolumes were recorded in September and October 2009 (8.7 mm^3/L and 8.5 mm^3/L, respectively) and the lowest in March 2010 (0.108 mm^3/L).

Comparing the total sample biovolumes with the alert level framework in the interim national cyanobacteria guidelines for fresh water (MfE/MoH 2009) showed that on three occasions (September and October 2009 and July 2010) the biovolume fell within the 'action (red mode)' level (Table 5.4). While this indicates that the water was potentially unsuitable for contact recreation at these times, no toxin analysis was carried out as part of this investigation to validate this.

33 On the other two sampling occasions, analysis was limited to identification and cell counts of just potentially cyanobacteria species.

Table 5.4: Cell counts for potentially toxic species identified in phytoplankton samples collected from Lake Waitawa over August 2009 to July 2010. Average cell volume (from MfE/MoH (2009)) and calculated biovolumes are also presented. The total biovolumes in each sample are coloured based on the alert level framework in MfE/MoH (2009): green=surveillance, amber=alert and red=action.

Month	Potentially toxic species identified in sample	Cell count (cells/mL)	Average cell volume (µm³)	Biovolume (mm³/L)	Total biovolume in sample (mm³/L)
August	*Anabaena circinalis*	5,500	208	1.144	1.144
September	*Anabaena circinalis*	42,000	208	8.736	8.736
October	*Anabaena circinalis*	41,000	208	8.528	8.528
November	*Anabaena circinalis*	2,800	208	0.582	0.582
December	*Anabaena circinalis*	1,100	208	0.229	0.229
January	*Anabaena circinalis*	2,600	208	0.541	0.541
	Pseudanabaena sp.	16	8.3	0.000	
February	*Anabaena flos-aquae f. flos-aquae*	15,000	116	1.740	1.740
	Aphanocapsa sp.	29	1.7	0.000	
	Microcystis sp.	17	19	0.000	
March	*Anabaena sp.*	930	116	0.108	0.108
May	*Anabaena sp.*	2,800	116	0.325	0.359
	Microcystis sp.	1,800	19	0.034	
June	*Anabaena sp.*	3,500	116	0.406	0.415
	Aphanocapsa sp.	26	1.7	0.000	
	Microcystis sp.	480	19	0.009	
	Pseudanabaena sp.	4	8.3	0.000	
July	*Anabaena sp.*	23,000	116	2.668	2.676
	Microcystis sp.	410	19	0.008	

5.3.2 Stratification

Following protocols in Burns et al. (2000), Lake Waitawa was considered stratified when the difference between water temperatures recorded between the surface and the lake bottom was greater than 3°C. Using this criterion, the lake was clearly stratified on four sampling occasions: November, December, January and February (Figure 5.7). On four additional sampling occasions (September, October, March and July) the difference was at least 2°C, which may potentially indicate some stratification. The maximum difference in temperature recorded between the lake surface and bottom was 7.2°C (February 2010). The thermocline[34] was generally found to develop at depths of around 3–4 m.

Concentrations of dissolved oxygen recorded from the lake surface ranged from 3.3 mg/L (March 2010) to 16.6 mg/L (September 2009). Supersaturation was only recorded in September 2009 (164% and 159% recorded at the surface and a depth of 2 m, respectively) and probably reflected the high levels of photosynthetic activity occurring at that time. Other indications of the high photosynthetic activity were that the highest concentrations of chlorophyll *a* and

[34] The layer where the water temperature changes rapidly, separating the warmer epilimnion (surface waters) from the colder hypolimnion (bottom waters).

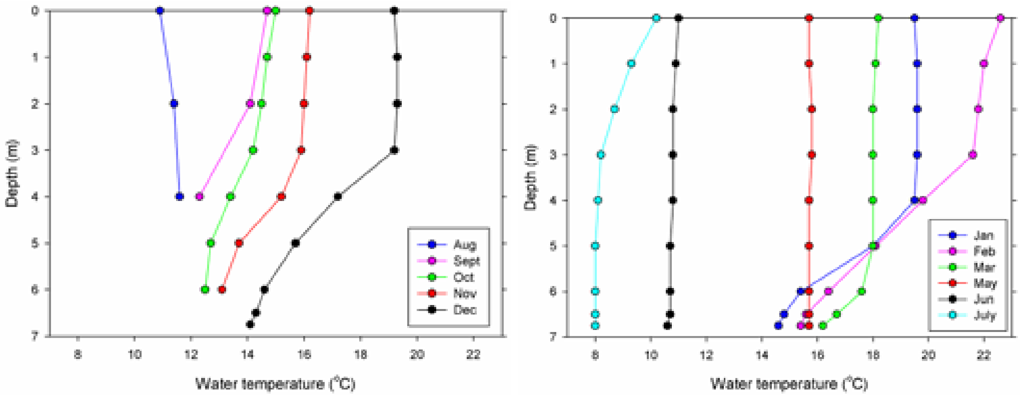

Figure 5.7: Water temperature depth profiles for Lake Waitawa, measured over August to December 2009 (left) and January to July 2010 (right)

the highest cyanobacteria cell count for the reporting period were also recorded on this sampling occasion. The highest pH value was also recorded on this sampling occasion which may also reflect a high level of photosynthetic activity (ie, carbon dioxide is used during photosynthesis which results in a rise in pH).

The presence of anoxic conditions in the lake bottom waters was investigated using a dissolved oxygen threshold of <3% (Burns et al. 2000). Using this criterion, anoxic conditions were measured on five occasions (November 2009 to March 2010), progressing up the depth profile to around 4 and 5 m deep during December 2009 to February 2010, before lowering to 6 m as stratification reduced in March 2010 (Figure 5.8).

Dissolved oxygen concentrations at the lake bottom were regularly below the 2 mg/L threshold considered to be detrimental to most fish species (Wetzel 1983) and from October 2009 through to March 2010, concentrations of dissolved oxygen at a depth of 6 m were all below 0.9 mg/L.

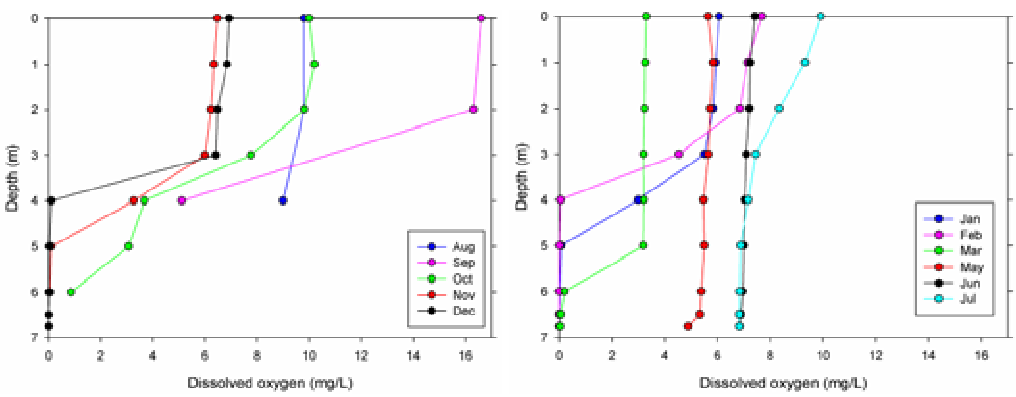

Figure 5.8: Dissolved oxygen depth profiles for Lake Waitawa, measured over August 2009 to December 2009 (left) and January 2010 to July 2010 (right)

Anoxic conditions also appear to have resulted in nutrients being released from lakebed sediments. This is evident in spikes in concentrations of dissolved reactive phosphorus and ammoniacal nitrogen that are observed to occur during the period of stratification and when stratification begins to breakdown in March 2010 and the lake begins to 'mix' (see Figure 5.4).

5.4 Discussion

Monitoring over the period August 2009 to July 2010 has shown that water quality in Lake Waitawa is severely degraded. Nitrogen and phosphorus concentrations are elevated, contributing to high phytoplankton biomass (dominated by potentially toxic cyanobacteria) and, in turn, low water clarity. Application of the TLI classes the lake as supertrophic (ie, 'very high' nutrient enrichment) and indicates that it is in a poorer state than both the median condition reported by Verburg et al. (2010) for New Zealand lakes draining predominantly pastoral catchments (eutrophic) and the average condition of other shallow coastal lakes reported by Drake et al. (2011) (mesotrophic/ eutrophic).

Stratification and anoxic conditions at the lake bottom were observed during spring/summer and appear to be a significant driver of water quality in the lake. Anoxic conditions spanned five months (November 2009 to March 2010) and on two occasions the layer of anoxia was recorded at depth of 4 m[35]. Given that sustained exposure to concentrations of dissolved oxygen below 2 mg/L is considered detrimental to most fish species (Wetzel 1983), anoxia of the bottom waters of Lake Waitawa for this extent of time is probably having a significant impact on the amount of habitat available for some fish species (ie, at times the bottom 3 m of the lake maybe unsuitable)[36]. Other fauna, particularly benthic fauna, are also likely to be impacted by this period of anoxia.

Anoxic conditions at the lake bottom can also result in the release of nutrients (both phosphorus and nitrogen) from the lakebed's sediments. This recycling of nutrients (or internal nutrient load) can be an important driver of phytoplankton production in some lakes (Vant 1987). Although targeted investigations determining external nutrient sources as well as nutrient burial rates would be required to determine the significance of internal nutrient cycling in Lake Waitawa, spikes in concentrations of dissolved reactive phosphorus and ammoniacal nitrogen recorded during and at the end of the observed period of anoxia indicate that internal nutrient cycling is probably occurring.

Algal biomass (based on chlorophyll *a* concentrations) decreased once the lake became stratified and generally stayed low until stratification began to break down around March. This may indicate that under stratified conditions, nutrients in the epilimnion or warmer surface layer may become limiting for phytoplankton growth. While examination of nutrient ratios to determine which nutrient may be limiting were inconclusive, concentrations of dissolved reactive phosphorus tended to decrease as concentrations of chlorophyll *a* increased, suggesting that Lake Waitawa may be phosphorus limited for at least part of the year.

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35 Stratification and the subsequent development of an anoxic layer at the lake bottom is not a new development and was recorded by Cunningham et al. (1953) in a one-off sampling event undertaken in 1949.

36 Fish sampling was not carried out as part of the 2009/10 investigation but recent fish surveys (Hicks 2006; Cahill et al. 2010) have shown a change from a purely native fish fauna recorded in 1949 (Cunningham et al. 1953) to a fauna dominated by exotic species. Two native species – common smelt and an unspecified species of galaxiid – recorded in 1949 have not been recorded in recent surveys. While this may potentially indicate that lake habitat and water quality are no longer suitable to support these species, their absence could be due to many other factors (eg, interactions with introduced species or loss of easy access to the sea for migratory purposes).

Potentially toxic cyanobacteria species were present in every phytoplankton sample collected, with *Anabaena* species consistently dominant. On three occasions the biovolumes recorded fell within the action level category of the MfE/MoH (2009) interim national cyanobacteria guidelines, indicating a potential health risk to recreational users of the lake. This risk is likely to be much higher closer to the shore where dense algal scums have been observed to accumulate at times. While no toxin analysis was carried out on any samples, extremely high toxin results have been previously recorded in this lake (Wood et al. 2006). Seasonality (directly) does not seem to be a strong driver of the occurrence of cyanobacteria blooms and as mentioned above, peaks in phytoplankton biomass (and subsequently cyanobacteria cell counts) appear to be more associated with mixed (rather than stratified) conditions. Consequently blooms may occur year-round and there is insufficient data to indicate when the risk to recreational users is highest.

Along with high phytoplankton biomass, the elevated nutrient concentrations are also likely to be fuelling nuisance growths of macrophytes such as hornwort (*Ceratophyllum demersum*) and *Egeria densa*. While the presence of macrophyte beds can benefit water quality through taking up nutrients and stabilising lakebed sediments, extensive macrophyte growths can hinder recreational activities such as boating and swimming on the lake, as can dense mats of the floating water fern (*Azolla* sp.) – now a common sight on the lake (Figure 5.9) (NewsWire 2008). *E. densa* has only appeared in the lake in the last few years and its introduction is an indication that the current management of some activities[37] on the lake (eg, boating and fishing) may need to be reviewed if the risk from further introductions of pest plant species is to be reduced.

Figure 5.9: Dense mats of the free-floating water fern (*Azolla* sp.) on the surface margins of Lake Waitawa (October 2011)

[37] *Egeria densa* does not produce seed and its introduction into water bodies is considered to be caused by human mediated activities (eg, via contaminated boats or fishing equipment) (de Winton et al. 2011).

Trials have been undertaken in the lake investigating the potential of controlling hornwort using the herbicide diquat. Application of the herbicide successfully reduced the occurrence of hornwort to below nuisance levels although it was never considered a viable option to eradicate hornwort. On-going control of hornwort using herbicide would require repeat seasonal applications (Dugdale & Champion 2002).

Overall, taking into account its highly modified catchment and its relatively small size and shallow depth, it is unsurprising that Lake Waitawa has poor water quality. The lake also has a long residence time (ie, low flushing rate) of around 351 days (Snelder 2006) which will contribute to the accumulation of nutrients in the lake and lakebed sediments. Furthermore, although only one year of monitoring was conducted, the extensive period of anoxia clearly appears to be resulting in internal nutrient recycling leading to further degradation in lake water quality.

The relative contributions of nutrient inputs from different sources have not been quantified to date but diffuse inputs from the largely agricultural catchment (entering the lake via shallow groundwater) are likely an important pathway. Grazing of stock up to or close to the lake margin as well as in some of the wetland areas is probably contributing inputs of both nitrogen and phosphorus and observations in Gabites (2009) of effluent pooling around the lake indicates that at times overland flow of nutrients may be occurring. Additional nutrient contributions in the immediate catchment include faecal matter from waterfowl that frequent the lake and wastewater from the Forest Lakes Camp and Conference Centre. Although the wastewater is treated and discharged to a wetland adjacent to the lake, some seepage of nutrients into the southern end of the lake is likely; this should be investigated and quantified as part of the Assessment of Environmental Effects prepared in support of an application for a new resource consent for the wastewater discharge in 2014. Similarly, the relative nutrient contributions from other external sources (eg, diffuse agricultural inputs and waterfowl) – and from internal recycling – need examination, particularly given recent interest in ‘restoring’ the water quality and ecosystem health of Lake Waitawa (Gabites 2009).

6. Parangarahu Lakes (Lakes Kohangapiripiri and Kohangatera)

This section provides a brief overview of Lakes Kohangapiripiri and Kohangatera (the Parangarahu Lakes) and then summarises the findings of LakeSPI surveys carried out on these lakes in March 2011. Full details of the surveys can be found in de Winton et al. (2011). Results from one-off water quality and phytoplankton sampling undertaken at the time of the surveys are also presented.

6.1 Introduction

Lakes Kohangapiripiri and Kohangatera are small, shallow, coastal lakes located in Greater Wellington's East Harbour Regional Park on Wellington's south coast. Together, these two lakes are referred to as the Parangarahu Lakes (or Pencarrow Lakes). They are situated side by side in drowned valley systems that are separated from Cook Strait by a gravel bar (Figure 6.1).

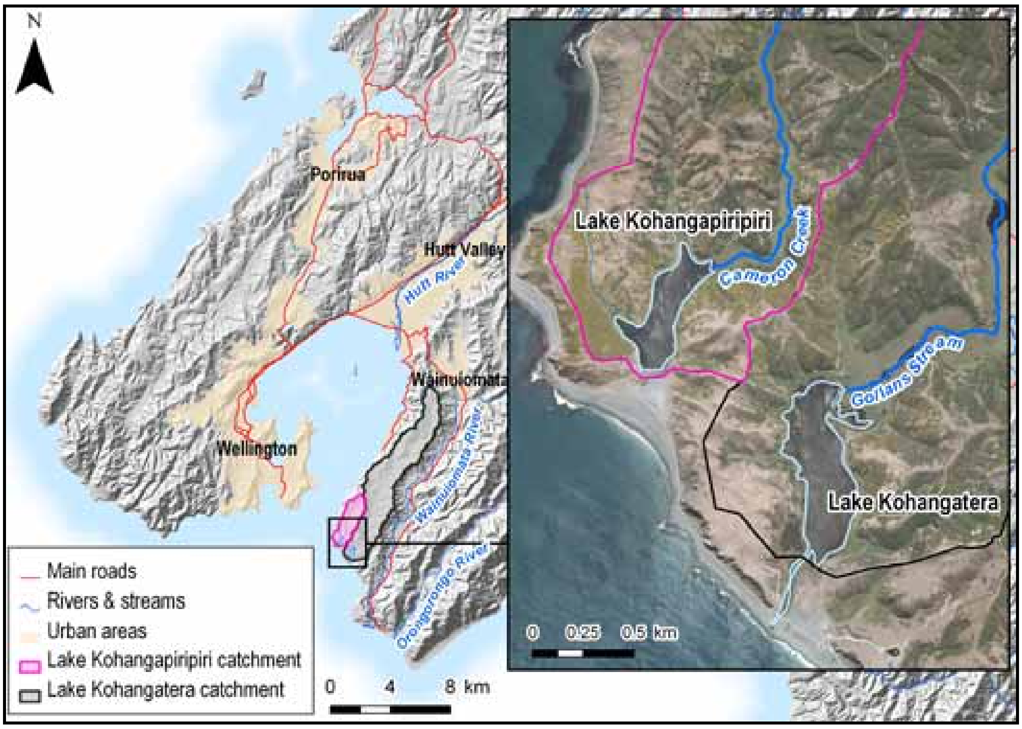

Figure 6.1: Parangarahu Lakes (Lakes Kohangapiripiri and Kohangatera)

Lake Kohangapiripiri is the smaller of the two lakes (approximately 11 ha in size) and is up to 1.8 m deep while Lake Kohangatera is around 21 ha in size and up to 2.1 m deep. The water of both lakes is humic stained and as a result of being subject to salt spray they are both slightly brackish. (Gibbs 2002). The catchment area of Lake Kohangatera is around five times greater than that of Kohangapiripiri (approximately 2,002 ha and 369 ha respectively). Both lakes are fed by extensive wetlands that discharge into their northern ends; these wetlands are in turn fed by Cameron Creek (Lake Kohangapiripiri) and Gollans Stream (Lake Kohangatera).

The lakes are typically thought to drain to the sea via seepage through a gravel bar and while complete breaching of the bar may occur during flood events, this was considered to occur infrequently (Gibbs 2002). However, in the last seven years or so the frequency of breaching is considered to have increased for Lake Kohangatera and can now occur after heavy rain (de Winton et al. 2011).

Little is known about the current water quality of the Parangarahu Lakes but an earlier survey of submerged vegetation identified the lakes as having high ecological values (Wells & Champion 2004). Unpublished data referred to in Gibbs (2002) and collected during 1991 to 1993 reported that water clarity in Lake Kohangapiripiri was generally good with the lake bottom always visible. In contrast, water clarity in Lake Kohangatera was more variable, with a minimum Secchi depth measurement of 0.72 m recorded during the monitoring period (mean of 1.42 m); an algal bloom was attributed as the cause of this poor water clarity. Gibbs (2002) speculated that due to the strong winds common in the area, water clarity was likely to be adversely affected by re-suspension of lakebed sediments. Based on measurements of chlorophyll *a* also undertaken during this period, Gibbs (2002) reported that Lake Kohangapiripiri was probably oligotrophic/mesotrophic and Lake Kohangatera mesotrophic. Wells and Champion (2004) came to similar conclusions on the trophic status of these lakes based on their observations of the submerged vegetation; they also speculated that the extensive occurrence of blue-green algae (*Nostoc sp.*) over much of the lakebed may indicate that the lake is a nitrogen-limited ecosystem.

6.1.1 Values

The Parangarahu Lakes, along with their associated wetlands and catchments, support a wide range of native plants and animals, including a number of threatened species (Gibbs 2002). Compared with other lowland coastal lakes in New Zealand, these lakes and their catchments are relatively unimpacted and not intensely modified; a survey of submerged vegetation undertaken in 2004 concluded that they were outstanding examples of 'healthy' lakes with extensive native vegetation and limited impacts from introduced aquatic weeds (Wells & Champion 2004). Wells and Champion (2004) also stated that Lake Kohangapiripiri is one of the few remaining catchments in New Zealand where no introduced freshwater fish species have been recorded.

Lakes Kohangapiripiri and Kohangatera have significant cultural values and around both lakes there is evidence of Maori hut, oven and workshop sites. The presence of dendroglyphs (a rare form of Maori art on the mainland of New Zealand) on karaka trees at the head of Lake Kohangapiripiri is considered especially noteworthy (Gibbs 2002).

The lakes and their catchments fall within Greater Wellington's East Harbour Regional Park and as such the lakes and their surrounds are a popular location for a range of recreational activities including walking, picnicking, mountain biking and bird watching. The lakes are also used by a limited number of duck-shooters during the hunting season (GWRC 2007) and, on occasion, kayakers Gibbs (2002). Boat access to the lakes is typically minimal and controlled by

Greater Wellington, although boats are still used by duck shooters to access hunting sites each year (G. Cooper,[38] pers. comm. 2011).

The Parangarahu Lakes are listed in Appendix 2 of Greater Wellington's existing Regional Freshwater Plan (RFP, WRC 1999) as lakes with a high degree of natural character and as such surface water is to be managed for aquatic ecosystem purposes. These lakes, along with their tributaries, are also listed in Appendix 3 of the RFP as water bodies with nationally threatened fish recorded in their catchments. The high native fish values of these lakes are further recognised in Greater Wellington's proposed RPS (GWRC 2010).

6.1.2 Land cover

The catchments of both lakes are dominated by indigenous forest and scrub (Figure 6.2 and Table 6.1). The values given in Table 6.1 for low-producing pastoral land cover in both lake catchments are considered to be over-estimated because there is no longer any active farming within the boundary of Greater Wellington's East Harbour Regional Park; this pastoral land is slowly regenerating to scrub (G. Cooper, pers. comm. 2011). Similarly, the areas of wetland presented in Table 6.1 are also inaccurate and, at least in the case of Lake Kohangapiripiri, are under estimated as significant wetland areas are present at the northern end of both lakes.

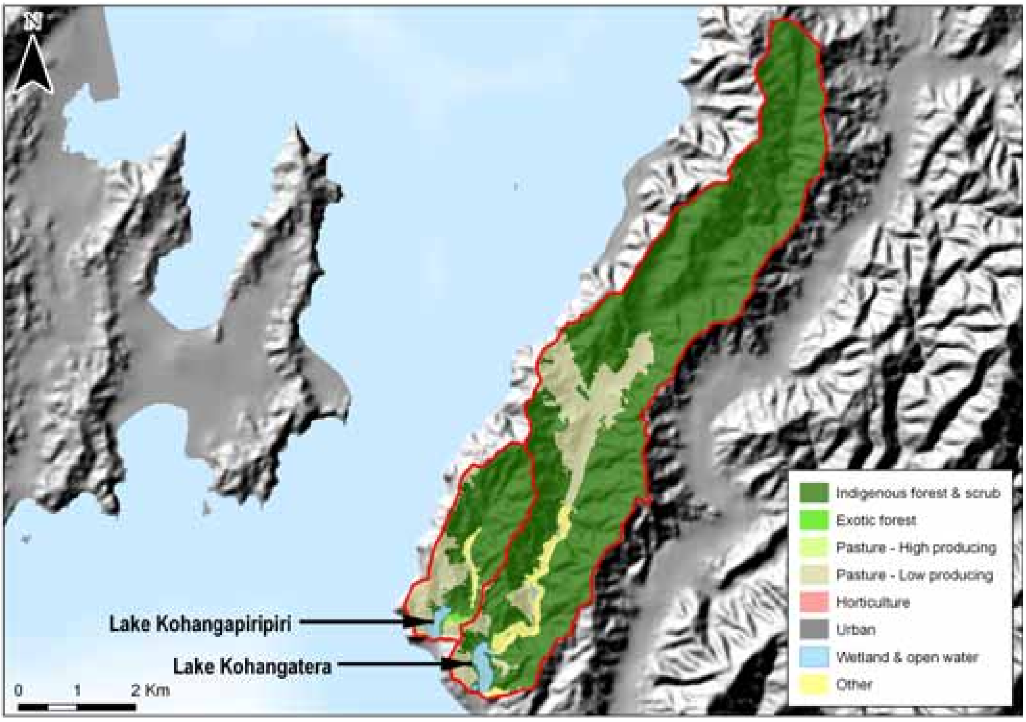

Figure 6.2: Major land cover classes in the catchments of the Parangarahu Lakes. The red lines indicate the lake's catchment boundary.

[38] Gareth Cooper, East Harbour Regional Park Ranger, Greater Wellington Regional Council.

Table 6.1: Area and percentage of major land cover and land use types in the Parangarahu Lakes catchment, derived from aerial photographs taken in 2008

(Source: LUCAS – MfE 2010)

Land cover	Lake Kohangapiripiri		Lake Kohangatera	
	Area (ha)	% of catchment	Area (ha)	% of catchment
Indigenous forest and scrub	250.6	67.8	1,661.7	83.0
Exotic forest	5.0	1.4	<1	<1
Pasture – low producing	102.2[1]	27.7[1]	276.7[1]	13.8[1]
Wetland & open water	0[1]	0[1]	3.0[1]	0.1[1]
Other	11.6	3.0	60.8	3.0
Total	369.4	100	2002.2	100

*Note that these values are considered questionable. In the case of low-producing pasture, the values are probably over estimated, whereas the areas of wetland are probably underestimated. See text for further detail.

6.1.3 Significant consented activities

There are no significant consented activities in the catchments of the Parangarahu Lakes. There is one active consent for a water take from Gollans Stream (Lake Kohangatera catchment) for the irrigation of pasture. This consent allows for up to 4.2 L/s of water to be abstracted from the stream for 4 hrs/day, up to 24 days/year. Gibbs (2002) cites an old domestic refuse tip site on a tributary of Gollans Stream and while he did not consider it a threat to the wildlife values of Lake Kohangatera, Greater Wellington's Selected Land Use Register database records that in 1997 a significant amount of leachate was discharging into the wetland to the north of the lake.

6.2 Monitoring protocol, sites and variables

The LakeSPI surveys in Lakes Kohangapiripiri and Kohangatera were undertaken by NIWA on 16 March 2011. Survey transects chosen to represent vegetation in the lakes are shown in Figure 6.3 (further details of survey site selection can be found in de Winton et al. 2011).

At the time of the surveys, one-off water samples were collected from the surface of each lake at a site chosen to be representative of the lake (Figure 6.3). Water quality was assessed by measuring a range of physico-chemical and biological variables: dissolved oxygen, water temperature, pH, conductivity, Secchi depth, turbidity, faecal indicator bacteria, dissolved and total nutrients, and chlorophyll *a*. Water temperature and dissolved oxygen measurements were also recorded at a series of depths to assess whether any stratification was present and a water sample was collected to allow for analysis of phytoplankton species richness and abundance.

Details of sampling and analytical methodology, along with the full list of variables measured, are provided in Appendix 1.

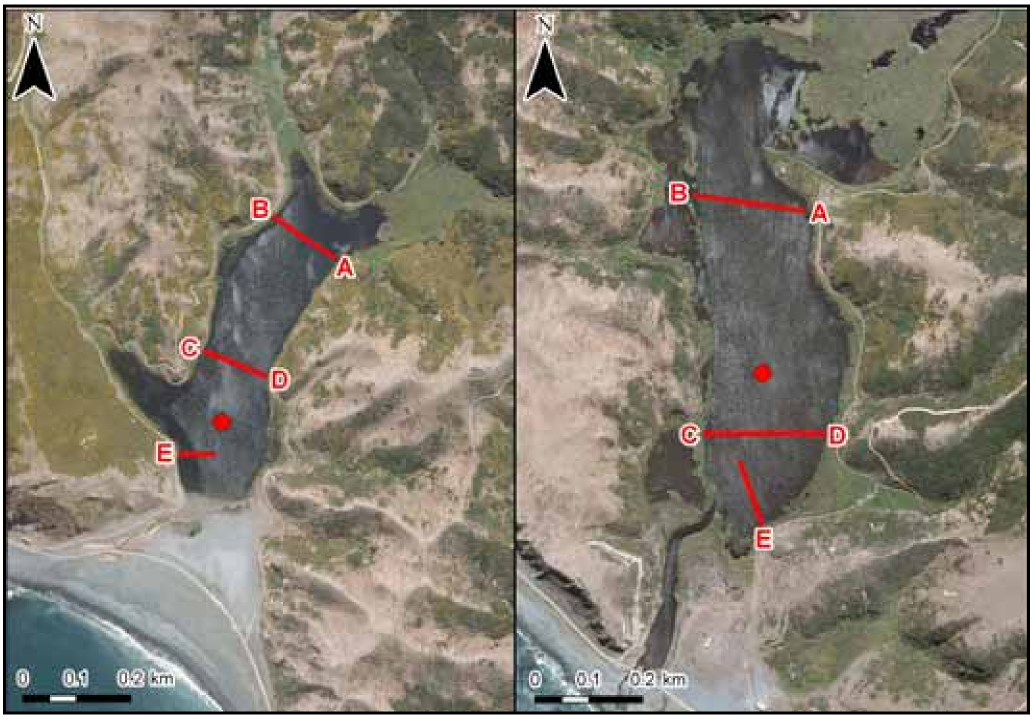

Figure 6.3: Location of the five LakeSPI transects (A to E) in Lake Kohangapiripiri (left) and Lake Kohangatera surveyed on 16 March 2011. The location of the sites where one-off water quality and phytoplankton samples were collected from each lake are also indicated (red circle).

6.3 LakeSPI findings

Overall LakeSPI scores of 63% and 89% were calculated for Lakes Kohangapiripiri and Kohangatera respectively (Table 6.2). This places Lake Kohangapiripiri in the 'high' category and Lake Kohangatera in the 'excellent' category for ecological condition. According to de Winton et al. (2011), out of the 206 lakes across New Zealand surveyed using this method to date, Lake Kohangapiripiri is ranked 47th and Lake Kohangatera 10th.

Table 6.2: Summary of LakeSPI results for Lakes Kohangapiripiri and Kohangatera from surveys undertaken by de Winton et al. (2011) on 16 March 2011

Lake	LakeSPI index (%)	Native condition index (%)	Invasive impact index (%)
Lake Kohangapiripiri	63	73	38
Lake Kohangatera	89	83	5

In both lakes all six key native community types recognised by LakeSPI were recorded as present and a diverse range of native vegetation was found extending across their lake beds; this included species considered rare and/or threatened. This resulted in a native condition index of 73% for Lake Kohangapiripiri and 83% for Lake Kohangatera. Species indicative of brackish conditions (eg, *Ruppia polycarpa*) were reported from both lakes. In Lake Kohangapiripiri, some areas of low vegetation cover were encountered which de Winton et al. (2011) attributed to some kind of disturbance, possibly swan grazing.

Ranunculus trichophyllus was the only exotic weed recorded during the survey of Lake Kohangapiripiri. It was limited to localised beds and is considered relatively benign. This resulted in an invasive index score of 38% for this lake. Similarly, only one exotic weed was recorded in Lake Kohangatera, *Elodea canadensis*, and it was only observed at one survey site where it formed low covers. This is the first time that *E. canadensis* has been recorded in Lake Kohangatera and resulted in an invasive index score of 5%.

Comparisons of the current lake vegetation with a survey undertaken by NIWA in 2004 (Wells & Champion 2004) led de Winton et al. (2011) to conclude that, despite the new record of *Elodea canadensis* in Lake Kohangatera, vegetation in both lakes has remained in a relatively stable state over the last seven years.

6.4 Water quality and phytoplankton

A summary of water quality measurements from one-off sampling undertaken in the Parangarahu Lakes on 16 March 2011 is presented in Table 6.3. Extreme care must be taken when interpreting just one set of water quality results but based on trophic categories in Burns et al. (2000):

- Lake Kohangapiripiri has a TLI score of 4.2 (eutrophic), with individual TL classifications as follows: total nitrogen (supertrophic), total phosphorus (eutrophic), Secchi depth (eutrophic[39]) and chlorophyll *a* (oligotrophic).
- Lake Kohangatera has a TLI score of 4.0 (on the border between mesotrophic and eutrophic), with individual TL classifications as follows: total nitrogen, total phosphorus, Secchi depth (all eutrophic) and chlorophyll *a* (oligotrophic).

Relative to national median values for lakes located in catchments dominated by indigenous forest land cover, concentrations of total nitrogen and total phosphorus from this one-off sampling event indicate that nutrients are elevated in both lakes.

Water temperature and dissolved oxygen depth profiles showed that on this sampling occasion there was negligible difference between lake surface and lake bottom measurements (0.2°C and 0.4°C in Kohangapiripiri and Kohangatera respectively), indicating both lakes were well mixed. Concentrations of dissolved oxygen also showed little variation between measurements undertaken from the surface and bottom of each lake (0.5 mg/L and 0.2 mg/L in Kohangapiripiri and Kohangatera respectively). Supersaturation was recorded throughout the water column of Lake Kohangatera and is suggestive of macrophyte photosynthesis.

Twenty five taxa were identified in the one-off phytoplankton sample collected from Lake Kohangatera (Table 6.4), including three potentially toxic cyanobacteria species: *Anabaena* sp., *Aphanocapsa* sp. and *Picocyanobacteria*. Only one phytoplankton taxon was identified in the one-off sample collected from Lake Kohangapiripiri: *Cryptomonas* sp. (1,000 cells/mL).

[39] The Secchi disc was recorded as being just visible on the lake bottom so assigning the eutrophic category is appropriate given that this category spans from 1.1 to 2.8 m.

Table 6.3: Summary of water quality measurements and results from one-off sampling of the Parangarahu Lakes on 16 March 2011. National median values for lakes in catchments dominated by indigenous forest land cover are also presented (taken from Verburg et al. 2010).

Variable	National median values	Lake Kohangapiripiri	Lake Kohangatera
Depth at sampling point (m)	—	1.49	1.85
Water temperature (°C) (surface)	—	18.3	19.1
Dissolved oxygen (% saturation) (surface)	—	98.0	106.9
Dissolved oxygen (mg/L) (surface)	—	9.3	9.8
pH	7.5	7.1	8.0
Conductivity (µS/cm)	228	574	954
Secchi depth (m)	6.4	>1.49	1.45
Turbidity (NTU)	0.8	0.8	2.4
Total suspended solids (mg/L)	—	<2	3
Total phosphorus (mg/L)	0.007	0.026	0.025
Dissolved reactive phosphorus (mg/L)	0.002	0.012	<0.004
Total nitrogen (mg/L)	0.149	0.72	0.49
Nitrite-nitrate nitrogen (mg/L)	—	<0.002	<0.002
Ammoniacal nitrogen (mg/L)	0.006	<0.010	<0.010
Total Kjeldahl nitrogen (mg/L)	—	0.72	0.49
Total organic carbon (mg/L)	—	10.4	7.1
Chlorophyll *a* (mg/m^3)	1.6	< 3	< 3
E. coli (cfu/100mL)	—	10	23

Table 6.4: Phytoplankton taxa identified in a one-off sample collected on 16 March 2011 from Lake Kohangatera. Unit and cell counts are also presented where available.

Taxa	Unit count (units/mL)	Cell count (cells/mL)
Anabaena sp.	2	41
Aphanocapsa sp.	490	3,800
Picocyanobacteria	24	190
Aphanothece sp.	1	
Aphanothece sp.	25	
Merismopedia sp.	14	
Merismopedia sp.	56	
Carteria sp.	2	
Chlamydomonas sp.	4	
Cocconeis sp.	6	
Crucigenia sp.	220	
Cryptomonas sp.	140	
Cyclotella sp.	65	
Dictyosphaerium sp.	41	
Elakatothrix sp.	2	
Euglena sp.	1	
Monoraphidium spp.	16	
Navicula sp.	1	
Nitzschia sp.	11	
Oocystis sp.	1,300	
Pediastrum sp.	6	
Peridinium sp.	3	
Scenedesmus sp.	550	
Small unicells (<5µm)	3,900	
Tetraedron sp.	14	

6.5 Discussion

Based on LakeSPI assessments undertaken in March 2011, the current ecological condition of Lake Kohangapiripiri and Lake Kohangatera is considered ‘high’ and ‘excellent’, respectively. This is especially so when compared to other lowland coastal lakes in New Zealand which are typically highly modified and degraded through land cover modification and impacts from introduced plant and fish species (Drake et al. 2011).

In both lakes the submerged plant communities appear to have remained in a relatively stable state since the last survey was undertaken seven years ago (de Winton et al. 2011). One-off water quality sampling is insufficient to characterise the trophic state of each lake, although the chlorophyll *a* concentration recorded in water samples from both lake was below the level of analytical detection, indicating low phytoplankton biomass[40]. This is despite the concentrations of total phosphorus and total nitrogen[41] being higher than might be expected for lakes situated in a relatively unmodified catchment (Verburg et al. 2010).

The high proportion of native vegetation in the catchment reduces the likelihood of a significant deterioration in the water quality of the Parangarahu Lakes. However, the presence of a new exotic weed, *Elodea canadensis*, in Lake Kohangatera highlights that introduced plants are a very real threat to the lake’s high native vegetation values. A delimitation survey carried by Wells et al. (2011) in April 2011 following the initial discovery of *E. canadensis* in March showed this species was relatively widespread in the lake (although generally limited in its extent and cover). Another exotic weed, *Egeria densa*, was also discovered during the delimitation survey; although this weed was limited to the upper wetland area and not recorded within the lake itself, like *E. canadensis, E. densa* can form dense mono-specific beds in shallow lakes and could potentially out-compete the native flora (de Winton et al. 2011).

E. canadensis and *E. densa* do not produce seeds, suggesting that, rather than arriving in the Lake Kohangatera catchment via waterfowl, their introduction is probably due to human mediated activities, such as a fragment attached to a boat or fishing equipment (de Winton et al. 2011). Given the high ecological values of the Parangarahu Lakes and the fact that further introduced weeds could potentially adversely affect these values, the occurrence of activities that could lead to the introduction of additional invasive aquatic weed species to the lakes, such as *Ceratophyllum demersum* and *Lagarosiphon major*, should be reviewed. Further LakeSPI assessments should also be undertaken at semi-regular (2 to 5-yearly) intervals in both lakes to keep track on the condition of the native vegetation and extent of exotic weeds. Wells et al. (2011) and de Winton et al. (2011) speculate that the potential threat from *E. canadensis* and *E. densa* might be limited as these species may not grow well under the moderately saline conditions of Lake Kohangatera. However, this will only be confirmed through on-going monitoring.

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[40] However, algal blooms have been recorded in Lake Kohangatera in the past (Gibbs 2002).

[41] Given the low level of modification within the catchments of both lakes, these ‘elevated’ concentrations may potentially represent natural levels. For example, while concentrations of total nitrogen were indicative of a supertrophic state in Lake Kohangatera, this nitrogen was largely present in an organic form and may be associated with natural dissolved organic matter in the lake.

7. Lake Pounui

This section outlines the characteristics and values of Lake Pounui and summarises the findings of a LakeSPI survey carried out on the lake in March 2011. Full details of this survey can be found in de Winton et al. (2011). Results from one-off water quality and phytoplankton sampling undertaken at the time of the survey are also presented.

7.1 Introduction

Lake Pounui is a small (~46 ha), moderately shallow (maximum depth 9.6 m), lowland coastal lake situated in the foothills of the Rimutaka Range in South Wairarapa. The lake was formed by a sedimentary obstruction of the valley (Lawless 1983) and is fed by two small streams draining into the north-western arm and one stream draining into the south-western arm of the lake. The lower reaches of these streams are ill-defined as they discharge into the swampy wetland margins of the lake (Jellyman 1990). The lake outflow is located on the eastern edge of the lake and drains into Battery/Pounui Stream which in turn flows into Pounui Lagoon and then into Lake Onoke (Figure 7.1).

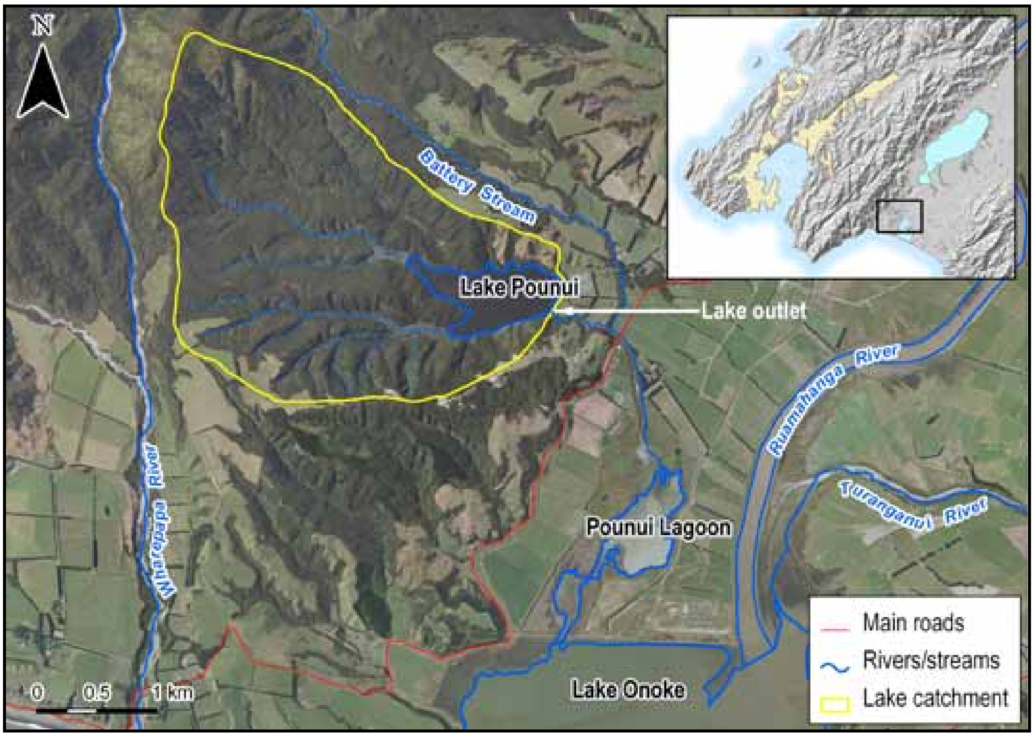

Figure 7.1: Lake Pounui and key features

Little is known about the current state of water quality in Lake Pounui; regular monitoring undertaken during the 1970s and early 1980s classified the lake as mesotrophic[42] or oligotrophic bordering a mesotrophic[43] state (Jellyman 1990, Lawless 1983). More recent one-off sampling undertaken in 2007 by Drake et al. (2011) has also indicated a mesotrophic state (TLI=3.5). In the last couple

[42] Based on a range of indicators assessed, including macrophyte community composition, primary production, presence of algal blooms, and chlorophyll *a* concentrations (Jellyman 1990).
[43] Based on chlorophyll *a* concentrations (Lawless 1983).

of years, anecdotal evidence has indicated an increased occurrence and persistence of algal blooms in the lake. A phytoplankton sample collected by Greater Wellington in 2009 confirmed the high abundance of a species of potentially toxic cyanobacteria.

7.1.1 Values

The almost completely unmodified state of Lake Pounui's catchment makes it relatively rare when compared to other lowland coastal lakes in New Zealand. The ecological values associated with the catchment's native vegetation are exceptionally high and the majority of the catchment is protected under a QEII open space covenant.

Lake Pounui is listed in Appendix 3 of Greater Wellington's existing RFP (WRC 1999) as a waterbody with nationally threatened fish recorded in its catchment and it is also listed in Greater Wellington's proposed RPS (GWRC 2010) as a lake with significant indigenous ecosystem values. Compared with other lakes and open water systems in the Wellington region, Lake Pounui is considered to have a high diversity of native fish species (Joy 2003), with a recent survey by McEwan (2010) identifying threatened species such as giant kokopu and a high abundance of longfin eels.

Lake Pounui is under private ownership and therefore access to it for contact recreation purposes is generally limited to the land owners.

7.1.2 Land cover

Lake Pounui's 627 ha catchment is dominated by unmodified indigenous forest with only a small amount of pastoral land cover present along the northern hill faces of the lake and the upper parts of the south-western side of the lake's catchment (Table 7.1 and refer Figure 7.1). This pastoral land was converted from manuka scrubland in early 1976 (Jellyman 1990).

Table 7.1: Area and percentage of major land cover and land use types in the Lake Pounui catchment, derived from aerial photographs taken in 2008
(Source: LUCAS – MfE 2010)

Land cover	Area (ha)	% of catchment
Indigenous forest	598.7	95.5
Pasture – high producing	8.5	1.3
Pasture – low producing	19.9	3.2
Total	627.2	100

7.1.3 Significant consented activities

There are no significant consented activities in the Lake Pounui catchment.

7.2 Monitoring protocol, sites and variables

A LakeSPI survey of Lake Pounui was undertaken by NIWA on 17 March 2011. Survey transects chosen to represent the lake vegetation are shown in Figure 7.2 (further details of survey site selection can be found in de Winton et al. 2011).

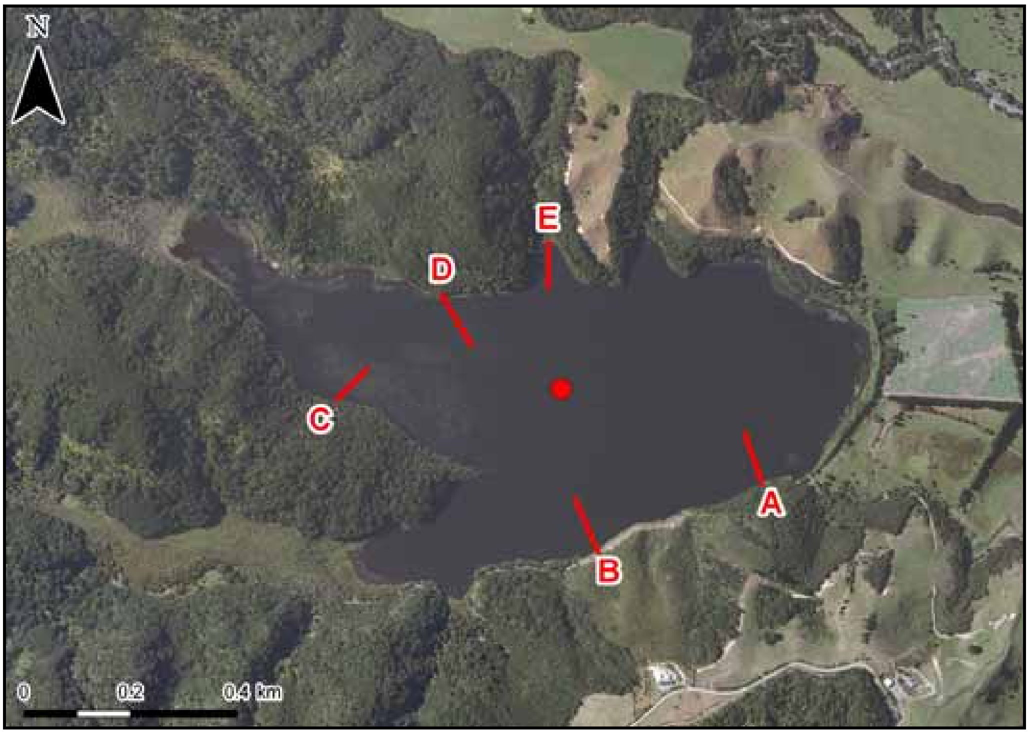

Figure 7.2: Location of the five LakeSPI survey transects (A to E) in Lake Pounui and the location where one-off water quality and phytoplankton samples were collected on 17 March 2011

At the time of the survey, one-off water samples were also collected from the lake's surface for a snapshot assessment of water quality from one site located at approximately the deepest part of the lake (Figure 7.2). Water quality was assessed by measuring a range of physico-chemical and biological variables: dissolved oxygen, water temperature, pH, conductivity, Secchi depth, turbidity, faecal indicator bacteria, dissolved and total nutrients, chlorophyll *a* and phytoplankton richness and abundance. Water temperature and dissolved oxygen measurements were also recorded at a series of depths to assess whether any stratification was present

Details of sampling and analytical methodology, along with the full list of variables monitored, are provided in Appendix 1.

7.3 LakeSPI findings

Lake Pounui was assessed as having an overall LakeSPI index score of 56% (Table 7.2) which places it in the 'high' category for ecological condition. Out of the 206 lakes across New Zealand that have been surveyed to date, Lake Pounui is ranked 66th (de Winton et al. 2011).

Table 7.2: Summary of LakeSPI results from a survey undertaken by de Winton et al. (2011) on 17 March 2011

LakeSPI index (%)	Native condition index (%)	Invasive impact index (%)
56	65	44

Lake vegetation was found to extend to moderate depths of 4.5 to 4.9 m and was relatively diverse, with all six key native community types present (eg, Figure 7.3). This resulted in a native condition index of 65%.

Two invasive weed species were recorded during the survey (*Potamogeton crispus* and *Elodea canadensis*) but were considered to have a relatively limited impact on the native vegetation present. This resulted in an invasive index score of 44%.

Comparisons of the current lake vegetation with descriptions from 1976 led de Winton et al. (2011) to conclude that lake vegetation has remained in a relatively stable state over the last 30 or 40 years.

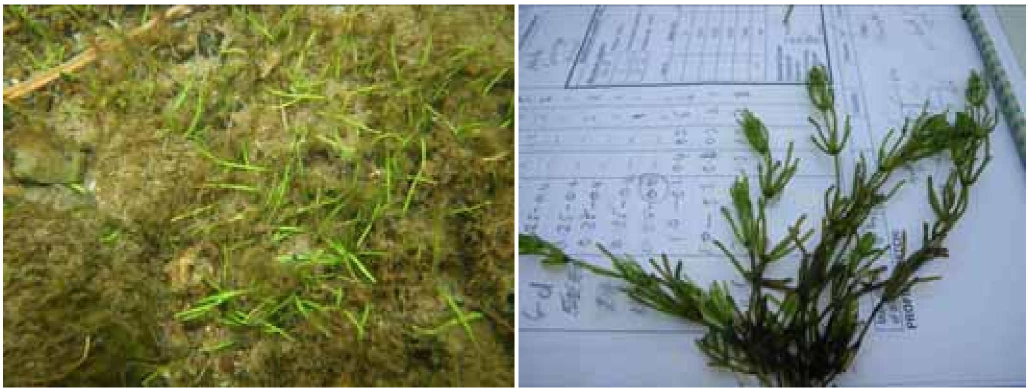

Figure 7.3: Examples of two of the six key LakeSPI native community types observed in Lake Pounui during the March 2011 LakeSPI survey; *Lilaeopsis novae-zelandiae* (left) which is a 'turf community' type and *Chara australis* which is a 'charophyte community' type.

7.4 Water quality and phytoplankton

A summary of water quality measurements from one-off sampling on 17 March 2011 is presented in Table 7.3. Extreme care must be taken when interpreting just one set of water quality results but based on trophic categories in Burns et al. (2000), the four TLI variables can be assigned into the following classes: total nitrogen and total phosphorus (eutrophic), chlorophyll *a* (supertrophic) and Secchi depth (mesotrophic). From this one sampling occasion an overall TLI score of 4.7 can be calculated, indicative of eutrophic conditions. Relative to national median values for lakes located in catchments dominated by indigenous forest land cover, concentrations of total nitrogen and total phosphorus from this one-off sampling event indicate that nutrients may be elevated in Lake Pounui.

Water temperature depth profiles showed that on this sampling occasion there was negligible difference between lake surface and lake bottom water temperatures, indicating the lake was well mixed (Figure 7.4). Dissolved oxygen depth profiles indicated an anoxic layer (<0.5 mg/L) occurring at a depth greater than around 7.5 m (Figure 7.3).

Table 7.3: Summary of water quality measurements and results from one-off sampling of Lake Pounui on 17 March 2011. National median values for lakes in catchments dominated by indigenous forest land cover are also presented (taken from Verburg et al. 2010).

Variable	National median values	Result
Water temperature (°C) (surface)	—	19.1
Dissolved oxygen (% saturation) (surface)	—	100.4
Dissolved oxygen (mg/L) (surface)	—	9.28
pH	7.5	8
Conductivity (µS/cm)	228	189
Secchi depth (m)	6.5	3.1
Turbidity (NTU)	0.8	1.37
Total suspended solids (mg/L)	—	<2
Total phosphorus (mg/L)	0.007	0.026
Dissolved reactive phosphorus (mg/L)	0.002	0.005
Total nitrogen (mg/L)	0.149	0.570
Nitrite-nitrate nitrogen (mg/L)	—	<0.002
Ammoniacal nitrogen (mg/L)	0.006	0.012
Total Kjeldahl nitrogen (mg/L)	—	0.570
Total organic carbon (mg/L)	—	6.8
Chlorophyll *a* (mg/m^3)	1.6	29
E. coli (cfu/100mL)	—	3

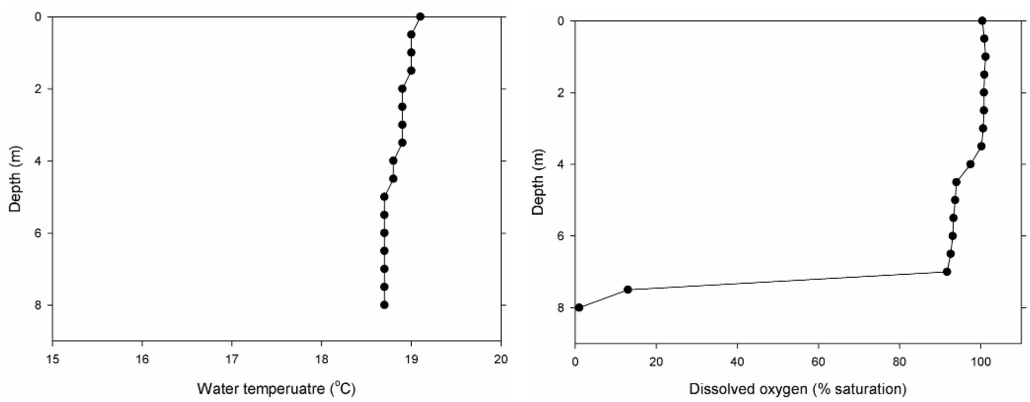

Figure 7.4: Lake Pounui depth profiles for water temperature (left) and dissolved oxygen (% saturation), based on measurements taken on 17 March 2011

Eleven phytoplankton taxa were identified in the one-off sample collected on 17 March 2011 (Table 7.4). One potentially toxic cyanobacteria species (*Anabaena* sp.) was identified as well as one species known to cause taste and odour problems (*Ceratium* sp.).

Application of the alert level framework outlined in the MfE/MoH (2009) interim national cyanobacteria guidelines for fresh water results in a biovolume[44] of 0.333 mm^3/L; this falls into the surveillance (green mode) of the framework, indicating that cyanobacteria taxa present in Lake Pounui in March 2011 posed a low health risk to recreational users.

[44] The species of *Anabaena* was not identified in this sample. However, phytoplankton analysis from samples collected in December 2009 recorded the presence of *Anabaena circinalis*. Therefore this species was used to calculate an indicative biovolume.

Table 7.4: Phytoplankton taxa identified in a one-off sample collected on 17 March 2011 from Lake Pounui. Unit and cell counts are also presented where available.

Taxa	Unit count (units/mL)	Cell count (cells/mL)
Anabaena sp.	15	1,600
Ceratium sp.	1	
Cryptomonas sp.	100	
Elakatothrix sp.	2	
Euglena sp.	300	
Monoraphidium spp.	37	
Nitzschia sp.	2	
Oocystis sp.	4	
Sphaerocystis sp.	47	
Staurastrum sp.	3	
Trachelomonas sp.	36	

7.5 Discussion

Based on the LakeSPI assessment undertaken in March 2011, the current ecological condition of Lake Pounui is 'high'. A range of native vegetation is present and appears to have remained in a relatively stable state over the last 40 or so years; this reflects the predominantly unmodified nature of the lake's catchment.

Further water quality sampling is required to adequately characterise the trophic state of the lake and whether water quality has deteriorated in recent years. The results from one-off water quality sampling in March 2011 are indicative of eutrophic conditions, placing Lake Pounui in a poorer trophic state than that calculated by Drake et al. (2011) from one-off sampling in 2007 (TLI =3.5, mesotrophic). Previous attempts to categorise the trophic status of Lake Pounui in the 1970s and 1980s using non-TLI methods have similarly placed water quality in the mesotrophic (Jellyman 1990) to oligotrophic/ mesotrophic range (Lawless 1983).

No thermal stratification was recorded during sampling in March 2011, which is generally consistent with regular measurements undertaken during the 1970s (Jellyman 1990[45]) and early 1980s (Lawless 1983). However, the lake bottom was found to be anoxic. Jellyman (1990) also recorded some deoxygenation occurring at the lake bottom (although not to the same extent) and suggested that, in the absence of thermal stratification, breakdown of the coloured dissolved organic matter present in the lake might be driving the anoxia. It is possible that breakdown from algal blooms in the lake may also be contributing to anoxia of the lake bottom.

The influence of bottom anoxia on Lake Pounui's water quality and ecology is not known but it is likely that anoxic conditions contribute to internal nutrient cycling and phytoplankton growth through the re-release of nutrients stored in the lakebed sediments. The concentration of chlorophyll *a* in March 2011 (29

[45] Jellyman (1990) did note some short-lived weak stratification events during periods of calm weather.

mg/m^3) was significantly higher than a number of measurements made by Lawless over 1980/81 (which ranged from 0.5 to 3.48 mg/m^3) and anecdotally there has been a significant increase in the occurrence and duration of algal blooms in Lake Pounui in recent years (Playle[46], pers. comm. 2011). This may indicate an increase in lake productivity, although further water quality and phytoplankton sampling is required before this can be confirmed.

[46] Steve Playle, Greater Wellington Biosecurity Officer in charge of pest animal trapping in the Lake Pounui catchment.

8. Discussion

This section revisits the main findings from monitoring and investigations presented in Sections 3 to 7 for Lakes Wairarapa, Onoke, Waitawa, Kohangapiripiri, Kohangatera and Pounui. The condition of these lakes is presented as a regional overview that is then placed in a national context. The principal impacts on lake condition are briefly discussed and monitoring limitations and knowledge gaps are outlined.

8.1 Regional overview

8.1.1 State

Water quality monitoring of Lakes Onoke, Wairarapa and Waitawa indicates that all three lakes are currently in a degraded state; concentrations of nutrients and chlorophyll *a* are typically elevated and water clarity is generally poor. Application of the Trophic Level Index (TLI, refer Section 2.2.1) classifies the three lakes as being supertrophic (ie, very high nutrient enrichment). In the terms of Lakes Wairarapa and Onoke, the TLI classification is largely driven by low water clarity and high concentrations of total phosphorus associated with high concentrations of suspended sediment. Given that trophic state is traditionally a measure of lake productivity, and that in both lakes concentrations of chlorophyll *a* are typically indicative of a better trophic state (as are concentrations of total nitrogen), it is probably more appropriate to classify these two lakes as eutrophic/supertrophic.

Re-suspension of lakebed sediments by wind appears to be a strong driver of water quality in both of these shallow lakes, particularly in Lake Wairarapa. Salinity (inferred from conductivity measurements) also influences some aspects of water quality in Lakes Wairarapa and Onoke. Water clarity generally was better and concentrations of total nitrogen, total phosphorus and chlorophyll *a* lower, at higher conductivity concentrations; this suggests that salinity has a ‘dilution’ effect on water quality in these lakes. Ruamahanga River flow also influenced water quality in Lake Onoke, with a deterioration of water quality typically occurring under high flow conditions.

Lake Waitawa has very poor water quality and, although natural dissolved organic matter has some influence on water clarity, it is considered that the TLI adequately characterises its condition; concentrations of both nutrients are elevated and support an elevated phytoplankton biomass that in turn reduces water clarity in the lake. Lake Waitawa has also been shown to stratify during late spring and summer which, during the 12-month period of monitoring, led to an extensive period of anoxia (deoxygenation) of the lake bottom waters. At times this anoxic layer occupied almost half the total lake depth and would likely be limiting the available habitat for sensitive aquatic organisms. Anoxic conditions at the lake bottom may also be leading to the release of nutrients, in particular soluble inorganic phosphorus and ammonia, from the lakebed sediments; this internal nutrient recycling may represent a significant nutrient source fuelling phytoplankton production at certain times of the year. Potentially toxic cyanobacteria species (in particular *Anabaena* species) dominated phytoplankton samples collected during the monitoring period and, based on biomass values outlined in the interim national cyanobacteria guidelines (MfE/MoH 2009), at times there is clearly a potentially high health risk to recreational users of the lake.

LakeSPI assessments carried out in Lakes Pounui, Kohangapiripiri and Kohangatera in March 2011 indicate that the ecological condition of these lakes is ‘high’ (Lakes Pounui and Kohangapiripiri) or ‘excellent’ (Lake Kohangatera). The six key native community types recognised by LakeSPI were recorded in all three lakes and Lakes Kohangapiripiri and Kohangatera had a diverse range of native vegetation extending across their lake beds. Lake Pounui also had a relatively diverse range of native vegetation and this extended to depths of around five metres. Examples of species considered to be rare, threatened or declining throughout New Zealand were recorded from all three lakes. One or two invasive species were also recorded in all three lakes including, for the first time, *Elodea canadensis* in Lake Kohangatera.

8.1.2 Trends

Only Lake Wairarapa had a data record of sufficient length to examine temporal trends in water quality and the sensitivity of the analysis to detect such trends is compromised by the current low sampling frequency. Analysis of the entire record available indicates that overall, Lake Wairarapa has remained in a relatively stable, yet poor, state since 1994. Several trends showing marginal improvements in some aspects of water quality (eg, water clarity) were present although these are probably of little consequence to the lake ecosystem (ie, they have not resulted in a change in trophic state) and may simply be an artefact of weather conditions at the time of sampling. The observed increasing trend in conductivity may also be related to conditions at the time of sampling (eg, back-flow of saline water from Lake Onoke); this requires further investigation.

No conclusive trend information is available for any of the other five lakes monitored. However, based on the literature:

- It is possible that some aspects of water quality may have declined in Lake Pounui (supported by anecdotal evidence of increased occurrence of algal blooms in recent years) but aquatic vegetation in the lake appears to have remained in a relatively stable state over the last 40 years; and

- Aquatic vegetation in Lakes Kohangapiripiri and Kohangatera has remained in a relatively stable state since surveys were last undertaken seven years ago – despite the recording in March 2011 of new invasive weed species in the Lake Kohangatera catchment.

8.2 National context

Based on a recent national report (Verburg et al. 2010), water quality in Lakes Onoke, Wairarapa and Waitawa ranks in a poorer than average condition compared to other lakes in New Zealand, including lakes that are similarly located in predominantly pastoral catchments (Figure 8.1). Lake Waitawa compares particularly unfavourably, with all four TLI variables (total phosphorus, total nitrogen, chlorophyll *a*, and Secchi depth) yielding values poorer than their respective national medians for lakes in pastoral catchments.[47]

For Lakes Onoke and Wairarapa, Secchi depth values indicated far poorer water clarity than the national median for lakes in pastoral catchments; as did total phosphorus in Lake Wairarapa. In contrast, concentrations of total nitrogen and chlorophyll *a* in both lakes compare quite favourably, yielding better values than their respective national medians.

The national overview of lake condition presented in Verburg et al. (2010) incorporates a wide variety of lake types, including large deep lakes which tend to be over-represented in New Zealand lake monitoring programmes (Sorrell 2006). Shallow coastal lakes differ in many fundamental ways from large deep lakes and may naturally be more productive ecosystems (ie, have poorer TLI scores). This is reflected in a nationwide assessment of 45 shallow coastal lakes by Drake et al. (2011) where the average condition across 45 lakes was mesotrophic/eutrophic (compared with an average of mesotrophic in Verburg et al. (2010) if no consideration is given to catchment land cover). While this average trophic state was generated from only a single water quality sampling event per lake, it does add further support that Lakes Waitawa, Wairarapa and Onoke are in a poorer condition than other similar lake types across New Zealand. In the case of Lakes Wairarapa and Onoke, which are especially shallow and exposed, it is clear that re-suspension of lake-

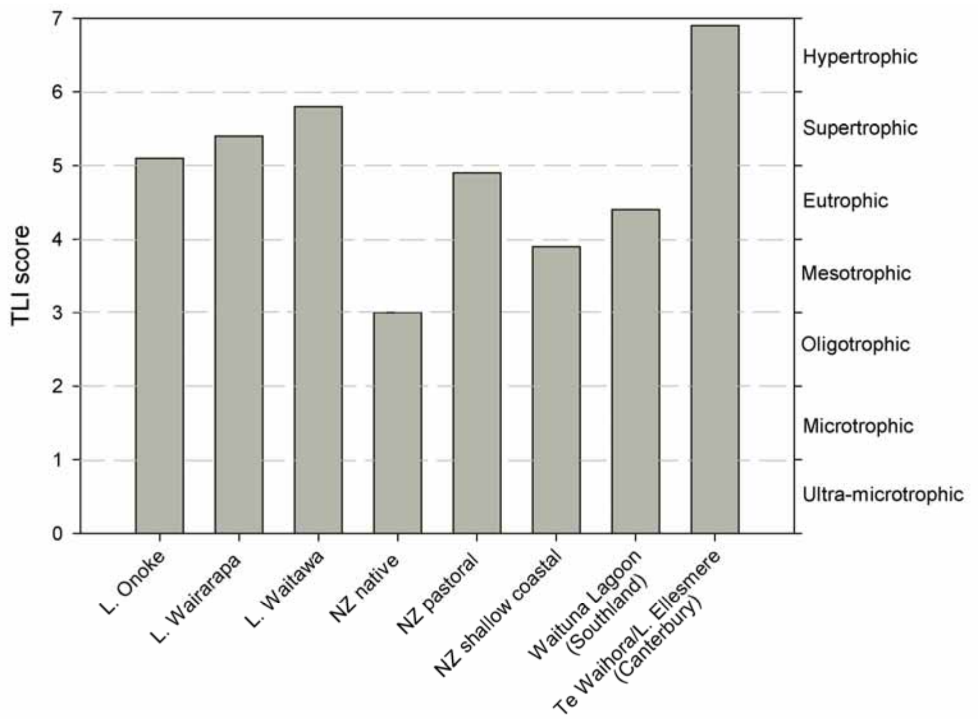

Figure 8.1: TLI scores calculated for Lakes Onoke, Wairarapa and Waitawa (this report). For comparison the national median scores for lakes in catchments dominated by native or pastoral land cover (Verburg et al. 2010) and the median TLI score of 45 shallow coastal lakes (Drake et al. 2011) are also shown, along with TLI scores for two large shallow coastal lakes from other regions (from Verburg et al. 2010).

[47] In addition, only seven of the 63 lakes assessed by Verburg et al. (2010) showed similar levels of oxygen depletion to that observed in Lake Waitawa and these lakes were typically deeper.

bed sediments drives lower water clarity and higher concentrations of total phosphorus in these lakes. For this reason, these lakes may be more appropriately classified as eutrophic/supertrophic.

Based on the LakeSPI surveys summarised in this report, the ecological condition of Lakes Kohangapiripiri and Pounui is 'high' and the condition of Lake Kohangatera is 'excellent', indicating that all three lakes are in better than the average ('moderate') condition reported for New Zealand lakes in Verburg et al. (2010). In a direct comparison of the LakeSPI scores from these three lakes against 206 other New Zealand lakes assessed using this methodology to date, de Winton et al. (2011) ranked Lake Kohangatera as the 10th best lake nationally, while Lakes Kohangapiripiri and Pounui were ranked 47th and 66th respectively (Figure 8.2). Overall, the high LakeSPI scores for the Parangarahu Lakes led de Winton et al. (2011) to consider them to be nationally outstanding examples of lowland lake/lagoon systems; equivalent vegetation values in coastal lakes/lagoons are becoming increasing rare due to widespread impacts on shallow coastal lakes associated with land use intensification.

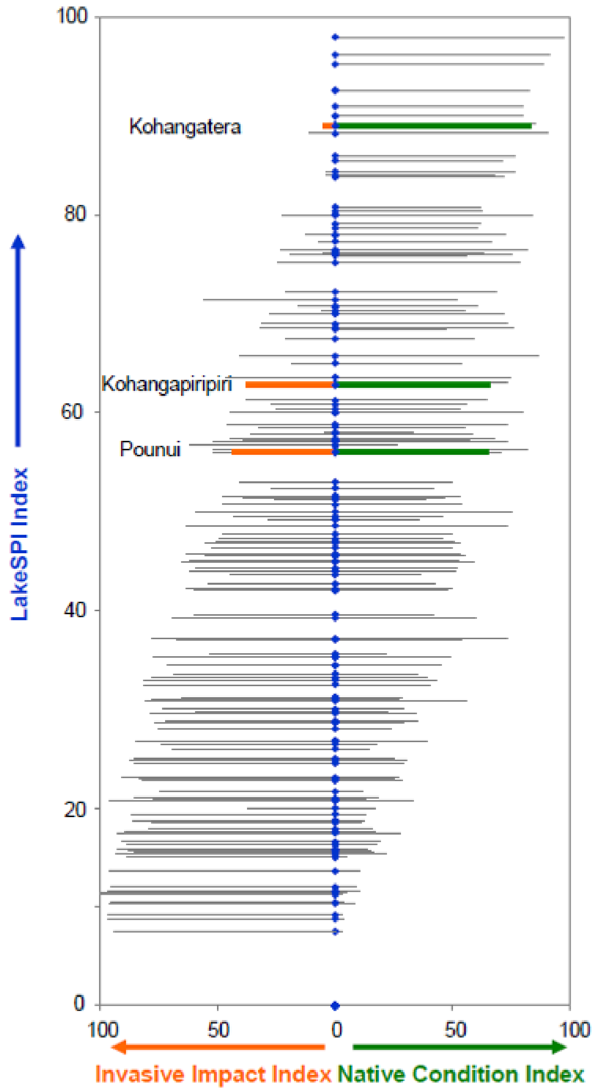

Figure 8.2: LakeSPI scores for 206 New Zealand lakes as at April 2011 (taken from de Winton et al. (2011)), with Lakes Kohangapiripiri, Kohangatera and Pounui indicated
Key: LakeSPI Index (blue dots), Native Condition Index (right hand bars), and Invasive Impact Score (left hand bars).

8.3 Managing lake condition

It is clear from the findings in Sections 3, 4 and 5, that managing the water quality and ecological condition of Lakes Onoke, Wairarapa and Waitawa will require careful management of existing and potential future land use practices within their catchments. This is particularly the case for Lakes Wairarapa and Onoke which are situated in relatively large catchments that have already undergone significant land use intensification in recent decades. The evidence for this intensification is reflected in the increasing amount of water allocated from rivers and groundwater in the Wairarapa for irrigation. For example, Keenan et al. (2012) report that of the four-fold increase in regional water allocation for irrigation between 1990 and 2010 (from around 37 million m^3/year to nearly 148 million m^3/year), 83% of that occurred in the Wairarapa, of which the large majority (72%) was for irrigation of dairy pasture. This increase in dairy irrigation has, in turn, translated to an increase in dairy intensification. For example, Livestock Improvement Corporation data indicate that between 2002 and 2010 the average dairy herd size in Wellington region increased 33%, from 299 cows to 399 cows, with the stocking rate in South Wairarapa increasing from around 2.5 to 2.9 cows per hectare (Sorensen 2012).

Further intensification is likely in at least some parts of the Wairarapa and will require careful management to avoid further degradation of water quality and ecosystem health in Lakes Wairarapa and Onoke. Similarly, intensification of land use in Lake Waitawa's catchment may further degrade water quality in this lake. Although quantifiable information is lacking on the relative inputs of nutrient and sediment to these lakes – including relative to historic inputs that are internally recycled from the lakebed – there are still a number of specific actions that could be taken to reduce existing land use impacts on lake water quality. Immediate measures should focus on:

- Removal of point source wastewater discharges such as that from the Featherston WWTP to Lake Wairarapa;
- Excluding stock from the lake (and associated wetland) margins, as well as from rivers, streams and drains that discharge into the lakes;
- Active and comprehensive on-farm nutrient budgeting to minimise nutrient loss/export from farmland activities such as stock grazing, and effluent and fertiliser application;
- Ensuring adequate storage is in place to minimise the application of dairyshed effluent to land in conditions which promote rapid leaching or runoff (eg, when soils are waterlogged). For example, as at the end of 2010, only around 40% of the 175-odd dairy farms in the Wairarapa Valley had some capacity for wet weather effluent storage (although Greater Wellington and DairyNZ have been working with dairy farmers to address this through the development of pond sizing guidelines) (S. Orr[48], pers. comm. 2012);

[48] Stephen Orr, Resource Officer, Greater Wellington.

- A re-evaluation of existing drainage techniques in the Lake Wairarapa catchment, including investigations to quantify and reduce the nutrient and sediment loads in the drainage water prior to release to the lake or its tributaries (eg, wetland treatment); and

- Increased riparian planting around lake margins and along tributary watercourses.

A review of the current management of water levels in Lakes Wairarapa and Onoke may also be required. Monitoring data presented in this report suggest that saline water (as indicated by higher conductivity measurements) has a positive effect on water quality in both lakes. However, current practice – to aid in the re-opening of the Lake Onoke mouth – is to close the Lake Wairarapa barrage gates when the mouth blocks, thus likely limiting the amount of saline water that can flow back into Lake Wairarapa and any associated improvements in water quality. While potential improvements in water quality may be seen as desirable, saline inputs may have some undesirable affects on aquatic ecosystems. For example, Schallenberg and Burns (2003) showed that saline inputs in Lakes Waihola and Waipori (Otago were a significant driver of zooplankton community dynamics, with a loss of some species occurring with only relatively small increases in salinity. Consequently a review of lake level management would need to assess the implications of increased movement of saline water into Lake Wairarapa not only in terms of water quality, but across all ecosystem components and also water users (ie, water takes for irrigation).

In contrast with Lakes Onoke, Wairarapa and Waitawa, Lakes Kohangapiripiri, Kohangatera and Pounui are located in catchments that are largely unmodified and still dominated by indigenous forest land cover. From the limited water quality data available, these lakes do not appear to be exposed to significant nutrient enrichment and habitat degradation that typifies lakes in highly modified catchments. However, the introduction of additional aquatic weed species – or a change in water quality conditions that allows the weed species currently found in these lakes to proliferate – remains a significant threat to the high ecological values of all three lakes. The new records of *Elodea canadensis* in Lake Kohangatera and *Egeria densa* in its upstream catchment highlight this risk; both of these species can potentially form vast, dense mono-specific beds that could smother and out-compete indigenous vegetation, significantly reducing the high native vegetation values of the lake system. Given that de Winton et al. (2011) have attributed the introduction of these weeds to human-mediated activities, such as a fragment attached to a boat or fishing equipment, a review is needed of existing recreational activities that could lead to the introduction of additional invasive aquatic weed species to this lake, and into Lakes Kohangapiripiri and Pounui.

As with introduced plants, introduced fish species can also have significant negative impacts on lake ecosystems and, in some cases, water quality. Although Greater Wellington does not undertake any regular fish monitoring in any lakes, several introduced species (eg, brown trout, perch and rudd) are widespread in the Wellington region and commonly found in Lakes Onoke, Pounui, Wairarapa and Waitawa (Hicks 1993; Hicks et al. 2006; McEwan

2009; Cahill et al. 2010; McEwan 2010). While the effects of such fish species on these lakes systems have not been quantified, at a minimum their presence is expected to have a negative impact on ecosystem health (ie, they are often numerically dominant and some are known to reduce populations of native fish (Rowe & Graynoth 2002)); as would the introduction of any additional exotic species that are not currently present (eg, brown bullhead catfish, gambusia and koi carp).

8.4 Monitoring limitations and knowledge gaps

A significant amount of knowledge has been gained about the Parangarahu Lakes and Lakes Onoke, Pounui, Wairarapa and Waitawa as a result of the monitoring and investigations documented in this report. However, there are also a number of limitations and knowledge gaps evident and a thorough review of Greater Wellington's existing lake monitoring programme is required. The main limitations and knowledge gaps associated with monitoring and investigations to date are outlined below.

- Lake Wairarapa is currently only monitored three or four times per year. As outlined in Section 3.4.3, this monitoring frequency is insufficient to characterise seasonal trends and reduces the ability to detect meaningful changes in water quality over an appropriate timeframe for SoE reporting and management response (five years).

- There is a lack of information around water quality linkages between Lake Wairarapa and Lake Onoke, specifically the conditions required for backflow events of saline water into Lake Wairarapa (from Lake Onoke) to occur, how often this happens, and to what it extent this may be influencing lake water quality and ecology. Deployment of continuous water quality instruments would help further our understanding of these linkages; measurements of both conductivity and turbidity would also assist with future reporting of lake condition by enabling the effects of weather (ie, wind) and salinity on water quality to be better accounted for in TLI calculations.

- Only one site in Lake Onoke has been sampled regularly and results from this site – which is located near the path of the Ruamahanga River inflow – are not necessarily representative of the lake as a whole.

- There is no regular monitoring of basic biological information (eg, phytoplankton species and fish populations) in Lake Onoke or Lake Wairarapa. Regular phytoplankton monitoring (species identification and cell counts) would help improve our understanding of phytoplankton population dynamics, in particular the occurrence of potentially toxic cyanobacteria blooms in these lakes.

- There is a lack of water quality monitoring data for some lakes, notably Lake Pounui in which water quality may be deteriorating.

- To date, all water samples from lakes have been collected using the sub-surface grab method (Appendix 1); this differs from protocols outlined in

Burns et al. (2000) for the sampling of isothermal lakes. Given that Lake Waitawa was found to stratify during some months of the year, a more appropriate sampling technique might be required for any future monitoring of this lake.

- To date, the analytical detection limits achieved for determining concentrations of chlorophyll *a* have been highly variable, and often very coarse. This has limited our interpretation of the chlorophyll *a* data sets for Lakes Onoke and Wairarapa. Furthermore, concentrations of chlorophyll *a* have not been corrected for phaeopigments in these two shallow lakes. This means that the reported concentrations may include a component of dead phytoplankton that has been re-suspended from lakebed sediments.

- There is limited quantifiable information on the relative contributions of different nutrient sources into each lake (including the relative contribution from internal nutrient cycling), although Greater Wellington has recently commenced preliminary investigations into a water and nutrient balance for Lake Wairarapa. Such a balance is considered critical for identifying and addressing the major nutrient pathways.

- The impacts of some consented activities on some lakes are poorly understood, in particular the nutrient contribution from the Forest Lakes Camp and Conference Centre wastewater on Lake Waitawa and the effects of the barrage gate operation on the backflow of saline water from Lake Onoke into Lake Wairarapa.

9. Conclusions

The six lakes featured in this report can all be classified as shallow, coastal lowland lakes. They range from being located in highly modified catchments dominated by pastoral land use through to minimally modified catchments dominated by indigenous forest and scrub. Subsequently, the state of these lakes – assessed in terms of water quality and aquatic vegetation values – ranges from being severely degraded to nationally outstanding examples of New Zealand lowland lakes systems.

Based on regular water quality monitoring, Lakes Wairarapa, Onoke and Waitawa can all be considered to be in a degraded state with typically elevated concentrations of nutrients and phytoplankton biomass, and poor water clarity. Application of the TLI results in all three lakes being classed as supertrophic. However, TLI scores for both Lakes Wairarapa and Onoke are significantly influenced by re-suspension of lakebed sediments (which influences Secchi depth and total phosphorus) and potentially both lakes would be more appropriately classified as eutrophic/supertrophic. Comparison of the TLI scores with those from other lakes across New Zealand indicates that all three lakes are typically in a poorer state than other similar lake types. Lake Waitawa has particularly poor water quality and on several occasions recorded concentrations of potentially toxic cyanobacteria above guideline levels for recreational use. Lake Waitawa was also stratified for a significant part of the year and this resulted in the lake bottom becoming anoxic for several months.

Only Lake Wairarapa had a water quality data record of sufficient length to examine temporal trends; analysis indicates that overall this lake has remained in a relatively stable, yet poor, state since 1994.

Based on LakeSPI assessments undertaken in March 2011, Lakes Pounui and Kohangapiripiri can be classified as having ‘high’ ecological values and Lake Kohangatera as having ‘excellent’ ecological values. All three lakes support higher than average ecological values when compared to other lakes across New Zealand, with the Parangarahu Lakes considered an outstanding national example of lowland lake systems. Despite the new occurrence of invasive plants species in Lake Kohangatera, the aquatic vegetation values of all three lakes appear to have remained relatively stable.

Water quality in Lakes Wairarapa, Onoke and Waitawa is affected by the large component of agricultural land use in their catchments; this includes intensive farming around much of the margins of all three lakes. These lakes also receive inputs from urban land use and, indirectly, discharges of treated municipal wastewater. As yet, the relative contributions from external sources of nutrients are not well understood in any of these lakes. Similarly, the role of internal nutrient cycling – a potentially significant factor for all three lakes – has not been quantified. Investigations into nutrient inputs is a high priority, particularly for Lakes Wairarapa and Onoke given that further land use intensification is expected in the Wairarapa Valley.

In contrast with Lakes Wairarapa, Onoke and Waitawa, Lakes Kohangapiripiri, Kohangatera and Pounui are located in catchments that are still dominated by indigenous forest land cover. Introduction of invasive aquatic weeds is the principal ongoing threat to the high ecological values of these lakes.

Greater Wellington's lake monitoring programmes and investigations summarised within this report have greatly improved our knowledge of lakes in the region. However, a number of limitations and knowledge gaps exist and there is a need to review the existing lake monitoring programme to address these.

9.1 Recommendations

1. Review Greater Wellington's existing lake monitoring programme, giving priority to:
    - Continuing routine monitoring of physico-chemical water quality in Lakes Wairarapa and Onoke, with a review of site representativeness, an increase in sampling frequency to monthly, collection of phytoplankton samples for taxonomic identification and cell counts, and investigation of deployment of continuous water quality (conductivity and turbidity) instrumentation;
    - Commencing monthly monitoring, for an initial 12-month period, of physico-chemical water quality and phytoplankton composition and abundance in Lake Pounui;
    - Checking the appropriateness of existing lake water sampling methods;
    - Seeking improved consistency in the analysis (including analytical detection limits) of lake water samples for chlorophyll *a*;
    - Conducting a LakeSPI survey and implementing 5-yearly year-long assessments of water quality in Lake Waitawa;
    - Repeating LakeSPI surveys at regular (2 to 5-yearly) intervals in Lakes Kohangapiripiri, Kohangatera and Pounui as recommended by de Winton et al. (2011); and
    - Assessing fish monitoring requirements, including surveys to assess the presence and extent of pest species.
2. Investigate the water and nutrient balance of Lake Wairarapa to aid in the determination of primary nutrient sources (both from within the catchment and internally from the lakebed), and the frequency and extent of the movement of saline water from Lake Onoke into Lake Wairarapa.
3. Consider using 'deweathered' water quality data and accounting for salinity in future analysis of the trophic state of Lakes Wairarapa and Onoke.
4. Take into account the findings of this report in the review of Greater Wellington's existing regional plans, particularly the need to:
    - Address issues around stock access to lake, wetland and stream margins;

- Promote nutrient budgeting to minimise nutrient loss/export from farmland in the lake catchments;
- Ensure adequate storage is in place to minimise the application of dairyshed effluent to land in unsuitable soil and weather conditions;
- Discourage the continuation of point source wastewater discharges to surface water;
- Promote increased riparian planting around lake margins and along tributary watercourses; and
- Prevent recreational activities in the Parangarahu Lakes catchments that have the potential to introduce or spread invasive pest plant or animal species.

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Acknowledgements

Many people have been involved with the collection of lake water quality data over the years and numerous people have provided valuable contributions/insights/ discussions/reviews of various aspects of this report (eg, historical background, interpretation of results, etc.). In particular we would like to thank –

Within Greater Wellington:

- Brett Cockeram, Wendy Purdon, Ed Lee and Joanna McVeagh who have been the key staff involved with the collection of lake water quality samples in recent years;
- The Harbours Department – in recent years particularly Grant Nalder and John Tattersall, for the early morning starts and enabling us to safely sample Lake Wairarapa;
- Des Peterson for his help in navigating Lake Onoke and the collection of the initial water quality samples;
- Ted Taylor, Ian Gunn, Philippa Crisp and Gareth Cooper for reviewing aspects of this report;
- Shyam Morar and Brett Cockeram for help with GIS maps. Shyam also compiled the resource consent information; and
- Owen Spearpoint for helping to organise LakeSPI surveys of the Parangarahu Lakes.

Outside of Greater Wellington:

- Staff from Forest Lakes Camp and Conference Centre for access to Lake Waitawa and assisting with boating and water quality sampling;
- Landowner of Lake Pounui for access to the lake;
- Keith Hamill (OPUS Consultants) for reviewing early draft versions of this report and aspects of later drafts; and
- Dr Marc Schallenberg for reviewing selected sections of this report.

Appendix 1: Sampling sites, and sampling and analytical methods

Coordinates (in both NZ Map Grid and NZ Trans Mercator format) for Greater Wellington's lake sampling sites are presented in Table A1.1. Note that the coordinates for the first samples collected from Lake Onoke (Site 1 & 2 1st sample) differ slightly from the sites sampled on this lake thereafter. Coordinates presented for sampling sites on Lakes Kohangapiripiri, Kohangatera and Pounui indicate the water quality sampling sites. Locations of LakeSPI transects are presented in Figures 6.2 and 7.2 for the Parangarahu Lakes and Lake Pounui, respectively.

Table A1.1: Greater Wellington's lake sampling site locations

Lake	Site	NZMG		NZTM	
		Easting	Northing	Easting	Northing
Lake Wairarapa	1	2703076	5438917.3	1793054.6	6000636
	2	2701666	5439152.6	1791644.6	6000871
	3	2697289	5432687.1	1787266.3	5994405
	4	2695198	5435526.5	1785175.8	5997244
Lake Onoke	1	2688855	5417842.7	1778829.6	5979559
	2	2686270	5416572.2	1776244.5	5978288
	Site 1 (1st sample)	2689145	5416918.6	1779119.4	5978635
	Site 2 (1st sample)	2687245	5416209.0	1777219.4	5977925
Lake Waitawa	1	2693091	5489539.0	1783073.9	6051253
	2	2693591	5489607.0	1783573.9	6051321
Lake Kohangapiripiri	—	2666156	5418561.6	1756132.2	5980274
Lake Kohangatera	—	2665314	5419347.7	1755290.5	5981060
Lake Pounui	—	2686807	5420844.3	1776782.8	5982560

All sampling sites are accessed by boat, except in the case of Lake Onoke, where, after the first samples were collected in August 2009, all sampling was carried out by wading from the lake edge. Water and periphyton samples are collected in accordance with the sub-surface grab method for sampling isothermal lakes described in Smith et al. (1989) and in the case of Lake Onoke, a 'grabber pole' is used to collect water samples in an effort to minimise the potential effects of re-suspension of lakebed sediments (caused by wading) on the samples.

Laboratory analytical methods used in the analysis of all lake water samples are outlined in Table A1.2, except in the case of water samples collected from Lake Wairarapa prior to August 2007 (see Table A1.3). Water samples for dissolved nutrient analysis are filtered in the laboratory. Field measurements (conductivity, dissolved oxygen, pH and temperature) were taken using either a YSI 556, Hach HQ40d or a WTW 350i field meter, with the field meter calibrated on the day of sampling. Secchi disc measurement methodology is consistent with the procedure outlined in Burns et al. (2000) except that an underwater viewer is not used. Note that all field measurements collected from Lake Onoke are made from a 'wading position', although care is taken to minimise any disturbance of lakebed sediments (ie, if the lakebed is disturbed the water is given sufficient time to clear before measurements are recorded).

Table A1.2: Laboratory analytical methods (RJ Hill Laboratories) for water samples collected from all lakes except Lake Wairarapa prior to August 2007 (see Table A1.3)

Variable	Method	Detection limit
pH (lab)	pH meter APHA 4500-H+ B 21st ed. 2005.	0.1 pH units
Electrical conductivity	Conductivity meter, 25°C APHA 2510 B 21sted. 2005.	0.1 mS/m / 1 µS/cm
Turbidity	Analysis using a Hach 2100N, Turbidity meter. APHA 2130 B 21st ed. 2005.	—
Total suspended solids	Gravimetric. APHA 2540 D 21st ed. 2005.	2 mg/L
Volatile suspended solids*	Filtration (GF/C, 1.2 µm). Ashing 550°C, 30 min. Gravimetric. APHA 2540 E 21st ed. 2005.	2 mg/L
Ammoniacal nitrogen	Filtered sample. Phenol/hypochlorite colorimetry. Discrete Analyser. (NH_4-N = NH_4+-N + NH_3-N) APHA 4500-NH_3 F (modified from manual analysis) 21st ed. 2005.	0.01 mg/L
Total Kjeldahl nitrogen	Kjeldahl digestion, phenol/hyperclorite colorimetry (Discrete Analysis). APHA 4500-Norg C. (modified) 4500- F (modified) 21st ed. 2005	0.1 mg/L
Nitrate-N + Nitrite-N (NNN)	Total oxidised nitrogen. Automated cadmium reduction, Flow injection analyser. APHA 4500-NO3 - I (modified) 21st ed. 2005.	0.002 mg/L
Nitrate-N	Calculation: (Nitrate-N + Nitrite-N) - Nitrite-N.	0.002 mg/L
Nitrite-N	Automated Azo dye colorimetry, Flow injection analyser. APHA 4500-NO3 - I (modified) 21st ed. 2005.	0.002 mg/L
Dissolved inorganic nitrogen (DIN)	Calculation: NH_4-N + NO_3-N + NO_2-N.	—
Total nitrogen	Calculation: TKN + Nitrate-N +Nitrite-N.	0.1 mg/L
Dissolved reactive phosphorus	Filtered sample. Molybdenum blue colorimetry. Discrete Analyser. APHA 4500-P E (modified from manual analysis) 21st ed. 2005.	0.004 mg/L
Total phosphorus	Total Phosphorus digestion, ascorbic acid colorimetry. Discrete Analyser. APHA 4500-P E (modified from manual analysis) 21st ed. 2005.	0.004 mg/L
E. coli *	APHA 21st Ed. Method 9222 G.	1 cfu/100mL
Faecal coliforms*	Membrane Filtration, Count on mFC agar, Incubated at 44.5°C for 22 hours. APHA 9222 D, 21st ed. 2005.	1 cfu/100mL
Carbonaceous Biochemical Oxygen Demand ($cBOD_5$)	Incubation 5 days, DO meter, nitrification inhibitor added, dilutions, seeded. APHA 5210 B 21st ed. 2005.	1.0g.O_2/m^3
Chlorophyll *a**	Acetone extraction. Spectroscopy. APHA 10200 H 21st ed. 2005.	0.003 mg/L

*Note the detection limit for these variables was not always achieved (ie, was often higher than indicated here). Chlorophylla *a* was not corrected for phaeopigments.

Table A1.3: Laboratory analytical methods for water samples collected from Lake Wairarapa prior to August 2007. All analyses were undertaken by Wairarapa Laboratory services except in the case of chlorophyll *a* (performed by Greater Wellington's in-house laboratory).

Variable	Date commenced	Method	Detection limit
pH (lab)	Jun-1994	APHA Standard Methods 1998, (20th Edition) 4500-H+, B Electrometric Method	
Electrical conductivity (lab)	Jun-1994	APHA Standard Methods 1998, (20th Edition) 2500 B, Conductivity Meter.	
Total suspended solids	Jul-1995	Gravimetric. APHA 2540 D 21st ed. 2005.	
Volatile suspended solids	Jul-1995	APHA Standard Methods 1998, (20th Edition) 2540 E, Fixed and Volatile Solids Ignited at 550°C.	1 mg/L
Ammoniacal nitrogen	Nov-1998	APHA Standard Methods 1998, (20th Edition) 4500-NH_3, F, Phenate Method.	0.005 mg/L
Nitrate-N	Nov-1998	Pearson, Cadmium Reduction Method Nitrite Finish.	0.002 mg/L
Nitrite-N	Nov-1998	APHA Standard Methods 1998, (20th Edition) 4500-NO2, B, Azo Dye Colourimetry.	0.002 mg/L
Total nitrogen	Jun-1994	Koroleff, Alakaline Persulphate Oxidation Method followed by Cadmium Reduction, Nitrite finish.	
Dissolved reactive phosphorus	Nov-1998	APHA Standard Methods 1998, (20th Edition) 4500-P, B & E Ascorbic Acid Method.	0.003 mg/L
Total phosphorus	Jun-1994	APHA Standard Methods 1998, (20th Edition) 4500-P, B & E Ascorbic Acid Finish Following Acid/Persulphate digestion.	
*E. coli**	Jan-2002	APHA Standard Methods 1998, (20th Edition) 9213 D, Membrane Filter on mTEC Agar Urea Substrate.	1 cfu/100 mL
Faecal coliforms*	Apr-1997	APHA Standard Methods 1998, (20th Edition) 9222 D, Membrane Filter on mTEC Agar Urea Substrate.	1 cfu/100mL
Carbonaceous Biochemical Oxygen Demand (cBOD5)	Nov-1998	APHA Standard Methods 1998, (20th Edition) 5210 B, 5-day BOD test.	0.1 $g.O_2/m^3$
Chlorophyll *a**	Jun-1994	APHA 20th Edition 10200 H.	0.001 mg/L

*Note the detection limit for these variables was not always achieved (ie, was often higher than indicated here).

Appendix 2: Supplementary water quality results and statistical test outputs

A comparison of selected water quality variables for the two sampling sites located on Lake Onoke (Sites 1 and 2), for the three occasions when Site 2 was sampled (August 2009, November 2009 and January 2010), is provided in Table A2.1. Summary statistics for Pearson Product Correlations between each of Lake Wairarapa's four sampling sites are presented in Table A2.2 and full temporal trend analysis results for Lake Wairarapa are presented in Tables A2.3 though A2.8.

Table A2.1: Comparison of selected variables from the two sampling sites located on Lake Onoke (Sites 1 and 2), based on sampling undertaken in August 2009, November 2009 and January 2010

Variable	Sampling date	Site 1	Site 2
Total suspended solids (mg/L)	Aug-2009	13	57
	Nov-2009	19	18
	Jan-2010	73	210
Conductivity (S/cm)	Aug-2009	3,000	45,500
	Nov-2009	5,621	8,014
	Jan-2010	256	335
Total nitrogen (mg/L)	Aug-2009	0.93	<0.210
	Nov-2009	0.36	0.28
	Jan-2010	0.78	1.1
Total phosphorus (mg/L)	Aug-2009	0.056	0.073
	Nov-2009	0.024	0.022
	Jan-2010	0.13	0.31
Secchi depth (m)	Aug-2009	0.5	>0.380*
	Nov-2009	0.515	0.53
	Jan-2010	0.185	0.055
Chlorophyll *a* (mg/m^3)	Aug-2009	<3.00	<3.00
	Nov-2009	17	6.2
	Jan-2010	<7.00	<4.00

*Secchi disc visible on lake bottom.

Table A2.2: Results (*p*-values) from Pearson Product Correlations undertaken between sites for all variables. Numbers in brackets denote *n* and values in bold indicate results that were not significant.

Total nitrogen (45)	Site 2	Site 3	Site 4	Total phosphorus (45)	Site 2	Site 3	Site 4
Site 1	0.000	0.000	0.000	Site 1	0.000	0.000	0.000
Site 2	—	0.000	0.000	Site 2	—	0.000	0.000
Site 3	—	—	0.000	Site 3	—	—	0.000
Secchi depth (45)	Site 2	Site 3	Site 4	Chlorophyll a (45)	Site 2	Site 3	Site 4
Site 1	0.000	0.000	0.000	Site 1	0.000	0.000	0.000
Site 2	—	0.000	0.000	Site 2	—	0.000	0.000
Site 3	—	—	0.000	Site 3	—	—	0.000
Conductivity (45)	Site 2	Site 3	Site 4	Turbidity (45)	Site 2	Site 3	Site 4
Site 1	0.000	0.000	0.000	Site 1	0.000	0.000	0.000
Site 2	—	0.000	0.000	Site 2	—	0.000	0.000
Site 3	—	—	0.000	Site 3	—	—	0.000
pH (45)	Site 2	Site 3	Site 4	BOD (35)	Site 2	Site 3	Site 4
Site 1	0.000	0.000	0.000	Site 1	0.000	0.000	0.000
Site 2	—	0.000	0.000	Site 2	—	0.000	0.000
Site 3	—	—	0.000	Site 3	—	—	0.000
Dissolved oxygen % (39)	Site 2	Site 3	Site 4	Temperature (41)	Site 2	Site 3	Site 4
Site 1	0.000	0.000	0.000	Site 1	0.000	0.000	0.000
Site 2	—	0.000	0.000	Site 2	—	0.000	0.000
Site 3	—	—	0.000	Site 3	—	—	0.000
Ammoniacal nitrogen (35)	Site 2	Site 3	Site 4	Nitrate (35)	Site 2	Site 3	Site 4
Site 1	0.000	0.027	0.000	Site 1	0.000	0.000	0.000
Site 2	—	0.000	0.000	Site 2	—	0.000	0.000
Site 3	—	—	0.025	Site 3	—	—	0.000
Dissolved reactive phosphorus (35)	Site 2	Site 3	Site 4	Total suspended solids (41)	Site 2	Site 3	Site 4
Site 1	0.000	0.000	0.000	Site 1	0.001	0.000	0.009
Site 2	—	0.000	0.000	Site 2	—	0.000	0.000
Site 3	—	—	0.000	Site 3	—	—	0.000
Volatile suspended solids (41)	Site 2	Site 3	Site 4	*E. coli* (26)	Site 2	Site 3	Site 4
Site 1	0.000	0.000	0.000	Site 1	**0.794**	**0.818**	**0.537**
Site 2	—	0.000	0.000	Site 2	—	**0.441**	**0.856**
Site 3	—	—	0.000	Site 3	—	—	0.001
Faecal coliforms (40)	Site 2	Site 3	Site 4				
Site 1	**0.143**	**0.166**	0.016				
Site 2	—	0.002	**0.111**				
Site 3	—	—	0.029				

Table A2.3: Temporal trend results for Lake Wairarapa based on deseasonalised data pooled for all four sampling sites. Note this table also includes results for several variables (*E. coli*, nitrite nitrogen, ammoniacal nitrogen and BOD_5) that were considered unsuitable for trend analysis (see Section 3.2.2 for more details).

Variable	Mean	Slope	PAC	*p*	Std Error	R
Water temperature (°C)	13.68	-0.06	-0.44	<0.001	0.02	-0.24
Dissolved oxygen (mg/L)	10.21	0.02	0.20	0.130	0.01	0.12
Dissolved oxygen (% saturation)	98.30	-0.05	-0.05	0.720	0.13	-0.03
Conductivity (µS/cm)	719.4	36.9	5.12	<0.001	9.16	0.29
5-day biochemical oxygen demand (mg/L)	0.81	0.03	3.71	0.020	0.01	0.2
pH	7.66	-0.02	-0.26	<0.001	0	-0.38
Secchi depth (m)	0.27	0.010	3.71	<0.001	0	0.21
Total suspended solids (mg/L)	83.90	-3.52	-4.20	0.020	1.54	-0.18
Volatile suspended solids (mg/L)	10.49	-0.76	-7.24	<0.001	0.12	-0.44
Turbidity (NTU)	62.21	0.72	1.16	0.250	0.63	0.09
Total nitrogen (mg/L)	0.546	-0.002	-0.37	0.540	3.33	-0.05
Ammoniacal nitrogen (mg/L)	0.016	0.0016	10.08	0.010	0.63	0.22
Nitrate nitrogen (mg/L)	0.194	-0.0043	-2.23	0.310	4.26	-0.09
Total phosphorus (mg/L)	0.133	-0.0033	-2.50	0.070	1.8	-0.14
Dissolved reactive phosphorus (mg/L)	0.011	-0.0006	-5.14	0.000	0.16	-0.28
Chlorophyll *a* (mg/m^3)	9.28	-0.0600	-0.65	0.600	0.11	-0.04
E. coli (cfu/100mL)	15	0.19	1.24	0.860	1.09	0.02
Faecal coliforms (cfu/100mL)	16	0.44	2.69	0.470	0.6	0.06

Table A2.4: Temporal trend analysis results for Lake Wairarapa, Site 1

Variable	Mean	Slope	PAC	*p*	Std Error	R
Water temperature (°C)	13.68	-0.06	-0.44	0.14	0.04	-0.23
Dissolved oxygen (mg/L)	10.23	0.01	0.10	0.78	0.03	0.05
Dissolved oxygen (% saturation)	98.73	-0.19	-0.19	0.47	0.26	-0.12
Conductivity (µS/cm)	603.4	37.68	6.24	0.03	16.64	0.33
5-day biochemical oxygen demand (mg/L)	0.82	0.05	6.07	0.12	0.03	0.27
pH	7.56	-0.02	-0.26	0.04	0.01	-0.3
Secchi depth (m)	0.30	0	0.00	0.55	0.01	0.09
Total suspended solids (mg/L)	87.4	-6.74	-7.71	0.16	4.75	-0.22
Volatile suspended solids (mg/L)	9.88	-0.57	-5.77	0	0.17	-0.47
Turbidity (NTU)	53.2	1.44	2.70	0.24	1.22	0.18
Total nitrogen (mg/L)	0.01	0.00	-0.44	0.7	7.45	0.06
Ammoniacal nitrogen (mg/L)	0.00	0.00	0.56	0.46	0.55	0.13
Nitrate nitrogen (mg/L)	0.00	0.00	-1.02	0.5	8.51	-0.12
Total phosphorus (mg/L)	0.09	-0.01	-7.71	0.71	3.21	-0.06
Dissolved reactive phosphorus (mg/L)	0.05	0.00	2.70	0.07	0.3	-0.32
Chlorophyll *a* (mg/m^3)	9.14	0.09	0.99	0.73	0.25	0.05
E. coli (cfu/100mL)	30	-0.01	-0.03	1	3.52	0
Faecal coliforms (cfu/100mL)	31	2.24	7.27	0.28	2.04	0.18

Table A2.5: Temporal trend analysis results for Lake Wairarapa, Site 2

Variable	Mean	Slope	PAC	*p*	Std Error	R
Water temperature (°C)	13.84	-0.04	-0.29	0.33	0.04	-0.15
Dissolved oxygen (mg/L)	10.19	0.03	0.29	0.37	0.03	0.15
Dissolved oxygen (% saturation)	98.53	0.04	0.04	0.88	0.27	0.03
Conductivity (µS/cm)	722.0	30.89	4.28	0.08	17.19	0.26
5-day biochemical oxygen demand (mg/L)	0.75	0.03	4.02	0.17	0.02	0.24
pH	7.68	-0.02	-0.26	0	0.01	-0.43
Secchi depth (m)	0.27	0.01	3.77	0.06	0.01	0.28
Total suspended solids (mg/L)	75.49	-2.05	-2.72	0.36	2.2	-0.15
Volatile suspended solids (mg/L)	10.11	-0.78	-7.72	0	0.23	-0.47
Turbidity (NTU)	64.1	0.36	0.56	0.77	1.22	0.04
Total nitrogen (mg/L)	0.01	0.00	-0.29	0.84	6.39	-0.03
Ammoniacal nitrogen (mg/L)	0.00	0.00	-0.23	0.03	0.52	0.36
Nitrate nitrogen (mg/L)	0.00	0.00	-3.32	0.67	8.38	-0.07
Total phosphorus (mg/L)	0.08	0.00	-2.72	0.35	4.92	-0.14
Dissolved reactive phosphorus (mg/L)	0.06	0.00	0.56	0.15	0.33	-0.25
Chlorophyll *a* (mg/m^3)	9.81	0	0.00	0.99	0.22	0
E. coli (cfu/100mL)	14	1.18	8.57	0.3	1.11	0.21
Faecal coliforms (cfu/100mL)	18	-0.67	-3.77	0.42	0.81	-0.13

Table A2.6: Temporal trend analysis results for Lake Wairarapa, Site 3

Variable	Mean	Slope	PAC	*p*	Std Error	R
Water temperature (°C)	13.55	-0.07	-0.52	0.04	0.04	-0.31
Dissolved oxygen (mg/L)	10.28	0.03	0.29	0.32	0.03	0.16
Dissolved oxygen (% saturation)	98.54	-0.02	-0.02	0.94	0.27	-0.01
Conductivity (µS/cm)	764.7	39.47	5.16	0.05	19.7	0.29
5-day biochemical oxygen demand (mg/L)	0.87	0.03	3.46	0.41	0.03	0.14
pH	7.72	-0.02	-0.26	0	0.01	-0.47
Secchi depth (m)	0.26	0.01	3.89	0.05	0	0.3
Total suspended solids (mg/L)	87.63	-3.44	-3.93	0.16	2.43	-0.22
Volatile suspended solids (mg/L)	10.97	-1.06	-9.66	0	0.3	-0.5
Turbidity (NTU)	63.3	0.87	1.37	0.51	1.31	0.1
Total nitrogen (mg/L)	0.01	0.00	-0.52	0.24	6.75	-0.18
Ammoniacal nitrogen (mg/L)	0.00	0.00	-1.46	0.11	2.24	0.27
Nitrate nitrogen (mg/L)	0.00	0.00	-2.64	0.59	9.09	-0.09
Total phosphorus (mg/L)	0.09	0.00	-3.93	0.16	2.41	-0.21
Dissolved reactive phosphorus (mg/L)	0.06	0.00	1.37	0.12	0.34	-0.27
Chlorophyll *a* (mg/m^3)	9.02	-0.13	-1.44	0.49	0.18	-0.11
E. coli (cfu/100mL)	9.	-1.18	-12.78	0.21	0.92	-0.25
Faecal coliforms (cfu/100mL)	8	-0.4	-5.04	0.24	0.33	-0.19

Table A2.7: Temporal trend analysis results for Lake Wairarapa, Site 4

Variable	Mean	Slope	PAC	*p*	Std Error	R
Water temperature (°C)	13.64	-0.07	-0.51	0.06	0.03	-0.29
Dissolved oxygen (mg/L)	10.14	0.03	0.30	0.4	0.03	0.14
Dissolved oxygen (% saturation)	97.42	-0.01	-0.01	0.96	0.26	-0.01
Conductivity (µS/cm)	787.6	39.44	5.01	0.05	19.97	0.29
5-day biochemical oxygen demand (mg/L)	0.79	0.03	3.79	0.29	0.03	0.18
pH	7.68	-0.02	-0.26	0	0.01	-0.42
Secchi depth (m)	0.25	0.01	3.99	0.13	0.01	0.23
Total suspended solids (mg/L)	85.07	-1.84	-2.16	0.39	2.14	-0.14
Volatile suspended solids (mg/L)	11.02	-0.63	-5.72	0.02	0.27	-0.35
Turbidity (NTU)	68.2	0.23	0.34	0.86	1.26	0.03
Total nitrogen (mg/L)	0.01	0.00	-0.51	0.76	6	-0.05
Ammoniacal nitrogen (mg/L)	0.00	0.00	-0.34	0.07	0.71	0.31
Nitrate nitrogen (mg/L)	0.00	0.00	-2.79	0.74	8.8	-0.06
Total phosphorus (mg/L)	0.09	0.00	-2.16	0.26	3.47	-0.17
Dissolved reactive phosphorus (mg/L)	0.07	0.00	0.34	0.09	0.34	-0.29
Chlorophyll *a* (mg/m^3)	9.16	-0.18	-1.97	0.41	0.22	-0.13
E. coli (cfu/100mL)	9	0.78	8.99	0.34	0.8	0.2
Faecal coliforms (cfu/100mL)	9	0.57	6.35	0.11	0.35	0.25

Table A2.8: Temporal trend analysis results for the residuals of selected variables that corrected for non-volatile suspended solid concentrations or conductivity

Variable	Slope	*p*	Std Error	R
Non-volatile suspended solid residual adjustment				
Total nitrogen (mg/L)	2.17	0.58	3.95	0.04
Total phosphorus (mg/L)	-1.20	0.40	1.42	-0.07
Chlorophyll *a* (mg/m^3)	-0.19	0.22	0.16	-0.12
Conductivity residual adjustment				
Secchi depth (m)	0.00	0.63	0.00	0.04

Appendix 3: Phytoplankton results

Table A3.1: Phytoplankton results for samples collected from Lake Onoke in November 2009. Relative abundance scores indicate 1=low through to 8=high.

Site 1		Site 2	
Taxa	Relative abundance	Taxa	Relative abundance
Carteria sp.	1	*Anabaena sp.*	1
cf. Quadricoccus sp.	1	*Aphanocapsa sp.*	1
Chlamydomonas sp.	1	*Carteria sp.*	1
Cocconeis sp.	2	*cf. Quadricoccus sp.*	2
Cryptomonas sp.	1	*Chlamydomonas sp.*	1
Cyclotella sp.	6	*Cocconeis sp.*	1
Diatoma	1	*Crucigeniella sp.*	2
Dictyosphaerium sp.	3	*Cyclotella sp.*	6
Gomphonema sp.	1	*Dictyosphaerium sp.*	2
Korshikoviella spp.	2	*Elakatothrix sp.*	1
Micractinium sp.	1	*Korshikoviella spp.*	1
Monoraphidium spp.	4	*Melosira sp.*	1
Nitzschia sp.	5	*Micractinium sp.*	1
Oocystis sp.	3	*Monoraphidium spp.*	2
Pinnularia sp.	1	*Nitzschia sp.*	4
Planktolyngbya sp.	1	*Oocystis sp.*	3
Scenedesmus sp.	1	*Peridinium sp.*	1
Small chain forming diatoms	8	*Planktolyngbya sp.*	3
Small flagellates (<5µm)	1	*Scenedesmus sp.*	1
Small unicells (<5µm)	1	Small chain forming diatoms	8
Synedra sp.	1	Smallflagellates (<5µm)	1
		Small unicells (<5µm)	1

Table A3.2: Phytoplankton results for samples collected from Lake Onoke in March 2011

Site 1			Site 2		
Taxa	Unit count	Cell count	Taxa	Unit count	Cell count
Phormidium sp.	1	3	*Coelosphaerium sp.*	2	10
Coelosphaerium sp.	1	19	*Pseudanabaenaceae*	14	
Actinastrum sp.	77		*Actinastrum sp.*	5	
Ankistrodesmus sp.	2		*Ankyra sp.*	1	
Ankyra sp.	15		*Chaetoceros sp.*	48	
cf. Quadricoccus sp.	1		*Chlamydomonas sp.*	8	
Chaetoceros sp.	70		*Cyclotella sp.*	550	
Cryptomonas sp.	7		*Cymbella sp.*	1	
Cyclotella sp.	3,100		*Dictyosphaerium sp.*	3	
Diatoma sp.	2		*Gyrosigma sp.*	1	
Dictyosphaerium sp.	9		*Mallomonas sp.*	4	
Elakatothrix sp.	1		*Melosira sp.*	4	
Mallomonas sp.	5		*Monoraphidium spp.*	23	
Melosira sp.	4		*Navicula sp.*	1	
Micractinium sp.	3		*Nitzschia sp.*	36	
Monoraphidium spp.	56		*Scenedesmus sp.*	2	
Navicula sp.	1		Small unicells (< 5 µm)	6	
Nitzschia sp.	570				
Oocystis sp.	3				
Peridinium sp.	7				
Scenedesmus sp.	19				
Skeletonema sp.	32				
Synedra sp.	1				
Tetraedron sp.	1				

Table A3.3: Phytoplankton results for samples collected from Lake Waitawa over the period August 2009 to July 2010

Taxa	August		September		October		November		December	
	Unit count	Unit count	Unit count	Cell count	Unit count	Cell count	Unit count	Cell count	Unit count	Cell count
Anabaena cf. circinalis	-	-	-	-	530	41,000	2,800	-	29	1,100
Anabaena circinalis	-	5,500	340	42,000	-	-	-	-	-	-
Anabaena flos-aquae f. flos-aquae	-	-	-	-	-	-	-	-	-	-
Anabaena sp.	-	-	-	-	-	-	-	-	-	-
Ankistrodesmus sp.	-	-	-	-	-	-	-	-	-	-
Ankyra sp.	-	-	-	-	-	-	-	-	1,100	-
Aphanocapsa sp.	-	-	-	-	-	-	-	-	-	-
Aulacosiera sp.	-	-	2	-	-	-	-	-	-	-
Botrycoccus sp.	-	-	-	-	-	-	-	-	-	-
Ceratium sp.	-	-	-	-	-	-	-	-	-	-
Chlamydomonas sp.	-	-	-	-	-	-	-	-	-	-
Closterium sp.	-	-	-	-	-	-	-	-	-	-
Cocconeis sp.	-	-	-	-	-	-	-	-	-	-
Coelastrum sp.	-	-	-	-	-	-	-	-	-	-
Cryptomonas sp.	-	-	26	-	-	-	-	-	340	-
Cyclotella sp.	-	-	-	-	-	-	-	-	-	-
Cymbella sp.	-	-	-	-	-	-	-	-	-	-
Dictyosphaerium sp.	-	-	1	-	-	-	-	-	-	-
Eudorina sp.	-	-	6	-	-	-	-	-	-	-
Euglena sp.	-	-	-	-	-	-	-	-	-	-
Eunotia sp.	-	-	-	-	-	-	-	-	-	-
Fragilaria sp.	-	-	-	-	-	-	-	-	-	-
Frustulia sp.	-	-	-	-	-	-	-	-	-	-
Gloeocystis sp.	-	-	-	-	-	-	-	-	-	-
Heteroleibleinia sp.	-	-	-	-	-	-	-	-	-	-
Mallomonas sp.	-	-	-	-	-	-	-	-	240	-
Melosira sp.	-	-	-	-	-	-	-	-	-	-
Melosira varians	-	-	-	-	-	-	-	-	-	-
Merismopedia sp.	-	-	-	-	-	-	-	-	-	-
Micractinium sp.	-	-	-	-	-	-	-	-	-	-
Microcystis sp.	-	-	-	-	-	-	-	-	-	-
Monoraphidium spp.	-	-	7	-	-	-	-	-	-	-
Navicula sp.	-	-	-	-	-	-	-	-	-	-
Nephrocytium sp.	-	-	-	-	-	-	-	-	-	-
Nitzschia sp.	-	-	1	-	-	-	-	-	-	-
Oocystis sp.	-	-	1	-	-	-	-	-	9	-
Pediastrum sp.	-	-	-	-	-	-	-	-	-	-
Planothidium sp.	-	-	-	-	-	-	-	-	-	-
Pseudanabaena sp.	-	-	-	-	-	-	-	-	-	-
Pseudanabaenaceae	-	-	13	-	-	-	-	-	-	-
Pseudosphaerocystis sp.	-	-	-	-	-	-	-	-	-	-
Romeria sp.	-	-	-	-	-	-	-	-	-	-
Scenedesmus sp.	-	-	-	-	-	-	-	-	-	-
Staurastrum sp.	-	-	9	-	-	-	-	-	7	-
Trachelomonas sp.	-	-	31	-	36	-	-	-	70	-
Volvox sp.	-	-	1	-	-	-	-	-	-	-
Small flagellates (<5 µm)	-	-	5	-	-	-	-	-	4,500	-
Small unicells (<10 µm)	-	-	-	-	-	-	-	-	-	-
Small unicells (<5 µm)	-	-	2	-	-	-	-	-	-	-

Table A3.3 *cont.*: Phytoplankton results for samples collected from Lake Waitawa over the period August 2009 to July 2010

Taxa	January		February		March		May		June		July	
	Unit count	Cell count	Unit count	Cell count	Unit count	Cell count	Unit count	Cell count	Unit count	Cell count	Unit count	Cell count
Anabaena cf. circinalis	28	2600	-	-	-	-	-	-	-	-	-	-
Anabaena circinalis	-	-	-	-	-	-	-	-	-	-	-	-
Anabaena flos-aquae f. flos-aquae	-	-	110	15,000	-	-	-	-	-	-	-	-
Anabaena sp.	-	-	-	-	19	930	21	2,800	13	3,500	82	23,000
Ankistrodesmus sp.	-	-	-	-	-	-	-	-	<1	-	-	-
Ankyra sp.	250	-	72	-	-	-	19	-	19	-	16	-
Aphanocapsa sp.	-	-	1	29	-	-	-	-	<1	26	-	-
Aulacosiera sp.	-	-	-	-	-	-	4	-	1	-	1	-
Botrycoccus sp.	-	-	-	-	-	-	1	-	-	-	-	-
Ceratium sp.	-	-	2	-	7	-	1	-	1	-	-	-
Chlamydomonas sp.	-	-	3	-	10	-	-	-	-	-	-	-
Closterium sp.	1	-	-	-	1	-	2	-	2	-	2	-
Cocconeis sp.	-	-	-	-	-	-	2	-	<1	-	-	-
Coelastrum sp.	47	-	-	-	-	-	1	-	-	-	-	-
Cryptomonas sp.	85	-	31	-	-	-	147	-	150	-	130	-
Cyclotella sp.	-	-	-	-	-	-	1	-	-	-	-	-
Cymbella sp.	-	-	-	-	-	-	1	-	-	-	-	-
Dictyosphaerium sp.	-	-	4	-	-	-	1	-	-	-	-	-
Eudorina sp.	-	-	-	-	-	-	19	-	14	-	-	-
Euglena sp.	1	-	13	-	-	-	1	-	-	-	-	-
Eunotia sp.	-	-	-	-	-	-	-	-	3	-	-	-
Fragilaria sp.	-	-	-	-	-	-	1	-	1	-	-	-
Frustulia sp.	-	-	-	-	-	-	1	-	-	-	-	-
Gloeocystis sp.	2	-	-	-	-	-	-	-	-	-	-	-
Heteroleibleinia sp.	-	-	-	-	-	-	-	-	1	30	-	-
Mallomonas sp.	30	-	-	-	-	-	17	-	1	-	17	-
Melosira sp.	-	-	-	-	-	-	-	-	<1	-	-	-
Melosira varians	-	-	-	-	-	-	1	-	-	-	-	-
Merismopedia sp.	-	-	-	-	-	-	1	2	-	-	-	-
Micractinium sp.	-	-	-	-	-	-	-	-	<1	-	-	-
Microcystis sp.	-	-	5	17	-	-	5	2,210	1	480	1	410
Monoraphidium spp.	-	-	3	-	-	-	-	-	-	-	-	-
Navicula sp.	-	-	-	-	-	-	1	-	-	-	-	-
Nephrocytium sp.	-	-	-	-	2	-	-	-	-	-	-	-
Nitzschia sp.	-	-	-	-	46	-	6	-	-	-	-	-
Oocystis sp.	10	-	17	-	2	-	9	-	4	-	3	-
Pediastrum sp.	-	-	-	-	8	-	-	-	-	-	-	-
Planothidium sp.	-	-	-	-	-	-	-	-	<1	-	-	-
Pseudanabaena sp.	1	16	-	-	-	-	-	-	1	4	-	-
Pseudanabaenaceae	-	-	-	-	2	-	-	-	-	-	-	-
Pseudosphaerocystis sp.	-	-	16	-	-	-	-	-	-	-	-	-
Romeria sp.	-	-	1	4	-	-	2	19	-	-	-	-
Scenedesmus sp.	-	-	-	-	-	-	1	-	-	-	-	-
Staurastrum sp.	5	-	19	-	-	-	9	-	7	-	4	-
Trachelomonas sp.	88	-	32	-	25	-	66	-	16	-	31	-
Volvox sp.	1	-	-	-	-	-	4	-	-	-	4	-
Small flagellates (<5µm)	1,900	-	-	-	-	-	10,015	-	250	-	10,000	-
Small unicells (<10 µm)	-	-	-	-	-	-	38	-	-	-	-	-
Small unicells (<5 µm)	-	-	-	-	1,100,000	-	-	-	-	-	-	-

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February 2012
GW/EMI-T-12/139