Ecological assessment of the Parangarahu Lakes

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Giant kokopu (Photo: M. Schallenberg)

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Executive summary

Lakes Kohangatera and Kohangapiripiri are shallow, coastal lakes in the Wellington Region. No detailed monitoring or investigations have been undertaken on the water quality and ecological condition of these lakes, although some limited water quality data is available, as are assessments of macrophyte and fish communities. This report applies five assessment methods to the available data to assess the condition of water quality and ecological integrity of the lakes, within a broader national context.

The following assessment methods were applied to the available information on the two Parangarahu Lakes:

(1) an assessment of reference (minimally-impacted) condition for New Zealand shallow, freshwater, lowland lakes developed by Schallenberg (2019) and calibrated to data collected from 36 similar lakes,

(2) an assessment of reference conditions, calibrated against modelled reference conditions for over 100 dune lakes and 25 peat lakes,

(3) an assessment of lake condition based on a set of water quality and macrophyte attributes from the National Objectives Framework outlined in the National Policy Statement for Freshwater Management, which classifies lakes into water quality and ecological health categories within a national context,

(4) the LakeSPI macrophyte condition assessment, which is calibrated to a dataset of over 300 lakes, and

(5) the lake health indicator outcome thresholds set out for the lakes within the Greater Wellington Regional Council's (GWRC) Proposed Natural Resources Plan.

Given the paucity of data on the lakes, the assessments in this report should be seen as preliminary. Further, this lack of data meant that the attribute states inferred from two of the assessment methods are not directly comparable with their prescribed methodologies.

Nevertheless, according to the assessment methods that I consider to be most directly applicable to the Parangarahu Lakes (methods 1 and 4), some measured attributes of Lake Kohangatera reflect reference conditions (and, thus, a very high state of ecological health) while others suggest only minor departures from reference conditions. The attributes that are reflective of somewhat degraded conditions are the total phosphorus concentration of the lake and the presence of two invasive macrophyte taxa.

According to the same methods, the condition of Lake Kohangapiripiri is a little more degraded, with only chlorophyll *a* reflecting the expected reference condition. Attributes such as total phosphorus concentrations, areal nitrogen loading from the catchment, and the macrophyte community indicate that the lake has degraded somewhat from reference conditions. Nevertheless, the lake still reflects a relatively good condition, in relation to similar lakes throughout New Zealand.

The lakes generally met the macrophyte, phytoplankton, nutrients and fish outcome narratives identified for these lakes in GWRC's Proposed Natural Resources Plan (PNRP). The only outcome for which quantitative assessment thresholds were provided in the PNRP was for macrophytes. When most recently sampled in 2016, Lake Kohangatera met the macrophyte outcome threshold but Lake Kohangapiripiri did not. However, the poor condition of macrophytes in that lake in 2016 was probably a result of natural water level decline due to drought, and the lake's macrophytes were expected to recover after the drought.

The following monitoring and research recommendations are provided to help improve management of the lakes:

Monitoring:

- Monitor water quality on a monthly basis for at least 1 year to inform water quality outcome thresholds for the lakes.
- Carry on with LakeSPI monitoring at 5-yearly intervals.
- Monitor temperature and dissolved oxygen in the bottom waters of the lakes using continuous DO sensors.

Research:

- Carry out a study on factors limiting phytoplankton proliferation in the lakes.
- Carry out a study to determine the reasons for high phosphorus levels in the lakes.

This report highlights the generally good quality of these lakes but also illustrates some issues which deserve attention, such as the source of the unusually high phosphorus concentrations in the lakes and the lakes' vulnerability to invasion by non-native macrophytes. The information in the report should assist with setting further relevant and appropriate water quality and ecological health outcome thresholds for these lakes.

Contents

1. Background

The Parangarahu Lakes are two small shallow, coastal lakes situated within the Wellington Region, on the southern coastline of the North Island, at the eastern side of Wellington Harbour (Fig. 1). Both lakes are separated from the ocean by gravel barrier bars and their discharge to the sea is mainly via seepage through the gravel bars. Background information on the lakes is available from Perrie & Milne (2012).

The larger of the two lakes is Lake Kohangatera (surface area = 21 ha, maximum depth = c. 2.1 m), which occasionally discharges to the sea via natural openings of the bar, which tends to occur after rain events (e.g., Fig. 2). Close examination of the lake levels after barrier breaches indicates that cut through of the barrier bar does not allow sea water to enter the lake, because there is no obvious tidal signal in the hydrograph at these times. This is backed up by measurements of electrical conductivity taken in the lake (GWRC data). Lake Kohangapiripiri (surface area = 11 ha, maximum depth = c. 1.8 m) rarely has a direct connection to the sea, usually discharging via seepage (e.g., Fig. 3).

Figure 1. *The Parangarahu Lakes. Lake Kohangapiripiri to the left and Lake Kohangatera to the right. Source: Google Earth.*

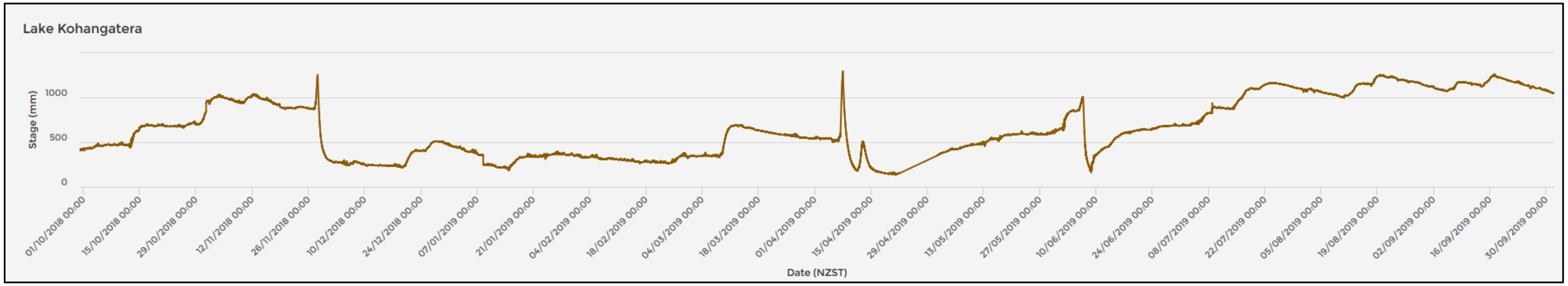

Figure 2. *Hydrograph of Lake Kohangatera from Oct 2018 to Sept 2019, showing three breaches of its gravel barrier bar and subsequent rapid drainage of the lake. Data are from the Greater Wellington Regional Council website (http://graphs.gw.govt.nz/?siteName=Lake Kohangatera&dataSource=Stage).*

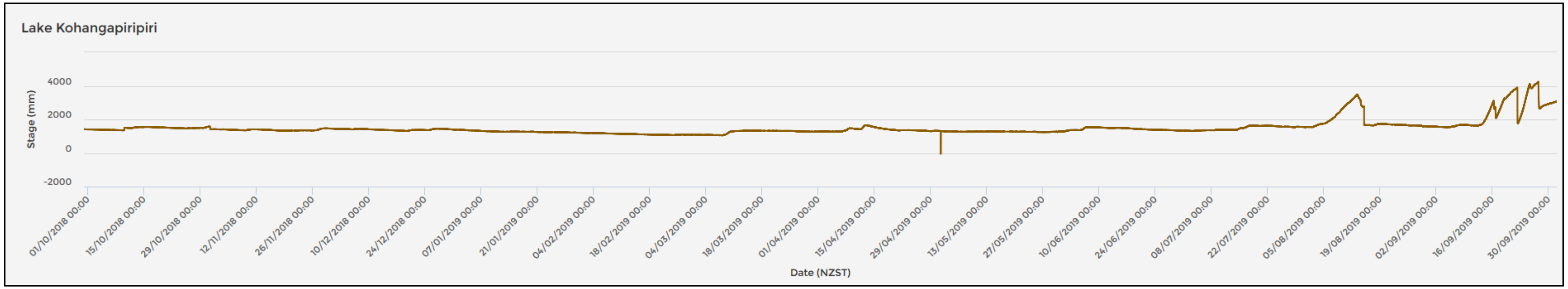

Figure 3. *Hydrograph of Lake Kohangapiripiri from Oct 2018 to Sept 2019, showing a pattern typical of seepage discharge, with no cutting through of the gravel barrier bar. Data are from the Greater Wellington Regional Council website (http://graphs.gw.govt.nz/?siteName=Lake Kohangapiripiri&dataSource=Stage).*

These lakes drain relatively small coastal catchments and both have significant areas of wetland in their upstream catchments. Gollans Creek drains into Lake Kohangatera, draining a catchment with an area of around 20 km^2 (around 95× the lake area), while Cameron Creek drains into Lake Kohangapiripiri, draining a catchment with an area of around 3.7 km^2 (around 34× the lake area). The water of both lakes is humic-stained due to the influence of wetlands in their catchments on the water chemistry of the lakes. At times, they may also be very slightly brackish due to the influence of salt spray.

Comparisons of historical maps and aerial photography of the lakes has shown that they have become progressively cut-off from the ocean since 1906, due in part to natural processes such as land uplift and gravel deposition, but also potentially due to the road (and associated culverts) that crosses the outlets of the lakes, which prevents deeper scouring and a larger breaches of the gravel bar during lake overflow events (McEwan 2013).

While the Parangarahu Lakes are recognised as having important biodiversity and cultural values (Gibbs 2002) and appear to be examples of "healthy lakes" (Wells & Champion 2004) with minimal anthropogenic impacts in their catchments (Perrie & Milne 2012), there have been incursions of invasive macrophytes into their catchments (deWinton 2016) and some concern has been expressed about relatively high nutrient levels in the lakes (Perrie & Milne 2012) and about the barrier to fish passage that the road crossing the lake outlets represents (McEwan 2013).

2. Scope of the report

The Greater Wellington Regional Council (GWRC) recognises the importance of biotic components of lake ecosystems when assessing lake health. For example, assessments of fish, macrophyte and phytoplankton communities have been carried out for the Parangarahu Lakes. However, apart from LakeSPI assessments on the macrophytes (e.g., de Winton 2016), the information collected on the lakes has not been put into an assessment framework that can reveal the ecological status of the lakes in relation to other similar lakes around New Zealand or in relation to the lakes' likely reference conditions.

Recent studies have attempted to ascertain the reference condition water quality and ecological integrity of New Zealand lakes – the conditions that lakes would be in in the absence of human pressures (Schallenberg et al. 2018; Abell et al. 2019; Schallenberg 2019). Some of this work has been applied to assessments of the current status of shallow, coastal Southland lakes to help understand how far the current conditions of lakes depart from their reference conditions (Schallenberg and Kelly 2013).

This report collates the most recent water quality and ecological information about the Parangarahu Lakes and undertakes five assessments of the water quality and ecological integrity/condition of the lakes:

(1) an assessment of reference (minimally-impacted) condition for New Zealand shallow, freshwater, lowland lakes developed by Schallenberg (2019) and calibrated to data collected from 36 similar lakes,

(2) an assessment of reference conditions, calibrated against modelled reference conditions for over 100 dune lakes and 25 peat lakes developed by Abell et al. (2019),

(3) an assessment of lake condition based on a set of water quality and macrophyte attributes from the National Objectives Framework outlined in the National Policy Statement for Freshwater Management (MfE 2017 and MfE 2019), which classifies lakes into water quality and ecological health categories within a national context,

(4) the LakeSPI macrophyte condition assessment developed by NIWA (deWinton 2016), which is calibrated to a dataset of over 300 lakes, and

(5) the lake health indicator outcome thresholds set out for the lakes within the GWRC's Proposed Natural Resources Plan (GWRC 2015).

These assessments of ecological condition and water quality for the Parangarahu Lakes will be useful for prioritising lake management policies and actions and for detecting future trends in the condition of the lakes.

3. Ecological integrity and reference condition (Schallenberg 2019)

Schallenberg et al. (2011) defined ecological integrity (EI) for New Zealand freshwaters as having four essential components: nativeness, pristineness, diversity and resilience (see Appendix A for definitions).

Lakes with high EI must exhibit high values in all four components. Schallenberg et al. (2011) identified a number of metrics for quantifying each of the four components of EI.

Schallenberg and Kelly (2013) and Schallenberg (2019) undertook lake EI assessment by first classifying the shallow lakes into freshwater and brackish classes of lakes using a conductivity threshold of 1000 µS cm^{-2} to differentiate the two lake types. Based on the GWRC's electrical conductance data, both Lakes Kohangatera and Kohangapiripiri are classed as freshwater lakes for the purposes of the following assessment[1]. Thirty-six of the 43 lakes in the national database used for EI assessment were classified as shallow, freshwater lakes (Schallenberg & Kelly 2013; Schallenberg 2019).

Schallenberg (2019) used the data from 36 lakes to develop a framework for determining which lakes in the nationwide shallow lake survey most closely reflected reference conditions and how much degraded lakes had departed from reference conditions. See Appendix A for a summary of the methodology used. Examples of how the reference

[1] Kohangapiripiri: median 589 µS cm^{-1}, range 567 to 1,358 µS cm^{-1} (*n*=5); Kohangatera: median 761 µS cm^{-1}, range 269 to 961 µS cm^{-1} (*n*=4).

conditions for certain attributes were derived are shown in Figure 4, along with the positions of the Parangarahu Lakes relative to the 36 South Island and North Island lakes.

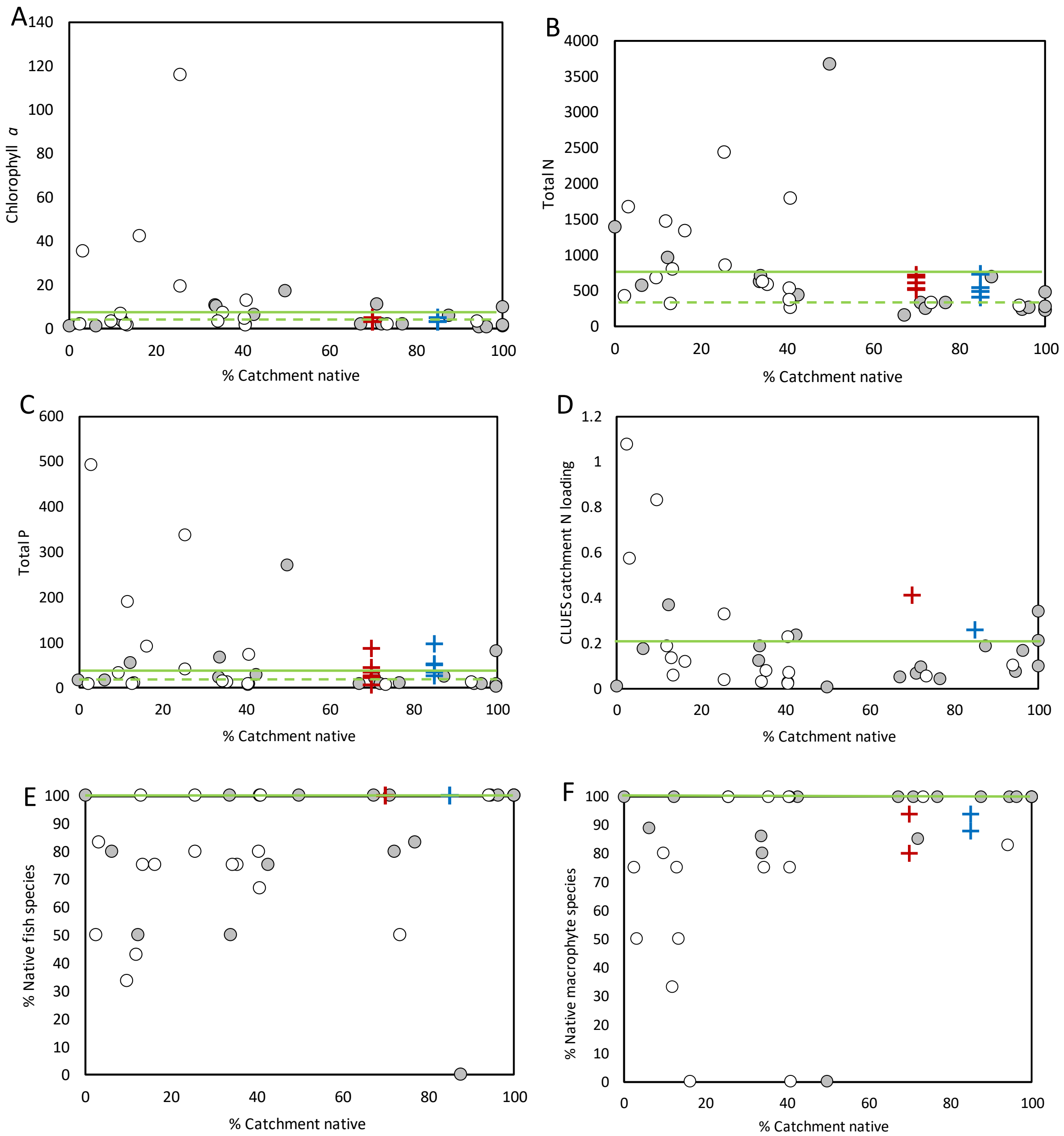

Figure 4. *Assessment of pristineness (A to D) and nativeness (E, F) of shallow freshwater lakes using EI indicators (see Table 1). Filled circles are 19 lakes from the South Island, Steward Island and Campbell Island. Open circles are 17 lakes from the North Island. Blue crosses are Kohangatera (85% native catchment vegetation cover) and the red crosses are Kohangapiripiri (70% native catchment vegetation cover). The dashed green line is the Tier 1 reference condition and the solid green line is the Tier 2 reference condition (or both)(See Appendix A for explanations of Tier 1 and Tier 2 reference conditions). Data presented for the Parangarahu Lakes are from sampling occasions over the past 10 years.*

Based on the analysis of Schallenberg (2019), 11 lake attributes showed meaningful associations with EI and with percent catchment in native vegetation allowing the estimation of reference condition thresholds for shallow lowland lakes (Table 1). For the Parangarahu Lakes, only data on total nitrogen, total phosphorus, chlorophyll *a*, nitrogen loading, fish nativeness and macrophyte nativeness were available to compare with the reference condition thresholds (Fig. 4, Table 1).

Table 1. *Shallow, freshwater lake attributes related to EI, derived from an analysis of 36 shallow freshwater lakes, as reported in Schallenberg (2019). Both Tier 1 and Tier 2 reference condition limits could only be determined for Pristineness indicators (see Appendix A for explanations of Tier 1 and Tier 2). No measures of diversity were meaningfully correlated with EI and, thus, the reference conditions for diversity measures could not be derived from the analysis (Schallenberg 2019). Medians and ranges for the Parangarahu Lakes are also shown. The DIN:TP ratio could not be calculated for the lakes because many of the nitrate and ammonium measurements were below analytical detection limits.*

Indicator	Unit	Tier 1 limit	Tier 2 limit	Kohangatera	Kohangapiripiri
Pristineness				**median (range)**	**median (range)**
Total nitrogen	µg L^{-1}	277	692	490 (410 to 730)	610 (510 to 720)
Total phosphorus	µg L^{-1}	11.7	23	42 (25 to 96)	34 (21 to 86)
Trophic Level Index		3.5	4.4	n/a	n/a
Chlorophyll *a*	µg L^{-1}	3.2	5.7	< 3 (<3 to 5)	<3 (<3 to 5)
Nitrogen loading	tonnes ha^{-1} y^{-1}	0.21	0.21	0.26	0.41
Nativeness				**percentage**	**percentage**
% native fish species	%	100	100	100	100
% native macrophyte species	%	100	100	88 to 94%	80 to 94%
% native macrophyte cover	%	100	100	n/a	n/a
Diversity					
Resilience					
Cyanobacteria	Cells mL^{-1}	≤ 1000	≤ 1000	n/a	n/a
Food chain length	Trophic levels	≤ 3.86	≤ 3.86	n/a	n/a
DIN:TP*		≤ 0.68	≤ 0.68	n/a	n/a

*ratio of dissolved inorganic nitrogen to total phosphorus

As described above and in Appendix A, an assessment of the ecological integrity of the Parangarahu Lakes can be made based on the percentage of native vegetation in their catchments, which is estimated to be around 85% for Lake Kohangatera and around 70% for Lake Kohangapiripiri (Perrie & Milne 2012) (Table 2). Unfortunately, no expert-EI assessment ranking was available for the lakes. However, by examining the relationship in Figure A1 in Appendix A, the expert EI ranking (scaled to 100) for Lake Kohangatera in inferred to be approx. 85. Again from Figure A1, the corresponding inferred EI expert assessment ranking percentile for Lake Kohangapiripiri would be approximately 70%, or perhaps slightly higher.

Table 2. *Land cover in the catchments of the Parangarahu Lakes. From Perrie & Milne (2012).*

(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.

To use the reference condition assessment method of Schallenberg (2019) appropriately, only data collected from the Parangarahu Lakes during late summer (i.e. February-April) were used. Data available from the Parangarahu Lakes allows for the assessment of the pristineness EI indicators: total nitrogen, total phosphorus, chlorophyll *a*, and lake-specific areal nitrogen loading (Fig. 4 A-D). The physico-chemical data comprise 5 samplings from Lake Kohangapiripiri and 4 sampling from Lake Kohangatera. All samplings of each lake occurred in different years between 2011 and 2019 within the period February to April. Chlorophyll *a* readings were mostly below the analytical detection limit (<3 μg L^{-1}) but in this assessment, the measurements were set to 3 μg L^{-1}. Despite this being an over-estimate of the actual chlorophyll *a* levels in the lakes, measurements for the Parangarahu Lakes fall within the range of Tier 1 reference conditions for such lakes (Fig. 4A).

For total nitrogen concentrations, the Parangarahu Lakes fall between the Tier 1 and Tier 2 reference condition thresholds for such lakes (Fig. 4B). With respect to total phosphorus concentrations, the Parangarahu Lakes fall slightly above the Tier 2 reference condition threshold (Fig. 4C). This could either reflect (1) the influence of historical superphosphate fertiliser use in the catchments which could either still be moving through the catchment into the lakes, (2) recycling of phosphorus into the water column from the lakes' sediments if they were to become anoxic during short periods of thermal stratification in summer, or (3) the influence of geological sources of P (e.g., basalts or other volcanic geology) in the catchments.

The data for catchment nitrogen loads were taken from the Takiwa website, which reports estimated typical annual loads for the lakes derived from the CLUES model (https://my.takiwa.co/). The estimated N-loads are higher than the reference condition estimates for shallow freshwater lakes, however the CLUES load estimates have some undisclosed margins of error. Therefore, the estimates of N-loading to the lakes in Figure 4D should be interpreted with some caution.

In terms of nativeness, data for two indicators were available: percentage native fish species, and percentage native macrophyte species (Fig. 4E, F). Fish species lists for the lakes were amalgamated from McEwan (2013) and GWRC fish surveys from April 2019 for Lake Kohangatera and March 2018 for Lake Kohangapiripiri. No non-native fish species have been recorded from the lakes, although one trout was caught further up in the catchment of Lake Kohangatera (McEwan 2013). Therefore, the lakes both achieve reference condition status for fish diversity (100% native fish species; Fig. 4E)[2].

Macrophyte species lists were obtained from deWinton (2016) for samplings in the years 2011, 2013 and 2016 for Lake Kohangatera and 2011 and 2016 for Lake Kohangapiripiri. These data indicated the presence of 2 invasive species in Lake Kohangatera and 1 invasive species in Kohangapiripiri. In the past 10 years, the total macrophyte species count in Lake Kohangatera was consistently 16 species, whereas, the total count has varied between 18 and 5 species in Lake Kohangapiripiri (deWinton 2016). Thus, the condition of macrophytes diversity in the lakes doesn't achieve reference condition, but is nevertheless quite high compared to many other shallow, lowland, freshwater lakes (Fig 4F).

4. Reference condition assessment (Abell et al. 2019)

Abell et al. (2019) conducted an analysis of the trophic state of over 1000 New Zealand lakes. The current mean annual total phosphorus (TP), total nitrogen (TN) and reference condition TP and TN concentrations of the >1000 lakes were both modelled and estimated from measured data. Reference conditions were modelled based on modelled river and stream reference condition estimates are from McDowell et al. (2018). The mean annual nitrogen and phosphorus reference conditions modelled and estimated from the whole lake dataset were much lower than the summer nutrient concentrations reported for the Parangarahu Lakes. The estimated mean annual total phosphorus reference condition using the >1000 lake dataset was 20% of the summer mean TP concentration of Lake Kohangatera and 25% of the mean summer TP concentration of Lake Kohangapiripiri. The estimated mean annual total nitrogen reference condition using the >1000 lake dataset was 40% of the summer mean TP concentration of Lake Kohangatera and 33% of the mean summer TP concentration of Lake Kohangapiripiri.

Abell et al. (2019) also estimated annual median nitrogen and phosphorus reference conditions for dune lakes and for peat lakes (Table 3; Fig. 5). Reference conditions for both lake types are presented here because the Parangarahu Lakes share certain features with both dune lakes and peat lakes. Again, it should be noted that the data for the Parangarahu Lakes are only from late summer samplings (February to April), whereas the reference condition estimates in Table 3 are annual medians. The data in Table 3 indicate that the total nitrogen and total phosphorus summer medians for the Parangarahu Lakes exceed all the annual median reference condition estimates from Abell et al. (2019).

Figure 5 shows that the total phosphorus medians for both Lake Kohangatera and Lake Kohangapiripiri fall within 1.5 times the upper interquartile range of estimated median reference conditions for both lake types. The total nitrogen medians for both lakes also fall

[2] Although note that this assessment does not consider any potential impacts from the road/culverts that might impact on the frequency of bar-breaching events and hence access for indigenous migratory fishes.

within 1.5 times the upper interquartile range of estimated total nitrogen reference conditions for dune lakes. However, total nitrogen concentrations in both lakes exceeds this range for estimated reference conditions for total nitrogen in peat lakes (Fig. 5a). Therefore, the nutrient data available suggest that nutrient concentrations in the Parangarahu Lakes are higher than the annual medians estimated as reference conditions, but are within a reasonable margin of error. However, for total nitrogen concentrations, the lakes are above the estimated range of annual median reference concentrations.

Table 3. *Estimated total nitrogen and total phosphorus concentrations for reference conditions and measured concentrations for the Parangarahu Lakes. The reference conditions are annual medians (µg L^{-1}) back-calculated from logged values in Abell et al. (2019). The current conditions (µg L^{-1}) are medians for late summer samples collected since 2011.*

	Total nitrogen medians (ranges)	**Total phosphorus medians (ranges)**
Reference condition		
Dune lakes	417	12.6
Peat lakes	251	14.1
Current condition		
Kohangatera	490 (410 to 730)	42 (25 to 96)
Kohangapiripiri	610 (510 to 720)	34 (21 to 86)

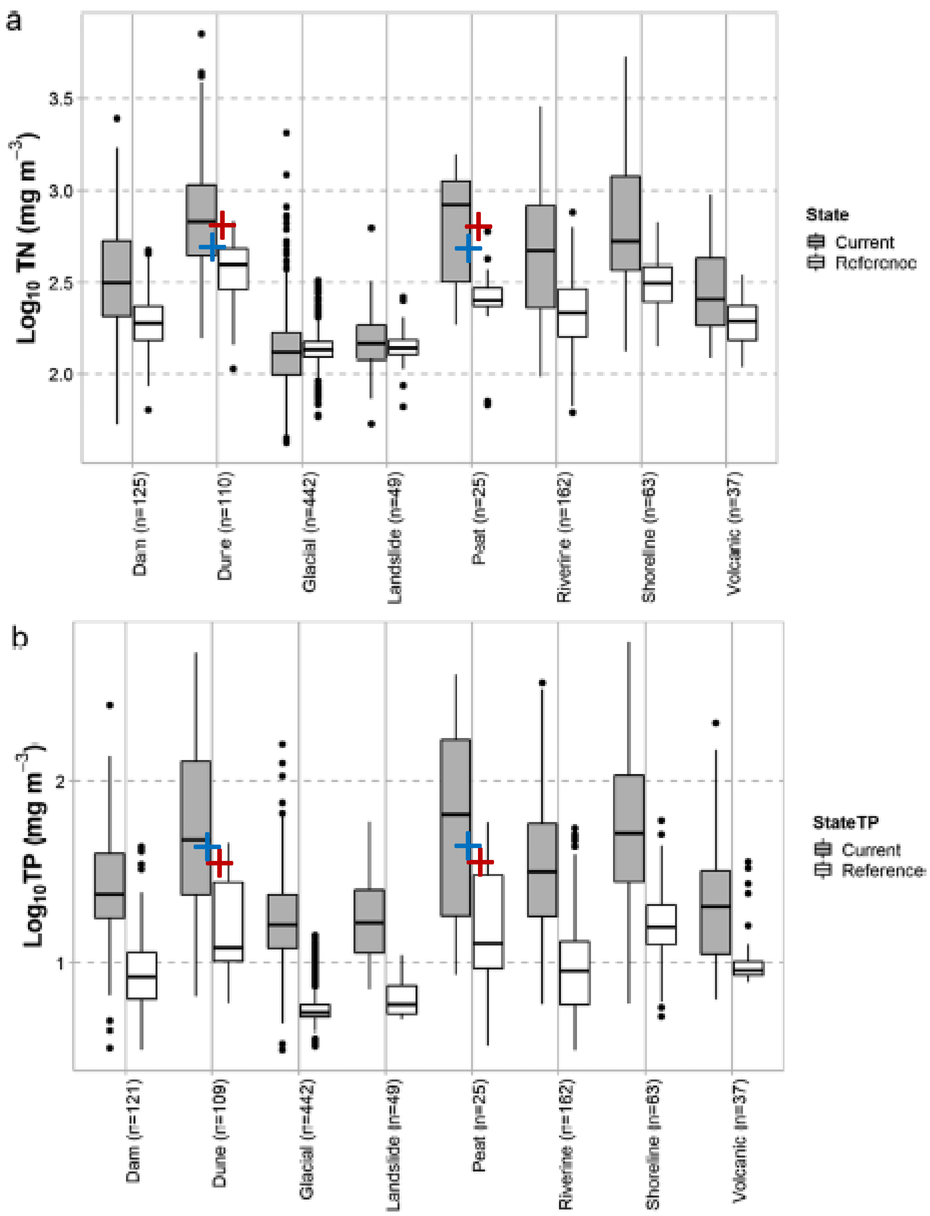

Figure 5. *Box-whisker plots for annual median total nitrogen (a) and total phosphorus (b) concentrations for different lake types, from Abell et al. (2019). Both the estimates for current state (filled) and reference conditions (open) are shown. For comparison, the summer median concentrations for Lake Kohangatera (blue crosses) and Lake Kohangapiripiri (red crosses) for both dune lake and peat lake classes are shown.*

5. NOF guidelines (MfE 2017 and MfE 2019)

The National Policy Statement for Freshwater Management 2017 provides national guidance on lake water quality in its appendices, called the National Objective Framework (NOF). Lakes which fall below "the bottom line" (i.e. C/D threshold) are considered unacceptably degraded. Above this bottom line, three other water quality grades are provided which are useful for placing lakes in a national context with regard to the condition of their water quality. Generally, the A band can be thought of as approximating reference conditions, the B band is considered “good”, the C band is considered “fair”, while the D band is unacceptable and requires remediation actions. The NOF includes guidance for chlorophyll *a*, total phosphorus and total nitrogen, with which data from the Parangarahu Lakes can be compared and also presents narratives, which describe the four quality grades or bands (see Appendix B).

The Parangarahu Lakes are likely to be in the A or B bands with respect to chlorophyll *a*, which rates the lakes in near reference condition. There is some uncertainty in this because most of the chlorophyll *a* data were below detection limits, making it difficult to ascertain exact concentrations. In terms of total nitrogen, Lake Kohangatera is in the B band while Lake Kohangapiripiri is in the C band. In terms of total phosphorus, both lakes are in the C band. Again, these assessments are based on comparison of annual data (NOF) with summer data (Parangarahu Lakes) and, thus, should be interpreted with caution.

Two attributes of the Lake Submerged Plant Index (LakeSPI) have been proposed as amendments to the NOF in MfE’s freshwater reforms package (MfE 2019) but are not yet official government policy. The two attributes are the Native Condition Index (NCI, which assesses the health of the native plant community) and the Invasive Impact Index (III, which assesses the threat to the plant community from invasive plant species that may be present in the lakes). For more information on LakeSPI, see Section 6.

In terms of the NCI, the LakeSPI data available for the past 10 years for Lake Kohangatera place it in the B band, whereas the data for Lake Kohangapiripiri place it in the B and C bands (Appendix B). The C band assessment, from LakeSPI work done in 2016, was due to unusually low water levels in the lake prior to the LakeSPI assessment (deWinton 2016). The low water level at the time reflected dry conditions and the low LakeSPI assessment at the time was deemed a normal response to dry conditions. The macrophytes present were predicted to recover once normal hydrological conditions prevailed (deWinton 2016), suggesting a recovery to B band status has likely occurred.

In terms of the III, the data consistently place Lake Kohangatera in the B band and Lake Kohangapiripiri in the C band. Thus, neither lake is in a reference condition with regard to submerged macrophytes, but neither lake falls below the bottom line, which would indicate severely degraded conditions. The macrophyte community in Lake Kohangatera is in a better condition than that of Lake Kohangapiripiri.

6. LakeSPI assessment (deWinton 2016)

LakeSPI is a lake assessment tool that quantifies the condition of the macrophyte community in terms of the impact of invasive species and the health of the native macrophyte community. It also accounts for water clarity by including an assessment of maximum macrophyte depth limits. The assessment of condition is compared to over 300 similar assessments made on New Zealand lakes. Assessments of LakeSPI are not adjusted for different lake types, but corrections are made for differences in lake depth because lake depth can limit the maximum achievable LakeSPI assessment score. Only lakes with macrophytes present can be assessed by the LakeSPI framework. Depth-adjusted LakeSPI scores are placed into four condition categories which are determined by percentiles of the maximum possible LakeSPI score (0 to 20% of maximum score = "poor"; 20 to 50% of the maximum score = "moderate"; 50 to 75% of the maximum score = "high"; 75 to 100% of the maximum score = "excellent"). For a critical assessment of LakeSPI as a lake monitoring tool, see Schallenberg & Schallenberg (2018).

LakeSPI assessments were undertaken by NIWA in the years 2011, 2013 and 2016 for Lake Kohangatera and in 2011 and 2016 for Lake Kohangapiripiri (de Winton 2016). The macrophyte condition of Lake Kohangatera as indicated by LakeSPI was "excellent" during all three samplings and indicated that the condition of the macrophyte community in this lake had been stable over the 6 years of sampling. In contrast, the macrophyte condition for Lake Kohangapiripiri declined significantly from "high" to "moderate" between 2011 and 2016. deWinton (2016) commented that this decline was likely due to unusually low water levels in the lake prior to the 2016 LakeSPI assessment, which had probably caused a macrophyte die-off. This was deemed to be part of the natural variation in macrophytes in this lake and it was suggested that the macrophyte community would probably recover well once a more normal water level regime was achieved at the end of the drought.

7. Assessment in relation to outcomes in the Proposed Natural Resources Plan (PNRP) for the Wellington Region

GWRC has established outcomes for lake water quality and aquatic ecosystem health and has narative outcomes for nutrients, phytoplankton, macrophytes and fish in the PNRP (GWRC 2015) (Table 4). For the macrophyte outcome, methods for assessment and quatitative outcome thresholds were proposed (Greenfield et al. 2015). In 2015, at the time of the first benchmarking exercise (Greenfield et al. 2015), the Parangarahu Lakes were only given LakeSPI outcome thresholds because few data, apart from macrophyte assessments, were available for the lakes. The macrophyte outcome thresholds accounted for both the percentage of aquatic vegetation in the lakes that is native and for the LakeSPI score. The performance of the Parangarahu Lakes in relation to the macrophyte outcome thresholds is shown in Table 5. The lakes met the outcomes in 2011 and 2013 and Lake Kohangatera met the outcome in 2016, but, as described above (Section 6), Lake Kohangapiripiri had only moderate macrophyte health in 2016 due to unusually low water levels at the time.

Table 4. *GWRC's PNRP aquatic ecosystem health narrative outcomes for lakes in the Wellington Region.*

Macrophytes	Phytoplankton	Nutrients	Fish
Submerged and emergent macrophyte communities are resilient and occupy at least one third of the lake bed that is naturally available for macrophytes, and are dominated by native species	Phytoplankton communities are balanced and there is a low frequency of nuisance blooms	Total nitrogen and phosphorus concentrations do not cause an imbalance in aquatic plant, invertebrate or fish communities	Indigenous fish communities are resilient and their structure, composition and diversity are balanced

Table 5. *Outcomes and outcome thresholds for macrophyte attributes as set out in Greenfield et al.* (*2015*) for GWRC's PNRP.

Lake	Attribute	Measure	Method/statistic	Outcome met?
Kohangatera	Macrophytes	Native vegetation cover (%) and LakeSPI score	Two thirds of the vegetation cover is native AND LakeSPI score ≥ 83	**2011**: cover >76% AND LakeSPI = 89 → YES **2013**: cover >96% AND LakeSPI = 87 → YES **2016**: cover > 96% AND lakeSPI = 82 → YES
Kohangapiripiri	Macrophytes	Native vegetation cover (%) and LakeSPI score	Two thirds of the vegetation cover is native AND LakeSPI score ≥ 58	**2011**: cover >76% AND LakeSPI = 63 → YES **2016**: cover ranged from 5 to 95% AND LakeSPI = 40 → NO

Greenfield et al. (2015) did not propose methodologies for assessing the narrative outcomes for phytoplankton or nutrients (Table 4) for the Parangarahu Lakes. However, in my opinion, and keeping in mind the data limitations, the phytoplankton outcome (using chlorophyll *a* concentrations) is met in both lakes. The nutrient narrative outcome states that total nitrogen and total phosphorus concentrations should "not cause an imbalance in aquatic plant, invertebrate or fish communities". One way that such an imbalance could occur is via ammonia and/or nitrate toxicity to fish, but the toxicity thresholds of these found in the National Objectives Framework appended to MfE (2017) are much higher than the total nitrogen concentrations reported in the lakes. Nitrogen and phosphorus can also unbalance aquatic ecoystems by fuelling proliferations of algae, cyanobacteria and macrophytes. The chlorophyll *a* levels reported for the lakes are extremely low, suggesting that for some reason phytoplankton (algae and cyanobacteria) are not utilising much of the nitrogen and phosphorus in the water column. Further studies on the nutrient-phytoplankton relationship in the lakes could reveal why there is low phytoplankton biomass in relation to the nutrient levels in the lakes.

The outcome narrative in the PNRP for native fish communities in lakes states that "Indigenous fish communities are resilient and their structure, composition and diversity are balanced". Keeping in mind the limited data, this would appear to be met for Lake Kohangatera according to the data in McEwan (2013) and more recent GWRC fish surveys, which show a relatively stable and diverse native fish community. On the other hand, recent fish survey data for Lake Kohangapiripiri indicates lower species diversity and lower abundance of long and shortfin eel. Thus, there is less certainty thatthe PNRP outcome is being met in this lake (Table 6). However, low diversity and abundance of some obligatory diadromous fish species may naturally be expected in Lake Koahangapiripiri given the limited opportunities for fish to migrate into the lake (e.g., breaches of the barrier bar – see Fig. 3). Further work to refine the expected fish communities in each lake would enable a more robust assessment against this outcome.

Table 6. *Fish survey data for Lakes Kohangatera and Kohangapiripiri. Results are based on the same level of fishing effort involving the use of gill nets with different mesh sizes, fine-meshed fyke nets and fine-meshed Gee-minnow traps set at a representative site. Data were provided by the GWRC.*

Fish species	**Lake Kohangatera**[1]	**Lake Kohangapiripiri**[2]
Shortfin eel	99	8
Longfin eel	107	11
Common bully	555	2262
Common smelt	111	44
Inanga	162	0
Giant kokopu	1	0
Total species richness	**6**	**4**

[1] sampled April 9 and 10, 2018

[2] sampled March 19 and 30 , 2018

8. Summary

The ecological condition of the Parangarahu Lakes was assessed in relation to 5 different lake assessment protocols, with a view to determining the ecological integrity and condition of the water quality of the lakes. The assessments specifically addressed the current conditions of the lakes in relation to their inferred reference (minimally impacted) conditions.

8.1 Schallenberg (2019) assessment

This assessment placed both lakes either in reference conditions or relatively close to reference conditions (Table 7). The main departures from reference conditions were in total phosphorus concentrations and macrophyte nativeness. The assessment has good validity in terms of the data for the Parangarahu Lakes because the assessment uses summer data, which were available for the Parangarahu Lakes for multiple years. The assessment is based on the inferred reference condition for shallow, lowland, freshwater lakes, which was estimated from a 36-lake dataset. The Schallenberg (2019) assessment method identified inferred reference condition thresholds, which reflect an upper limit for reference conditions. In my opinion, this assessment method provides high confidence in the assessment of reference conditions and departures from reference conditions for the Parangarahu Lakes.

Table 7. *Summary of Parangarahu Lakes assessment using the protocol of Schallenberg (2019). See also Fig. 4, Table 1.*

Schallenberg (2019)	Kohangatera	Kohangapiripiri
Chlorophyll *a*	Reference condition	Reference condition
Total nitrogen	Tier 2 reference condition, close to Tier 1	Tier 2 reference condition, close to Tier 1
Total phosphorus	Slightly higher concentrations than reference condition	Slightly higher concentrations than reference condition
Nitrogen load	Close to reference condition	Somewhat higher than reference condition
Fish nativeness	Reference condition	Reference condition
Macrophyte nativeness	Slightly lower than reference condition	Somewhat lower than reference condition

8.2 Abell et al. (2019) assessment

Abell et al. (2019) used a dataset of 110 and 109 dune lakes for the assessments of total nitrogen and total phosphorus reference conditions, respectively, while it used a dataset of 25 peat lakes for the assessments of both total nitrogen and total phosphorus. The reference conditions reported were either mean or median reference conditions (Table 3), not upper limits, and Abell et al. (2019) showed substantial variation around the median reference condition estimates (Fig. 5). The Parangarahu Lakes nutrient data were only measured in late summer. Given these caveats and the uncertainty in attributing lake type to the Parangarahu Lakes, I only have moderate confidence in these median reference condition estimates, as applied to the lakes.

According to the Abell et al. (2019) assessment framework, the water quality data for the Parangarahu Lakes falls above the median reference conditions for both dune and peat lakes (Table 8). However, summer total nitrogen concentrations in Lake Kohangatera are close to the annual median reference condition inferred for dune lakes. The median total nitrogen concentrations for Lake Kohangapiripiri fell well above the range of estimated median reference conditions for total nitrogen in peat lakes (Fig. 5). Although higher than the estimated reference condition medians, all the other medians for the Parangarahu Lakes fell within the 1.5× interquartile range of the estimated median reference conditions. Thus, they were within reasonable error estimates of reference condition medians for this assessment.

Table 8. *Comparison of Parangarahu Lakes nutrient data against estimates of annual median reference conditions for total nitrogen and total phosphorus concentrations for dune lakes and peat lakes, from Abell et al. (2019).*

Dune lakes (median)	**Kohangatera**	**Kohangapiripiri**
Total nitrogen	Higher (c. 1.2×)	Higher (c. 1.4×)
Total phosphorus	Higher (c. 3.3×)	Higher (c. 2.7×)
Peat lakes (median)		
Total nitrogen	Higher (c. 2×)*	Higher (c. 2.4×)*
Total phosphorus	Higher (c. 3×)	Higher (c. 2.4×)

*falls above 1.5×interquartile range.

8.3 NOF (MfE 2017 and MfE 2019) assessments

Ministry for the Environment guidance on lake water quality can be found in the NOF guidelines of the NPSFM (MfE 2017). The NOF attribute bands generally apply to all New Zealand lakes, however, the total nitrogen attribute shown in Appendix B is specific to polymictic lakes, such as the Parangarahu Lakes. The NOF bands for water quality are based on annual medians of monthly samples, so the water quality data for the Parangarahu Lakes (being late summer samples) do not apply directly to the NOF data. However, the LakeSPI data are directly applicable to the NOF attributes, but these are only proposed attributes and have not yet been gazetted (MfE 2019). Each NOF band for each attribute has its own narrative describing the condition related to the band (Appendix B).

I have confidence that the NOF bottom lines reflect a threshold beyond which serious degradation has occurred. In my opinion, the other band thresholds are less exact in differentiating the various states as described in the narratives.

When the data for the Parangarahu Lakes are compared to the NOF guidelines, the inferred condition of the lakes spans the range from reference condition (Band A) to fair condition (Band C), with Lake Kohangatera generally showing better or similar condition to Kohangapiripiri (Table 9).

Table 9. *NOF bands for some attributes of the Parangarahu Lakes.*

	Kohangatera	Kohangapiripiri
Chlorophyll *a*	A/B	A/B
Total nitrogen	B	C
Total phosphorus	C	C
Native condition index*	B	B/C
Invasive impact index*	B	C

*from the proposed update to the NOF (MfE 2019)

8.4 deWinton (2016) assessment

The LakeSPI assessments of deWinton (2016) revealed that the integrity of the macrophyte community to be excellent and stable for Lake Kohangatera and high but unstable for Lake Kohangapiripiri. The latter lake declined to a “moderate” condition in 2016 (Table 10), but deWinton (2016) suggested that this was due to a naturally low water level at the time of sampling and that the lake had a high chance of recovery with the ending of the 2016 drought.

The LakeSPI measurements for the lakes were collected in a way that is consistent with the national survey of lakes which is used to calibrate LakeSPI assessments. The assessment of condition is compared to over 300 similar assessments made on New Zealand lakes. Scores are adjusted for differences in lake depth, but not for other differences among lakes. I have a high degree of confidence that this assessment for the Parangarahu Lakes is accurate.

Table 10. *Summary of LakeSPI assessments from deWinton (2016).*

	Kohangatera	Kohangapiripiri
2011	Excellent	High
2013	Excellent	-
2016	Excellent	Moderate

8.5 PNRP outcomes assessment

The PNRP (GWRC 2015) sets outcomes and outcome thresholds for the Parangarahu Lakes, based on macrophyte community indicators which are assessed as part of LakeSPI assessments. The outcomes were met in 2011 for both lakes and was met in 2013 for Lake Kohangatera (Kohangapiripiri was not assessed). In 2016 Lake Kohangatera met the outcome while Kohangapiripiri did not (Table 11). Reasons for not meeting the outcome in 2016 are discussed in Section 8.4, above.

Table 11. *Summary of Proposed Natural Resources Plan outcome assessments*

	Kohangatera	Kohangapiripiri
2011	Met outcome	Met outcome
2013	Met outcome	-
2016	Met outcome	Did not meet outcome

The performance of the lakes in relation to the narrative outcomes for phytoplankton, nutrients and fish are more difficult to assess. However, in my opinion, they are very likely meeting the outcome for phytoplankton and probably meeting the outcome for nutrients. The fish community for Lake Kohangatera is also likely meeting its outcome, whereas Lake Kohangapiripiri is less likely to be meeting it.

9. Conclusions and Recommendations

The different assessment methods used in this report provide somewhat different perspectives on the current condition of the Parangarahu Lakes. However, the methods in which I have the greatest confidence in applying to the Parangarahu lakes data (Schallenberg 2019 and deWinton 2016) show that Lake Kohangatera is in an excellent condition, with some attributes indicating that it reflects a minimally impacted, reference condition for shallow lakes. Lake Kohangapiripiri, appears to be a little more degraded, particularly due to the influence of invasive macrophytes. Invasion by non-native macrophytes and their potential proliferation in the lakes would appear to be a threat to the long-term stable health of the lake ecosystems. However, the data show that Lake Kohangapiripiri is still in a relatively good condition for its lake type.

Both lakes have higher levels of total phosphorus than other minimally-impacted shallow lowland lakes. Phosphorus is a plant nutrient that can fuel both algal and macrophyte proliferations in lakes. While high phosphorus levels may be due to historical and/or natural factors related to catchment biogeochemistry, studies on phosphorus fluxes and cycling should be able to determine why phosphorus is unusually high in the lakes.

With phosphorus availability being relatively high, why are chlorophyll *a* concentrations so low in these lakes? Phytoplankton growth in these lakes is apparently controlled by factors other than phosphorus availability. Knowledge of which factors control phytoplankton growth in these lakes should be useful in effectively managing the lakes to safeguard their values.

Lake Kohangatera has consistently met its macrophyte outcome as outlined in the GWRCs PNRP, while Lake Kohangapiripiri failed to meet its macrophyte outcome in 2016. However, the low water levels at the time compromised the macrophyte community, which was expected to recover when the drought in 2016 broke (de Winton 2016). Although sufficient data and assessment thresholds are lacking, in my opinion the condition of the lakes is consistent with the phytoplankton, nutrient and fish outcome narratives in the PNRP, although the fish community in Lake Kohangapiripiri appears to be in a substantially poorer condition than that of Lake Kohangatera. As more water quality and fish data become available for the Parangarahu Lakes, it will be possible to set lake-specific outcome thresholds for further attributes for these lakes. In the meantime, the information provided in this report provides an indication of the appropriate condition of these lakes and such information could be used to help set outcomes and outcome thresholds.

To help safeguard the good condition of the Parangarahu Lakes, a number of monitoring and research recommendations are presented in Table 12.

Table 12. *Monitoring and scientific research recommendations to help safeguard the condition of the Parangarahu Lakes.*

Recommendations	
Monitoring	M1. Monitor water quality on a monthly basis for at least 1 year to inform water quality outcome thresholds for the lakes.
	M2. Carry on with LakeSPI monitoring at 5-yearly intervals.
	M3. Monitor temperature and dissolved oxygen in the bottom waters of the lakes using continuous DO sensors.
Science	S1. Carry out a study on factors limiting phytoplankton proliferation in the lakes.
	S2. Carry out a study to determine the reasons for high phosphorus levels in the lakes.

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11. Appendix A: Methods for determining the ecological integrity and reference conditions of shallow lakes

Schallenberg et al. (2011) defined ecological integrity (EI) for New Zealand freshwaters as having four essential components:

1. **Nativeness—**The degree to which the structural components of an ecosystem represent the native biota that are, or would have been, representative of the region.

2. **Pristineness—**The degree to which functional, structural and physicochemical components of an ecosystem reflect the processes that would be expected in an unmodified ecosystem. Pristineness also requires that the natural connectivity within and between ecosystems is maintained.

3. **Diversity—**The degree of taxonomic diversity or taxonomic richness of an ecosystem. Diversity may also include the evenness of species, i.e. how biomass is distributed among the constituents of biological communities, as measured by diversity indices.

4. **Resilience**—The degree to which structural and functional components of an ecosystem can return the ecosystem to its stable state after a perturbation. Resilience relates to an ecosystem's self-renewal capacity and long-term viability.

Lakes with high EI exhibit high values in all four components. Schallenberg et al. (2011) identified a number of metrics for quantifying each of the four components of EI.

Drake et al. (2011) also assessed EI in 43 shallow (maximum depth < c. 10m), lowland lakes using expert subjective assessments after site visits to the lakes. The lakes spanned from Northland to Southland and also included lakes on Stewart and Campbell Islands. The high degree of correlation between the EI rankings of the three experts ($r^2 > 0.80$) indicates that expert assessment can be a robust measure of lake EI. The expert EI rankings for the 43 lakes also correlated well with measures of water quality and biotic characteristics of the lakes, and also with inferred anthropogenic (e.g. catchment development, modelled nitrogen and phosphorus loading) and invasive species pressure scores.

Schallenberg and Kelly (2013) and Schallenberg (2019) undertook lake EI assessment by first classifying the shallow lakes into freshwater and brackish classes of lakes using a conductivity threshold of 1000 µS cm^{-2} to differentiate the two lake types. Based on the Greater Wellington Regional Council electrical conductance data, both Lakes Kohangatera (27 to 97 µS cm^{-2}) and Kohangapiripiri (57 to 136 µS cm^{-2}) are classed as freshwater lakes for the purposes of the following assessment. In the national database used for EI assessment, 36 lakes were classified as shallow, freshwater lakes (Schallenberg 2019).

To determine which lakes in the nationwide shallow lake survey most closely reflected reference conditions, first two independent indicators of EI were plotted against each other: (1) the expert-assessed EI ranking and (2) the percentage of the lakes' catchments with native vegetation cover at the time of the EI assessment (Schallenberg 2019). By correlating these two variables, lakes that represented both high catchment and lake integrity could be identified and it was those lakes that were inferred to reflect reference conditions (Fig. A1). Note that the lakes with the highest values of both these variables group together quite closely in the bivariate plot (Fig. A1).

The data for each lake in the dataset represented only one sampling, which is a limitation on the analysis because lake ecological conditions can vary somewhat from year-to-year. Furthermore, the inference of reference conditions by this method is somewhat normative. Therefore, two different standards of reference condition were defined from the dataset: Tier 1 reference lakes are those above the 90th percentiles for both EI rank and % catchment in native vegetation, while Tier 2 reference lakes are those above the 80th percentiles for EI rank and % catchment in native vegetation (Fig. A1). Thus, Tier 1 reference conditions reflect a slightly higher EI reference standard that Tier 2 reference lakes.

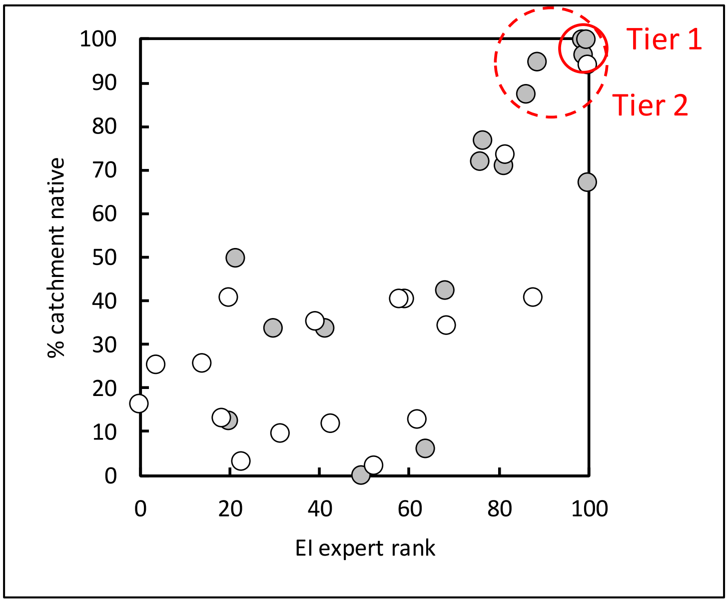

Figure A1. Derivation of Tier 1 (90th percentile) and Tier 2 (80th percentile) reference lakes from a dataset of 36 shallow, lowland, freshwater lakes. Filled circles are South Island lakes and open circles are North Island lakes.

Having determined two correlated but independent indicators of EI, it was then possible to determine the reference conditions for various measured attributes of the lakes by identifying where the reference lake were positioned in a biplot of lake attribute vs. EI. This was done by correlating lake attributes measured in the 36 lakes (e.g., water quality and ecological attributes) against each of the two EI indicators (Schallenberg 2019). If the relationships were significant or at least meaningful, the reference condition ranges and thresholds in the measured lake attributes were estimated from the distribution of the reference lakes in the bi-plots (e.g., Fig. 4).

12. Appendix B: NOF attributes

Putative placement of Parangarahu Lakes (highlighted green) into quality groups or bands for water quality (MfE 2017) and macrophyte community health according to LakeSPI (MfE 2019). LakeSPI attributes are currently proposed and, have not yet been officially gazetted.

Chlorophyll *a* (μg L^{-1})	Annual median	Annual maximum	Narrative	Kohangatera (median)	Kohangapiripiri (median)
A	≤2	≤10	Lake ecological communities are healthy and resilient, similar to natural reference conditions.	<3	<3
B	>2 and ≤5	>10 and ≤25	Lake ecological communities are slightly impacted by additional algal and/or plant growth arising from nutrient levels that are elevated above natural reference conditions.	<3	<3
C	>5 and ≤12	>25 and ≤60	Lake ecological communities are moderately impacted by additional algal and plant growth arising from nutrient levels that are elevated well above natural reference conditions. Reduced water clarity is likely to affect habitat available for native macrophytes.		
National Bottom Line	**12**	**60**			
D	>12	>60	Lake ecological communities have undergone or are at high risk of a regime shift to a persistent, degraded state (without native macrophyte/ seagrass cover), due to impacts of elevated nutrients leading to excessive algal and/or plant growth, as well as from losing oxygen		

			in bottom waters of deep lakes.		
Total nitrogen (µg L^{-1})		Annual median (polymictic)	Narrative	Kohangatera (median)	Kohangapiripiri (median)
A		≤300	Lake ecological communities are healthy and resilient, similar to natural reference conditions.		
B		>300 and ≤500	Lake ecological communities are slightly impacted by additional algal and/ or plant growth arising from nutrient levels that are elevated above natural reference conditions.	490	
C		>500 and ≤800	Lake ecological communities are moderately impacted by additional algal and plant growth arising from nutrient levels that are elevated well above natural reference conditions.		610
National Bottom Line		**800**			
D		>800	Lake ecological communities have undergone or are at high risk of a regime shift to a persistent, degraded state, (without native macrophyte/seagrass cover) due to impacts of elevated nutrients leading to excessive algal and/or plant growth, as well as from losing oxygen in bottom waters of deep lakes.		

Total phosphorus (µg L^{-1})		Annual median	Narrative	Kohangatera (median)	Kohangapiripiri (median)
A		≤10	Lake ecological communities are healthy and resilient, similar to natural reference conditions.		
B		>10 and ≤20	Lake ecological communities are slightly impacted by additional algal and plant growth arising from nutrient levels that are elevated above natural reference conditions.		
C		>20 and ≤50	Lake ecological communities are moderately impacted by additional algal and plant growth arising from nutrient levels that are elevated well above natural reference conditions.	42	34
National Bottom Line		50			
D		>50	Lake ecological communities have undergone or are at high risk of a regime shift to a persistent, degraded state (without native macrophyte/seagrass cover), due to impacts of elevated nutrients leading to excessive algal and/or plant growth, as well as from losing oxygen in bottom waters of deep lakes.		

LakeSPI Native condition index		Percent of maximum potential score	Narrative	Kohangatera	Kohangapiripiri
A		>75%	Excellent ecological condition. Native submerged plant communities are almost completely intact.		
B		50% to 75%	High ecological condition. Native submerged plant communities are largely intact.	83% (2011) 83% (2013) 81% (2016)	73% (2011)
C		20% to 50%	Moderate ecological condition. Native submerged plant communities are moderately impacted.		36% (2016)
National Bottom Line		20%			
D		<20%	Poor ecological condition. Native submerged plant communities are largely degraded or absent.		

LakeSPI Invasive impact index		Percent of maximum potential score	Narrative	Kohangatera	Kohangapiripiri
A		0	No invasive plants present in the lake. Native plant communities remain intact.		
B		1% to 25%	Invasive plants having only a minor impact on native vegetation. Invasive plants will be patchy in nature co-existing with native vegetation. Often major weed species not present or in early stages of invasion.	5% (2011) 8% (2013) 16% (2016)	
C		26% to 90%	Invasive plants having a moderate to high impact on native vegetation. Native plant communities likely displaced by invasive weed beds particularly in the 2 – 8 m depth range.		38% (2011) 61% (2016)
National Bottom Line		90%			
D		>90	Tall dense weed beds exclude native vegetation and dominate entire depth range of plant growth. Species concerned likely hornwort and Egeria.		