Waikato Regional Council Technical Report 2021/26

State of the environment monitoring Waikato lake water quality

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Disclaimer

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Abstract

The present report describes the current and past state of water quality, and its trends, within the Waikato Regional Council State of the Environment (SOE) lakes monitoring network. The Waikato regions shallow lakes are under pressure from a combination of factors, including nutrient loads above critical loading, impacts of pest fish, lake level fluctuations, climate change and in many lakes hysteresis and negative feedback loops derived from alternative turbid stable states. For example, hysteresis in turbid Waikato lakes prevents a barrier to restoration based on the past history of lake water quality degradation, and a negative feedback loop example would be increased turbidity resulting from the loss of macrophytes (submerged plants), which then prevents macrophyte establishment due to light limitation caused by high turbidity. Lake water quality was assessed using National Policy Statement for Freshwater (NPS-FM 2020) bands. Most shallow Waikato lakes were below the national bottom line for at least one attribute, and there has been degradation of water quality from baseline state. Future planning will require lake specific action plans to address lakes not meeting targets, which will include identifying environmental outcomes for target attributes. These action plans could include land-use control and catchment load limit setting or targeted within lake restoration options. However, success or failure of shallow lake restoration will depend on addressing key challenges to shallow lake restoration which are in order of priority; sufficient reductions in external load and subsequent internal load control to address hysteresis and negative feedback loops preventing macrophyte reestablishment, providing limits that are resilient to climate change, and the need for lake specific approaches. Lake specific approaches are also required to protect lakes that have not yet flipped into an alternative stable state. This is critical, as the costs of prevention are far lower than those that will be required in a lake facing hysteresis (flipped lake).

Executive summary

The present report describes the current and past state of water quality, and its inherent trends, within the Waikato Regional Council State of the Environment (SOE) lakes monitoring network.

The Waikato regions shallow lakes are under pressure from a combination of factors, including nutrient loads well above critical loading, impacts of pest fish, lake level fluctuations, climate change and in many lakes hysteresis and negative feedback loops derived from alternative turbid stable states. Lake water quality was assessed using National Policy Statement for Freshwater (NPS-FM 2020) bands, and results show that most shallow Waikato lakes are below the national bottom line for at least one attribute. Since monitoring began, there has been more degradation in total suspended solids (TSS), total nitrogen (TN) and water clarity, and improving trend in chlorophyll a (CHLA) and total phosphorus (TP).

Of the twelve long term monitoring lakes, marked water quality degradation monitored (and inferred from observations) in peat and riverine lakes in the late 1970’s (Waikare macrophyte collapse) 1980’s and 1990’s has not been observed post year 2000, however many lakes are hypertrophic, and have “flipped” into an alternative stable state dominated by suspended sediment and phytoplankton. The last SOE report evaluated water quality trends since the early 1980s and showed water quality had deteriorated at Lake Rotomanuka and Lake Ngaroto, but improved at Lake Waahi (Environment Waikato, 1998). We note that the water quality of Lake Waahi has degraded since 1998, and further degradation of Lake Rotomanka has occurred in terms of TN, TSS and Secchi depth (however TP and CHLA have improving trends).

In contrast to riverine lakes, some peat and dune lakes still contain macrophytes and have relatively good water quality (e.g., Lake Rotomanuka and Rotopiko North/East). However, some lakes are degraded, and are not responding to lake restoration initiatives (e.g. Lake Ngaroto). Long term trend analysis at all 12 long term sites indicates a general increase in TN and TSS concentrations, and a general decrease in TP. However over shorter timescales (3-5 years) notable reductions in TLI have occurred in six out of 12 long term monitoring SOE lake sites. We note here that on time scales of 3-5 years, there is potential for climate driven changes in water quality to dominate those derived from changes within lake catchments (Snelder et al. 2021). In particular, lower rainfall in the past few years could be responsible for decreased nutrient loading to lakes.

NPS-FM 2020 requires lake specific action plans to address lakes not meeting national bottom lines, which will include identifying environmental outcomes for target attributes. These action plans could include land-use control and catchment load limit setting or targeted within lake restoration options. Success or failure of shallow lake restoration will depend on addressing key challenges to shallow lake restoration which are in order of priority; sufficient reductions in external load and subsequent internal load control to address hysteresis and negative feedback loops preventing macrophyte reestablishment, providing limits that are resilient to climate change, and the need for lake specific approaches. Lake specific approaches are also required to protect lakes that have not yet flipped into an alternative stable state. Lake specific approaches are also required to protect lakes that have not yet flipped into an alternative stable state. This is critical, as the costs of prevention are far lower than those that will be required in a lake facing hysteresis (flipped lake).

1 Introduction

The first Waikato State of the Environment Report was published in 1998, by Environment Waikato, now Waikato Regional Council (Environment Waikato 1998). It covered the five years up to 1 January 1998 and presented selected "Environmental Indicators", used to summarise data and show temporal trends. Specifically for the indicator "Water Quality and Biodiversity in Lakes" the following parameters were considered relevant: water clarity; oxygen concentrations and oxygen depletion rates (stratified lakes only); microbiological faecal indicators (*E.coli*); level of nutrient enrichment (trophic status); water level control/maintenance; change in land cover/land use; health and condition of lake margins; presence/absence of pests. It adopted a framework of Pressure-State-Response (PSR) to report its findings, the most relevant being that the condition of many Waikato lakes was the result of poor land management practices in surrounding catchments.

Peat and riverine lakes, particularly in the Lower Waikato, showed a decline in water quality that could be directly attributed to nutrient inflows from adjacent land; to reduction in lake size and depth due to drainage; to sediment discharge; to the removal of riparian vegetation and to the introduction of invasive aquatic weeds. Most dune lakes had been modified by vegetation clearance, impacting the catchments around those areas. Lake Taupo, due to its size and importance, had historically been addressed separately from all other lakes (including other volcanic lakes). Additionally, unlike other lakes in the Waikato, the trends seen at Lake Taupo suggested a continued improvement of overall water quality. Despite the stated intention of issuing a State of the Environment Report every five years the fact is that since 1998 no such comprehensive exercise has been undertaken. However, other reports have characterised the environmental state of Waikato lakes in that period (Abell 2018; Pearman et al. 2021).

More recently, national reports such as *Our fresh water 2017* or *Environment Aotearoa 2019* have contributed to provide a picture of the national environmental conditions, detailing regional variations whenever possible (Ministry for the Environment & Stats NZ, 2017; 2019). *Our fresh water 2017* started by recognising the existence of several gaps in the available information that might constraint the confidence in the conclusions. The report specified that information on the effect that land-use and land-management practices have on freshwater quality was an information gap. This is even more relevant for lakes, as currently less than 5 % of New Zealand's lakes larger than 1 ha are monitored, although the Waikato region is relatively well represented in this dataset.

Our fresh water 2017 reported that most monitored lakes meet national bottom lines, assessed in terms of ecosystem health toxicity (ammoniacal nitrogen) and ecosystem health trophic state (total nitrogen, total phosphorus, and phytoplankton biomass, measured as chlorophyll *a*). However, when looking at the trophic level index (TLI), the better part of the monitored lakes were rated poor or very poor, which indicates risk of degradation in lake ecological communities (TLI is a numerical indicator of eutrophication integrating four indicators; total nitrogen, total phosphorus, chlorophyll a and Secchi depth). It should be mentioned that the network of monitored lakes is biased towards lakes with known water quality issues. For that reason, trends in water quality are particularly difficult to assess. Microbial pathogens, such as *E. coli*, are monitored at very few lakes and data for the Waikato region is scarce (Larned et al. 2019). Another index used to provide an indication of the ecological condition of lakes is the submerged plant index (LakeSPI). LakeSPI includes a native condition index, invasive impact index, and overall LakeSPI index which provides a single index of overall condition. LakeSPI results showed that nationally, most of surveyed lakes were in good ecological condition, however it was highlighted that only 10 % of the lakes didn't show invasive plant species. *Our fresh water 2017* included results from the first cultural health index of freshwater sites, assessed and reported by tangata whenua. The assessed sites concerned riverine locations; however, it is expected that in the future lakes could be assessed similarly.

Environment Aotearoa 2019 employed a whole system approach to report on the state of the environment, recognising that most of the issues deemed a priority are transversal to several ecosystems. Amongst those identified as a priority issue was "Our waterways are polluted in farming areas" (Priority Issue 4). It reported clear evidence that waterways in farming areas (such as the Waikato region) have higher pollution by nutrients (nitrogen and phosphorus), microbial pathogens, and sediment than waterways in native catchments.

The present report describes the current and past state of water quality, and trends, within the Waikato Regional Council State of the Environment (SOE) lakes monitoring network, excluding Lake Taupo which is covered in a separate technical report (Vant and Hadfield, 2022). This report follows in the footsteps of *Environment Aotearoa 2019*, which adopted a Pressure-State-Impact (PSI) framework for reporting and extends it by adopting a Drivers–Pressures–State-Impact-Response (DPSIR) framework, following the recommendations of the Parliamentary Commissioner for the Environment (2019). Information presented in this report contributes to fulfil the principles of *Kaitiakitanga* and *Governance*, ensuring that fresh water is managed in a way that gives effect to Te Mana o te Wai principles stated in the National Policy Statement for Freshwater Management (Ministry for the Environment 2020).

State and trends are considered in the DPSIR framework or conceptual model (Fig. 1), however some drivers and pressures are considered in other technical reports which contribute to overall knowledge on state of the environment.

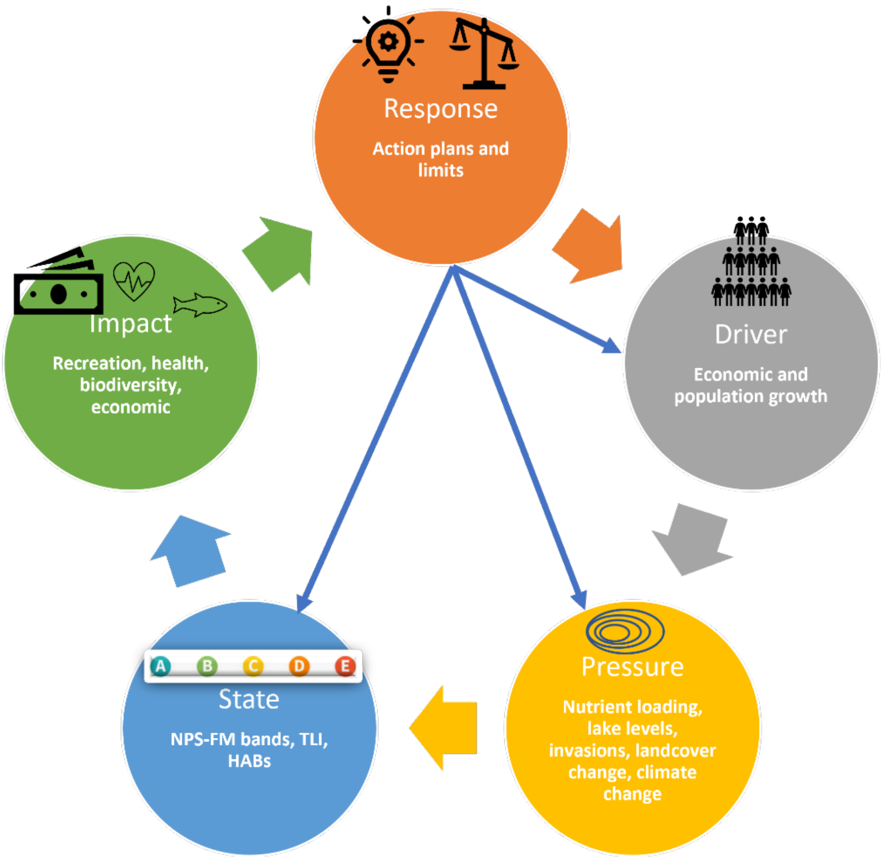

Figure 1. Driver, Pressure, State, Impact, and Response (DPSIR) framework or conceptual model for lakes. HAB is harmful algal bloom.

Lakes are considered to have a current state as defined by the National Policy Statement for Freshwater (NPS-FM 2020) (MfE 2020), generally for a five-year period from 2017-01-01 until 2021-12-31. Baseline state for long term monitoring sites (Fig. 3) used samples collected from 2012-09-08 until 2017-09-07.

2 Methods

2.1 Monitoring network

Out of the 232 Waikato lakes identified in the Freshwater Ecosystems of New Zealand (FENZ) database (Leathwick et al. 2010) alongside other lakes not in FENZ, there were 109 lakes that were assesed as being lakes by defintion (Fig. 2) and deemed a managable ecosystem type. A lake is defined in the regional plan (WRC 2012) and the RMA as a body of fresh water which is entirely or nearly surrounded by land. Johnson & Gerbeaux (2004) define a lake as a large body of water surrounded by land, its major dimension generally 0.5 km or more, though smaller bodies of water can be validly referred to as lakes on the basis of depth, permanence, or local custom (Johnson & Gerbeaux, 2004). Many of the lakes within the FENZ database were deemed to be too small, actually wetlands, or not lakes by the definitions above.

Many of riverine lakes are located in the Lower Waikato zone, with most peat lakes located in Middle Waikato and Waipa zones, and dune lakes scattered along the West Coast zone. Artificial lakes are mostly associated with Lake Taupo inflows and dams on the Waikato river. Volcanic lakes are generally present in the Lake Taupo catchment and the Upper Waikato (Fig. 2).

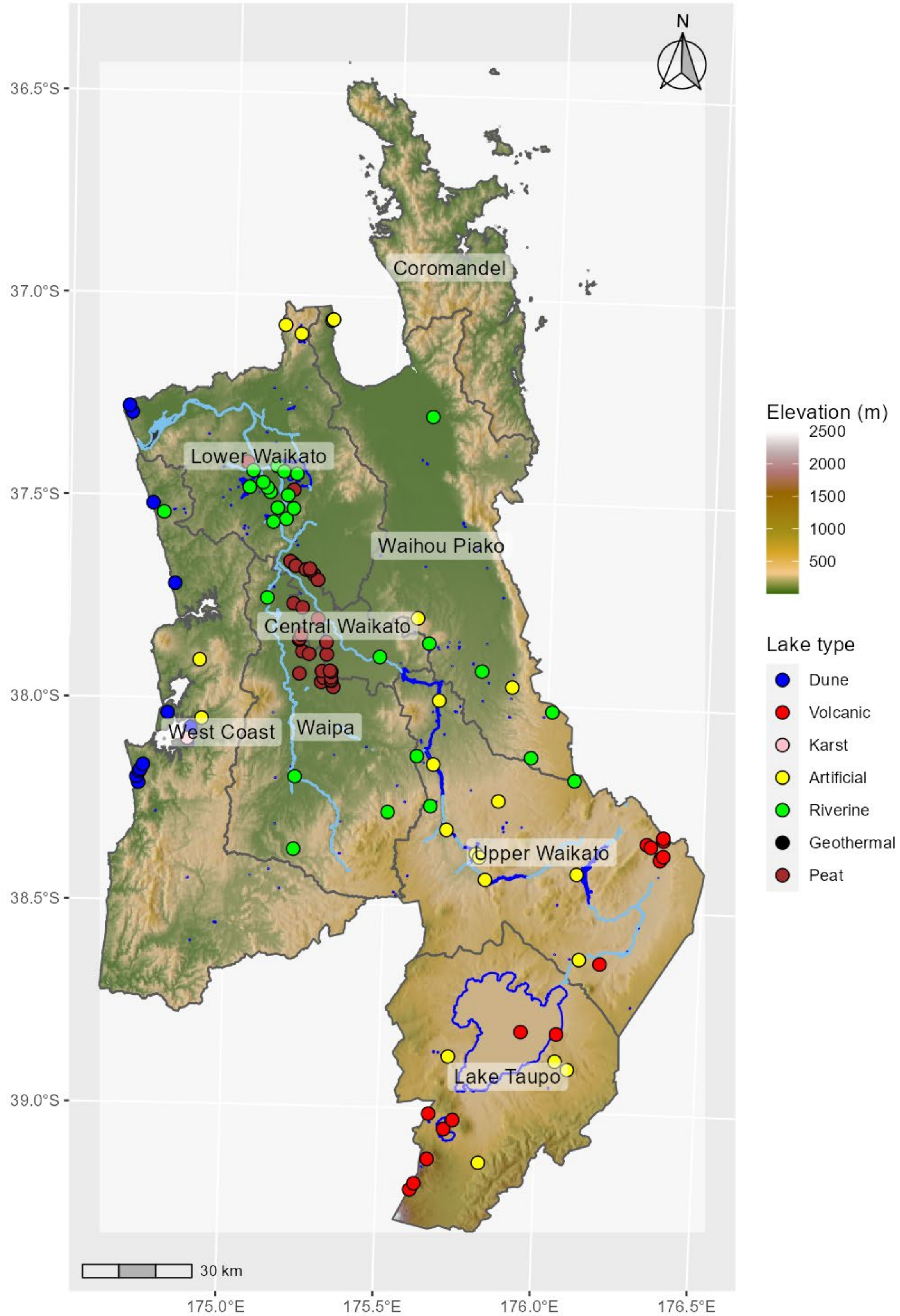

Figure 2. The 109 lakes from the FENZ database that have been checked and identified as being actual lakes. Note that lakes less than 1 ha were not necessarily included in FENZ.

Historically there are 12 long term monitoring lake sites in the Waikato region (Fig. 3) which are legacy sites, however requirements of the NPS-FM 2020 meant a redesigned monitoring network was needed to achieve representativeness at a regional and freshwater management scale. A probabilistic network was designed, aiming at generating sample representativeness through randomisation. The goal of the network was to generate an un-biased estimate of regional trophic state and NPS-FM 2020 current state. This estimate allows inferences about unmonitored lakes.

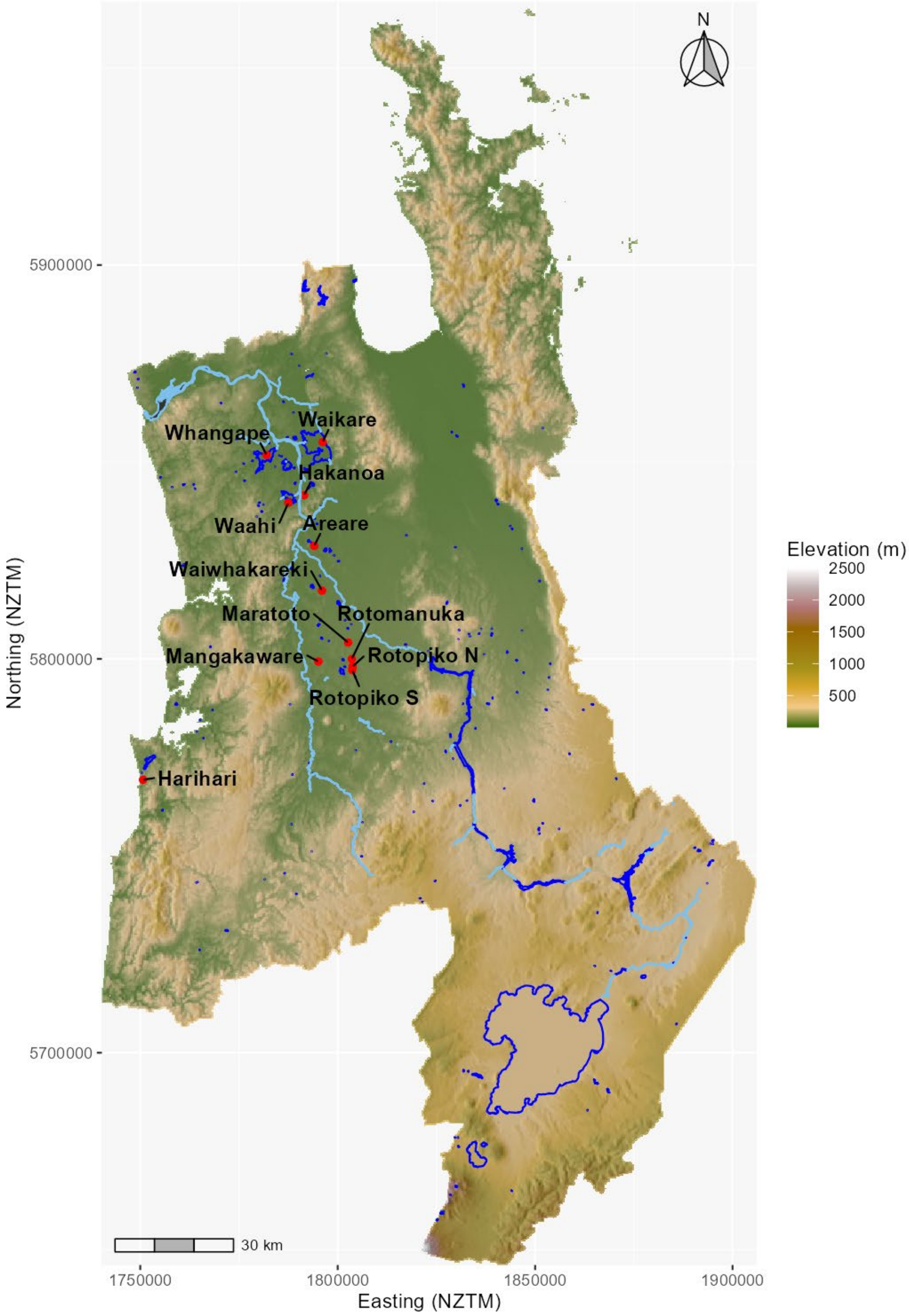

Figure 3. Twelve long term monitoring sites which are legacy monitoring sites also included in the new 38 lake monitoring network.

A lake sample frame was selected which included all natural and perennial lakes greater than 1 ha in size (n=81). Geothermal and artificial lakes were excluded (volcanic lakes were included), alongside Lake Taupo, which has an individual monitoring programme.

The number of lakes to enable reasonable precision was 38, calculated through a power analysis, and included 14 replacement lakes. Site selection was based on a Generalized Random-Tessellation Stratified (GRTS) algorithm. Sample design for the lake was unstratified, equal probability.

Through this design, a number of limitations were identified. Firstly, the relatively large number of selected sites compared to the size of the sample frame (not ideal for GRTS algorithm). Full spatial balance is difficult to achieve due to naturally occurring lake clusters in the landscape. All lakes had equal probability of being selected - no weighting was given to lake “importance” (i.e., all lakes are important). Incorporating “legacy” sites (i.e., existing long-term and special interest sites) into the network was required to maintain usefulness of long-term data sets.

The new SOE 38 lakes programme commenced in July 2019, with sites added periodically until the full 38 lakes programme was active in May 2021 (Fig. 4). Until the new SOE monitoring network was in place, sampling frequency varied between monthly and bi-monthly depending on site and year, with sampling frequency moving to monthly for all sites under the 38 lakes SOE network. Included within these 38 lakes are designated lake Freshwater Management Units (FMU) including dune, riverine, volcanic and peat lake catchments.

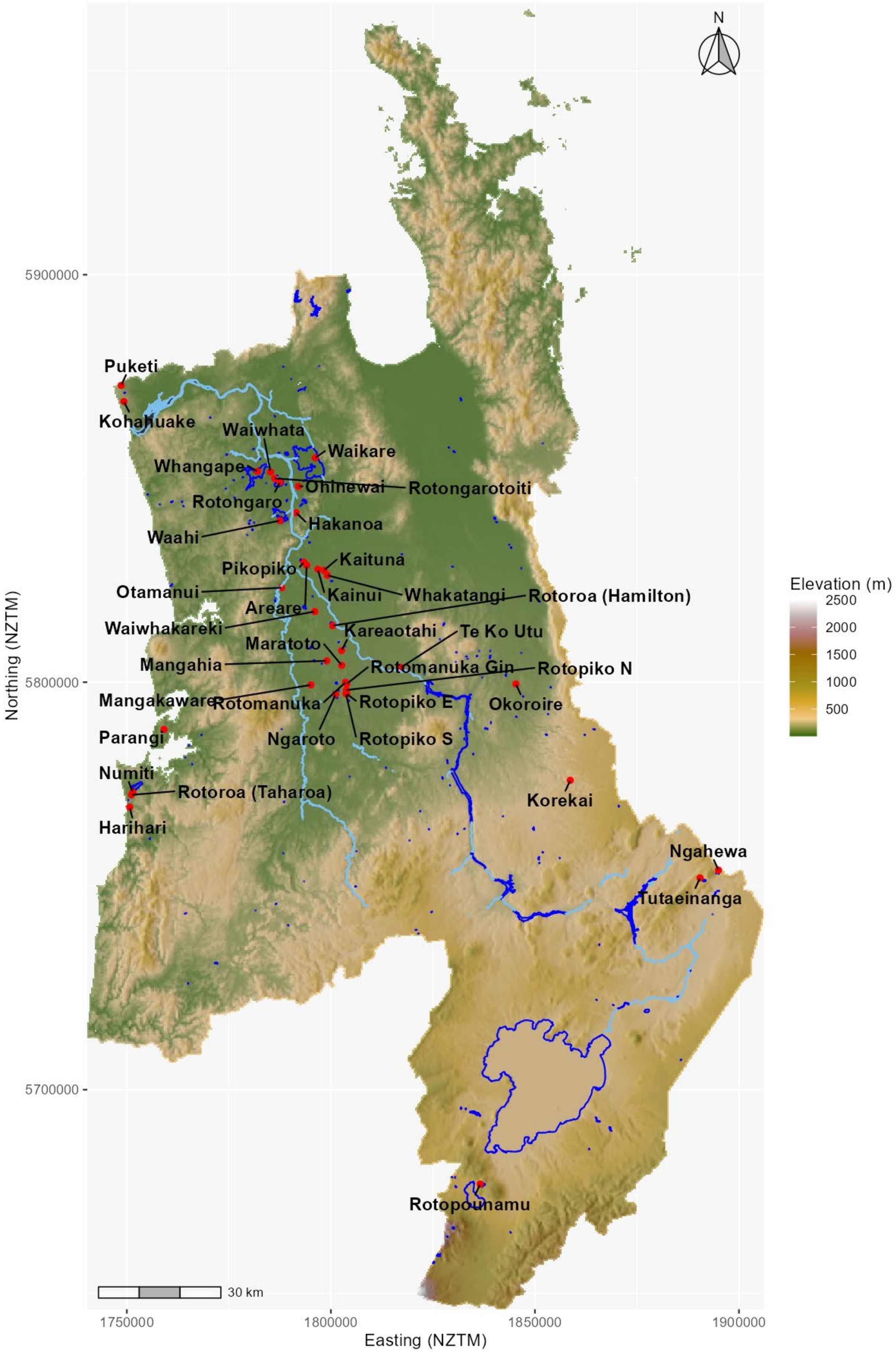

Figure 4. The 38 SOE network monitored lakes within the Waikato.

2.2 Autonomous monitoring buoys

Waikato Regional Council owns and operates autonomous lake monitoring buoy platforms in Lakes Ngaroto, Whangape, Waahi and Lake Waikare. These monitoring platforms take water quality and meteorological measurements every 15 minutes, which are telemetered to WRC. The four buoys are generally similar, but differ in the types and number of sensors installed. The Ngaroto buoy was originally commissioned by Waipa District Council. Ownership and management of the buoy was transferred to Waikato Regional Council in July 2017.

The meteorological variables on these buoys include wind speed, wind gust and direction, air temperature, relative humidity, and barometric pressure. Water quality variables include surface and bottom dissolved oxygen, chlorophyll fluorescence and phycocyanin, water temperature at regular intervals through the water column, and turbidity. Real time data is currently transmitted to HydroQuest Solutions Ltd (McBride 2017). The data from these buoys is not used in the present report as it is not representative of SOE, but rather special interest sites.

2.3 NPS-FM 2020 attributes

Lakes are considered to have a current state as defined by the NPS-FM 2020 (Ministry for the Environment 2020), generally for a five-year period from 2016-01-01 until 2021-12-31. However, for some lakes this state is provisional, and uses available data collected over a shorter and more recent time period. Baseline state for long term monitoring sites (**Error! Reference source not found.**) used samples collected from 2012-09-08 until 2017-09-07.

Seasonally stratifying lakes were defined as having an average yearly thermocline depth of greater than 2 m and predicted to stratify using the equation from Davies-Colley (1988). Twelve lakes met this criterion, and where possible these lakes were checked using colour contour plots of water temperature. Note that this is a preliminary analysis using the best available data. As more data is collected on recently added SOE lakes, estimations of stratification will improve. Thermocline depth was calculated using the Lake Analyzer R package (Winslow et al 2019). Mid-hypolimnion was approximated as half of lake profile depth below thermocline. Only monthly or bi-monthly dissolved oxygen and temperature profiles were used (no high frequency data).

Water quality state was assessed based on attributes and attribute state bands defined by NPS-FM 2020 (Table 1).

Table 1. Lake water quality variables relating to NPS-FM 2020 attribute value and numeric attribute.

NPS-FM NOF attribute	Value	Numeric attribute	Period	Plan/Limit	Units
Phytoplankton (trophic state)	Ecosystem health (Aquatic Life)	Annual median and maximum	5	Limit	mg chl-a m^{-3}
TN	Ecosystem health (Aquatic Life)	Annual median stratified and polymictic	5	Limit	mg chl-a m^{-3}
TP	Ecosystem health (Aquatic Life)	Annual median	5	Limit	mg chl-a m^{-3}
Ammonia (toxicity)	Ecosystem health (Aquatic Life)	Annual median, Annual maximum	5	Limit	mg chl-a m^{-3}
Submerged plants (natives)	Ecosystem health (Aquatic Life)	Lake Submerged Plant (Native Condition Index)		Plan	Index
Submerged plants (invasive species)	Ecosystem health (Aquatic Life)	Lake Submerged Plant (Invasive Impact Index)		Plan	Index
Lake-bottom dissolved oxygen	Ecosystem health (Water quality)	Measured or estimated annual minimum	5	Limit	mg L^{-1}

Mid-hypolimnetic dissolved oxygen	Ecosystem health (Water quality)	Measured or estimated annual minimum	5	Limit	
Escherichia coli (E. coli)	Human contact	% exceedances over 540/100 mL % exceedances over 260/100 mL Median concentration/100 mL) 95th percentile of E. coli/100 mL	max 5 (min 60 samples). Bathing season.	Limit	CFU 100 mL^{-1}
Escherichia coli (E. coli) (primary contact sites)	Human contact	95th percentile of E. coli/100 mL		Plan, lakes with a perimeter of 1.5 km or more	CFU 100 mL^{-1}
Cyanobacteria (planktonic)	Human contact	80th percentile (min 12 samples)	3	Limit	Biovolume (mm^3 L^{-1})

2.4 Zooplankton

Zooplankton samples were collected from three vertical hauls (haul speed 1 ms^{-1}). These samples were immediately fixed in isopropyl alcohol according to the methods of Duggan et al. (2001) and sent to The University of Waikato for taxonomic identification and enumeration. A Rotifer Trophic Level Index (TLI) was calculated for each lake. This index is based on a study by Duggan (2001) that indicated that lake trophic state was a major determinant controlling rotifer species distribution among North Island lakes, including the lake type sampled during the present survey. Based on the response of rotifers to nutrient enrichment (i.e. eutrophication), a quantitative bioindicator rotifer index was developed. In the laboratory rotifer samples were enumerated where possible until a total of at least 100 individuals of “indicator species” were recorded, i.e., species that have an assigned TLI optima and tolerance score given by Duggan et al. (2001). Based on the resulting lists, the bioindicator method was used to determine lake trophic state. All identifications were made to species level wherever possible.

2.5 Phytoplankton

Phytoplankton samples were collected using sub-surface scoops of unfiltered water. Samples were immediately preserved using Lugol's Iodine and placed in the dark until analysis. Phytoplankton identification and enumeration was carried to genus level by The National Institute of Water and Atmospheric Research (NIWA, Hamilton) using standard analytical procedures and abundances were recorded in cells $mL\text{-}^{1}$ and biovolume (mm^3 L^{-1}).

2.6 Water chemistry

In the field, dissolved oxygen and temperature profiles of the lakes were evaluated using standardised WRC protocols, along with Secchi depth (m). Water samples were collected from each lake by WRC staff and placed immediately on ice using standardised WRC protocols (Burns et al. 2000). Samples were sent to Hill laboratories in Hamilton for nutrient analyses using standard protocols. A range of water quality parameters were assessed including total nitrogen, total phosphorus, and chlorophyll *a* concentration (all units are g/m^3). However, it is noted here that from 2004-12 there were changes made to the laboratory methods used for TP and DRP (Vant 2018).

2.7 Trend analysis methods

Trend analysis used the LWP Trends Library Version 2102, based on the work of McBride (2018) and Snelder and Fraser (2021). The method assumes that water quality data will show either an increasing or decreasing trend over time.

Data are first tested for seasonal effects and either analyses with a seasonal or non-seasonal non-parametric Mann-Kendall Slope Test (seasonal analysis was used for all lakes). The test evaluates pairwise combinations of the data and comparing temporal change from earlier and later observations for each pair. The magnitude of this change is not considered, only the sign. As Waikato lake water quality data had variable sampling frequency between monthly and bi-monthly for different years, the limited monthly observations (quarterly analysis) example within LWP script was applied. Sites that do not meet the requirements for trend analysis are reported as 'not assessed'.

3 Results

3.1 Pressures

Pressures on lake ecosystems can be either direct (e.g., fish harvesting), or indirect (e.g., internal and external nutrient loading) (Schallenberg et al. 2013). In New Zealand lakes, regime shifts whereby a lake can "flip" into an alternate stable state, related to lake eutrophication, have been primarily related to deforestation, agricultural intensification and introduced aquatic taxa (Schallenberg & Sorrell 2009). In a 2009 study of 37 known regime shifting lakes, 14 Waikato lakes were included. Regime shifts were generally associated with lakes with greater than 30 % catchment pasture. In addition, the presence of introduced *E. densa* and presence of introduced fish *A. nebulosus* (brown bullhead), *Carassius aurantus* (goldfish), *Scardinius erythrophthalamus* (rudd), *Tinca tinca* (tench), and *Ca. carpio* (koi carp) were positively associated with regime shifts. Generally shallow lakes are shown to be more susceptible to regime shifts (Schallenberg & Sorrell, 2009; Genkai-Kato & Carpenter 2005).

A pest fish implementation plan in the Waikato region identified some key actions for addressing pest fish populations in the Waikato Region. This included a partnership between DOC and WRC to co-ordinate the organizations freshwater biosecurity work (Archer and McKenzie 2018). A lake prioritization tool was developed which summarised knowledge on pest fish distribution in Waikato lakes, recommending lake specific actions. A total of 51 lakes (or clusters of lakes) were reviewed, with 12 lakes being identified as containing koi carp (all hypertrophic). Forty of the lake sites contained at least one species of pest fish.

Climate change is likely to enhance eutrophication by enhancing nutrient cycling (decomposition, mineralisation, oxygen depletion), biological growth rates, phenology shifts, stratification, increased precipitation, and storm flows will likely increase loads to lakes (storm flows and nitrate in rainwater) (Schallenberg et al. 2013). Climate change could also increase algal production and increase the dominance of cyanobacteria, increasing the frequency of harmful algal blooms (Rolighed et al. 2016; Trolle et al. 2011). Climate change is likely increasing severity and frequency of storms and droughts, resulting in increased water level fluctuation, and increased pressures on ecological communities, especially submerged macrophytes. In addition, turbidity will likely increase due to increase in resuspension and algal growth (Schallenberg et al. 2013).

Alongside pasture extent, indirect pressures include stocking rates, farming systems and fertiliser application. In 19 out of 38 SOE lakes, stocking rates have increased from 2002 till 2019 (Fig. 5, Fig. 6). Stocking rate is calculated by converting farm animals to a common stock unit and dividing by the area of land that the stock graze on. FENZ catchments were used for this analysis. Stock numbers are derived from the AgriQuality AgriBase database. Peat lakes have generally had both the largest increase and decrease in stocking density. Apart from Lake Hakanoa and Te Koutu (which have partly/all urban catchments), all riverine lakes have undergone increased stocking density. Volcanic lakes have generally undergone stocking density reductions or no change. Generally, the highest current stocking density is observed in peat lake catchments.

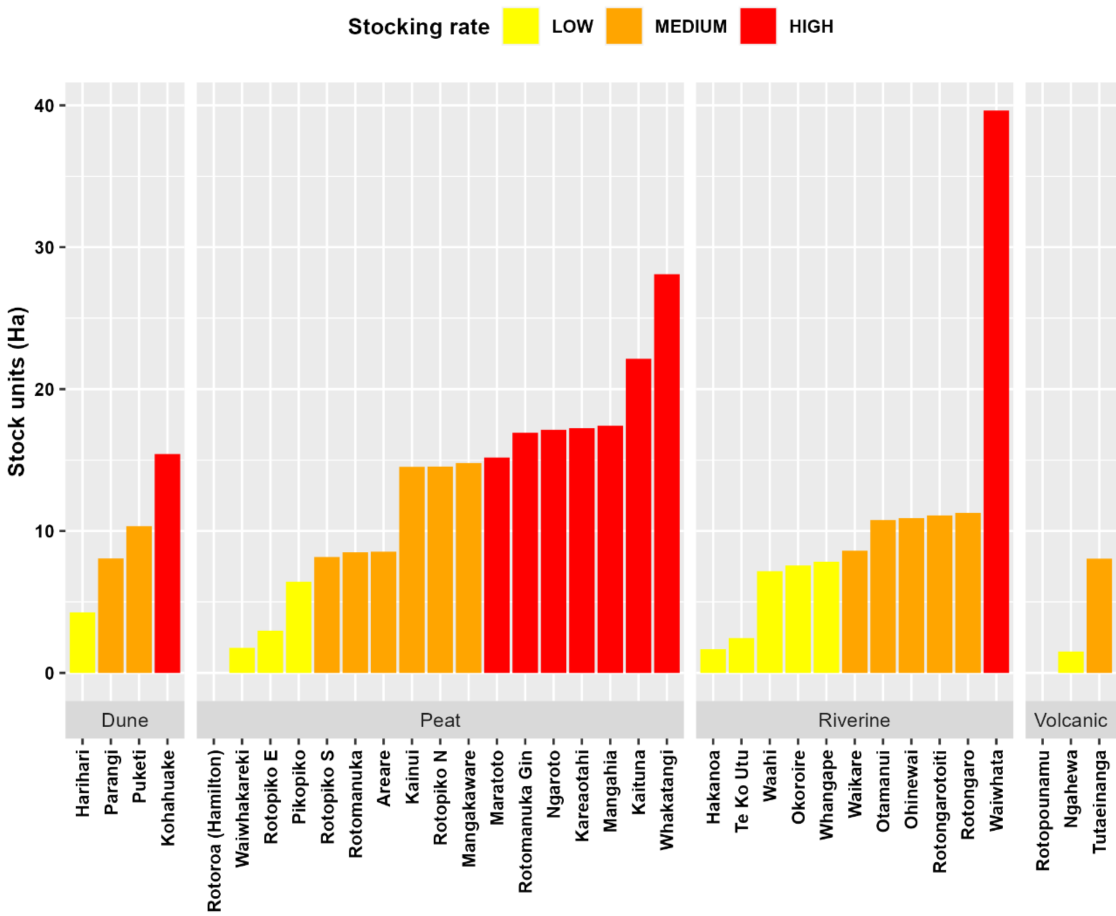

Figure 5. Stock units per hectare in 2019.

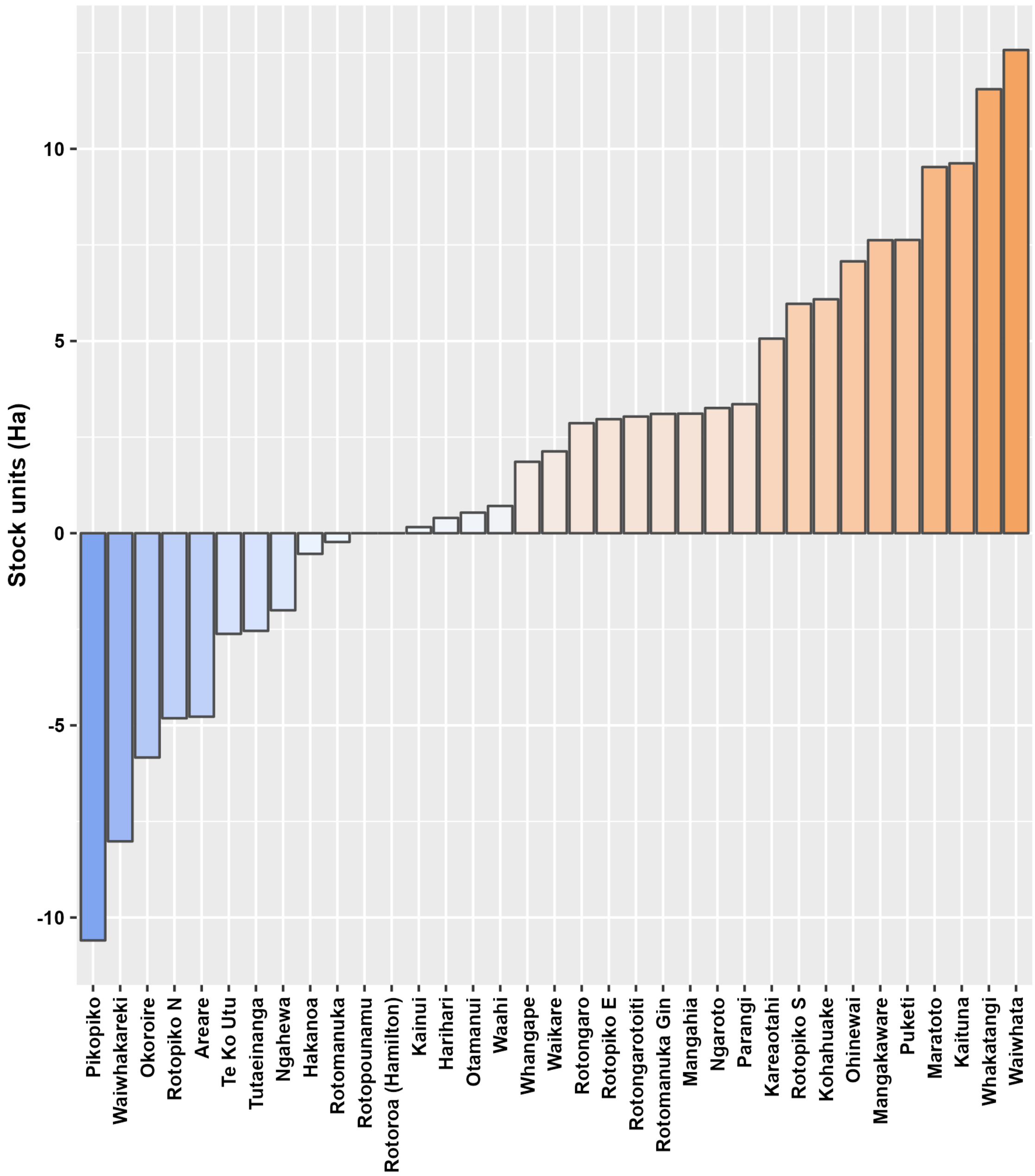

Figure 6. Change in areal stocking rates from 2002 to 2019.

3.2 Macrophytes

Lake Submerged Plant Indicators (LakeSPI) have been applied to survey submerged macrophyte condition since 2003 (Edwards et al. 2008), however in most lakes multiple surveys over time have not been carried out. This data includes native condition index, invasive impact index and LakeSPI index (overall indication of ecological condition) up to the year 2018.

Out of 64 lakes which have been surveyed since 2003, for status, 31 are non-vegetated, 12 lakes are poor, 12 lakes are moderate, two lakes are high, and two lakes are excellent (Fig. 7 Fig. 8). Most non-vegetated lakes were found in peat lake systems; however, all riverine lakes were non-vegetated (Fig. 8). Excellent lakes included Serpentine North (SPI index 80) and Koraha (SPI index 97). Lake Koroha is a karst lake which has the highest index out of any lake nationally, and no invasive species (Fig. 9). It's likely that this site attains its high index due to the lack of pressures, combined with isolation. The lake was dominated by charophytes (*Nitella cristata*) and bryophytes (*Drepandocladus aduncus*) to a depth 2.6 m, with *Potamogeton ochreatus* found in deeper areas. *Myriophyllum propinquum* was also present.

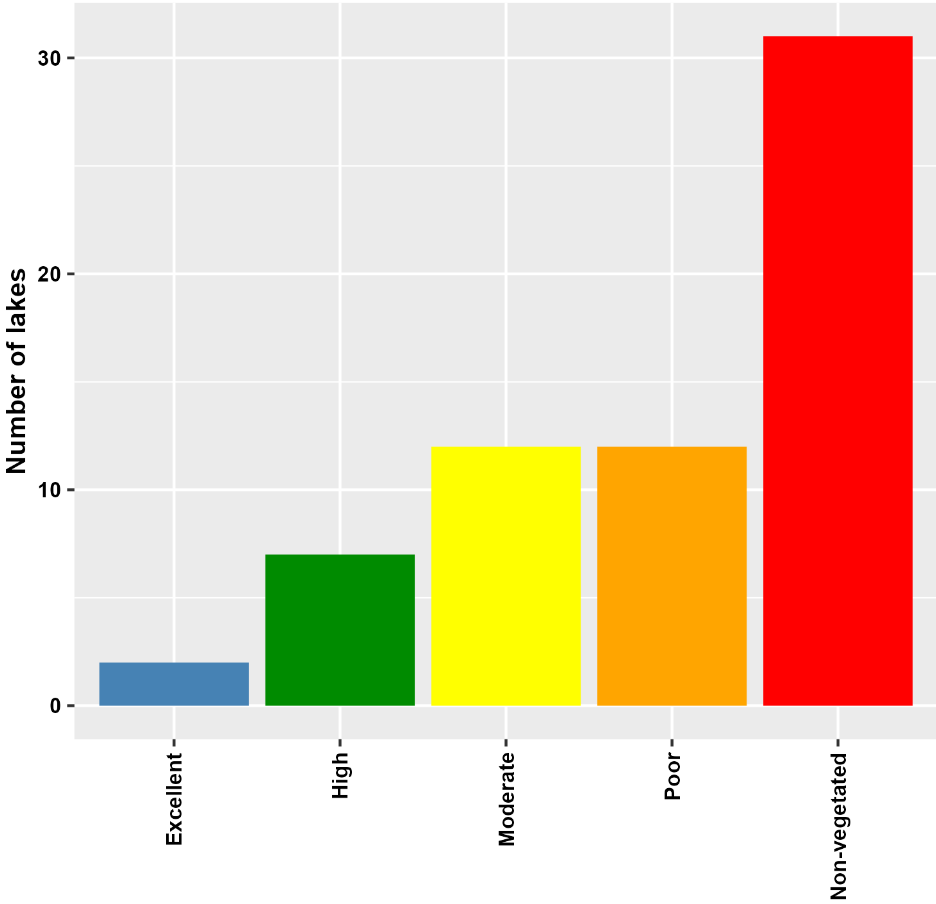

Figure 7. Overall Lake Submerged Plant Indicators (LakeSPI) status of all 64 Waikato lakes sampled from 2003 until 2018, generally one survey per lake.

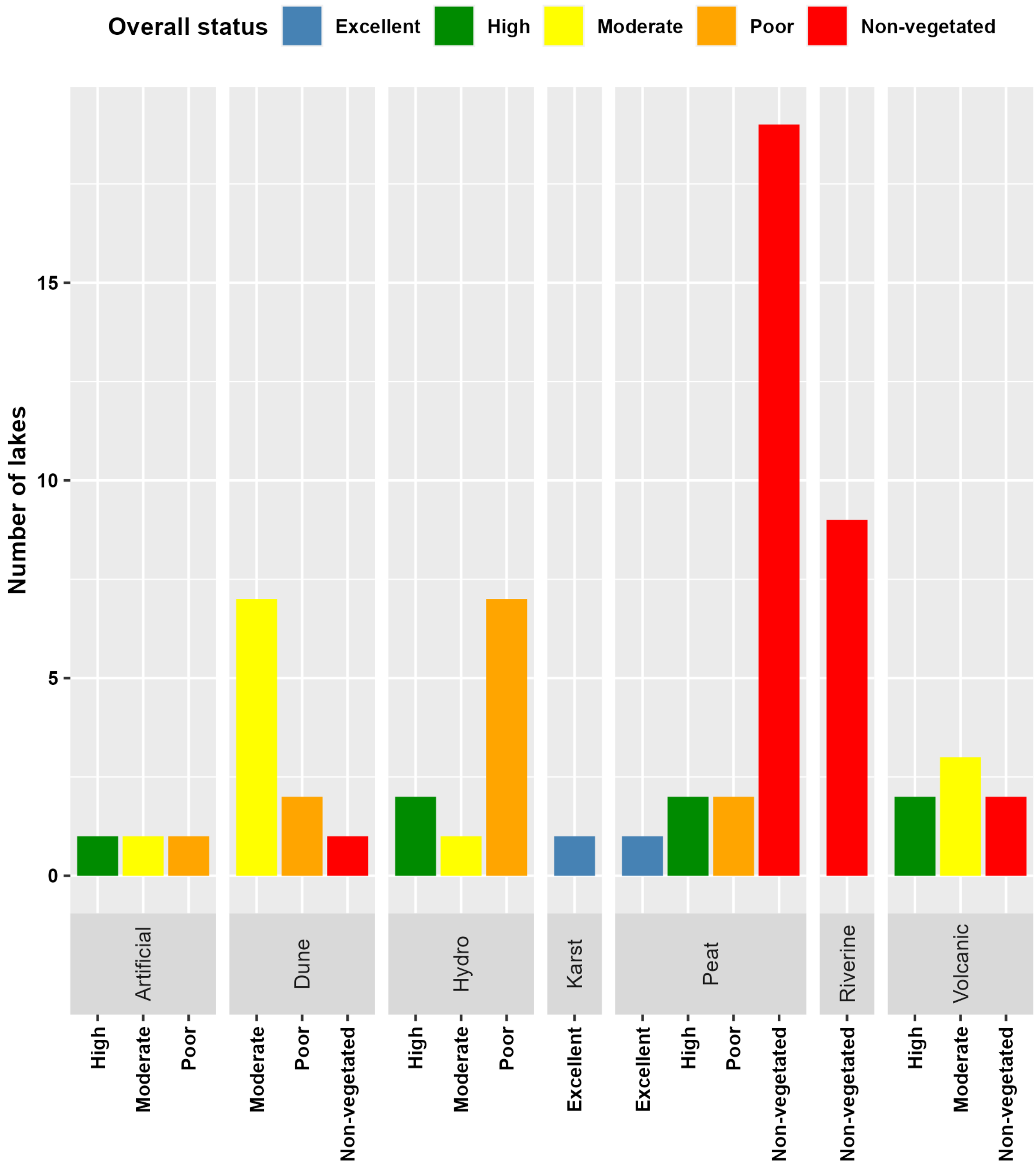

Figure 8. Overall Lake Submerged Plant Indicators (LakeSPI) status of all 64 Waikato lakes sampled from 2003 until 2018, grouped by lake type.

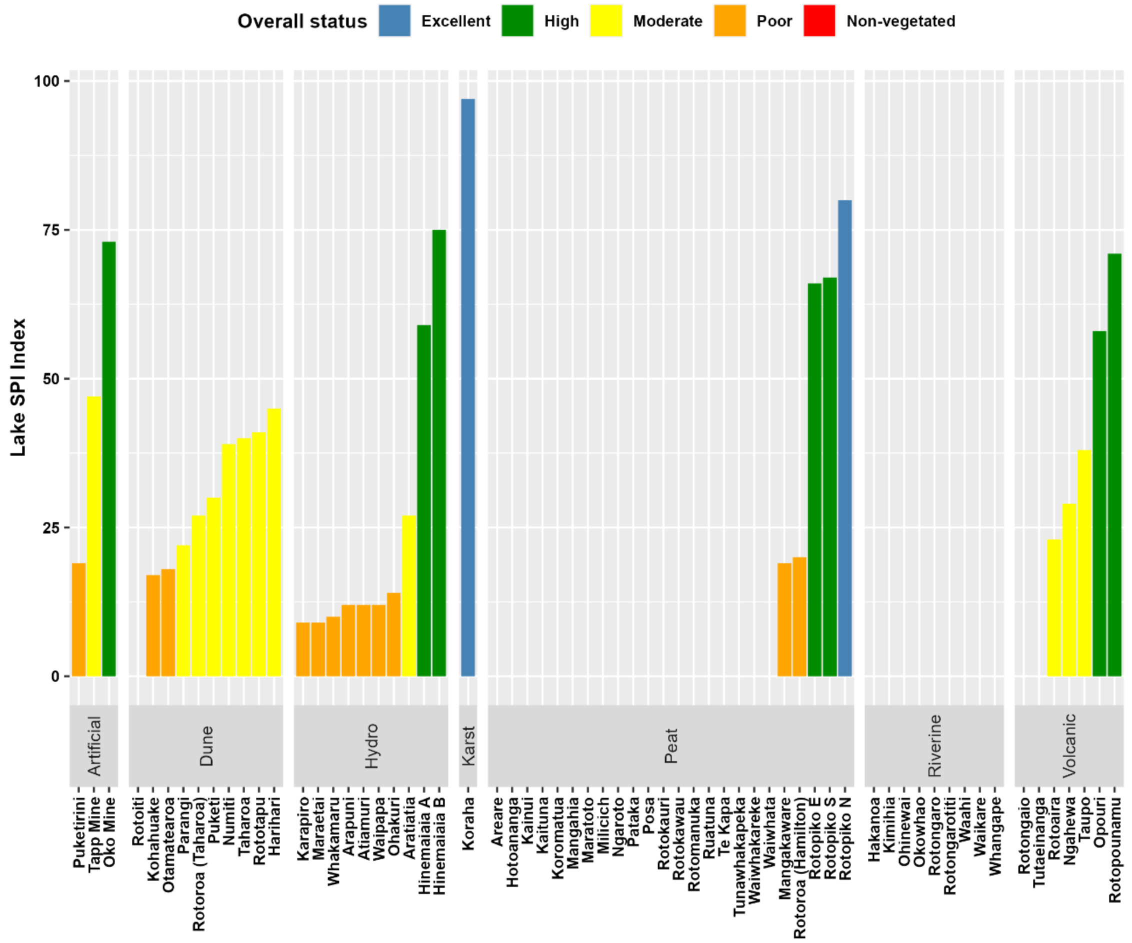

Figure 9. Lake Submerged Plant Indicators (LakeSPI) index of all 64 Waikato lakes sampled from 2003 until 2018, grouped by lake type.

3.3 Zooplankton

Zooplankton were collected from 13 regularly or semi-regularly sampled Waikato Regional Council lakes between mid-2017 and mid-2021, generally bi-monthly. These were used to explore trends in rotifer inferred TLI assessments, as well as changes in the proportions of native versus non-native zooplankton, and crustaceans versus rotifers, through time, including from historic samples.

Based on the complete 2020/2021 results, lakes with regular monitoring can be ranked in the following order, from lowest to highest rotifer inferred TLI values; Maratoto (2.5; oligotrophic), Harihari (3.3), Serpentine North (3.6; mesotrophic), Areare (4.1), Serpentine South (4.3), Rotomanuka (4.5), Ruatuna (4.6), Waiwhakareke (4.6; all eutrophic), Mangakaware (5.2), Hakanoa (5.7; supertrophic), Waahi (6.9), Whangape (8.3) and Waikare (8.0; all hypertrophic). While most of these results are consistent with monitoring results from previous years, Lake Waikare was assessed to have continued to decline in water quality relative to previous years, moving from the eutrophic/supertrophic boundary between 2011 and 2016, to a hypertrophic assessment.

Lakes Harihari, Serpentine North, Serpentine South, Maratoto and Waikare continued to have consistently low proportions of non-native zooplankton species; for the former three lakes, this may be because these are among the most isolated and least accessible in this study. Lake Rotomanuka showed similar patterns, with all samplings prior to 2014 having less than 5% non-native species; this proportion of non-natives has increased, with one sample above 30% in 2020. Lakes Areare, Hakanoa and Mangakaware have in general been more greatly affected, with non-native species commonly comprising up to around 20% of their communities;

however, Areare and Mangakaware both had very low proportions in the current samplings, while Hakanoa had greater than 30% in one 2020 sample. For Lake Waiwhakareke, while several samplings in 2016 and 2017 had non-native species comprising above 20% of the community, since 2018 none have reached this level. Lake Waahi was the most compromised, with non-native species making up >60% of the community in 2014 and 2015, and again in 2020. The combined TLI assessments and proportion of non-native species in Lake Waahi indicate that this lake is the poorest with respect to lake health, having one of the poorest TLI assessments and being the most compromised by non-native species. Lake Maratoto, on the other hand, had the lowest assessed TLI and 100% of zooplankton individuals across the four samples examined were native.

Clear-cut patterns in crustacean or rotifer dominance were not evident for most lakes. However, Lake Waahi was heavily crustacean dominated in recent time periods, primarily due to high proportions of the Australian copepod *Boeckella symmetrica* and North American cladoceran *Daphnia galeata*. Lake Whangape is increasingly becoming crustacean dominated, which is seemingly unrelated to invasions by non-native zooplankton. Lake Serpentine North appears to be becoming more frequently crustacean dominated, a result of increases in the proportions of both native copepods and cladocerans (and lessening importance of rotifers).

3.4 Phytoplankton

Phytoplankton cell counts were used to calculate biovolume and relative abundance in long term lakes (Fig. 10). For long term lakes dinoflagellates and diatoms often had the highest relative biomass, however in lakes Areare, Mangakawere and Waikare, cyanobacteria were generally more dominant. Lakes Harihari, Maratoto and Rotopiko North (Serpentine North) had the most diverse phytoplankton assemblages, and low cyanobacterial biovolume.

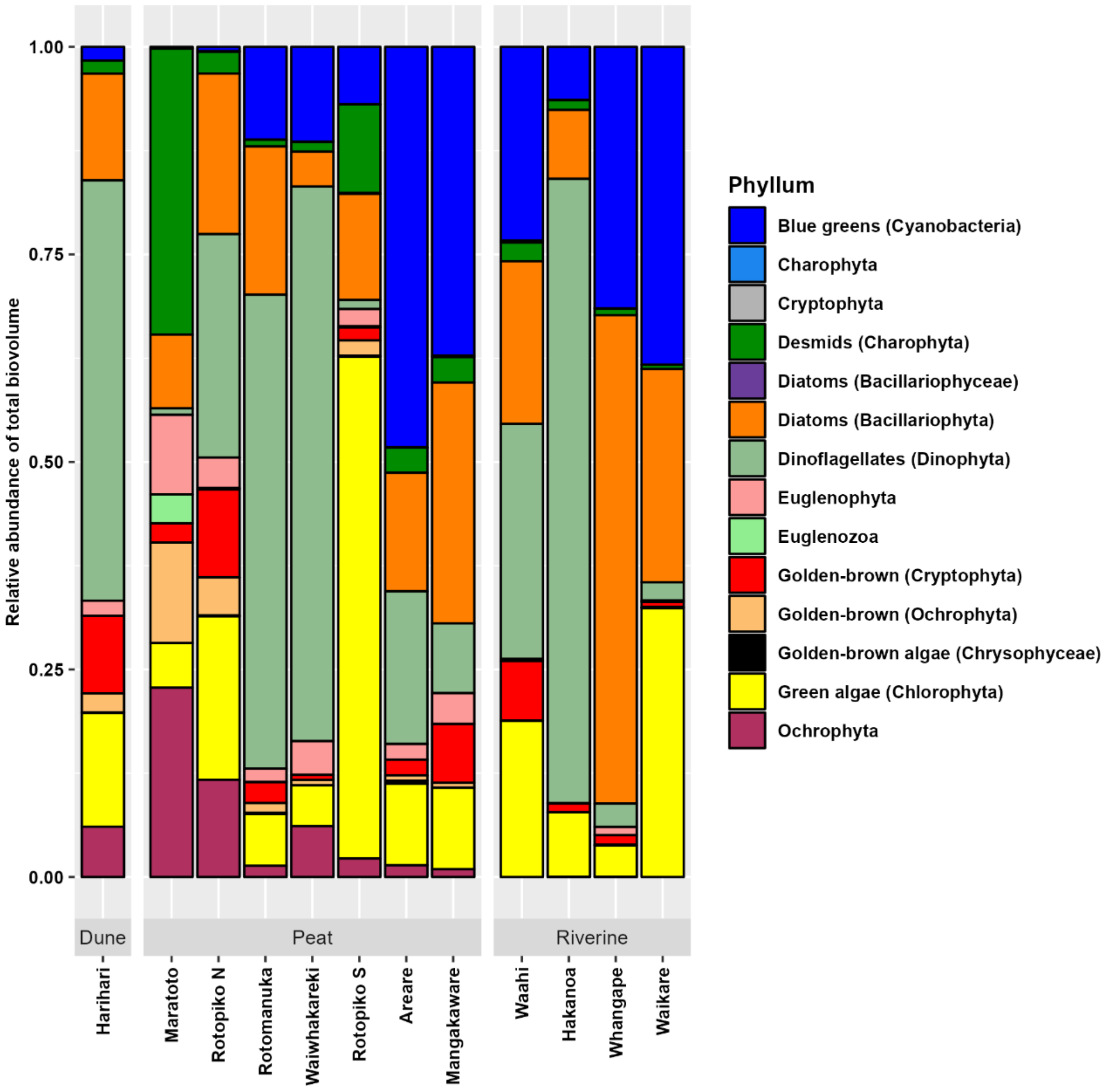

Figure 10. Relative abundance of total biovolume for phytoplankton data collected from 2003 to 2021 for long term lake monitoring sites.

Median total biovolume of all phylum's indicated riverine lakes generally had higher biovolume with lakes Waikare and Hakanoa supporting the largest algal mass. Lakes Korekai, Otamanui, and Okoroire had relatively low median biovolume (Fig. 11).

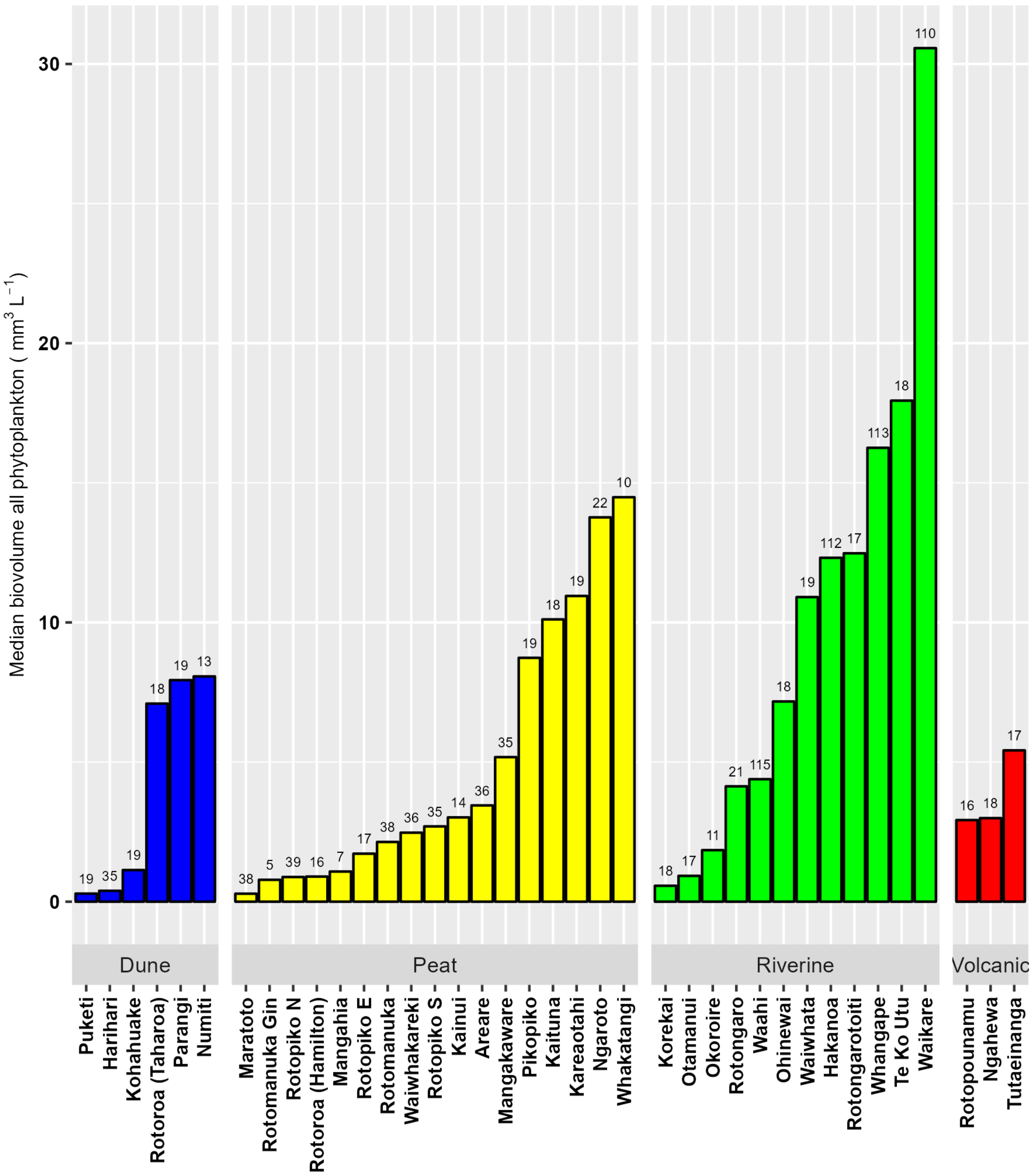

Figure 11. Median phytoplankton biovolume (all phylum's) in the 38 lake SOE network, over the current NPS-FM 2020 state period (2017-2021), with number of samples at the top of each bar.

Cyanobacteria plotted in relation to NPS-FM 2020 bands indicate cyanobacteria blooms have caused potential health risks in c. half of lakes monitored over the period 2016 to 2021 (Fig. 12).

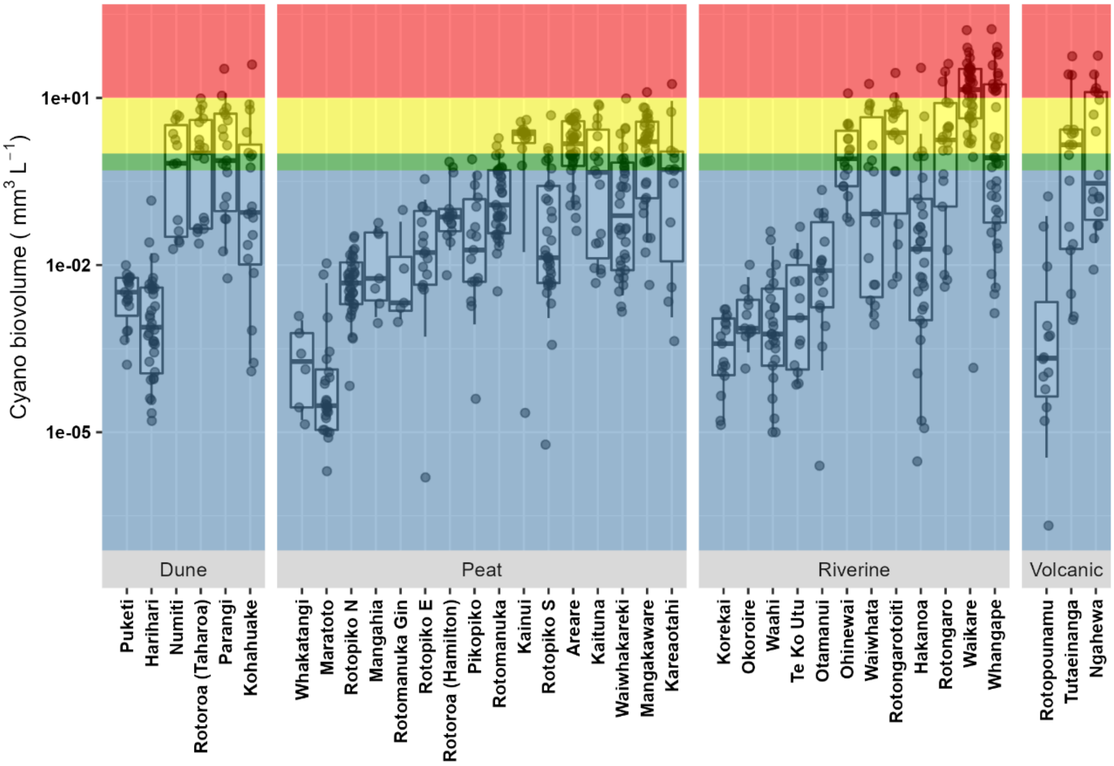

Figure 12. All cyanobacteria biovolume from 2017 to 2021, plotted with NPS-FM 2020 band shading, assuming (D band shading in red is equivalent to >= 10 mm^3 L^{-1} cyanobacteria biovolume toxic/non-toxic). Note log scale of y axis.

Cyanobacteria biovolume of specific genus or species has also shown significant variation through time (Fig. 13). After 2011 there was a shift to less concerning species where *Apanizomenon sp.* and *Apanizomenon gracile* emerged as one of the dominant cyanobacteria. Previously *Dolichospermum planktonica* and *Microcystis sp.* were often present. Other common genus included *Cylindrospemopsis sp.* and *Planktolyngbya sp.*

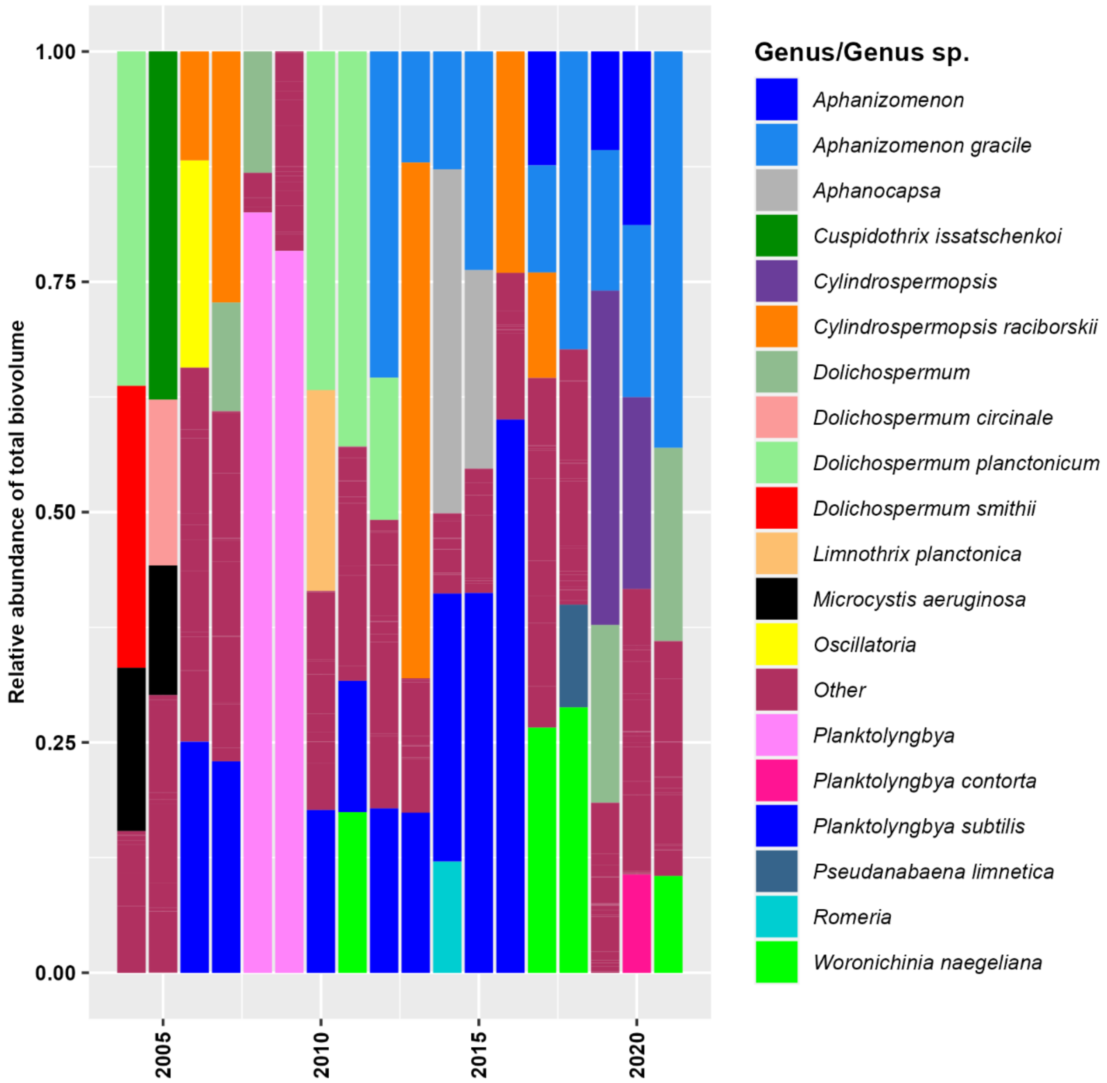

Figure 13. Cyanobacteria relative abundance by genus or genus species, summarized for all 12 long term lake SOE sites.

3.5 Secchi depth viewed (bathyscope) vs un-viewed

Secchi depth has been both measured with and without viewer (bathyscope) in Waikato lakes. To determine a baseline in water clarity that can relate to both viewed and un-viewed Secchi depth, an overlapping study was caried out measuring both, with CDOM samples collected during the later stages of the period. The overlapping study period began July 2019 and ended July 2022. The results from the study indicate that Secchi depth can be modelled from concentrations of CHLA, TSS and CDOM. A random forest model retrieved an R^2 of 0.91, intercept of -0.087 and slope of 1.01 (Fig. 14). Note this has not been used in TLI calculations.

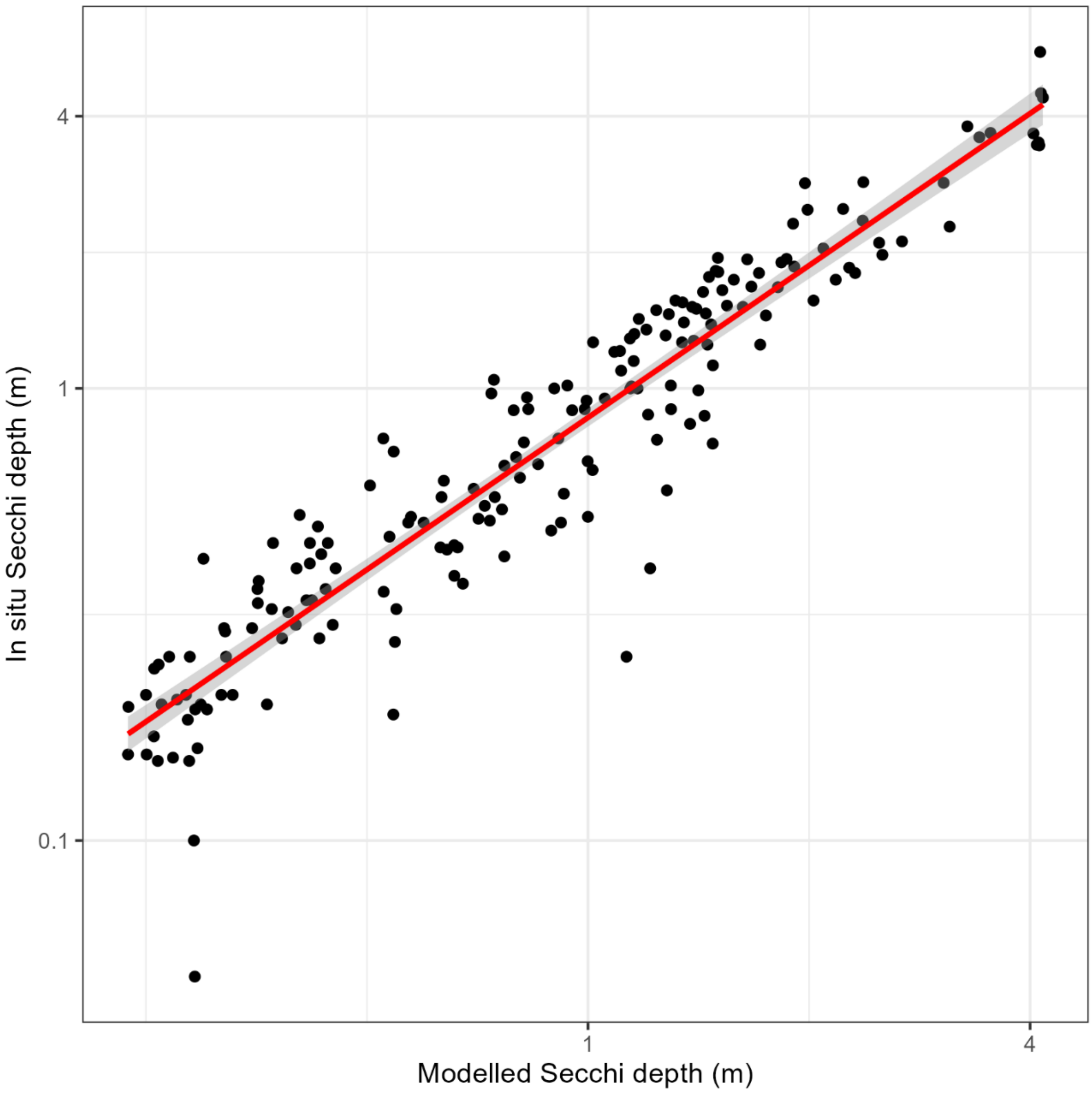

Figure 14. Relationship between in situ and modelled Secchi depth via random forest.

3.6 Lake state and trends

3.7 Trophic Lake Index

The Trophic Lake Index (TLI) is designed to be an integrator of four water quality variables, TN, TP, CHLA and Secchi depth, where lower TLI indicates better water quality. In six out of 12 long term monitoring SOE lake sites, TLI has reduced within the last three years (Fig. 15). In all long term sites apart from Harihari (fair water quality), water quality is poor or very poor.

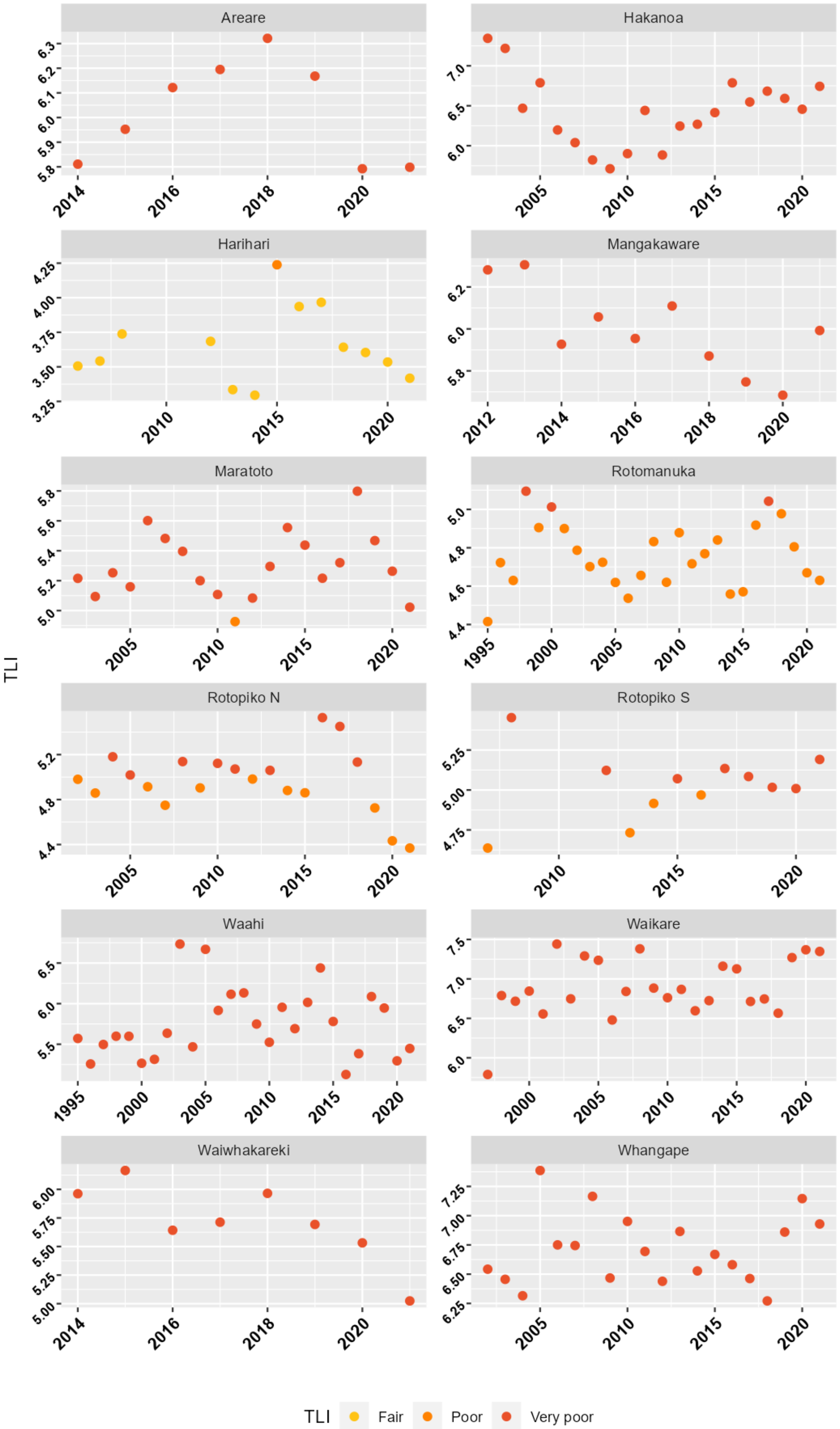

Figure 15. Trophic Lake Index (TLI) for the variable time period historical monitoring within the 12 long term SOE monitoring site lakes.

3.8 Trend for lakes with data from 2003 onwards

There has been more degradation in TSS, TN and water clarity, and more improving trends in CHLA and TP (Fig. 16, Fig. 17). There is a potential link between increasing TSS and decreasing CHLA, potentially due to light limitation.

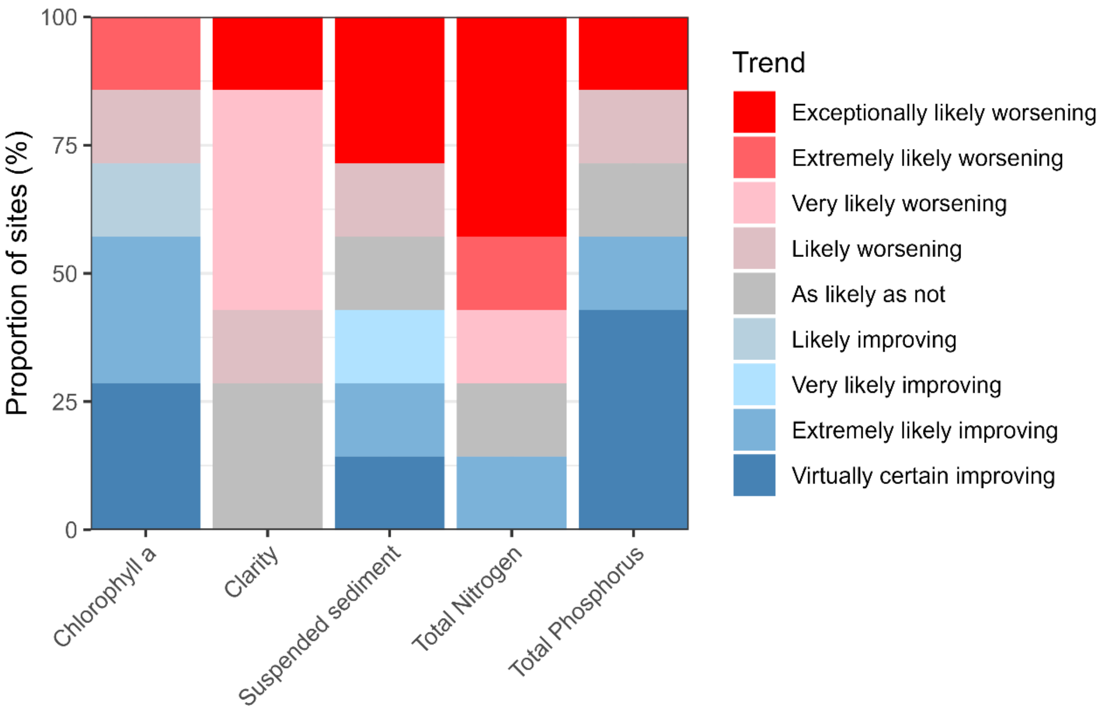

Figure 16. Trend direction percentage summary for 2003-2021.

Notably Lake Hakana had worsening trends for all variables and Lake Waahi had improving trends for all variables except clarity and TSS (**Error! Reference source not found.**).

Figure 17. Trend by lake site for period 2003-2021.

When trends are interpreted spatially the most degrading trends are apparent in TN and clarity (Fig. 18).

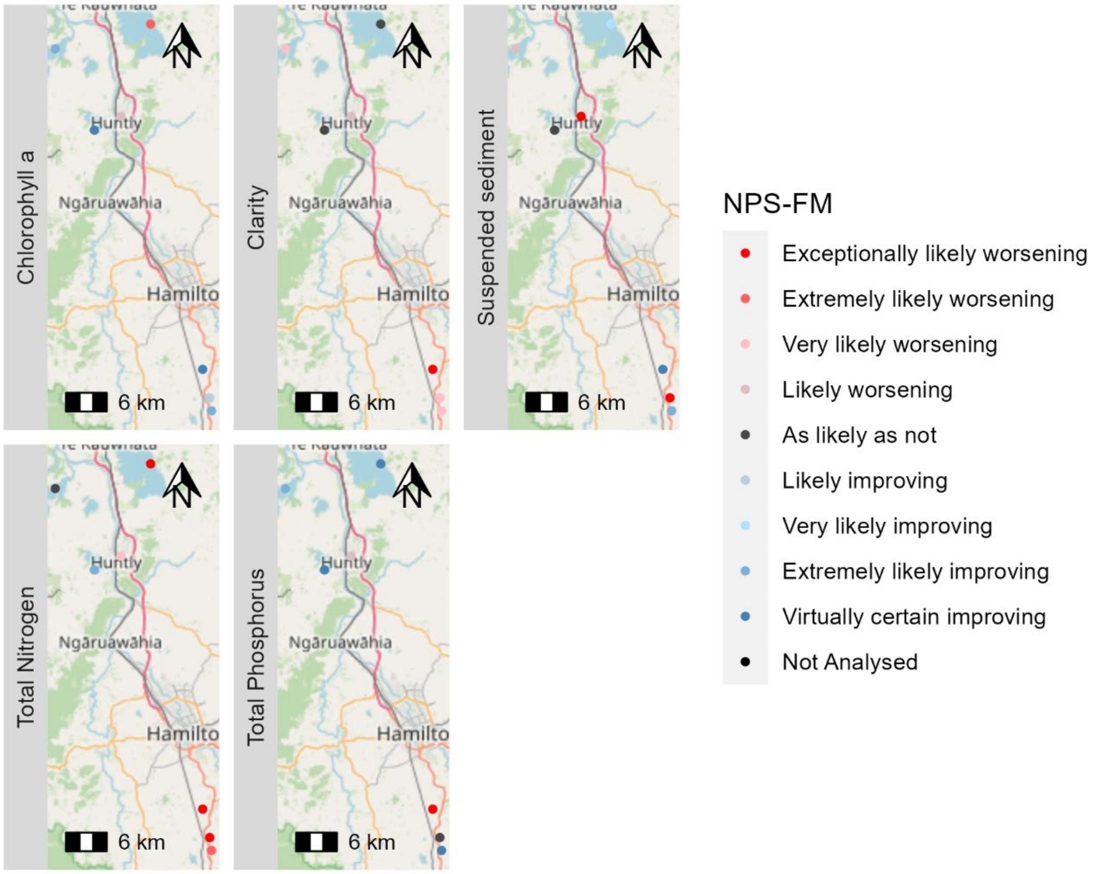

Figure 18. Trend by lake site for all years monitored for period 2003-2021.

3.9 Lake current state

The current NPS-FM 2020 attribute state for SOE lakes (Table 2, Fig. 19, Fig. 20) indicates that almost all lakes (except for Lake Rotopounamu) fail to meet the national bottom line for at least one attribute. Riverine and peat lakes generally have more attributes below the bottom line than volcanic and dune lakes.

Table 2. Current NPS-FM 2020 attribute state for SOE lakes as of the five-year period from 2017 to 2021. Note that for 26 out of these 38 lakes (bottom section of table), SOE monitoring commenced within this period, therefore current state may also be considered baseline state. Note *E.coli* attributes are preliminary and based on a minimum of 10 samples. Note that current/baseline state for new SOE lakes not based on the full five-year period – see samples column. *E.coli* colour scale differs from other attributes with the addition of yellow as C band.

Site	FMU	Samples (n)	Phytoplankton median (mg CHLA m^{-3})	Phytoplankton max (mg CHLA m^{-3})	Total Nitrogen median polymictic (mg L^{-1})	Total Nitrogen median stratified (mg L^{-1})	Total Phosphorus median (mg L^{-1})	Ammonia median (mg NH4-N L^{-1})	Ammonia max (mg NH4-N L^{-1})	Cyanobacteria 80th percentile (Biovolume mm3 L^{-1})	Lake Submerged Plant (Invasive Impact Index)	Lake Submerged Plant (Native Condition Index)	Lake-bottom dissolved oxygen min (mg L^{-1})	Mid-hypolimnetic dissolved oxygen min (mg L^{-1})	E.coli % exceedances over 540/100 mL	E.coli % exceedances over 260/10 mL	E.coli Median concentration/100 mL	95th percentile of E.coli/100 mL	E.coli overall state	E.coli primary contact 95th percentile
Harihari	Dune	49	3.000 (B)	9.000 (A)		0.272 (B)	0.010 (A)	0.010 (A)	0.120 (B)	0.004 (A)	66.000 (C)	60.000 (B)	0.040 (D)	0.060 (D)	0.000 (A)	0.000 (A)	8.000 (A)	21.500 (A)	(A)	21.500 (A)
Maratoto	Peat	48	3.500 (B)	99.000 (D)	2.010 (D)		0.032 (C)	0.161 (B)	0.660 (B)	0.000 (A)	0.000 (A)	0.000 (D)	0.050 (D)		0.000 (A)	2.222 (A)	50.000 (A)	137.500 (A)	(A)	137.500 (B)
Rotopiko N	Peat	50	7.500 (C)	64.000 (D)		1.208 (D)	0.022 (C)	0.022 (A)	0.197 (B)	0.012 (A)	11.000 (B)	69.000 (B)	0.050 (D)	0.110 (D)	0.000 (A)	2.083 (A)	43.500 (A)	184.000 (A)	(A)	184.000 (B)
Rotomanuka	Peat	48	10.000 (C)	39.000 (C)		1.104 (D)	0.020 (B)	0.094 (B)	0.340 (B)	0.510 (B)	0.000 (A)	0.000 (D)	0.010 (D)	0.010 (D)	0.000 (A)	0.000 (A)	35.000 (A)	162.000 (A)	(A)	162.000 (B)
Rotopiko S	Peat	46	13.500 (D)	44.000 (C)	1.004 (D)		0.032 (C)	0.010 (A)	0.128 (A)	0.270 (A)	25.000 (B)	60.000 (B)	0.030 (D)		6.818 (B)	13.636 (A)	95.000 (A)	830.000 (B)	(B)	830.000 (D)
Areare	Peat	47	29.000 (D)	82.000 (D)	2.260 (D)		0.085 (D)	0.022 (A)	0.500 (B)	3.853 (C)	0.000 (A)	0.000 (D)	0.110 (D)		4.444 (A)	8.889 (A)	50.000 (A)	502.500 (A)	(A)	502.500 (C)
Waiwhakareki	Peat	47	31.000 (D)	151.000 (D)	1.148 (D)		0.067 (D)	0.016 (A)	0.470 (B)	0.718 (B)	0.000 (A)	0.000 (D)	0.060 (D)		0.000 (A)	11.111 (A)	41.000 (A)	380.000 (A)	(A)	380.000 (C)
Mangakaware	Peat	49	38.000 (D)	115.000 (D)	1.385 (D)		0.087 (D)	0.010 (A)	1.340 (C)	3.948 (C)	42.000 (C)	27.000 (C)	0.080 (D)		4.348 (A)	10.870 (A)	40.500 (A)	440.000 (A)	(A)	440.000 (C)
Waahi	Riverine	48	23.000 (D)	114.000 (D)	1.120 (D)		0.047 (C)	0.010 (A)	0.470 (C)	0.004 (A)	0.000 (A)	0.000 (D)	2.750 (B)		0.000 (A)	0.000 (A)	10.000 (A)	20.200 (A)	(A)	20.200 (A)
Whangape	Riverine	48	60.000 (D)	590.000 (D)	2.002 (D)		0.130 (D)	0.010 (A)	1.790 (C)	17.573 (D)	0.000 (A)	0.000 (D)	3.060 (B)		0.000 (A)	0.000 (A)	10.000 (A)	98.000 (A)	(A)	98.000 (A)
Hakanoa	Riverine	48	85.000 (D)	350.000 (D)	2.202 (D)		0.132 (D)	0.010 (A)	0.197 (C)	0.219 (A)	0.000 (A)	0.000 (D)	2.150 (B)		0.000 (A)	0.000 (A)	19.000 (A)	100.000 (A)	(A)	100.000 (A)
Waikare	Riverine	48	134.000 (D)	880.000 (D)	4.002 (D)		0.155 (D)	0.010 (B)	1.010 (D)	33.719 (D)	0.000 (A)	0.000 (D)	5.160 (B)		0.000 (A)	0.000 (A)	10.000 (A)	136.000 (A)	(A)	136.000 (B)
Puketi	Dune	26	3.000 (B)	76.000 (D)	0.476 (B)		0.012 (B)	0.010 (A)	0.196 (B)	0.006 (A)	79.000 (C)	42.000 (C)	0.550 (C)		0.000 (A)	0.000 (A)	8.000 (A)	52.000 (A)	(A)	52.000 (A)
Parkinson (Kohahuake)	Dune	26	10.000 (C)	95.000 (D)		0.995 (D)	0.068 (D)	0.032 (A)	0.730 (C)	2.002 (C)	86.000 (C)	10.000 (D)	0.050 (D)	0.070 (D)	0.000 (A)	0.000 (A)	10.000 (A)	42.400 (A)	(A)	42.400 (A)
Parangi	Dune	27	29.000 (D)	200.000 (D)		1.102 (D)	0.047 (C)	0.035 (B)	0.700 (B)	5.379 (C)	75.000 (C)	11.000 (D)	0.030 (D)	0.050 (D)	0.000 (A)	0.000 (A)	16.000 (A)	47.050 (A)	(A)	47.050 (A)
Rotoroa	Dune	26	30.500 (D)	193.000 (D)		0.637 (C)	0.052 (D)	0.010 (A)	0.280 (B)	4.198 (C)	69.000 (C)	22.000 (C)	0.010 (D)	0.030 (D)	0.000 (A)	0.000 (A)	3.500 (A)	21.000 (A)	(A)	21.000 (A)
Numiti	Dune	21	31.000 (D)	106.000 (D)		0.522 (C)	0.037 (C)	0.010 (A)	0.110 (B)	3.920 (C)	56.000 (C)	37.000 (C)	0.020 (D)	0.030 (D)	0.000 (A)	0.000 (A)	7.000 (A)	36.900 (A)	(A)	36.900 (A)
Rotoroa (Hamilton)	Peat	25	6.000 (C)	16.000 (B)	0.713 (C)		0.016 (B)	0.220 (B)	0.530 (B)	0.209 (A)	37.000 (C)	17.000 (D)	0.560 (C)		0.000 (A)	4.000 (A)	47.000 (A)	192.500 (A)	(A)	192.500 (B)
Rotomanuka Gin	Peat	8	7.000 (C)	37.000 (C)	1.825 (D)		0.042 (C)	0.235 (B)	0.330 (B)		0.000 (A)	0.000 (D)	0.090 (D)		12.500 (C)	37.500 (D)	135.000 (D)		(D)	
Rotopiko East	Peat	22	15.000 (D)	96.000 (D)	2.830 (D)		0.034 (C)	0.057 (A)	0.570 (B)	0.099 (A)	33.000 (C)	72.000 (B)	0.060 (D)		13.636 (C)	22.727 (B)	150.000 (D)	570.000 (B)	(D)	570.000 (D)
Mangahia	Peat	7	18.000 (D)	31.000 (C)	2.850 (D)		0.300 (D)	0.170 (B)	0.650 (B)		0.000 (A)	0.000 (D)	4.070 (B)		28.571 (D)	42.857 (D)	120.000 (A)		(D)	
Kainui	Peat	25	20.000 (D)	53.000 (C)		1.292 (D)	0.033 (C)	0.010 (A)	0.054 (A)	2.657 (C)	0.000 (A)	0.000 (D)	0.060 (D)	0.140 (D)	0.000 (A)	0.000 (A)	16.000 (A)	63.000 (A)	(A)	63.000 (A)
Pikopiko	Peat	26	25.500 (D)	220.000 (D)	1.707 (D)		0.163 (D)	0.010 (A)	0.970 (C)	0.175 (A)			0.100 (D)		7.692 (B)	11.538 (A)	90.000 (A)	700.000 (B)	(B)	700.000 (D)
Whakatangi	Peat	10	33.000 (D)	220.000 (D)	5.440 (D)		0.132 (D)	1.180 (C)	2.700 (C)				0.110 (D)		10.000 (C)	10.000 (A)	70.000 (A)		(C)	
Kaituna	Peat	26	47.000 (D)	380.000 (D)	3.598 (D)		0.146 (D)	0.102 (B)	1.410 (C)	3.095 (C)	0.000 (A)	0.000 (D)	6.300 (B)		7.692 (B)	7.692 (A)	95.000 (A)	522.000 (A)	(B)	522.000 (C)
Kareaotahi	Peat	26	51.000 (D)	290.000 (D)	2.903 (D)		0.545 (D)	0.014 (A)	0.500 (B)	1.118 (C)			0.070 (D)		3.846 (A)	23.077 (B)	130.000 (A)	704.000 (B)	(B)	704.000 (D)
Ngaroto	Peat	26	54.000 (D)	390.000 (D)	1.953 (D)		0.098 (D)	0.010 (A)	0.610 (B)		0.000 (A)	0.000 (D)	0.090 (D)		0.000 (A)	0.000 (A)	18.000 (A)	162.500 (A)	(A)	162.500 (B)
Korekai	Riverine	25	3.000 (B)	17.000 (B)		0.442 (C)	0.013 (B)	0.010 (A)	0.053 (A)	0.001 (A)			0.100 (D)	0.130 (D)	0.000 (A)	4.000 (A)	10.000 (A)	135.000 (A)	(A)	135.000 (B)
Okoroire	Riverine	13	9.000 (C)	41.000 (C)	1.047 (D)		0.033 (C)	0.016 (A)	0.063 (A)				0.050 (D)		0.000 (A)	23.077 (B)	90.000 (A)	497.000 (A)	(B)	497.000 (C)
Otamanui	Riverine	26	13.000 (D)	73.000 (D)	0.707 (C)		0.048 (C)	0.010 (A)	0.136 (B)	0.073 (A)			0.100 (D)		3.846 (A)	3.846 (A)	35.500 (A)	408.000 (A)	(A)	408.000 (C)
Rotongaro	Riverine	25	16.000 (D)	230.000 (D)	1.940 (D)		0.066 (D)	0.014 (A)	1.420 (C)	9.490 (C)	0.000 (A)	0.000 (D)	5.170 (B)		0.000 (A)	4.000 (A)	10.000 (A)	132.000 (A)	(A)	132.000 (B)
Ohinewai	Riverine	27	38.000 (D)	260.000 (D)	2.020 (D)		0.087 (D)	0.051 (A)	0.540 (B)	3.041 (C)	0.000 (A)	0.000 (D)	0.150 (D)		0.000 (A)	0.000 (A)	20.000 (A)	126.500 (A)	(A)	126.500 (A)
Waiwhata	Riverine	26	38.000 (D)	97.000 (D)	3.604 (D)		0.265 (D)	0.014 (A)	2.100 (C)	6.112 (C)	0.000 (A)	0.000 (D)	2.830 (B)		11.538 (C)	23.077 (B)	160.000 (D)	960.000 (B)	(D)	960.000 (D)
Te Ko Utu	Riverine	25	44.000 (D)	131.000 (D)	1.162 (D)		0.152 (D)	0.010 (A)	0.270 (B)	0.014 (A)			0.090 (D)		4.000 (A)	8.000 (A)	34.000 (A)	845.000 (B)	(B)	845.000 (D)
Rotongarotoiti	Riverine	25	53.000 (D)	450.000 (D)	2.702 (D)		0.116 (D)	0.010 (A)	3.700 (C)	6.129 (C)	0.000 (A)	0.000 (D)	4.960 (B)		4.000 (A)	8.000 (A)	50.000 (A)	377.500 (A)	(A)	377.500 (C)
Rotopounamu	Volcanic	22	4.500 (B)	14.000 (B)	0.232 (A)		0.006 (A)	0.010 (A)	0.014 (A)	0.007 (A)	0.000 (A)	43.000 (C)	7.040 (B)		0.000 (A)	0.000 (A)	1.000 (A)	10.000 (A)	(A)	10.000 (A)
Ngahewa	Volcanic	26	25.000 (D)	116.000 (D)		0.666 (C)	0.104 (D)	0.015 (B)	0.500 (B)	12.998 (D)	67.000 (C)	26.000 (C)	0.020 (D)	0.070 (D)	0.000 (A)	0.000 (A)	10.000 (A)	46.000 (A)	(A)	46.000 (A)
Tutaeinanga	Volcanic	26	25.500 (D)	144.000 (D)		1.268 (D)	0.144 (D)	0.057 (B)	1.640 (C)	4.991 (C)	23.000 (B)	0.000 (D)	0.010 (D)	0.030 (D)	0.000 (A)	3.846 (A)	29.000 (A)	208.000 (A)	(A)	208.000 (B)

Dune and volcanic lakes were the only lakes that attained any A band for TP, TN and phytoplankton max (Fig. 19).

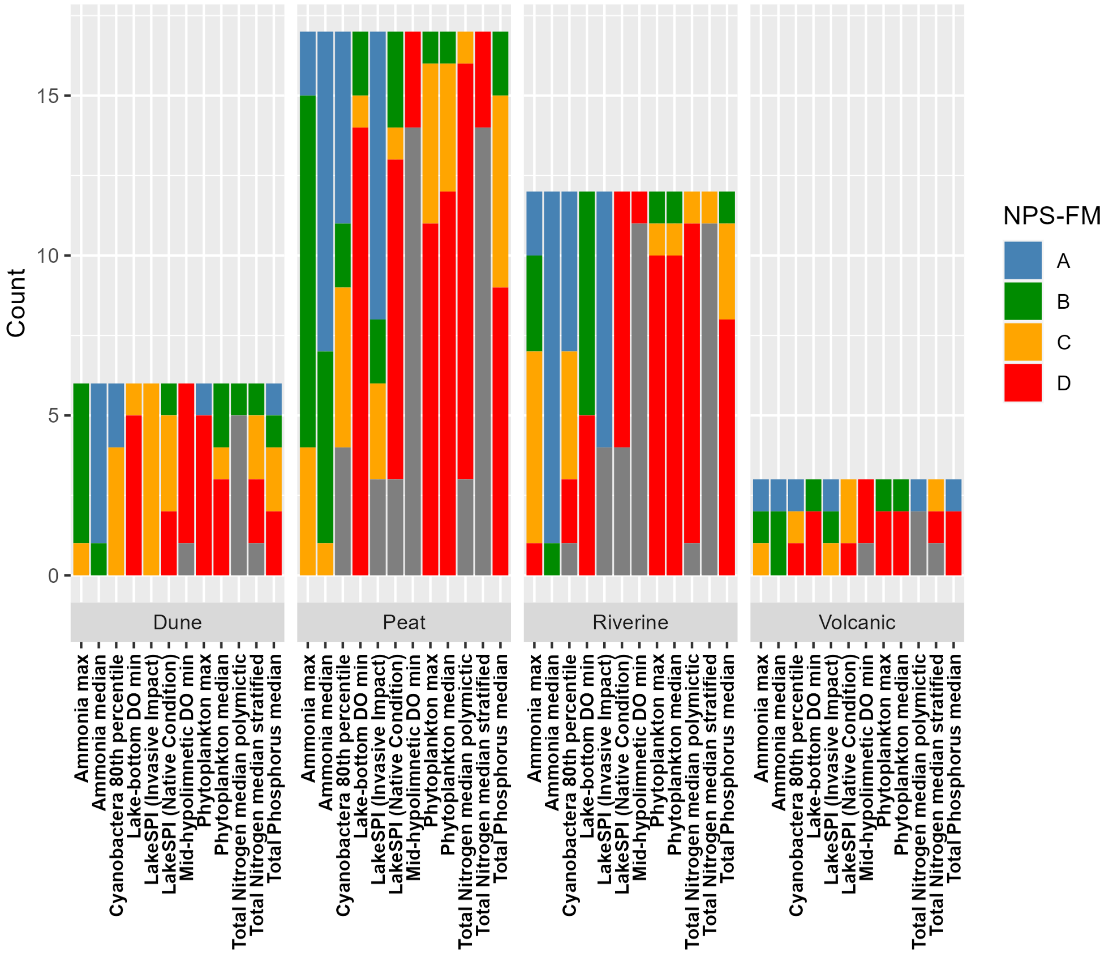

Figure 19. Current state NPS-FM 2020 counts by lake type.

Generally, dune and volcanic lakes to the west, south and east have more potential to meet the national bottom line for TN and TP (Fig. 20).

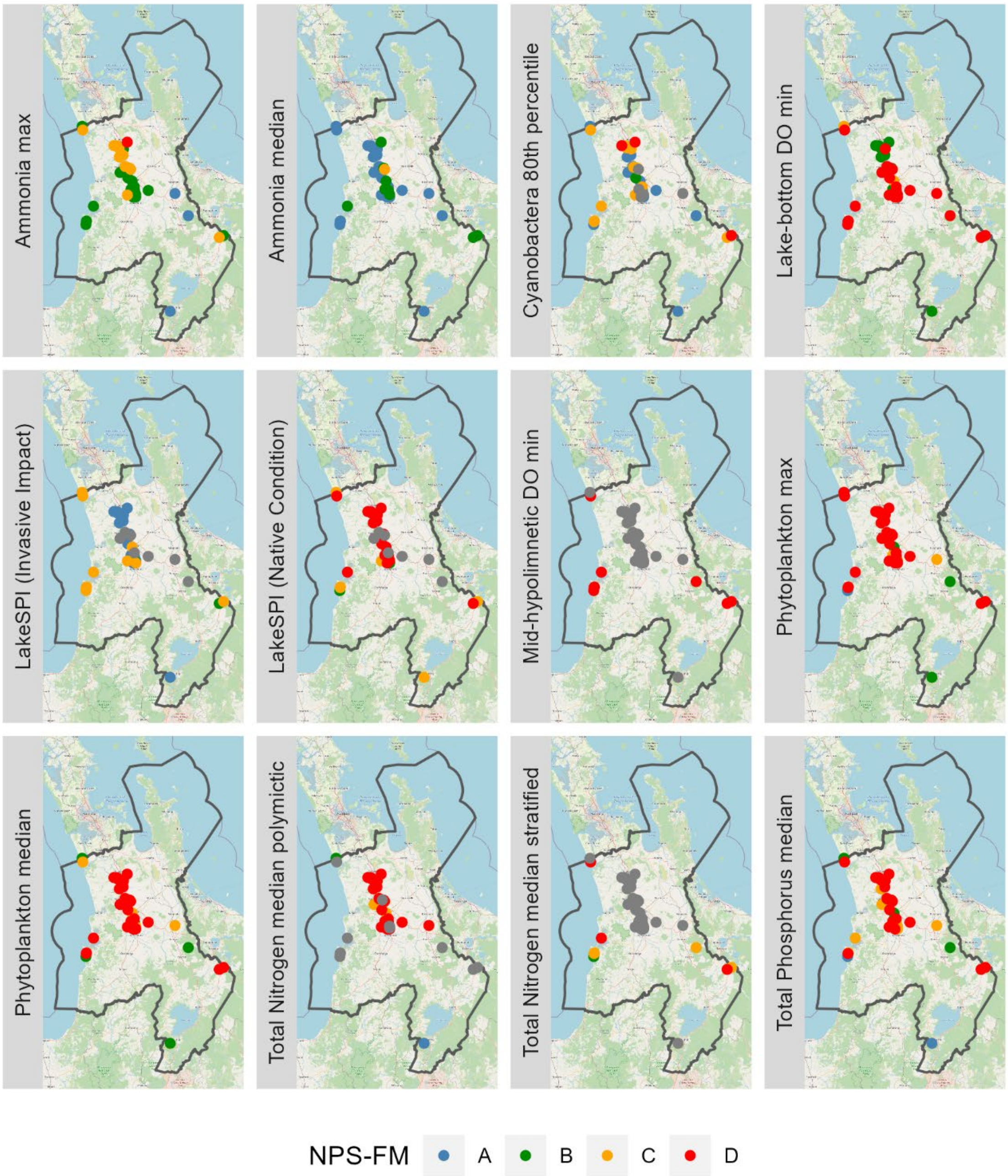

Figure 20. Current state (2017-2021) NPS-FM 2020 bands by spatial location in SOE lakes. Grey dots indicate that state could not be calculated due to insufficient data or mixing regime.

3.10 Lake baseline state

The baseline state of legacy lake sites indicate that all sites failed to meet the national bottom line for at least one attribute (Table 3). Lake Harihari (dune lake) had much better water quality than any peat or riverine lake with only once C band (apart from dissolved oxygen attributes). Peat lakes were more likely to meet national bottom line than riverine lakes, but attributes still indicated poor or very poor water quality.

Table 3. Baseline NPS-FM 2020 attribute state for SOE legacy sites used samples collected from 2012-09-08 until 2017-09-07. Note *E.coli* attributes are not present as were not samples over this period.

Site	FMU	Phytoplankton median (mg CHLA m^{-3})	Phytoplankton max (mg CHLA m^{-3})	Total Nitrogen median polymictic (mg L^{-1})	Total Nitrogen median stratified (mg L^{-1})	Total Phosphorus median (mg L^{-1})	Ammonia median (mg NH4-N L^{-1})	Ammonia max (mg NH4-N L^{-1})	Cyanobacteria 80th percentile (Biovolume mm3 L^{-1})	Lake Submerged Plant (Invasive Impact Index)	Lake Submerged Plant (Native Condition Index)	Lake-bottom dissolved oxygen min (mg L^{-1})	Mid-hypolimnetic dissolved oxygen min (mg L^{-1})
Harihari	Dune	3.000 (B)	22.000 (B)		0.297 (B)	0.010 (A)	0.010 (A)	0.026 (A)		66.000 (C)	60.000 (B)	0.030 (D)	0.040 (D)
Maratoto	Peat	7.000 (C)	45.000 (C)	1.790 (D)		0.026 (C)	0.185 (B)	0.590 (B)		0.000 (A)	0.000 (D)	0.030 (D)	
Rotopiko N	Peat	10.000 (C)	36.000 (C)		1.007 (D)	0.018 (B)	0.118 (B)	0.820 (B)		0.000 (A)	0.000 (D)	0.000 (D)	0.010 (D)
Rotomanuka	Peat	11.000 (C)	34.000 (C)	0.930 (D)		0.028 (C)	0.010 (A)	0.141 (B)		25.000 (B)	60.000 (B)	0.060 (D)	
Rotopiko S	Peat	14.000 (D)	64.000 (D)		1.201 (D)	0.026 (C)	0.021 (A)	0.220 (B)		11.000 (B)	69.000 (B)	0.030 (D)	0.050 (D)
Areare	Peat	25.000 (D)	62.000 (D)	2.130 (D)		0.088 (D)	0.030 (A)	0.500 (B)		0.000 (A)	0.000 (D)	0.110 (D)	
Waiwhakareki	Peat	39.000 (D)	130.000 (D)	1.391 (D)		0.094 (D)	0.014 (A)	0.470 (B)		0.000 (A)	0.000 (D)	0.110 (D)	
Mangakaware	Peat	39.000 (D)	101.000 (D)	1.551 (D)		0.116 (D)	0.021 (A)	0.490 (B)		42.000 (C)	27.000 (C)	0.080 (D)	
Waahi	Riverin	15.500 (D)	100.000 (D)	1.096 (D)		0.063 (D)	0.018 (B)	0.330 (C)	13.159 (D)	0.000 (A)	0.000 (D)	4.050 (B)	
Whangape	Riverin	48.000 (D)	300.000 (D)	1.922 (D)		0.119 (D)	0.014 (A)	0.500 (B)	1.109 (C)	0.000 (A)	0.000 (D)	3.920 (B)	
Hakanoa	Riverin	67.500 (D)	580.000 (D)	1.850 (D)		0.114 (D)	0.010 (A)	1.020 (C)	15.930 (D)	0.000 (A)	0.000 (D)	4.370 (B)	
Waikare	Riverin	104.000 (D)	260.000 (D)	2.802 (D)		0.138 (D)	0.010 (B)	1.700 (D)	18.175 (D)	0.000 (A)	0.000 (D)	5.830 (B)	

3.11 Lake restoration

Lake management approaches for Waikato lakes have had more frequent actions in more degraded peat and riverine lakes, with dune and volcanic lakes receiving more attention recently.

Common catchment actions within Waikato riverine and peat lakes include the installation of silt traps and wetlands, riparian fencing and planting, and weir installation to maintain water levels. Common in lake actions include biological surveys of water chemistry, algae, zooplankton, fish and macrophytes (Fig. 21).

Figure 21. Lake management actions documented from 2000 to 2010. Note not all actions have been documented after 2010, therefore this period is shown.

A recent review of lake restoration was specifically compiled to be relevant to degraded Waikato lakes (Abell et al. 2020). The review highlighted the need for major financial investment and a lake specific approach. The paper emphasised that control of external nutrient loads is fundamental to successful lake restoration projects but identified seven major challenges or barriers to lake restoration (Fig. 22).

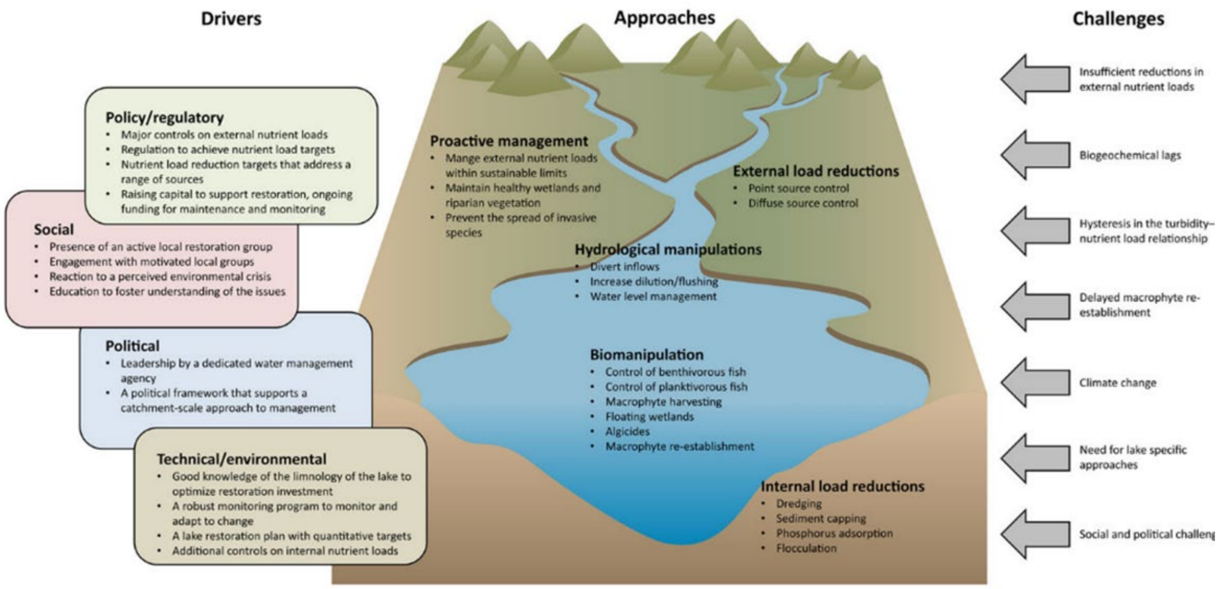

Figure 22. Lake restoration drivers, approaches, and challenges (figure sourced from Abell et al. 2020).

Shallow lake management and restoration efforts should consider catchment land use as a key factor to facilitate restoration (Shallenberg and Sorrell 2009). Establishment of macrophytes is critical if a clear water stable state in shallow lakes is desired (Scheffer et al. 1993; Jeppesen et al. 1997). In regards to nutrient limitation the general scientific consensus that dual nutrient management and reduction is needed for effective lake restoration (Abell et al., 2010, 2016). However even after a reduction of external loading, the lag time for sediments to reach equilibrium could be between 10 and 15 years (Jeppesen et al. 2005), but sometimes persisting for more than 20 years for internal loading of phosphorus (Søndergaard et al. 2003).

4 Conclusions

The Waikato regions shallow lakes are under pressure from a combination of factors, including nutrient loads well above critical loading (Abell et al., in prep), impacts of pest fish, lake level fluctuations, climate change and in many lakes hysteresis and negative feedback loops derived from alternative turbid stable states.

Of the twelve long term monitoring lakes, marked water quality degradation monitored (and inferred from observations) in peat and riverine lakes in the late 1970's (Waikare macrophyte collapse) 1980's and 1990's has not been observed post year 2000, however many lakes are hypertrophic, and have "flipped" into an alternative stable state dominated by suspended sediment and phytoplankton. The last SOE report evaluated water quality trends since the early 1980s and showed water quality had deteriorated at Lake Rotomanuka and Lake Ngaroto, but improved at Lake Waahi (Environment Waikato, 1998). We note that the water quality of Lake Waahi has degraded since 1998, and further degradation of Lake Rotomanka has occurred in terms of TN, TSS and Secchi depth (however TP and TCHLA have improving trends).

In contrast to riverine lakes, some peat and dune lakes still contain macrophytes and relatively good water quality (e.g., Lake Rotomanuka and Rotopiko lakes). However, most lakes are still degraded, and are not responding to lake restoration initiatives. For example, Lake Ngaroto has had a restoration program for the last 25 years including fencing, planting, sediment treatment, weir, and inflow diversion. However, the lake still fails to meet the national bottom line for many attributes.

Long term trend analysis at all 12 long term sites indicates a general increase in TN and TSS concentrations, and a general decrease in total phosphorous. However over shorter timescales (3-5 years) notable reductions in TLI have occurred in six out of 12 long term monitoring SOE lake sites. We note here that on time scales of this period, there is potential for climate driven changes in water quality to dominate those derived from changes within lake catchments (Snelder et al. 2021). In particular lower rainfall in the past few years could be responsible for decreased nutrient loading to lakes.

Hysteresis in turbid alternate state lakes (such as Lake Waikare and Lake Ngaroto) means that restoring the lakes to a clear water stable state, or NPS-FM 2020 band C is hugely challenging task. Long term trends (full monitoring period) indicate improving trends in TP and TSS for Waikare, however in the last five years degrading trends exist for all variables (except dissolved nutrients which did not meet requirements for a trend analysis).

The trend analysis highlights the need for a lake specific targets and action plans, with inconsistent trends across FMUs. This indicates that pressures in each catchment are variable and need to be considered individually. While not included in the long-term trend analysis, lakes can experience perturbations on the spatial scales of hours to months, therefore timeseries data inspection of individual lakes is still a critical aspect of proactive and responsive lake science and management. For example, the recent passerine bird roosting (c 500000 birds) within the very small catchment of Rotopiko East has led to large spikes in nutrient concentrations. Management response is currently being formulated and will require very different actions to those in most other Waikato lakes.

The impacts of degraded water quality observed in Waikato lakes are significant economically and socially. Lake restoration is hugely expensive and likely will require changes in land use or land management practices, which will impact profit margins for agricultural production. Society is impacted due to reduced opportunities for recreation, and potential health risks to humans and animals.

Future planning will require lake specific action plans to address lakes not meeting targets, which will include identifying environmental outcomes for target attributes. These action plans could include land-use control and catchment load limit setting or targeted within lake restoration options. However, success or failure of shallow lake restoration will depend on addressing key challenges to shallow lake restoration which are in order of priority; sufficient reductions in external load and subsequent internal load control to address hysteresis and negative feedback loops preventing macrophyte reestablishment, providing limits that are resilient to climate change, and the need for lake specific approaches (Abell et al. 2020). Lake specific approaches are also required to protect lakes that have not yet flipped into an alternative stable state. This is critical, has the costs of prevention are far lower than those that will have to respond to lake facing hysteresis.

5 Recommendations

The current expanded SOE lake monitoring program has allowed us to identify degrading lakes and lakes that do not meet the NPS-FM 2020 national bottom line. A key component to restoring lake water quality in degraded lakes will be reducing external nutrient loads, however there is high uncertainty regarding the magnitude of these loads in many lake catchments. Therefore, one key recommendation would be to monitor inflow nutrient concentrations within selected lake catchments, and in particular likes at risk of flipping into a turbid alternate stable state such as Rotopiko East. However, NPS-FM 2020 does allow for the use of our best estimates from modelled data, and national databases such as CLUES provide initial estimations of load magnitudes and potential scale of required mitigations.

An emerging water quality issue is the presence of high concentrations of *E.coli*, derived from farming activities and more recently introduced waterfowl and passerine birds (documented in Rotopiko East). Passerine birds roosting near lakes also have the potential to increase external nutrient loading and have proven very difficult to manage. Therefore, the creation of roosting habitats, especially around small Waikato peat lakes needs to be considered carefully in this regard.

Harmful algal blooms are an issue in the greater proportion of Waikato lakes. Current monitoring methods do not have the temporal or spatial resolution to effectively protect human health. This is due to the transient nature of bloom formation, and the vertically on horizontal patchiness in abundance. In addition, lab analysis can lead to delays in alert authorities and health warnings being issued. Therefore, there needs to be increased communication regarding the health risks harmful algal blooms present, and education will increase the ability for lake users to identify harmful algal blooms and avoid contact recreation and protect animals from water contact. This could be provided through existing online platforms such a LAWA (Land, Air, Water Aotearoa (LAWA) - The homepage) which already has fact sheets regarding harmful algal blooms. Use of emerging technologies such as remote sensing and automated sampling platforms could enable greater temporal and spatial coverage while being more cost effective and is an area of active research at WRC.

The current SOE report has identified that it will be challenging to meet NPS-FM 2020 bottom lines in most Waikato D band lakes, while maintaining current land use. Therefore, we recommend any lake management needs to target critical source areas and take a landscape approach to catchment management, with a targeted approach focusing on lakes at risk of regime shifts, of which there are relatively few left in clearwater state (e.g., Rotopiko and Rotomanuka), or presenting risks to human and animal health (e.g., Ngaroto and Waikare). Nonpoint source pollution is difficult to manage through policy due to asymmetric information, spatial and temporal variability and uncertainty within both monitoring and modelling (Graeme and Paragahawewa 2011). In addition, policy arising from the NPS-FM 2020 will need economic analysis to determine economic outcomes resulting from limit setting within lake catchments.

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6 Appendix

Table 4. Site metadata. Report name refers to lake site name used in the report. Key, Site and Station are used in the WISKI database.

Key	Site	Station	Report name	Easting	Northing	FMU
1456_14	Lake Serpentine	South (Surface)	Rotopiko S	1803684	5797171	Peat
1456_3	Lake Serpentine	North (Surface)	Rotopiko N	1803782	5798071	Peat
1456_5	Lake Serpentine	East (Surface)	Rotopiko E	1803865	5797116	Peat
1457_3	Lake Kaituna (Lake B)	Kaituna A (Surface)	Kaituna	1798314	5827468	Peat
1976_5	Lake Rotongarotoiti	Lake Rotongaroiti Deepest Point	Rotongarotoiti	1786215	5850022	Riverine
1977_4	Lake Whakatangi (Lake A)	Deepest Point	Whakatangi	1799120	5826238	Peat
1978_2	Lake Pikopiko	Lake Pikopiko Deepest Point	Pikopiko	1793373	5829447	Peat
1994_1	Lake Harihari	Harihari A (Surface)	Harihari	1750716	5769293	Dune
2009_1	Lake Horseshoe	Rotokauri Road	Waiwhakareki	1796030	5817338	Peat
2019_4	Lake Tutaeinanga	Deepest point	Tutaeinanga	1890468	5751981	Volcanic
2020_2	Lake Parangi	Centre (Surface)	Parangi	1759089	5788407	Dune
286_9	Lake Kainui (Lake D)	Deepest point	Kainui	1796818	5827692	Peat
290_2	Lake Areare	Centre-Surface	Areare	1794057	5828696	Peat
291_3	Lake Cameron	Deepest Point	Kareaotahi	1802605	5807761	Peat
292_6	Lake Hakanoa	Centre (Surface)	Hakanoa	1791489	5841583	Riverine
298_10	Lake Mangahia	Buoy At Deepest Basin	Mangahia	1798989	5805246	Peat
299_1	Lake Mangakaware	Lake Centre	Mangakaware	1795104	5799325	Peat
301_8	Lake Maratoto	Centre (Surface)	Maratoto	1802642	5804158	Peat
302_2	Lake Ngahewa	Centre (surface)	Ngahewa	1894992	5753869	Volcanic
303_17	Lake Ngaroto	Monitoring Buoy	Ngaroto	1801177	5797031	Peat
307_15	Lake Ohinewai	Lake Ohinewai Deepest Point	Ohinewai	1792078	5848039	Riverine
3108_1	Lake Numiti	Taharoa Area South of Kawhia	Numiti	1751455	5772996	Dune
3109_1	Lake Rotoroa	Taharoa Area South of Kawhia	Rotoroa (Taharoa)	1751130	5772342	Dune
311_1	Lake Parkinson (Kohahuake)	Whiriwhiri Rd	Kohahuake	1749272	5868873	Dune
312_1	Lake Puketi	Coe's Rd	Puketi	1748616	5872835	Dune
3138_1	Lake Waiwhata	Lake Centre (Surface)	Waiwhata	1785198	5851599	Riverine
317_2	Lake Rotomanuka	Lake Gin Centre (Surface)	Rotomanuka Gin	1803880	5799572	Peat
317_4	Lake Rotomanuka	Lake Centre (Surface)	Rotomanuka	1803580	5799971	Peat
318_3	Lake Rotongaro	East Of Centre-Surface	Rotongaro	1787499	5849056	Riverine
319_1	Lake Rotoroa (Hamilton Lake)	Centre South Basin (Surface)	Rotoroa (Hamilton)	1800458	5813870	Peat
3208_1	Lake Otamanui	Te Otamanui Deepest Point	Otamanui	1787937	5823201	Riverine
3209_1	Lake Korekai	Lake Korekai Deepest Point	Korekai	1858656	5775917	Riverine
3226_1	Lake Rotopounamu	Lake Rotopounamu Deep	Rotopounamu	1836572	5676825	Volcanic
323_7	Lake Te Koutu	Lake Te Koutu Deepest Point	Te Ko Utu	1817203	5803639	Riverine
324_2	Lake Waahi	Centre (Surface)	Waahi	1787514	5839655	Riverine
326_4	Lake Waikare	Epilimnion	Waikare	1796190	5855072	Riverine
3289_1	Lake Okoroire	Deepest Point	Okoroire	1845339	5799560	Riverine
330_14	Lake Whangape	Centre - Buoy (Surface)	Whangape	1781993	5851747	Riverine