Restoration Planning for Deep Dune Lakes: Data Review and Recommendations

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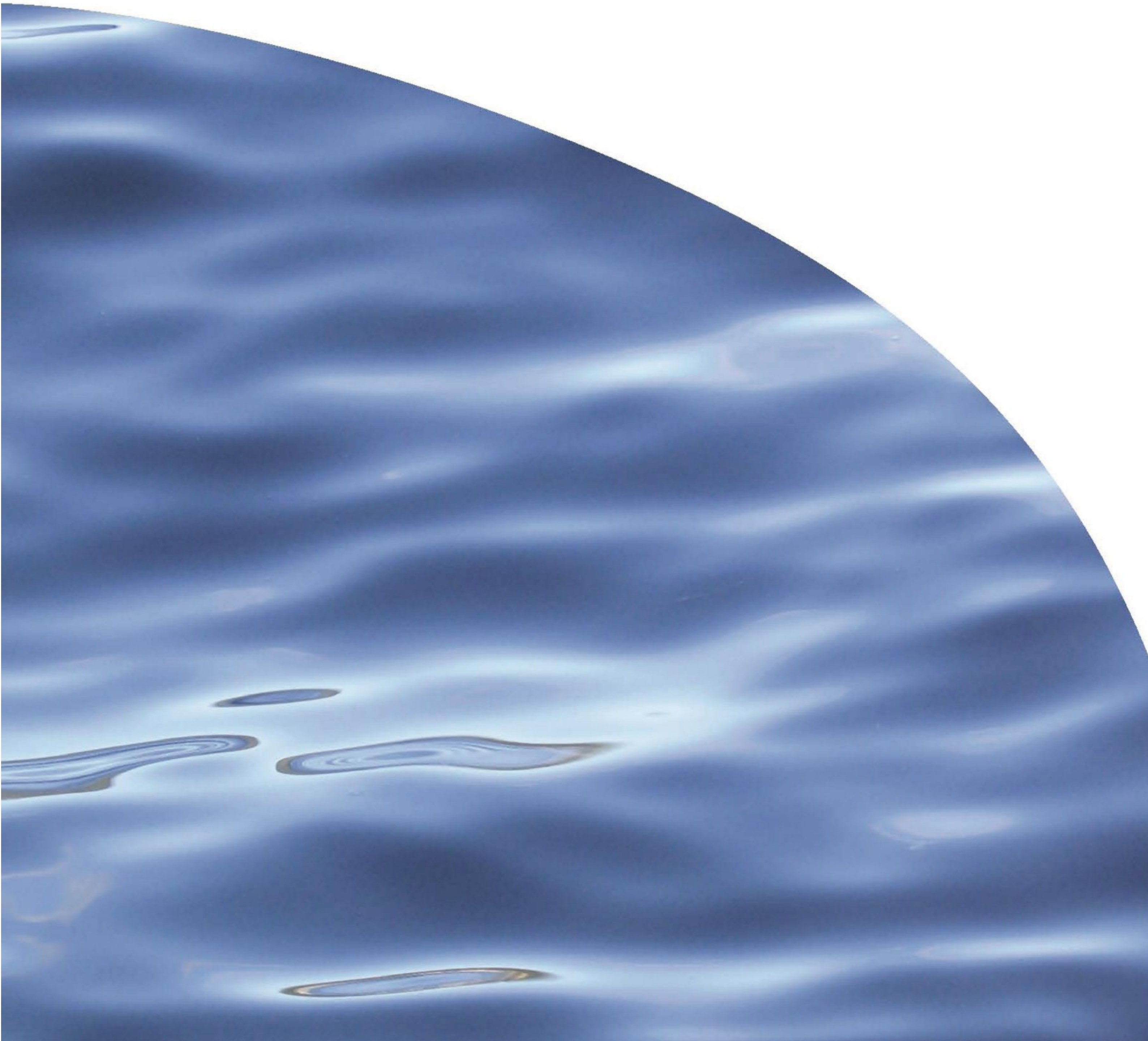
RESTORATION PLANNING FOR DEEP DUNE LAKES: DATA REVIEW AND RECOMMENDATIONS



RESTORATION PLANNING FOR DEEP DUNE LAKES: DATA REVIEW AND RECOMMENDATIONS

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EXECUTIVE SUMMARY

The Manawatu-Whanganui region has approximately 57 coastal dune lakes, both deep (> 10 m maximum depth) and shallow in nature, which occur in the paleo-dune complex of the area's west coast. These environments are internationally rare and the Horizons Regional Council (Horizons) One Plan lists numerous ecological, cultural, recreational, commercial and aesthetic values associated with these lakes and their catchments.

Horizons is required under the National Policy Statement for Freshwater Management (NPS-FM) to meet various objectives for the state of freshwater bodies in the region. These include maintaining or improving the overall quality of fresh water and setting objectives at or above national bottom lines for various freshwater attributes. The One Plan also sets water quality targets for the region's lakes. Recent monitoring indicates that water quality parameters in many of the dune lakes in the area regularly exceed both NPS-FM bottom lines and One Plan targets. Horizons is committed to improve degraded water quality in the region and to that end is planning restoration programmes for a number of dune lakes. Cawthron Institute was commissioned to review the existing data available for a selection of deep dune lakes in the region, identify gaps in the knowledge required to inform restoration planning, and make recommendations for future research and monitoring. Lakes Pauri, Wiritoa and Dudding have been used as case studies.

The water quality and ecological data for the deep coastal dune lakes reviewed in this report suggest very poor conditions exist in these lakes. The eutrophic to supertrophic status of the lakes indicates very high nutrient enrichment with nutrient and phytoplankton concentrations which routinely exceed the NPS-FM bottom lines. The phytoplankton community commonly includes potentially-toxic cyanobacteria species at biovolumes that exceed Ministry for the Environment action guidelines. The ecology of the lakes is severely compromised with numerous invasive macrophyte and fish species. As such, the ecological, cultural and recreational values of these lakes are highly degraded.

The data available for the deep dune lakes reviewed in this report allow some insight into likely nutrient sources and dynamics within the lake systems, however the data have some significant omissions, making it challenging to determine appropriate restoration planning. The export of nutrients from the catchment via surface or groundwater is the ultimate source of nutrient enrichment in the lakes, however, almost no data exist to allow this flux to be quantified and/or apportioned. A high proportion of the nutrient inflows are commonly retained in dune lake systems which generally have high hydraulic residence times. This and the available water quality data suggest that recycling of nutrients within the lakes (internal loading) is likely to be key. However, no data exist on sediment nutrient geochemistry or likely rates of nutrient release from the lakebed sediments. Trend analysis is likely to be key to any future restoration planning and monitoring; however, current quarterly monitoring frequency makes that challenging. Higher resolution of data gathering would also allow short term and seasonal variations in water quality to be monitored, providing useful insights into nutrient dynamics in the lake system. There were also insufficient data on aquatic plant and

fish distributions to accurately assess potential ecosystem effects or trends of invasive pest species for the region's dune lakes.

To address these knowledge gaps we recommend the following priority of actions:

- Surface and groundwater monitoring and modelling to enable mass balance modelling of external nutrient loads. Targets for external nutrient load reductions need to be clearly defined to enable goals to be set for catchment management initiatives.
- One-off investigations of sediment geochemistry to determine the likely extent of internal loading of nutrients from sediments during anoxic or high pH events.
- Modifying lake water quality monitoring to monthly time-scale to enable time-trend analyses and improve the resolution of seasonal variation.
- Adoption of high-frequency instrumentation (thermistor chain, DO, pH, chlorophyll-*a*, and turbidity sensors) for monitoring real time lake physicochemical variation (priority lakes). This monitoring could be focused over the summer stratification season and occur on an annual rotation cycle between lakes to more efficiently utilise monitoring resources.
- Bathymetric sonar surveys—hypsographic map production for lakes where recent sonar survey data are not available.
- Implement 5-yearly pest fish surveys to gain an understanding of the potential for pest fish enhancement of internal nutrient cycling (e.g., bioturbation, herbivory, trophic effects).
- One-off investigations into seasonal nutrient limitation (i.e., 4 sampling rounds in a single year) in a number of lakes in the region, including monthly nutrient ratios and nutrient bioassays.
- One-off seasonal macrophyte biovolume surveys to establish the extent to which macrophyte die-back enhances lake anoxia cycles (i.e., 4 sampling rounds in a single year).
- Waterbird counts on high usage lakes to quantify TN and TP loading by birds (as a one-off quarterly monitoring investigation).
- Inclusion of heterocyte counts on quarterly cyanobacteria analyses over a year of monitoring as an indication for N-fixation potential in monitored lakes.
- Paleolimnological investigations at key lakes to evaluate reference conditions for dune lake types in the region and paleo-history of water quality.

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1. INTRODUCTION

The National Policy Statement for Freshwater Management (NPS-FM) requires regional authorities to meet various objectives for the state of freshwater bodies in their region. These objectives include maintaining or improving the overall quality of fresh water and setting objectives at or above national bottom lines for various freshwater attributes. In the Manawatu-Whanganui region, the Horizons Regional Council (HRC) has recently commenced water quality monitoring of fifteen coastal dune lake systems. The preliminary results of this monitoring indicate that water quality in many of the monitored lakes is likely to fall below NPS-FM national bottom lines. These lakes also fail to meet the Regional Council's own water quality targets for deep lakes contained in the One Plan, the Council's statutory planning document.

Eutrophication of lake systems occurs when the lake becomes progressively more enriched with nutrients, resulting in increasing levels of primary productivity (Wetzel 2001). This is a natural process which generally occurs very slowly; however, anthropogenic activities in the catchment may accelerate the process, leading to degraded waterways with detrimental impacts on ecological, cultural, and recreational values. The NPS-FM requires that councils develop plans to improve their lakes to the national bottom line standards or above. Therefore, as part of their long-term planning process Horizons is proposing to investigate restoration options for Lakes Pauri, Wiritoa and Dudding as well as other deep coastal lakes in the region. In order to plan such restoration, a good understanding of the sources of nutrients to each lake and of the processes which influence nutrient retention and cycling within the lake system are required (Cooke et al. 2005). However, the current monitoring regime may not provide sufficient insight into the functioning of these lake ecosystems to allow the formulation of restoration plans. Furthermore, it is likely that more comprehensive monitoring will be required to inform and evaluate future restoration decisions. This is due to the complex nature by which nutrients can be sourced (surface and groundwater inflows) and recycled (internal loading from sediments) within dune lakes (Gibbs 2011; Kelly et al. 2016). A detailed understanding of the importance of sources and processes that drive water quality degradation in the lake is required before restoration measures can be effectively prioritised.

Horizons Regional Council commissioned Cawthron Institute (Cawthron) to assist in evaluating the information available to inform restoration planning for deep coastal lakes in the Manawatu-Whanganui region. This report focusses on three lakes—Pauri, Wiritoa and Dudding as case studies for which environmental monitoring data are presently available. The water quality and ecological condition of these lakes is briefly addressed in this report but only in the capacity of identifying gaps in the existing data sets. Specifically, this report aims to:

- review and evaluate the data which are currently available to inform restoration planning for these three lakes

- assess information gaps in the available monitoring data
- recommend monitoring actions to address the identified information gaps and allow comprehensive restoration planning for the lakes in question.

This work is linked to another Cawthron report which addresses similar questions for shallow coastal lakes in the Manawatu-Whanganui region (Waters et al. 2018). The reports are similar with significant overlap, however the contrasting lake depths results in variations in significant aspects of the information required to inform restoration plans. The reports are based on publicly available information and/or data supplied by HRC for this work.

2. REVIEW OF EXISTING DATA

2.1. General lake characteristics and values

The coastal Manawatu-Whanganui region has approximately 57 coastal dune lakes (Figure 1). The lakes have formed amongst the paleo-dune complexes, generally due to the blockage of stream valleys and depressions by blown sand. Dune lake environments are rare internationally and, in relatively unmodified catchments, typically have high ecological and human recreational values (Drake et al. 2009). The Horizons One Plan lists numerous ecological (life supporting capacity, fish habitat, pollution assimilation), cultural (mauri), recreational (contact recreation, fisheries), commercial (irrigation, abstraction, stock water, infrastructure), and aesthetic values associated with these lakes and their catchments. Biodiversity values for the water management zones containing the three case-study Lakes Pauri, Wiritoa and Dudding are presented in Appendix 1.

The coastal lakes in the region are generally small and most are shallow (< 10 m depth), however a number of these dune lakes, including Lakes Pauri, Wiritoa and Dudding, are characterised as deep lakes (> 10 m) meaning that they could be subject to seasonal stratification and are therefore managed as stratifying lakes (Table 1; Figure 2). The exact number of deep lakes in this coastal region is difficult to ascertain as there is often a significant discrepancy in depth data between different sources (Table 2). The Takiwa lakes platform (lakes.takiwa.co) utilises depth data from Freshwater Ecosystems of New Zealand (FENZ; Leathwick et al. 2010) which cites either measured (where known) or modelled depth information for all dune lakes in the region greater than 1 ha in area. Land, Air, Water Aotearoa (www.lawa.org.nz) also present depth data from Livingston et al. (1986), but this information is only available for a limited number of lakes.

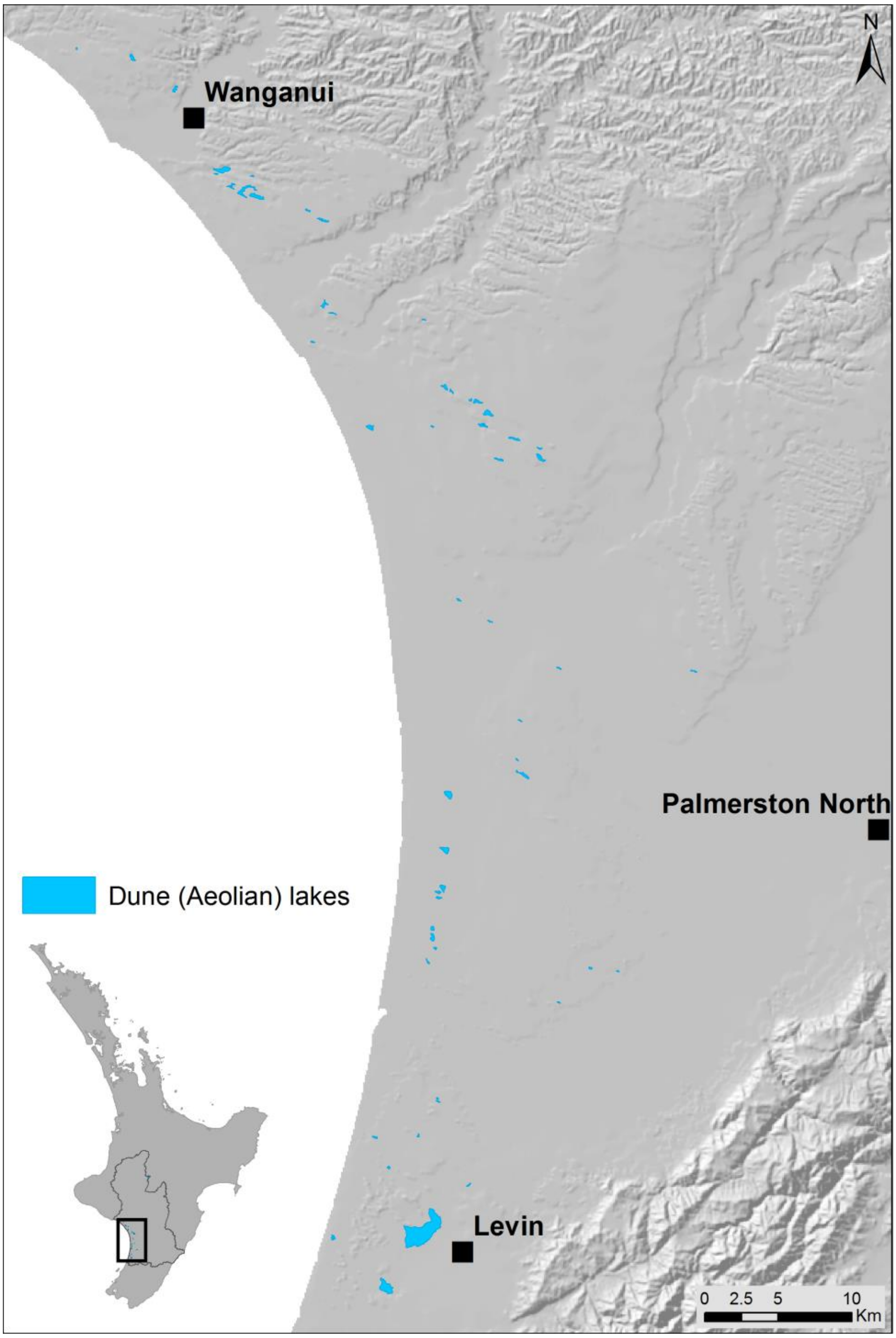

Figure 1. Locations of 57 dune lakes (Aeolian lake class in Freshwaters of New Zealand geodatabase, Leathwick et al. 2010) in the Manawatu-Whanganui region.

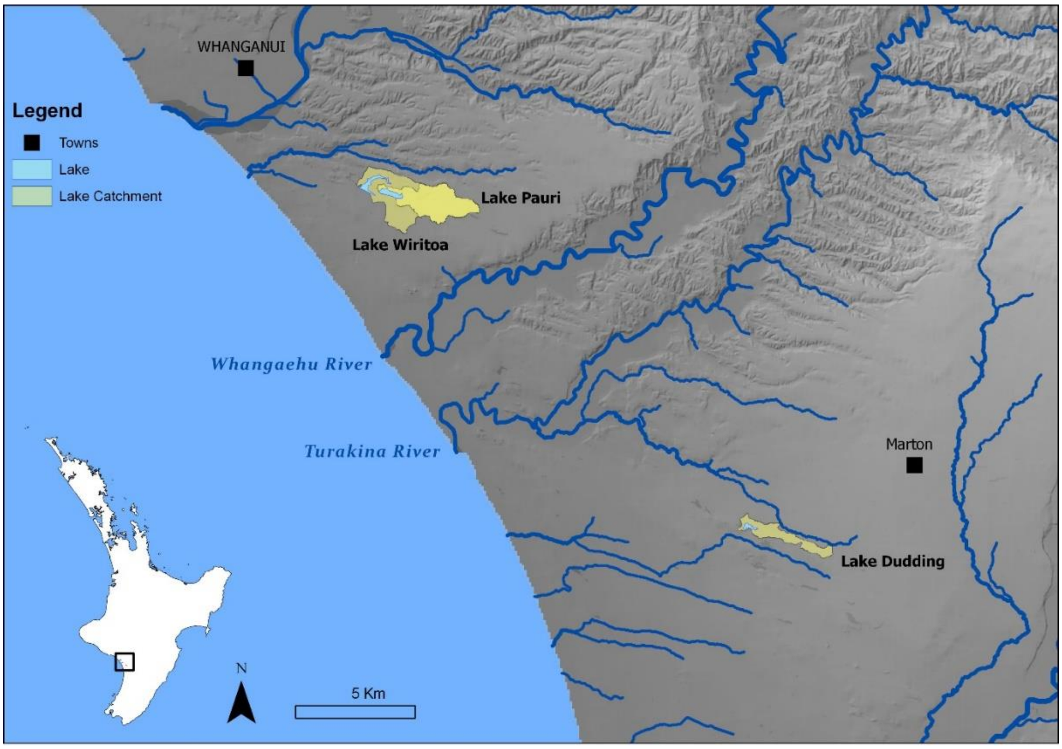

Figure 2. The locations of Lakes Pauri, Wiritoa and Dudding and their respective catchments in the Manawatu-Whanganui region.

The depths presented in Table 1 are based on the most recent sonar transect surveys that have been conducted on the case study lakes. These provide an accurate assessment of lake bathymetry that can be used to produce bathymetric maps as shown in Appendix 2. Lake Pauri appears to be the only deep lake for which such a map has been produced thus far, although the sonar survey data also exist for Lakes Wiritoa and Dudding.

Table 1. Lake morphometric and catchment data for Lakes Pauri, Wiritoa and Dudding.

Lake	FENZ[1] ID	Lake Area[2] (ha)	Surface Catchment area[2] (ha)	Geomorphic Class[3]	Elevation[2] (masl)	Estimated residence time[5] (y)
Pauri	18933	19.20	382	W[4]	57.6	1.58
Wiritoa	18934	21.80	696	W[4]	51.1	3.77
Dudding	13447	7.84	184	W[4]	91.9	2.29

[1] Freshwater Ecosystems of New Zealand
[2] retrieved from lakes.takiwa.co based on FENZ data. masl = meters above sea level
[3] from FENZ
[4] formed by wind (= dune lakes)
[5] retrieved from lakes.takiwa.co based on modelling in Catchment Land Use for Environmental Sustainability model (Woods et al. 2006).

Table 2. Contrasting depth data from various sources for Lakes Pauri, Wiritoa and Dudding

Lake	FENZ[1]		Livingston et al[2]		Recent sonar data[3]	
	Max depth (m)	Mean depth (m)	Max depth (m)	Mean depth (m)	Max depth (m)	Mean depth (m)
Pauri	7.9	2.6	14.9	6.3	13.8	6.1
Wiritoa	28.9	9.6	19.5	9.1	17.7	5.2
Dudding	19.7	6.6	11.9	5.0	12.6	3.5

[1] Freshwater Ecosystems of New Zealand

[2] Livingston et al. (1986).

[3] Data provided by Horizons Regional Council (L. Brown, pers. comm. 2018)

The lake catchments are generally small and limited in extent by paleo-dune morphology (Table 1). Lake Pauri drains into Lake Wiritoa and its catchment is a sub-catchment of the greater Wiritoa catchment. Land use in the three lake catchments is predominantly for high producing grassland, reflective of the agricultural landscape of the area (Table 3). Early forestry has largely cleared the land and cattle and sheep grazing now predominate (Gibbs & Champion 2013). There is limited urban development in the catchments of these lakes, however Lake Dudding has a publicly owned campground/picnic area adjacent to the lake while Lakes Pauri and Wiritoa have the Whanganui Prison close by, straddling the southern catchment boundary. Catchment land use maps generated using the Catchment Land Use for Environmental Sustainability (CLUES) model (Woods et al. 2006) are presented in Appendix 3.

Table 3. Land use in the catchments of Lakes Pauri, Wiritoa and Dudding. The data are derived from CLUES[1] catchment modelling and has been retrieved from https://lakes.takiwa.co.

Land use category	Lake		
	Pauri	Wiritoa	Dudding
	% of catchment		
Grassland	82.5	68.9	88.3
Forest	2.4	17.1	3.4
Shrubland	0	0	0.8
Cropland	8.1	4.4	1.3
Urban	0	2.3	0.9
Wetland	1.7	1.3	0.3
Water	5.3	3.1	5.0

[1] Catchment Land Use for Environmental Sustainability model (Woods et al. 2006).

2.2. Lake water quality data

2.2.1. *Data availability*

The majority of water quality (WQ) data in Lakes Pauri, Wiritoa and Dudding is from recent monitoring. Gibbs and Champion (2013) provide a comprehensive review of data available for Pauri and Wiritoa up to 2013 and this is not revisited in detail here. In brief, data collected prior to 2004 were very occasional with only 27 samples recorded between 1974–1982. In the years 1982 to 2005 sporadic samples were analysed from Lake Wiritoa for turbidity, *E. coli* and cyanobacterial cell counts (Gibbs & Champion 2013). Details of the monitoring undertaken in the lakes between 2004–2018 are presented in Appendix 4 and are briefly commented on here. Weekly sampling for *E. coli* was undertaken between 2004–2008 in Lakes Wiritoa and Dudding and 2005–2008 in Lake Pauri. Nutrient sampling was added to this monitoring programme from 2007–2008 in order to gather data to inform the development process of HRC's One Plan (L Brown, Horizons, 2018 pers. comm.*)*. A more rigorous monitoring programme has seen quarterly sampling and analysis of a comprehensive suite of WQ parameters in the lakes from 2014 to the present time. In this programme, quarterly sampling has been conducted at three sites per lake during which integrated 0-5 m samples have been collected from the epilimnion and analysed for a basic suite of parameters. A composite sample from all three sites (for site locations see Appendix 5) has then been analysed for a more comprehensive suite of parameters. A deeper sample was also taken from the hypolimnion at site 1 in each lake and was analysed for the same comprehensive suite of parameters. Water column profiles (temperature, dissolved oxygen, pH, oxidation-reduction potential, conductivity, salinity) have been measured at each site in all three lakes using a Smartroll data sonde. These were done at the same time as the quarterly monitoring sampling in 2014, 2016 and 2017. Only one profile at each site appears to have been conducted in 2015.

2.2.2. *Results*

Epilimnion water quality

Key statistics present a poor picture of water quality in Lakes Pauri, Wiritoa and Dudding. The annual mean trophic level index (TLI), based on annual means of total phosphorus, total nitrogen and chlorophyll-*a*, indicates that Lakes Pauri and Wiritoa are eutrophic to supertrophic while Lake Dudding is consistently within the supertrophic category (2014–2017, Table 4), indicating that all the lakes have very high trophic status and productivity. Gibbs and Champion (2013) report TLIs of 3.94 and 4.90 (mesotrophic and eutrophic) for Lake Pauri in 1982 and 2008 respectively, and Wiritoa having TLIs of 4.19 and 7.20 (eutrophic and hypertrophic) for the same years. While the 2008 TLI calculations were based on incomplete data, the TLI figures for Lake Pauri appear to have deteriorated significantly since the 1980s.

Table 4. Trophic level index figures for Lakes Wiritoa, Pauri and Dudding. The TLI(3) excludes the Secchi disc parameter. Trophic level classifications and TLI boundaries are provided for reference.

Year	TLI(3)[1]		
	Lake Pauri	Lake Wiritoa	Lake Dudding
2014	4.94	5.77	5.49
2015	4.82	4.98	5.49
2016	5.37	5.93	5.75
2017	5.41	5.41	5.78

Trophic Level Index classifications and boundaries

Lake type	Trophic level
Microtrophic	1.0-2.0
Oligotrophic	2.0-3.0
Mesotrophic	3.0-4.0
Eutrophic	4.0-5.0
Supertrophic	5.0-6.0
Hypertrophic	6.0-7.0

1. TLI(3) includes total phosphorus, total nitrogen and chlorophyll-*a* concentrations.

Median total phosphorus and total nitrogen values exceed the NPS-FM national bottom lines for all three lakes (Table 5), while only Lake Wiritoa exceeds the chlorophyll-*a* bottom line. Annual maximum ammoniacal nitrogen concentrations occasionally exceed the bottom lines for toxicity. Such exceedances indicate unacceptably high concentrations. All three lakes exceeded the One Plan water quality targets for lakes for total phosphorus, total nitrogen and chlorophyll-*a* concentrations. It should be noted that a direct comparison between the Table 5 data and NPS-FM bottom lines is problematic as the attribute tables in the NPS-FM for total phosphorus, total nitrogen, and phytoplankton are for annual median and maximum values and assume at least 12 samples (e.g. monthly) for each statistic. The data available for Lakes Pauri, Wiritoa and Dudding are sampled quarterly and hence do not meet this criterion.

In order to meet the 12-sample criterion, the data presented in Table 5 are for the entire monitoring period for which such quarterly sampling has been undertaken. This has the effect of ‘hiding’ some of the peaks of the data; e.g. in the Pauri and Dudding data the medians for 2016 and 2017 chlorophyll-*a* concentrations exceed the NPS annual median bottom line, but this is not evident in Table 5 due to relatively low concentrations in the 2014 and 2015 data. This effect can be seen in the plots of the data through the monitoring period (Figure 3 to Figure 5) with summer chlorophyll-*a* peaks during the summers between 2016–2018. Wiritoa has a higher overall chlorophyll-*a* median with high concentrations during summer and also demonstrates winter peaks with concentrations exceeding the NPS-FM annual maximum bottom line in August of 2014 and 2016.

Table 5. Median, maximum and minimum values for key water quality parameters from composite epilimnion samples at Lakes Pauri, Wiritoa and Dudding from the period for which quarterly monitoring data are available (February 2014 to February 2018). pH is from site-specific samples (i.e. not composite samples) and is not for the full period (see footnote to this table). The National Policy Statement for Freshwater Management (2014) bottom lines are included for comparison.

WQ parameter	**Statistic**	**Lake**			**NPS-FM[e] Bottom line concentrations**
		Pauri	**Wiritoa**	**Dudding**	
Total phosphorus (mg.m^{-3})	Median	59	61	74	50
	Maximum	97	414	239	
	minimum	29	25	32	
Dissolved reactive phosphorus (mg.m^{-3})	Median	18	9.0	8.0	
	Maximum	34	29	78	
	minimum	6.0	3.0	3.0	
Total nitrogen (mg.m^{-3})	Median	1060	960	1220	750
	Maximum	1520	1480	2730	
	minimum	910	694	687	
Ammoniacal nitrogen[a] (mg.L^{-1})	Median	0.030	0.010	0.031	1.3
	Maximum	0.100	0.140	1.21	2.2
	minimum	0.000	0.001	0.005	
Nitrate-nitrite nitrogen (mg.m-^{3})	Median	151	34	84	
	Maximum	697	574	973	
	minimum	3.0	2.0	0.0	
Chlorophyll-*a* (mg.m^{-3})	Median	6.20	14.0	9.00	12
	Maximum	35.0	98.0	48.0	60
	minimum	0.950	0.950	1.00	
pH	Median	7.74[b]	7.91[c]	8.28[d]	
	Maximum	9.85[b]	9.35[c]	10.89[d]	
	minimum	7.18[b]	7.30[c]	6.65[d]	

a. Note the different unit for ammoniacal nitrogen. This is presented as mg.L^{-1} to provide consistency with the NPS-FM guidelines

b. from Sites 2, 3, October 2015-August 2017

c. from Sites 1, 2, October 2015-November 2016

d. from sites 1, 2, 3, October 2015-August 2017.

e. National Policy Statement for Freshwater Management (2014)

In 2008 Lake Pauri water quality appeared to be significantly more degraded than that of Wiritoa (Gibbs & Champion 2013), however the present-day picture is less clear. Whereas in the earlier data Lake Pauri had substantially higher epilimnion nutrient concentrations, Wiritoa now has higher total phosphorus while Pauri has slightly higher total nitrogen and dissolved nutrients. Lake Dudding in turn has the highest total phosphorus and total nitrogen of the three lakes. Lake Dudding also has the highest median and maximum pH of the three lakes. Maximum pH in all three lakes exceeds the threshold (pH 9.2) which may result in the release of phosphorus bound to lakebed and suspended sediments (Gibbs et al. 2015).

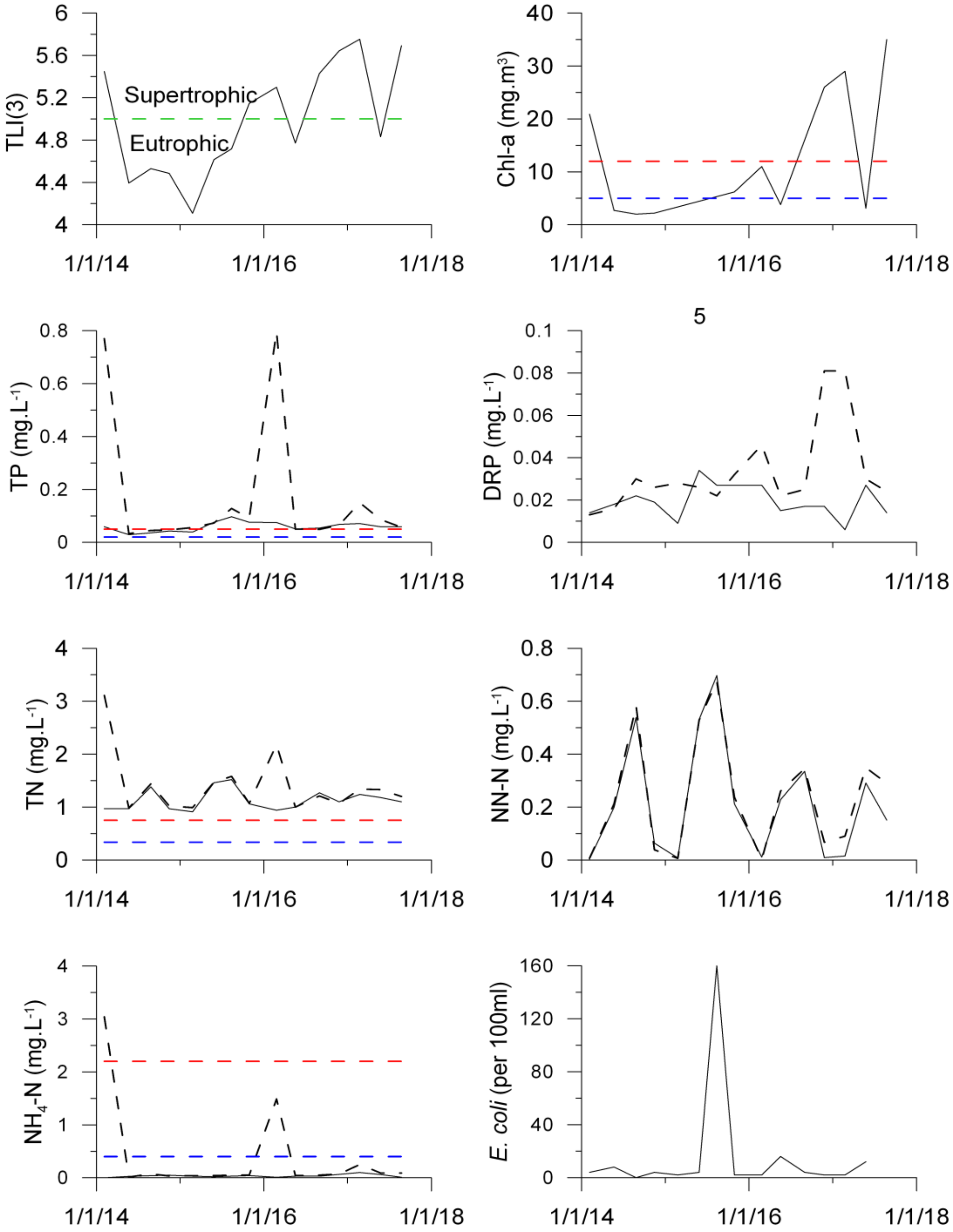

Figure 3. Lake Pauri water quality parameters from Horizons Regional Council monitoring from January 2014 to August 2017. Solid black lines in all plots are composite epilimnion samples from three sites. The dotted black lines in the TP, TN, DRP, NH_4-N and NN-N plots are hypolimnion samples from a single site. The red dotted lines indicate the National Policy Statement–Freshwater Management (2014) national bottom line concentrations (annual medians except NH_4-N which is annual maximum). The blue dotted lines indicate One Plan targets (annual means). The green dotted line in the first graph indicates Trophic Level thresholds. TLI(3) = trophic level index during each sampling (without Secchi disc parameter), Chl-a = chlorophyll-*a*, TP= total phosphorus, DRP = dissolved reactive phosphorus, TN = total nitrogen, NN-N = nitrate + nitrite nitrogen, NH4-N = ammoniacal nitrogen, *E. coli* = *Escherichia coli.*

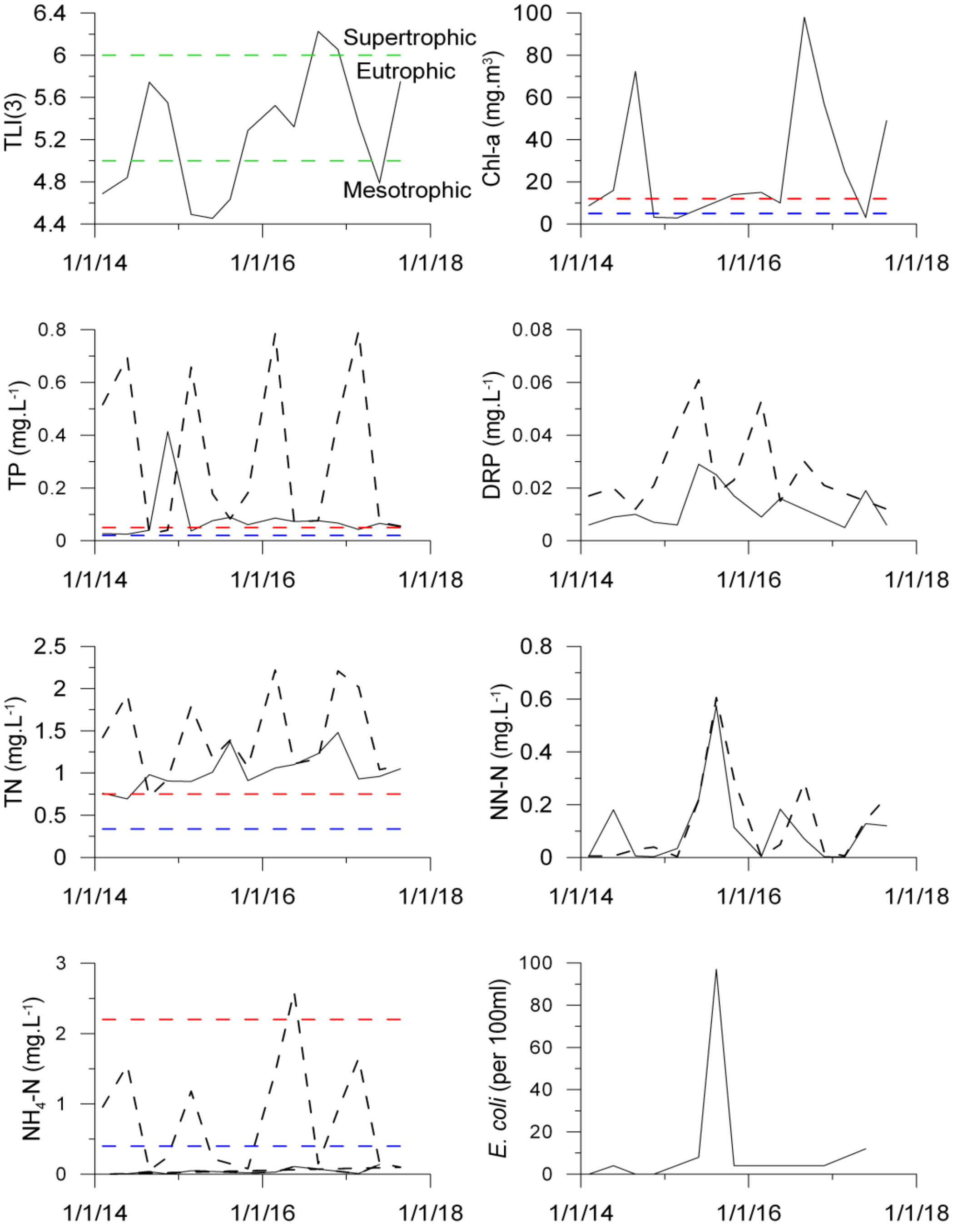

Figure 4. Lake Wiritoa water quality parameters from Horizons Regional Council monitoring from January 2014 to August 2017. Solid black lines in all plots are composite epilimnion samples from three sites. The dotted black lines in the TP, TN, DRP, NH4-N and NN-N plots are hypolimnion samples from a single site. The red dotted lines indicate the National Policy Statement–Freshwater Management (2014) national bottom lines (annual medians except NH4-N which is annual maximum). The blue dotted lines indicate One Plan targets (annual means). Green dotted lines in the first graph indicate Trophic Level thresholds. TLI(3) = trophic level index during each sampling (without Secchi disc parameter), Chl-a = chlorophyll-*a*, TP= total phosphorus, DRP = dissolved reactive phosphorus, TN = total nitrogen, NN-N = nitrate + nitrite nitrogen, NH4-N = ammoniacal nitrogen, *E. coli* = *Escherichia coli.*

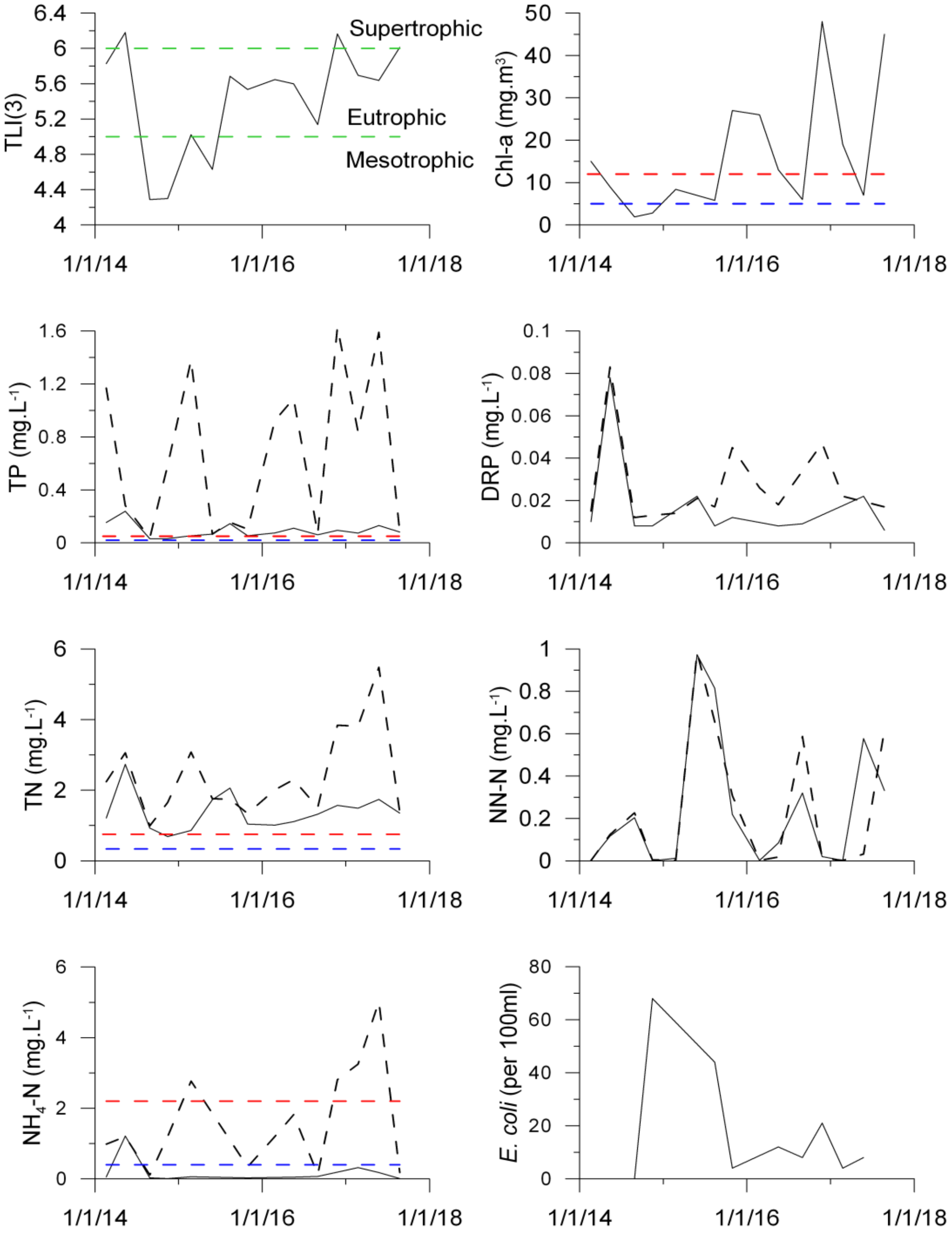

Figure 5. Lake Dudding water quality parameters from Horizons Regional Council monitoring from January 2014 to August 2017. Solid black lines in all plots are composite epilimnion samples from three sites. The dotted black lines in the TP, TN, DRP, NH_4-N and NN-N plots are hypolimnion samples from a single site. The red dotted lines indicate the National Policy Statement–Freshwater Management (2014) national bottom line concentrations (annual medians except NH_4-N which is annual maximum). The blue dotted lines indicate One Plan targets (annual means). Green dotted lines in the first graph indicate Trophic Level thresholds. TLI(3) = trophic level index during each sampling (without Secchi disc parameter), Chl-a = chlorophyll-*a*, TP= total phosphorus, DRP = dissolved reactive phosphorus, TN = total nitrogen, NN-N = nitrate + nitrite nitrogen, NH4-N = ammoniacal nitrogen, *E. coli* = *Escherichia coli.*

Stratification and hypolimnion water quality

Water column profiles of temperature and dissolved oxygen indicate that seasonal stratification and hypolimnetic deoxygenation (Figure 6) regularly occur in all three lakes. Some profiles are difficult to interpret as they do not appear to have encompassed the full depth of the lakes. Some of this variation may be due to lake level changes while some profiles, e.g. February 2017 in Lake Wiritoa, are incomplete.

The depth and duration of stratification and deoxygenation varies between the lakes, which has important ramifications for nutrient dynamics within the lake water columns. Lake Dudding exhibits strong, persistent stratification at depths as shallow as three metres and hypolimnetic deoxygenation occurs at all three sampling sites. The stratification in Lake Pauri appears to be much weaker and short-lived with only the February 2016 profile demonstrating complete deoxygenation of the hypolimnion below a thermocline occurring at approximately 6 m. Lake Wiritoa displayed a strong and prolonged stratification in 2016 with thermoclines occurring at around 6 m (February) and 8 m (November). A shorter stratification period occurred in 2017. Gibbs and Champion (2013) noted a similar stratification depth of 8 m for Lake Wiritoa in March 2013. Lake Pauri was also stratified at that time with a thermocline depth of 10.5 m. They also note, based on observations by Fowles (1982), that stratification in Lake Pauri may not be particularly stable and the lake may be periodically mixed in summer and hence is polymictic rather than monomictic. A review of the quarterly sonde profiles from 2014–2017 does not resolve this issue due to infrequency of profile measurement and the occasional non-full depth profiles.

Hypolimnetic water quality suggests poor conditions for aquatic life with high nutrient concentrations. In all the lakes, periods of thermal stratification coincide with higher hypolimnion total phosphorus and total nitrogen concentrations relative to the epilimnion. The stronger, more persistent stratification events that occur in Lakes Wiritoa and Dudding relative to Pauri are reflected in the regular, summertime nutrient peaks in these two lakes (Figures 2–5). In contrast, elevated total nutrient concentrations in the hypolimnion, relative to the epilimnion, only occurred during two of the four summers in Lake Pauri. This is consistent with the more intermittent thermal stratification and deoxygenation patterns observed in Lake Pauri.

Concentrations of ammoniacal nitrogen and dissolved reactive phosphorus are higher in the hypolimnion relative to the epilimnion, while nitrate-nitrite nitrogen remains similar throughout the water column. This is consistent with deoxygenated bottom waters driving redox-related release of nutrients from the lake-bed sediments (Figure 3, graph for NH_4-N, lower left-hand corner).

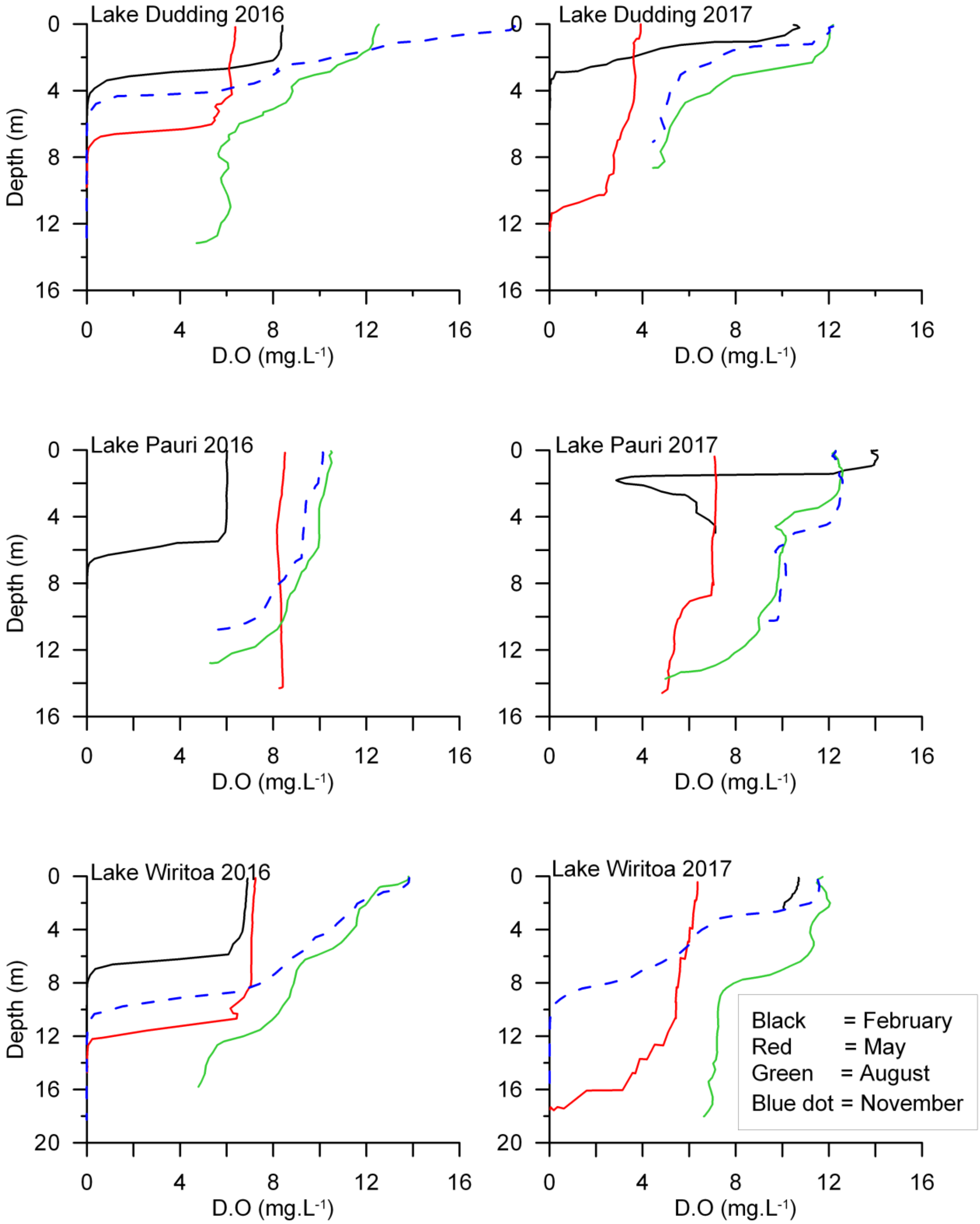

Figure 6. Water column profiles of dissolved oxygen in Lakes Dudding, Pauri, and Wiritoa (all at Site 1) from quarterly sampling during 2016 and 2017.

2.3. Phytoplankton

2.3.1. Data availability

Cyanobacteria data were available for Lakes Dudding and Wiritoa from weekly, summer monitoring between November 2010 and April 2014. The data reviewed included cell counts and biovolumes for the potentially toxic species *Dolichospermum* sp. (basionym/original name *Anabaena*) and *Microcystis* sp., as well as concentrations of cyanotoxins.

Comprehensive phytoplankton data were also available from the quarterly monitoring programme for all three lakes for the years 2015–2017. These data include full species lists and cell counts for all sampling occasions except the first two samplings of 2015 when species were recorded as relative abundance. Biovolumes were calculated for potentially toxic species. Samples for phytoplankton analysis were taken from the composite samples of all three monitoring sites at each lake as described in Section 2.2.1. The locations for these sites are provided in Appendix 5. In addition, weekly samples were taken at lake swim sites during the summer season. These swim site locations were not specified. For these samples *Dolichospermum* sp. and *Microcystis* sp. cell counts were conducted in-house by Horizons Regional Council (J Kamke, HRC, pers. comm.). Data for these samples and samples taken for cyanobacterial toxin analysis post-2014 were only briefly reviewed. Details of the Ministry for the Environment/Ministry of Health alert level framework for planktonic cyanobacteria (MfE/MoH 2009) are provided in Appendix 6.

2.3.2. Results

In Lakes Wiritoa and Dudding, biovolumes of the potentially toxic cyanobacteria taxa *Dolichospermum* sp. and *Microcystis* sp. regularly exceeded the action (red) alert levels during three summers of monitoring between 2010–2014 (Figure 7; MfE/MoH 2009). Similarly, during the summer periods of 2015–2017 total biovolumes of potentially toxic cyanobacteria species exceeded alert and action levels in all three lakes (Table 6). In Lakes Dudding and Wiritoa, the total biovolume action alert level was breached on two occasions (February and November) in both 2016 and 2017. In Lake Pauri, events where cyanobacteria cell densities breached criteria were less frequent, with only two breaches over the two years of monitoring. Lake Pauri's apparent lower levels of cyanobacterial blooms during 2016/17, were consistent with the generally lower concentrations of nutrients observed in the lake. These lower levels are in contrast to Gibbs and Champion's (2013) results, who reviewed cyanobacterial cell counts for the period 2005–2009 and reported more 'potentially scum-forming bloom events' in Lake Pauri than in Wiritoa.

The cyanobacteria *Dolichospermum* sp. was the dominant species over most of the more-recent monitoring data, with *Microcystis* sp. also occasionally reaching high cell abundances. It is noted that other potentially toxic species such as *Pseudanabaena* sp. (present occasionally at high cell counts, e.g. up to 9500 cells mL^{-1} in Wiritoa) were not utilised in the calculations of total biovolumes in Table 6 because no biovolume data were available. Similarly, the potentially toxic species *Aphanocapsa* sp. (Pauri) and *Phormidium* sp. (Pauri and Wiritoa) were present at low cell counts in some samples but biovolumes were not provided in the data reviewed.

Despite the high cyanobacterial biovolumes that occurred for the three lakes, cyanotoxin concentrations measured in phytoplankton samples over the period 2010 to 2014 (Table 7) were consistently low, and well below the recommended recreational activity action threshold (> 12 µg.L^{-1} microcystins) (MfE-MoH 2009). Post-2014 data was only reviewed briefly but provided a similar picture of high (alert level) biovolumes with low cyanotoxin concentrations.

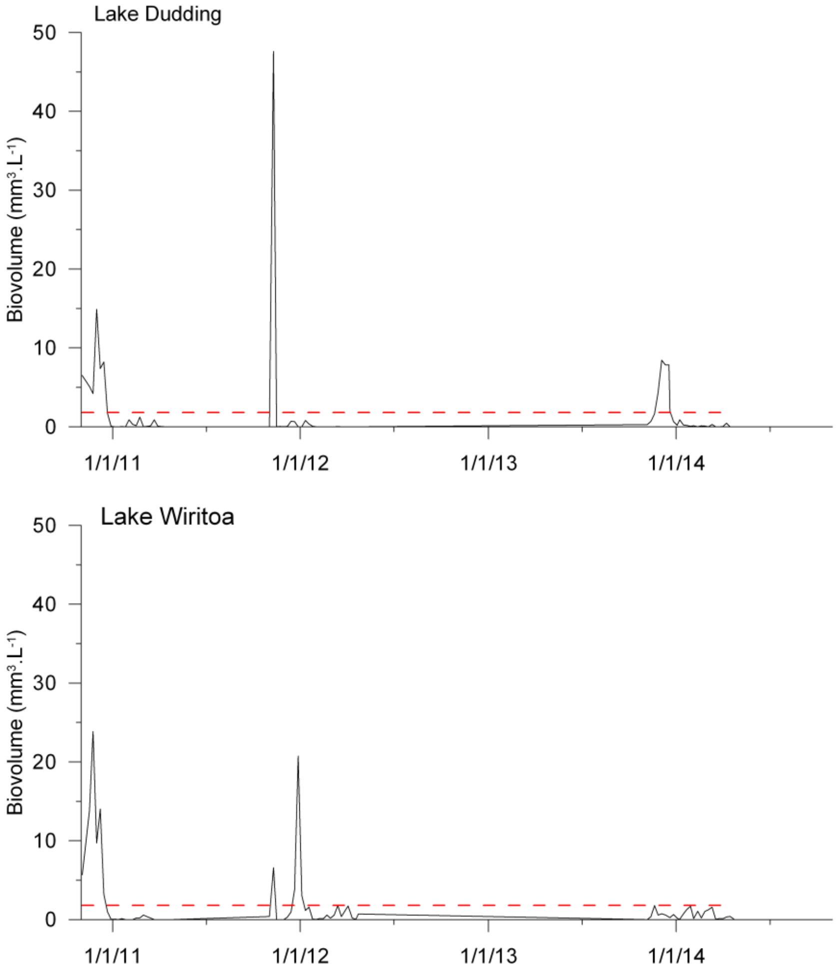

Figure 7. Total biovolumes of *Dolichospermum* sp. and *Microcystis* sp. from monitoring samples collected weekly over summer (November–April) 2010–1014 from Lakes Dudding and Wiritoa. The red dotted line is the action alert level biovolume (1.8 mm^3.L^{-1}; MfE-MoH 2009).

Table 6. Cell concentrations and biovolumes of potentially toxic cyanobacterial species from monitoring samples taken in 2016–2017 for which biovolumes have been provided. Biovolumes were calculated from average cell volumes. The colour coded boxes refer to the Alert level framework for planktonic cyanobacteria. Red = Action (biovolume > 1.8 mm^3.L^{-1}), Amber = Alert and Green = Surveillance (biovolume < 0.5 mm^3.L^{-1}) modes respectively (MfE/MoH 2009)

Lake	year	month	Potentially toxic species identified in sample	Cell concentration	Biovolume per species (mm^3/L)	Total biovol in sample (mm^3/L)
Dudding	2017	February	*Dolichospermum* cf. *circinale*	45,000	9.36	9.67
			Microcystis sp.	5,900	0.31	
		November	*Dolichospermum* cf. *circinale*	30,000	6.00	6.00
	2016	February	*Dolichospermum* cf. *circinale*	2,700	0.56	2.14
			Microcystis sp.	17,000	1.58	
		May	*Dolichospermum* sp.	24	0.005	0.019
			Microcystis sp.	740	0.014	
		August	*Microcystis* sp.	290	0.006	0.006
		November[1]	*Dolichospermum* sp.	130,000		🟥
Pauri	2017[2]	February	*Dolichospermum* cf. *circinale*	18,000	3.74	4.03
			Microcystis sp.	15,000	0.29	
		May	*Dolichospermum* cf. *circinale*	55	0.011	0.011
		August	*Microcystis* sp.	9	0.0008	
	2016	February	*Dolichospermum* cf. *circinale*	390	0.07	0.12
			Microcystis sp.	2,500	0.05	
		May	*Dolichospermum* cf. *circinale*	500	0.10	0.13
			Microcystis sp.	430	0.03	
		August	*Dolichospermum* cf. *circinale*	1400	0.291	0.291
		November	*Dolichospermum* cf. *circinale*	3100	0.6	0.600
			Microcystis sp.	29	0.0006	
Wiritoa	2017	February	*Dolichospermum* cf. *circinale*	12,000	2.5	2.52
			Microcystis sp.	190	0.02	
		May	*Dolichospermum* cf. *circinale*	79	0.014	0.014
		November	*Dolichospermum* sp.	8,093	2.01	2.01
	2016	February	*Microcystis* sp.	18,000	1.67	1.67
		May	*Dolichospermum* sp.	1,700	0.306	0.306
		August	*Dolichospermum* cf. *circinale*	33	0.007	0.007
		November	*Dolichospermum* cf. *circinale*	59,000	12.3	12.3

1. a biovolume was not included in the provided data for November despite a very high cell count. A red alert level has been assumed.

2. phytoplankton data was not provided for November

Table 7. Total cyanotoxin concentrations in monitoring samples collected weekly over summer (November -April) 2010-2014 from Lakes Dudding and Wiritoa.

Lake	**Date**	**Total cyanotoxin concentration ($\mu g.L^{-1}$)**
Dudding	15/12/2010	< 0.5
	10/11/2011	1
	20/11/2013	< 0.1
	18/12/2013	< 0.1
Wiritoa	15/12/2010	0.3
	10/11/2011	1
	21/12/2011	< 0.1
	28/12/2011	< 0.5
	4/01/2012	< 0.5
	20/11/2013	< 0.1
	18/12/2013	< 0.1

2.4. Macrophytes

2.4.1. Data availability

Lake Submerged Plant Indicator (SPI) scores for Lakes Dudding and Wiritoa have been calculated for the years 2001 (Edwards & Clayton 2002) and 2015 (Burton 2017), while a single score (2015) is available for Lake Pauri (Burton 2017). Lake SPI surveys are conducted by SCUBA divers to assess the diversity, depth extent, and quality of indigenous plant communities with regard to the impact from invasive weed species. From the survey, a 'Native Condition Index' and 'Invasive Impact Index' are derived and are then combined into an overall 'LakeSPI Index'. Prior to 2001, Kelly (1978) reported on surveys over the period 1977/78 which sampled 12 lakes in the region, including the three lakes in this report. NIWA conducted spot samples In Lake Wiritoa in 1994 and 1999 while Ogle (1999) sampled the same lake. More recently (2016), aquatic vegetation biovolumes have been surveyed by sonar transects in Lakes Pauri and Wiritoa (see Appendix 7).

2.4.2. Results

Lake SPI results (Table 8) indicate that Lakes Pauri and Wiritoa are in poor condition with respect to macrophyte communities and have been heavily impacted by invasive species. Lake Wiritoa results showed a slight decrease in LakeSPI condition in 2015 relative to 2001; however, further surveys are needed to determine if this is a trend or simply variance between sample dates/methods.

Appendix 8 presents a more detailed summary of the results from the various vegetation surveys including some of the main species present and maximum depths at which growth was observed. Lake Pauri is extensively dominated by invasive hornwort (*Ceratophyllum demersum*) growing to a depth of 6.3 m. This species was not detected in earlier surveys in 1977 and 2003. *Potamogeton crispus* was recorded in 1977 and *Egeria* and *Elodea* were present in 2003. In 2015 native plants were only present at low coverage and included pondweeds and charophyte species. Of particular note in the 2015 survey was observation of the near-threatened liverwort *Ricciocarpos natans* (Burton 2017).

Table 8. Lake SPI results for Lake Pauri, Wiritoa and Dudding.

	Date	**LakeSPI (%)**	**Condition**	**Native Condition (%)**	**Invasive Impact (%)**	**Dominant weed species**
Lake Pauri	2015	16	Poor	22	96	Hornwort
Lake Wiritoa	2001	16	Poor	16	96	Hornwort
	2015	14	Poor	20	96	
Lake Dudding	2001	48	Moderate	50	48	Egeria
	2015	22	Moderate	24	87	

Lake Wiritoa was characterised by the LakeSPI as being in poor ecological condition in both 2001 and 2015. Thick bands of the invasive species *Vallisneria australis* and *Ceratophyllum demersum* (to a depth of 6.3 m) occur along with *Potamogeton crispus* and *Egeria densa. Potamogeton crispus and Vallisneria australis* have occurred in the lake since at least 1977. *Elodea canadensis* (1994) and *E. densa* and *C. demersum* (1997) were noted in subsequent surveys. Native species observed in the most recent LakeSPI survey include pondweeds, milfoils and charophytes (Burton 2017).

Lake Dudding is characterised as having LakeSPI scores in the moderate range but appears to have significantly declined since 2001, and is only slightly above the threshold for 'poor' condition (20%). Currently *E. densa* dominates the submerged vegetation community and grows to a depth of 6.3 m. This invasive weed has colonised the lake since the 2001 survey when the lake was described as 'predominantly native'. The invasive species *E. canadensis*, *P. crispus* and *Ranunculus trichophyllus* also occur in the lake but their impact is considered minor compared to *E. densa.* Native species include pondweeds, charophytes and the turf-forming *Glossostigma diandrum* (Burton 2017). Species composition and maximum depth in the 2001 survey was described as similar to that in Kelly (1978). Maximum depth range of aquatic vegetation in 2015 remains similar to those previously recorded.

2.5. Fish

2.5.1. Data availability

Data on fish occurrence in the three lakes appear to be sparse with only limited data available from the New Zealand Freshwater Fish database (NZFFD). Gibbs and Champion (2013) note that a fish survey was conducted in Lake Wiritoa in April 2005, however no further details are recorded and the NZFFD has no records from these dates.

In an effort to enhance the paucity of the fish record, a fish prediction model was utilised to ascertain the likelihood of fish being present in the lakes. Fish distributions were predicted using a spatial database as described by Leathwick et al. (2008). The model is built around the river network developed originally as the River Environment Classification (REC; Snelder et al. 2004) and predicts the probability of presence for each species at all rivers and streams throughout New Zealand. This model does not predict for static water bodies and hence predictions were only for stream reaches connected to the lakes.

2.5.2. Results

The NZFFD lists occurrences of rainbow trout (*Oncorhynchus mykiss)* and perch (*Perca fluviatilis)* in all three lakes, in fact Lakes Wiritoa and Dudding are listed as recreational trout and perch fisheries on the fishing website www.nzfishing.com. Goldfish (*Carassius auratus)* were also recorded for Lakes Wiritoa and Dudding. In terms of native species, the only records are of unspecified eels (*Anguilla* sp.) in Lake Wiritoa and common bully (*Gobiomorphus cotidianus*) in Lake Dudding.

The fish prediction model (Leathwick et al. 2008) predicted probabilities of > 50% for shortfin eels in stream reaches connected to all three lakes while longfin eels were predicted (> 50%) in stream reaches connected to Lakes Pauri and Wiritoa. For native fish, banded kokopu were also predicted in stream reaches connected to Pauri and Wiritoa while common bullies were predicted in reaches connected to Pauri only.

It is also worth noting that populations of *Echyridella* (kakahi) have been confirmed in Lake Dudding and reported for Lake Pauri (L. Brown, Horizons, pers. comm.).

2.6. Lake nutrient sources

2.6.1. Data availability

Surface water flows and external nutrient loads

Limited measured data appear to be available for surface water inflows and hence nutrient inflows from the catchments for all three lakes (external loading). Gibbs and Champion (2013) present three records sourced from Fowles (1982), of surface water flows into and out of Lakes Pauri and Wiritoa. Estimates for total, long term (steady-state) 'loads to lake' for phosphorus and nitrogen have been modelled using Catchment Land Use for Environmental Sustainability model (CLUES, Woods et al. 2006) and these data have been retrieved from https://lakes.takiwa.co.

Groundwater is considered likely to be a significant component of the hydrology in these lake systems, but no data have been obtained that provide insight into potential nutrient fluxes to/from the lakes via groundwater sources. A report on groundwater catchment zones (Nicol & Thomas 2017) provides useful information on the geological setting and modelled groundwater catchments of these lakes. However, no monitoring information was available on groundwater nutrient concentrations within the capture zones of these lakes.

Internal nutrient loads

Lake sediments have the potential to be a major source of nutrients to the lakes, particularly during periods when low dissolved oxygen or high pH facilitate the solubilisation (internal loading) of nutrients that are loosely bound to sediments (Waters 2016). No data have been obtained on lake sediment nutrient geochemistry from any of the lakes. The only insight to potential internal nutrient loading (flux of nutrient from the lake bed sediments to the water column) is from the differences in water quality monitoring parameters between the epilimnion and hypolimnion (see Section 2.2.2).

2.6.2. Results

Surface water flows and external nutrient loads

Lake Pauri is connected via surface water flows to Lake Wiritoa and normally water flows from Pauri to Wiritoa. The majority of surface flows to Lake Wiritoa are via Lake Pauri although a smaller sub-catchment to the north-east flows directly into Lake Wiritoa. Outflows from Lakes Wiritoa and Dudding are small and typically dry up in summer (Gibbs & Champion 2013; Nicol & Thomas 2017). Such hydrology is likely to lead to very long residence times which is consistent with modelled estimates (Table 1).

The only flow data reviewed here are taken from Gibbs and Champion (2013). Gauging occurred on three dates in October and November 1974 and results showed more water leaving Lakes Wiritoa and Pauri, than entering via inflows (Table 9). This was taken to indicate that groundwater inflows are likely to be a significant component of lake inflows, particularly during periods of higher flow. Groundwater capture zones have been modelled, but a number of poorly constrained parameters limit the applicability of these results for estimating groundwater flows and, in particular, nutrient inflows via groundwater (Nicol & Thomas 2017).

Table 9. Gauged flows into and out of Lakes Wiritoa and Pauri. Data are from Fowles (1982). Groundwater inflow is calculated from the difference between inflows and outflows. All flows are in $L.s^{-1}$.

Date	Lake Wiritoa			Lake Pauri		
	Inflow	Outflow	Groundwater inflow	Inflow	Outflow	Groundwater inflow
25/10/1974	161	311	150	63	161	98
7/11/1974	32	50	18	6	32	26
26/11/1974	11	12	1	0	11	11

The Department of Corrections has recently had consent granted to continue the discharge to land of up to 350 m^3 treated wastewater from the Whanganui Prison. This discharges to rapid infiltration beds (RIB) on the south side of the prison and south of Lake Pauri. Evidence presented in the consent application indicated that the groundwater-dependent systems of Lake Wiritoa and Lake Pauri are located up-gradient from the prison site and cannot be affected by the discharge to the RIBs. Groundwater in the RIBs is likely to flow towards the west to south west in the shallow unconfined groundwater system. Stormwater is also discharged from the prison complex to the stream connecting Lakes Pauri and Wiritoa. Samples taken from this stormwater in 2013 were highly enriched with nutrients and dissolved metals (copper and zinc) (Gibbs & Champion 2013).

Lake Dudding also has a consented effluent discharge nearby. The Rangitikei District Council has a consent to discharge up to 15 m^3 per day of filtered effluent from a septic tank to low pressure, effluent dosed trenches in a disposal field on the south side of the lake. Consent application evidence noted that the location and design of the system should potentially eliminate runoff to the lake, ponding at the surface, and groundwater contamination.

No water quality data for inflow streams or groundwater have been found for this report. The Catchment Land Use for Environmental Sustainability model (CLUES, Woods et al. 2006) has been used to estimate inflow concentrations and areal loads for the three lakes (Table 10). These modelled predictions suggest inflows to the lakes are likely to be very high in both TN and TP, particularly for Lakes Pauri and Wiritoa.

Table 10. Estimated total phosphorus (TP), total nitrogen (TN) inflow concentrations and areal loads to the lake. These estimates are long-term (steady state) concentrations obtained using the Catchment Land Use for Environmental Sustainability model (CLUES, Woods et al. 2006) and retrieved from https://lakes.takiwa.co.

Lake	Average TP inflow concentration ($mg.m^{-3}$)	Average TN inflow concentration ($mg.m^{-3}$)	Areal Total Phosphorus load ($kg.ha^{-1}.y^{-1}$)	Areal Total Nitrogen load ($kg.ha^{-1}.y^{-1}$)
Pauri	285	8012	0.24	7.54
Wiritoa	64.8	1886	0.05	1.51
Dudding	22.3	825	0.03	1.01

Internal nutrient load

No data describing direct analyses of lake sediment geochemistry or nutrient release rates have been obtained for this report. The high hypolimnetic concentrations of total and dissolved nutrients relative to concentrations in the epilimnion during periods of thermal stratification (discussed in Section 2.2.2) strongly suggest that internal fluxes of nutrients from the lakebed sediments to the water column are likely to be significant. These internal loads likely result from low hypolimnetic oxygen concentrations that develop during thermally stratified conditions, and could be a major source of nutrients to the lake. Such loads are likely to be self-perpetuating as they drive increased primary productivity, which results in greater organic material settling to the lake bottom and therefore higher oxygen demand as the organic load decomposes (Wetzel 2001). These processes appear to be most significant in Lakes Wiritoa and Dudding but potentially less so in Pauri. This trend is supported by the discrepancies between predicted water column nutrient concentrations in inflows (modelled in CLUES) and concentrations observed in lake water quality monitoring data (Table 11). Significantly higher than predicted mean total phosphorus and nitrogen concentrations occur in Lakes Wiritoa and Dudding, suggesting an alternative nutrient source than the catchment fluxes utilised in the modelling of the predicted values. Internal nutrient loading is potentially the most likely source to explain this discrepancy.

We note that highly reducing conditions in groundwaters can also facilitate desorption of phosphorus from aquifers and provide a source of nutrients to dune lakes (Kelly et al. 2015). However, no information on groundwater quality was available to confirm if this could be a significant factor for any of these lakes.

Table 11. Estimated total phosphorus (TP), total nitrogen (TN) concentrations (conc), and measured mean concentrations (2014-2018) from lake water quality (WQ) monitoring data for the same parameters. Estimated concentrations are long term (steady state) concentrations obtained using the Catchment Land Use for Environmental Sustainability model (CLUES, Woods et al. 2006) and retrieved from https://lakes.takiwa.co.

Lake	Estimated TP conc ($mg.m^{-3}$)	Mean TP conc from WQ monitoring ($mg.m^{-3}$)	Estimated TN conc ($mg.m^{-3}$)	Mean TN conc from WQ monitoring ($mg.m^{-3}$)
Pauri	82.4	59.0	129.4	1117
Wiritoa	20.7	77.0	129.0	1009
Dudding	12.1	90.0	75.9	1360

3. DISCUSSION AND RECOMMENDATIONS

The water quality and ecological data for the deep coastal dune lakes reviewed as case study lakes in this report suggest that very poor conditions exist. The eutrophic to supertrophic status of the lakes indicates very high nutrient enrichment with phytoplankton concentrations routinely exceeding the NPS-FM bottom lines. The phytoplankton community regularly includes potentially toxic cyanobacteria species at biovolumes which exceed Ministry for the Environment action guidelines. The ecology of the lakes is severely compromised with numerous invasive macrophyte species contributing to poor LakeSPI scores, and by the presence of exotic fish species. As such, the ecological, cultural and recreational values of these lakes are highly degraded.

While Gibbs and Champion (2013) record that poor water quality and weed invasion were noted by HRC in Lake Pauri and Wiritoa in 1982, it appears that water quality has continued to decline significantly since then. However, it is difficult with the data available to determine whether this worsening is continuing. The ecological integrity of all the lakes appears to have declined with respect to macrophyte assemblages and Lake Dudding in particularly has experienced a significant recent weed invasion. Exotic fish are present in all the lakes, but numbers and relative impact are not known.

3.1. Reasons for elevated nutrients

The ultimate source of most nutrients in a lake system is erosion and transport from the lake catchment (external loading), however once in the lake, biogeochemical processes may dictate the availability of those nutrients for primary producers such as macrophytes and algae. Lakebed sediments may be a sink or source of nutrients depending on prevailing biogeochemical conditions in the lake, and in many nutrient-rich systems the recycling of nutrient from the sediments to the water column (internal loading) constitutes a large proportion of the nutrient budget of the lake. Because of the low hydraulic flow-through rates associated with most dune lakes, historical nutrient and sediment loading is largely retained within the lake sediments, making them highly prone to internal recycling.

3.1.1. External nutrient loads

The data available for assessing the transport of nutrients from the catchments of the three lakes reviewed here are extremely limited. Little hydrological information and almost no surface or groundwater WQ data for lake inflows are available. However, a catchment land use pattern of predominantly high producing grassland (Table 3 and Appendix 3) indicate that nutrient fluxes from the catchment are likely to be high. The best data we have are derived from modelling of catchment land use (Table 9 and Table 10) and suggest significant loads to the lakes, although catchment yields are significantly less than, for instance, Lake Horowhenua (modelled total phosphorus yield in Lake Pauri = 0.24 $kg.ha^{-1}.y^{-1}$, Lake Horowhenua = 0.59 $kg.ha^{-1}.y^{-1}$; data from CLUES modelling retrieved from lakes.takiwa.co).

The lack of significant outflows from these lakes and hence long residence times (Table 1), means that most nutrients reaching the lakes from the catchment will be retained within the lake system. The inputs from stormwater discharges are likely to be significant for Lake Wiritoa and possibly Lake Pauri; however, it is not possible to estimate this from current data. Similarly, the potential input from wastewater discharges at all three lakes is uncertain. The discrepancy between gauged inflows and outflows at Lakes Wiritoa and Pauri (Table 9) confirms that, as might be expected for dune lakes in sandy soils, groundwater is likely to be a highly important but currently unknown portion of the annual nutrient budget.

The lack of information on groundwater quality within the capture zones of the lakes is a major information gap.

3.1.2. Internal nutrient loads

Sediment geochemistry and water column dynamics

Internal loading of nutrients within lake systems can be a major contributor to increased water column nutrients and decreased ecological integrity (Wetzl 2001; Schallenberg & Sorell 2009). No sediment geochemistry investigations appear to have been conducted in the three lakes reviewed here, however the lake sediments are likely to reflect high primary productivity. Collapsing phytoplankton populations and a potentially large flux of organic matter from senescing macrophytes, are likely to result in sediment with high organic content and hence a high sediment oxygen demand. This is turn will increase deoxygenation rates in the hypolimnion, reducing redox potential in the sediments and potentially causing the release of nutrients to the water column. Although less than four years of quarterly monitoring data exist, it appears that such redox-related nutrient release is a significant driver of nutrient loads to the water column of Lakes Wiritoa and Dudding and less frequently, Lake Pauri. The dissolved oxygen water column profiles, and the decoupling of nutrient concentrations in the epilimnion and hypolimnion, support this suggestion. Elevated pH (> 9.2–9.5) will also cause phosphorus nutrient release from the bed sediments of lakes (Jacoby et al. 1982). Although such high pH is unlikely in lake hypolimnions (due to lower primary productivity) and hence is often discounted as a significant driver of nutrient release in deeper lakes, the relatively shallow mean depths in these lakes (Table 2), in particular in Lake Dudding, could mean that significant portions of the lakebed sediments are in contact with the epilimnion and hence may be exposed to high pH. However, the existing pH data are very limited and further monitoring is required to confirm the significance of pH as a driver of internal nutrient loading.

Effects of fish on internal load

Some fish species also have the potential to promote nutrient cycling within lakes thereby reducing water quality and potentially causing collapse of macrophytes (Schallenberg & Sorrell 2009). Catfish (*Ameiurus nebulosus*), goldfish (*Carassius auratus*), rudd (*Scardinius erythrophthalmus*), koi carp (*Cyprinus carpio*),and tench (*Tinca tinca*) have all been associated with degraded water quality and regime shifts in New Zealand lakes. This may occur due to the physical release of nutrients by excretion in forms which are more bioavailable for phytoplankton uptake, the translocation of nutrients from the hypolimnion to the photic epilimnion, and from the bed sediments to the water column due to physical disruption of the sediment during feeding (Vanni 2002). Tench, rudd and koi carp are known to increase nutrient cycling (Rowe & Graynoth 2002), however these are not reported for the lakes reviewed here. These fish are, however, present in similar lakes relatively nearby (e.g. Lake Waitawa), and therefore pose a significant threat of invasion.

3.2. Reasons for elevated phytoplankton and cyanobacteria

High cyanobacteria concentrations are generally a symptom of high water-column nutrients. These may be due to ‘external’ inputs from the lake catchment and/or from ‘internal’ nutrient cycling (see previous section). Some cyanobacterial species, such as *Dolichospermum* sp. which are dominant in these lakes, can utilise atmospheric nitrogen and thrive in conditions with low N:P ratios. Provided some phosphorus is available (e.g. from internal loading processes) this allows them to bloom even when nitrogen concentrations are relatively low. It is unknown whether the *Dolichospermum* in the dune lakes reviewed here actively fix nitrogen. This can be assessed relatively simply by identifying the presence and abundance of heterocysts in their filaments.

Fish populations in lakes may also have significant trophic impacts on phytoplankton populations due to predation of zooplankton grazers (Vanni 2002). Perch, which commonly form stunted populations of small fish in New Zealand (Duncan 1967), are reported from all three of the lakes reviewed here and juveniles are known to consume zooplankton (Duncan 1967; Attayde & Hansson 2001). However, no data exist (to our knowledge) on zooplankton communities in the three lakes and hence, it is impossible to gauge the trophic effects of fish predation of zooplankton. Data on zooplankton and how they vary seasonally with perch spawning and recruitment patterns, as well as how this might compare with zooplankton communities from non-invaded dune lakes, would provide insight into the relative importance of the control of exotic fish in these lake systems.

The changes in macrophyte dominance to exotic species in Lake Dudding may indicate that the lake is at some risk of ‘flipping’ to a phytoplankton-dominated state. *Egeria densa,* the species now dominant in Lake Dudding has been well documented to be associated with cyclical collapses of macrophytes (Schallenberg & Sorrell 2009; Kelly 2015). While *Ceratophyllum,* the dominant species in Lakes Pauri and Wiritoa has not been regularly cited as a species associated with flipping, instances of *Ceratophyllum* collapse have occurred (e.g. Lake Oingo, Hawkes Bay; Andy Hicks, Hawke's Bay Regional Council, pers. comm.). In Lake Horowhenua, seasonal senescence of *Potamogeton crispus* is strongly linked to nutrient cycling (Gibbs 2011) and restoration measures in that lake include macrophyte harvesting (de Winton et al. 2015). Despite the lakes in this review being classified as 'deep' lakes, the mean depths are shallow (Table 2). Lake Dudding for instance has a mean depth of 3.5 m but *Egeria* is reported to grow to 6.3 m deep indicating that much of the lake may be vegetated. The current macrophyte data set is too sparse to assess whether periodic or seasonal dieback of lake macrophyte populations has occurred, or whether cover is sufficient to be of concern.

Previous studies of shallow coastal lakes have identified a phosphorus threshold of around 50 mg TP m^{-3} (annual median) above which macrophyte loss occurs (Kelly et al. 2013). This concentration is presently exceeded in all three lakes. Therefore a moderate to high risk of macrophyte collapse exists for the lakes, but this may be moderated by the resilience of species such as *C. demersum* which are more tolerant to epiphytic growth and cyanobacteria (Wium-Andersen et al. 1982, 1983).

3.3. Knowledge gaps; recommendations for research and monitoring

The data available for the deep dune lakes reviewed in this report allows some insight into likely nutrient sources and nutrient dynamics within the lake systems; however, the data have some significant gaps making it challenging to determine appropriate restoration planning. A summary of data gaps and recommendations is presented in the following subsections.

3.3.1. General data management

Documents relevant to understanding these lake systems and in particular to the planning of lake restoration appear to be scattered and data are often not well collated. Some effort should be expended to compile all the available information into single coherent lake-specific databases into which future data can be incorporated.

3.3.2. Bathymetry

Lake bathymetry and lake levels will be required to enable an internal nutrient budget and or modelling to be established for the lake from sediment flux rates and anoxia/pH patterns. While recent sonar transect data are available for all three lakes reviewed here they appear to have only be processed into map form for Lake Pauri. If not already done, the data for the other two lakes should also be processed. It is unclear whether lake level data exist and if not, a lake level gauge should be installed and monitored. For determining a water budget for the lakes, continuous water level recording would provide the most effective data to enable modelling water exchange through the lake. For other lakes, where not already conducted, lake bathymetry will be required for lake restoration planning. Publicly available data sources such and FENZ and LAWA should have lake depth information updated to the most recent data.

3.3.3. Lake trophic status monitoring;

NPS-FM guidelines for nutrients and chlorophyll-*a* are based on monthly monitoring for annual medians. Regular monitoring data are only available for the period 2014 to 2018 and are only conducted on a quarterly basis. The data collected at each sampling are comprehensive and provide useful insight into nutrient and phytoplankton dynamics; however, quarterly sampling is insufficient to discount seasonal or interannual variation and may miss significant events such as algal blooms completely (Cooke et al. 2005). Trend analysis will be a critical component of any future management plan for the lakes and current data are likely to be insufficient due to the length of record required to statistically detect trends in monitoring data. In addition, current monitoring does not allow rigorous comparison to the NPS-FM guidelines. We recommend that monthly water quality monitoring should be conducted in these lakes and continued for at least five years.

The current understanding of temporal variability in water column profiles of temperature, dissolved oxygen and pH is limited. Ideally deployment of temperature, dissolved oxygen and pH loggers should be undertaken at the sampling locations in the lake to improve knowledge on oxygen and pH dynamics in the lake. However, in these deeper lakes continuing with the current practice of conducting a water column profiles during the monthly water sampling may be sufficient if monthly sampling is instigated, depending on the frequency of mixing events which are difficult to ascertain from quarterly data. Monthly profile data would improve the reliability of this information. Lake level records and consistency with respect to profile depth are required.

3.3.4. External nutrient loading

Beyond high level CLUES modelling, the loading of nutrients from catchment to lake is poorly known for all the lakes reviewed. To target appropriate mitigation and restoration measures a lake-specific understanding of the dominant nutrient transport pathways is required. We recommend:

- Development of lake-specific water balance models which incorporate surface and groundwater water data (inflows/outflows, connectivity between surface and groundwater, direct rain inputs and evapotranspiration, lake level). Continuous lake-level monitoring data would be critical to this.

- Validation monitoring of surface and groundwater quality in inflows is needed to better evaluate the utility of land-use models for predicting nutrient loads to dune lakes in the region. Previous work with CLUES suggests highly underestimated nutrient loss rates from sandy soils in dune areas of Northland (Kelly et al. 2016). If a similar situation is found in the Manawatu-Whanganui region, better resolution/ nutrient loss modelling may be required for the lake catchments.
- The water balance models combined with estimated catchment nutrient losses should then be used to produce nutrient loading models for each lake.
- These models should include data specific to stormwater and wastewater discharges (to surface and groundwater) in the vicinity of the lakes where the discharges occur.

Nutrient loads from waterbirds

Nutrient loads from bird excreta may be significant, however no data are available to quantify such a loading source in the lakes reviewed. Previous information for the Ashburton basin suggests that P-loading from birds could account for as much as 10% of the lake external load (Kelly et al. 2014). Data are available on the nutrient contents of various bird excreta and the likely volume per bird. However, there are no data on the number of birds at these lakes and regular bird counts are required (conducted as part of the monitoring effort?). This could be conducted for a single lake and applied to the other lakes on an areal basis.

3.3.5. Sediment legacies and internal nutrient loading

The indications from the limited water quality data available are that internal nutrient loading is likely to be a very significant source of nutrients to the lake water column for deep, seasonally-stratifying dune lakes. However, the current understanding of legacy nutrients in the lake sediment is minimal. We suggest the following:

- Nutrient fractionation, binding and release analyses should be undertaken on lakebed surface sediment samples in order to quantify the reservoir of legacy nutrients and understand how nutrients are retained in, and released from, the sediments. Spatial variation in these legacy nutrients should be investigated. This will inform nutrient budgets, provide a better understanding of the drivers of nutrient release and guide potential management interventions.
- As mentioned above, monthly water column profiles for temperature and dissolved oxygen would resolve mixing frequency (especially to understand mixing frequency in Lake Pauri), duration of stratification etc., which directly affects internal loading potential and informs potential management interventions such as oxygenation/circulation. For most lakes this could be conducted at a single central monitoring site, but for larger or more complex lake basins monitoring at multiple sites may be required. Water column profiling to determine within lake spatial variation during the summer season could inform these decisions.

- Flux rates due to geochemical drivers should be determined in order to inform mass balance nutrient budgets. These could be derived from *in situ* or core incubation measurements of the sediment to water-column nutrient flux rates. Such rates can then be combined with the data on the areal extent of DO and pH (see above) to estimate nutrient loads from the sediment.
- Sedimentation rates should be calculated in order to inform nutrient budgets and to understand nutrient fluxes/organic loads and hence potential burial rate of present organic loads. Understanding the composition (e.g., nutrient fractionation/organic material) of the seston will also help inform budgets. Use of suspended sediment traps would be ideal for this analysis (see Appendix 9 for a diagram of sediment trap design).

3.3.6. Macrophytes

Current monitoring data are insufficient to determine trends in macrophyte cover and/or community composition. We recommend that macrophyte monitoring (LakeSPI) should be conducted at least every five years.

Macrophytes provide important ecological structuring elements in lake systems as well as absorbing and retaining nutrients. Therefore, in addition to long-term trend monitoring of aquatic vegetation, an understanding of seasonal changes in macrophytes, focusing on susceptibility to collapse and effect of the macrophytes on nutrient cycling is desirable. Hence, in addition to the monitoring discussed above, we recommend the following, potentially as a one-off study:

- The vegetation biomass survey (by sonar transect) conducted in 2016 in Lakes Pauri and Wiritoa provides a useful snapshot of vegetation biovolumes and coverage. This rapid monitoring method could be used as a means of assessing seasonal changes in macrophyte biomass and determining whether annual dieback was likely to be promoting water column conditions that drive internal nutrient loading; such as pH increases or deoxygenation in bottom waters. This should be conducted for the other lakes targeted for restoration and could provide a useful tool to assess seasonal changes.
- Sampling of macrophyte health (epiphytic biomass cover, root alcohol dehydrogenase assays) and growth, along transects to establish epiphytic and phytoplankton stress on macrophytes could help better understand mechanisms behind macrophyte collapse.

3.3.7. Fish and food webs

Current data are insufficient to determine trends in fish density or changes in species present. This information is required for assessing trends in ecological condition as well as potential impacts on nutrient cycling. Standardised fish surveys should be conducted every five years to monitor pest-species status.

The effect of exotic fish on the nutrient dynamics of the lake food webs is currently unquantified but has the potential to be a significant effect of lake nutrient recycling. Food web analysis would provide some insight into the likely ‘trophic cascade’ effects. Analysis of zooplankton dynamics over a year in comparison to another lake in the region would provide insight into zooplankton abundances and whether or not perch are supressing zooplankton populations.

3.3.8. Phytoplankton and cyanobacteria

Summertime weekly cell count analyses are currently conducted by HRC’s in-house laboratories (weekly samples) with quarterly samples analysed by Cawthron phytoplankton laboratories. This creates issues in comparability with quarterly testing data with weekly data due to slight variation in laboratory counting procedures. Therefore, we recommend that the cell count analyses are conducted in a standardised manner for both laboratories to allow better use of the data.

Nutrient limitation of phytoplankton communities should be investigated to ascertain potential nutrient targeting for lake restoration. Analysis of monthly monitoring data will allow some insight on nutrient ratios over season and growth assays may assist in clarifying nutrient limitation status. This could include seasonal bioassays of phytoplankton under nutrient enrichment treatments (+N, +P, +N&+P, control) for a range of lakes.

Some cyanobacterial species, such as *Dolichospermum* are capable of fixing atmospheric nitrogen and contributing to nitrogen loads in the lake. No data are currently available on nitrogen fixation in the lakes. To ensure an accurate nutrient budget is developed, consideration could be given to counting heterocytes in cyanobacteria cell monitoring or by measuring fixation rates using lake samples and acetylene reduction assays.

3.3.9. Lake modelling

Lake modelling (e.g. with Dyresm/Caedym) could be considered as a future option, although this would have significant data requirements. This option has not been considered in detail in this report but at the least, detailed bathymetry and continuous lake level data, continuous inflow/outflow data (nutrients, volumes, temperature and salinity), water quality data (monitoring and continuous logger data) and meteorological data (continuous short/longwave length radiation, rainfall, wind speed, relative humidity air temperatures) would all be required. Therefore, it is likely this intensive modelling would be conducted only for high priority lakes in the region.

3.3.10. Paleolimnology

No data exist that provide a picture of the likely reference state of these lakes. The paucity of historical data also prevents assessments of the long-term trends or of significant events that may drive changes in the lake system. A paleolimnological investigation would provide some insight into these areas and help inform targets for restoration. Analysis of cores could be tailored to fit key questions or knowledge gaps, for example, when did water quality deterioration begin and what were the drivers? What macrophyte species were historically present in the lake? Have cyanobacterial blooms always been present, and if not, what events triggered their occurrence. A range of traditional paleolimnology (i.e., pollen, macrophyte fossils) and molecular methods are available.

4. CONCLUSIONS AND PRIORITIES

The data reviewed for the deep dune lake case studies in this report are sufficient to gain an overall picture of high trophic status and poor ecological health. Poor water quality, excessive primary production and invasive macrophyte and fish populations all indicate that these ecosystems are in a degraded state. However, a number of data gaps exist in the current understanding of lake and catchment processes that control water quality and lake ecology. An understanding of the relative importance of these processes is an important consideration prior to implementing management interventions to stop the decline and/or improve ecological health of the lakes. Monitoring to fill information gaps has been recommended in the form of routine monitoring and one-off investigations. Limitations in monitoring resources are an important consideration for the region, where there are 57 dune lakes which Horizons Regional Council must manage.

We recommend the following priority of actions to address these gaps:

- Surface and groundwater monitoring and modelling to enable mass balance modelling of external nutrient loads. Targets for external nutrient load reductions need to be clearly defined to enable goals to be set for catchment management initiatives.
- One-off investigations of sediment geochemistry to determine the likely extent of internal loading of nutrients from sediments during anoxic or high pH events
- Intensifying lake water quality monitoring to a monthly time-scale to enable time-trend analyses and improve the resolution of seasonal variation.
- Adoption of high-frequency instrumentation (thermistor chain at 3 m intervals, surface & near-bed DO, surface pH, surface chlorophyll-*a*, and surface turbidity sensors) for monitoring real time lake physicochemical variation (all lakes for which restoration is planned).
- Bathymetric sonar surveys—hypsographic map production for lakes where recent sonar survey data are not available.
- Implement 5-yearly pest fish surveys to gain an understanding of the potential for pest fish enhancement of internal nutrient cycling (e.g., bioturbation, herbivory, trophic effects).
- One-off investigations into seasonal nutrient limitation in a few priority lakes in the region, including monthly nutrient ratios and nutrient bioassays.
- One-off seasonal macrophyte biovolume surveys to establish the extent to which macrophyte die-back enhances lake anoxia cycles (quarterly). Side-scan sonar transects could be used to do this cost effectively.
- Waterbird counts on high usage lakes to quantify TN and TP loading by birds (as a one-off quarterly monitoring investigation)

- Inclusion of heterocyte counts on quarterly cyanobacteria analyses over a year of monitoring as an indication for N-fixation potential in monitored lakes
- Paleolimnological investigations of a few priority lakes to evaluate reference conditions for dune lake types in the region and paleo-history of water quality.

The Manawatu-Whanganui region is fortunate in having numerous dune lakes which represent internationally rare environments with high ecological, recreational and cultural values. However, typical of lowland lake systems worldwide, many of the lakes in this region are degraded. A data-rich understanding of catchment and lake characteristics is key to returning these valuable systems to ecological health. The research and monitoring recommended in this report should provide the data which are essential to successful planning for lake restoration.

5. ACKNOWLEDGEMENTS

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7. APPENDICES

Appendix 1. Biodiversity values in the Water Management sub-zones containing Lake Pauri, Wiritoa and Dudding.

Table A1.1. An overview of the biodiversity values of some of the dune lakes in the Manawatu-Whanganui region according to their water management subzones. Source from McArthur Section 42A Report and DOC regional office data sources

Subzone	Lake name	Lake Area (HA)	Catchment Area (HA)	Biodiversity values
Kaitoke Lakes West_4	Wiritoa	21.8	696	• Known populations of kakahi (freshwater mussel) in Lake Pauri (L. Brown, pers. comm.) and likely to be in other lakes. • Ms McArthur (S42A report) lists the water body values for this water management subzone as including inanga spawning and whitebait migration. • Historic cultural and commercial eel fishery. • Rare and threatened plants recorded, most being turf plants (J. Campbell, pers. comm.). • The Kaitoke stream (outflow from Kaitoke lake) is probably the most highly whitebaited stream (aside from the mainstem of the Whanganui River) in the Whanganui region (J. Campbell, pers. comm.). • Two nationally threatened species: the New Zealand dabchick (weweia) and the Australasian bittern (matuku-hurepo) are found here (J. Campbell, pers. comm.). • Lake Kaitoke has a wildlife refuge status.
	Pauri	19.2	383	
	Kaitoke	25.3	3265	
	Kohata	5.2	84	
	3 unnamed lakes			
Southern Whanganui Lakes (West_5)	Bernard	8.0	734	• Known populations of kakahi (freshwater mussel) in Lake Dudding (L. Brown, pers. comm.) and likely to be in other lakes. • Ms McArthur (S42A report) lists the water body values for this water management subzone as including inanga spawning, whitebait migration and includes sites of significance – aquatic (banded kokopu). • Longfin eel (now listed as being in gradual decline: Allibone et al. 2010) found in both Koitata stream and Lake Koitiata (New Zealand Freshwater Fish Database (NZFFD)). • Rare plant assemblages exist around Lake Alice in the largest area of dune forest north of the Manawatu River in the Foxton ecological district (J. Campbell, pers. comm.).
	Koitiata	9.6	1406	
	Dudding	7.8	184	
	Heaton	14.4	956	
	William	6.8	71	
	Alice	11.9	238	
	Hebert	4.7	375	
	3 unnamed lakes			
Hoki 1a, 1b	Horowhenua	304.0	6253	• Inflowing streams hold remnant populations of banded and giant kokopu (NZFFD). • Ms McArthur (S42A report) lists the water body values for this water management subzone as including inanga spawning, whitebait migration and includes sites of significance – aquatic (giant kokopu). • Known populations of kakahi (freshwater mussel) (L. Brown, pers. comm.) • Historic cultural and commercial eel fishery. • Longfin eels recorded from Hokio stream (outlet of Lake Horowhenua) (NZFFD)

Appendix 2. Bathymetric map for Lake Pauri.

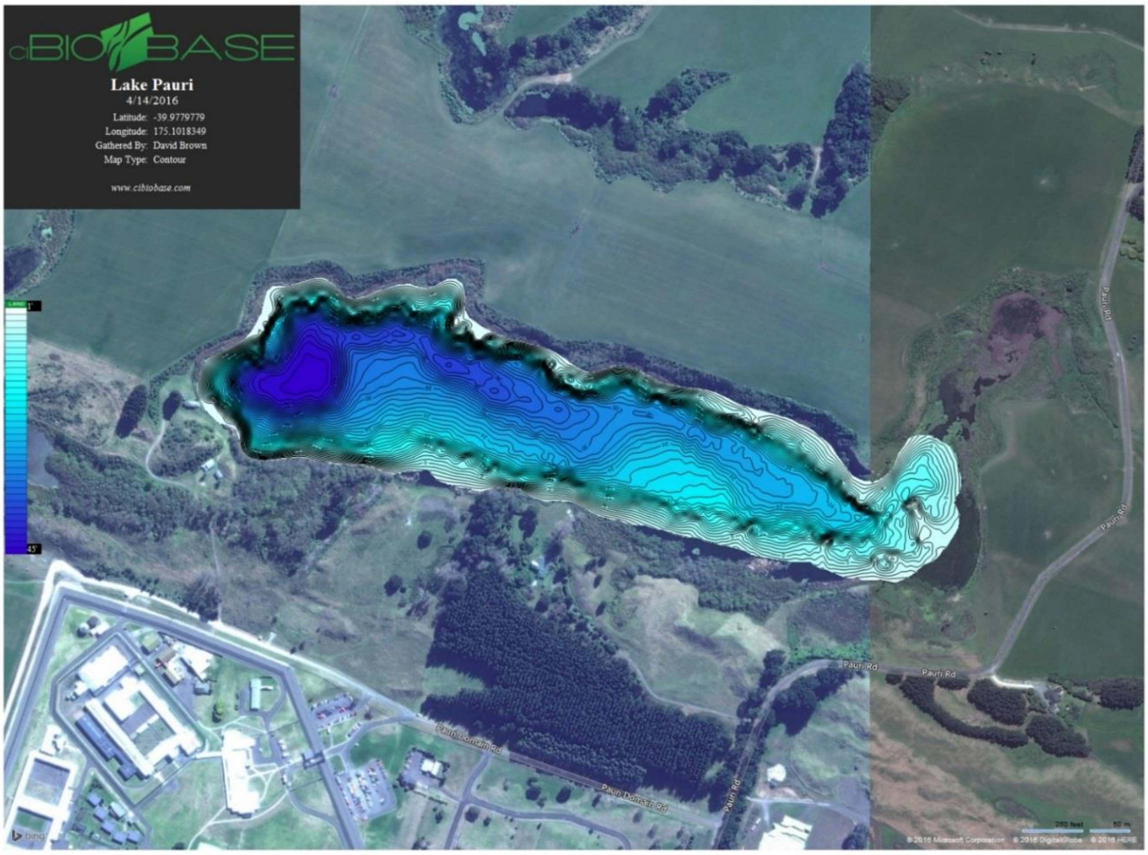


Figure A2.1. Bathymetric map of Lake Pauri produced from sonar transect data (L. Brown, HRC, pers. comm. 2018).

Appendix 3. Land-use maps for the catchments of Lake Pauri, Wiritoa and Dudding, generated using the CLUES model.

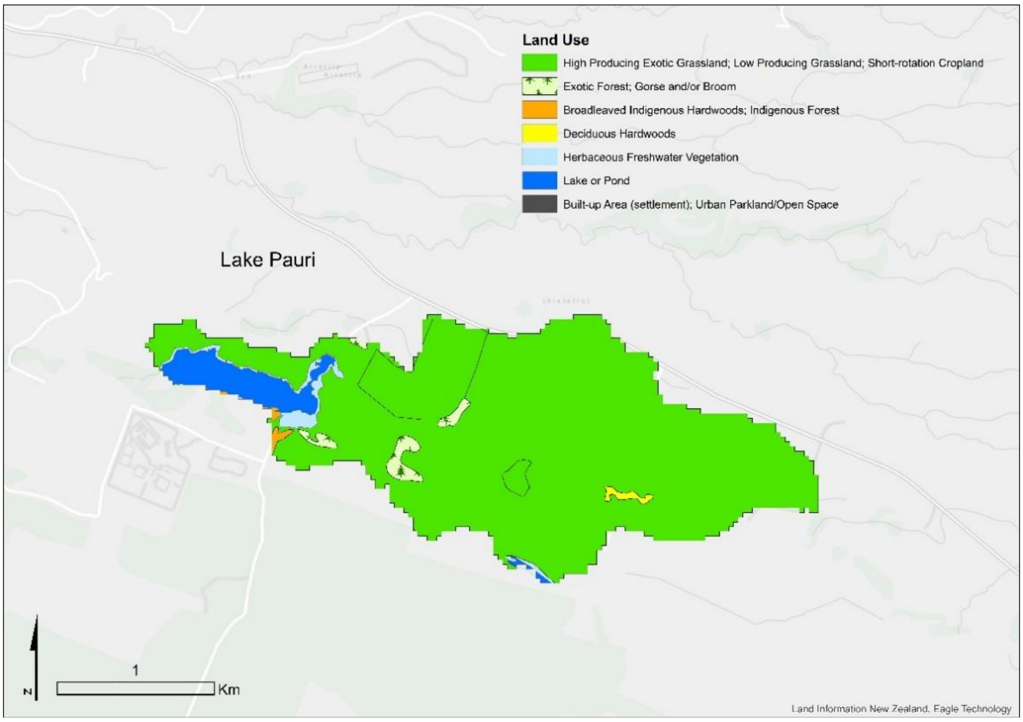


Figure A3.1 Land-use map for the Lake Pauri catchment generated using the CLUES model (Woods et al. 2006).

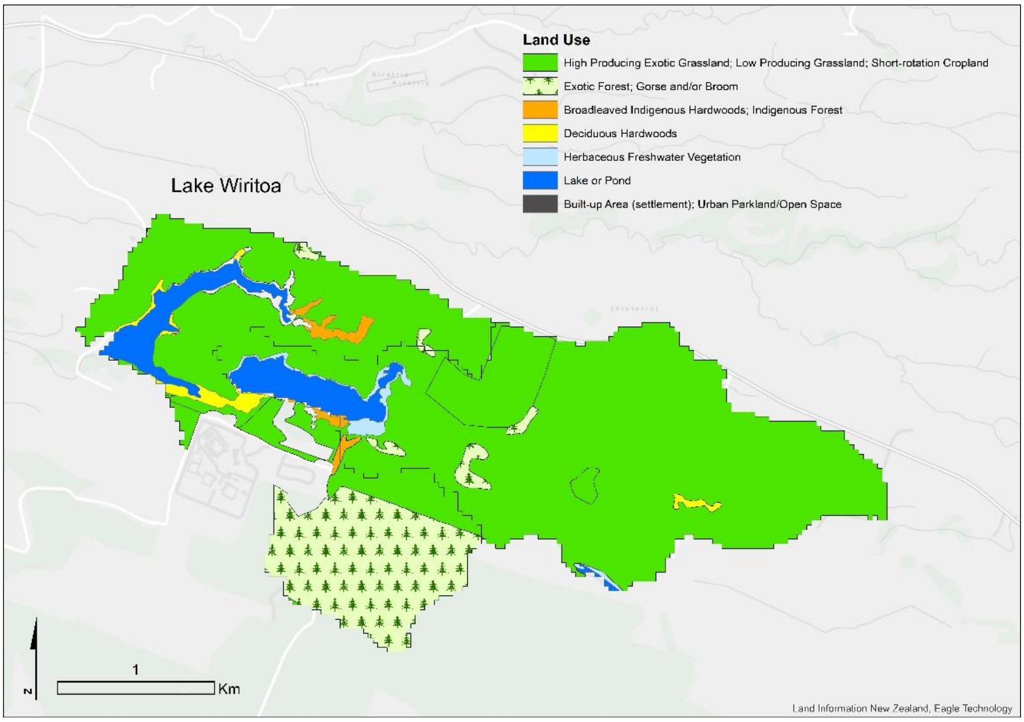


Figure A3.2 Land-use map for the Lake Wiritoa catchment generated using the CLUES model (Woods et al. 2006).

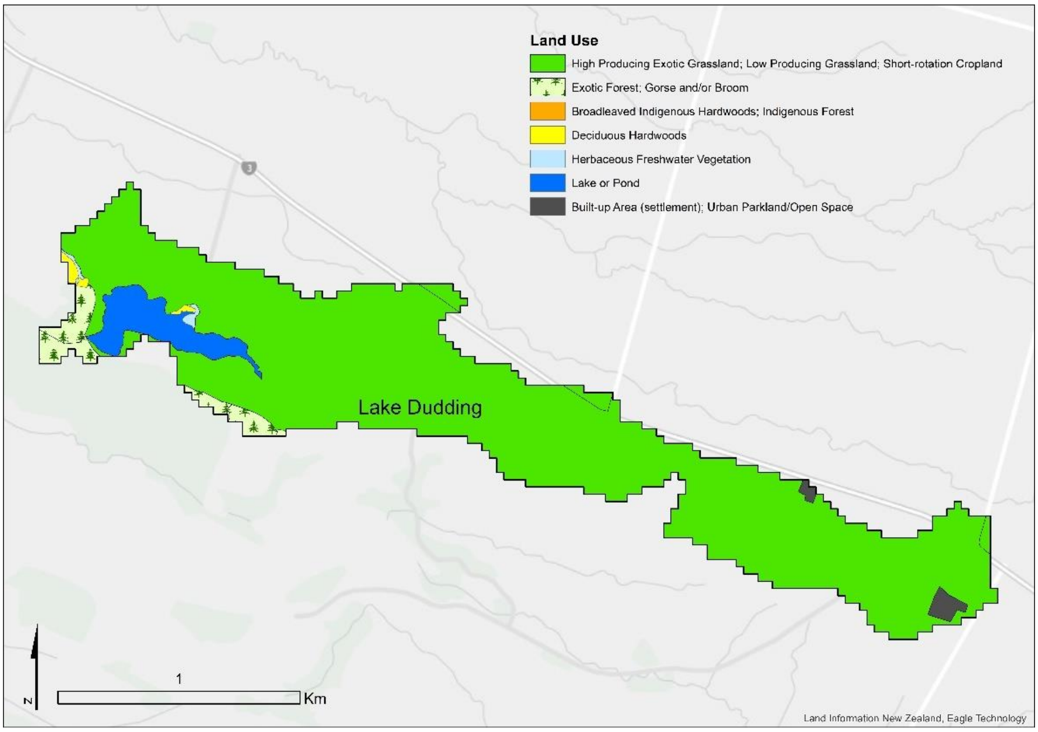


Figure A3.3. Land-use map for the Lake Dudding catchment generated using the CLUES model (Woods et al. 2006).

Appendix 4. Water quality monitoring data availability for Lakes Wiritoa, Pauri and Dudding for the period 2004-2018. Data supplied by Horizons Regional Council (L. Brown pers comm. 2018).

Lake	**Site**	**Water column position**	**Dates covered**	**Sampling interval**	**Parameter suite (see table footnote)**
Wiritoa	Comp[1]	epilimnion	Feb 2014-Feb 2018	quarterly	A (Feb 2014 = D)
	1	epilimnion	Oct 2015-Aug 2017	quarterly	B
	2	epilimnion	Oct 2015-Aug 2017	quarterly	B
	2	epilimnion	Nov-2016-Apr 2017	weekly	C
	3	epilimnion	Oct 2015-Aug 2017	quarterly	B
	Bed[2]	hypolimnion	Feb 2014-Aug 2017	quarterly	A (Feb 2014 = D)
	173[3]		Jan 2004-Apr 2008	Weekly Nov-Apr	C
	173[3]		Nov 2007-Apr 2008	Weekly Nov-Apr	E
Pauri	Comp[1]	epilimnion	Feb 2014- Feb 2018	quarterly	A (Feb 2014 = D)
	1	epilimnion	Oct 2015-Aug 2017	quarterly	B
	1	epilimnion	Nov-2016-Apr 2017	weekly	C
	2	epilimnion	Oct 2015-Aug 2017	quarterly	B
	3	epilimnion	Oct 2015-Aug 2017	quarterly	B
	Bed[2]	hypolimnion	Feb 2014-Jul 2017	quarterly	A (Feb 2014 = D)
	171[3]		Nov 2005-Apr 2008	Weekly Nov-Apr	C
	171[3]		Nov 2007-Apr 2008	Weekly Nov-Apr	E
Dudding	Comp[1]	epilimnion	Feb 2014-Aug 2017	quarterly	A (Feb 2014 = D)
	1	epilimnion	Oct 2015-Aug 2017	quarterly	B
	1	epilimnion	Nov-2016-Apr 2017	weekly	C
	2	epilimnion	Oct 2015-Aug 2017	quarterly	B
	3	epilimnion	Oct 2015-Aug 2017	quarterly	B
	Bed[2]	hypolimnion	Feb 2014-Jul 2017	quarterly	A (Feb 2014 = D)
	155[3]		Jan 2004-Apr 2008	Weekly Nov-Apr	C
	155[3]		Nov 2007-Apr 2008	Weekly Nov-Apr	E

1. Composite samples = integrated depth tube samples from top 5 m of the water column of each site, combined into a composite sample for analysis.
2. Bed = near bottom samples (approximately 1 m above bottom) collected from Site 1.
3. Land Air Water Aotearoa (LAWA) site id (sid) numbers.

A = dissolved silica, *E. coli,* total suspended solids, turbidity, volatile matter, ammoniacal nitrogen, total nitrogen, nitrate nitrogen, nitrite nitrogen, dissolved reactive phosphorus, total phosphorus, total dissolved phosphorus, chlorophyll-*a.*

B= Secchi disc (black disc), temperature, dissolved oxygen, conductivity, pH, chlorophyll-*a*.

C= *E.coli.*

D= A+B.

E = Total phosphorus, total nitrogen, dissolved reactive phosphorus, ammoniacal nitrogen, nitrate nitrogen.

Appendix 5. Horizons Regional Council lake monitoring sample sites.

Lake Pauri

Site 1. WGS84: -39.977270, 175.096845
Site 2. WGS84: -39.978154, 175.101252
Site 3. WGS84: -39.978997, 175.103971

Lake Wiritoa

Site 1. WGS84: -39.974649, 175.088826
Site 2. WGS84: -39.973944, 175.089999
Site 3. WGS84: -39.971783, 175.094394

Lake Dudding

Site 1. WGS84: -40.101060 175.278664
Site 2. WGS84: -40.100040 175.279914
Site 3. WGS84: -40.100821 175.281783

Appendix 6. Ministry for the Environment/Ministry of Health alert level framework for planktonic cyanobacteria (MfE/MoH 2009)

Decision Chart 1: Alert-level framework for planktonic cyanobacteria

Alert Level	Actions
Surveillance (green mode) *Situation 1:* The cell concentration of total cyanobacteria does not exceed 500 cells/mL.[a] *Situation 2:* The biovolume equivalent for the combined total of all cyanobacteria does not exceed 0.5 mm^3/L.	• Undertake weekly or fortnightly visual inspection[b] and sampling of water bodies where cyanobacteria are known to proliferate between spring and autumn.
Alert (amber mode) *Situation 1:* Biovolume equivalent of 0.5 to < 1.8 mm^3/L of potentially toxic cyanobacteria (see Tables 1 and 2); **or** *Situation 2*[c]*:* 0.5 to < 10 mm^3/L total biovolume of all cyanobacterial material	• Increase sampling frequency to at least weekly.[d] • Notify the public health unit. • Multiple sites should be inspected and sampled.
Action (red mode) *Situation 1:* ≥ 12 µg/L total microcystins; **or** biovolume equivalent of ≥ 1.8 mm^3/L of potentially toxic cyanobacteria (see Tables 1 and 2); **or** *Situation 2* [c]*:* ≥ 10 mm^3/L total biovolume of all cyanobacterial material; **or** *Situation 3* [e]*:* cyanobacterial scums consistently present.	• Continue monitoring as for alert (amber mode).[d] • If potentially toxic taxa are present (see Table 1), then consider testing samples for cyanotoxins.[f] • Notify the public of a potential risk to health.

a) A cell count threshold is included at this level because many samples may contain very low concentrations of cyanobacteria and it is not necessary to convert these to a biovolume estimate.

b) In high concentrations planktonic cyanobacteria are often visible as buoyant green globules, which can accumulate along shorelines, forming thick scums (see Appendix 3). In these instances, visual inspections of water bodies can provide some distribution data. However, not all species form visible blooms or scums; for example, dense concentrations of *Cylindrospermopsis raciborskii* and *Aphanizomenon issatschenkoi* are not visible to the naked eye (see Appendix 3).

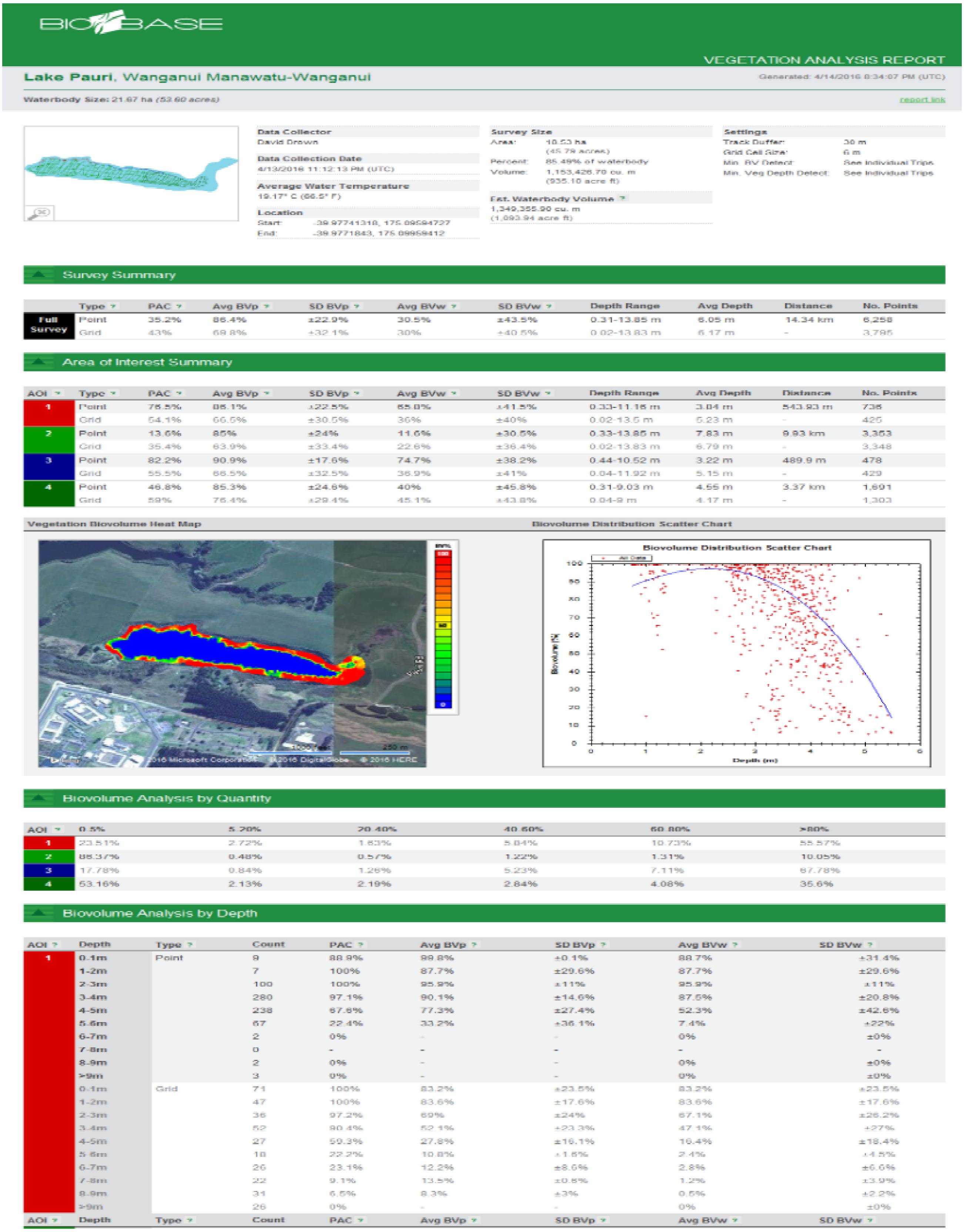
c) This applies where high cell densities or scums of 'non-toxigenic' cyanobacteria taxa are present (i.e., where the cyanobacterial population has been tested and shown not to contain known toxins).

d) Bloom characteristics are known to change rapidly in some water bodies, hence the recommended weekly sampling regime. However, there may be circumstances (e.g., if good historical data/knowledge is available) when bloom conditions are sufficiently predictable that longer interval sampling is satisfactory.

e) This refers to the situation where scums occur at the recreation site for more than several days in a row.

f) Cyanotoxin testing is useful to: provide further confidence on potential health risks when a health alert is being considered; enable the use of the action level 10 mm^3/L biovolume threshold (i.e., show that no toxins are present; and show that residual cyanotoxins are not present when a bloom subsides).

Appendix 7. Analysis report from lake vegetation biomass sonar survey for Lakes Pauri and Wiritoa, supplied by Horizons Regional Council (L. Brown, pers. comm. 2018).



VEGETATION ANALYSIS REPORT

Lake Pauri, Wanganui Manawatu-Wanganui

Generated: 4/14/2016 8:34:07 PM (UTC)

Waterbody Size: 21.67 ha *(53.60 acres)*

report link

Data Collector
David Brown

Data Collection Date
4/13/2016 11:12:13 PM (UTC)

Average Water Temperature
19.17° C (66.5° F)

Location
Start: -39.97741318, 175.09594727
End: -39.9771843, 175.09959412

Survey Size
Area: 18.53 ha (45.79 acres)
Percent: 85.49% of waterbody
Volume: 1,153,426.70 cu. m (935.10 acre ft)

Est. Waterbody Volume
1,349,355.90 cu. m
(1,093.94 acre ft)

Settings
Track Buffer: 30 m
Grid Cell Size: 6 m
Min. BV Detect: See Individual Trips
Min. Veg Depth Detect: See Individual Trips

Survey Summary

	Type	PAC	Avg BVp	SD BVp	Avg BVw	SD BVw	Depth Range	Avg Depth	Distance	No. Points
Full Survey	Point	35.2%	86.4%	±22.9%	30.5%	±43.5%	0.31-13.85 m	6.05 m	14.34 km	6,258
	Grid	43%	69.8%	±32.1%	30%	±40.5%	0.02-13.83 m	6.17 m	-	3,795

Area of Interest Summary

AOI	Type	PAC	Avg BVp	SD BVp	Avg BVw	SD BVw	Depth Range	Avg Depth	Distance	No. Points
1	Point	76.5%	86.1%	±22.5%	65.8%	±41.5%	0.33-11.16 m	3.84 m	543.93 m	736
	Grid	54.1%	66.5%	±30.5%	36%	±40%	0.02-13.5 m	5.23 m	-	425
2	Point	13.6%	85%	±24%	11.6%	±30.5%	0.33-13.85 m	7.83 m	9.93 km	3,353
	Grid	35.4%	63.9%	±33.4%	22.6%	±36.4%	0.02-13.83 m	6.79 m	-	3,348
3	Point	82.2%	90.9%	±17.6%	74.7%	±38.2%	0.44-10.52 m	3.22 m	489.9 m	478
	Grid	55.5%	66.5%	±32.5%	36.9%	±41%	0.04-11.92 m	5.15 m	-	429
4	Point	46.8%	85.3%	±24.6%	40%	±45.8%	0.31-9.03 m	4.55 m	3.37 km	1,691
	Grid	59%	76.4%	±29.4%	45.1%	±43.8%	0.04-9 m	4.17 m	-	1,303

Vegetation Biovolume Heat Map

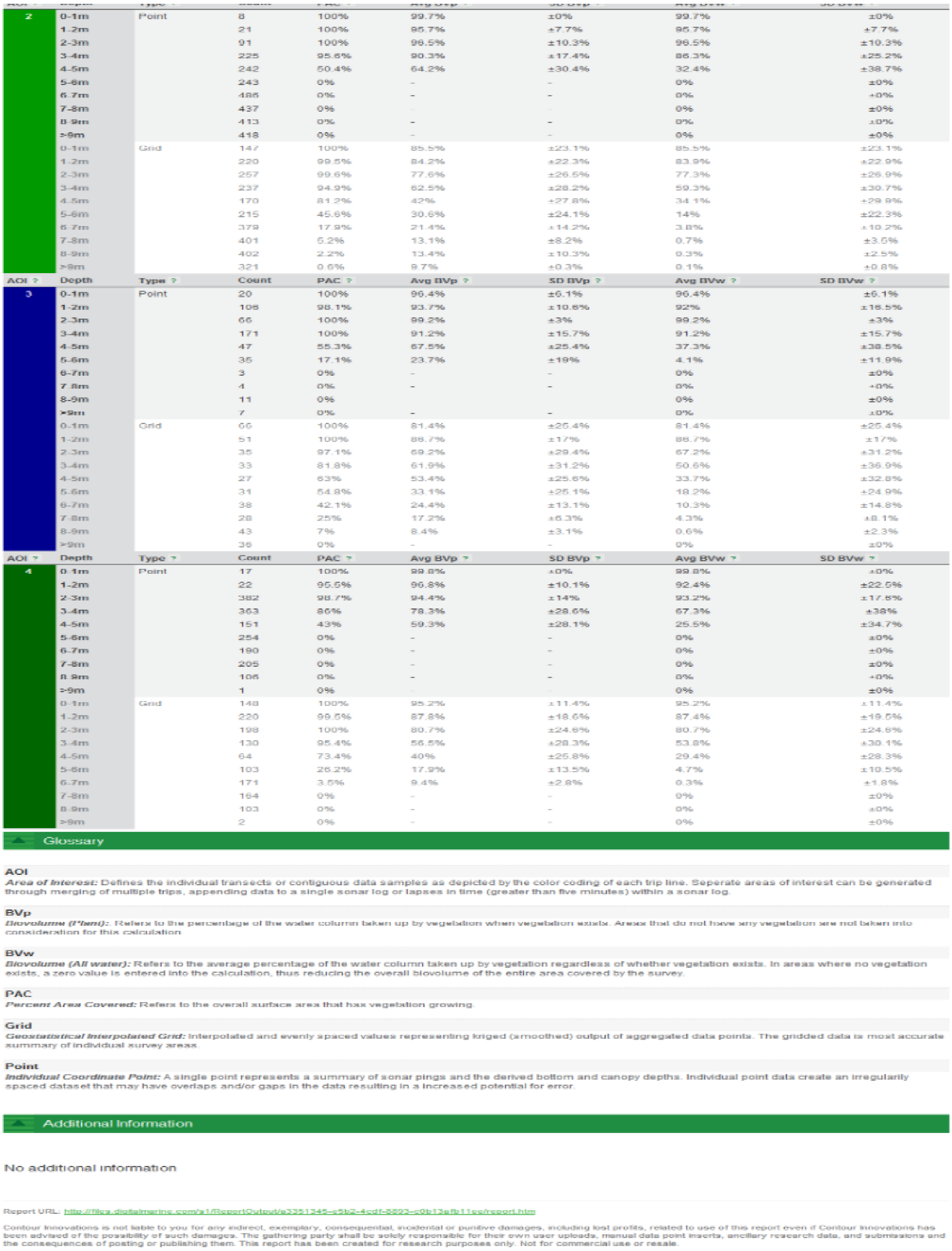
Biovolume Distribution Scatter Chart

Biovolume Analysis by Quantity

AOI	0-5%	5-20%	20-40%	40-60%	60-80%	>80%
1	23.51%	2.72%	1.63%	5.84%	10.73%	55.57%
2	86.37%	0.48%	0.57%	1.22%	1.31%	10.05%
3	17.78%	0.84%	1.26%	5.23%	7.11%	67.78%
4	53.16%	2.13%	2.19%	2.84%	4.08%	35.6%

Biovolume Analysis by Depth

AOI	Depth	Type	Count	PAC	Avg BVp	SD BVp	Avg BVw	SD BVw
1	0-1m	Point	9	88.9%	99.8%	±0.1%	88.7%	±31.4%
	1-2m		7	100%	87.7%	±29.6%	87.7%	±29.6%
	2-3m		100	100%	95.9%	±11%	95.9%	±11%
	3-4m		280	97.1%	90.1%	±14.6%	87.5%	±20.8%
	4-5m		238	67.6%	77.3%	±27.4%	52.3%	±42.6%
	5-6m		67	22.4%	33.2%	±36.1%	7.4%	±22%
	6-7m		2	0%	-	-	0%	±0%
	7-8m		0	-	-	-	-	-
	8-9m		2	0%	-	-	0%	±0%
	>9m		3	0%	-	-	0%	±0%
	0-1m	Grid	71	100%	83.2%	±23.5%	83.2%	±23.5%
	1-2m		47	100%	83.6%	±17.6%	83.6%	±17.6%
	2-3m		36	97.2%	69%	±24%	67.1%	±26.2%
	3-4m		52	90.4%	52.1%	±23.3%	47.1%	±27%
	4-5m		27	59.3%	27.8%	±16.1%	16.4%	±18.4%
	5-6m		18	22.2%	10.8%	±1.6%	2.4%	±4.5%
	6-7m		26	23.1%	12.2%	±8.6%	2.8%	±6.6%
	7-8m		22	9.1%	13.5%	±0.8%	1.2%	±3.9%
	8-9m		31	6.5%	8.3%	±3%	0.5%	±2.2%
	>9m		26	0%	-	-	0%	±0%
AOI	Depth	Type	Count	PAC	Avg BVp	SD BVp	Avg BVw	SD BVw



2	0-1m	Point	8	100%	99.7%	±0%	99.7%	±0%
	1-2m		21	100%	95.7%	±7.7%	95.7%	±7.7%
	2-3m		91	100%	96.5%	±10.3%	96.5%	±10.3%
	3-4m		225	95.6%	90.3%	±17.4%	86.3%	±25.2%
	4-5m		242	50.4%	64.2%	±30.4%	32.4%	±38.7%
	5-6m		243	0%	-	-	0%	±0%
	6-7m		486	0%	-	-	0%	±0%
	7-8m		437	0%	-	-	0%	±0%
	8-9m		413	0%	-	-	0%	±0%
	>9m		418	0%	-	-	0%	±0%
	0-1m	Grid	147	100%	85.5%	±23.1%	85.5%	±23.1%
	1-2m		220	99.5%	84.2%	±22.3%	83.9%	±22.9%
	2-3m		257	99.6%	77.6%	±26.5%	77.3%	±26.9%
	3-4m		237	94.9%	62.5%	±28.2%	59.3%	±30.7%
	4-5m		170	81.2%	42%	±27.8%	34.1%	±29.9%
	5-6m		215	45.6%	30.6%	±24.1%	14%	±22.3%
	6-7m		379	17.9%	21.4%	±14.2%	3.8%	±10.2%
	7-8m		401	5.2%	13.1%	±8.2%	0.7%	±3.5%
	8-9m		402	2.2%	13.4%	±10.3%	0.3%	±2.5%
	>9m		321	0.6%	9.7%	±0.3%	0.1%	±0.8%
AOI ?	**Depth**	**Type ?**	**Count**	**PAC ?**	**Avg BVp ?**	**SD BVp ?**	**Avg BVw ?**	**SD BVw ?**
3	0-1m	Point	20	100%	96.4%	±6.1%	96.4%	±6.1%
	1-2m		108	98.1%	93.7%	±10.6%	92%	±16.5%
	2-3m		66	100%	99.2%	±3%	99.2%	±3%
	3-4m		171	100%	91.2%	±15.7%	91.2%	±15.7%
	4-5m		47	55.3%	67.5%	±25.4%	37.3%	±38.5%
	5-6m		35	17.1%	23.7%	±19%	4.1%	±11.9%
	6-7m		3	0%	-	-	0%	±0%
	7-8m		4	0%	-	-	0%	±0%
	8-9m		11	0%			0%	±0%
	>9m		7	0%	-	-	0%	±0%
	0-1m	Grid	66	100%	81.4%	±25.4%	81.4%	±25.4%
	1-2m		51	100%	88.7%	±17%	88.7%	±17%
	2-3m		35	97.1%	69.2%	±29.4%	67.2%	±31.2%
	3-4m		33	81.8%	61.9%	±31.2%	50.6%	±36.9%
	4-5m		27	63%	53.4%	±25.6%	33.7%	±32.8%
	5-6m		31	54.8%	33.1%	±25.1%	18.2%	±24.9%
	6-7m		38	42.1%	24.4%	±13.1%	10.3%	±14.8%
	7-8m		28	25%	17.2%	±6.3%	4.3%	±8.1%
	8-9m		43	7%	8.4%	±3.1%	0.6%	±2.3%
	>9m		36	0%	-	-	0%	±0%
AOI ?	**Depth**	**Type ?**	**Count**	**PAC ?**	**Avg BVp ?**	**SD BVp ?**	**Avg BVw ?**	**SD BVw ?**
4	0-1m	Point	17	100%	99.8%	±0%	99.8%	±0%
	1-2m		22	95.5%	96.8%	±10.1%	92.4%	±22.5%
	2-3m		382	98.7%	94.4%	±14%	93.2%	±17.6%
	3-4m		363	86%	78.3%	±28.6%	67.3%	±38%
	4-5m		151	43%	59.3%	±28.1%	25.5%	±34.7%
	5-6m		254	0%	-	-	0%	±0%
	6-7m		190	0%	-	-	0%	±0%
	7-8m		205	0%	-	-	0%	±0%
	8-9m		106	0%	-	-	0%	±0%
	>9m		1	0%	-	-	0%	±0%
	0-1m	Grid	148	100%	95.2%	±11.4%	95.2%	±11.4%
	1-2m		220	99.5%	87.8%	±18.6%	87.4%	±19.5%
	2-3m		198	100%	80.7%	±24.6%	80.7%	±24.6%
	3-4m		130	95.4%	56.5%	±28.3%	53.8%	±30.1%
	4-5m		64	73.4%	40%	±25.8%	29.4%	±28.3%
	5-6m		103	26.2%	17.9%	±13.5%	4.7%	±10.5%
	6-7m		171	3.5%	9.4%	±2.8%	0.3%	±1.8%
	7-8m		164	0%	-	-	0%	±0%
	8-9m		103	0%	-	-	0%	±0%
	>9m		2	0%	-	-	0%	±0%

Glossary

AOI
Area of Interest: Defines the individual transects or contiguous data samples as depicted by the color coding of each trip line. Seperate areas of interest can be generated through merging of multiple trips, appending data to a single sonar log or lapses in time (greater than five minutes) within a sonar log.

BVp
Biovolume (Plant): Refers to the percentage of the water column taken up by vegetation when vegetation exists. Areas that do not have any vegetation are not taken into consideration for this calculation.

BVw
Biovolume (All water): Refers to the average percentage of the water column taken up by vegetation regardless of whether vegetation exists. In areas where no vegetation exists, a zero value is entered into the calculation, thus reducing the overall biovolume of the entire area covered by the survey.

PAC
Percent Area Covered: Refers to the overall surface area that has vegetation growing.

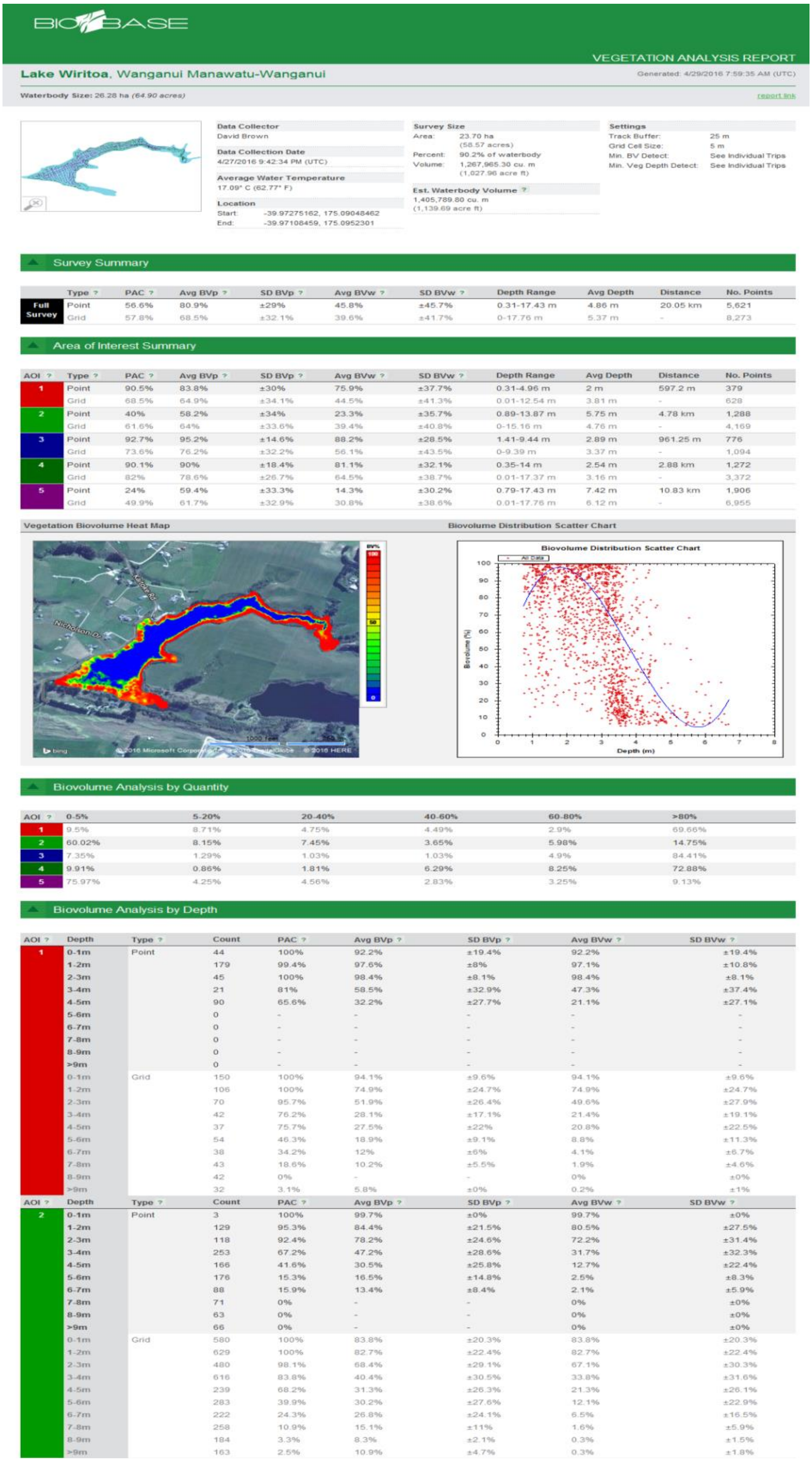
Grid
Geostatistical Interpolated Grid: Interpolated and evenly spaced values representing kriged (smoothed) output of aggregated data points. The gridded data is most accurate summary of individual survey areas.

Point
Individual Coordinate Point: A single point represents a summary of sonar pings and the derived bottom and canopy depths. Individual point data create an irregularly spaced dataset that may have overlaps and/or gaps in the data resulting in a increased potential for error.

Additional Information

No additional information

Report URL: http://files.digitalmarine.com/s1/ReportOutput/e3351345-c5b2-4cdf-8893-c0b13efb11ec/report.htm



VEGETATION ANALYSIS REPORT

Lake Wiritoa, Wanganui Manawatu-Wanganui

Generated: 4/29/2016 7:59:35 AM (UTC)

Waterbody Size: 26.28 ha *(64.90 acres)*

report link

Data Collector
David Brown

Data Collection Date
4/27/2016 9:42:34 PM (UTC)

Average Water Temperature
17.09° C (62.77° F)

Location

Start:	-39.97275162, 175.09048462
End:	-39.97108459, 175.0952301

Survey Size

Area:	23.70 ha (58.57 acres)
Percent:	90.2% of waterbody
Volume:	1,267,965.30 cu. m (1,027.96 acre ft)

Est. Waterbody Volume ?
1,405,789.80 cu. m
(1,139.69 acre ft)

Settings

Track Buffer:	25 m
Grid Cell Size:	5 m
Min. BV Detect:	See Individual Trips
Min. Veg Depth Detect:	See Individual Trips

Survey Summary

	Type ?	PAC ?	Avg BVp ?	SD BVp ?	Avg BVw ?	SD BVw ?	Depth Range	Avg Depth	Distance	No. Points
Full Survey	Point	56.6%	80.9%	±29%	45.8%	±45.7%	0.31-17.43 m	4.86 m	20.05 km	5,621
	Grid	57.8%	68.5%	±32.1%	39.6%	±41.7%	0-17.76 m	5.37 m	-	8,273

Area of Interest Summary

AOI ?	Type ?	PAC ?	Avg BVp ?	SD BVp ?	Avg BVw ?	SD BVw ?	Depth Range	Avg Depth	Distance	No. Points
1	Point	90.5%	83.8%	±30%	75.9%	±37.7%	0.31-4.96 m	2 m	597.2 m	379
	Grid	68.5%	64.9%	±34.1%	44.5%	±41.3%	0.01-12.54 m	3.81 m	-	628
2	Point	40%	58.2%	±34%	23.3%	±35.7%	0.89-13.87 m	5.75 m	4.78 km	1,288
	Grid	61.6%	64%	±33.6%	39.4%	±40.8%	0-15.16 m	4.76 m	-	4,169
3	Point	92.7%	95.2%	±14.6%	88.2%	±28.5%	1.41-9.44 m	2.89 m	961.25 m	776
	Grid	73.6%	76.2%	±32.2%	56.1%	±43.5%	0-9.39 m	3.37 m	-	1,094
4	Point	90.1%	90%	±18.4%	81.1%	±32.1%	0.35-14 m	2.54 m	2.88 km	1,272
	Grid	82%	78.6%	±26.7%	64.5%	±38.7%	0.01-17.37 m	3.16 m	-	3,372
5	Point	24%	59.4%	±33.3%	14.3%	±30.2%	0.79-17.43 m	7.42 m	10.83 km	1,906
	Grid	49.9%	61.7%	±32.9%	30.8%	±38.6%	0.01-17.76 m	6.12 m	-	6,955

Vegetation Biovolume Heat Map

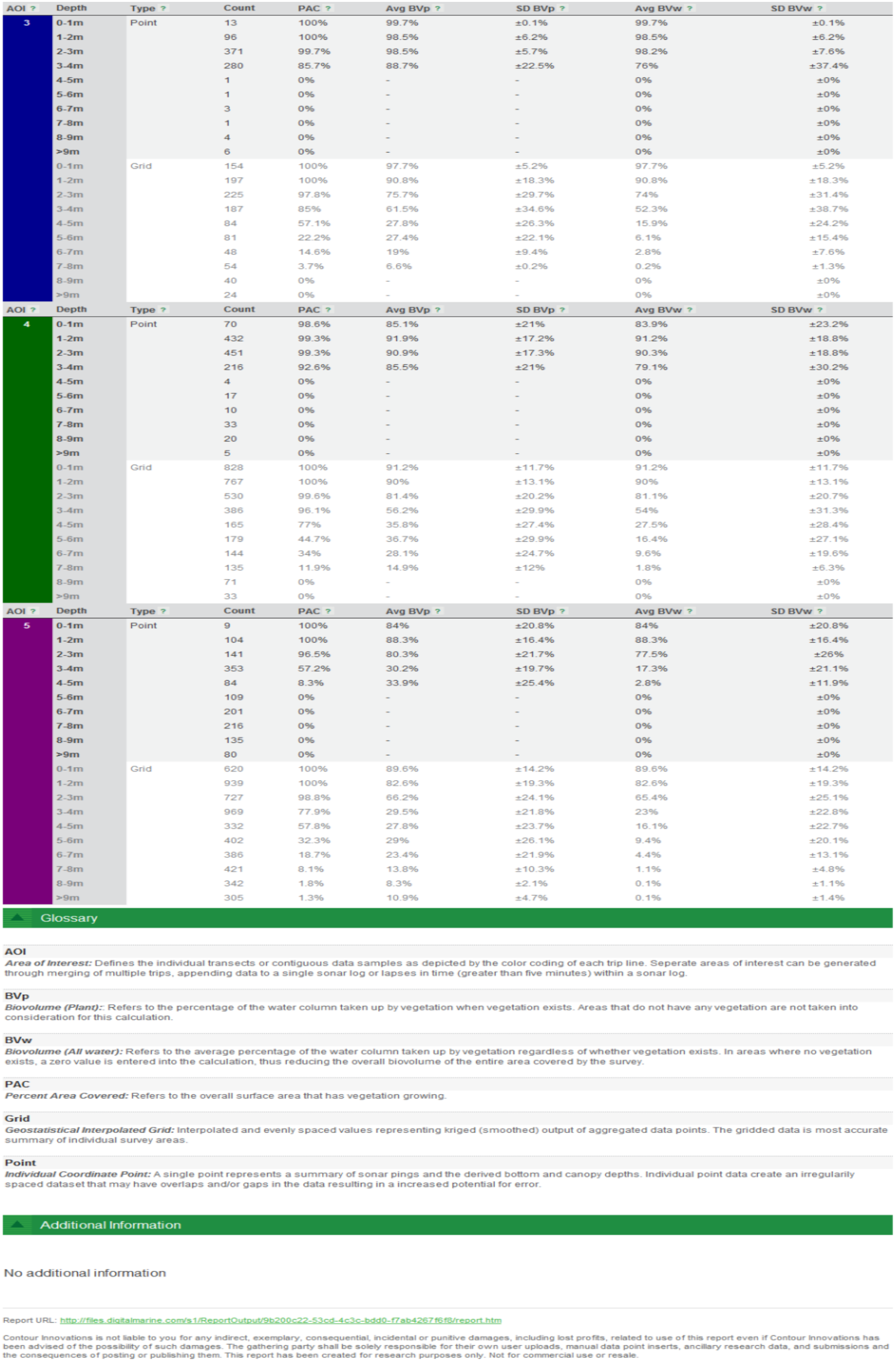
Biovolume Distribution Scatter Chart

Biovolume Analysis by Quantity

AOI ?	0-5%	5-20%	20-40%	40-60%	60-80%	>80%
1	9.5%	8.71%	4.75%	4.49%	2.9%	69.66%
2	60.02%	8.15%	7.45%	3.65%	5.98%	14.75%
3	7.35%	1.29%	1.03%	1.03%	4.9%	84.41%
4	9.91%	0.86%	1.81%	6.29%	8.25%	72.88%
5	75.97%	4.25%	4.56%	2.83%	3.25%	9.13%

Biovolume Analysis by Depth

AOI ?	Depth	Type ?	Count	PAC ?	Avg BVp ?	SD BVp ?	Avg BVw ?	SD BVw ?
1	0-1m	Point	44	100%	92.2%	±19.4%	92.2%	±19.4%
	1-2m		179	99.4%	97.6%	±8%	97.1%	±10.8%
	2-3m		45	100%	98.4%	±8.1%	98.4%	±8.1%
	3-4m		21	81%	58.5%	±32.9%	47.3%	±37.4%
	4-5m		90	65.6%	32.2%	±27.7%	21.1%	±27.1%
	5-6m		0	-	-	-	-	-
	6-7m		0	-	-	-	-	-
	7-8m		0	-	-	-	-	-
	8-9m		0	-	-	-	-	-
	>9m		0	-	-	-	-	-
	0-1m	Grid	150	100%	94.1%	±9.6%	94.1%	±9.6%
	1-2m		106	100%	74.9%	±24.7%	74.9%	±24.7%
	2-3m		70	95.7%	51.9%	±26.4%	49.6%	±27.9%
	3-4m		42	76.2%	28.1%	±17.1%	21.4%	±19.1%
	4-5m		37	75.7%	27.5%	±22%	20.8%	±22.5%
	5-6m		54	46.3%	18.9%	±9.1%	8.8%	±11.3%
	6-7m		38	34.2%	12%	±6%	4.1%	±6.7%
	7-8m		43	18.6%	10.2%	±5.5%	1.9%	±4.6%
	8-9m		42	0%	-	-	0%	±0%
	>9m		32	3.1%	5.8%	±0%	0.2%	±1%
AOI ?	**Depth**	**Type ?**	**Count**	**PAC ?**	**Avg BVp ?**	**SD BVp ?**	**Avg BVw ?**	**SD BVw ?**
2	0-1m	Point	3	100%	99.7%	±0%	99.7%	±0%
	1-2m		129	95.3%	84.4%	±21.5%	80.5%	±27.5%
	2-3m		118	92.4%	78.2%	±24.6%	72.2%	±31.4%
	3-4m		253	67.2%	47.2%	±28.6%	31.7%	±32.3%
	4-5m		166	41.6%	30.5%	±25.8%	12.7%	±22.4%
	5-6m		176	15.3%	16.5%	±14.8%	2.5%	±8.3%
	6-7m		88	15.9%	13.4%	±8.4%	2.1%	±5.9%
	7-8m		71	0%	-	-	0%	±0%
	8-9m		63	0%	-	-	0%	±0%
	>9m		66	0%	-	-	0%	±0%
	0-1m	Grid	580	100%	83.8%	±20.3%	83.8%	±20.3%
	1-2m		629	100%	82.7%	±22.4%	82.7%	±22.4%
	2-3m		480	98.1%	68.4%	±29.1%	67.1%	±30.3%
	3-4m		616	83.8%	40.4%	±30.5%	33.8%	±31.6%
	4-5m		239	68.2%	31.3%	±26.3%	21.3%	±26.1%
	5-6m		283	39.9%	30.2%	±27.6%	12.1%	±22.9%
	6-7m		222	24.3%	26.8%	±24.1%	6.5%	±16.5%
	7-8m		258	10.9%	15.1%	±11%	1.6%	±5.9%
	8-9m		184	3.3%	8.3%	±2.1%	0.3%	±1.5%
	>9m		163	2.5%	10.9%	±4.7%	0.3%	±1.8%



AOI ?	Depth	Type ?	Count	PAC ?	Avg BVp ?	SD BVp ?	Avg BVw ?	SD BVw ?
3	0-1m	Point	13	100%	99.7%	±0.1%	99.7%	±0.1%
	1-2m		96	100%	98.5%	±6.2%	98.5%	±6.2%
	2-3m		371	99.7%	98.5%	±5.7%	98.2%	±7.6%
	3-4m		280	85.7%	88.7%	±22.5%	76%	±37.4%
	4-5m		1	0%	-	-	0%	±0%
	5-6m		1	0%	-	-	0%	±0%
	6-7m		3	0%	-	-	0%	±0%
	7-8m		1	0%	-	-	0%	±0%
	8-9m		4	0%	-	-	0%	±0%
	>9m		6	0%	-	-	0%	±0%
	0-1m	Grid	154	100%	97.7%	±5.2%	97.7%	±5.2%
	1-2m		197	100%	90.8%	±18.3%	90.8%	±18.3%
	2-3m		225	97.8%	75.7%	±29.7%	74%	±31.4%
	3-4m		187	85%	61.5%	±34.6%	52.3%	±38.7%
	4-5m		84	57.1%	27.8%	±26.3%	15.9%	±24.2%
	5-6m		81	22.2%	27.4%	±22.1%	6.1%	±15.4%
	6-7m		48	14.6%	19%	±9.4%	2.8%	±7.6%
	7-8m		54	3.7%	6.6%	±0.2%	0.2%	±1.3%
	8-9m		40	0%	-	-	0%	±0%
	>9m		24	0%	-	-	0%	±0%

AOI ?	Depth	Type ?	Count	PAC ?	Avg BVp ?	SD BVp ?	Avg BVw ?	SD BVw ?
4	0-1m	Point	70	98.6%	85.1%	±21%	83.9%	±23.2%
	1-2m		432	99.3%	91.9%	±17.2%	91.2%	±18.8%
	2-3m		451	99.3%	90.9%	±17.3%	90.3%	±18.8%
	3-4m		216	92.6%	85.5%	±21%	79.1%	±30.2%
	4-5m		4	0%	-	-	0%	±0%
	5-6m		17	0%	-	-	0%	±0%
	6-7m		10	0%	-	-	0%	±0%
	7-8m		33	0%	-	-	0%	±0%
	8-9m		20	0%	-	-	0%	±0%
	>9m		5	0%	-	-	0%	±0%
	0-1m	Grid	828	100%	91.2%	±11.7%	91.2%	±11.7%
	1-2m		767	100%	90%	±13.1%	90%	±13.1%
	2-3m		530	99.6%	81.4%	±20.2%	81.1%	±20.7%
	3-4m		386	96.1%	56.2%	±29.9%	54%	±31.3%
	4-5m		165	77%	35.8%	±27.4%	27.5%	±28.4%
	5-6m		179	44.7%	36.7%	±29.9%	16.4%	±27.1%
	6-7m		144	34%	28.1%	±24.7%	9.6%	±19.6%
	7-8m		135	11.9%	14.9%	±12%	1.8%	±6.3%
	8-9m		71	0%	-	-	0%	±0%
	>9m		33	0%	-	-	0%	±0%

AOI ?	Depth	Type ?	Count	PAC ?	Avg BVp ?	SD BVp ?	Avg BVw ?	SD BVw ?
5	0-1m	Point	9	100%	84%	±20.8%	84%	±20.8%
	1-2m		104	100%	88.3%	±16.4%	88.3%	±16.4%
	2-3m		141	96.5%	80.3%	±21.7%	77.5%	±26%
	3-4m		353	57.2%	30.2%	±19.7%	17.3%	±21.1%
	4-5m		84	8.3%	33.9%	±25.4%	2.8%	±11.9%
	5-6m		109	0%	-	-	0%	±0%
	6-7m		201	0%	-	-	0%	±0%
	7-8m		216	0%	-	-	0%	±0%
	8-9m		135	0%	-	-	0%	±0%
	>9m		80	0%	-	-	0%	±0%
	0-1m	Grid	620	100%	89.6%	±14.2%	89.6%	±14.2%
	1-2m		939	100%	82.6%	±19.3%	82.6%	±19.3%
	2-3m		727	98.8%	66.2%	±24.1%	65.4%	±25.1%
	3-4m		969	77.9%	29.5%	±21.8%	23%	±22.8%
	4-5m		332	57.8%	27.8%	±23.7%	16.1%	±22.7%
	5-6m		402	32.3%	29%	±26.1%	9.4%	±20.1%
	6-7m		386	18.7%	23.4%	±21.9%	4.4%	±13.1%
	7-8m		421	8.1%	13.8%	±10.3%	1.1%	±4.8%
	8-9m		342	1.8%	8.3%	±2.1%	0.1%	±1.1%
	>9m		305	1.3%	10.9%	±4.7%	0.1%	±1.4%

Glossary

AOI

Area of Interest: Defines the individual transects or contiguous data samples as depicted by the color coding of each trip line. Seperate areas of interest can be generated through merging of multiple trips, appending data to a single sonar log or lapses in time (greater than five minutes) within a sonar log.

BVp

Biovolume (Plant):: Refers to the percentage of the water column taken up by vegetation when vegetation exists. Areas that do not have any vegetation are not taken into consideration for this calculation.

BVw

Biovolume (All water): Refers to the average percentage of the water column taken up by vegetation regardless of whether vegetation exists. In areas where no vegetation exists, a zero value is entered into the calculation, thus reducing the overall biovolume of the entire area covered by the survey.

PAC

Percent Area Covered: Refers to the overall surface area that has vegetation growing.

Grid

Geostatistical Interpolated Grid: Interpolated and evenly spaced values representing kriged (smoothed) output of aggregated data points. The gridded data is most accurate summary of individual survey areas.

Point

Individual Coordinate Point: A single point represents a summary of sonar pings and the derived bottom and canopy depths. Individual point data create an irregularly spaced dataset that may have overlaps and/or gaps in the data resulting in a increased potential for error.

Additional Information

No additional information

Report URL: http://files.digitalmarine.com/s1/ReportOutput/9b200c22-53cd-4c3c-bdd0-f7ab4267f6f8/report.htm

Appendix 8. A summary of macrophyte vegetation survey data for Lakes Pauri, Wiritoa and Dudding. (Data from Burton 2017).

Lake Pauri

LakeSPI data

Date	Lake SPI %	Native Condition %	Invasive Impact %	Native		Invasive	
				Type	Max depth (m)	Type	Max depth (m)
Nov 2015	Poor 16	22	96	Pondweeds Charophyte species *Myriophyllum triphyllum* *Ricciocarpos natans* *Lilaeopsis novae-zelandiae*		*Ceratophyllum demersum* *Egeria densa* *Elodea canadensis* *Potamogeton crispus* *Potamogeton crispus* *Ranunculus trichophyllus*	6.3

Non-LakeSPI data

Date	Native		Invasive	
	Type	Max depth (m)	Type	Max depth (m)
1977	Chara sp Pondweeds		*Potamogeton crispus* *Ranunculus trichophyllus*	

Lake Dudding

LakeSPI data

Date	Lake SPI %	Native Condition %	Invasive Impact %	Native		Invasive	
				Type	Max depth (m)	Type	Max depth (m)
Nov 2001	Moderate 48	50	48	Charophyte meadows	6.5	*Elodea canadensis* *Potamogeton crispus*	6.5
				Pondweeds Charophyte species (*Nitella*)	6.1		
Nov 2015	Moderate 22	24	87	Charophyte meadows	6.1	*Egeria densa* *Potamogeton crispus* *Ranunculus trichophyllus*	6.3
				Pondweeds Charophyte species (*Nitella*) *Glossostigma diandrum*	6.1		
						Elodea	

Non-LakeSPI data

Date	Native		Invasive	
	Type	Max depth (m)	Type	Max depth (m)
1977	Charophyte meadows	5m	*Potamogeton crispus*	1.5
	Pondweeds			

Lake Wiritoa

LakeSPI data

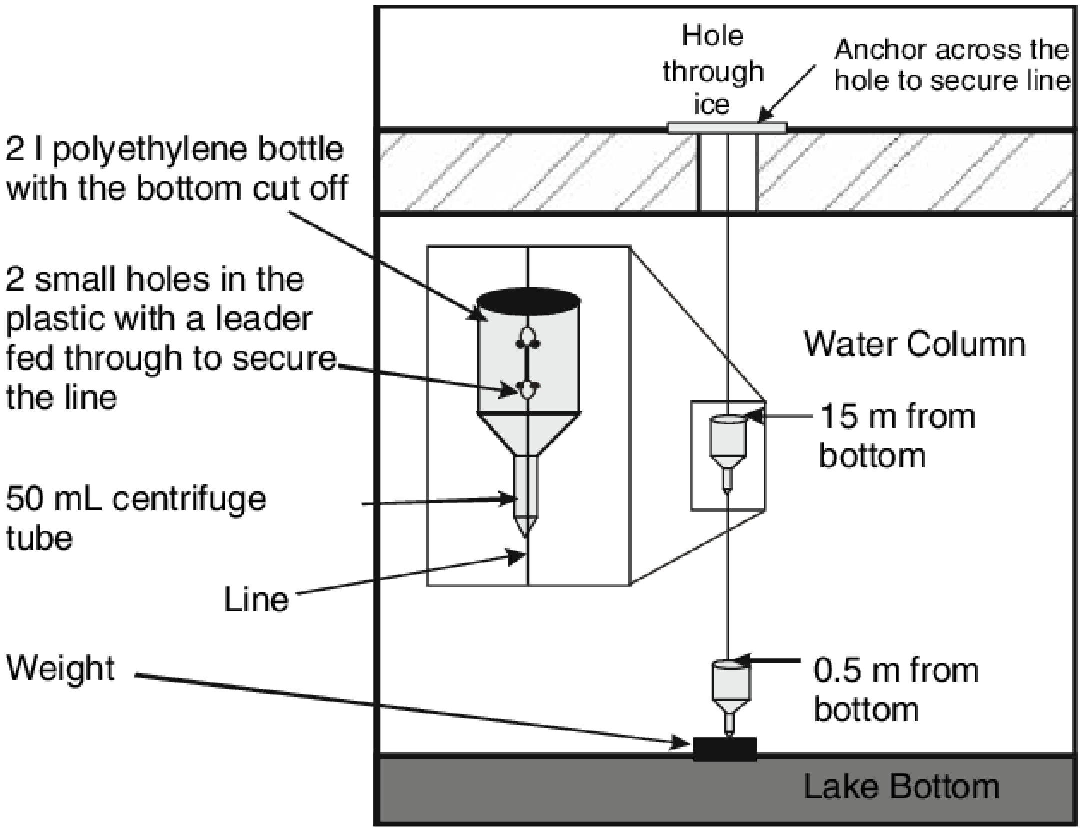
Date	Lake SPI %	Native Condition %	Invasive Impact %	Native		Invasive	
				Type	Max depth (m)	Type	Max depth (m)
Nov 2001	Poor 16	16	96	Pondweeds Charophyte species (*Nitella*)	6.1	*Ceratophyllum demersum* *Vallisneria australis*	9
Nov 2015	Poor 14	20	96	Pondweeds Charophyte species (*Nitella*) *Myriophyllum triphyllum*	6.1	*Ceratophyllum demersum* *Egeria densa* *Potamogeton crispus* *Vallisneria australis*	6.3

Non-LakeSPI data

Date	Native		Invasive	
	Type	Max depth (m)	Type	Max depth (m)
1977	Charophyte species Pondweeds *Myriophyllum triphyllum* *Ruppia megacarpa*		*Potamogeton crispus* *Vallisneria australis* *Ranunculus trichophyllus*	1.5
1994			*Elodea canadensis*	
1997			*Ceratophyllum demersum* *Egeria densa*	
1999			*Ceratophyllum demersum* *Egeria densa* *Elodea canadensis*	

Appendix 9. Diagram of sediment traps for the collection of settling seston.

The diagram below illustrates the setup of easily constructed sediment traps in a deep lake. The diagram has an ice cover however for New Zealand situations the anchor across the ice hole can be replaced with a float. A polyethylene bottle such as a soft-drink bottle often screws straight onto a 50 ml centrifuge tube. The depths of the traps can be adjusted to suit the lake and there may only be a requirement for a single trap in a shallow lake. The frequency of clearing the traps will be dependent on sedimentation and primary production rates.



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