Restoration Planning for Shallow Dune Lakes: Data Review and Recommendations

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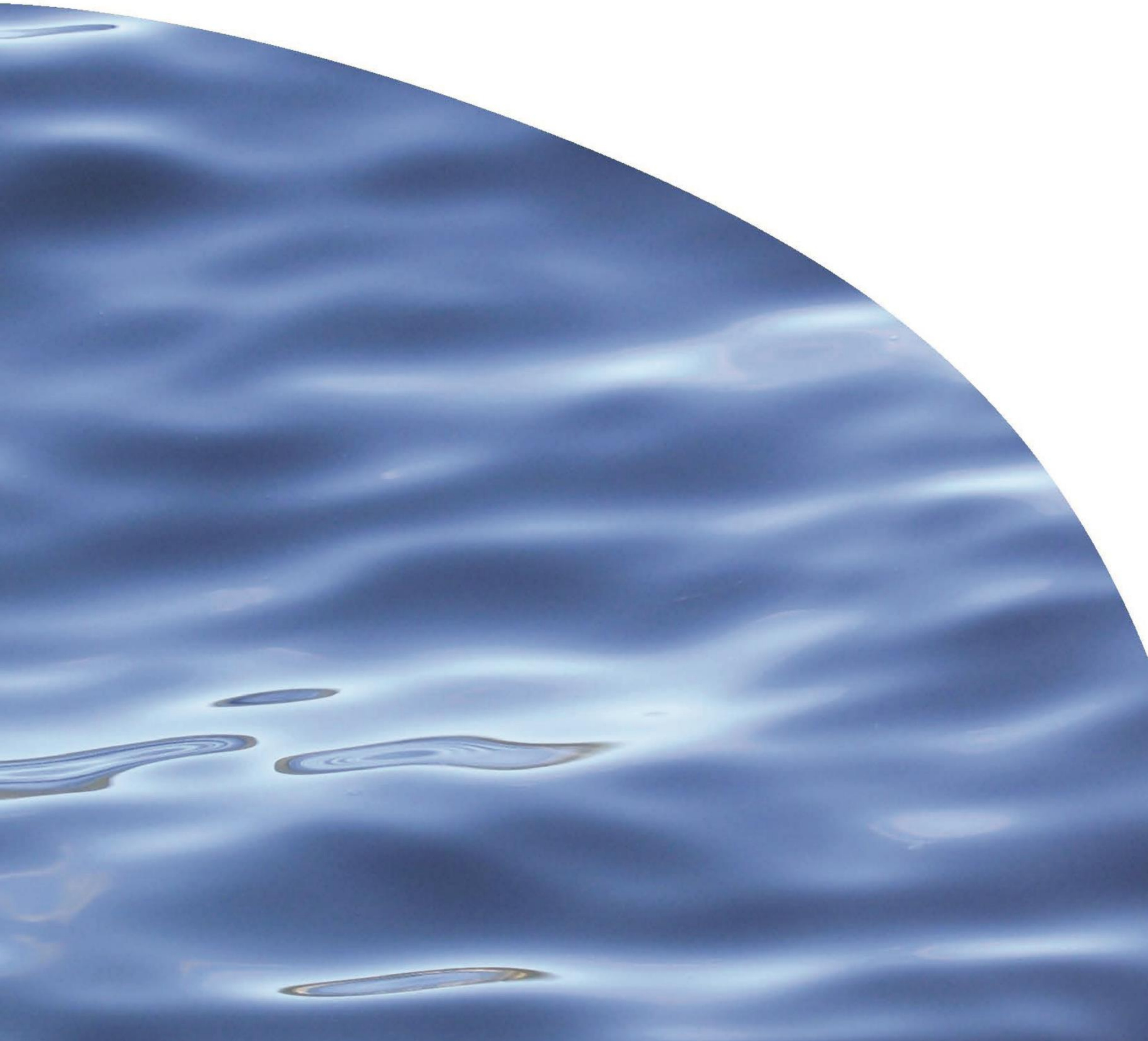

RESTORATION PLANNING FOR SHALLOW DUNE LAKES: DATA REVIEW AND RECOMMENDATIONS

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EXECUTIVE SUMMARY

The Manawatu-Whanganui region has approximately 57 coastal dune lakes, both deep 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 better than 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 fail to meet 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 shallow dune lakes in the region, identify gaps in the knowledge required to inform restoration planning, and make recommendations for future research and monitoring. Lakes Waipu and William have been used as case studies.

The data from both these lakes suggest very poor water quality and ecological conditions. The supertrophic to hypertrophic status of the lakes indicated extremely high nutrient enrichment with nutrient and phytoplankton concentrations which routinely exceed the NPS-FM bottom lines and One Plan water quality targets. The phytoplankton community includes potentially-toxic cyanobacteria species at biovolumes that, on occasion, exceed MfE-MoH action guidelines. The ecology of the lakes is severely compromised with the near absence of macrophytes in Lake Waipu and dominance of the collapse-prone invasive species *Egeria* in Lake William. As such, the ecological, cultural and recreational values of these lakes are highly degraded.

The data available for the two lakes reviewed in this report do allow some insight into probable nutrient sources and dynamics within the lake systems, but the data have major omissions, making it challenging to rigorously 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 lake bed sediments. 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. In addition, trend analysis is likely to be key to any future restoration planning and monitoring, but current quarterly monitoring frequency makes that challenging. Insufficient data currently exist to assess ecosystem effects or trends of invasive pest species and indeed no data are available at all for invasive fish.

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. This would include inflow water quality monitoring to assist in validating land-use model (e.g. CLUES) nutrient load predictions. Targets for external nutrient load reductions need to be clearly defined to enable goals to be set for catchment land use management initiatives.
- Adoption of high-frequency instrumentation (thermistor chain, DO, pH, chlorophyll-*a*, and turbidity sensors) for monitoring real-time lake physicochemical variation (all lakes for which restoration is planned).
- One-off investigations of sediment geochemistry to determine the likely extent and rate of internal loading of nutrients from sediments during anoxic or high pH events.
- One-off seasonal macrophyte biovolume surveys to establish the extent to which macrophyte die-back enhances lake anoxia cycles.
- Modifying lake water quality monitoring to monthly time-scale to enable time-trend analyses and improve the resolution of seasonal variation.
- One-off investigations of seasonal nutrient status of a number of lakes in the region including monthly nutrient ratios and nutrient bioassays.
- 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).
- Implement 5-yearly macrophyte surveys to gain an understanding of the macrophyte trends and, where the lake is vegetated, risk of collapse.
- 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 (Horizons) has recently commenced water quality monitoring of fifteen coastal lake systems. The preliminary results of this monitoring indicate that water quality in many of the monitored lakes falls below NPS-FM national bottom lines These lakes also fail to meet the Horizon's own water quality targets for shallow lakes contained in the One Plan, their statutory planning document.

The 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 Waipu and William and a number of other shallow coastal lakes (e.g., Lake Horowhenua). In order to plan such restoration, a good understanding of the sources of nutrients to the 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 lake ecosystems to allow the formulation of restoration plans and it is likely that more comprehensive monitoring may be required to inform and evaluate future restoration decisions.

Horizons commissioned Cawthron Institute (Cawthron) to assist in evaluating the information available to inform restoration planning for shallow coastal lakes in the Manawatu-Whanganui region. This report focusses on Lakes Waipu and William as case studies. 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:

1. review and evaluate the data which are currently available to inform restoration planning for these two shallow dune lakes
2. assess information gaps in the available monitoring data
3. 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 report which addresses similar options for deep coastal lakes in the Manawatu-Whanganui region. The reports are very similar with significant overlap, however the contrasting depths of the lakes results in variations in some information required to inform restoration plans. The reports are based on publicly available information and/or data supplied by Horizons 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 including Lakes Waipu and William (Figure 1). Most of these 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). Horizon's 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. As an example, biodiversity values for the water management zones containing Lake William are presented in Appendix 1.

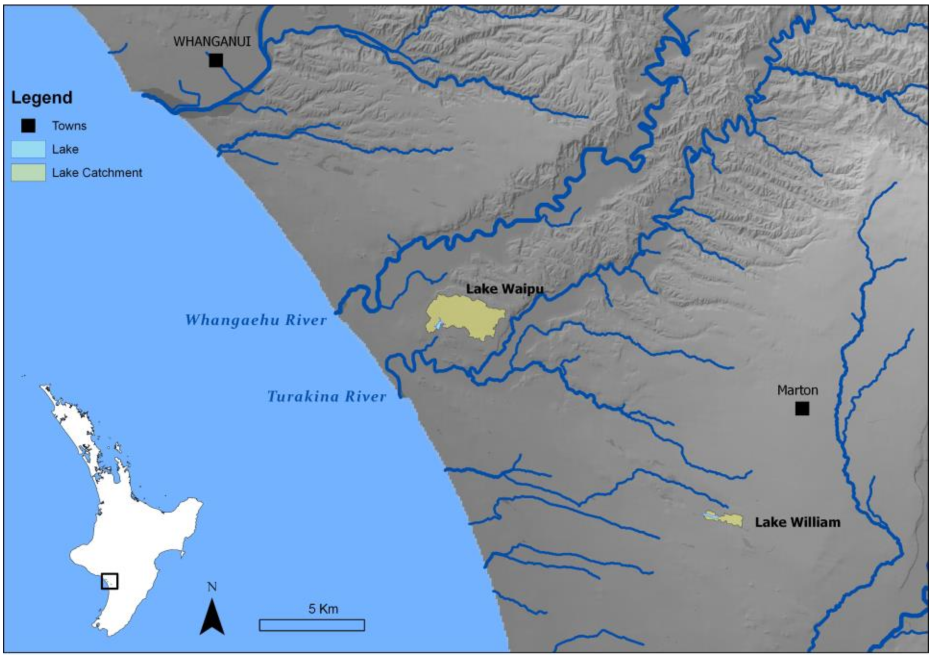

Figure 1. The locations of Lakes Waipu and William and their respective catchments in the Manawatu-Whanganui region.

The coastal lakes in the region are generally small (Table 1), and most are shallow (< 10 m), including Lake Waipu for which various maximum depths are listed from differing sources (Table 2). Lake William is listed in the Freshwater Ecosystems of New Zealand (FENZ) database as having a maximum depth of 11.8 m; however, in this database the depths listed for several lakes in the region (e.g. Waipu, Wiritoa, Dudding) have been deeper than more recently surveyed depth data. For Lake William the most recent datum is a single figure reported in a macrophyte survey report (Table 1, Burton 2017). Despite this figure exceeding the One Plan delineation of deep from shallow lakes (5 m), Horizons have included Lake William in this review as a shallow lake.

Table 1. Lake morphometric and catchment data for Lakes Waipu and William.

Lake	FENZ[1] ID	Lake Area[2] (ha)	Catchment area[2] (ha)	Geomorphic Class[3]	Elevation[2] (masl)	Estimated residence time[5] (y)
Waipu	16939	7.04	527	W[4]	20.3	0.28
William	13437	6.79	71.3	W[4]	105.8	2.58

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 Waipu and William

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)
Waipu	7.0	2.3	4.7	2.2	3.7	1.6
William	11.8	3.9			9.8	

1. Freshwater Ecosystems of New Zealand
2. Livingston et al (1986).
3. Data provided by Horizons Regional Council (L. Brown, pers. comm. 2018) and from Burton (2017).

The lake catchments are generally small and limited in extent by paleo-dune morphology (Table 1), however, groundwater capture zones can be larger with aquifers linked to clusters of dune lakes (Nichol & Thomas 2017). There is limited urban development in the catchments of these lakes, although the Lake Waipu catchment includes the small settlement of Ratana (population 327 in 2013). Catchment land use maps for the two lakes, 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 Waipu and William. The data are derived from CLUES[1] catchment modelling and have been retrieved from https://lakes.takiwa.co.

Land use category	Lake	
	Waipu	William
	% of catchment	
Grassland	93.0	80.4
Forest	2.0	5.1
Shrubland	0.0	0.0
Cropland	0.0	2.8
Urban	3.6	0.0
Wetland	0.0	0.0
Water	1.3	11.7

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

2.2. Lake water quality data

2.2.1. Data availability

All the reviewed water quality (WQ) data from Lakes Waipu and William are from recent monitoring since late 2015. Details of the monitoring undertaken in the lakes from 2015 to 2018 are presented in Appendix 4 but are briefly commented on here. State of the environment water quality sampling has been conducted quarterly during that period. In this programme, sampling is conducted at three sites per lake and samples from each site are analysed for a basic suite of parameters (temperature, dissolved oxygen, conductivity and pH). For site locations see Appendix 5. A composite sample from all three sites is then analysed for a more comprehensive suite of parameters (see Appendix 4). Data provided by Horizons also indicate that weekly sampling for *E. coli* was undertaken in Lake William at Site 1 from December 2016 to April 2018, but no equivalent sampling data were available for Lake Waipu. Water column profile data for the three sites in Lake Waipu, collected using an EXO Sonde, has been provided for a single date (October 2015). No similar data for Lake William have been reviewed.

2.2.2. Results

Key statistics present a picture of very poor water quality in Lakes Waipu and William. The annual mean trophic level index (TLI), based on annual means of total phosphorus, total nitrogen and chlorophyll-*a*, indicate that Lake Waipu is hypertrophic and William is supertrophic (2016-2017, Table 4), indicating that both lakes have very high nutrient enrichment and productivity.

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

Year	TLI(3)[1]	
	Lake Waipu	Lake William
2016	6.37	5.59
2017	6.48	5.98

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.

For the limited monitoring period, median total phosphorus and nitrogen values and chlorophyll-*a* all exceeded the NPS-FM national bottom lines in both lakes (Table 5). Lake William also exceeded the maximum chlorophyll-*a* concentration. Such exceedances indicate unacceptably high concentrations. Both lakes also exceed the One Plan water quality targets for lakes for total phosphorus, total nitrogen and chlorophyll-*a* concentrations (i.e. 30 mg TP m^{-3}, 490 mg TN m^{-3}, 30 mg Chl-*a* m^{-3}). Total nutrients exceeded NPS-FM bottom lines throughout the entire monitoring period in both lakes, while chlorophyll-*a* generally had high summertime concentrations which decreased during winter months (Figures 2 and 3).

It should be noted that a direct comparison between the Table 5 data and NPS bottom lines and One Plan targets is slightly 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) in each statistic. The data available for Lakes Waipu and William are sampled quarterly and hence do not meet these criteria. In order to meet the 12 sample criteria, the data presented in Table 5 are for the entire 3-year monitoring period for which such quarterly sampling has been undertaken. Lake Waipu has extremely high nutrient and *E. coli* concentrations although Lake William has higher median and maximum chlorophyll-*a* concentrations.

Table 5. Median, maximum and minimum values for key water quality parameters from composite epilimnion samples at Lakes Waipu and William from the period for which quarterly monitoring data are available (2015- 2018). pH is from site specific samples (i.e. not composite samples) and is not for the full period (see footnote to table).

WQ parameter	**Statistic**	**Lake**		**NPS-FM bottom line concentrations**
		Waipu	**William**	
Total phosphorus ($mg.m^{-3}$)	Median	345	94	50
	Maximum	414	155	
	Minimum	211	58	
Dissolved reactive phosphorus ($mg.m^{-3}$)	Median	85	33	
	Maximum	118	71	
	Minimum	33	13	
Total nitrogen ($mg.m^{-3}$)	Median	2460	1370	750
	Maximum	3010	1990	
	Minimum	1310	970	
Ammoniacal nitrogen[1] ($mg.L^{-1}$)	Median	0.27	0.03	1.30
	Maximum	0.52	0.06	2.20
	Minimum	0.03	0.01	
Nitrate-nitrite nitrogen ($mg.L^{-1}$)	Median	0.406	0.031	
	Maximum	0.825	1.010	
	Minimum	0.004	0.002	
Chlorophyll-*a* ($mg.m^{-3}$)	Median	7	11	12
	Maximum	37	71	60
	Minimum	3	4	
E. coli (per 100 ml)	Median	175	8	
	Maximum	9700	54	
	Minimum	8	2	
pH	Median	7.38[2]	7.63[3]	
	Maximum	7.93[2]	8.27[3]	
	Minimum	5.98[2]	5.96[3]	

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

2. from Sites 1, 2, 3, October 2015–July 2017

3. from Sites 2, 3, December 2015–July 2017

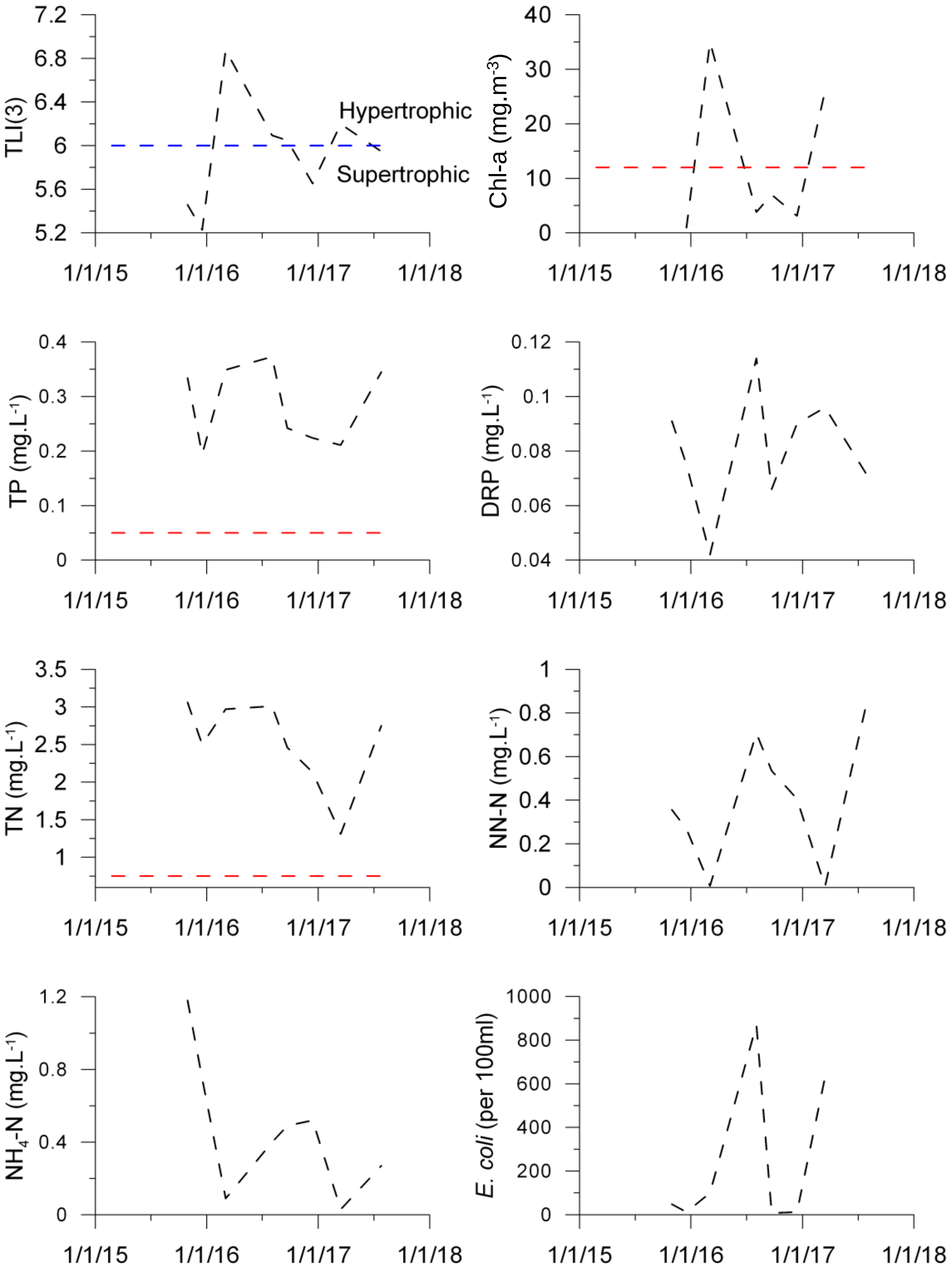

Figure 2. Water quality parameters for Lake Waipu from Horizons Regional Council monitoring data. (October 2015–March 2018). Dotted black lines in all plots are composite samples from three sites. The red dotted lines indicate the National Policy Statement–Freshwater Management (2014) national bottom line concentrations. The blue dotted line is the threshold between supertrophic and hypertrophic trophic level categories. 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.*

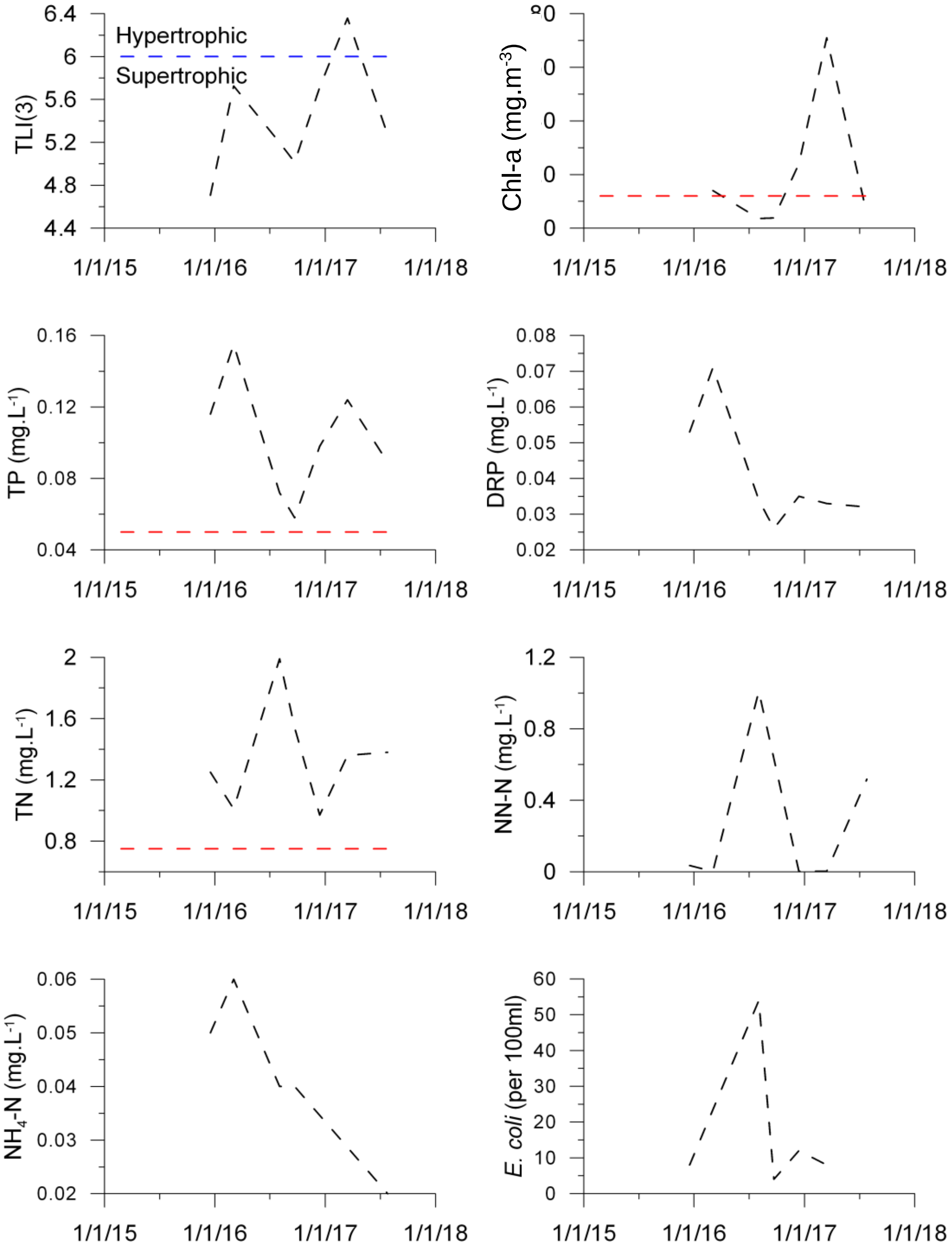

Figure 3. Water quality parameters for Lake William from Horizons Regional Council monitoring data. (December 2015–March 2018). Dotted black lines in all plots are composite samples from three sites. The red dotted lines indicate the National Policy Statement - Freshwater Management (2014) national bottom line concentrations. The blue dotted line is the threshold between supertrophic and hypertrophic trophic level categories. 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.*

Water column stratification

Thermal stratification of the water column can be an important factor in nutrient recycling in lake systems due to deoxygenation of stratified bottom water and consequent redox-related nutrient release. However, the water column profiles taken at the three sites in Lake Waipu in October 2015 all displayed well-mixed water columns with no sign of thermal stratification or bottom water deoxygenation. New Zealand lakes that seasonally stratify normally commence their stratification in October and remain stratified through to April. Therefore, it is possible that stratified conditions persist in Lake William later in summer and are not detected by these earlier spring water column profiles. In addition, shallow lakes are often polymictic with only intermittent stratification. More regular water column profiling or continuous temperature monitoring would better detect if stratified conditions are prevalent in the lake.

2.3. Phytoplankton

2.3.1. Data availability

Phytoplankton data are available for Lakes Waipu and William from quarterly sampling by Horizons, for the period October 2015 to the present. The data reviewed included species identification, cell counts and some biovolume calculations. Some cyanotoxin data are also available for these samples. Weekly data including cell counts, and biovolumes have been reviewed for the period November 2017 to April 2018. 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

Cell counts of potentially toxic species indicate that blooms of both *Dolichospermum* sp. and *Microcystis* sp. occur in Lake William (Table 6). Calculated biovolumes provided from the quarterly data frequently exceeded the action levels based on the Ministry for the Environment/Ministry of Health alert level framework (Appendix 6, MfE/MoH 2009). For some sampling occasions, biovolume calculations were not made for some of the potentially toxic cyanobacteria species. In these instances, biovolumes in Table 6 were estimated using average biovolumes for the appropriate species in the same lake. For example, during March 2017 *Dolichospermum* sp. cell counts of 48,000 were recorded in the lake. Although biovolume was not calculated, these are almost certain to have exceeded the action alert level in terms of biovolume. The potentially toxic cyanobacteria species *Pseudanabaena* sp., *Aphanocapsa* sp. and rare *Phormidium* sp. also occurred in the Lake William quarterly sampling records.

The brief period of weekly monitoring data reviewed here confirmed that the action alert level was exceeded during the summer of 2017/18 (Figure 4). Of the 25 sampling occasions 15% exceeded the action alert (red) level while a further 74% exceeded the alert (amber) level. Despite high cell counts in Lake William water samples, cyanotoxin concentrations were below detection for all cyanotoxins tested (Table 7).

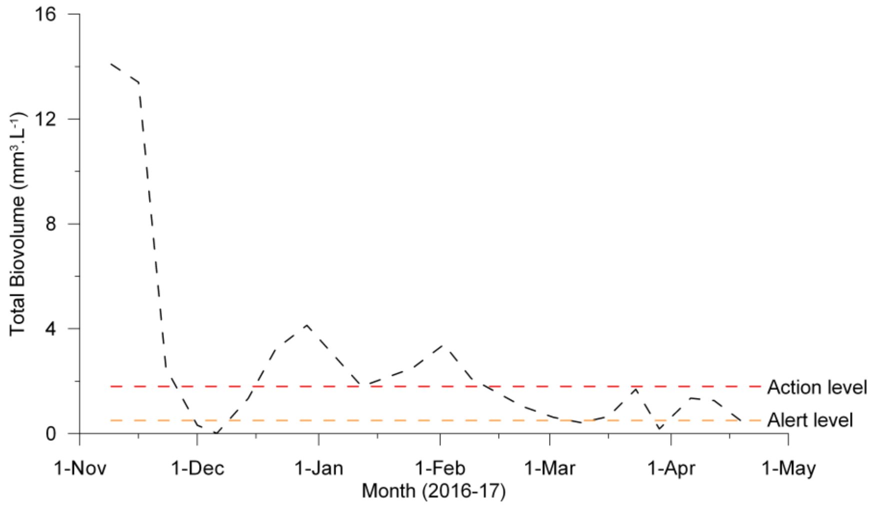

Figure 4. Total potentially toxic cyanobacterial biovolumes from monitoring samples collected weekly over summer 2017/18 (November–April) from Lake William. The red and amber dotted lines are the action (red, > 1.8 $mm^3.L^{-1}$) and alert (amber, > 0.5 $mm^3.L^{-1}$) levels respectively, based on the Ministry for the Environment/Ministry of Health cyanobacterial recreation alert level framework (MfE/MoH 2009).

Cyanobacterial blooms in Lake Waipu were dominated by *Aphanocapsa* sp. with high cell counts in March of both 2016 and 2017 (Table 6). Calculated and estimated biovolumes of potentially toxic cyanobacteria were below alert levels (MfE/MoH 2009). The potentially toxic cyanobacterial species *Dolichospermum* sp., *Microcystis* sp. and *Pseudanabaena* sp. also occurred in the samples at lower cell counts. Scum-forming algal blooms are not reported in this lake by the sampling teams but there were comments on very low clarity (L. Brown, Horizons, pers. comm. 2018). The cyanotoxin concentrations reviewed were also below alert levels.

Table 6. Cell concentrations and biovolumes of potentially toxic cyanobacterial species from quarterly monitoring samples taken in 2016–2017 from Lakes William and Waipu. Colour coding is from the cyanobacteria alert level framework. Red = Action (biovolume > 1.8 mm^3.L^{-1}), Green = surveillance (biovolume < 0.5 mm^3.L^{-1}). White indicates where biovolume data has not been recorded. Biovolumes were calculated from average cell volumes (MfE/MoH 2009).

Lake	year	month	Potentially toxic species identified in sample	Cell concentration	Biovolume per species (mm^3 L^{-1})	Total biovol in sample (mm^3 L^{-1})
William	2017	March	*Dolichospermum* cf. *circinale*	48,000		13.3[1]
			Microcystis sp.	33,000		
		July	*Pseudanabaena* sp.	3		0.008
			Microcystis sp. *(small)*	42	0.0008	
			Phormidium sp.	110		
		September	*Dolichospermum* cf. *circinale*	1400	0.3	0.3
		December	*Microcystis* sp. *(large)*	220,000	20	27
			Dolichospermum cf. circinale	32,000	7	
			Pseudanabaena sp.	9,400		
	2016	March	*Microcystis* sp. *(small)*	44,000		4.0[2]
			Pseudanabaena sp.	3,700		
			Aphanocapsa sp..	120		
		August	*Dolichospermum* sp.	1,200	0.216	0.22
			Microcystis sp. *(small)*	200	0.004	
		September	*Dolichospermum* sp.	770	0.16	0.16
			Aphanocapsa sp.	11		
		December[1]	*Dolichospermum* sp.	1,400	0.252	0.299
			Microcystis sp. *(large)*	500	0.047	
			Pseudanabaena sp.	26		
Waipu	2017[2]	March	*Aphanocapsa* sp.	640,000		0.36[3]
			Microcystis sp.	3,690		
			Dolichospermum sp.	2,650		
		July	*Aphanocapsa* sp.	688	0.003	0.003
		December	*Microcystis* sp.	6,700	0.6	0.6
			Pseudanabaena sp.	74		
	2016	March	*Aphanocapsa* sp.	129,800		0.072[3]
			Pseudanabaena sp.	20		
		August	*Aphanocapsa* sp.	110,000	0.057	0.057
			Pseudanabaena sp.	12		
		September	*Pseudanabaena* sp.	12		
		December	*Aphanocapsa* sp.	1200	0.002	0.003
			Microcystis sp. (*large*)	8	0.0007	

[1] Biovolume not supplied. This figure is an estimate based on the average biovolumes of *Dolichospermum* cf. *circinale* in September, December 2017, and August, December 2016, and *Microcystis* sp. in December 2017.

[2] Biovolume not supplied. This figure is an estimate based on the average biovolume of *Microcystis* sp. in December 2017

[3] Biovolume not supplied. This figure is an estimate based on the average biovolumes of *Aphanocapsa* sp. in the July 2016 and August and December 2017.

Table 7. Cyanotoxin concentrations in monitoring samples 2015–2017 from Lakes Waipu and William. The action (red) alert threshold is ≥ 12 µg.L^{-1} based on the Ministry for the Environment/Ministry of Health cyanobacterial recreation alert level framework (MfE/MoH 2009).

Lake	Date	Cyanotoxin	Concentration (µg.L^{-1})
Waipu	17/12/2015	Anatoxin-a	< 0.2
	3/3/2016	Microcystin (total)	< 5
		Nodularin	< 1
	15/3/2017	Anatoxin-a	< 0.2
		Homo-anatoxin-a	< 0.2
		Cylindrospermopsin	< 0.2
		Deoxycylindrospermopsin	< 0.2
	21/12/2017	Anatoxin-a	< 0.2
		Homo-anatoxin-a	< 0.2
		Cylindrospermopsin	< 0.2
		Deoxycylindrospermopsin	< 0.2
William	17/12/2015	Anatoxin-a	< 0.2
		Homo-anatoxin-a	< 0.2
		Cylindrospermopsin	< 0.2
		Deoxycylindrospermopsin	< 0.2
	3/3/2016	Nodularin	< 1
		Microcystin (total)	< 5
	15/3/2017	Anatoxin-a	< 0.2
		Homo-anatoxin-a	< 0.2
		Cylindrospermopsin	< 0.2
		Deoxycylindrospermopsin	< 0.2
	21/12/2017	Anatoxin-a	< 0.2
		Homo-anatoxin-a	< 0.2
		Cylindrospermopsin	< 0.2
		Deoxycylindrospermopsin	< 0.2

2.4. Macrophytes

2.4.1. Data availability

Lake Submerged Plant Indicator (SPI) scores for Lakes Waipu and William have only been calculated for 2015 (Burton 2017). The SPI survey, conducted by SCUBA divers, assesses 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'. NIWA conducted spot sampling in both lakes in 2003. More recently, (2016) aquatic vegetation biovolumes have been surveyed by sonar transects in Lake Waipu but these remain in tabulated data form and have not been processed into a biovolume map.

2.4.2. Results

Macrophyte survey results (Table 8 and Appendix 7) indicate that Lake Waipu and William are in very poor condition with respect to macrophyte communities. Lake Waipu is classified by the LakeSPI system as non-vegetated, but the submerged invasive species *Potamogeton crispus* was present at a single site to depths of 0.8 m. Filamentous green algae was also present in small amounts, as were native pondweeds *Potamogeton ochreatus* and *Stuckenia pectinata.* The turf forming species *Glossostigma diandrum* was also recorded. The spot sampling in 2003 recorded a similar species list along with *Lilaeopsis novae-zelandiae*, *Ludwigia palustris* and *Ruppia polycarpa* (Burton 2017).

Table 8. Lake SPI results for Lakes Waipu and William.

	Date	LakeSPI (%)	Condition	Native Condition (%)	Invasive Impact (%)
Lake Waipu	2015	0	Non-vegetated	0	0
Lake William	2015	11	Poor	0	93

Lake William has the lowest LakeSPI index of 22 lakes in the Manawatu-Whanganui region surveyed in 2015 (Table 8). Lake vegetation was dominated by the invasive species *Egeria densa,* which grows to a depth of 6 m. Occasional plants of *Elodea canadensis* and *Potamogeton crispus* were also recorded. Very poor visibility (< 0.2 m) was noted during the survey. In the 2003 spot sampling, *Egeria* was present along with *P. crispus* and the natives *P. ochreatus, Glossostigma elatinoides and L. novae-zelandiae.* Appendix 7 presents a more detailed summary of the results from the various vegetation surveys including some of the main species present and maximum depths (Burton 2017).

2.5. Fish

2.5.1. Data availability

No data on fish occurrence were available in either Lake Waipu or Lake William based on records from the New Zealand Freshwater Fish Database (NZFFD). In addition, no mention of either lake was made on the popular fishing website, www.nzfishing.com.

In an effort to enhance the paucity of the fish record, a fish prediction model was utilised in an effort 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. 2002) 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. Predictions do not include exotic fish species.

2.5.2. Results

The fish prediction model (Leathwick et al. 2008) predicted probabilities of > 50% for shortfin eels in stream reaches connected to both lakes while longfin eels were predicted (> 50%) in stream reaches connected to Lake Waipu. No other native fish were predicted (at a confidence of > 50%) in reaches connected to the two lakes.

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 either lake (external loading). 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 to nutrient fluxes to/from the lakes via groundwater. A report on groundwater catchment zones (Nicol & Thomas 2017) provides useful information on the geological setting and modelled groundwater capture zones of these lakes.

Internal nutrient loads

No data have been obtained on lake sediment nutrient geochemistry from any of the lakes.

2.6.2. Results

Surface water flows and external nutrient loads

For its size Lake Waipu has a reasonably large catchment (Table 1) relative to other dune lakes in the region. A number of surface streams drain to the lake and a single outflow drains the lake to the Turakina River. The lake is predicted to have a short hydraulic residence time (0.28 y) relative to the other dune lakes reviewed. In contrast Lake William has a smaller catchment with a single mapped surface inflow and a modified (sandbag weir) outflow that flows intermittently. This leads to a long, estimated residence time of 2.58 y.

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).

The Rangitikei District Council is currently consented to discharge 136 $m^3.d^{-1}$ of treated wastewater from the Ratana Wastewater Treatment Plant direct to an inflowing tributary of Lake Waipu. Monthly monitoring upstream and downstream of the outfall are conducted but these data have not been reviewed in detail. However, highly elevated downstream concentrations of ammoniacal nitrogen (exceeding 7 $g.m^{-3}$) and elevated dissolved reactive phosphorus are reported (Rangitikei District Council 2014). Such an outfall is likely to have been a major source of nutrients to the lake. This consent is due for renewal in July 2018 and our understanding is that it is intended to change its disposal method to discharge to land. Upgrades to the wastewater treatment plant are planned using funding from the Central Government Freshwater Improvement Fund.

No other water quality data for inflow streams or groundwater have been sighted for this report. The Catchment Land Use for Environmental Sustainability model (CLUES Woods et al. 2006) was used to estimate inflow concentrations for inflows and areal loads for the two lakes (Table 9). The estimated inflow nutrient concentrations for Lake Waipu are very high, reflecting a large catchment with a very high proportion (93%) of high producing grasslands. This contributes to high areal loads of nutrients to the lake even before considering the point source wastewater discharges which are not accounted for in the CLUES modelling. Lake William on the other hand is predicted to have relatively low modelled inflow concentrations and areal loads.

Table 9. 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 ($mg.m^{-2}.y^{-1}$)	Areal Total Nitrogen load ($mg.m^{-2}.y^{-1}$)
Waipu	513.0	10,080	4,269.0	83,931
William	9.7	694	14.7	1,057

Internal nutrient load

No direct analyses of lake sediment geochemistry or internal nutrient release rates were obtained for this report. However, the mean total nutrients measured during water quality monitoring are substantially higher than the predicted lake concentrations estimated by CLUES (except total nitrogen in Lake Waipu, Table 10).

This result is indicative that internal loading of nutrients, particularly phosphorus, from lake sediments is likely to be a factor for both lakes.

Table 10. Estimated total phosphorus (TP), total nitrogen (TN) and chlorophyll-*a* (Chl-*a*) 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})
Waipu	142.00	304.0	4432.00	2429
William	7.28	96.1	7.76	1360

3. DISCUSSION AND RECOMMENDATIONS

The water quality and ecological data for the two shallow coastal dune lakes reviewed as case study lakes in this report suggest very poor conditions exist. The super-hypertrophic status of the lakes indicates very high nutrient and phytoplankton concentrations that routinely exceed the NPS-FM bottom lines. The phytoplankton community includes potentially toxic cyanobacteria, the biovolumes of which regularly exceed MfE action guidelines in Lake William. The ecology of the lakes is severely compromised with Lake William having one of the poorest water clarities and lowest Lake SPI score among 22 surveyed dune lakes in the region (Burton 2017). Large numbers of dead or dying kakahi (freshwater mussels) have also been noted in Lake William (Burton 2017). Lake Waipu is one of only a few non-vegetated lakes in the region, and no records were found to indicate when the lake underwent a transition to this state. As such, the water quality, ecological, cultural and recreational values of these lakes are highly compromised.

With very limited historical data and only limited current data, it is difficult to determine or estimate any trends in the state of these lakes. The macrophyte assemblage may have declined in Lake William since 2003, however this is based purely on a spot sampling visit in that year.

3.1. Reasons for elevated nutrients

The ultimate source of most nutrients in a lake system is transport from the lake catchment (external loading); however, once nutrients are 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 nutrients 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 the lakes 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 two lakes reviewed here are extremely limited. No hydrological information and almost no surface or groundwater water quality data 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 suggest very significant loads to Lake Waipu, equivalent to those predicted for Lake

Horowhenua (the modelled total phosphorus yield at Lake Waipu = 0.57 kg.ha^{-1}.y^{-1}, Lake Horowhenua = 0.59 kg.ha^{-1}.y^{-1} [data from CLUES modelling retrieved from lakes.takiwa.co]). Lake William has significantly lower catchment yield (0.01 kg.ha^{-1}.y^{-1}). The lack of significant outflow from Lake William and hence long residence times (Table 1), means that most nutrients reaching the lake from the catchment will be retained within the lake system, increasing the likelihood for in-lake nutrient recycling. For Lake Waipu, inputs from wastewater discharges are likely to be significant, however it was not possible to accurately estimate this from the reviewed data (e.g., lack of flow data to calculate load). Given the geology of the lake catchments, groundwater is likely to be a highly important but currently unconstrained part of any 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 (Wetzel 2001; Schallenberg & Sorell 2009). No sediment geochemistry investigations appear to have been conducted in either of the two lakes, but lake sediments are likely to have high legacy nutrient contents, reflecting the high primary productivity of both lakes. Collapsing phytoplankton populations (in both lakes) and potentially large fluxes of organic matter from senescing macrophytes (in Lake William) are likely to result in sediments with high organic content and hence, a high sediment oxygen demand. Although shallow lakes are generally considered to be well mixed with oxygenated water columns, short-lived periods of water column stratification can occur (Waters 2016). For instance, Kelly and Waters (2017) observed five separate stratification-deoxygenation events in Lake Oporoa (within the Horizons region) during a single summer monitoring period, and this lake is considerably shallower (maximum depth of 2.5 m). Stratification may occur during periods of quiescence water, or within dense macrophyte beds. Where sediments have a high oxygen demand, deoxygenation of bottom waters may occur very rapidly and result in redox-related nutrient release. Additionally, shallow lakes are prone to sediment resuspension which can increase total phosphorus concentrations and may drive increases in bioavailable phosphorus due to the release of sediment pore water and/or equilibrium dynamics in the water column. The significantly higher measured total phosphorus concentrations in the two lakes relative to modelled inflow concentrations suggests some, or all, of these processes are occurring in these lakes.

Elevated pH (> 9.2–9.5) can also cause phosphorus release from the bed sediments of lakes (Jacoby et al. 1982). Although such high pH values were not evident in data sets from these lakes, spot monitoring data are notably insufficient in their resolution to detect pH-related nutrient release events in shallow lakes, which can be very dynamic in their water quality conditions (Gibbs et al. 2015; Kelly & Waters 2017).

Effects of fish on internal load

Some fish species also have the potential to promote nutrient recycling within lakes. This may occur due the physical release of nutrients by excretion in forms which are more bioavailable for phytoplankton uptake, or the transfer of nutrients 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) and it is worth noting that these fish are present in similar lakes relatively nearby (e.g. tench and rudd in Lake Waitawa and koi carp in Horowhenua). However, the potential for fish to influence nutrient recycling in Lakes Waipu and William is unknown due to the absence of fish survey data.

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 the *Dolichospermum, Microcystis* and *Aphanocapsa* species, which are dominant in these lakes, can fix atmospheric nitrogen and thrive in conditions with low N:P ratios. Provided some phosphorus is available (e.g. from internal loading processes) this allows cyanobacteria to bloom even when nitrogen concentrations are relatively low. It is unknown whether the *Dolichospermum, Microcystis* and *Aphanocapsa* in the dune lakes reviewed here are capable of fixing nitrogen. This could be assessed relatively simply by identifying the presence and abundance of heterocytes in their filaments.

Fish populations in lakes may also have significant trophic impacts on phytoplankton populations due to predation of zooplankton grazers. Perch, which commonly form stunted populations of small fish in New Zealand (Duncan 1967), are among the species known to have this effect due to juveniles consuming zooplankton (Duncan 1967; Attayde & Hansson 2001). Although there are no records of perch in the two lakes reviewed, they are present in other nearby lakes in the regions (e.g. Lakes Alice Dudding, Wiritoa, Pauri, Waitawa). No data have been reviewed on zooplankton communities in the two lakes and hence as with the effect of fish feeding on internal nutrient cycling, it is impossible with the current data to gauge the trophic effects of fish predation of zooplankton. Further food web analyses, including fish and zooplankton surveys would provide insight into the relative importance of the control of exotic fish in these lake systems.

Lake Waipu is already in a largely non-vegetated, phytoplankton-dominated state. *Egeria densa,* the invasive species dominant in Lake William, is well known to be associated with cyclical collapses of macrophytes (Schallenberg & Sorrell 2009) and this indicates that this lake may also be at risk of 'flipping' to a phytoplankton-dominated state. In Lake Horowhenua, seasonal senescence of macrophytes is strongly linked to nutrient cycling (Gibbs 2011) and restoration measures in that lake include macrophyte harvesting (de Winton et al. 2015). The current macrophyte data set is too sparse to assess whether periodic or seasonal dieback of lake macrophyte populations occurs in Lake William, 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) for macrophyte loss (Kelly et al. 2013), which is significantly exceeded in both the reviewed lakes. Therefore, Lake William appears to be predisposed to the collapse of macrophytes and hence to 'flipping' to a phytoplankton-dominated state.

3.3. Knowledge gaps, recommendations for research and monitoring

The data available for the shallow dune lakes reviewed in this report allow 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 sub-sections.

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 each lake from sediment flux rates and anoxia/pH patterns. Recent sonar transect data are available for Lake Waipu and have been processed into map form (Appendix 2). If not already completed, sonar surveys and data processing should be conducted for Lake William and any other shallow lakes targeted for restoration. 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, lake bathymetry will be required for lake restoration planning where not already conducted. Publicly available data sources such as 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 2015 to 2018 and are only collected on a quarterly basis. The data collected at each sampling are comprehensive and provide useful insight into nutrient and phytoplankton dynamics, but 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. In shallow lakes, water column stratification and deoxygenation as well as variation in pH can be highly dynamic and, in some cases spatially discrete, but nonetheless important for nutrient dynamics. Deployment of temperature, dissolved oxygen and pH data loggers is essential to capturing spatial and temporal variability and should be undertaken at each of the sampling locations in the lakes.

3.3.4. External nutrient loading

Beyond high level CLUES modelling, the loading of nutrients from catchment to lake is poorly constrained for both 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

During the LakeSPI surveys a large number of swans were noted in Lake William and bird excreta may be a significant source of nutrients to either lake. Previous information for the Ashburton basin suggests that P-loading from birds could account for as much as 10% of the lake external P-load (Kelly et al. 2014). No data are available to quantify such a loading source in the lakes reviewed. 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 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 significant source of nutrients to the lake water column of these shallow 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 lake bed 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, high resolution data logging of temperature, dissolved oxygen and pH, parameters which may directly affect internal loading potential, is critical. This will inform 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.
- Sediment-to-water column 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. Such rates can then be combined with the data on the areal extent of deoxygenation and elevated 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 8 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 the 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 2017 in Lake Waipu provides a potentially useful snapshot of vegetation biovolumes and coverage in this sparsely vegetated lake. This rapid monitoring method could be used as a means of assessing seasonal changes in macrophyte biomass, and determining whether annual dieback is likely to be promoting water column conditions that drive internal nutrient loading such as pH increases or deoxygenation in bottom waters. This method should be utilised in the other lakes 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

No data exist on fish populations in the lakes. It is uncertain if this denotes fish absence or the lack of survey effort. 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 (see further discussion below).

The effect of exotic fish on the nutrient dynamics of the lake food webs is currently unquantified but has the potential to have a significant effect on 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 Horizons’ in-house laboratories (weekly samples) with quarterly samples analysed by Cawthron phytoplankton laboratories. This creates issues in comparing 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 could 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 enriched treatments (+N, +P, +N &+P, control) for a range of lakes in the region.

Some cyanobacterial species, such as *Dolichospermum* and *Aphanocapsa* are capable of fixing atmospheric nitrogen and contributing to nitrogen loads in the lake. No data are currently available on nitrogen fixation in the lake. 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, 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 which 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

A number of data gaps exist in the current understanding of lake and catchment processes that control water quality in the two case-study dune lakes. Monitoring to fill these 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 that Horizons must manage. An understanding of the relative importance of these processes is an important consideration prior to implementing management interventions to stop the decline and improve ecological health of the lakes.

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

- Surface and groundwater monitoring and modelling to enable external mass balance modelling of external nutrient loads. This would include inflow water quality monitoring to assist in validating land-use model (e.g. CLUES) nutrient load predictions. Targets for external nutrient load reductions need to be clearly defined to enable goals to be set for catchment land-use management initiatives.
- Adoption of high-frequency instrumentation (thermistor chain, 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).
- One-off investigations of sediment geochemistry investigations to determine the likely extent and rate of internal loading of nutrients from sediments during anoxic or high pH events.
- 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.
- Intensifying lake water quality monitoring to a monthly time-scale to enable time-trend analyses and improve the resolution of seasonal variation.
- One-off investigations into seasonal nutrient status of a few priority lakes in the region including monthly nutrient ratios and nutrient bioassays.
- 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).
- Implement 5-yearly macrophyte surveys to gain an understanding of the macrophyte trends and, where the lake is vegetated, risk of collapse, and exotic incursions (LakeSPI methodology + side-scanning biovolume survey in late summer).
- Paleolimnological investigations at a few priority lakes to evaluate reference conditions for dune lake types in the region and paleo-history of water quality.

- Waterbird counts on high usage lakes to quantify TN and TP loading by birds
- Inclusion of heterocyte counts on quarterly cyanobacteria analyses over a year of monitoring as an indication for N-fixation potential in monitored lakes.

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 that are essential to successful planning for lake restoration.

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APPENDICES

Appendix 1. Biodiversity values in the Water Management sub-zones containing Lake William.

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. Lake William is highlighted. 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 Lakes) is probably the most highly whitebaited stream (aside from the mainstem of the Whanganui River) in the Whanganui region (J. Campbell, pers com). • Two nationally threatened species: New Zealand dabchick (weweia) and 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 Koitiata 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 Waipu.

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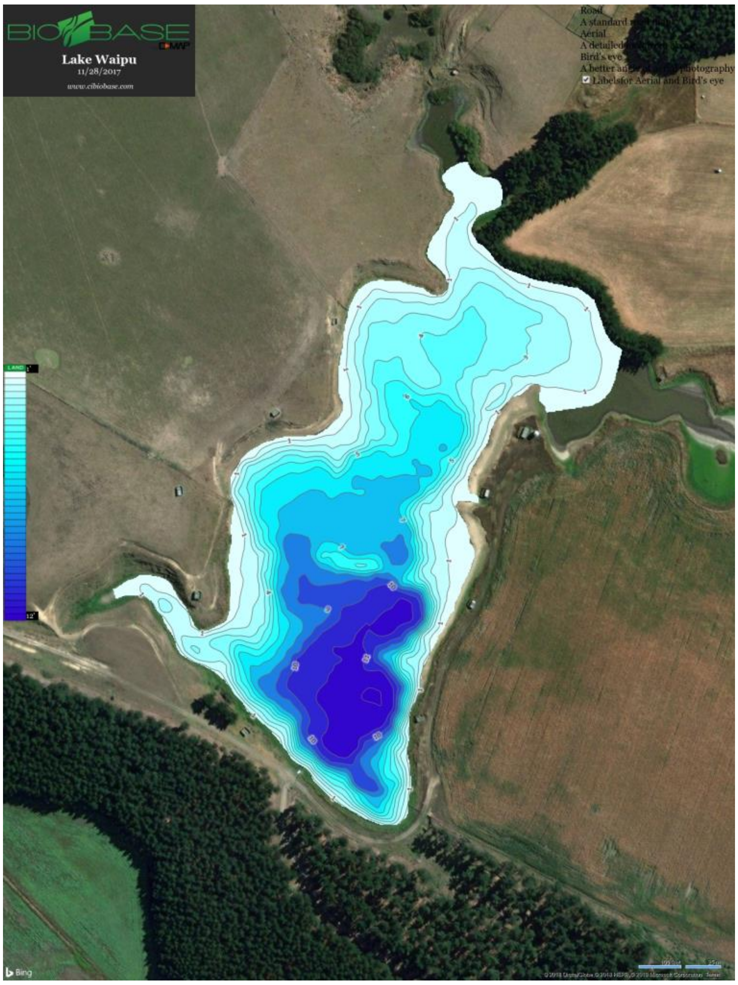


Figure A2.1. Bathymetric map of Lake Waipu produced from sonar transect data (supplied by Horizons, L. Brown, pers. comm. 2018).

Appendix 3. Land-use maps for the catchments of Lakes Waipu and William, generated using the CLUES model.

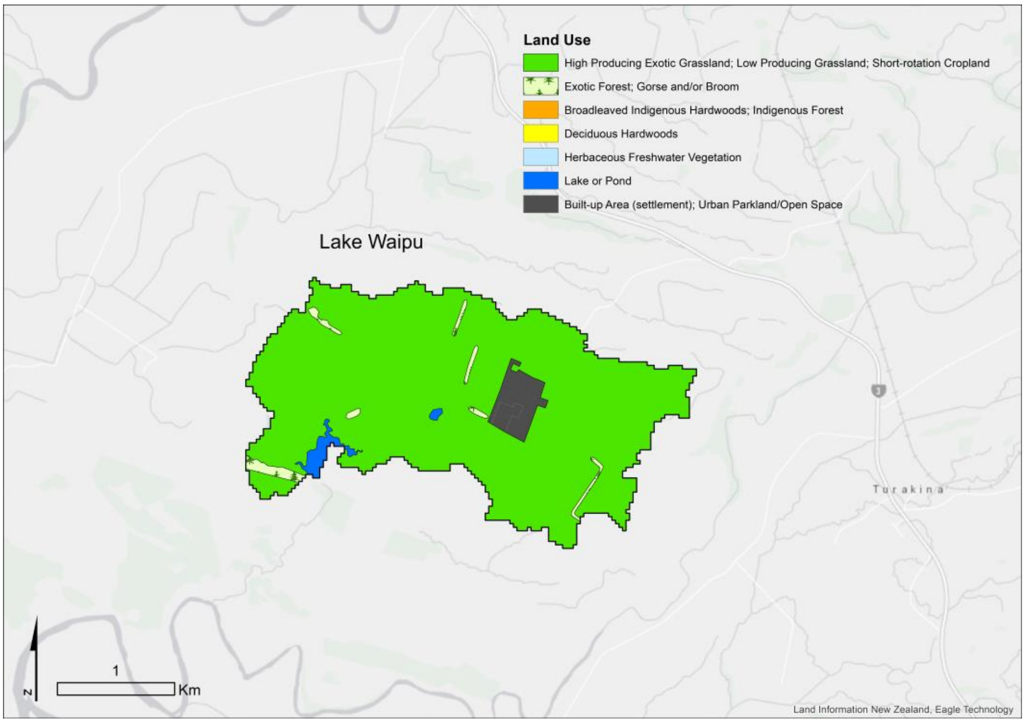


Figure A3.1. Land-use map for the Lake Waipu catchment generated using the CLUES model (Woods et al 2006).

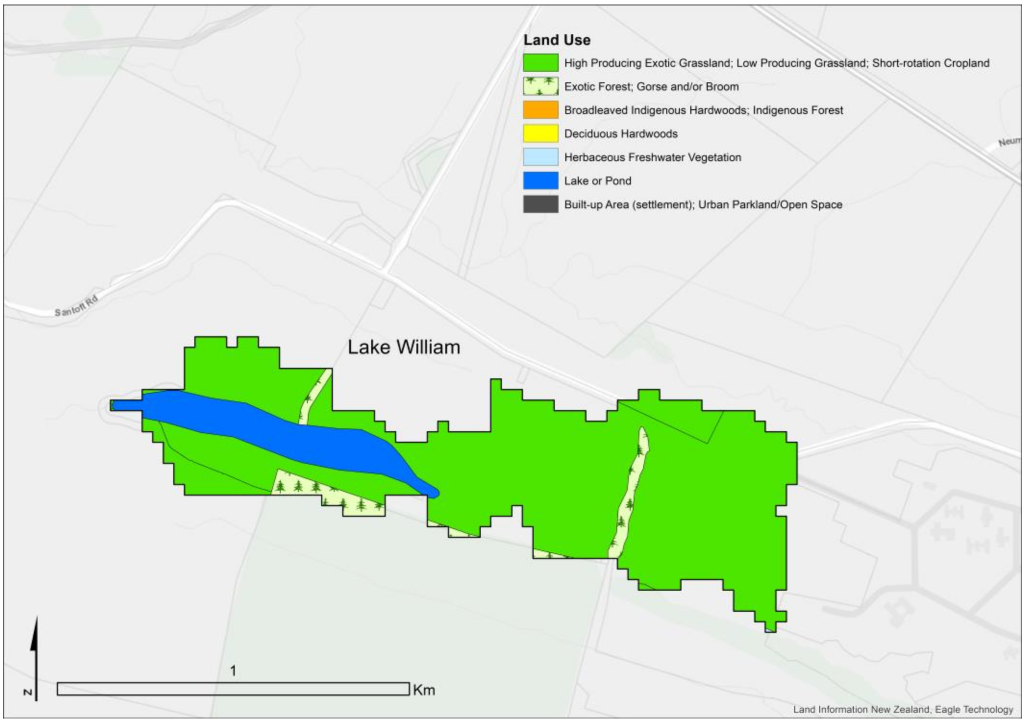


Figure A3.2. Land-use map for the Lake William catchment generated using the CLUES model (Woods et al 2006).

Appendix 4. Water quality monitoring data availability for Lakes Waipu and William for the period 2015-2018. (information supplied by Horizons, L. Brown pers. comm. 2018).

Lake	**Site**	**Water column position**	**Dates covered**	**Sampling interval**	**Parameter suite (see table footnote)**
Waipu	Comp[1]	epilimnion	Oct 2015-Mar 2018	quarterly	A
	1	epilimnion	Oct 2015-July 2017	quarterly	B
	2	epilimnion	Oct 2015-July 2017	quarterly	B
	3	epilimnion	Oct 2015-July 2017	quarterly	B
William	Comp[1]	epilimnion	Dec 2015-Mar 2018	quarterly	A
	1	epilimnion	Dec 2016-Jul 2017	quarterly	B
	2	epilimnion	Dec 2015-Jul 2017	weekly	B
	3	epilimnion	Dec 2015-Jul 2017	quarterly	B

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.

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 (Oct 2015 only), temperature, dissolved oxygen, conductivity, pH, chlorophyll-*a*.

Appendix 5. Horizons Regional Council Lake Monitoring sample sites in Lakes Waipu and William.

Lake Waipu

Site 1. WGS84: -40.043009 175.156932
Site 2. WGS84: -40.044016 175.156233
Site 3. WGS84: -40.044746 175.155958

Lake William

Site 1. WGS84: -40.123310 175.313462
Site 2. WGS84: -40.122894 175.311067
Site 3. WGS84: -40.122528 175.308906

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^{-1}.[a] *Situation 2:* The biovolume equivalent for the combined total of all cyanobacteria does not exceed 0.5 mm^3 L^{-1}.	• 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^{-1} of potentially toxic cyanobacteria (see Tables 1 and 2); **or** *Situation 2[c]:* 0.5 to < 10 mm^3 L^{-1} 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^{-1} total microcystins; **or** biovolume equivalent of ≥ 1.8 mm^3 L^{-1} of potentially toxic cyanobacteria (see Tables 1 and 2); **or** *Situation 2[c]:* ≥ 10 mm^3 L^{-1} 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 (eg, 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^{-1} biovolume threshold (i.e., show that no toxins are present; and show that residual cyanotoxins are not present when a bloom subsides).

Appendix 7. A summary of macrophyte vegetation survey data for Lakes Waipu and William. (Data from Burton 2017).

Lake Waipu

LakeSPI data

Date	Lake SPI %	Native Condition %	Invasive Impact %	Native		Invasive	
				Type	Max depth (m)	Type	Max depth (m)
Nov 2015	Non-vegetated			*Potamogeton ochreatus* *Stuckenia pectinata* *Glossostigma diandrum*	< 1	*Potamogeton crispus*	0.8

Non-LakeSPI data

Date	Native		Invasive	
	Type	Max depth (m)	Type	Max depth (m)
2003	*Potamogeton ochreatus* *Stuckenia pectinata* *Glossostigma diandrum* *Lilaeopsis novae-zelandiae* *Ludwigia palustris* *Ruppia polycarpa*		*Potamogeton crispus*	

Lake William

LakeSPI data

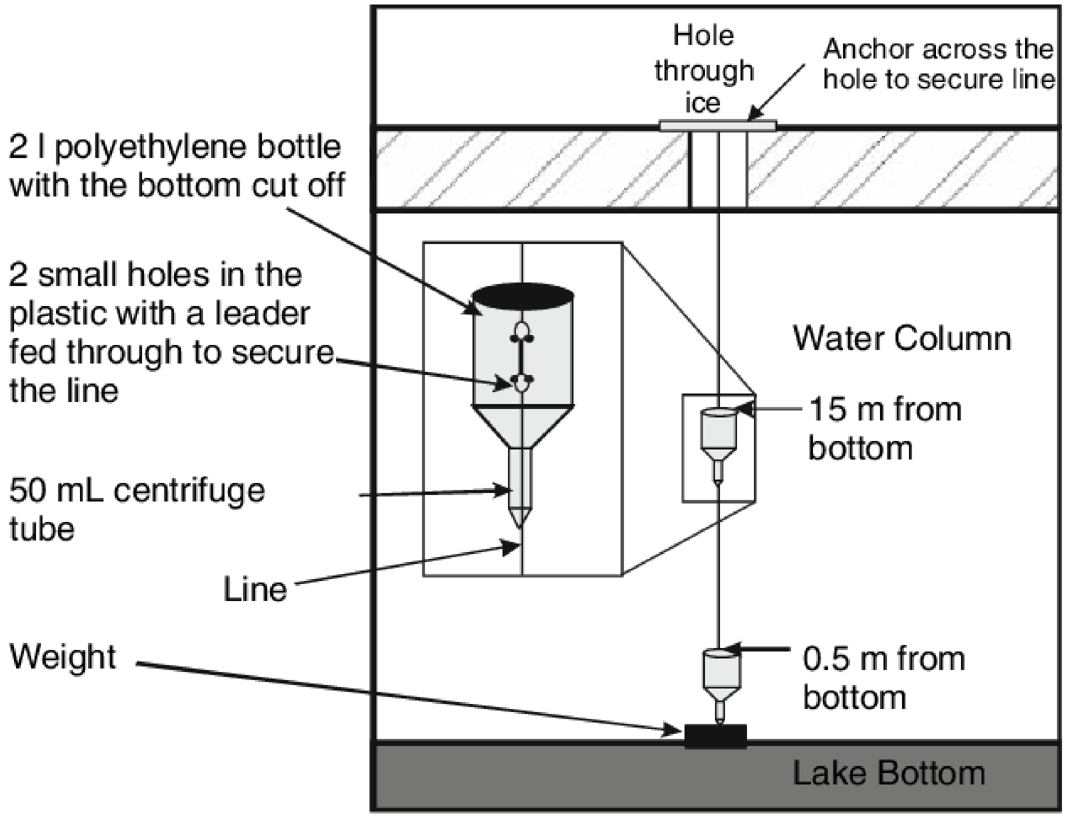
Date	Lake SPI %	Native Condition %	Invasive Impact %	Native		Invasive	
				Type	Max depth (m)	Type	Max depth (m)
Nov 2015	Poor 11	0	93			*Egeria densa* *Elodea canadensis* *Potamogeton crispus*	6

Non-LakeSPI data

Date	Native		Invasive	
	Type	Max depth (m)	Type	Max depth (m)
2003	*Potamogeton ochreatus* *Glossostigma elatinoides* *Lilaeopsis novae-zelandiae*		*Egeria densa* *Potamogeton crispus*	1.5

Appendix 8. 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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