Opportunities to Address Water Quality Issues in Lakes Wiritoa and Pauri

June 2013

Horizons Report 2013/EXT/1327
Envirolink 1283-HZLC96

Prepared for:

Dr Jon Roygard
Freshwater and Science Manager
Horizons Regional Council
Palmerston North

June 2013
Report No. 2013/EXT/1327
ISBN 978-1-927250-30-3

Prepared by:

Max Gibbs & Paul Champion
National Institute of Water & Atmospheric Research Ltd
Gate 10, Silverdale Road
Hillcrest, Hamilton 3216
PO Box 11115, Hillcrest
Hamilton 3251
New Zealand

Phone: +64-7-856 7026
Fax: +64-7-856
Email: max.gibbs@niwa.co.nz

Report No: HAM2013-053
Project: ELF13226

CONTACT	**24 hr Freephone 0508 800 800**		**help@horizons.govt.nz**		**www.horizons.govt.nz**
SERVICE CENTRES	**Kairanga** Cnr Rongotea and Kairanga-Bunnythorpe Roads Palmerston North **Marton** Hammond Street **Taumarunui** 34 Maata Street	**REGIONAL HOUSES**	**Palmerston** North 11-15 Victoria Avenue **Wanganui** 181 Guyton Street	**DEPOTS**	**Levin** 11 Bruce Road **Taihape** Torere Road Ohotu **Woodville** 116 Vogel Street
POSTAL ADDRESS	Horizons Regional Council, Private Bag 11025, Manawatu Mail Centre, Palmerston North 4442				F 06 9522 929

Opportunities to address water quality issues in Lakes Wiritoa and Pauri

Prepared for Horizons Regional Council

June 2013

Authors/Contributors:
Max Gibbs
Paul Champion

For any information regarding this report please contact:

Max Gibbs
Limnologist and Environmental Chemist
Freshwater Ecology
+64-7-856 1773
max.gibbs@niwa.co.nz

National Institute of Water & Atmospheric Research Ltd
Gate 10, Silverdale Road
Hillcrest, Hamilton 3216
PO Box 11115, Hillcrest
Hamilton 3251
New Zealand

Phone +64-7-856 7026
Fax +64-7-856 0151

NIWA Client Report No:	HAM2013-053
Report date:	June 2013
NIWA Project:	ELF13226

Cover Photo by Max Gibbs: Lake Pauri viewed from the Pauri Road access to the prison.

Contents

Tables

Figures

Reviewed by

Dr Dave Rowe

Approved for release by

D. Roper

Formatting checked by

Executive summary

Horizons Regional Council (Horizons), with funding from Envirolink contract 1283-HZLC96, has asked the National Institute of Water and Atmospheric Research (NIWA) to collate and review the information from historic investigations and other relevant research into the water quality of Lake Wiritoa and Lake Pauri. Despite a sizable programme by Horizons to protect these lakes over the last 10 years, the mitigation measures implemented, including elimination of direct stock access to the lakes with exclusion fencing, and reduction of bank erosion and groundwater nutrient seepages into the lakes through planting and restoration of riparian buffer zones, have not fixed the algal bloom problem. Consequently, the aim of this review is to identify the likely causes of water quality degradation and assess options for addressing water quality issues through:

- Actions in the catchment to improve water quality.
- Remedial actions within the lakes.
- Design of water quality monitoring programmes to provide the data required to assess the efficacy of management strategies implemented and long-term information about these lakes.

Within this context, this report provides an overview of all available data and information on the water quality, and the changes that have affected that water quality, in these two lakes from 1974 to the present day. It also identifies gaps in the data. The assessment of options for remediation of the water quality in these lakes draws on the authors' experience from contemporary studies and scientific literature on lake restoration in New Zealand and overseas.

Data Review

Although these lakes have been sampled periodically since 1974, the only true monitoring programme has been the bathing beach monitoring since 2005. Consequently water quality data are minimal. For example there was only one set of chlorophyll *a* data for the lakes and they were taken in 1982. However, given the available data, including a six-month period of more detailed measurements over summer 2007/2008, it is apparent that the water quality in both lakes has deteriorated substantially since 1982. The trophic level index (TLI) for Lake Wiritoa changed from 3.94 in 1982 (Mesotrophic) to around 4.9 in 2008 (Eutrophic). For Lake Pauri, the TLI changed from 4.19 in 1982 (Eutrophic) to around 7.2 in 2008 (Hypertrophic) making it one of the worst lakes in terms of water quality of any monitored lake in New Zealand. The recent TLI values are for summer 2007/2008 only, not a full year.

The cause of the degradation of both lakes can be attributed to the conversion of native vegetation surrounding the lakes to pasture and the effects of farming over the last 150 years including historical landuse practices (tillage and top dressing) allowing sediment and nutrients to wash into the lakes. There are still possible wastewater irrigation issues and questions about land disposal of septic tank and treated effluent within the catchment that need further investigation.

The surface water nutrient concentrations in Lake Wiritoa are only around 10% of those in Lake Pauri. The reason for the higher nutrient loads in Lake Pauri is uncertain but, in part, may be attributed to wind-induced internal waves (seiches) that may form due to the orientation of the lake to the prevailing wind and the lake bed morphometry. These lake currents may be continuously disturbing the sediments and causing nutrient release into the upper water column during summer stratification. Internal waves are less likely to develop in Lake Wiritoa because the lake is narrower with more protection from the wind, and the bed morphometry has features which would disrupt the circulation currents that are fundamental to an internal wave, thereby reducing its action on the lake bed. In this lake, nutrients may be stored in the lake bed sediments to a greater extent.

The catchment, as defined by land surface topography, for Lake Pauri is estimated to be 1515 ha, excluding the lake. Lake Pauri flows into Lake Wiritoa, which has a further 277 ha of direct catchment. Despite the large nutrient load from Lake Pauri, Lake Wiritoa has a much higher water quality. This can be attributed to the smaller direct catchment area plus the nutrient filtering power of the extensive submerged macrophyte beds in the south end of Lake Wiritoa where the outflow from Lake Pauri enters the lake.

The macrophyte communities in both lakes have changed over time from largely pond-weed type communities in the 1970s to dense exotic macrophyte dominance by the early 2000s. Circumstantial evidence indicates that the introduction of these pest species was associated with boating. While these exotic macrophytes can produce surface-reaching nuisance growths in summer, they perform an important part of the current lake ecosystems providing refugia for juvenile fish and zooplankton, and stripping nutrients, especially inorganic nitrogen species from the water column.

Remediation opportunities and recommendations

Future management strategies for these lakes should have goals and these should include indicators of success to ensure that those goals have been achieved. The following topics could provide a basis for management strategies to improve water quality. We recommend that they are investigated further for adoption in full or in part.

Catchment

1. Farm management plans (FMP) should be developed to reduce nutrient discharge to land. They should also cover land disposal by irrigation or infiltration near the lakes and especially between the two lakes. Whey should not be used on the land near or between the lakes.

2. While there are presently no dairy farms in the catchments of these lakes, any new conversions should be subject to rules and FMPs.

3. These FMPs should include plans to minimise the use of fertiliser near the lakes or the stream channels draining into these lakes.

4. The FMPs should include plans for sediment reduction through best farming practices, including using non-tillage versus tillage options where appropriate.

5. The small embayments or expansions of the stream channel width at the mouths of stream inflows (both permanent and ephemeral) could be used as sediment traps to reduce or prevent sediment entering the lakes during rainfall events.

6. Stock exclusion fences should be maintained.

7. Riparian buffer zone plantings should be maintained and enhanced.
8. The connecting stream running between the two lakes and the outlet stream from Lake Wiritoa should be managed to have one-way flow only from Lake Pauri into Lake Wiritoa.
9. The connecting stream running between the two lakes needs to be shaded with evergreen native trees which will reduce weed and grass growth in the water and on the stream banks. This will also reduce the incidence of frosts cooling the stream water so that it plunges as a density current to the bottom of Lake Wiritoa.
10. The stormwater from the prison complex should not be discharged into the connecting stream where the nutrients will have an effect on these lakes. The stormwater pipes should be re-aligned along the side of the road to the outlet stream to discharge downstream from Lake Wiritoa.
11. Domestic septic tanks and disposal fields (including the camp sites) should be inspected to determine whether they are a problem, or not. As a general rule domestic septic tanks should be inspected at least once every three years and regularly maintained. Replacement or new septic tank disposal systems should be multiple chamber systems with a denitrification stage before discharge to subsurface dripper irrigation fields.
12. The direction of flow of infiltrating effluent water from the prison wastewater treatment plant should be determined and action taken to divert the direction of flow away from the lakes should it be found to be moving towards the lakes.
13. Where practical, deciduous trees e.g., willows and other broad leaf, should be removed close to the lake to reduce leaf drop into the lake as a carbon source for oxygen depletion.
14. A windbreak of *Casuarina* trees should be planted across the western end of Lake Pauri. This will reduce exposure to prevailing winds that are thought to play a role in its poorer water quality. However, as the lake is used by sailing schools and others for yachting, an investigation of internal lake currents is needed first and consultation is recommended.
15. The outflow from Lake Pauri could be diverted directly to the outflow stream from Lake Wiritoa to reduce the nutrient load on that lake.

In lake management strategies

In lake management strategies require more data (preferably a years' worth) to enable informed decisions about what could improve water quality and what would not. Based on the available data, potential strategies that could be tested include:

- Aeration for preventing thermal stratification and thus bottom water anoxia with coupled nutrient release in summer in both lakes.

- Engineered structures could be placed on the bed of Lake Pauri to disrupt any lake currents or internal waves that resuspend sediment and release nutrients into the water column.

- The use of phosphorus-inactivation agents to prevent dissolved reactive phosphorus release from the lake beds in summer.

- The use of a flocculent to precipitate cyanobacteria from the water column in spring before they bloom in summer or as a "knock-down" action to allow the bathing beaches to re-open sooner after a bloom has occurred.

Macrophyte weed beds and marginal plants

Although they can be a nuisance obstructing lake access for boats and bathers, the submerged macrophytes play an important role in maintaining the relatively high level of water quality in Lake Wiritoa. Their collapse would result in poorer water quality.

- It is recommended that grass carp are not released in either lake. While they may be capable of reducing the macrophyte biomass, they are indiscriminate feeders and will eventually destroy all macrophytes (native and exotic) turning the lakes from macrophyte dominated, clear-water lakes to algal dominated, turbid lakes.

The data available indicates that both lakes are at or near "tipping points" between these two states.

- The lake access points should be managed, by clearing by using a harvester or selective herbicides to clear only enough of the macrophyte beds to provide that boat access or a clear length of bathing beach.

- The riparian buffer zone plants block the seepage of nutrients in the ground water and prevent bank erosion by wind-waves and boat wakes. They should be protected and not sprayed to provide better lake views or new beach areas.

Monitoring

Water quality monitoring programmes should be designed to assess the efficacy of restoration measures for adaptive management and to provide long-term SOE data to assess trends.

1. A water quality monitoring programme should be established to provide the data required for informed management decisions. The sampling site for each lake should be the deepest water and should be marked with a permanent marker buoy. This monitoring is independent of the bathing beach monitoring programme although samples can be collected for both on the same day.

2. The water quality monitoring programmes should be in two parts:
   - <u>The first</u> as a long-term SOE monitoring programme collecting data at 2-monthly intervals over several years. Measurements should include total nitrogen, total phosphorus, water clarity (Secchi depth) and chlorophyll *a* as required for estimating Trophic Level Index (TLI).

- The second is an investigative monitoring programme that is designed to provide short-term information to assess the efficacy of the remediation actions implemented and to identify when the management goal(s) have been met or exceeded. The data from this investigative monitoring programme should be sufficient to allow adaptive management of the remedial action. It should augment the SOE monitoring and should use the same sampling sites and methods plus additional measurements such as dissolved reactive phosphorus and dissolved inorganic nitrogen species. Samples can be collected at the same time as the SOE monitoring but should include more frequent sampling to allow more detailed assessment of changes in lake processes affected by the remediation measures.

3. Lake levels should be measured on every sampling visit. Staff gauges may need to be installed.

4. To obtain better data on thermal stratification (timing, response to wind stress events), thermistor chains could be installed in each lake at the deepest site with temperature loggers staring 1 m above the lake bed and then at 2 m intervals up to the near surface. These thermistor chains would be attached to the marker buoys used to locate the monitoring programme sampling sites. Dissolved oxygen probes could also be included on each thermistor chain at 1 m below the surface and 1 m above the lake bed and timed for synchronous logging with the thermistors, to establish the rate of sediment oxygen demand and the period of low oxygen which may result in nutrient release from the sediments.

   The thermistor chains and dissolved oxygen loggers would be set to record data at 15-minute intervals and would be left in these lakes for a period of at least 12 months. The temperature and dissolved oxygen loggers would be down loaded at 6-monthly intervals and the data compiled in a data base with wind and rainfall records from the Whanganui Airport met station.

If possible, a water quality profiler measuring depth-referenced temperature, dissolved oxygen, conductivity and chlorophyll fluorescence should be used in each lake at one or more sites along the length of the main axis on every sampling visit.

1 Introduction

Despite a sizable programme by Horizons Regional Council (Horizons) to protect Lake Wiritoa and Lake Pauri over the last 10 years, the mitigation measures implemented, including elimination of direct stock access to the lakes with exclusion fencing, and reduction of bank erosion and groundwater nutrient seepages into the lakes through planting and restoration of riparian buffer zones, have not fixed the algal bloom problem. Consequently, Horizons, with funding from Envirolink contract 1283-HZLC96, has asked the National Institute of Water and Atmospheric Research (NIWA) to collate and review the information from historic investigations and other relevant research into the water quality of these lakes in order to identify options for addressing water quality issues. Horizons also seeks advice on options for monitoring lake water quality.

Objectives of this report are to provide information that will enable the community to make sound and informed decisions regarding the future management of the lakes.

Potentially the advice provided may inform or direct:

- Actions in the catchment to improve water quality.
- Remedial actions within the lakes.
- Design of water quality monitoring programmes to provide the data required to assess the efficacy of management strategies implemented and long-term information about these lakes.

Within this context, this report provides an overview of all available data and information on the water quality, and the changes in the lakes and catchments that have affected their water quality since 1974. It also identifies gaps in the data. The assessment of options for remediation of the water quality in these lakes draws on the experience from contemporary studies and scientific literature on lake restoration in New Zealand and overseas.

The development of a water quality monitoring programme for these lakes is an essential part of understanding the drivers influencing their water quality and it is also required to fill gaps in the knowledge about these lakes. The design of the monitoring programme is required to provide data that will enable assessment of the efficacy of any remediation actions and allow adaptive management strategies to be developed. It is also required to provide state of environment (SOE) monitoring data for SOE reporting.

On completion of the report, Horizons has requested a presentation by the research experts to Horizons' staff, landowners from around the lakes, Whanganui District Council, and other stakeholders. Horizons specifically request that the report and presentation include the following components:

1. Assessment and interpretation of water quality information.

2. Where possible, an interpretation of water quality state in terms of trophic level index (TLI) and trends.

3. Options for remediation, including options for addressing sediment loads and nutrient sources.

4. Information on how the options relate to specific goals of lake restoration and water quality improvement (e.g., rehabilitation measures that restore the suitability of the lakes to support recreation use / reduction of toxic algal blooms).

5. Recommendations for monitoring with options of different levels of intensity – basic and comprehensive monitoring strategies – identifying the information that is provided under each monitoring option and the information gaps that result with less intensive options.

2 Data review

Lake Wiritoa and Lake Pauri (Figure 1) are valued for both recreational opportunities and for their contribution to the remaining wetland biodiversity in the Manawatu-Wanganui Region. The lakes are home to a variety of rare native birds, including spotless crake and historically were a key location of fresh water mussels (kākahi). The lakes are significant to both Ngati Apa and Tupoho.

Figure 1: Lakes Wiritoa and Pauri showing the inflows, outflows and the short stream linking the two lakes. Stormwater from the Kaitoke Prison discharges into the linking stream between the lakes. Red markers are profiling sites used in 2013. Aerial photo provided by Horizons..

The farm surrounding these lakes was established more than 150 years ago. Early forestry landuse has been cleared and presently, most of the farming around the lakes is cattle and sheep grazing, although there is some cropping (Buckenham et al. 2002). Wanganui prison on the southern side of Lake Pauri has a resource consent to discharge stormwater into Lake Pauri (granted 1998, expires 2013) although the actual point of discharge is into the stream between the lakes (Figure 1). The prison also has a permit to discharge up to 250 cubic metres of oxidation pond treated sludge to Pauri Road land (granted 1993, expires 2013) and had a permit to discharge dewatered oxidation pond sludge onto neighbour's land on Pauri Road (granted 2001, expired 2002) (Buckenham et al. 2002). The effluent water from the wastewater treatment plant is discharged to land on the southern side of the prison.

Although the stormwater discharge is occasionally discoloured leading to suspicion that it might be contaminated with wastewater effluent, assurances have been given from the prison authorities that it is not. Consequently, the deterioration of the lakes is believed to be caused by changing local land uses (i.e., from forestry to farming) (Buckenham et al. 2002).

The lakes have a range of recreational use including swimming, boating, water-skiing, jet-skiing, picnicking, camping, duck shooting and fishing. The lake environment is valuable habitat for a range of birdlife including shoveller ducks, mallard ducks, grey ducks, black swan, pukeko, bittern and white-faced heron. The lakes are also habitat for a range of fish species including common bullies, eels, trout and perch (NZFFDB, pers comm. D. Rowe). Given their low altitude and connection to the sea, they would also be expected to contain smelt, inanga, mullet and kokopu but these species are now rare or absent as a koura (D. Rowe pers comm. A fish survey of Lake Wiritoa was carried out 18-22 April 2005).

2.1 Physical information

Physical (morphological) information on Lakes Wiritoa and Pauri are provided in Table 1, which was extracted from a report by Fowles (1982). However, the catchment area data in the Fowles report (Table 1) does not agree with the visual assessment of the catchment areas (Figure 2) drawn using a recent topographical map and checked against Google Earth satellite imagery. The revised catchment areas have been included in Table 1 below the original data. The revised data show that Lake Pauri has a larger, mostly pastoral catchment and the false colour inset (Figure 2) shows that the land is gently sloping from an elevation of about 100 m above mean sea level above the Whangaehu River to the east to the lake level at 46 m above mean sea level in the west. The lakes are downstream of surface erosion channels which indicate the direction of surface flows (see inset Figure 2).

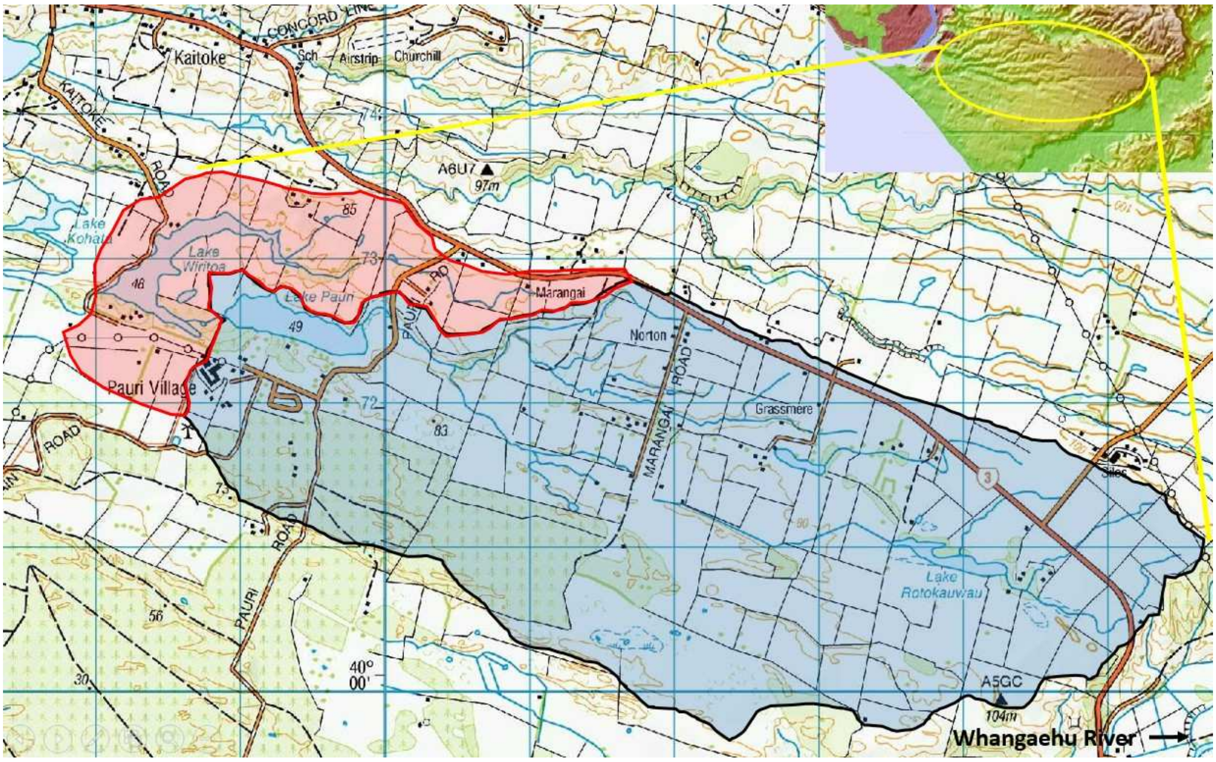

Figure 2: Catchment boundaries of Lake Wiritoa (red) and Lake Pauri (blue) as defined using recent surface topography. The corner inset shows relative elevation above mean sea level in false colour (red-brown = >80 m). Note that the Lake Pauri catchment, including Lake Pauri, is part of the Lake Wiritoa catchment. Grid lines are 1 km.

Lake Wiritoa is a drowned valley closed at the seawards-end by a sand dune. The outlet would cut through this but it was artificially maintained to keep the water level up by a culvert, which was perched in April 2005. The lake has a maximum depth of around 20 m and the deep water extends along the axis from the dune (Figure 3). Lake Pauri is also a dune lake with its maximum depth of around 14 m (Figure 4) close to the outlet end of the lake.

Table 1: Morphological data for Lakes Wiritoa and Pauri. Data extracted from the Fowles 1982. *Catchment area revised from recent maps. Lake Wiritoa catchment includes the Lake Pauri catchment but excludes the area of Lake Wiritoa.

		Lake Wiritoa	Lake Pauri
Surface Area	ha	26.47	23.61
Perimeter	km	5.4	2.875
Length (max)	km	2.03	1.14
Width (max)	m	131	208
Depth - Maximum	m	20.4	14.95
- Mean	m	6.82	6.04
Volume	m^3	1,804,537	1,427,825
Catchment area	ha	1280	560
Catchment area (2013 estimate)*	ha	1814	1515
Shoreline development		4.19	2.36
Altitude (above mean sea level)	m	45	46

Shoreline development, which is the ratio of the length of the shoreline to the length of the circumference of a circle with an area equal to that of the lake, shows that Lake Pauri has a simple form (Figure 4) slightly more complex than an ellipse, which would have a shoreline development of 2. In contrast, Lake Wiritoa, with a shoreline development of 4.19, has a more complex, narrow sinuous shape (Figure 3).

2.1.1 Surface hydrology

Lake Pauri connects with Lake Wiritoa to the west via a short stream (Figure 1). Under normal conditions, water flows from Lake Pauri into the south-eastern end of Lake Wiritoa, which discharges into the outlet stream from the south-western end of the lake. During a site visit on 5th February 2013, the flow was in the opposite direction due to obstruction of the outlet stream from Lake Wiritoa by a slip / bank collapse (Figure 5). Lake Wiritoa also has a small inflow from the smaller north-eastern catchment.

Data from stream gaugings on 25 October and 7 and 26 November 1974 (Table 2) indicate more water leaves each lake than enters, implying that there is a substantial groundwater seepage into these lakes. The sequential measurements also indicate that the surface flows decline towards summer and may dry up. This is also consistent with the changes in lake level in the monitoring data from 1975 to 1981 where recorded variation in water levels were up to 2 m in Lake Wiritoa and 0.95 m in Lake Pauri. A study by James & Joy (2009) found that the outflow from Lake Wiritoa dried up at the lake in summer but emerged further down the stream channel. They also noted that there was a weir installed across the stream bed upstream of where the stream re-emerged.

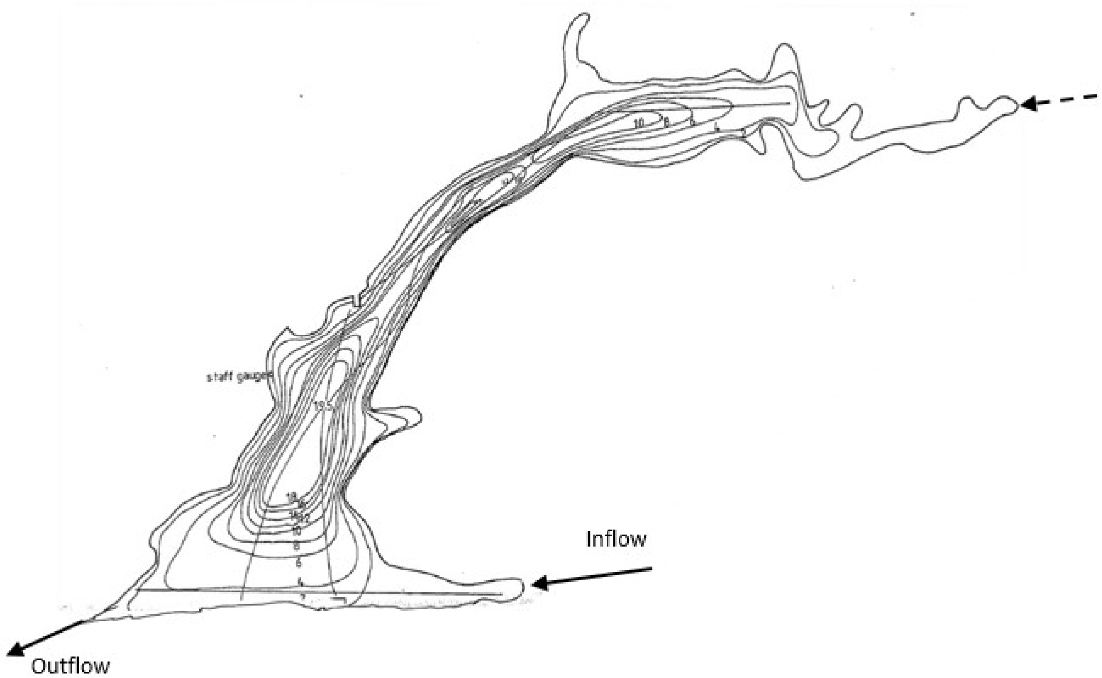

Figure 3: Lake Wiritoa bathymetry. Redrawn from Fowles 1982.

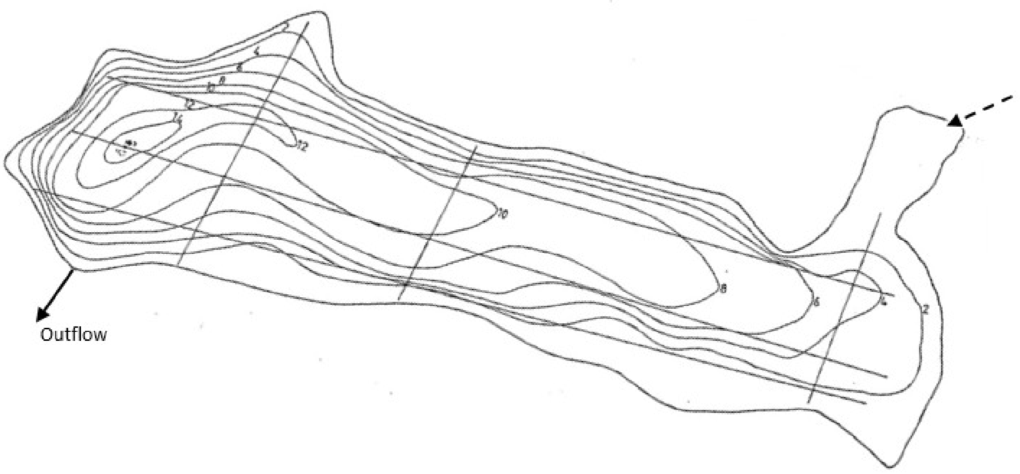

Figure 4: Lake Pauri bathymetry. Redrawn from Fowles 1982.

Table 2: Flow data into and out of Lakes Wiritoa and Pauri. Data from Fowles 1982.

Flows (L/s)	Lake Wiritoa			Lake Pauri		
Date	Inflow	Outflow	Groundwater Streams	Inflow	Outflow	Groundwater Streams
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

These lakes are on highly permeable iron sands which implies that they are likely to be on clay lense geological formations similar to those at Lake Dudding (Figure 6). Because of the permeable sandy soil in the catchment, there will be rapid infiltration of rainfall, along with stock effluent and seepage from domestic septic tanks, which will leach nutrients into the surface groundwater aquifer where they can seep into the lakes. Because the outflow from these lakes is small at best and nil during the summer, the theoretical residence time of water entering these lakes will be very long. Consequently, nutrients in the inflows will accumulate in the lake to augment the internal load.

Figure 5: Collapse of the stream bank partially blocked the outflow from Lake Wiritoa. The sub-soil is black iron sand with a thin layer of soil on top. The blocked stream is covered with duck weed (*Lemna disperma*). (Photo: Max Gibbs 5/02 2013).

Figure 6: Lake Dudding at low water level exposing the hard impermeable clay layer that underlies the lake. (Photo: Max Gibbs 5/02 2013).

Stormwater from the Kaitoke Prison complex on the southern side of Lake Pauri discharges directly into the stream channel between the two lakes via two pipes (Figure 7). Samples taken of the stormwater discharge on 4 February 2013 showed that they were enriched with nutrients (Table 3).

Figure 7: Stormwater drains (2) discharging into the connecting stream between the two lakes from the crossing. A) View east towards Lake Pauri, B) View west towards Lake Wiritoa. The connecting stream was heavily overgrown. (Photos Max Gibbs 5/02/2013).

Table 3: Selected water quality results from the stormwater discharge from the Kaitoke Prison on 5/02/2013. Results from Horizons Regional Council. Highlighted values exceed the POP or ANZEEC standard given. (NO_3-N = nitrate + nitrite; D-Cu = dissolved copper; D-Zn = dissolved zinc).

Test	TSS	Turbidity	E. coli	DRP	TDP	TP	NO_3-N	NH_4-N	TN	TCu	TZn	D-Cu	D-Zn
units	g/m³	NTU	MPN/100	g/m³	g/m³	g/m³	g/m³	g/m³	g/m³	g/m³	g/m³	g/m³	g/m³
Conc.	95	18.1	2600	0.08	0.235	0.354	0.49	0.02	3.97	0.012	0.18	0.0094	0.156
POP or ANZEEC standard			260-550	<0.015	(<0.020)	<0.020	<0.167		<0.337			<0.0014	<0.012

2.1.2 Temperature structure

The temperature structure of the two lakes follows a seasonal cycle of warming in summer and cooling in winter. The temperature range in the surface water was similar in both lakes although the 1974 to 1982 data indicates that Lake Pauri was slightly cooler that Lake Wiritoa (Table 4). More recent monitoring data from November to April in 2007/08 and 2010/11 suggest that the surface temperatures are more similar with <0.5°C difference between the two lakes over the summer months.

Both lakes thermally stratify in summer (Table 4; Figure 8) although the stability of that stratification in Lake Pauri was questioned by Fowles (1982), who suggested that the lake mixed after strong winds and then became stratified again. Unfortunately, the sampling frequency by Fowles (1982) was insufficient to determine whether mixing and breakdown of thermal stratification was a regular occurrence during the summer months, and subsequent monitoring from 2005 to present (Horizons data) did not include bottom water measurements. If we accept Fowles (1982) observations, which are consistent with the exposure of Lake Pauri to predominant south-westerly winds, it is likely that this lake is periodically mixed during summer and should, therefore, be classified as polymictic rather than monomictic.

Table 4: Physical and chemical parameter data summary from the monitoring period October 1974 to March 1982. Data transcribed from Fowles 1982.

		Lake Wiritoa				Lake Pauri			
		Top		Bottom		Top		Bottom	
Parameter	unit	Range	Median	Range	Median	Range	Median	Range	Median
Temperature	°C	9.5 - 24.0	-	9.0 - 22.1	-	9.6 - 23.5	-	9.0 - 20.4	-
Secchi Depth	m	1.55 - 4.2	2.8	-	-	1.0 - 3.0	1.6	-	-
Conductivity (25°C)	µS/cm	220 - 295	270	230 - 315	270	240 - 300	270	240 - 340	280
pH		7.5 - 9.0	7.9	6.8 - 8.5	7.4	7.6 - 9.2	7.8	6.3 - 8.3	7.5
DO	g/m^3	5.8 - 10.1	9.1	0 - 10.3	6.5	6.2 - 10.8	9.2	0 - 10.1	6.9
DRP	g/m^3	0 - 0.01	-	0 - 0.34	0.01	0 - 0.02	-	0 - 0.31	<0.01
NO_3-N	g/m^3	0 - 0.06	-	<0.01 - 0.06	-	<0.01 - 0.35	-	0.02 - 0.35	-
NH_4-N	g/m^3	0 - 0.02	0.005	0.01 - 0.75	0.09	<0.005 - 0.030	0.01	0.025 - 0.460	0.045
Alkalinity [eqv $CaCO_3$]	g/m^3	56 - 78	-	52 - 95	-	57 - 79	-	56 - 106	-
Chloride	g/m^3	30 - 40	34	30 - 44	34	28 - 38	32	30 - 38	32
Sulphate	g/m^3	8.0 - 15.5	-	4.0 - 16.0	-	12 - 22	-	12 - 18	-
Magnesium	g/m^3	28 - 52	38	28 - 48	-	31 - 46	40	30 - 56	-
Calcium	g/m^3	24 - 38	32	22 - 40	-	28 - 40	34	28 - 42	-
Total Hardness [eqv $CaCO_3$]	g/m^3	62 - 78	70	60 - 84	70	66 - 64	72	66 - 92	74
Feacal coliforms	/100 ml	0 - 226	6	-	-	0 - 350	10	-	-
Maximum Depth	m	-	-	18.4 - 20.4	-	-	-	14.0 - 14.95	-
Data from October 1974 to March 1982									

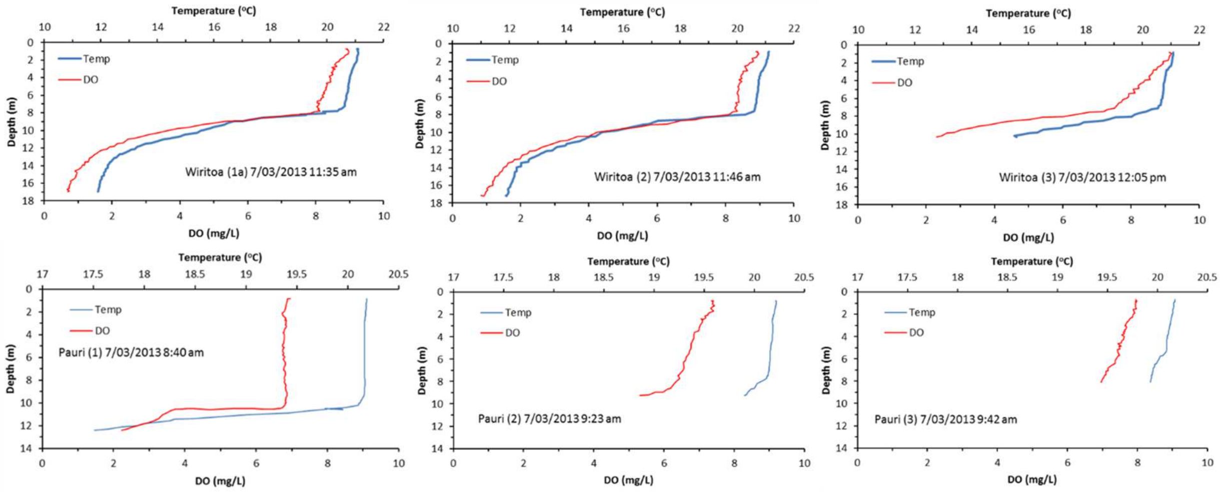

Figure 8: Temperature and dissolved oxygen (DO) profiles at three sites in Lakes Wiritoa (upper) and Pauri (lower) on 7 March 2013. Site locations are indicated on the location map (Figure 1) moving sequentially from 1 to 3 along the lake axis.

Temperature profiles taken from the two lakes in March 2013 (Figure 8) show that, on that day, Lake Wiritoa was thermally stratified with the thermocline at a depth of 8 m while the thermocline in Lake Pauri was at a depth of 10.5 m. These profiles indicate that the pool of bottom water below the thermocline (hypolimnion) in Lake Wiritoa was substantially larger than in Lake Pauri. Estimates based on the bathymetric data (Figure 3; Figure 4) indicate that the hypolimnion holds about 35% of the total volume in Lake Wiritoa compared with only 5% of the volume in Lake Pauri (Figure 9).

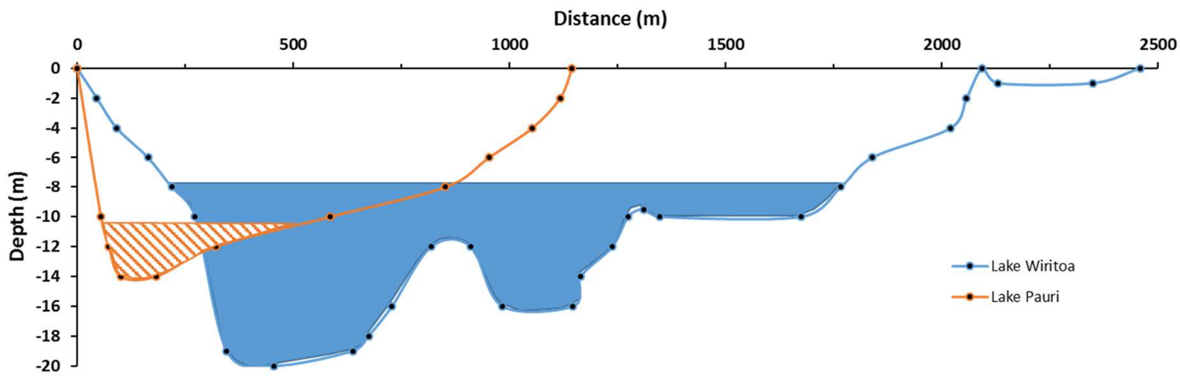

Figure 9: Schematic comparison of water column depths along the main axes of Lakes Wiritoa and Pauri relative to their depths of thermal stratification on 7 March 2013. Coloured areas represent the hypolimnion below the thermocline on that day.

The gentle shelving bottom towards the eastern end of Lake Pauri (Figure 9) implies that the thermocline is likely to “rub” against a large area of lake bed during wind events that start the thermocline moving i.e., an internal wave (seiche). Changing water level in the lake and changes in the depth of the thermocline through summer would affect the total area of lake bed affected by a seiching action. In Lake Wiritoa, a seiching action would have less effect on the lake bed as the thermocline boundary would be in contact with a steeper bed slope and thus a much smaller sediment surface area.

The flow patterns associated with any internal wave in Lake Wiritoa would also be disrupted by the shape of the lake bed (Figure 9). Notwithstanding this, any strong wind event that generates an internal seiche in Lake Pauri is likely to cause a disturbance of the lake sediments in both lakes releasing nutrient-rich pore water into the lake water column and producing an upwelling of bottom water nutrients at the up-wind end of Lake Pauri (Figure 10).

Internal seiche

Seiches are naturally occurring water movements that occur in thermally stratified lakes in response to wind forcing on the lake surface.

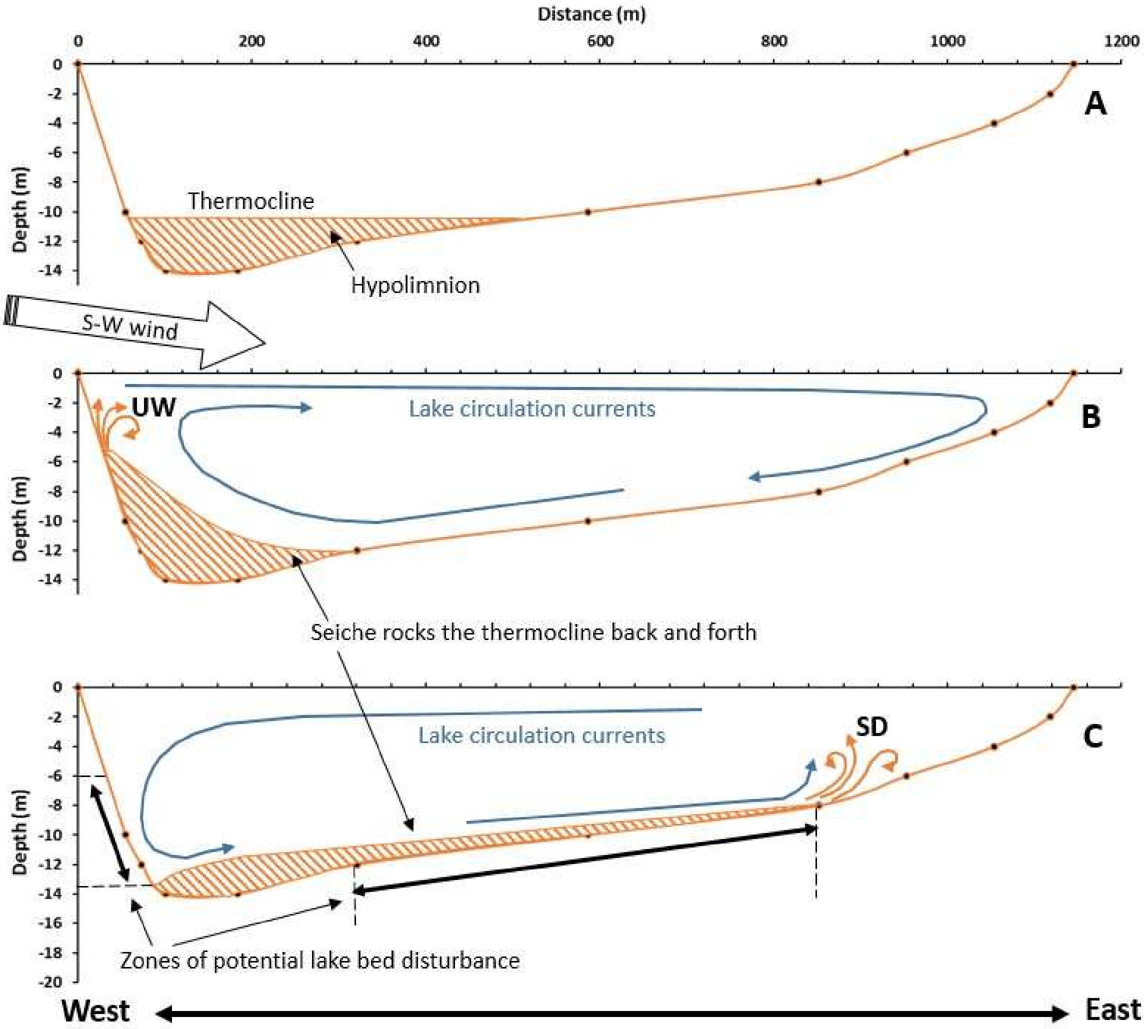

Figure 10: Schematic of how an internal seiche would affect Lake Pauri. UW = up welling zone; SD = sediment disturbance.

In Figure 10A, Lake Pauri is at rest in calm conditions and the thermocline is horizontal. When a strong south-westerly wind blows along the axis of the lake (Figure 10B), the surface water is pushed to the eastern end causing the thermocline to tilt up at the western (up-wind) end. When this happens, nutrients that have accumulated in the hypolimnion can be released in the up welling current that is generated. This is referred to as a “set up”. When the wind stops blowing (Figure 10C), the set up relaxes allowing the water in the hypolimnion to flow towards the eastern end. However, because the flow will overshoot the resting condition (Figure 10A), a bottom current is generated that disturbs the sediment releasing the pore water nutrients into the overlying water. At the end of its eastern travel, the hypolimnetic water will stop and flow back to the west where there will be a smaller overshoot. This rocking action of the thermocline is the internal seiche and it may continue for several days. Each time the lake bed is swept by the seiche current more nutrients are pumped out of the sediment into the water column. The internal seiche is part of the mixing process and may even cause the lake to destratify if it is vigorous enough.

2.1.3 Dissolved oxygen (DO)

Dissolved oxygen data from the 1974 to 1982 monitoring (Table 4) show ranges from 0 mg/L (anoxic) to 10.8 mg/L indicating that the surface waters in both lakes are well oxygenated throughout the year and that the water in the hypolimnion can become anoxic. Horizons data from 2005 to 2013 does not include bottom water DO measurements. The DO profiles collected in March 2013 (Figure 8) show bottom water anoxia at site 1 in Lake Wiritoa and very low DO concentrations (<2 mg/L) at the other two sites and at the deep site, site 1, in Lake Pauri. These data are consistent with the earlier data records (Fowles 1982) and demonstrate that the bottom waters of both lakes become anoxic during summer stratification.

2.2 Environmental data

2.2.1 Plant communities

Environmental data collected in 1974 (Kelly 1978) and subsequently (Fowles 1982; Edwards & Clayton 2002; Rangitikei-Wanganui Catchment Board and Manawatu-Wanganui Regional Council data) indicates that the water quality in these lakes has deteriorated substantially over time, with the development of cyanobacteria blooms. Exotic macrophytes were probably introduced on boat trailers.

Kelly (1978) described a belt of rooted macrophytes around the entire lake comprised of combinations of *Potamogeton crispus*, *P. ochreatus* and *Myriophyllum triphyllum*. Two patches of *Vallisneria australis* (eel grass) were found in Lake Wiritoa, one near the ski club and the other in the north-eastern arm. Some possible plantings of *Nymphaea alba* (water lily) were also found in the north-eastern arm. In clearer areas there were patches of *Ranunculus trichophyllus* and *Ruppia megacarpa*. In deeper water a band of characeans extended down to a depth of 5 m. The most common species was *Chara australis* although a large area of *C. globularis* was found near the lake outlet.

A similar aquatic macrophyte assemblage was found in a belt around Lake Pauri but with a maximum depth limit of 4 m for the characeans. Three patches of *Nymphaea alba* were found, the largest filling the northern arm of the lake. *Nitella* sp. aff*. cristata* was found in the south-eastern section of the lake.

Kelly (1978) noted that the macrophytes appeared to deteriorate in condition during late summer and attributed this to dense growths of filamentous algae or fungus.

Lake edge plants were generally raupo (*Typha orientalis*) with *Ludwigia palustris*, *Phormium tenax* (flax), *Nasturtium officinale* (water cress), *Eleocharis acuta* and *Persicaria* spp. (willow weed) except where grazing by stock limited development of edge vegetation.

This essentially "pond weed" dominated ecosystem has now been replaced with exotic macrophyte species. In 1994, NIWA recorded beds of *Elodea canadensis* for the first time. However, three years later *E. canadensis* was not recorded but the species *Egeria densa* and *Ceratophyllum demersum* (hornwort) were recorded for the first time (Ogle 1997). In 1999 NIWA found all three species forming surface-reaching weed beds, and *P. crispus* and *V. australis* were noted as common around the lake margin. In November 2001 the lake vegetation had undergone extensive vegetation changes with the weed beds entirely dominated by tall dense hornwort beds. In sheltered areas the hornwort beds were surface reaching excluding all other species from around 2 m depth and deeper. *Vallisneria australis* formed a dense narrow fringe around much of the lake margin, occupying the shallow water from around 0.5 m to 1.5 m depth (Edwards & Clayton, 2002). Hornwort is not a rooted macrophyte and was present down to 6.5 m with drifting clumps down to 9 m (Figure 11).

Inspection of the lakes on 5 February 2013 found *Ceratophyllum demersum*, *Elodea canadensis*, and *Egeria densa* in the shoreline drift, and some areas of *Vallisneria australis*. The previously noted patches of *Nymphaea alba* were also apparent. The introduced ferny azolla (*Azolla pinnata*) was collected from Lake Wiritoa. This is a recent invasion with the species first reported here by Ogle (2009 – Te Papa herbarium no. P022442). Filamentous algae found in Lake Wiritoa was a branched green, most likely *Cladophora* sp.

The lake edge plants were dominated by raupo but there was evidence that spraying had been used in Lake Pauri to keep some lake-shore areas clear for lake access (Figure 12).

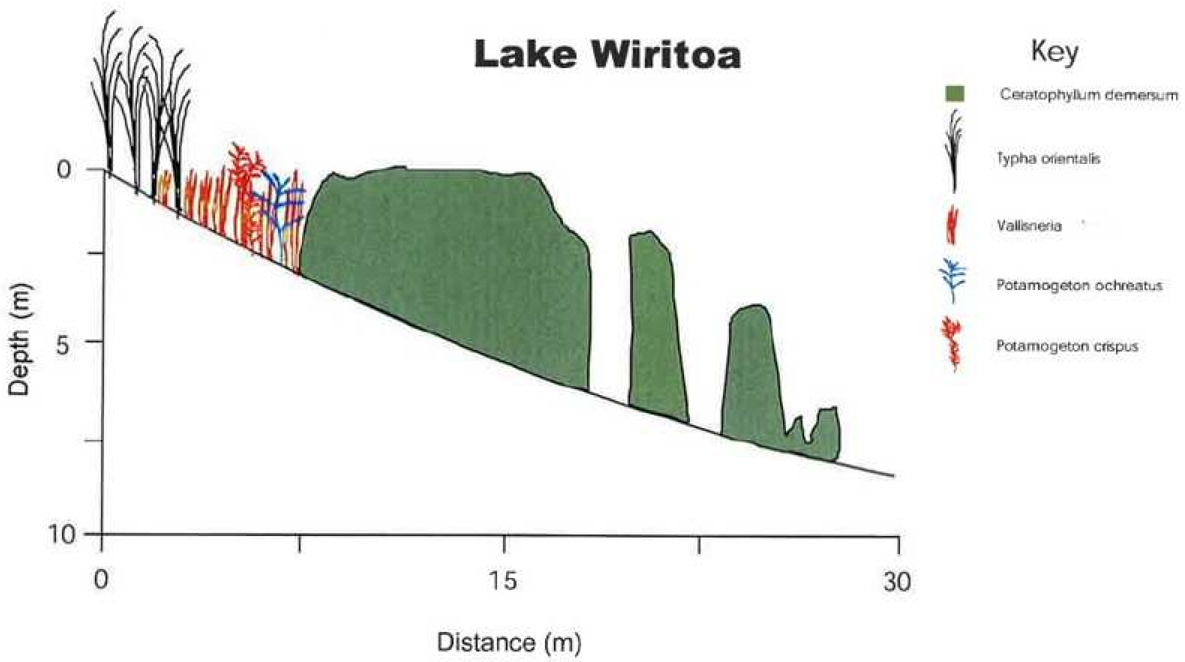

Figure 11: Stylised aquatic vegetation profile for Lake Wiritoa. Redrawn from Edwards and Clayton (2002).

Figure 12: Spay damage to the raupo on the lake margin in Lake Pauri (5/02/2013). The green dense leaf mass of growing plants surrounds most of the lake. (Photo: Max Gibbs 5/02 2013).

2.2.2 Cyanobacteria

Horizons comment that work undertaken in 1982 identified the lakes as being affected by poor water quality and weed invasion and it was recommended that the catchments be fenced and restored as one means of enhancing biodiversity and restoring water quality.

Horizons comment that, although this work has been undertaken, the lakes are still often closed or limited for recreation due to cyanobacteria blooms. Horizons also noted that it was likely that elements of indigenous biological diversity such as fish and aquatic invertebrates (including freshwater mussels) were also compromised at these times.

During the inspection of the lakes on 5 February 2013, patches of *Microcystis* spp. were found in the grass and dead raupo along the edge of Lake Pauri (Figure 13), and a few, more-dispersed cells were found at the boat ramp in Lake Wiritoa.

Figure 13: Cyanobacteria (*Microcystis* sp.) proliferations in the edge waters of Lake Pauri (5/02/2013). (Photos: Max Gibbs 5/02 2013).

Data from Horizons bathing beach monitoring programme (measuring cyanobacteria) weekly during the summer from 2005 to 2009 (Figure 14) show the seasonality of occurrence of cyanobacteria in the two lakes. It is immediately apparent that there were more potentially scum-forming bloom events in Lake Pauri than Lake Wiritoa during this monitoring period.

High cyanobacteria cell counts correlated with high microcystin toxicity with the highest concentration of 3580 mg/m^3 for a cell count of 2.5 million cells/ml (Horizons data). However, a cell count almost six times higher (14.1 million cells/ml) produced a microcystin concentration of 1360 mg/m^3. The higher cell count but lower toxin values preceded the lower cell count but higher toxin values, indicating that the physiological state of the algal cells is important and that toxins are mostly released as the cyanobacteria senesce and die.

Lake Pauri was one of the sampling sites for *Microcystis* sp. used in a study to develop a *Dolichospermum planctonicum* specific TaqMan QPCR assay (Rueckert et al. 2007). That the more easily accessible Lake Wiritoa was not used suggests that Lake Pauri had a higher *Microcystis* biomass.

Unfortunately, despite the monitoring of these lakes since 1974, there are very few chlorophyll *a* data available for Lake Wiritoa or Lake Pauri. Consequently, while the cyanobacteria cell count data reflect the inshore waters associated with bathing areas, it is not possible to assess the relationship between those data and the chlorophyll *a* concentrations, as an indicator of water quality, in the open lake. Chlorophyll *a* data from Vant (1982) are referred to in Smith et al. (1993) indicating open lake chlorophyll *a* concentrations of 4.3 mg/m^3 in Lake Wiritoa compared with 5.5 mg/m^3 in Lake Pauri. This pattern of higher concentrations in Lake Pauri is consistent with the cyanobacteria cell count data (Figure 14). Species composition data were not available.

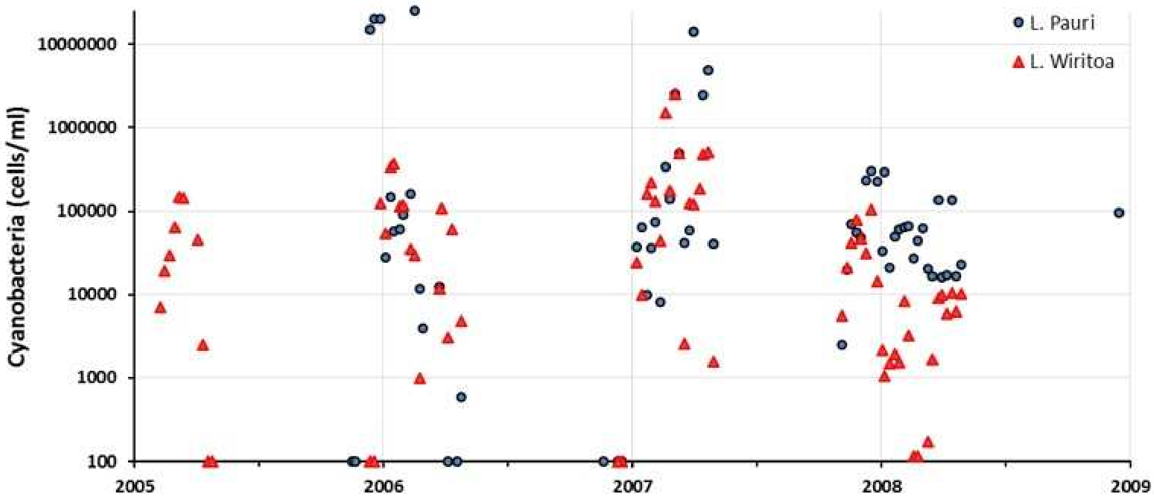

Figure 14: Cyanobacteria cell counts from Lake Wiritoa and Lake Pauri for the period from 2005 to 2009. Bathing water limits are <20,000 cells/ml. (Horizons Regional Council data).

Chlorophyll fluorescence profiles taken in March 2013 show that the algal biomass was spread throughout the upper water column and that there was a small increase at the depth of the thermocline (Figure 15). Chlorophyll fluorescence values are equivalent to chlorophyll *a* concentrations in mg/m^3 at these levels. While the cyanobacteria cell counts from 2005 to 2009 (Figure 14) suggest that there was probably a higher algal biomass in Lake Pauri than in Lake Wiritoa, the chlorophyll fluorescence profiles demonstrate that in March 2013 there was almost three times as much algal biomass in the epilimnion of Lake Wiritoa than in Lake Pauri (Figure 15). Considering the greater mixed depth in the Lake Pauri water column, part of the difference may be due to dilution and/or light limitation to growth in Lake Pauri as the cyanobacteria cells would spend more time in the dark in the deeper water than the equivalent cells in Lake Wiritoa (i.e., this may be a “critical depth” effect).

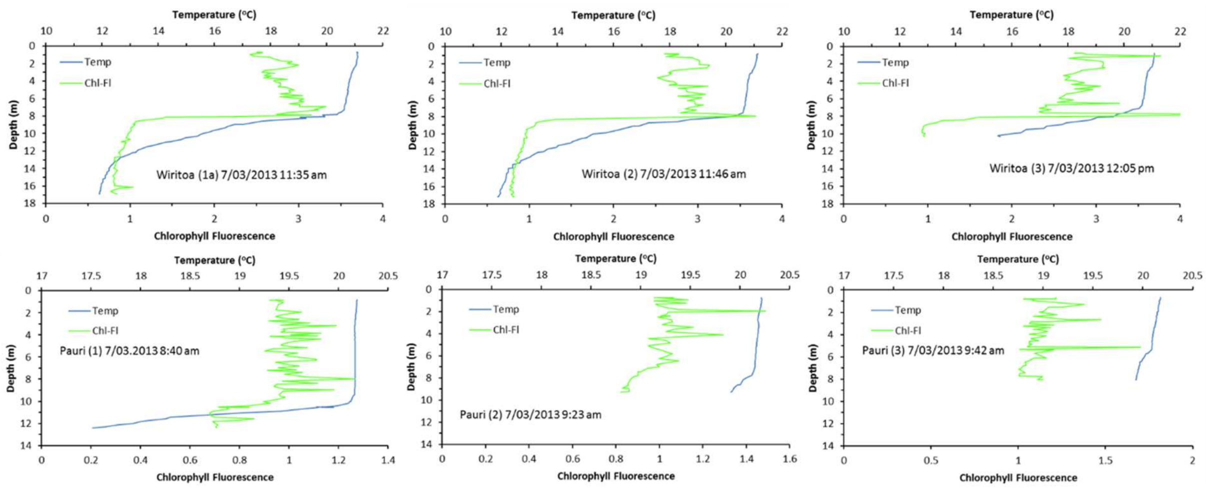

Figure 15: Temperature and chlorophyll fluorescence profiles at three sites in Lakes Wiritoa (upper) and Pauri (lower) on 7 March 2013. Chlorophyll fluorescence values are equivalent to chlorophyll *a* concentrations in mg/m^3 at these levels. Site locations are indicated on the location map (Figure 1) moving sequentially from 1 to 3 along the lake axis.

2.2.3 Nutrients and general water quality data

Overall there is a paucity of water quality data for Lakes Wiritoa and Pauri. Data collected between 1974 and 1982 were occasional (total of 27 data) and have been summarised in the report to the Rangitikei–Wanganui Catchment Board (Fowles 1982) and reproduced in this report in Table 4. Those data included top and bottom sampling and temperature and DO profiles in both lakes.

Data collected between November 1998 and March 2013 for Lake Wiritoa and from November 2005 and March 2013 for Lake Pauri by Horizons Regional Council contain mostly *E. coli,* turbidity and cyanobacteria cell count data, the latter implying they were sampled in the near shore waters at bathing beaches. More intensive monitoring with more parameters was undertaken in both lakes from 5 November 2007 to 28 April 2008 and from 10 November 2010 to 27 April 2011. The data are assumed to be surface open lake water.

Interpretation of the Horizons data relies on the information obtained from the earlier study in terms of stratification and mixing.

Turbidity

The longest continuous data record in Lake Wiritoa is turbidity. In general, high turbidity implies suspended solids either from disturbed sediments, sediment laden inflows or elevated algal biomass. In the case of Lake Wiritoa and Pauri, the turbidity data is mostly associated with algal biomass, in particular cyanobacteria (Figure 16). A linear correlation between cyanobacteria and turbidity data has an $r^2 = 0.95$ for Lake Pauri but only 0.35 for Lake Wiritoa which has fewer very high cell counts or high turbidity. Turbidity data in Lake Pauri compare with the turbidity data in Lake Wiritoa at the same time of year, suggesting that there may have been scum-forming blooms in both lakes. The apparent increase in the peak late summer / autumn turbidity in Lake Wiritoa between 2000 and 2007 (Figure 16) may indicate an increase in the cyanobacteria biomass and therefore, a trend of decreasing water quality over that period. Management strategies of excluding stock from the lake and enhancing lake edge (riparian buffer zone) plantings may have contributed to the lower values from 2008 on in Lake Wiritoa, although there is insufficient data to be certain (Figure 16). There is no evidence of any significant reduction in turbidity or cyanobacteria cell counts in Lake Pauri.

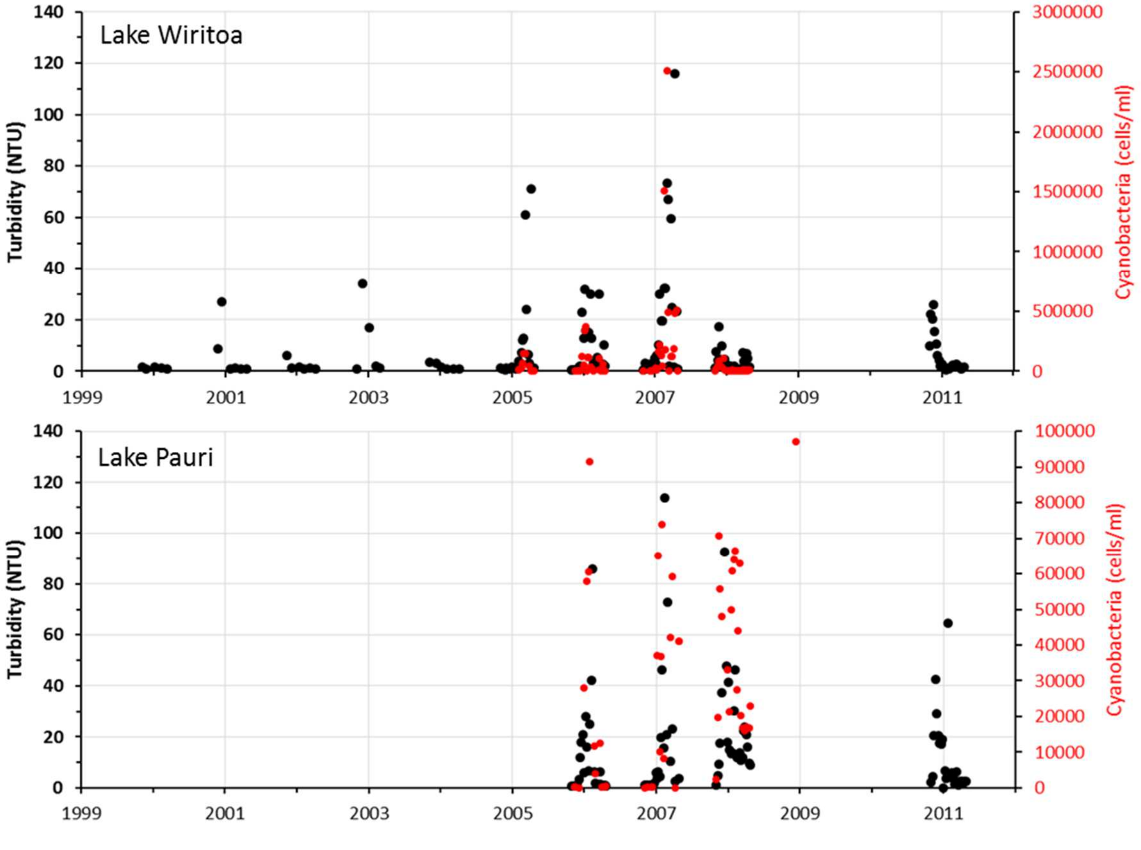

Figure 16: Turbidity (black) versus cyanobacteria cell counts (red) in Lakes Wiritoa and Pauri. Some high cell counts off-scale in Lake Pauri (see Figure 14 for full range). Horizons data.

E. coli

The *E. coli* data are not well correlated with turbidity in either lake, with $r^2 = 0.03$ for both (Figure 17). Elevated *E. coli* values typically occur following rainfall and are associated with runoff washing the bacteria into the lake. The *E. coli* versus turbidity data show instances where the *E. coli* values are high and the turbidity increases subsequently. This would be consistent with surface runoff carrying nutrients as well as the bacteria into the lake. As with turbidity, there may be a reduction in *E. coli* in Lake Wiritoa from 2008, but not in Lake Pauri.

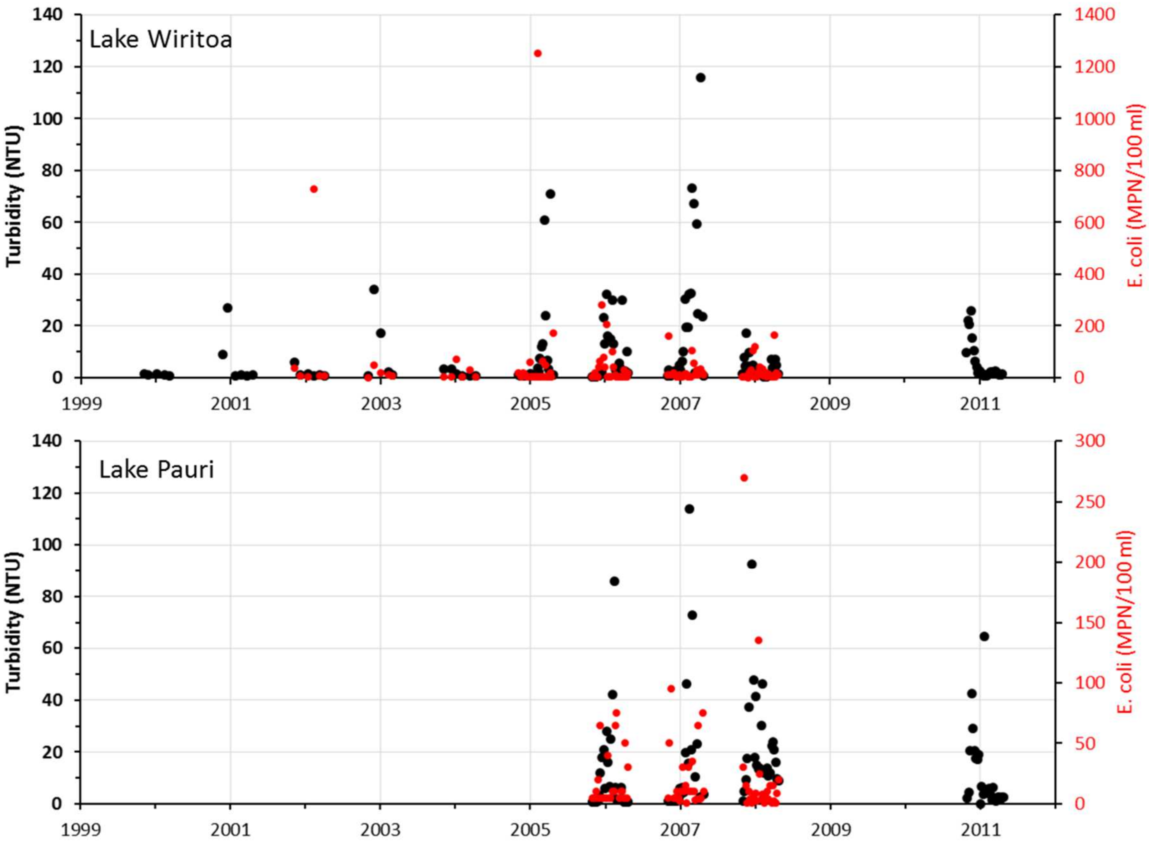

Figure 17: Turbidity versus *E. coli* values for Lakes Wiritoa and Pauri. Horizons data.

Temperature and DO

Surprisingly, the water temperature was not collected regularly in either lake until November 2007 and DO data was only collected for the summer of 2007/2008. These data show a typical summer warming and autumn cooling phase (Figure 18) with similar maxima and minima in both lakes. Unless the DO probe was faulty, a sudden drop in DO concentration may indicate a destratification event. For example, the DO concentration drop corresponding with a temperature drop in late December in both lakes could be interpreted as a wind-induced mixing event which brought low oxygen concentration water to the surface. This scenario is consistent with observations by Fowles (1982) of wind mixing events briefly disrupting thermal stratification or causing an internal seiche with associated upwelling.

The lower DO concentrations in the surface waters during the heat of summer are due to the lower solubility of oxygen in warmer water. Temperature and DO profiles measured in March 2013 (Figure 8) confirm low oxygen or anoxic bottom waters.

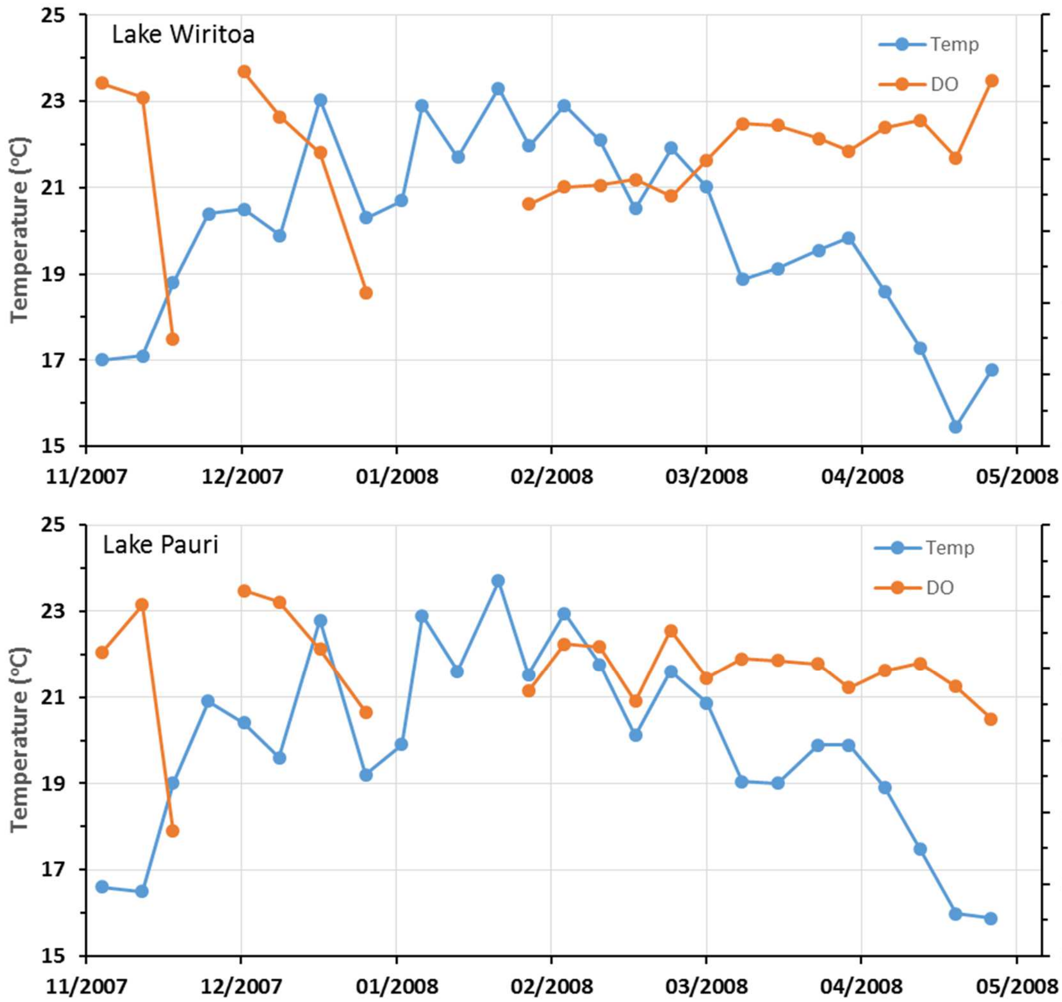

Figure 18: Temperature (blue) and dissolved oxygen (orange) values in Lake Wiritoa and Pauri over the summer of 2007/2008. Horizons data.

Nutrients

Dissolved reactive phosphorus and NO_3-N are key nutrients for plant growth. During the summer of 2007/2008, the surface water nutrient data for Lake Wiritoa were very different to those from Lake Pauri (Figure 19). Concentrations of DRP and NO_3-N in Lake Wiritoa were substantially lower (10%) than those in Lake Pauri and showed no obvious seasonal pattern. The time-series data had occasional blips which are common when dealing with very low concentrations. Such low nutrient concentrations are often associated with surface waters of a stratified lake where the nutrients released from the sediments accumulate in the hypolimnion and can only slowly diffuse up into the surface waters. Fowles (1982) reports hypolimnetic NH_4-N and DRP concentrations of up to 0.75 mg/L and 0.34 mg/L, respectively in Lake Wiritoa, and 0.46 mg/L and 0.31 mg/L, respectively, in Lake Pauri (Table 4). Marginal plants, macrophyte weed beds and phytoplankton quickly utilise all available nutrients in the upper water column (epilimnion), which becomes nutrient depleted. This appears to be the scenario in Lake Wiritoa.

In contrast, Lake Pauri has substantially higher nutrient concentrations in the surface water with a pattern of increasing DRP through summer and autumn (Figure 19). As the inflow to Lake Pauri is reduced to just groundwater seepage during summer (Table 2), and the very low nutrient concentrations in Lake Wiritoa indicate that marginal vegetation (i.e., raupo) and aquatic macrophytes can sequester all the nutrients from those inflows, the source of the nutrients in Lake Pauri is most likely from sediment release. Considering the bathymetry of the two lakes (Figure 3; Figure 4) and the depth of thermal stratification in each lake (Figure 8), it is likely that the thermocline in Lake Pauri does not isolate the nutrients released from the sediments, as occurs in Lake Wiritoa. Typically in shallow lakes, as the summer warming progresses and the water level declines, the thermocline is likely to move down. In Lake Pauri, this would have the potential to expose a larger area of sediment to disturbance while mixing some of the accumulated nutrients from the reduced hypolimnetic volume into the epilimnion.

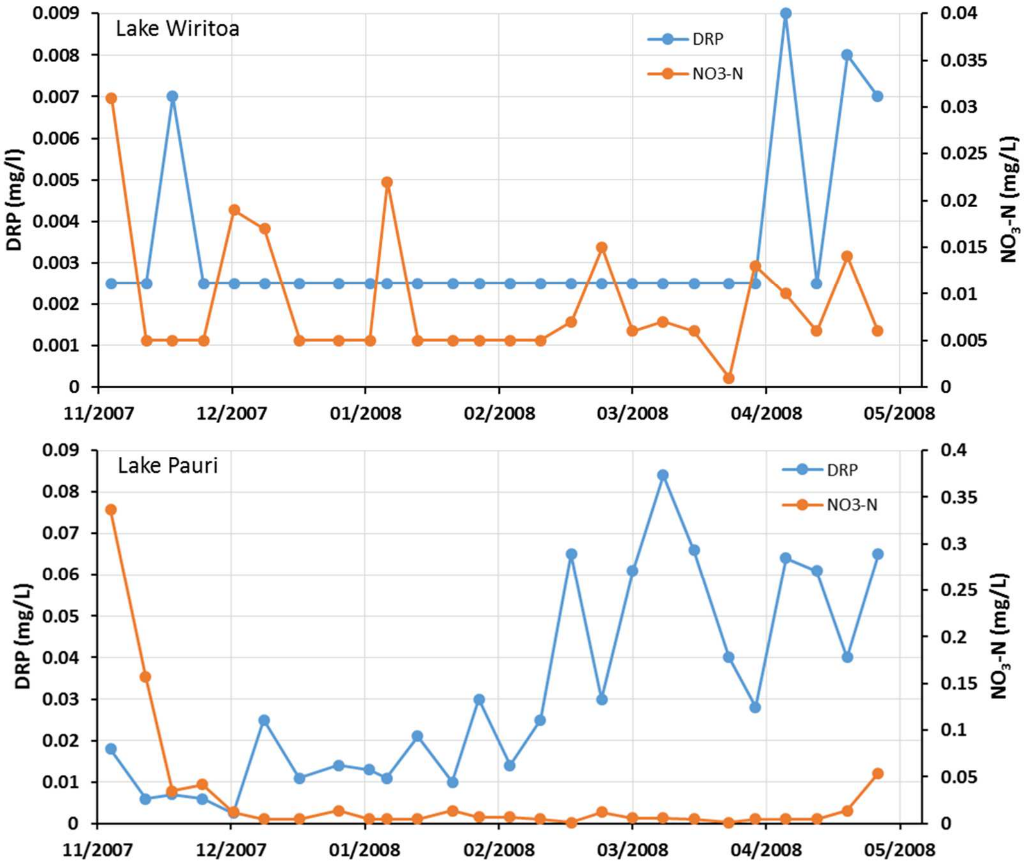

Figure 19: Dissolved reactive phosphorus (blue) and nitrate nitrogen (orange) data from Lake Wiritoa (upper) and Lake Pauri (lower) over the summer of 2007/2008. Horizons data.

A possible consequence of this process, and the presence of macrophyte weed beds in the lake, is that all the inorganic nitrogen is removed from the water column in late summer (Feb-Mar) leaving a surplus of DRP in the water column (Figure 19). These data indicate that the lake water is nitrogen limited for plant and algal growth. Such conditions along with warm water temperatures, high light and prolonged calm weather tend to favour the growth of nitrogen-fixing cyanobacteria such as *Dolichospermum* spp. (formerly *Anabaena* spp.). [Note: *Microcystis* sp., observed in the edge waters of Lake Pauri (Figure 13), is not a nitrogen fixing species].

In the aquatic environment, DRP and NO_3-N are mostly assimilated into macrophyte and algal biomass. These algae along with organic detritus from the macrophyte beds become part of the total phosphorus (TP) and total nitrogen (TN) pool in both the water column and the sediment (Figure 20). As with the dissolved nutrients, the TP and TN concentrations in Lake Wiritoa were substantially lower than the concentrations in Lake Pauri. In Lake Wiritoa, the initially high concentrations of TP and TN in December 2007 and January 2008 declined through summer suggesting that the particulate material, comprising most of the TP and TN pools, was settling out of the upper water column. In contrast, the TP and TN concentrations in Lake Pauri were closely correlated, and the peak concentration on 10 December 2007 (Figure 20) coinciding with the initial growth phase of a cyanobacteria bloom (see Figure 22).

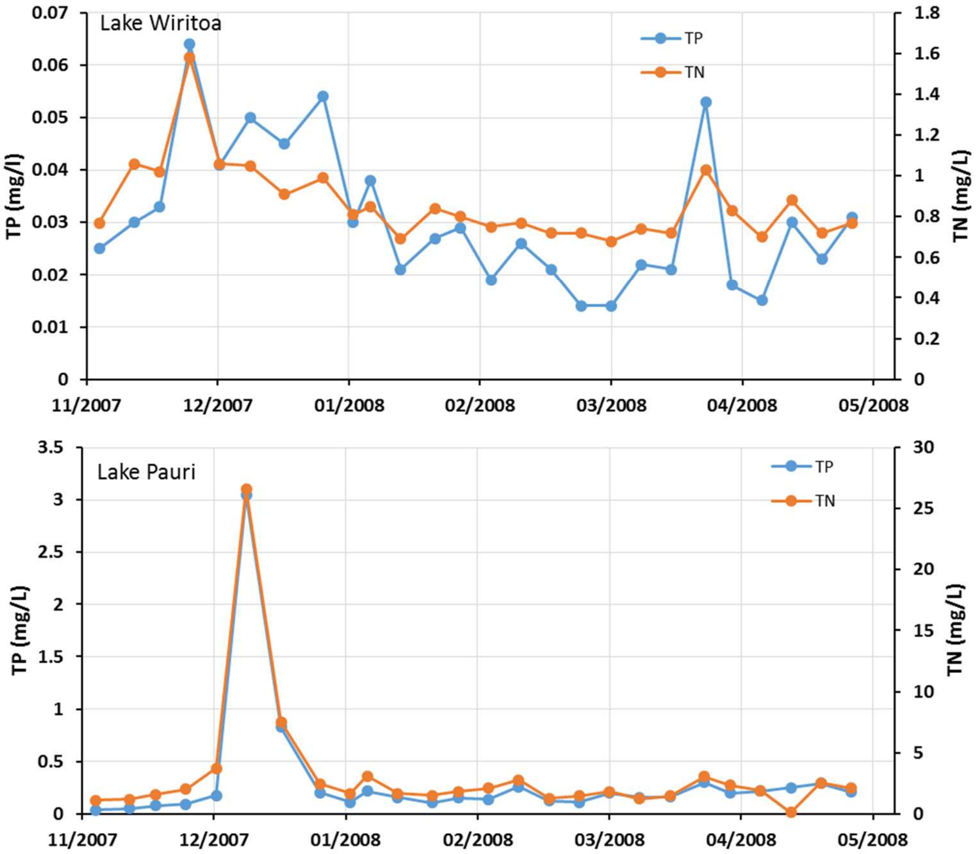

Figure 20: Total phosphorus (blue) and total nitrogen (orange) data from Lakes Wiritoa and Pauri over the summer of 2007/2008. Horizons data.

The ratio of total N to total P (TN:TP) provides information on the utilisation of the dissolved nutrients in the lake. In Lake Wiritoa, the TN:TP ratio ranged from 18:1 to 52:1. Ratios >17:1 are regarded as indicating that phosphorus can be a potential growth limiting nutrient to algae (Pridmore, 1987). In Lake Pauri, the TN:TP ratio ranged from 0.5:1 to 28:1 (Figure 21). Ratios <10:1 are regarded as indicating that nitrogen is a potential growth limiting nutrient to algae. It is not uncommon for lakes to switch between phosphorus and nitrogen as the potential growth limiting nutrient during the course of a year.

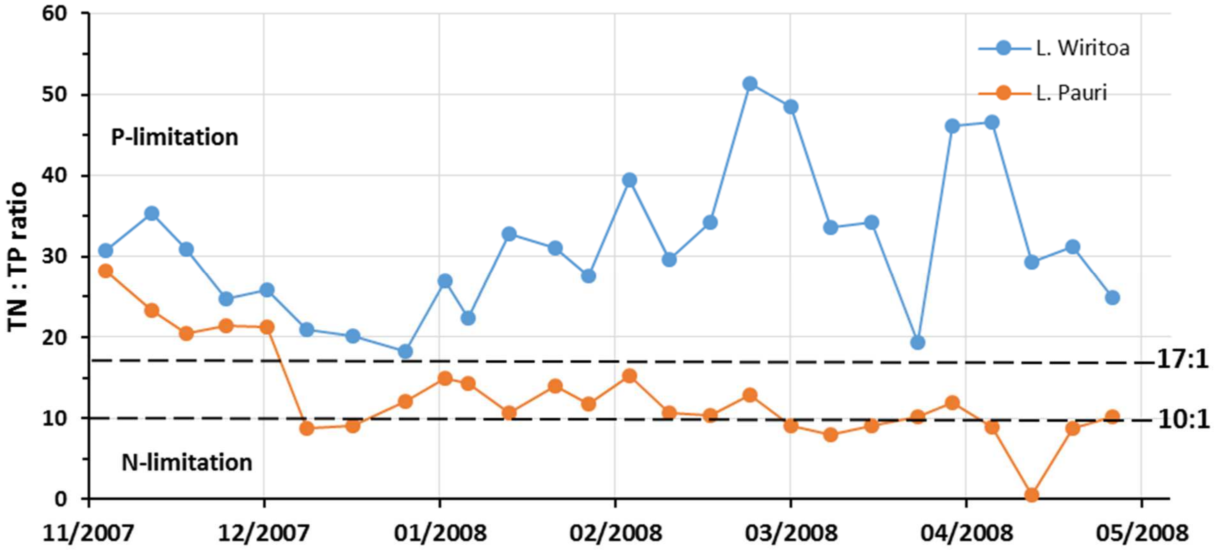

Figure 21: TN:TP ratios in Lakes Wiritoa and Pauri during the summer period November 2007 to April 2008. TN:TP > 17:1 indicates potential P-limitation to algal growth. TN:TP <10:1 indicates potential N-limitation to algal growth. Horizons data.

The higher nutrient levels and lower TN:TP ratios in Lake Pauri relative to Lake Wiritoa in summer 2007/2008 indicate that Lake Pauri would be experiencing larger cyanobacteria blooms than Lake Wiritoa at that time. The limited cyanobacteria cell count data for Lake Pauri at this time (Figure 14), indicate that cyanobacteria were more abundant in Lake Pauri than in Lake Wiritoa.

Inshore effects

Inshore effects can stimulate the growth of different cyanobacteria species. As algae grow, they consume CO_2 from the water causing the pH to rise from around mid-7s to a maximum of around 10.5 (Figure 22). The geochemistry of phosphorus is that, under well oxygenated (aerobic) conditions and pH <8.5, any DRP in the water column not used by algae will be sequestered by and bound to iron oxides in the sediment on the lake bed. As the shallow inshore waters of a lake are always well oxygenated, the expectation would be for there to be no DRP in the water column (except in groundwater seepages, especially those associated with septic tanks) even though there is a continuous release of dissolved inorganic nitrogen as NH_4-N.

When a cyanobacteria bloom accumulates as a wind-drift scum inshore, it can make use of the NH_4-N released from the sediment to grow. As algae and macrophytes grows, the pH increases eventually passing the threshold (pH 9.2) for desorption of DRP from iron oxides in the sediment. The DRP is released into the water column where it can sustain further growth of the cyanobacteria bloom (Gao et al. 2012). Another effect of the increase in pH is the conversion of ammonium nitrogen (NH_4-N) to ammonia (NH_3), which is highly toxic and is probably the cause of fish kills around the edge of a lake during a cyanobacteria bloom. Small fish (e.g., bullies) swim into the toxic water as they come into the shallows, and die.

The NH_3 is also thought to inhibit the nitrification process that converts NH_4-N to NO_3-N, thereby shutting down the denitrification process, preventing the loss of N. These biologically driven actions mean that there is a source of both inorganic N and P in the water beneath the cyanobacteria bloom allowing it to continue to grow. This process is likely to be a contributing factor in the growth of *Microcystis* sp. when there is no apparent inorganic nitrogen source. In Lake Pauri, the *Microcystis* was growing in the edge waters and the shallow water between the dead raupo stems (Figure 13).

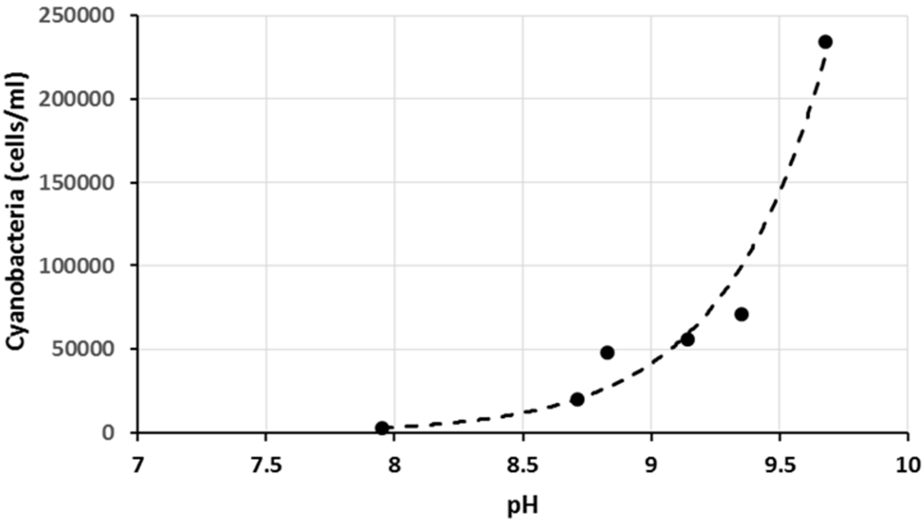

Figure 22: Changes in pH during the growth phase of a cyanobacteria bloom in Lake Pauri, December 2007. The broken line is an exponential curve. Horizons data.

Missing data

Assessing the water quality in Lakes Wiritoa and Pauri has been hampered by the lack of available water quality data. There is very little chlorophyll *a* data for either lake anywhere within the database that spans 1974 to the present. There is no complete set of data for a complete year and consequently winter conditions are poorly represented. Only the early work from 1974 to 1982 sampled both the upper and lower water column and measured water clarity (Secchi depth) (Table 4).

There is only one set of data where parameters can be correlated by cause and effect but that is for a six month period over the summer of 2007/2008. While a second more detailed set of data exist for the summer of 2010/2011 that set of data does not include any nutrient data.

2.2.4 Trophic Status

Trophic Status is a classification system that can be used to compare the water quality of different lakes. It is based on the mean annual values of four key parameters – TN, TP, chlorophyll *a* and Secchi depth – which, in combination, give a numeric value for the lake as a trophic level index or TLI (Table 5). The TLI values have been associated with lake classification descriptors and the range of each of the four parameter values for each descriptor has been set to give lake classification transitions at whole TLI values (Burns et al. 2000).

Table 5: Lake classifications, trophic levels and values of the four key variables that define the different lake classifications. The trophic level has no upper limit. (From Burns et al. 2005).

Lake classification	Trophic level	Concentration (mg m^{-3})			Secchi depth (m)
		Chla	TP	TN	
Ultra-microtrophic	0.0 – 1.0	0.13 – 0.33	0.84 – 1.8	16 - 34	24 - 31
Microtrophic	1.0 – 2.0	0.33 – 0.82	1.8 – 4.1	34 - 73	15 - 24
Oligotrophic	2.0 – 3.0	0.82 – 2.0	4.1 – 9.0	73 - 157	7.8 - 15
Mesotrophic	3.0 – 4.0	2.0 – 5.0	9.0 - 20	157 - 337	3.6 – 7.8
Eutrophic	4.0 – 5.0	5.0 – 12.0	20 - 43	337 - 725	1.6 – 3.6
Supertrophic	5.0 – 6.0	12.0 – 31.0	43 - 96	725 - 1558	0.7 – 1.6
Hypertrophic	>6	>31	>96	>1558	< 0.7

Based on the data in Table 5, if the lake classification is known, then the average annual concentration range of each of the four key parameters is known. Conversely, even if there is insufficient data to calculate a TLI value for a lake, as is the case with Lakes Wiritoa and Pauri, the lake classification can be estimated by comparing the mean annual values for those parameters which are available with the ranges in Table 5.

Both lakes are presently highly enriched but the water quality wasn't always this bad. Based on the data from 1982 (Vant 1982), the TLI value for Lake Wiritoa was 3.94 giving it a classification of Mesotrophic. Lake Pauri had slightly poorer water quality with a TLI value of 4.19 giving it a classification of Eutrophic (Table 6). In the subsequent 26 years, the water quality has deteriorated in Lake Wiritoa to Eutrophic while Lake Pauri has become Hypertrophic (Table 6). These 2008 classifications may change if there were data available for all four parameters for a complete year.

Table 6: TLI values calculated from available data in 1982 and 2008 for Lake Wiritoa and Lake Pauri. (* best estimate based on the 6-months of TN and TP values provided).

Lake	year	TN	TP	Chla	SD	TLI	Classification
Wiritoa	1982	152	19	4.3	2.8	3.94	Mesotrophic
	2008	864	30.5	-	-	4.9*	Eutrophic
Pauri	1982	916	28	5.5	1.6	4.19	Eutrophic
	2008	3085	303	-	-	7.2*	Hypertrophic

2.3 Summary

- Lakes Wiritoa and Pauri are situated in rolling land which has been used for pasture and cropping for more than 150 years.
- The water quality in both lakes has deteriorated over time. Both lakes had anoxic bottom waters in 1974. In 1982, Lake Wiritoa was classified as being mesotrophic and Lake Pauri was eutrophic. In 2008 the water quality of the lakes had deteriorated further with Lake Wiritoa having an estimated trophic Level Index (TLI) of 4.9 or classification of eutrophic and Lake Pauri with an estimated TLI of 7.2 or a classification of hypertrophic.
- The narrow sinuous morphometry and roughly north-south orientation of Lake Wiritoa is likely to offer that lake greater protection from the prevailing south-westerly winds than Lake Pauri, which is wider and orientated more in line with the prevailing wind, and may develop internal waves and strong lake currents.
- Both the surface inflows and the outflow dry up in summer meaning the lakes are receiving only groundwater inputs and hence, have very long residence times.
- They are relatively deep dune lakes with maximum depths of 20.4 m and 14.95 m, respectively.
- They thermally stratify for periods during summer and, in March 2013, the thermocline was at around 8 m in Lake Wiritoa and 10.5 m in Lake Pauri.
- Episodic mixing events associated with strong winds can destratify the lakes and the bathymetry indicates that Lake Pauri is more susceptible to mixing than Lake Wiritoa and may be more polymictic in character.
- Based on the thermocline depths in March 2013, the bathymetric data indicate that the hypolimnion holds about 35% of the total volume of Lake Wiritoa but only 5% of the volume of Lake Pauri. These proportions may vary depending on lake water level.
- The hypolimnion becomes anoxic in both lakes in summer.
- Sediment nutrient release during anoxic events results in elevated concentrations of both DRP (>0.3 mg/L) and NH_4-N (>0.45 mg/L) accumulating in the hypolimnion.
- Epilimnetic nutrient concentrations in Lake Wiritoa are only 10% of the nutrient concentrations in Lake Pauri. This difference is likely to be a function of more frequent mixing in Lake Pauri. Because the water from Lake Pauri flows into Lake Wiritoa, nutrients in that water are likely to be removed by the macrophyte weed beds around the inflow, thereby protecting the open waters of Lake Wiritoa from enhanced nutrient loading.
- During mixing events, nutrients that have accumulated in the hypolimnion are released into the epilimnion where they can stimulate algal growth. Highest cyanobacteria cell counts occur in Lake Pauri.

- Both lakes have a perimeter of mainly exotic macrophyte weed beds extending down to at least 5 m depth with drifting clumps of hornwort at greater depths.
- The band of macrophyte beds around both lakes can be expected to remove much of the dissolved inorganic nitrogen from the epilimnion of these lakes.
- Both lakes have a riparian buffer zone of mainly raupo around most of the shore line. These buffer zone plants can be expected to intercept nutrients in the shallow groundwater before they reach the lake and hence, reduce nutrients from this source.

3 Nutrient Sources

Eutrophication is a natural process whereby a lake progressively becomes more enriched as it accumulates nutrients. Human activity in the catchment can accelerate this process by increasing the nutrient load to the lake. In most large lakes, about 50% of the nutrient inputs are retained in the lake. In dune lakes the retention of nutrients from external sources can be up to 100% (no outlet stream). In order to restore a lake, the sources of external nutrients need to be identified so that they can be reduced (i.e., by treatment, diversion or reduction at source). So where do the nutrients in Lakes Wiritoa and Pauri come from?

3.1 Legacy

From the review of the available data, it is apparent that the water quality in Lakes Wiritoa Pauri has been declining for many years as a consequence of converting the land from native vegetation into pasture for farming starting 150 years ago. In those 150 years to present, the lakes have received organic matter from algal and plant biomass growing in the lakes, top soil from tillage washed into the lakes, wastewater effluent from septic tanks, excretions from stock with direct access to the lake, and nutrients from fertiliser applied to the catchment. Because of the long hydraulic residence times, these inputs have accumulated in the lake sediments and are recycled each year during summer as an internal nutrient load on the lake. Consequently, the internal load is regarded as a legacy of past land-use practice in the catchments.

Remediation actions including stock exclusion from the lake and planting of the riparian buffer zone around these lakes have been occurring over the past 10 years but these haven't been enough to stop the algal blooms. Consequently, this report looks at what can be done next to add to the current work.

Lake Okaro near Rotorua is also highly degraded after being similarly developed from native scrub into pasture, with direct stock access to the lake and the use of fertiliser to enhance production. It also has a long hydraulic residence time leading to a large internal nutrient load as a legacy from past land-use practice in the catchment. However, Lake Okaro is currently the focus of a study for the restoration of degraded lakes and can provide some insights on practical remediation strategies that might be applied to Lakes Wiritoa and Pauri.

3.2 Phosphorus

3.2.1 Fertiliser

Sand dunes are usually highly depleted in nutrients, especially phosphorus which can be strongly bound to the iron in the sand under aerobic conditions. The source of the legacy phosphorus is fertiliser applied to the land, and inadvertently to the lakes, to improve farm production. Historically, superphosphate would have been used as an annual fertiliser application.

Superphosphate known as "Super" was invented in 1842 and has been a reliable and cost-effective fertiliser in New Zealand since 1882. Application rates varied depending on the level of soil deficiencies of both phosphorus and sulphur. Super was used on around a quarter of all farms in New Zealand. In the 1920s and 1930s the government promoted Super, backed with research and, during the Second World War, the government subsidised the price of Super to allow farmers to continue applying this fertiliser to the land each year. Aerial top dressing began in 1940 and has become the method of choice for spreading Super on farms since the War.

If applied before rain, the Super can wash off into the lakes. If applied accidentally directly to lakes by aerial top dressing, the Super can enter the lakes at a similar application rate as applied to the farm land. Fertilizer drift from aerial topdressing over Lake Parawanui, Northland, increased the DRP concentration in the lake water to >300 mg/m^3 (M. Gibbs, NIWA, unpubl. data).

Typically there were three common application rates of Super, 188 kg/ha, 376 kg/ha and 564 kg/ha (McBride et al. 1990), which, assuming direct application and/or rapid leaching via surface runoff, could indicate an annual addition of from about 5000 kg up to almost 15,000 kg Super to each lake. At a phosphorus content of 7 - 9.5%, that would be equivalent to an addition in the range from 350 kg up to 1425 kg phosphorus each year to each lake for much of the last century. This gives an indication of the potential magnitude of the phosphorus legacy in the sediments of these lakes.

The current rate of Super application should be investigated.

3.2.2 Other phosphorus sources

Because of the long residence time, the flushing of nutrients from Lakes Wiritoa and Pauri is very slow. Furthermore, the nutrients flushed from Lake Pauri have to pass through Lake Wiritoa before they leave the system. This should result in Lake Wiritoa eventually becoming as degraded as Lake Pauri. Consequently, the TLI estimates (Table 6) are inconsistent with the logical progression of water between these lakes. This implies that there are one or more nutrient sources that affect Lake Pauri more than Lake Wiritoa, or that the macrophyte weed beds in Lake Wiritoa around the inflow from Lake Pauri are removing a substantial proportion of the nutrients from that water.

Several potential sources of additional nutrients to Lake Pauri include:

1. The stormwater from the prison. Although the discharge point is between the two lakes and the flow should be from Lake Pauri into Lake Wiritoa, observations on 5 February 2013 (Figure 7) show that this is not always the case. If the outlet from Lake Wiritoa becomes blocked, the flow reverses discharging high concentrations of nutrients (TP 0.354 g/m^3; TN 3.97 g/m^3) into Lake Pauri (Table 3).

2. Wastewater effluent from the prison. Due to its location on the south side of the prison, it is considered that the effluent discharge from the prison to land is unlikely to flow towards the lake. Unlikely, but not impossible. Since these lakes are in porous sand country, their existence depends on there being a clay lens beneath the sand to hold that water. The boundaries of that clay lens may not coincide with the surface topography as sand dunes shift and the topography changes over time. If the prison is built inside the boundary of the clay lense, all of that effluent water will flow via groundwater into the lakes, and most likely into Lake Pauri.

3. Infiltration of nutrients from fertiliser and farm wastewater irrigation. All soluble nutrients from these sources can enter the groundwater and eventually reach the lakes. Even if all land applications ceased immediately, there will be an historical load still in the groundwater that will continue to seep into the lake for many years. Mitigation measures that have been implemented include exclusion of stock from direct access to the lakes, and refurbishing/ augmenting lake edge buffer zone plants that have the capacity to assimilate and therefore remove those nutrients before they enter the lake.

4. Soil erosion. Top soil exposed by tilling for crops or re-grassing back to pasture is vulnerable to erosion in heavy rain. Much of the soil lost from the farmland will be deposited in the lake. As top soil contains the phosphorus applied as fertiliser, soil erosion can be a major external source of phosphorus to the lake where it accumulates in the sediments augmenting the existing internal phosphorus load. Phosphorus bound to particulate matter is the main source of new phosphorus in Lake Okaro.

5. Sediment nutrient release. While both lakes may have received an excess load of organic matter, nutrients and potentially fertilizer in past 150 years, their morphological differences may influence the way those legacy nutrients affect each lake today. Specifically, the slope of the lake bed in Lake Pauri (Figure 9) and the depth of thermal stratification in summer is likely to allow substantial disturbance of the sediments during any wind event. Wind induced mixing could resuspend the surficial sediments releasing nutrient-rich pore water into the overlying water column. The development of an internal seiche could also allow nutrients that have accumulated in the hypolimnion to be mixed up into the water column at each end of the lake, which become upwelling zones (Figure 10). This effect will be minimal in Lake Wiritoa and could be one of the factors causing the differences in water quality.

4 Remediation opportunities

Because degradation of Lakes Wiritoa and Pauri is the result of a range of natural and human activities over a long time, restoration of these lakes will require a range of interventions in both the catchment and in each lake over a period of time. Because the lakes have adapted to the current degraded state, implementation of remedial actions will improve the water quality in the lakes to a new less degraded state, which will depend on the goals set by the community.

The remedial actions suggested in this report may be implemented individually or in combination and some may have been implemented already. More detailed information on potential remediation actions can be found in a report on the MfE Envirolink tools website: http://www.envirolink.govt.nz/PageFiles/31/Guidelines%20for%20artificial%20lakes.pdf

4.1 Catchment based options

Turning off or reducing the nutrient sources into the lakes is very important. It is recommended that a farm management plan (FMP) is developed for each farm to manage nutrient sources around the lakes and elsewhere in the lake catchments.

4.1.1 Stock exclusion

Stock should remain excluded from these lakes and the wetlands around the lakes with permanent fencing. This has already been done and only requires maintenance of the fences.

4.1.2 Land disposal of effluent

Farm wastewater

Ideally, spray irrigation of effluent water should be excluded from the immediate lake catchment, especially the land between the two lakes. Disposal of effluent water should be discussed as part of the FMPs.

Domestic wastewater

Septic tanks should be large enough to cope with the “normal” domestic load. They should be serviced on a regular (3 yearly maximum) basis and the drainage fields should be checked and maintained. New septic tanks should have at least two chambers with a denitrification stage before discharge into a dripper style subsurface irrigation system.

Prison wastewater

Effluent water from the treatment plant should be discharged into a disposal field that drains away from the lakes. More detail is required about the existing system which appears to include a series of surface channels running back towards the lakes (Figure 23). If the flow path of the effluent discharge is not known, further investigation should be undertaken to determine that flow path. For example, it may be necessary to determine the slope of the surface groundwater aquifer from boreholes. It may be possible to obtain that information from existing irrigation boreholes or groundwater. The depth of the clay lense may also be obtained from the bore logs for the water supply boreholes.

If the effluent water is found to be flowing back into the lakes via the groundwater, remedial options may be to pipe the outflow from the treatment plant to an infiltration location where the groundwater does flow away from the lakes, or to spray irrigate the wastewater onto pine forest in a catchment that does not drain back to the lakes.

Disposal of sludge from the treatment plant should be on land outside the groundwater catchment of the lakes.

Prison stormwater

The discharge of stormwater from the prison complex into the stream between the two lakes ensures that the high nutrient load in that water enters one or both lakes, depending on relative lake levels. Ideally the stormwater discharge should be into the outflow stream downstream of Lake Wiritoa. This could be achieved by re-aligning the existing stormwater pipes along the side of the road.

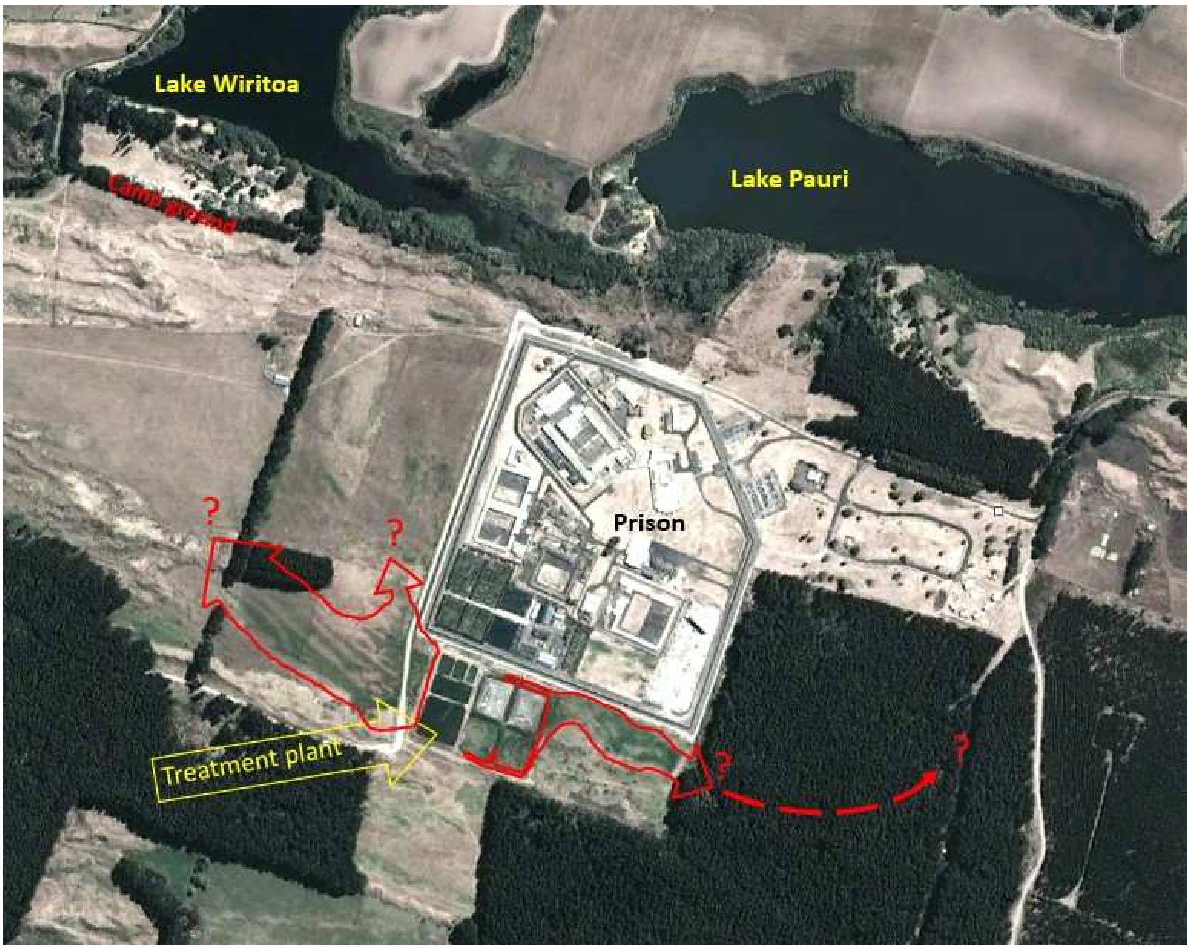

Figure 23: Kaitoke (Wanganui) Prison showing the positions of the prison and the wastewater treatment plant relative to Lakes Wiritoa and Pauri. The image [Google Earth] was flown on 11 March 2013 during a drought. Green areas (excluding dark green pine forest) are interpreted as receiving water. Areas enclosed in red polygons may indicate surface discharge of treated wastewater. Arrow heads on the red polygons indicate potential direction of flow. The broken red line indicates a possible flow path to a gulley leading into Lake Pauri.

Camp site

Effluent from the septic tanks on the camp site may seep into Lake Wiritoa. A sample of water seeping from the ground near the camp boat ramp on 5 February 2013 had around 50 mg/m^3 DRP in it. This may have been due to leaching by the heavy rain at that time, rather than a normal occurrence. This should be investigated further.

4.1.3 Stream flows

The outlet stream from Lake Wiritoa should be cleared and the clearance maintained to enable the maximum water level in Lake Wiritoa in winter to always be around 1 m lower than the water level in Lake Pauri (based on historical data from Fowles 1982). This will ensure that water will always flow from Lake Pauri into Lake Wiritoa. It will also ensure that the stormwater inflow from the prison also flows into Lake Wiritoa, not back into Lake Pauri. The inflow from Lake Pauri enters Lake Wiritoa at the same end of the lake as the outlet, thereby short circuiting the Lake Pauri water to the outlet.

Note that if Lake Pauri becomes colder than Lake Wiritoa in winter, the lake Pauri water will underflow to the bottom of Lake Wiritoa. This would most likely occur on frosty mornings. To reduce the chance of this happening, the stream between the two lakes needs to be protected from frosts by having a canopy of evergreen trees over the stream channel. These should be native species such as five-finger and lemonwood which will also shade out aquatic macrophytes, reducing the instances of channel blockage.

4.1.4 Sediment reduction

Tillage or non-tillage

The transition from pasture to cropping historically requires the soil to be tilled to enable the seeds to be planted. However, bare soil exposed to heavy rainfall can result in substantial amounts of top-soil erosion. The topsoil is the most fertile soil and probably contains the majority of the super phosphate fertiliser applied to the land. Timing of planting and the use of long-range forecasts can reduce the loss of soil into streams and subsequently into the lake. Where appropriate, spraying of the pasture prior to planting and then drilling the seed through the untilled land will greatly reduce soil erosion.

Transition from crops back to pasture does not require tillage in many cases. Drilling the grass seed through the crop stubble is becoming common practice. This approach has advantages to the farm other than a reduction is planting costs. Soil fungi (mycorrhizas) that developed in the crop root zone, aid the growth of the new seed, which would otherwise have to develop new mycorrhizas to obtain the nutrients out of the soil.

If tillage is undertaken then best management practices (BMP) to avoid sediment getting into the lakes are recommended.

Fertiliser application

The timing of fertiliser application based on rain forecasts can reduce the loss of fertiliser through runoff. Several smaller applications are often better that a single large dose. Aerial topdressing should be avoided around or near the lakes. FMPs should be developed and implemented to assess and mitigate nutrient loss. This will be a requirement for farms undertaking >20 ha cropping for off-farm use under Horizon's One Plan, which will come into effect from 2015.

Stream inputs

Because suspended sediments entering these lakes via the stream inflows will recharge the sediment on the lake bed with nutrients, it is important to reduce the sediment load on the lakes from the catchment. Apart from the stream from Lake Pauri, Lake Wiritoa has a single significant ephemeral surface inflow, which dries up in summer. Where this flow enters the north-eastern end of the lake, a small culverted causeway has isolated a small section of the lake into an impoundment (James & Joy, 2009). Whether it was intended as such, this small impoundment will act as a sediment trap catching sediment carried down the ephemeral stream during rainfall events. The efficiency of the trap may be enhanced by manipulating the size and elevation of the culverts.

In Lake Pauri, a much larger ephemeral stream enters the lake through the northern arm, which is widely occupied by water lilies. The northern arm of Lake Pauri could be converted into a sediment trap by constructing a culverted causeway across the arm to stop the direct discharge of sediment out into the main body of the lake during rainfall events. Another ephemeral stream discharges rainwater and sediment into the back of a wetland in the south-eastern corner of the lake.

There are several other natural ephemeral channels running into Lake Wiritoa where similar techniques could be employed.

Shoreline erosion

Wave action against an exposed shoreline is often a major source of suspended sediment in a lake. This problem can be overcome by excluding direct access by stock to the lake edge vegetation and refurbishing the riparian buffer zones with appropriate plants to fill in gaps and strengthen the natural lake edge vegetation. Both Lake Wiritoa and Pauri have almost complete perimeters of buffer zone plants dominated by raupo.

Organic matter inputs

Organic matter in the form of tree leaves can be a major source of organic carbon to these lakes. Increasing the carbon load on the lake increases sediment oxygen demand in the lake and accelerated the rate of deoxygenation of the sediment and the water overlying the sediment. Phosphorus can be released from the sediments at increasing rates as the DO concentrations fall below 5 mg/L with total release at 0 mg/L – anoxic conditions.

The most common sources of leaves in lakes are the introduced deciduous species including willows.

4.2 Lake based options

4.2.1 Aquatic macrophytes

While dense beds of submerged aquatic macrophytes, especially invasive weed species, are regarded as a nuisance to most lake users, they provide a number of valuable ecosystem functions in the lake. Services include stabilisation of bottom sediments from wave resuspension by decreasing wind-induced wave velocity and therefore increased turbidity and suspension of nutrients, especially phosphorus, in the water column (Barko and James 1998). Submerged macrophytes and their epiphytic algae also remove nutrients from the water column (Wetzel 1995) and enhance deposition of fine suspended sediments. This effect is seen in Lake Horowhenua (Gibbs 2011). Additionally in small shallow lakes, macrophyte beds provide refuges for zooplankton (Carpenter and Lodge 1986) that are preyed on by fish such as perch. Zooplankton in turn prey on planktonic algae. Thus submerged plants can reduce the nutrients available to planktonic algae, also supressing algal their impact by providing habitat to predatory zooplankton.

In shallow water lakes, Sheffer et al. (1993) discussed the ability of submerged macrophytes to maintain water quality in systems with increasing nutrient inputs. However, once the macrophytes are lost the system switches to one dominated by planktonic algae. For macrophytes to re-establish, a much lower nutrient status/algal biomass is required. This is due to shading impacts from algal blooms and the mobilisation of nutrients, from bottom sediments not protected from wave action by macrophyte beds, into the water column continuing to support planktonic algal growth. Thus two stable states — one clear water, macrophyte dominated and one turbid, algal dominated — can occur under the same lake trophic status (Sheffer et al. 1993). However, the higher the nutrient status of the lake, the more likely the loss of macrophytes becomes. As submerged macrophytes occupy a large proportion of both Lakes Wiritoa and Pauri, their role in influencing lake conditions is likely to be large.

Emergent macrophytes like raupo are also perceived as a nuisance by many lake users, mostly through prevention of lake access and obstruction of lakeside views. These plants also provide a wide range of ecosystem services. These include stabilisation of shallow water sediments from mobilisation (as with submerged macrophytes), shading of shallow water margins, interception of nutrient-rich groundwater at the lake margin and nutrient removal, provision of organic matter (detritus) into bottom sediments, oxidation of bottom sediments through radial oxygen loss from the extensive rhizome/root system and provision of habitat for a range of water birds. Nutrient removal occurs both through the growth of plants and also denitrification (conversion of soluble N to atmospheric N_2) by bacteria requiring a combination of low concentrations of DO and organic substrate, both provided in sediments accumulating under emergent reed beds.

Management options for aquatic macrophytes must be sensitive to the roles that both submerged and emergent species perform regarding lake function. Control options include mechanical removal of submerged plant biomass, use of selective herbicides to manage macrophyte biomass and the use of the herbivorous fish grass carp to remove all plant biomass. These methods are described on the NIWA website (http://www.niwa.co.nz/our-science/aquatic-biodiversity-and-biosecurity/our-services/aquaticplants/outreach/weedman) and are briefly discussed below:

Mechanical removal

Mechanical weed harvesters provide a direct method to remove nuisance submerged weed growths from high-use areas by cutting the upper portions of a submerged weed bed and then harvesting and removing these plants from the lake. Such control will only check the growth of the plants and re-growth is likely to occur in the same season or the next.

However, this method has good public acceptability and may help reduce nutrient loading in the lake through the removal of plant biomass.

Herbicides

Two herbicides are registered for aquatic use in New Zealand, Diquat and Endothall. Both are relatively selective, neither impacts on most native submerged plant species or damages emergent vegetation. Both herbicides provide rapid and targeted control of susceptible weed species and although only temporary control is likely (although usually much longer than mechanical removal) this provides an opportunity for native plants to establish and reproduce. Of the worst submerged weeds in Lakes Wiritoa and Pauri, Diquat effectively controls both hornwort and Egeria, whereas Endothall only controls hornwort. The use of either herbicide requires a resource consent. Costs are considerably less than mechanical options.

Grass carp

Grass carp provide an eradication option for submerged vegetation in lakes. Eradication of weed species would be a desirable consequence of grass carp introduction with no additional annual control needed over the life span of the fish. However, control of macrophytes cannot be targeted to nuisance weed beds as with the other options and the eventual total loss of submerged vegetation and reduction of emergent plants would impact on the ability of this vegetation to ameliorate nutrient impacts and increased algal blooms are likely to increase from current levels.

Overview

Of the macrophyte control options, either harvesting or herbicide use are seen as the most appropriate for both Lakes Wiritoa and Pauri. The use of grass carp is not recommended because weed removal would most likely result in algal dominance and thus reduced water clarity.

The use of these control options needs to be tempered by considering the benefits of having the weed beds. In practical terms, the very large 1515 ha direct catchment of Lake Pauri is 5.5 times greater than the 277 ha direct catchment of Lake Wiritoa. All the nutrients from Lake Pauri flow into the southern arm of Lake Wiritoa, which explains why that arm is heavily infested with macrophytes. The presence of those macrophytes, which can sequester all the N and P from Lake Pauri, explains why the water quality in Lake Wiritoa is better than in Lake Pauri and the nutrient concentrations in the open lake are an order of magnitude lower than in Lake Pauri. Eradication of the macrophyte beds is not recommended.

Our recommendations for macrophyte control are:

1. Do not use grass carp in either lake.
2. Do not allow any new herbivorous exotic fish species (e.g., Koi carp, rudd) to be introduced. Once established, it is impractical to remove or eradicate pest fish.
3. Use local applications of herbicide to provide access through the macrophyte beds from the shore to the open lake in summer for boating.

4. Use herbicides sparingly to manage lake edge plants, such as raupo, for local access to the lake and to keep bathing beaches clear for swimming.

5. Use a weed harvester (if available) to remove the weed biomass from the lake for composting in the catchment downstream of Lake Wiritoa or anywhere else outside the lake catchments. Long term nutrient removal in the weed biomass can reduce the internal nutrient load on the lake as happens in Lake Rotoehu.

4.2.2 Sediment nutrient release

In almost all lakes, the release of nutrients from the sediments is the largest single nutrient source in summer. The management strategies required depend on how that release disperses into the upper water column of the lake. In deeper lakes (>10 m), the lower water column (hypolimnion) becomes isolated from the upper water column (epilimnion) by the thermocline that forms due to faster heating of the surface water by solar radiation in summer (i.e., thermal stratification).

Stabilising the water column

The nutrient concentrations in the upper water column in Lake Wiritoa are around 10% of those in Lake Pauri because the thermocline is rarely mixed during summer stratification. This means that there will be one period each year when the lake mixes and those nutrients will become available to stimulate algal growth. Because that mixing period occurs in autumn when there is low light and probably elevated rainfall, the production of algal biomass is likely to have less effect on lake users.

In contrast, the thermocline in Lake Pauri may be frequently mixed or disturbed during summer stratification due to strong wind along the main axis of the lake. To stabilise the water column and reduce the incidence of thermocline disturbance by seiching, trees could be planted across the western end of the lake as a windbreak to reduce or stop that wind effect. For example, shelter belts of *Casuarina equisetifolia* or Coastal She Oak, are grown around orchards in the Bay of Plenty and elsewhere. They are hardy, tolerating dry sandy conditions and yet potentially growing to 30+ m in height. They tolerate being trimmed as a hedge and retain foliage from the ground up the full height of the tree.

The downside of reducing the wind velocity across Lake Pauri is the effect on lake use – the lake is used by sailing schools and others for yachting. Consultation is recommended.

The disadvantage with simply stabilising the water column is that the nutrients are still released from the sediment and accumulate in the hypolimnion to be dispersed throughout the whole water column when the lake mixes in autumn. Both DRP and NH_4-N accumulate to high concentrations in the hypolimnion of these lakes.

De-stabilising the water column

The alternative action is to destabilise the water column i.e., destratification. This is typically achieved using aerators to mix the water column. These can be Solar Bees, which are commercially available, solar powered devices that can be set to draw water from below a specific depth and disperse it on the lake surface where it becomes oxygenated through contact with the atmosphere. Alternatively, the aerator can be an air pipe suspended just above the lake bed. Compressed air blown though the aerator pipe emerges from a number of holes in the air pipe to form a rising curtain of bubbles which entrains ambient lake water with it to the surface where it adsorbs oxygen from the atmosphere. The resulting circulation current gradually mixes the lake.

This is the preferred method of treating lakes used for domestic water supplies (e.g., the 10 water-supply reservoirs run by Watercare Services Limited for Auckland City). Provided the aeration process starts before the lakes strongly thermally stratify in spring, the reservoirs can be kept well mixed throughout the summer period when they would have otherwise developed thermal stratification. (See Gibbs & Hickey, 2012 for operating details).

Destratification works to reduce cyanobacteria growth in two ways:

1. By keeping the whole water column mixed, the cyanobacteria cannot float to the surface but are mixed down through the full depth of the water column and spend part of that cycle in the dark bottom waters. In the light they grow (production phase) but in the dark they begin to die (respiration phase). As the mixing currents move the cyanobacteria up and down through the water column, the cyanobacteria cells spend different proportions of their time in the light and dark. The point of balance between production and respiration is the “critical depth” (Sverdrup 1953) for that species and if the lake is deeper than the critical depth, the cells die. Lake Wiritoa may be deep enough for this process to be effective. (See also Gibbs & Hickey, 2012 for more details).

2. Mixing the lakes puts oxygen through the full depth of the water column. If mixing keeps the DO concentrations in the water above 5 mg oxygen/L it will prevent the release of DRP from the sediment. Below this concentration, DRP begins to be released from manganese oxides in the sediment, and below 2 mg oxygen/L DRP begins to be released from iron oxides (Stumm & Morgan, 1995). As excess phosphorus favours the growth of cyanobacteria, reducing or eliminating free DRP from the water column has the potential to limit or eliminate the growth and development of cyanobacteria blooms. Under anoxic conditions the nitrogen released from the sediment is in the form of NH_4-N. Under aerobic conditions, the NH_4-N is nitrified to NO_3-N which can be denitrified thereby reducing the internal nitrogen load.

The disadvantage of destratification is that the whole water column warms up to the maximum summer temperature, which may adversely affect some aquatic biota such zooplankton and fish. Oxygen concentrations over 5 mg/L are thought to be required for healthy fish populations.

Stabilising the water column with bottom water oxygenation

If the lake is allowed to thermally stratify but the bottom waters are kept well oxygenated, the nutrient releases are the same as for the destabilised water column but the bottom waters remain cool, providing a cool refuge for fish. This bottom-water oxygenation without destratification is achieved by using a bottom water aerator. These devices consist of a closed loop system which draws bottom water to the surface where it can adsorb oxygen from the atmosphere before it is returned to the bottom of the lake below the thermocline, or it adsorbs oxygen from an air bubble stream (Figure 24).

While both bottom water aerators (Figure 24) are shown with air bubblers inducing the flow, option 2 can be used with a solar powered motor lifting the water. Aeration occurs in the surface chamber where the bottom water comes in contact with the air before returning to the bottom of the lake. Further details are provided in Gibbs and Hickey (2012). Option 2, run with solar power, would be suitable for Lake Pauri. Note that this approach requires a shelter belt of trees as a wind break to stabilise the thermocline.

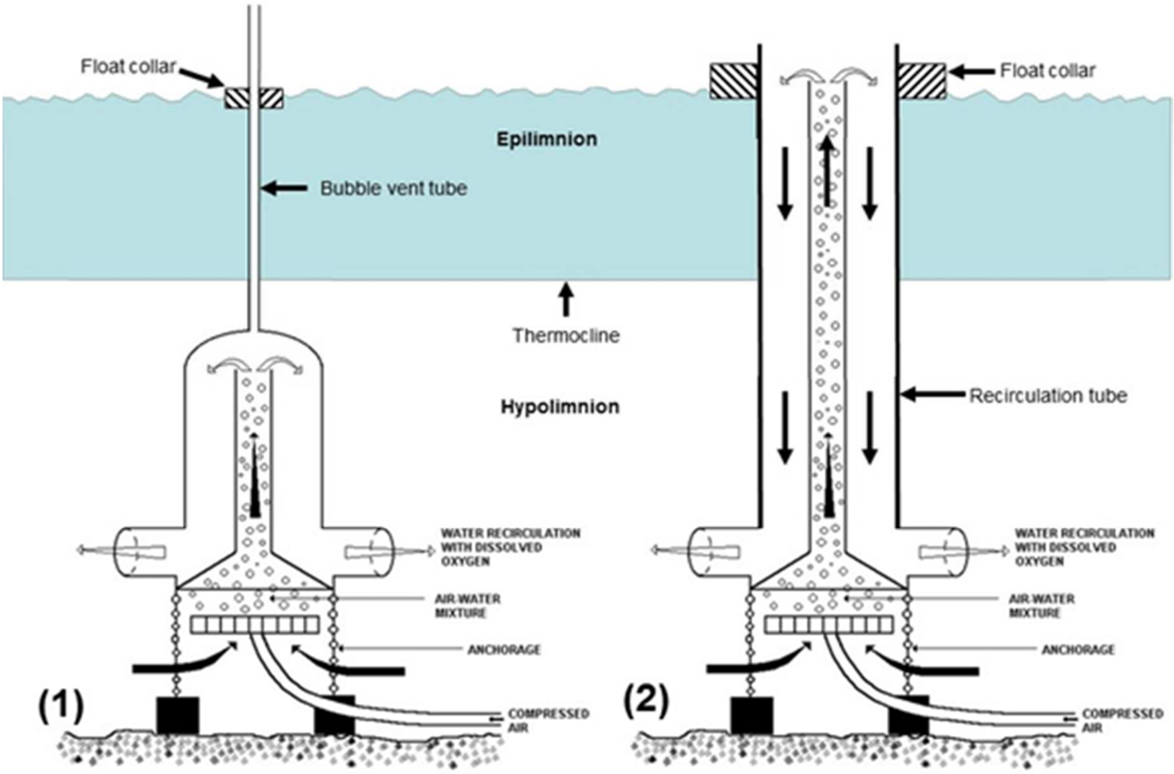

Figure 24: Bottom water aerators. (1) Mounted in the hypolimnion; (2) Suspended from the surface. Both systems do not warm the hypolimnion while they re-oxygenate the water. (From Gibbs and Hickey 2012).

Reducing internal wave action

Wind induced lake currents including internal waves on the thermocline (seiches) in Lake Pauri may be reduced by planting a wind break of tall trees (*Casuarina*) across the western end of the lake. A possible engineering option would be to install baffles across the lake bed to disrupt the bottom currents that can disturb the sediment. These conceptual ideas need further investigation. If implemented, it would be beneficial to management options using phosphorus-inactivation to block sediment release of phosphorus.

Phosphorus inactivation

Because the imbalance between low dissolved inorganic nitrogen and relatively high dissolved reactive phosphorus favours the development of cyanobacteria blooms, a practical option is to focus on the phosphorus released from the sediment and sequester the DRP before it is available for algal biomass production. Sequestration converts the DRP into an insoluble mineral precipitate which is not biologically available.

Several products are available as phosphorus-inactivation (P-inactivation) agents including allophane (a natural volcanic ash), alum (aluminium sulphate), which is a swimming pool and water treatment plant flocculent with a strong affinity for phosphorus at pH values between 6 and 7.5, and proprietary formulations such as Aqual-P which is a modified New Zealand zeolite clay that adsorbs both NH_4-N and DRP, and Phoslock™, which is an Australian or Chinese bentonite clay impregnated with the rare earth element lanthanum. Internationally there is also a range of new products that are being developed and tested for the sequestration and inactivation of phosphorus from the lake water column.

With all of these products, the objective is to produce a metal-bound-phosphorus compound which will not dissolve and release the phosphorus back into solution under low oxygen conditions and normal pH as happens with naturally occurring iron and manganese oxides. These products are discussed in detail in Gibbs & Hickey (2012) and Hickey & Gibbs (2009). Two products are discussed briefly below.

Alum

The limitation of all P-inactivation agents is that they only sequester soluble phosphate (DRP) and not dissolved organic phosphorus or particulate phosphorus, with the exception of products that can precipitate particulates i.e., flocculants. Consequently, the most effective P-inactivation agent is alum, which is primarily used as a flocculent to clarify drinking water in treatment plants and in swimming pools from domestic back-yard pools to large municipal pools.

A recent example of lake remediation success using alum is Lake Rotorua which has been brought back from supertrophic (TLI >5) to bordering on mesotrophic with a TLI just above 4.

Alum can be applied as a liquid at a low dose sprayed onto the lake surface, or injected directly into the hypolimnion. Alum should not be applied if the pH is >8 as high pH reduces the phosphorus binding capacity.

- As a surface application, the alum floc will cause aggregation of particulate matter in the water column causing it to sink to the lake bed. As the particulate matter in these lakes is closely associated with cyanobacteria biomass (Figure 16), this has the potential to reduce or remove the cyanobacteria from the surface waters. When the alum has reached the sediment surface it forms a thin layer a few mm thick. The phosphorus binding capacity of the alum in the layer is still available to sequester DRP as it is released from the sediments and diffuses up into the anoxic bottom water.
- Injected directly into the hypolimnion, the amount of alum used can be targeted to match the DRP release rate from the sediments. The end result is the same as for a surface application in that it forms a thin layer on the sediment surface that can sequester the DRP released from the sediment. The difference is that the particulate load in the water column is not removed and has the potential to bury the alum layer when it settles. This is an important consideration as Horizons 2007/2008 data indicate that the mean DRP concentrations in Lake Pauri are in the order of 30 mg/m^3 while the mean TP concentrations can be ten times higher at >300 mg/m^3. The sedimenting TP replenishes the phosphorus reservoir in the sediment reducing the efficacy of the direct injection treatment.

Consequently, the direct injection approach requires several treatments over several years. However, the doses applied are much smaller than are required for the surface application and this approach may have a higher efficacy than a single surface application.

The downside to using alum, is the potential for the formation of toxic Al^{3+} ions in the water column if the pH goes below 5.5. It is also not effective at pH values above 8.5 when the phosphorus binding action can reverse. Consequently, it should not be applied as a surface treatment during a cyanobacteria bloom where the pH can go as high as 10 (Figure 22). Applied with a sodium carbonate or bicarbonate buffer at pH 7is the recommended application method.

Aqual-P

This product is a fine granular “powder” that can be applied to the surface of the lake as a slurry. It will settle to the lake bed where it forms a thin layer about 1-2 mm thick that can sequester DRP released from the sediment. During application, this P-inactivation agent may reduce particulates as it settles but it is primarily designed as a sediment capping agent. Whereas alum is applied when the lake is thermally stratified and all the DRP is in the hypolimnion water column, Aqual-P is applied in late winter before the lake stratifies and all the DRP is retained in the sediments.

An application of Aqual-P to Lake Okaro prevented cyanobacteria blooms the following summer. The efficacy was subsequently diminished by a large input of sediment that buried the cap. That is unlikely to happen in Lakes Wiritoa and Pauri with denser sandy soils that are less likely to be carried with water, especially if the sediment trapping options are implemented.

Unlike alum, Aqual-P does not release toxic Al^{3+} ions at low pH but the phosphorus binding capacity is affected by high pH in the same way as alum. Aqual-P is the only P-inactivation agent that reduces the nitrogen load released from the sediments as the zeolite carrier adsorbs NH_4-N.

Dose rates

Dose / treatment rates are calculated based on the amount of bioavailable phosphorus in the sediment and the concentrations of DRP and TP in the water column. Dose rates for Lake Okaro were estimated for alum (as $Al_2(SO_4)_3.18H_2O$) to be 80 g/m^2 and Aqual-P at 190 g/m^2. More information about sediment phosphorus content, the phosphorus concentrations in the water column and the water column pH is needed as a first step in calculating the dose rate. An estimation of the phosphorus and NH_4-N release rates / effluxes from the sediment would also assist with the estimation of treatment rates for these lakes.

To obtain this information, water and sediment samples would be needed from both lakes, and a set of sediment cores would need to be incubated to determine nutrient effluxes.

5 Monitoring

The assessment of Lakes Wiritoa and Pauri in this report have been based on minimal actual data and a lot of weight has been put on the few numbers that are available, based on best scientific practice and current understanding. It is recommended that, to aid the remediation measures applied to these lakes, a monitoring programme is established.

In all monitoring programmes, the lake levels should be monitored in order to maintain the flow from Lake Pauri through Lake Wiritoa to the sea. Staff gauges may need to be installed.

5.1 Investigative monitoring

If any management strategy is implemented, the strategy should include an expectation of outcome goal as an integral part of the management strategy. The “investigative” monitoring is required to determine the efficacy of that management strategy towards meeting those expectations and when that goal has been achieved. This type of monitoring targets specific aspects of the lake water quality and can include observations of the efficacy of land-based actions in the catchment.

Assessing the efficacy of a management strategy that only has an effect at one time of year (e.g., aeration for destratification) may require more intensive measurements/observations in order to determine when to activate that strategy in spring and then regular observations to allow adaptive management actions until the aeration is turned off in autumn.

Similarly, investigative monitoring may target short-term events including migration of diadromus fish into / out of the lake (can only be done when the outflow from Lake Wiritoa allows continuous connectivity with the sea), or the amount of sediment transported from different land treatments during a rainfall event (can only be done during the rainfall event).

5.1.1 Simple goals

If the stated goal is “*to reduce the number of closures of bathing beaches due to cyanobacteria blooms*”, then monitoring the cyanobacteria abundance at bathing beaches and recording the lake levels is all that is required. Other parameters / variables can also be measured.

The benefits of this monitoring is that it is cheap and can be reported by locals using the lake. The disadvantages are that you have to wait until after the swimming season is over before the success or failure is determined and if the number of closures is not reduced, it is not known why the remediation action failed. Was it the remediation action that failed? or was it an unusual year? What factors influenced the failure? What changes need to be made?

5.1.2 Complex goals

If the stated goal is “*to reduce the number of closures of bathing beaches due to cyanobacteria blooms by preventing thermal stratification and the release of DRP from the sediments in summer*”, then the minimum monitoring programme must include:

1. Lake levels.
2. Regular temperature and DO measurements at selected depth intervals at the deepest part of the lake (marked with a buoy so that every profile is taken at the same location).
3. Water clarity by Secchi depth.
4. An integrated tube water sample (Appendix A) for chlorophyll *a* measurement from at least the top 5 m at that location.
5. Algal species and cell counts for algal biovolume should be done on part of the chlorophyll *a* sample.
6. Top and bottom water nutrients (DRP and TP) and pH at that location. The top sample can be an aliquot from the integrated tube sample. The bottom sample should be about 1 m above the lake bed. During stratified periods this will be below the thermocline.
7. Two replicate zooplankton samples as upwards hauls from the lake bed to surface.
8. A set of sediment samples, including cores, should be also collected annually in winter from below the thermocline and in the shallow near-shore zones.

The management strategy in this case would be the use of aeration. The description and reasoning for the above measurements are as follows:

1) The lake levels must be recorded so that the connecting stream between the two lakes is always an outflow from Lake Pauri into Lake Wiritoa. The monitoring allows maintenance of the streams in a timely manner.

2) The temperature and DO profiles would need to be monitored over winter at monthly intervals until the lakes became mildly stratified in both temperature and DO. The frequency of monitoring would increase to fortnightly until the DO concentrations fell below 7 mg/L in the bottom water. Then the aeration system would be turned on to maintain the DO concentration at above 6.5 mg/L. In autumn, as the DO concentrations increased towards 8 mg/L, the aeration system would be turned off. (See Gibbs & Hickey 2012 for more details).

3) Secchi depth values give an estimate of water clarity and the depth of light penetration (photic zone) that can support photosynthesis. This is likely to coincide with the depth limit for aquatic macrophytes and the critical depth for algal growth.

4) The integrated tube water sample overcomes the problem of uneven distribution of algae and nutrients through the upper water column due to algal buoyancy variability. A minimum tube length of 5 m is recommended for ease of handling, even though the thermocline may be at 8 m depth. The chlorophyll *a* data provides a numerical value that will allow correlation with Secchi depth and algal cell biomass.

5) Species enumeration can follow the seasonal succession of algal species and define which species are present and those that are dominant.

6) The top and bottom water samples will provide information on nutrient concentrations in the lake water column. Although the monitoring only calls for phosphorus monitoring, the water samples could also be analysed for nitrogen species looking for NH_4-N and NO_3-N relationships and TN concentrations. The pH is important in terms of the release of nutrients from inshore waters during the phytoplankton growth phase and the accumulation of CO_2 in the bottom waters during stratification.

7) Zooplankton species and biomass can follow the season cycles of the herbivorous grazers and their impact on algal biomass. Zooplankton are often overlooked and yet they can completely remove an algal bloom or prevent its development if their numbers are high enough at the start of spring. Some species are better than others at grazing specific algal cells.

8) The sediment data provides a reference value for the phosphorus legacy in the lake and will allow an estimate of the efficacy of management strategies to reduce the internal load. Deep lake sediment cores will allow assessment of the rate of burial in the deeper parts of the lake while inshore cores will provide information on the changes in phosphorus content in those areas due to sediment transport processes and algal deposition. The sample timing in winter ensures that most of the phosphorus in the lake will be held in the sediment.

The water quality parameters can be measured monthly or every two weeks in summer, depending on the results of the previous samples and the changes in temperature and DO.

The above monitoring programme, with minor adjustments, could be adopted for the implementation of any mitigation action. Ideally there should be at least a year's worth of monitoring data before implementing the remedial action, but that is not essential. However, where there is essentially no historical data, as with Lake Wiritoa and Pauri, it normally requires at least 5 years of data before trends can be determined with any degree of certainty. While some remedial actions can cause dramatic changes within the first year/season, the monitoring programme should continue for at least another year at the same intensity before the monitoring frequency is reduced. Lake Okaro became mesotrophic for one year after a treatment with Aqual-P. The benefits of that treatment were lost when a storm event deposited a new layer of sediment over the P-inactivation cap.

Within the above monitoring programme data are the four key parameters TP, TN, chlorophyll *a*, and Secchi depth, which allow the calculation of TLI. As the remediation action progresses, it will be important to follow the changes in the lake water quality and identify events which adversely affect the lake or enhance the efficacy of the remediation action. The monitoring data can be used to guide adaptive management with small changes being made to improve the efficacy of the remediation action.

5.2 General monitoring

For general monitoring, the use of in-situ temperature and dissolved oxygen loggers should be considered. A simple thermistor chain made from a number of individual temperature loggers all measuring synchronously would give the highly detailed information required to define the timing of thermal stratification, and whether the lakes were experiencing internal seiche actions and the wind conditions that induced those seiches. This would allow planning for establishing shelter belts to reduce wind stress on the lake surface, if that management strategy were adopted.

Dissolved oxygen loggers attached to the thermistor chains, top and bottom, would allow estimates of sediment oxygen demand and also determine the degree of mixing of oxygenated surface water down into the lake during storm events. This information is needed for the design of aeration systems if that remediation strategy was to be employed.

The thermistor chains and dissolved oxygen loggers would be set to record data at 15-minute intervals and would be left in these lakes for a period of at least 12 months. The temperature and dissolved oxygen loggers would be down loaded at 6-monthly intervals and the data compiled in a data base correlated with wind and rainfall records from the Whanganui Airport met station.

5.3 State of Environment monitoring

State of environment (SOE) monitoring provides the long-term data base for trend analysis and for SOE reporting. Unlike investigative monitoring, which runs for the duration of the remediation action or targeted activity, SOE monitoring is a long term monitoring programme with fewer sampling times but at least 6 visits per year evenly spaced to cover both summer and winter conditions.

Traditionally, four visits per year have been used as the basis for SOE monitoring programmes. Information from the long term monitoring programme on Lake Taupo (Gibbs, 2013) indicates that there has been a shift in the timing of the seasonal cycle for phytoplankton growth in that lake which may be linked to changes in climatic conditions and climate variability. Six visits per year would ensure that variability due to climate effects are less likely to produce bias in the SOE reporting.

The SOE sampling data can come from the investigative monitoring programme where these coincide. This means that the monitoring methodology must be the same and at the same site for both types of monitoring.

SOE monitoring should measure a temperature /dissolved oxygen profile and take water samples as suggested above, or according to the protocols specified by Burns et al. (2000), at the deepest point in the lake. Water sample variables should include TN, TP, chlorophyll *a* and Secchi depth to enable the calculation of a mean annual TLI value for SOE reporting.

It is recommended that

1. a SOE monitoring programme is developed for Lakes Wiritoa and Pauri first and implemented as soon as possible, and

2. the investigative monitoring programme is added to the SOE monitoring programme when the remediation action requiring monitoring is decided and before it is implemented.

5.4 Recommended monitoring programme

The recommended monitoring programme for Lakes Wiritoa and Pauri (Table 7) show the full range of parameters required to meet the One Plan standards. Although not all parameters are required for SOE monitoring, the recommended monitoring programme indicates parameters that are essential for a SOE database (high-lighted in yellow) and therefore should be collected on each visit.

To match the seasonal cycles of dune lakes along the Manawatu-Whanganui coast, one sampling date must be in mid-March and that determines the other sampling dates. Reduced options for just collecting TLI data are also indicated with boxes. Notwithstanding this, site details and observations should be recorded on every occasion.

Note that cyanobacteria toxins are only tested for when high levels of cyanobacteria appear in the lake. However, the toxin monitoring must continue after the cyanobacteria bloom has disappeared until toxin levels are below prescribed levels for contact recreation water quality.

Table 7: Monitoring programme recommended for Lakes Wiritoa and Pauri. The minimum programme should be six samplings per year for the essential data.

Monitoring Programme for Lakes Wiritoa and Pauri														
Monitoring Equipment														
DO/Temperature	Dissolved oxygen / temperature probe on depth-marked cable													
Secchi disc	Weighted black and white quartered 20 cm disc on a soft tape measure													
Water sampler - integrated tube	Composite of 3 integrated tube samples from deepest site													
Water sampler - van Dorne	Sample from about 1 m above the lake bed from the deepest site													
Zooplankton net	Composite of 3 net hauls (63µm mesh on cod end) from lake bed to surface - OPTIONAL													
Sampling time to be around 10 am														
Parameter	**Sample type**	**Units**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**
On-Site observations														
Start and finish time	Date and time	yyyy:mm:dd hh:mm												
Lake Level	Staff guage	m												
Wind condition and direction	estimate	text												
Cloud cover	estimate	%												
Algal bloom / scum *	shoreline	Yes / No												
In-Lake measurements														
Temperature	Instrument profile	°C												
Dissolved oxygen	Instrument profile	g m^{-3}												
Clarity	Secchi depth	m												
Water depth	Echo sounder or Tape measure	m												
Laboratory Measurements														
Algal species (lugols preserved)	water sample	cell counts, biovolume												
Chlorophyll *a*	water sample	mg m^{-3}												
SS/VSS	water sample	g m^{-3}												
Turbidity	water sample	NTU												
E. coli *	water sample	MPN / 100ml												
Conductivity @ 25°C	water sample	µS cm^{-1}												
pH	water sample	pH												
DRP	water sample	mg m^{-3}												
TP	water sample	mg m^{-3}												
NH_4-N	water sample	mg m^{-3}												
NO_3-N	water sample	mg m^{-3}												
TN	water sample	mg m^{-3}												
Cyanotoxins	water sample	mg m^{-3}												

* Data may come from bathing beach monitoring | **TLI parameters** | Essential data | sampling month

6 Acknowledgements

The authors would like to thank Horizons regional Council staff for an interesting, if somewhat wet, site visit to the lakes, and for providing the temperature / DO profiles which defined the water column structure during summer stratification.

This report was funded by Envirolink grant 1283-HZLC96.

7 References

Barko, J.W., James, W.F. (1998) Effects of submerged macrophytes on nutrient dynamics, sedimentation, and resuspension. *In:* Jeppesen, E., Søndergaard, M., Christoffersen, K (eds). *The Structuring role of Submerged Macrophytes in Lakes.* Ecological studies. Springer–Verlag, New York: 197–214.

Buckenham, B., Morgan, B., Baines, J. (2002) Host Communities: Siting and Effects of Facilities. *Case study: An analysis of the host community experience of Wanganui Prison*. Working Paper FS29 by Taylor Baines & Associates. Public Good Science Fund Contract TBA X0002.

Burns, N., Bryers, G., Bowman, E. (2000) *Protocol for monitoring trophic levels of New Zealand lakes and reservoirs*. Ministry for the Environment.

Burns, N., McIntosh, J., Scholes, P. (2005) Strategies for Managing the Lakes of the Rotorua District, New Zealand. *Lake and Reservoir Management,* 21: 61–72.

Carpenter, S., Lodge, D. (1986) Effects of submersed macrophytes on ecosystem processes. *Aquatic Botany,* 26: 341–370.

Edwards, T., Clayton, J. (2002) Aquatic vegetation in Lakes Dudding, Wiritoa, Horowhenua and Pukepuke Lagoon. *NIWA Client Report* HMW02201 to Manawatu-Wanganui Regional Council.

Fowles, C.R. (1982) A biological, physical, and chemical survey of 15 coastal lakes in the Rangitikei-Wanganui Catchment Board region. *Report to Rangitikei-Wanganui Catchment Board and Regional Water Board.*

Gao, Y., Cornwell, J.C., Stoecker, D.K., Owens, M.S. (2012) Effects of cyanobacterial-driven pH increases on sediment nutrient fluxes and coupled nitrification-denitrification in a shallow fresh water estuary. *Biogeosciences*, 9: 2697–2710.

Gibbs, M. (2011) Lake Horowhenua review: Assessment of opportunities to address water quality issues in Lake Horowhenua. *NIWA Report* HAM2011-046, report to Horizons Regional Council, funded through Envirolink: 109.

Gibbs, M. (2013) Lake Taupo Long-term Monitoring Programme: 2011 – 2012. *NIWA Client Report* HAM2013-020, prepared for Waikato Regional Council. March: 136. Available on line from the Waikato Regional Council website as Technical Report 2013/23.

Gibbs, M., Hickey, C. (2012) Guidelines for Artificial Lakes: Before construction, maintenance of new lakes, rehabilitation of degraded lakes. *NIWA Report No.* HAM2011-045, prepared for Ministry of Science and Innovation. June: 157. http://www.envirolink.govt.nz/PageFiles/31/Guidelines%20for%20artificial%20lakes.pdf

Hickey, C.W., Gibbs, M.M. (2009) Lake sediment phosphorus release management—Decision support and risk assessment framework. *Journal of Marine and Freshwater Research,* 43: 819–856.

James, A., Joy, M. (2009) Prioritisation for restoration of out-flow stream habitat of coastal wetlands on the west coast of the Manawatu-Wanganui region*. Massey University report prepared for Horizons Regional Council*: 110.

Kelly, D. (1978) A plant distribution survey of twelve coastal lakes. *Report to Rangitikei-Wanganui Catchment Board and Regional Water Board.*

McBride, S.D., Nguyen, M.L., Rickard, D.S. (1990) Implications of ceasing annual superphosphate topdressing applications on pasture production. *Proceedings of the New Zealand Grassland Association,* 52: 177–180.

Ogle, C.C., Wanganui Botanical Group (1999) Wetland plants and forest remnants list, Lake Wiritoa, Wanganui. *Unpublished Wanganui Plant List* No. 101.

NIWA (2013) Aquatic weed management. (http://www.niwa.co.nz/our-science/aquatic-biodiversity-and-biosecurity/our-services/aquaticplants/outreach/weedman)

Pridmore, R.D. (1987) Phytoplankton response to changed nutrient concentrations. Chapter 18. *In:* Vant, W.N. (*Ed*) Lake Managers Handbook: A guide to undertaking and understanding investigations into lake ecosystems, so as to assess management options for lakes. *Water & Soil Miscellaneous Publication*, No. 103: 183–194: 230.

Rueckert, A., Wood, S.A., Cary, S.C. (2007) Development and field assessment of a quantitative PCR for the detection and enumeration of the noxious bloom-former *Anabaena planktonica*. *Limnology and Oceanography Methods*, 5: 474–483.

Scheffer, M., Hosper, S.H., Meijer, M-L., Moss, B., Jeppesen, E. (1993) Alternative Equilibria in Shallow Lakes. *TREE.* 8: 275–279.

Smith, C.M., Wilcock, R.J., Vant, W.N., Smith, D.G., Cooper, A.B. (1993) Towards sustainable agriculture: freshwater quality in New Zealand and the influence of agriculture. *MAP Policy Technical Paper*, 93/10.

Stumm, W., Morgan, J.J. (1995) *Aquatic chemistry: chemical equilibria and rates in natural waters.* 3rd ed. New York, Wiley-Interscience: 1022.

Sverdrup, H.U. (1953) On conditions for the vernal blooming of phytoplankton. *Journal du Conseil International pour l' Exploration de la Mer,* 18: 287–295.

Vant, W.N. (1982) Rangitikei-Wanganui Catchment Board sand county lakes: results of MWD chemical and biochemical analysis*. Water Quality Centre report to Rangitikei-Wanganui Catchment Board*: 9.

Wetzel, R.G. (1995) Death, detritus and energy flow in aquatic ecosystems. *Freshwater Biology,* 33: 83–89.

Appendix A Integrated tube sampler

For Lake Wiritoa and Pauri being sampled from a boat, the integrated tube sampler consists of a 5.2 m length of ~20 mm diameter **transparent flexible** plastic (PVC) tube (Figure A-1). Considered vertically, the top is trimmed to be a smooth right-angled end and fitted with a plastic plumping ball-valve which can close the tube with a 90º turn. A length of cord is tied around the tube just below the tap leaving about 2 m of free end – this is the safety tether. Another length of cord is run the full length of the tube to the bottom, leaving about a metre spare at each end – this is the retrieval cord. The lower end of the cord is tied through one small hole drilled through the wall of the tube just above the bottom so that the cord has minimal effect on the inside diameter of the tube. The remaining free end of this cord is used to secure a lead weight (e.g., about 250 g) made from lead flashing wrapped around the tube so that the weight is about 5 cm above the bottom end of the tube. A layer of 'Duck' tape or wide electrical tape would held secure the weight. Tie a small plastic float to the top end of the long retrieval cord so that it can be easily recovered if it falls out of the boat. Before and after use, wash the tube thoroughly with tap water and store it out of sunlight.

Put band of electrical tape 20 cm below the top end of the tube as the surface indicator for 5 m. The integrated sample is ready to use. A 5-litre sample bottle and a funnel with a wide spout that will fit into the sample bottle, are also needed.

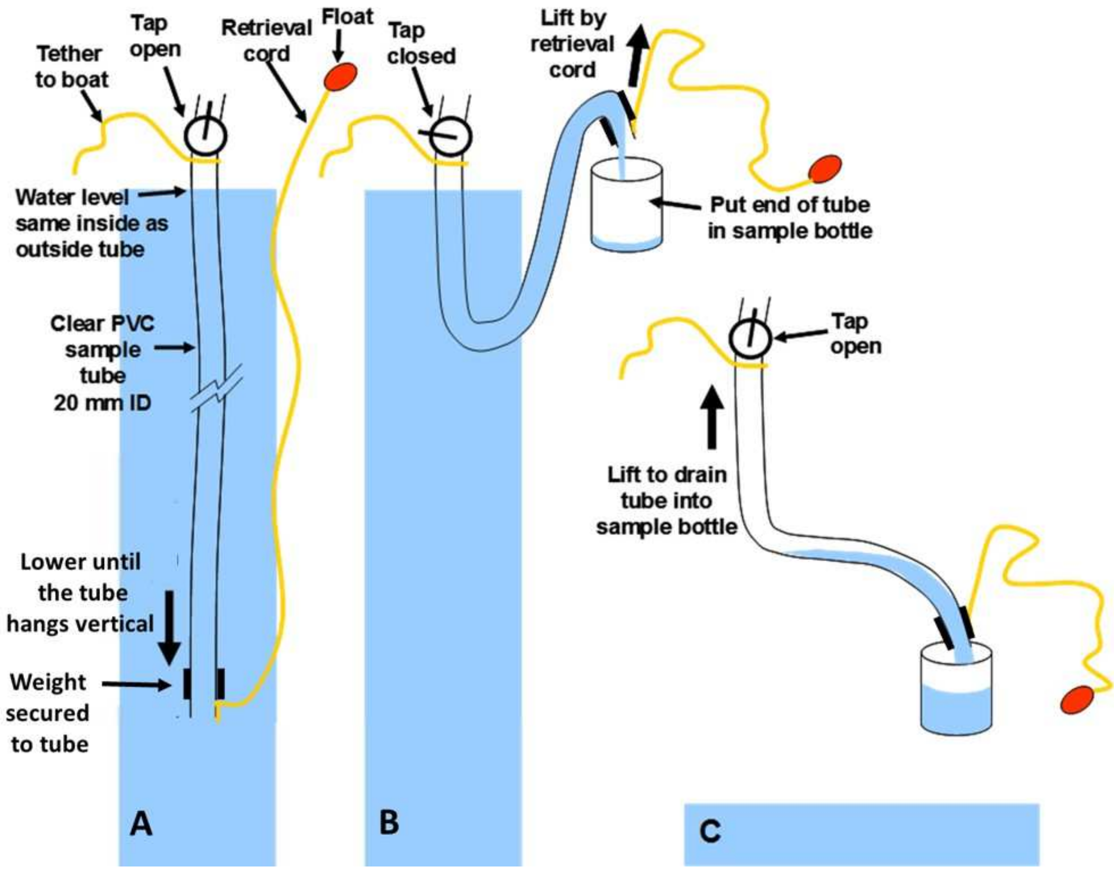

Figure A-1: Integrated tube sampler operation schematic. A) collecting sample, B) retrieving sample, and C) transferring sample to sample bottle. See text for details.

Operating the integrated tube sampler on the boat is as follows:

1 Rinse all sampling gear and the sample bottle with surface lake water.

2 **Open the tap** and tie the safety tether cord to the boat leaving plenty of slack line.

3 Lower the weighted end of the tube slowly through the water column **so that the water level inside the tube remains at the same level as the water outside the tube**. (Figure A-1 A).

4 Stop when the water level in the tube is at the surface (5 m) marker.

5 **Close the tap** and let the tap end lie in the bottom of the boat.

6 Use the retrieval cord to lift the bottom end of the tube to the surface and immediately put the bottom end of the tube in the sample bottle (Figure A-1 B).

7 Raise the top end of the tube above the rest of the tube before **opening the tap**.

8 Drain the water into the sample bottle (Figure A-1 C).

9 Repeat steps 3 to 8 twice more to collect three integrated tube samples and combine them in the sample bottle to form a composite sample.

10 Mix well before filling the sample bottle via the funnel.

To prevent the spread of nuisance algal species, the integrated tube sampler for Lakes Wiritoa and Pauri should not be used on any other lakes.

horizons regional council
11-15 Victoria Avenue
Private Bag 11 025
Manawatu Mail Centre
Palmerston North 4442
T 0508 800 800
F 06 952 2929
help@horizons.govt.nz
www.horizons.govt.nz