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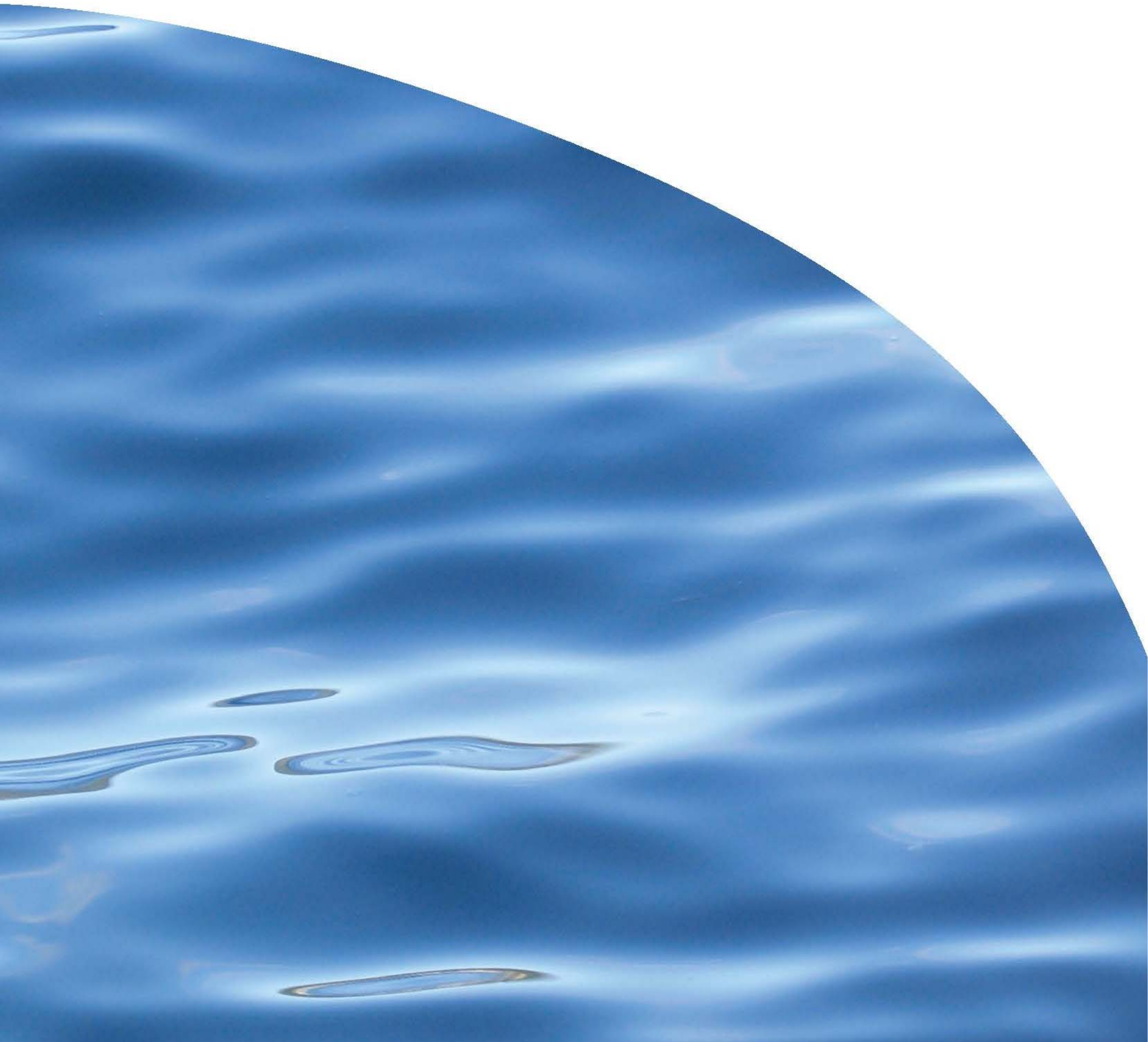
ECOLOGICAL CONDITION OF SIX SHALLOW SOUTHLAND LAKES



ECOLOGICAL CONDITION OF SIX SHALLOW SOUTHLAND LAKES

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MSI Envirolink Report prepared for Environment Southland

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EXECUTIVE SUMMARY

This report was commissioned by Environment Southland (ES) to assess the water quality and ecological condition of six shallow Southland lakes. We examined the water quality and physico-chemistry, phytoplankton communities, zooplankton communities, aquatic macrophyte communities, benthic invertebrate communities, fish communities and expert-assessed ecological integrity of these lakes.

We collated data from three sources for our analysis. Our primary database was collected as part of a 2004-2008 New Zealand-wide survey of the ecological integrity of shallow coastal lakes. In 2012, we conducted a repeat sampling in three Southland lakes from that survey (Lakes George/Uruwera, Vincent and The Reservoir) we also surveyed three new lakes (Lake Brunton and Lakes Sheila and Calder on Stewart Island/Rakiura). Additionally, we included water quality data collected by Environment Southland from three of the six lakes in 2000 and 2007 in our analysis.

Our research objectives were to (i) assess the ecological condition of the shallow lakes and (ii) to place them in a national context by comparing them to over 40 other shallow coastal lakes from around New Zealand. We also aimed to identify any special characteristics of the Southland lakes and to provide information on key knowledge gaps and management implications of our findings.

Overall, the mainland Southland lakes were of moderate to good water quality compared to other shallow lakes around New Zealand. It must be emphasised however, that such lakes in New Zealand have generally been heavily impacted by agricultural land use and introductions of numerous noxious invasive fish and macrophyte species.

Lake George/Uruwera has a very short water residence time and this probably prevents phytoplankton proliferation in this lake. It is the only lake in our dataset to contain *Daphnia carinata*, a native water flea which may play an important role in regulating phytoplankton biomass in the lake. Total phosphorus (TP) and total nitrogen (TN) both declined markedly between 2000 and 2004. It is not known why this occurred.

Lake Vincent is oligotrophic and the phytoplankton growth in this lake may be limited by phosphorus availability because nitrate levels in the lake tend to be high. Therefore, this lake would probably be particularly vulnerable to intensifying land use resulting in additional phosphorus input to the lake. However, a large decrease in phytoplankton biomass in this lake seems to have occurred between 2000 and 2004.

In 2012, The Reservoir was eutrophic and has high phytoplankton biomass dominated by the large desmid, *Staurastrum*. This contrasts with the prior sampling in 2004 when the lake had a lower phytoplankton biomass and was dominated by cyanobacteria and small green algae. The water quality data seem to suggest that phytoplankton in the lake are now nutrient

saturated and it is not known what currently limits further increases in their biomass and growth.

Lake Sheila and Calder are pristine lakes which are strongly influenced by surrounding wetlands. They are humic-stained and have low nutrient concentrations and phytoplankton biomass. Lake Calder has an unusually low pH and very low solute concentrations suggesting that it is a rain-fed, seepage lake.

Lake Brunton is different to the other lakes in this study as it is an intermittently closed and open lake/lagoon (ICOLL), regulated by the natural breaching and closing of a seaward barrier. The lake undergoes large variations in salinity and when open to the sea, it is substantially flushed with sea water. At the time of sampling in 2012 it had just begun to fill after a short period of opening to the sea. It had low phytoplankton biomass and almost no zooplankton. However, it had high nitrate concentrations.

In 2004, the phytoplankton communities of the mainland Southland lakes were dominated by cyanobacteria and small green algae. To the best of our knowledge, the cyanobacteria taxa present in 2004 are not nitrogen-fixing and are not known to produce toxins. Casual observation in 2012, suggested that the phytoplankton community in The Reservoir had changed markedly, to be dominated by the large desmid, *Staurastrum*.

The metazooplankton communities of the Southland lakes showed low diversity and low biomass, being dominated by a calanoid copepod and small cladocerans. However, the native *Daphnia carinata* was present in Lake George/Uruwera in 2004 and 2012, the only shallow lake in New Zealand in which this zooplankter was found. While it was recorded at low densities both times, it is not clear how important a role *Daphnia* plays in regulating phytoplankton biomass in Lake George/Uruwera. An unusual cladoceran (a bosminid) was observed in the 2012 samples from Lakes Sheila and Vincent and we are not sure if it is a variant or sub-species of the common *Bosmina meridionalis*.

Overall, the submerged macrophyte communities of the Southland lakes have low taxonomic diversity and two of the lakes contain a non-indigenous species. While macrophyte communites were present in all six lakes, macrophyte beds in Lake George/Uruwera and The Reservoir were sparse. This is probably normal for Lake George/Uruwera due to its large fetch and exposure to winds, but this may indicate that macrophyte community in The Reservoir is vulnerable. The abundant macrophyte community of Lake Vincent no doubt confers some resilience to the effects of eutrophication for this lake. The macrophyte community of Lake Brunton consisted solely of *Ruppia megacarpa*, which has a broad salinity tolerance and is an inhabitant in healthy ICOLL ecosystems.

Benthic invertebrate communities in the Southland lakes were quite varied. The pristine Lakes Sheila and Calder had low densities of invertebrates but had relatively high diversity. Lake Vincent had a high diversity of invertebrates, including the native freshwater mussel, *Echyridella menziesi* (kākahi). This species was also found in Lake George/Uruwera, and while it has the potential to filter substantial amounts of phytoplankton from lake water, its importance in regulating phytoplankton biomass in these lakes is unknown. Overall, the macrobenthos of Southland shallow lakes tended to fall into three broad categories, either, those of lakes influenced by saline conditions, those with high macroinvertberate diversity associated with lakes dominated by macrophytes, and those with low diversity associated with lakes with *. e.* little or no macrophyte communities).

Generally, both native and non-indigenous fish diversity in the Southland lakes is low. The nationally declining longfin eel was found in Lakes George/Uruwera, Vincent and The Reservoir, while the regionally declining giant kokopu was found in Lakes Vincent and The Reservoir, indicating that Southland lakes are a stronghold for these native species. The exotic perch was found in Lake Vincent and Lake George/Uruwera and its presence may play a role in the unusually low catch per unit effort of native fish in these two lakes.

In comparison to 41 shallow lakes around New Zealand, the ecological integrity of the mainland Southland lakes was ranked only moderately by an expert panel. Reasons for downgrading specific lakes include the presence of the non-indigenous macrophyte, *Elodea canadensis* and non-indigenous perch, generally intensive catchment development, low native fish catch per unit effort, and moderately high phytoplankton biomass.

The Southland lakes show moderate condition in terms of water quality and ecological condition. They rank well in some indicators and not so well in others. This report lists a number of knowledge gaps which, if addressed, would provide a better understanding of the vulnerabilities and degrees of resilience these lakes have to increasing anthropogenic pressures. The key aspects of these lakes to monitor and manage are the maintenance and enhancement of their macrophyte communities, controlling the downstream impacts of agricultural land uses in their catchments, and preventing the spread of invasive pest species into the lakes.

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1. SCOPE OF THIS REPORT

Environment Southland requested an analysis of the ecological condition of selected shallow Southland lakes. This report utilises historical Environment Southland data, data collected during a 2004 sampling campaign of New Zealand shallow coastal lakes and new data collected from six lakes in 2012. It examines the ecological condition of the lakes as represented by water quality, phytoplankton, zooplankton, macrophytes, benthic invertebrates and fish. The report focuses on placing the ecological condition of the Southland lakes within the context of shallow coastal lakes throughout New Zealand. This report is similar in scope to a report on the ecological condition of three Northwest Nelson lakes commissioned by the Tasman District Council (Schallenberg 2011).

2. BACKGROUND INFORMATION ABOUT THE LAKES

2.1. Lake George/Uruwera

Lake George/Uruwera is a shallow coastal dune lake on the south coast of New Zealand, just west of Colac Bay/Oraka. The lake is situated within the Lake George/Uruwera Wildlife reserve and drains a mixture of protected lands (the Longwood Mountains and the Owen Conservation Project), pasture and fringing wetlands (Figure 1; Table 1). Historical gold mining activities in the lake's catchment have resulted in substantial sediment infilling of the lake bed. The protection of the land immediately around the lake is resulting in the regeneration of native vegetation. Its value as a wildlife reserve is also reflected in the lake's reputation as a local stronghold for giant kokopu.

The lake has a fairly major freshwater inflow in relation to its volume, resulting in a very short theoretical water residence time (a high flushing rate) of 19 days (Table 1). This indicates that the lake is likely to be strongly influenced by catchment-scale activities which result in the mobilisation of sediment and nutrients, further suggested by the high estimated nitrogen (N) and phosphorus (P) loading values (Table 1).

Table 1. Morphometric, hydrological and catchment data for Lake George/Uruwera, Southland. Data are from Drake *et al.* (2009, 2010) and from the Freshwater Ecosystems New Zealand (FENZ) database (Leathwick *et al.* 2010).

Lake George/Uruwera	
Altitude (m a. s. l.)	10
Lake area (ha)	90. 8
Maximum depth* (m)	2. 0
Lake volume* (m^3)	605401
Lake water residence time* (days)	19
Catchment area (km^2)	29. 12
N loading* (T/y)	17. 0
P loading* (T/y)	0. 76
Catchment % pasture	50
Catchment % natural	43

Note: Lake volume and water residence time are estimated based on modelled lake bathymetry (using a digital terrain elevation model) and catchment flow using the TOPNET model (http://www. niwa. co. nz/news-and-publications/publications/all/wru/2008-26/available).
Catchment data are from the Land Cover Database 2 (Ministry for the Environment).
Nitrogen (N) loading estimate is from the CLUES model (http://www. maf. govt. nz/environment-natural-resources/water/clues).
*These are rough estimates as calculated in FENZ (Leathwick *et al.* 2010).

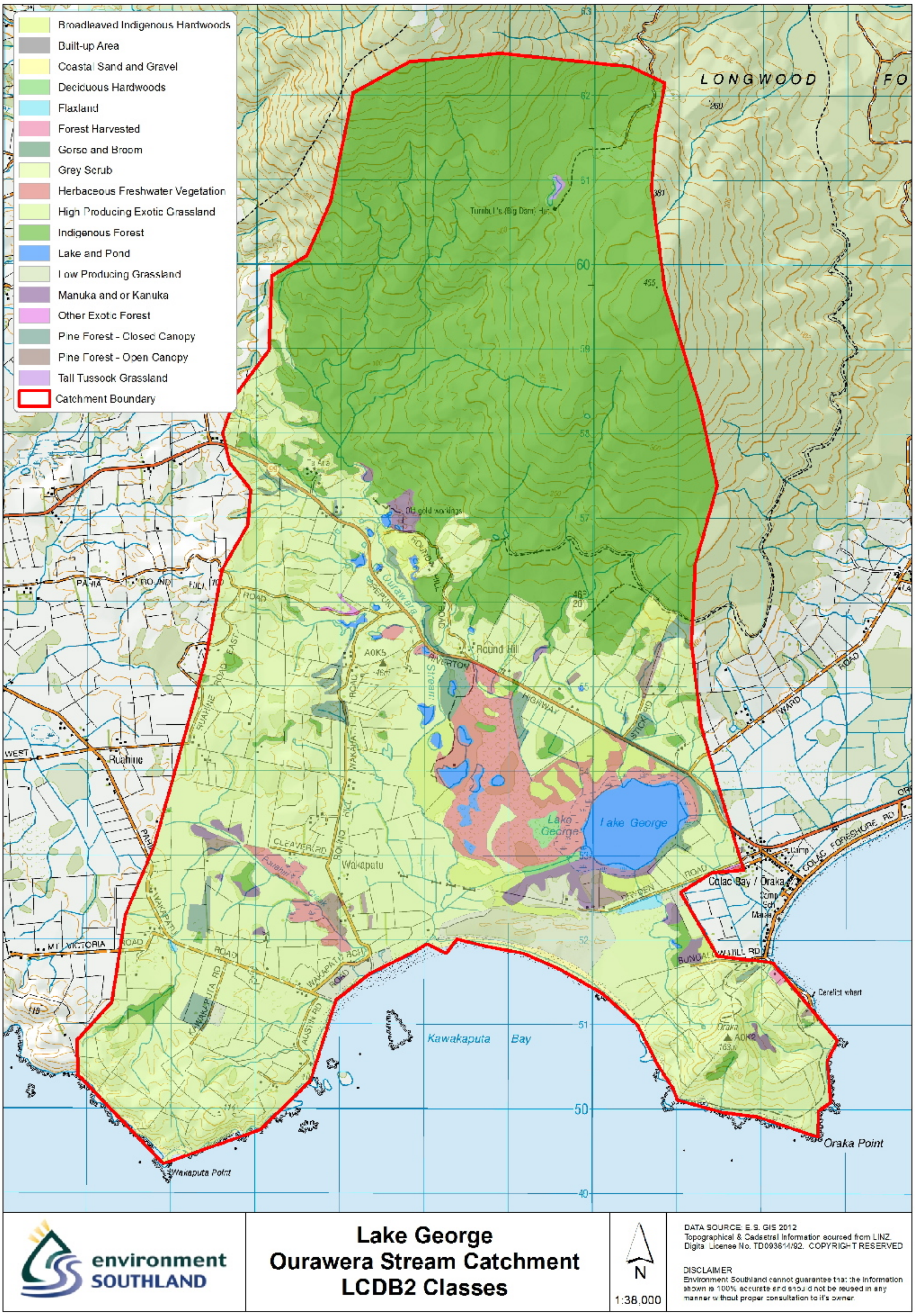

Figure 1. Location of Lake George/Uruwera, Southland. Catchment land use information is from the Land Cover Database 2 (Ministry for the Environment). Map provided by Environment Southland.

2.2. Lake Vincent

Lake Vincent is a shallow dune lake located on the south east coast of the South Island, between the Mataura River mouth and Waipapa Point (Figure 2). It drains a relatively small catchment dominated by intensive agriculture including dairying (Table 2). Freshwater inflows are small and, therefore, Lake Vincent has an intermediate theoretical water residence time of 49 days. This suggests that in-lake processes are likely to have some influence on water quality and the ecology of the lake.

Table 2. Morphometric, hydrological and catchment data for Lake Vincent, Southland. Data sources are as described in Table 1.

Lake Vincent	
Altitude (m a. s. l.)	19
Lake area (ha)	17. 2
Maximum depth* (m)	5. 0
Lake volume* (m^3)	286801
Lake water residence time* (days)	49
Catchment area (km^2)	3. 14
N loading* (T/y)	6. 0
P loading* (T/y)	0. 05
Catchment % pasture	91
Catchment % natural	6

*These are rough estimates as calculated in FENZ (Leathwick *et al.* 2010).

Figure 2. Location of Lake Vincent, Southland. Catchment land use information is from the Land Cover Database 2 (Ministry for the Environment). Map provided by Environment Southland.

2.3. The Reservoir

The Reservoir is a shallow reservoir located near Slope Point and Haldane Bay, which resulted from the damming of a small coastal creek. The outlet of the lake is not regulated. The headwaters of the lake are indigenous forest, but the lake's small catchment is mainly dominated by intensive agriculture including dairying (Figure 3; Table 3). As in the case of Lake Vincent, the small inflow to the lake results in an intermediate theoretical water residence time of 55 days, suggesting that in-lake processes have some influence on the lake's water quality and ecology.

Table 3. Morphometric, hydrological and catchment data for The Reservoir, Southland. Data as described in Table 1.

The Reservoir	
Altitude (m a. s. l.)	13
Lake area (ha)	35. 5
Maximum depth* (m)	5. 0
Lake volume* (m^3)	592115
Lake water residence time* (days)	55
Catchment area (km^2)	5. 73
N loading* (T/y)	2. 0
P loading* (T/y)	0. 20
Catchment % pasture	66
Catchment % natural	34

*These are rough estimates as calculated in FENZ (Leathwick *et al*. 2010).

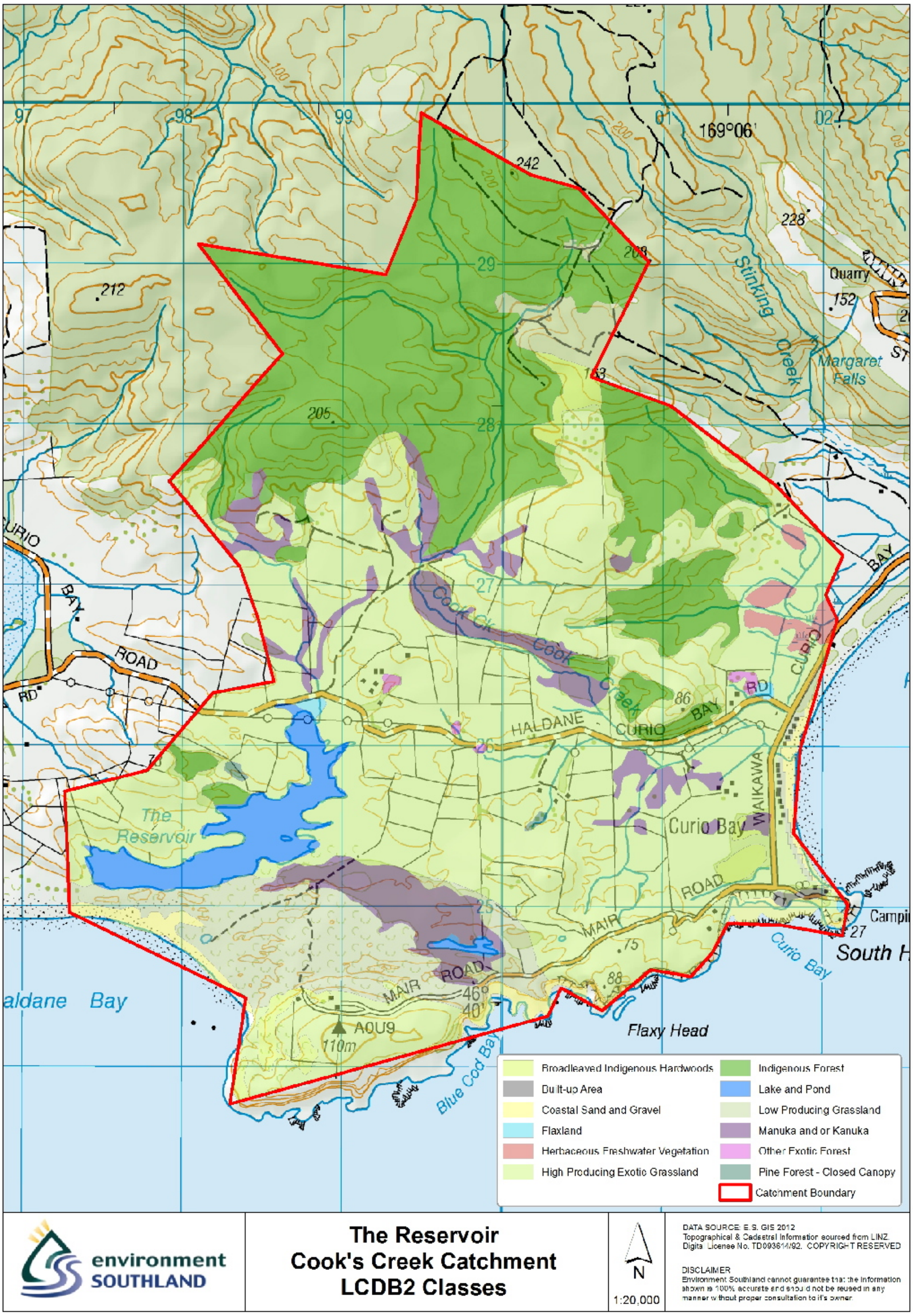

Figure 3. Location of The Reservoir, Southland. Catchment land use information is from the Land Cover Database 2 (Ministry for the Environment). Map provided by Environment Southland.

2.4. Lakes Sheila and Calder

Lakes Sheila and Calder are located less than 1 km apart near the centre of the Freshwater River catchment in Stewart Island/Rakiura. The lakes are situated on opposite sides of Freshwater River, within an extensive unmodified wetland complex (Figure 4). Despite their close proximity, the lakes are quite different in their hydrology. Lake Sheila has a moderate inflow and has a relatively short theoretical water residence time compared to Lake Calder, which appeared to be seepage fed at the time of our sampling and generally has a longer theoretical water residence time than Lake Sheila (Table 4). The higher elevation of Lake Calder suggests that it might be a perched lake and may not be connected to Freshwater Creek by surface water flows. The hydrological data in Table 4 are estimated from maps and, as such, are rough estimates of the hydrological characteristics of lakes located within wetlands. .

Lakes Sheila and Calder represent water quality and ecological conditions of pristine and unmodified shallow, wetland lakes.

Table 4. Morphometric, hydrological and catchment data for Lakes Sheila and Calder, Stewart Island/Rakiura. Data sources as described in Table 1.

	Lake Sheila	**Lake Calder**
Altitude (m a. s. l.)	6	13
Lake area (ha)	14. 1	4. 1
Maximum depth* (m)	3. 5	6. 7
Lake volume* (m^3)	163016	91487
Lake water residence time* (days)	37	69
Catchment area (km^2)	1. 03	0. 31
N loading* (T/y)	4. 8	0. 9
Catchment % pasture	0	0
Catchment % natural	100	100

*These are rough estimates as calculated in FENZ (Leathwick *et al.* 2010).

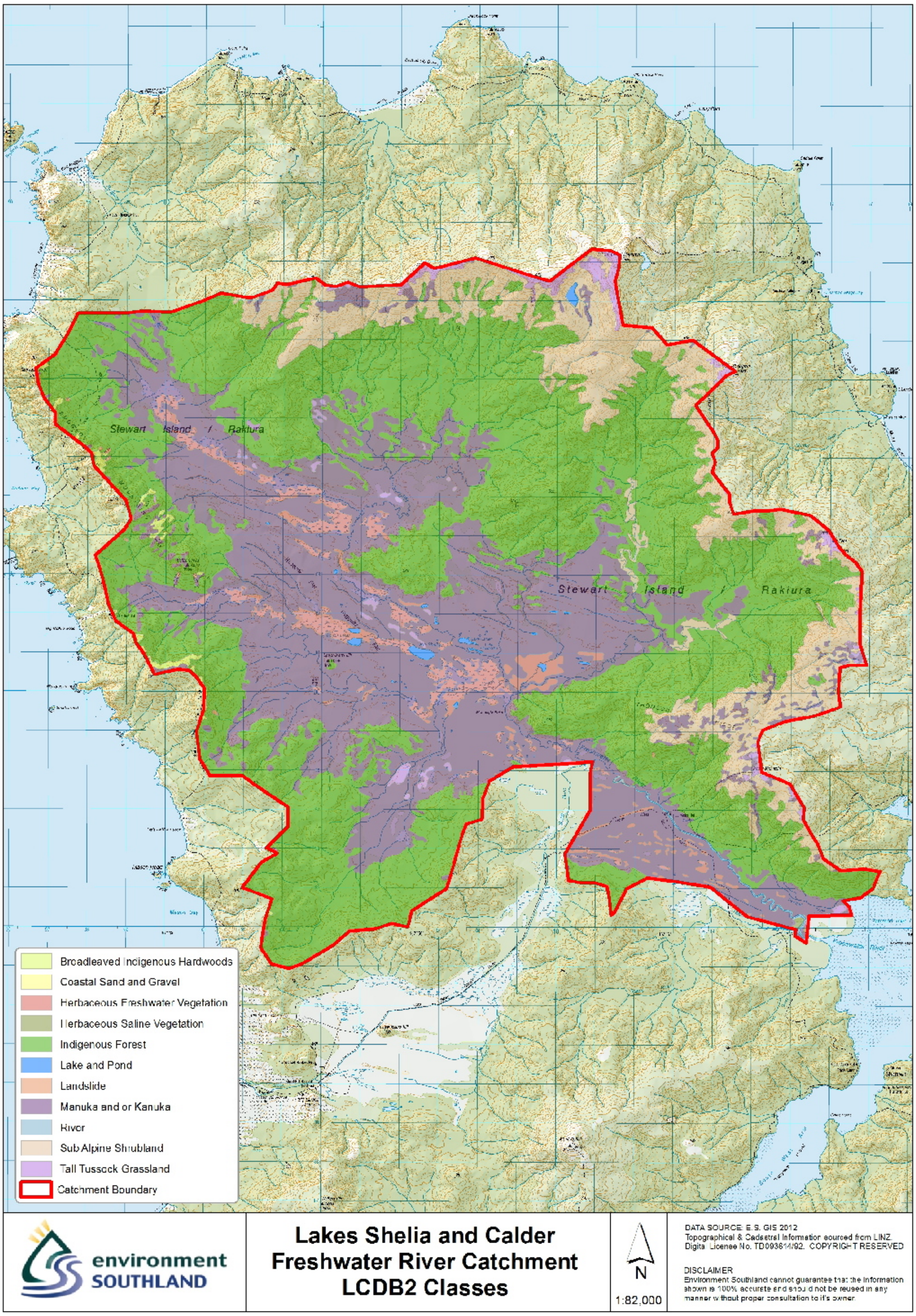

Figure 4 Locations of Lake Sheila and Calder, Stewart Island/Rakiura. Catchment land use information is from the Land Cover Database 2 (Ministry for the Environment). Map provided by Environment Southland.

2.5. Lake Brunton

Lake Brunton is a shallow, intermittently closed and open lake/lagoon (ICOLL) located near Waipapa Point on the south coast of the South Island. Its catchment is low-lying and is almost entirely intensively farmed (Figure 5). Lake Brunton is surrounded by a narrow band of wetlands. Upstream from this ICOLL, former wetlands have been converted to pasture, although some small ponds persist. Lake Brunton is very shallow and has a very short theoretical water residence time and a high nitrogen load (Table 5). However, the effects of this loading will likely be modified greatly by the opening and closing of this ICOLL to the sea, which occurs naturally.

Although we examined other ICOLLs in this report, none of the ICOLLs sampled had as great a marine influence as Lake Brunton. At the time of sampling, Lake Brunton had just closed to the sea and was beginning to infill from riverine sources, but was still at a very low water level and was highly saline. This strong marine influence means that our data from Lake Brunton are quite divergent from other lakes and ICOLLs analysed in this report.

Table 5. Morphometric, hydrological and catchment data for Lake Brunton, Southland. Data sources as described in Table 1.

Lake Brunton	
Altitude (m a. s. l.)	6
Lake area (ha)	25. 8
Maximum depth* (m)	3. 3
Lake volume* (m^3)	286580
Lake water residence time* (days)	10
Catchment area (km^2)	16. 00
N loading* (T/y)	12. 63
P loading* (T/y)	0. 84
Catchment % pasture	87
Catchment % natural	13

Note: The water residence time is based on the mean annual freshwater inflow and on a static volume. When the lake is closed to the sea and filling, the water residence time will be substantially longer than the estimate provided here.
*These are rough estimates as calculated in FENZ (Leathwick *et al.* 2010).

Figure 5. Location of Lake Brunton, Southland. Catchment land use information is from the Land Cover Database 2 (Ministry for the Environment). Map provided by Environment Southland.

3. OBJECTIVES

Our focus is to provide an ecological assessment of six shallow lakes in the Southland region that have not been previously studied in detail. There is an increasing recognition of the biodiversity values and ecosystem services provided by shallow coastal lakes. At the same time, increasing pressures such as nutrient runoff, hydrological alteration, and climate change are expected to affect such lakes. Therefore, in this study we adopt a comparative research design to assess the ecological health of six shallow lakes to help inform the prudent management of these systems. Within this research framework our methodology and objectives include:

- The analysis of a multi-lake dataset (Drake *et al.* 2009, 2010) to compare the state of the Southland lakes to other shallow coastal lakes around New Zealand. The data include measures of water quality, macrophytes, phytoplankton, zooplankton, benthic invertebrates, fish, and ecological integrity. The mainland Southland lakes were sampled in 2004 as part of this study.
- Collection of data in 2012 from three lakes previously sampled in 2004 and an additional three lakes using similar methodology as Drake *et al.* (2009). The data include all previous measures, excluding fish.
- The collation of all previous data collected by Environment Southland on these six lakes to examine trends in water quality variables over time.
- The identification of special characteristics or features of these lakes which could merit special management.
- The identification of knowledge gaps concerning these shallow coastal lakes.

This report greatly enhances the present understanding of these lakes in a national context and is similar in scope to a previously published report on northwest Nelson shallow lakes (Schallenberg 2011).

4. DATA SOURCES

This study makes use of data from three sources:

1. An extensive, multi-lake dataset collected in late summers from 2004-2008 (Drake *et al.* 2009; 2010). The data were collected as part of a Cross Departmental Research Pool (CDRP) project and we reanalyse the data, acknowledging that it was collected under a joint Department of Conservation/NIWA/University of Otago research programme. The multi-lake dataset includes data from shallow coastal lakes located from Northland to Campbell Island. Each lake was sampled once in late summer (February - April) and variables included measures of water quality (46 lakes), phytoplankton (46 lakes), zooplankton (46 lakes), fish (41 lakes), macrophytes (41 lakes), invertebrates (41 lakes), catchment land use and hydrology (46 lakes) (refer to the Drake *et al*. (2009, 2010) for methodological details). Data for Southland Lakes George/Uruwera, Vincent and The Reservoir collected in March 2004 form part of the CDRP dataset.
2. Data we collected in March 2012 at Lakes George/Uruwera, Vincent and the Reservoir, using similar methods to those for collecting the CDRP data, excluding fish data. In addition, we collected data from Lakes Sheila, Calder and Brunton in March 2012. While all of the field and laboratory protocols were kept consistent between the 2004 and 2012 sampling campaigns, there were some unavoidable changes which could have affected between-year comparisons. Laboratory water quality measurements were carried out by a different laboratory and so detection limits differ somewhat between the CDRP data and 2012 data. Although macroinvertebrate sampling and laboratory sorting protocols were consistent between years, macroinvertebrates identifications were conducted by a different laboratory. To make the macroinvertebrate taxonomic data more consistent between datasets, we grouped many species into their respective genera for analysis.
3. A dataset provided for Lakes George/Uruwera, Vincent and The Reservoir by Environment Southland including measures of water quality collected in March/April 2000. We used four water quality parameters from this dataset in our analysis of temporal changes.

We edited all the data for accuracy and errors. Samples with values below analytical detection limits were attributed a value of half the detection limit.

5. VALUES

5.1. Water quality

Water quality samples and physico-chemical measurements were taken from two open water sites in each lake during CDRP and 2012 sampling. Samples were collected with an integrated tube sampler from either the entire water column or the upper 1. 5 m at deeper sites.

Eutrophic Lake George/Uruwera was one of the more turbid lakes we sampled (Table 6), showing a tendency toward relatively high turbidity and a shallow euphotic depth, however we don't think this lake is turbid enough for primary productivity to be light limited under normal conditions. The euphotic depth of around 1 m indicates that there should be sufficient light for macrophytes to be able to colonise the majority of the lake bottom, although light penetration would be reduced temporarily by sediment resuspension during windy periods. Although the chlorophyll-*a* (chl-*a)* levels measured in Lake George/Uruwera in 2012 (Table 6) are not unusual for shallow lakes, in 2004 chl-*a* was slightly higher. Similarly, dissolved inorganic nutrients were lower than in 2012. This might have been related to the lower water level in the lake in 2004 than in 2012, when we found the water level to be unusually high. A lower water level in 2004 could either indicate that weather conditions had been drier with low freshwater inflows in 2004 or that the outflow of the lake had been raised in 2012. Either of these situations can affect the water residence time. It is likely that with an average water residence time of 19 days (Table 1), phytoplankton growth and proliferation in this lake may be limited by dilution and wash out. This water residence time of Lake George/Uruwera is much shorter than the average (262 d) and median (79 d) water residence times for all the shallow lakes sampled.

Lake Vincent had very high nitrate concentrations, however it had a low phytoplankton biomass (chl-*a*). The occurrence of high nitrate concentrations and low soluble reactive phosphorus concentrations together with the high DIN:TP ratios indicates that the phytoplankton growth is probably phosphorus-limited. The unusually low phytoplankton biomass in this lake may also be related to the substantial macrophyte beds because some macrophytes (*e. g.* charophytes) are known to produce chemical compounds that inhibit phytoplankton growth. Known as allelopathy, this type of chemical inter-species competition has been demonstrated to occur in some lakes (see van Donk & van de Bund 2002; Mulderij *et al*. 2006). So, depending on the variable of focus, the trophic state of Lake Vincent could be considered oligotrophic (based on chlorophyll-*a*) or eutrophic (based on TN).

The Reservoir was eutrophic with high phytoplankton biomass. In 2004, nutrient data suggested that phytoplankton growth was limited by both nitrogen and phosphorus. In contrast, in 2012, high dissolved nutrient concentrations suggest that nutrient availability may not have been limiting to phytoplankton growth. This suggests the lake may currently be receiving nutrients in excess of its present phytoplankton demands levels, which increased markedly between 2004 and 2012. It's possible the lake may be reaching a critical state with regard to phytoplankton biomass, but the limited extent of data warrants some caution in this interpretation. In 2012, a bloom of large-celled (> 50 µm) *Staurastrum* sp. was present, and the large size of this phytoplankter helps explains why water clarity and light penetration (*i. e.* euphotic depth) are still quite high in the lake. If Staurastrum were to be replaced by other bloom-forming phytoplankters (*e. g.* colonial greens or cyanobacteria), the lake could experience a sudden decline in water clarity.

Oligotrophic Lake Sheila is a wetland lake, connected to the Freshwater River. Being located in a remote part of Stewart Island/Rakiura, it is not surprising that it has very low levels of phytoplankton biomass and nutrients and that it is somewhat coloured by dissolved humic matter from vegetation and soil humus. Oligotrophic Lake Calder shows similarities with Sheila in its very low phytoplankton and nutrient levels and moderate humic acid staining, but Calder has some striking differences to Sheila. From our observations and from the lake elevation data in Table 4, we believe that Calder is a perched seepage lake and is not directly connected to Freshwater River by surface water flow. The very low pH and dissolved solute concentrations (*i. e.* calcium and magnesium) measured in the lake support this hypothesis.

When the ICOLL, Lake Brunton, was sampled, it had recently closed and had begun to fill after being substantially flushed by seawater. As such, it showed very high specific conductivity, calcium and magnesium concentrations. It also had extremely high nitrate concentrations for a shallow coastal lake. The high nitrate concentrations may have come from flooded lake bed sediments during filling. Schallenberg *et al*. (2010) observed a similar spike in nitrate after the initial stages of filling of Waituna Lagoon, and they attributed the source of the nitrate loading to newly flooded lake bed sediments. As the lake sediments are dewatered after the barrier bar is breached, reduced sediments become oxidised and organic nitrogen mineralises to nitrate. Thus, flooding dewatered lake bed sediments may be a source of nitrate to ICOLLs as they fill up. Depending on which trophic state variable is considered, the trophic state of Lake Brunton at the time of sampling was either oligotrophic (based on chl-*a*) or eutrophic (based on TN and TP).

Table 6. Physico-chemical data for Southland lakes.

		CDRP (2004) values			2012 values					
Variable	**Unit**	**George**	**Vincent**	**Reservoir**	**George**	**Vincent**	**Reservoir**	**Sheila**	**Calder**	**Brunton**
Conductivity	µS/cm	182	282	248	186	333	284	273	127	29850
pH		7.1	7.5	7.3	8.09	7.95	7.75	7.14	5.3	7.37
Turbidity	NTU				21	3	11.5	1	5.5	16
Secchi depth	m	0.30	1.40	1.0				2.40	1.60	
Water colour	abs@440 nm /10 cm	0.192	0.154	0.267	0.225	0.090	0.180	0.265	0.195	0.065
Chloride ion	mg/L	43	56	64	38	75	59	65	32	9750
Calcium ion	mg/L	3.0	3.3	2.7	6.9	9.5	7.3	3.8	1.1	225
Magnesium ion	mg/L	4.0	5.1	5.1	4.4	7.7	5.5	5.3	2.3	645
DOC	mg/L	11.5	8.8	10.7	9.6	6.8	8.8	10.4	6.8	7.0
Euphotic depth	m	0.7	3.5	2.6	1.26	3.95	3.27	3.00	2.54	1.64
Chlorophyll-*a*	µg/L	6.2	1.0	10.3	4.0	1.5*	20	1.5*	1.5*	1.5*
TN	µg/L	434	563	615	460	670	630	265	220	595
TP	µg/L	26.7	14.7	20.7	33	19	36	2.0*	6.5	27
NO3	µg/L	0.25	24.1	0.25	2.5	52	6.5	2.0*	3.0	166
NH4	µg/L	9.7	21.5	17.8	5.0*	8.5	5.0*	5.0*	5.0*	9.0
SRP	µg/L	0.2*	0.2*	0.2*	2.0*	2.0*	2.0*	2.0*	2.0*	2.0*
DON	µg/L	164	330	358	39	53	42	19	19	34
DOP	µg/L	11.5	14.5	24.3	6.0	9.5	15	3.0*	3.0*	3.0*
DIN:TP		0.38	3.02	0.91	0.2	3.3	0.4	4.8	1.3	6.6
TLI_N		4.3	4.6	4.8	4.4	4.9	4.8	3.7	3.4	4.7
TLI_P		4.4	3.6	4.1	4.4	4.0	4.7	1.1*	2.6	4.4
$TLI_{Chl\text{-}a}$		4.2	2.2	4.8	3.8	2.7*	5.5	2.7*	2.7*	2.7*
TLI_{Secchi}		6.4	4.7	5.0			4.2	4.6		
TLI		4.9	3.8	4.7			4.8	3.3		

Note: Conductivity was measured as specific conductivity. Water colour was measured as the absorbance of light by filtered water at 440 nm. DOC is dissolved organic carbon. Euphotic depth is the depth to which 1% of photosynthetically active radiation reaching the lake surface penetrates. TN is total nitrogen. TP is total phosphorus. NO3 is nitrate (measured as nitrate+nitrite). NH4 is ammonium. SRP is soluble reactive phosphorus. DON is dissolved organic nitrogen. DOP is dissolved organic phosphorus. DIN is dissolved inorganic nitrogen (nitrate + ammonium). TLI is the tropic level index (Burns *et al.* 2000), calculated for TN, TP, chl-*a,* Secchi depth and the average of these TLI indices, where all were able to be calculated.
*Values were below detection limit (were set at half detection limit).

Table 7. Physico-chemical data for Southland lakes presented as percentiles of the CDRP dataset plus the lakes sampled in 2012. Percentile colour codes: dark blue ≥ 90th percentile; turquoise is between 75th and 89th percentile; pink is between 25th and 11th percentile; red ≤ 10th percentile. See Table 6 for information on variables measures.

	CDRP (2004) percentiles			2012 percentiles						Number	Number of
Variable	**George**	**Vincent**	**Reservoir**	**George**	**Vincent**	**Reservoir**	**Sheila**	**Calder**	**Brunton**	**of samples**	**lakes**
Conductivity	27	49	45	29	63	51	47	14	100	51	48
pH	39	51	45	75	69	61	37	4	47	50	47
Turbidity				90	58	81	39	68	84	31	31
Secchi depth	11	55	45				77	64		44	44
Water colour	65	75	88	84	51	71	86	76	37	51	48
Cl-	51	29	25	43	73	63	69	27	100	51	48
Ca++	27	29	25	49	63	51	35	12	100	51	48
Mg+	35	49	45	41	69	53	51	14	100	51	48
DOC	63	41	59	47	29	39	57	31	33	49	46
Euphotic depth	9	64	47	15	68	60	53	43	30	47	44
Chlorophyll-*a*	65	12	75	57	22	88	24	25	27*	51	48
TN	43	51	57	45	63	61	27	10	55	51	48
TP	61	43	57	67	53	69	2	16	63	51	48
NO3	12	90	14	69	94	78	65	71	98	51	48
NH4	25	65	59	4	20	10	6	8	22	51	48
SRP	12	14	16	65	67	73	69	71	75	51	48
DON	31	55	61	12	16	14	6	4	10	51	48
DOP	65	71	88	47	57	73	35	37	39	51	48
DIN:TP	29	80	41	16	82	31	88	53	92	51	48
TLI_N	43	51	57	45	63	61	27	10	55	51	48
TLI_P	61	43	57	67	53	69	2	16	63	51	48
TLI_{Chl-a}	65	12	75	57	22	88	24	25	27*	51	48
TLI_{Secchi}	91	48	57			25	39			44	44
TLI	68	48	64			66	18			44	44

*Values were below detection limit (were set at half detection limit).

We conducted a principal components analysis to identify which variables best informed the similarity in water quality among Southland lakes and to compare these lakes to other shallow lakes throughout New Zealand (Figures 6 and 7). The distribution of the physico-chemical variables along the first two axes shows that the main axis can be interpreted as a gradient of trophic state and water clarity, which explains 54. 4 % of the variance in the physico-chemical data (Figures 6 and 7). The second major axis can be interpreted as a gradient of water colour (humic acid staining) and pH, which explains 19. 5% of the variance in the physico-chemical data (Figure 6). The third main axis can be interpreted as a gradient of dissolved organic matter, but this axis only explains 8. 3% of the physico-chemical data (Figure 7).

Southland lakes tend to be of moderate to low trophic state and moderate to high water clarity (Figure 6). They also tend to be more humic-stained and have a lower pH than most shallow coastal lakes in New Zealand (Figure 6). The water quality of Lakes Sheila and Calder is most similar to a group of relatively unmodified to near-pristine lakes located on the west coast of the South Island (Figure 6). These lakes have a low trophic state and a relatively high water clarity which is somewhat compromised by moderately high humic acid staining.

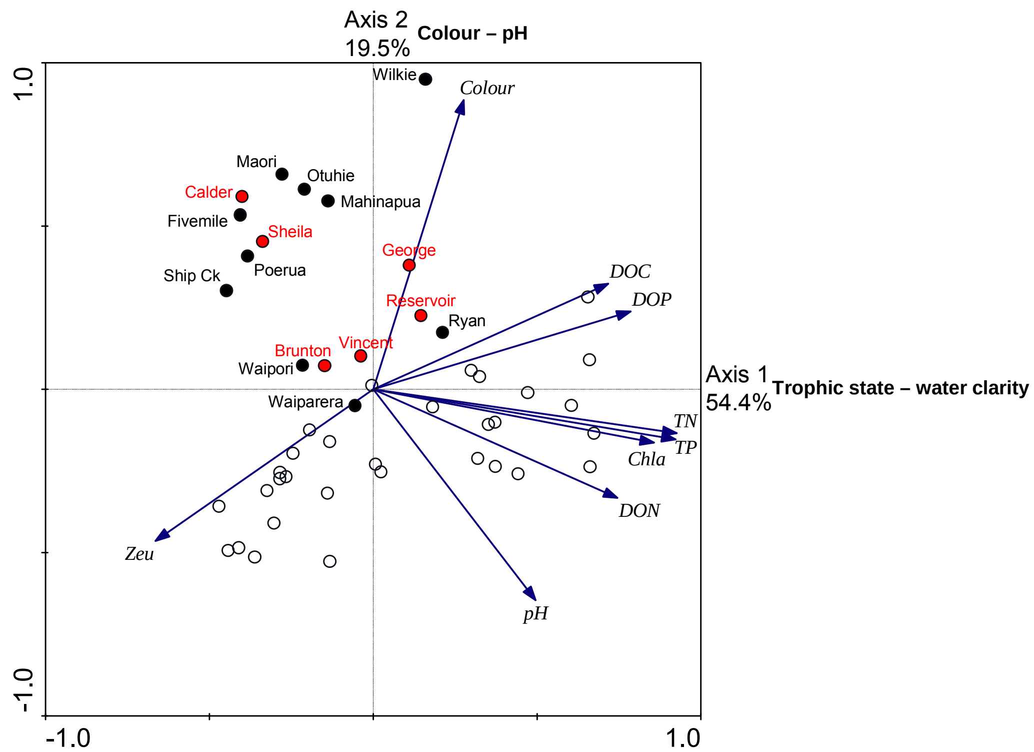

Figure 6. Ordination diagram (principle components analysis on the correlation matrix) showing the two principle gradients in physico-chemistry for 48 New Zealand shallow coastal lakes. Axis 1 represents a gradient of trophic state/water clarity. Axis 2 represents a gradient of water colour/pH. Combined the axes explain 73. 9% of the variance in the physic-chemical data. Arrow lengths represent the correlations between the individual variables and the axes. Red circles are the Southland lakes. Filled black circles are labelled lakes similar to the Southland lakes. Open circles are other unlabelled lakes from the CDRP in dataset.

More productive lakes tend to have higher levels of dissolved organic matter (carbon and nitrogen) (Figure 7). As such, Lakes George/Uruwera, Vincent and The Reservoir are only moderately enriched in dissolved organic matter. However, Lakes Sheila, Calder and Brunton have very low levels of dissolved organic nitrogen (Figure 7, Tables 6 and 7).

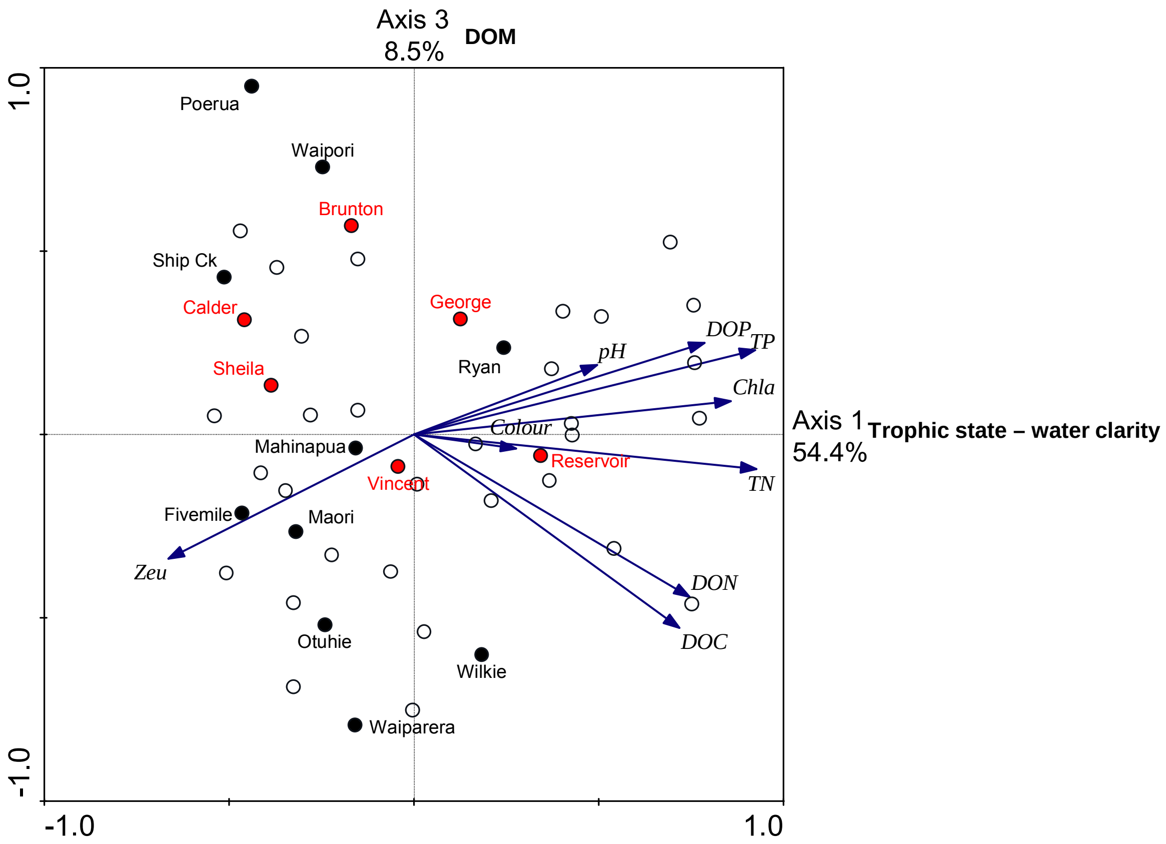

Figure 7. Ordination diagram (principle components analysis on the correlation matrix) showing the first and third principle gradients in physico-chemistry for 48 New Zealand shallow coastal lakes. Axis 1 represents a gradient of trophic state/water clarity. Axis 3 represents a gradient of non-coloured dissolved organic matter. Arrow lengths represent the correlations between the individual variables and the axes. Red circles are the Southland lakes. Filled black circles are labelled lakes similar to the Southland lakes from Figure 6. Open circles are other unlabelled lakes from the CDRP dataset.

Figure 8 shows how key water quality variables have varied between the years 2000 and 2012 in Lakes George/Uruwera, Vincent and The Reservoir. Although the data a far too few to draw strong conclusions about temporal trends, the data for Lake Vincent suggest that chl-*a* decreased around 10-fold between 2000 and 2004 and that levels have remained low to 2012. Conversely, the data suggest that phytoplankton biomass has increased 4-fold between 2000 and 2012 in The Reservoir.

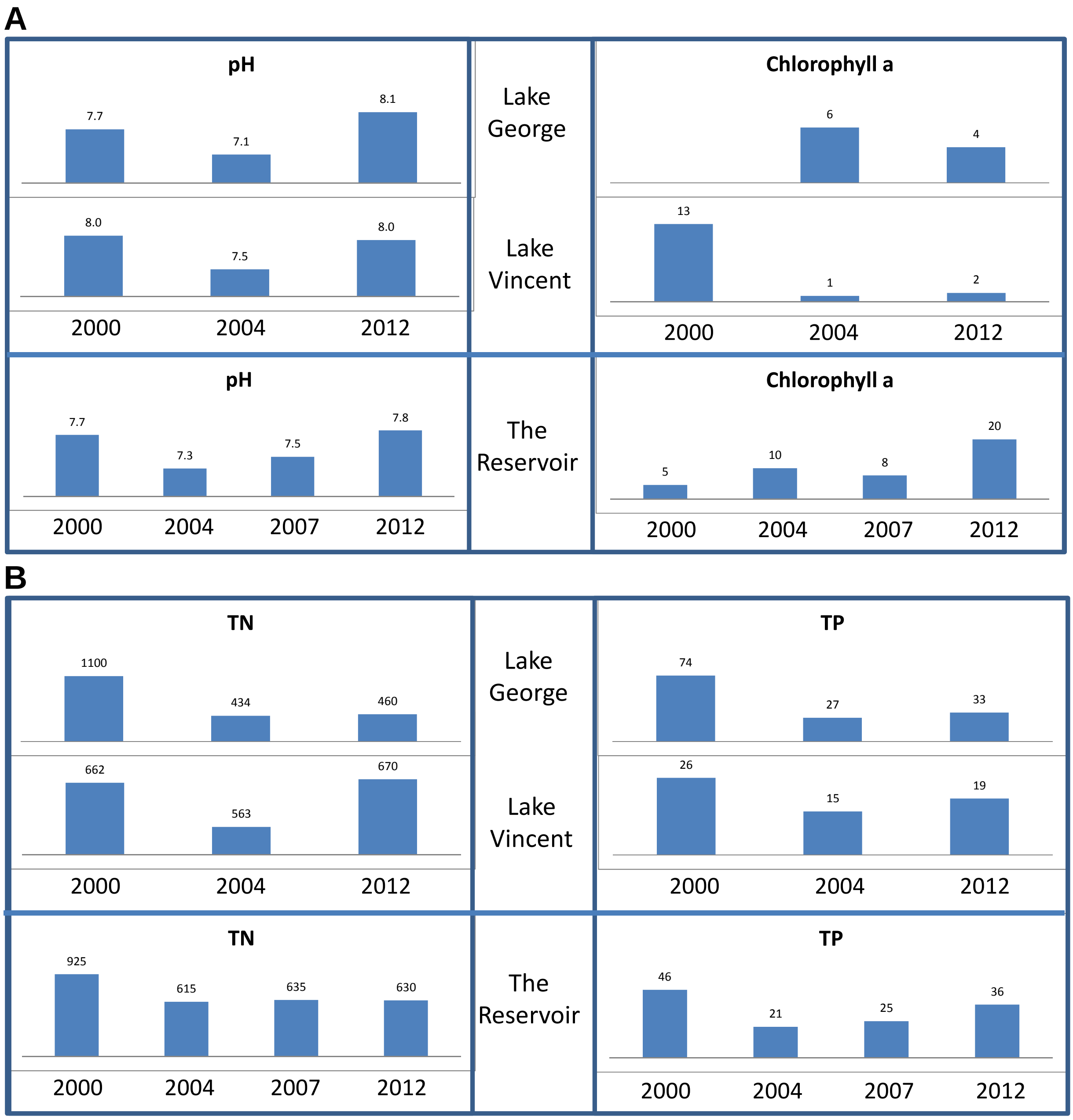

Figure 8. Water quality measures in Lakes George/Uruwera, Vincent and The Reservoir measured in 2000, 2004, 2007 and 2012. A. Changes in pH and chl-*a*. B. Changes in total nitrogen (TN) and total phosphorus (TP).

Both TN and TP decreased markedly in Lake George/Uruwera between 2000 and 2004 and were also low in 2012. While TN did not show a consistent decrease in Lake Vincent between 2000 and 2012, TP showed a weak decline, consistent with the large reduction in phytoplankton biomass as indicated by chl-*a*.

While TN and TP declined markedly in The Reservoir between 2000 and 2004, total phosphorus has shown a steady increase from 2004 to 2012, consistent with the observed increase in phytoplankton biomass.

5.2. Phytoplankton

Phytoplankton communities are typically quite diverse in lakes, except during times of severe phytoplankton blooms. The community composition and presence of species can change rapidly due to the ability of phytoplankton to proliferate during favourable conditions and because some taxa sink rapidly (*e. g.* large diatoms) whereas others regulate their buoyancy (*e. g*. some cyanobacteria, green algae and dinoflagellates). Therefore, one-off samplings of phytoplankton should be interpreted with caution because it only captures dynamic phytoplankton communities at a single point in time. Phytoplankton samples were collected from two sites per lake using an integrated tube sampler from either the entire water column or the upper 1. 5 m at deeper sites.

The phytoplankton communities of Lakes George/Uruwera, Vincent and The Reservoir in 2004 were remarkably similar, consisting mainly of colonial cyanobacteria and small chlorophytes < 5 µm in diameter (Table 8). Lakes George/Uruwera and Vincent also contained the filmentous cyanobacterium, *Phormidium mucicola*. Some cyanobacteria are capable of noteworthy biological processes. Phormidium and Microcystis are cyanobacterial genera with some toxin-producing species, however the species found in these lakes have not previously been reported to produce cyanotoxins. While some species of *Phormidium* can fix atmospheric nitrogen, a capacity to fix nitrogen has not been demonstrated for the species found in these lakes. The genus Microcystis contains no nitrogen-fixing species. The colonial chroococcal species which dominated the phytoplankton of The Reservoir was not identified and therefore its potential to fix nitrogen or produce toxins is unknown. However, casual observation during our sampling in 2012 showed that the large desmid, *Staurastrum sp*., was dominant in The Reservoir, as large numbers of this phytoplankter were responsible for clogging our 50 µm zooplankton net.

The phytoplankton communities of these three Southland lakes are quite typical of shallow coastal lakes in New Zealand. The few data that are available for these lakes are not particularly informative with regard to ecological or water quality issues. However, as The Reservoir seems to have become more eutrophic in recent years and has undergone a major shift in its dominant phytoplankter, it would be prudent to monitor both phytoplankton biomass and dominant phytoplankters in this lake.

Table 8. Dominant phytoplankters sampled in the lakes in 2004. * Indicates numerically most abundant.

George/Uruwera	Vincent	The Reservoir
*Microcystis minutissima**	*Microcystis minutissima**	Colonial chroococcal species*
Small green unicells < 5 µm*	Small green unicells < 5 µm*	Small green unicells < 5 µm*
Colonial chroococcal species*	Colonial chroococcal species	*Microcystis minutissima*
Cyclotella sp.	*Stichococcus*?	*Microcystis* sp.
Microcystis sp.	*Phormidium mucicola*	*Stichococcus*?
Stichococcus?		
Phormidium mucicola		

5.3. Aquatic macrophytes

Aquatic macrophytes are a key biotic community in the ecology of shallow lakes (Scheffer 2004; Schallenberg & Sorrel 2009). They provide habitat and refuge from predation for zooplankton, invertebrates and small fish. They also provide a substrate for the growth of periphyton which removes nutrients directly from the water. They inhibit sediment resuspension, thereby reducing the recycling of nutrients from sediments into the water column while improving water clarity. Some macrophyte taxa have been shown to exude chemicals into the water which inhibit phytoplankton growth and proliferation. These roles of macrophytes provide ecological resilience against the unfavourable effects of increasing nutrient loading in shallow lakes. However, macrophytes are not invulnerable to these effects and have been shown to suffer collapse and extirpation in many lakes which have undergone eutrophication. The loss of macrophytes from shallow lakes can occur relatively rapidly (*e. g*. from one year to the next), allowing the enhancement of internal nutrient loading and phytoplankton growth, thereby facilitating the establishment of an ecological regime typically dominated by phytoplankton blooms (Scheffer 2004). This type of catastrophic regime shift has been observed numerous times in shallow New Zealand lakes (Schallenberg & Sorrell 2009). Therefore, the presence of macrophytes is generally considered a positive attribute of shallow lakes.

We used different sampling protocols in 2012 than those used to determine macrophyte cover in the CDRP dataset (Drake 2009), which was done by SCUBA transects. In 2012, we collected cover data either visually (shallow depths) or by benthic grab samples (deep depths) at 5 m intervals along a 50 m transect perpendicular to the shore. We replicated this at three transects distributed around each lake perimeter. For some lakes such as Lakes George/Uruwera, Brunton, and Sheila, visual assessments were able to be made over the whole transect range, whereas for Lakes Vincent, Calder, and The Reservoir benthic grabs were required. For Lakes George/Uruwera, Vincent and The Reservoir, the sites we sampled in 2012 were the same as those sampled in 2004.

Apart from Lake Brunton, the lakes in Southland had moderately diverse macrophyte communities with relatively little influence of non-indigenous species; *Elodea canadensis* was present in three of the six lakes surveyed (Table 9). Lake Brunton undergoes rapid changes in salinity as a result of the breaching and closing of its barrier bar and this limits the macrophyte diversity, resulting in the presence of the seagrass, *Ruppia megacarpa,* with a fairly good coverage within 50 m of the lake margin at the time of sampling.

Macrophyte distributions within lakes can be very patchy. As such, our sampling design is best suited to provide an indication of macrophyte cover rather than to determine lake-wide macrophyte distributions or average lake macrophyte cover. However, our data suggest that Lake Vincent has the most vigorous and spatially contiguous macrophyte beds, consisting mainly of charophytes (Table 9). Lake Sheila also has proliferations of macrophytes, mostly *Ruppia megacarpa*. Lakes George/Uruwera and Calder have patchy distributions of macrophytes with generally low-canopy height. It is likely that macrophyte growth is limited in Lake Calder by both the low pH (and alkalinity) of the lake and by sub-optimal sediment characteristics. Lake George/Uruwera is exposed to southerly and westerly winds and the lake's relatively large fetch probably results in sufficient wind-induced turbulence to reduce macrophyte biomass in the lake. The Reservoir has a very patchy distribution of macrophytes with generally low cover within 50 m of the shore.

Macrophyte community data for the CDRP lakes did not lend themselves to a New Zealand wide comparison because 15 out of 46 shallow lakes contained introduced invasive species, 11 lakes had ≤ 10% macrophyte cover at the transects and five lakes were macrophyte-free. Thus, patterns among lakes reflected the presence/absence of invasive species and were based on assessments of generally sparse and patchy distributions of macrophytes.

From our data it appears that the mainland Southland lakes, and especially Lake Vincent, are provided a degree of resilience to eutrophication due to the presence of macrophytes, with the macrophytes contributing to the water quality values of these lakes. At present, the macrophyte community of The Reservoir is probably the most vulnerable of the lakes. We did notice a fragment of the invasive non-indigenous macrophyte, *Potamogeton crispus,* at Lake Sheila; it is likely that this macrophyte can be transported by waterfowl and has probably become established in the Freshwater Creek catchment and Lake Sheila. Other lakes are probably equally susceptible to waterfowl introductions of this invasive macrophyte.

Table 9. Macrophytes sampled in the Southland lakes. Macrophytes not native to New Zealand are indicated by red text. Percentage cover values relate to the three transects only, not to the whole lake bed.

2004 CDRP dataset		
George/Uruwera	**Vincent**	**The Reservoir**
0. 5% cover •*Nitella hookeri* •*Myriophyllum triphyllum* •*Lilaeopsis ruthiana*	86% cover •*Potamogeton ochreatus* •*Nitella hookeri* •*Chara corralina* •*Glossostigma elatinoides* •*Lilaeopsis ruthiana* •*Ranunculus triphylis* •*Limosella lineata* •*Elodea canadensis*	10% cover •*Potamogeton ochreatus* •*Myriophyllum triphyllum* •*Glossostigma elatinoides* •*Ranunculus triphylis* •*Limosella lineata* •*Elatine gratioloides* •*Elodea canadensis*

2012 dataset					
George	**Vincent**	**The Reservoir**	**Sheila**	**Calder**	**Brunton**
36% cover •*Lilaeopsis ruthiana* (locally abundant) •*Nitella hookeri* (locally abundant) •*Myriophyllum triphyllum* (locally abundant)	66% cover •*Potamogeton ochreatus* (locally abundant) •*Nitella hookeri* (locally abundant) •*Chara corralina* (locally abundant) •*Lilaeopsis ruthiana* (sparse) •*Elodea canadensis* (sparse)	16% cover •*Potamogeton ochreatus* (locally abundant) •*Chara corralina* (locally abundant) •*Ranunculus triphylis (locally abundant)* •*Elodea canadensis* (sparse)	52% cover •*Ruppia megacarpa* (extensive beds and floating root mats) •*Potamogeton cheesmani* (abundant) •*Potamogeton crispus* (fragment found)	31% cover •*Ruppia megacarpa* (locally abundant) •*Myriophyllum propinquum* (sparse) •*Potamogeton cheesmani* (sparse) •Bryophyte (unidentified; locally abundant)	64% cover •*Ruppia polycarpa* (locally abundant)

5.4. Metazooplankton

Metazooplankton are both important grazers of phytoplankton in lakes and are important prey for larval and juvenile fish. Thus, the biomass and community structure of zooplankton can influence both water quality and fish productivity in shallow lakes. Generally, filter-feeding cladocerans are stronger grazers and faster reproducers than copepods and, thus, have greater impacts on water quality, but are also more episodic in their population and community dynamics. Generally in New Zealand, cladocerans such as *Daphnia carinata* are vulnerable to salinity, whereas the copepod *Boeckella hamata* has a moderate salinity tolerance and the estuarine copepod, *Gladioferens pectinatus* is a true brackish species which is able to do well in a wide range of salinities (Schallenberg *et al*. 2003). In shallow lakes where *Daphnia* spp. are present, they are considered a keystone species because of their relatively large size, high grazing rate and rapid rate of reproduction.

Zooplankton samples were collected from two sites per lake using an integrated tube sampler from either the entire water column or the upper 1.5 m at deeper sites. Depending on zooplankton densities, between 20 and 60 litres of water was collected and then filtered through a 50 μm plankton net to concentrate the zooplankton. The data presented in this report have been pooled from the two sites at each lake.

Daphnia were recorded in 11 of the 46 CDRP lakes, and only in lakes without saline influence. Most records of *Daphnia* were of the non-indigenous *D. dentifera*, whereas Lake George/Uruwera was the only lake to have the native *D. carinata*, albeit in low densities (Table 10). None of the other Southland lakes had *Daphnia*. Where *Daphnia* is present in moderate or high densities, it probably confers a degree of ecological resilience to problems associated with eutrophication because of its effectiveness grazing phytoplankton.

The other unusual zooplankter found in the Southland lakes was a type of bosminid, similar to but distinct from the typical and widespread cladoceran, *Bosmina meridionalis*. Three individuals of this possible variant or sub-species were recorded from Lake Sheila (two specimens) and Lake Vincent (one specimen). This zooplankter was not recorded from any of the lakes in 2004 (Table 10).

Other than these interesting findings, the zooplankton communities of the Southland lakes are fairly typical, containing at least one species of copepod (*e. g. Boeckella hamata*) and one or two smaller cladocerans (*Ceriodaphnia dubia* and/or *Bosmina meridionalis*). These species are commonly found in the CDRP lakes throughout New Zealand.

Lake Brunton was an exception in that there were virtually no metazooplankton present in the samples (*e. g*. 0. 05 individuals per litre of *B. meridionalis* and *Boeckella hamata*). This is probably due to the large salinity variations that occurred just before the 2012 sampling due to the opening and closing of the barrier bar.

Table 10. Metazooplankton sampled in the Southland Lakes. *Bosmina?* was a rare unidentified bosminid found in Lake Sheila and Lake Vincent and is distinct in appearance from typical *Bosmina meridionalis.*

	George	Vincent	The Reservoir	Sheila	Calder	Brunton
2004 CDRP dataset						
Copepods	Nauplii *Boeckella hamata** Cyclopoid	Nauplii *Boeckella hamata** Cyclopoid	Nauplii *Boeckella hamata** Cyclopoid			
Cladocerans	*Ceriodaphnia dubia* *Daphnia carinata*	*Bosmina meridionalis** *Ceriodaphnia dubia**	*Bosmina meridionalis**			
2012 dataset						
Copepods	Nauplii *Boeckella hamata**	Nauplii *Boeckella hamata**	Nauplii *Boeckella hamata** Cyclopoid	Nauplii *Boeckella hamata**	Nauplii *Boeckella hamata**	Nauplii *Gladioferens pectinatus* Cyclooid Harpacticoid
Cladocerans	*Bosmina meridionalis* *Daphnia carinata*	*Bosmina meridionalis** *Bosmina?* *Ceriodaphnia dubia*	*Bosmina meridionalis**	*Bosmina meridionalis** *Bosmina?*	*Bosmina meridionalis*	*Bosmina meridionalis*

* Numerically dominant or co-dominant.

Among lake comparisons of the zooplankton communities of the CDRP and the 2012 shallow lakes was carried out by conducting ordinations of the metazooplankton presence/absence data. Due to the predominant effect of salinity on zooplankton community structure (Schallenberg *et al*. 2003; Schallenberg & Burns 2003), separate analyses were conducted on the freshwater (Figure 9) and brackish (Figure 10) lakes.

The first two ordination axes for freshwater lakes (n = 31) explained relatively little (? %) of the total variance in the zooplankton communities (Figure 9). However, the Southland freshwater lakes group distinctly as lakes with relatively simple communities containing *B. hamata*. While *B. meridionalis* is also common in the Southland lakes, it was present in 82 % of all freshwater lakes, whereas *B. hamata* was mainly found in Southland (but also in some lakes in Otago, West Coast South Island, and North Island). The ordination also shows the influence of *D. carinata* found only in Lake George/Uruwera, and the unidentified bosminid found only in Lakes Sheila and Vincent. The ordination suggests that the Southland lakes are fairly distinctive in these characteristics.

The densities of the zooplankters found in Lakes George/Uruwera, Vincent and The Reservoir in 2004 were moderately low compared to the other lakes in the CDRP dataset (data not shown).

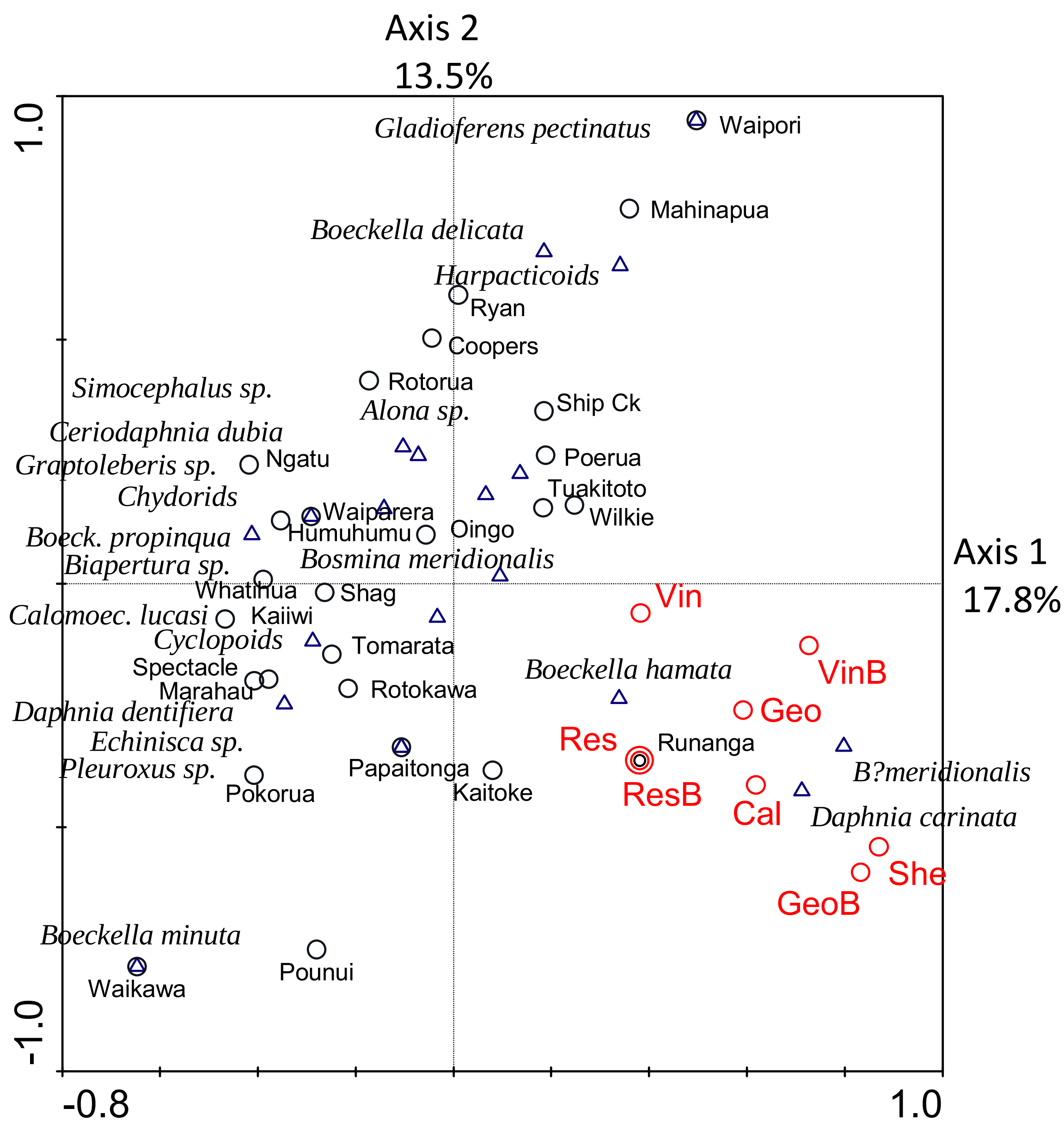

Figure 9. Ordination diagram (correspondence analysis on presence/absence) of metazooplankton taxa for 31 freshwater shallow coastal lakes. Red labels and circles represent Southland lakes. Codes ending in 'B' are samples from the 2012 campaign. Black circles represent other lakes. Triangles and text in italics represent zooplankton taxa.

A comparison of the zooplankton community of Lake Brunton with other brackish lakes in the CDRP dataset is shown in Figure 10. The first two ordination axes in the ordination of brackish lakes (n = 12) explained around two thirds of the total variance in the zooplankton communities (Figure 10). The zooplankton species richness and abundances (data not shown) in the brackish lakes are far lower than the freshwater lakes, confirming previous research done in a seasonally brackish lake (Schallenberg *et al*. 2003).

The ability to compare the Lake Brunton zooplankton community to the other brackish lakes was limited because of the extremely low densities of zooplankton found there at the time of sampling. Lake Brunton had low densities of *B. hamata* and *B. meridionalis*. *B. hamata* has a moderate salinity tolerance and was found in 3 other brackish lakes, whereas *B. meridionalis* appears to have a low salinity tolerance as it was not found in any other brackish lakes. It would seem that *B. hamata* may have been a rare resident in Lake Brunton at the time of sampling, but that the *B. meridionalis* specimen was probably dead when sampled, a residual specimen that lived in the lake when it was in its freshwater phase.

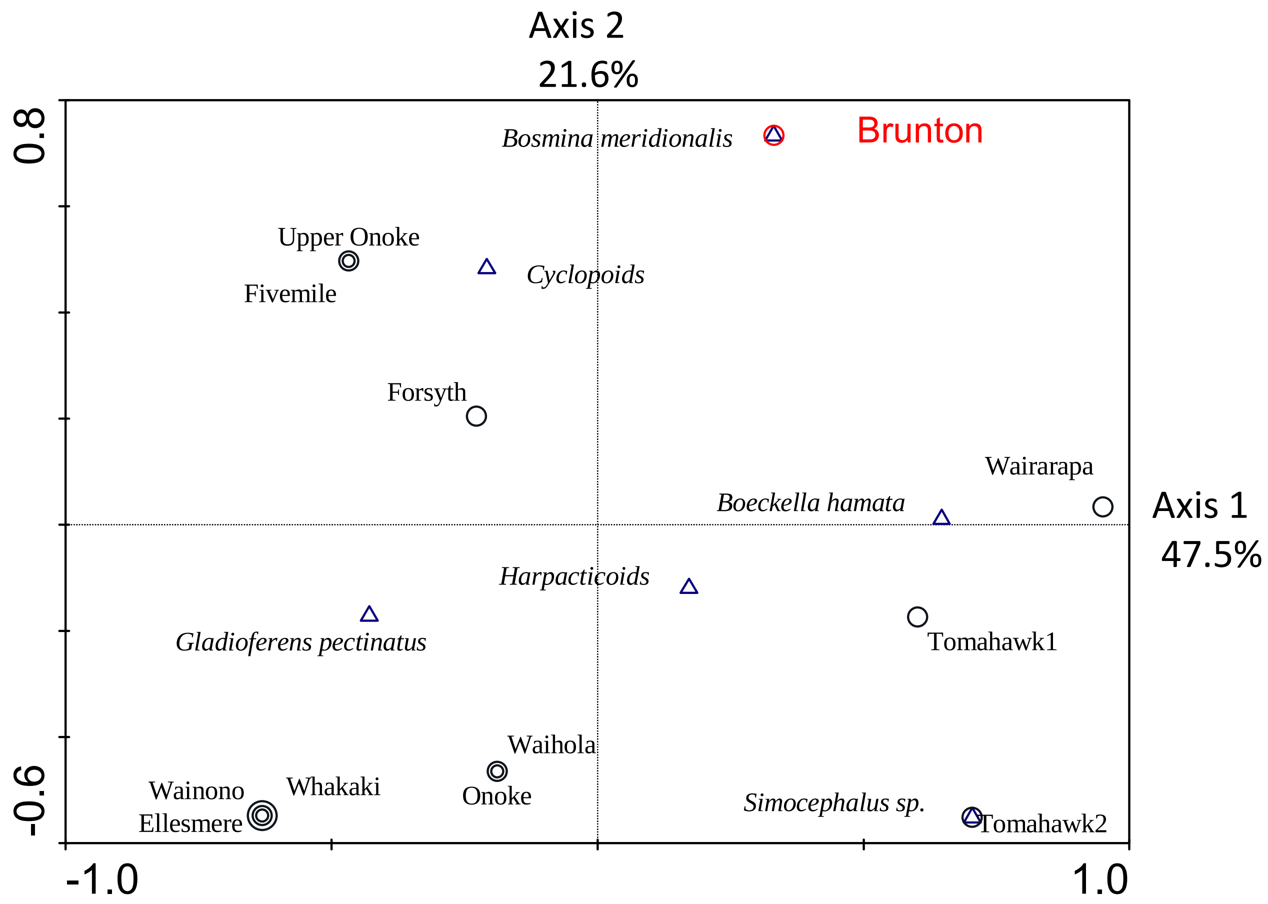

Figure 10. Ordination diagram (correspondence analysis on presence/absence) of metazooplankton taxa for 12 brackish shallow coastal lakes. Red labels and circles represent Southland lakes. Black circles represent other lakes. Triangles and text in italics represent zooplankton taxa.

In summary, the metazooplankton communities of the Southland freshwater lakes form a relatively distinct grouping due to their low species richness and the presence of the calanoid copepod, *B. hamata*. The zooplankton densities were relatively low compared to other lakes in the CDRP dataset. Lake George/Uruwera is notable in that it contains the only *Daphnia carinata* sampled from all the lowland lakes in this analysis. This could be a keystone species in Lake George/Uruwera if it at time achieves higher densities and may afford a degree of ecological resilience to some of the potential effects of eutrophication. Finally, Lakes Sheila and Vincent contain what appears to be a distinct species or variant of bosminid, though it was rare in both lakes.

5.5. Macroinvertebrates

Benthic macroinvertebrates tend to be relatively long-lived taxa and tend not to be very mobile. Therefore, they can reflect longer-term conditions in lakes. However, they can also be strongly influenced by substrate characteristics and their distribution and density in lakes can be patchy. Therefore, sampling to reflect the lake-wide macroinvertebrate community and densities is very difficult. In our sampling, we collected benthic macroinvertebrates in the predominantly littoral areas of the lakes 10 m from the shoreline along the same transects used for macrophyte surveys.

The benthic macroinvertebrate communities showed much variation among the Southland lakes (Table 11). Taxonomic richness ranged from 24 in the Stewart Island/Rakiura lakes to 12 in Lake Brunton. Densities were not correlated to taxonomic richness. Interestingly, the highest richness was recorded in the Stewart Island/Rakiura lakes which had the lowest densities of macroinvertebrates. By far the highest density of benthic macroinvertebrates was recorded in Lake Vincent, followed by Lake George/Uruwera.

The freshwater mussel, *Echyridella menziesi* was found in Lakes George/Uruwera and Vincent and in six of the other 44 shallow coastal lakes sampled. In high densities, this species has the potential to clear substantial amounts of phytoplankton from the water column of shallow lakes (Ogilvie & Mitchell 1995, Phillips 2007). Its distribution tends to be quite patchy in lakes.

Table 11. Taxonomic richness and types of benthic macroinvertebrates collected from the Southland lakes.

2004 CDRP datasets	**George/Uruwera**	**Vincent**	**The Reservoir**
	Richness=18	Richness=19	Richness=14
	Density= 48,884 / m^2	Density= 116,258 / m^2	Density= 13,849 / m^2
	Caddis Dipterans Amphipod Isopod Mysid Clam (*Echyridella menziesi*) Snails Nematodes Worms Leech	Caddis Dipterans Damselfly Amphipod Moth Clam (*Echyridella menziesi)* Snails Worms Leech Mite	Caddis Dipterans Damselfly Amphipod Moth Snails Worms Springtail Mite
2012 CDRP datasets	**Sheila**	**Calder**	**Brunton**
	Richness=24	Richness=23	Richness=12
	Density= 5,200 / m^2	Density= 4,400 / m^2	Density= 13,102 / m^2
	Caddis Dipterans Dragonfly Damselfly Amphipod Ostracods Snails Nematodes Worms Flatworm Leech Mite Glass shrimp	Caddis Dipterans Damselfly Copepods Chydorids Amphipod Ostracods Snails Nematodes Worms Mite Ribbon worm Glass shrimp	Dipterans Amphipod Copepods Ostracods Snails Nematodes Worms Polychaete Isopod

We compared the similarity of benthic communities in Southland lakes and other shallow coastal lakes using ordination analysis. The first two axes of the ordination of macrobenthic presence/absence data only explained 21. 8% of the variation in macroinvertebrate communities. This is typical for macrobenthos because, as mentioned above, it is difficult to obtain samples representative of an entire lake due to spatial heterogeneity, and because of the importance of site-specific substrate and habitat type to the macrobenthos. In addition, macrobenthic diversity among lakes in New Zealand is relatively high compared to other communities examined in this report.

Due to the poor performance of the ordination based on presence/absence data, we repeated the analysis using macroinvertebrate densities. Only a slight improvement was achieved, with the first two axes explaining 26. 5% of the variation in macroinvertebrate communities (Figure 11). The ordination suggests quite distinct communities are apparent in the six Southland lakes. For example, Lake George/Uruwera was the only lake in the CDRP dataset in which haplotaxid and phreodrilid oligochaete worms were found. It was also one of the two lakes in which isopods (*Astridotea lacustris*) were found (the other being Lake Waihola).

The macrobenthic communities of The Reservoir and Lake Vincent were also somewhat distinct in the context of the CDRP dataset, but their communities were similar to other South Island lakes located in Otago, the West Coast and Canterbury (Figure 11). These lakes tended to be dominated by snails, worms, chironomids and amphipods, but also contained caddisfly and damselfly larvae.

As mentioned above, the macrobenthos of Lakes Sheila and Calder was very diverse but of low numerical density. As such, they contained relatively low numbers of many taxa which were commonly observed in other lakes of the CDRP dataset. However, they also contained low numbers of a few uncommon taxa. These included the amphipod *Paraleptamphopus* sp., the glass shrimp *Paratya curvirostris*, ribbon worms (*Nemertea* sp.; Lake Calder), a water moth (*Hygraula* sp.; Lake Calder) and a stick caddisfly (*Triplectides* sp.; Lake Sheila).

Not surprisingly, Lake Brunton was part of a fairly distinctive group of lakes which included the brackish lakes, Onoke, Upper Onoke and Wairarapa (all in the Wairarapa) as well as the Kaihoka Lakes in northwest Nelson (Figure 11). Lake Brunton shared polychaetes with the Kaihoka Lakes and Lake Onoke and contained an abundance of marine amphipods (*Paracorophium excavatum*), indicating its saline condition. It also contained a moderate abundance of freshwater amphipods (*Paracalliope fluviatilis*), snails and oligochaetes, which were common in many lakes in the CDRP dataset.

In summary, the macrobenthos of Southland shallow lakes tended to fall into three broad categories, those of lakes influenced by saline conditions, those with high macroinvertbeerate diversity associated with lakes dominated by macrophytes, and those with low diversity associated with lakes with little or no macrophyte communities.

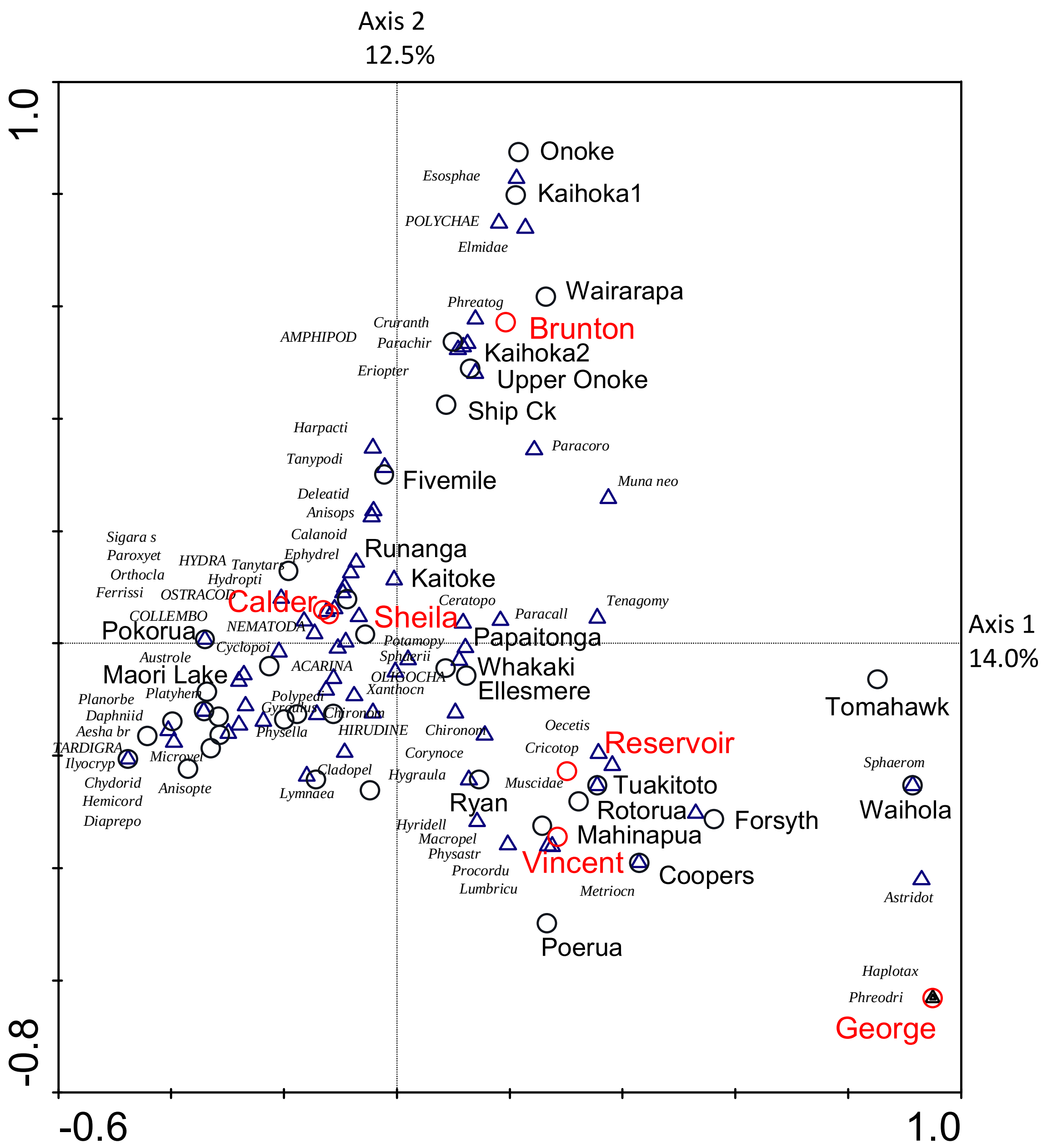

Figure 11. Ordination diagram (correspondence analysis on density) of benthic macroinvertebrate taxa for 44 shallow coastal lakes. Red labels and circles represent Southland lakes. Black circles represent other lakes. Only lakes with similar communities to the Southland lakes are labelled. Triangles and text in italics represent zooplankton taxa.

5.6. Fish

Fish were sampled in 2004 using both fyke nets and minnow traps. The fish communities in Lakes George/Uruwera, Vincent and The Reservoir have low diversity of both native and introduced species (Table 12). The native species comprise eels, bullies and giant kokopu and the catch per unit effort (CPUE) for native fish in these lakes was lower than the average native fish CPUE for the CDRP lakes (mean CPUE

= 1. 45, median CPUE = 0. 66). Of note is the presence of the regionally declining giant kokopu (Allibone *et al*. 2010) in both Lakes Vincent and The Reservoir. Of the 41 shallow lakes sampled in the CDRP campaign, this species was only caught in five lakes, the others being Lakes Mahinapua, Poerua and Ship Creek (all on the West Coast). Despite being in national decline in freshwaters in general (Allibone *et al*. 2010), longfin eels were relatively common in many shallow coastal lakes (caught in 31 of 41 lakes).

In 2004, perch was the only exotic species found in the Southland lakes (caught in Lakes George/Uruwera and The Reservoir). This species is a voracious predator and has been shown to control native fish abundance in ponds (Ludgate & Closs 2003), which may explain the low native CPUE in lakes where perch was present (Table 12). Perch was fairly common in the CDRP shallow lakes, being caught in 12 of the 41 lakes sampled.

We did not sample fish communities in 2012, however we did assemble fish records from the Double Lakes (near Lake Calder) and the upper Freshwater River catchment from the New Zealand Freshwater Fisheries Database (NIWA). Our interpretation of the fish records from this catchment suggest that the fish communities for Lakes Sheila and Calder could consist of up to six native species, and no non-indigenous species were recorded from the catchment (Table 11). This list of potential inhabitants remains to be confirmed.

Table 12. Fish collected from the Southland lakes.

2004 CDRP dataset George/Uruwera*	**Vincent**	**The Reservoir**	**Sheila/Calder****
Native CPUE=0. 09	Native CPUE=0. 02	Native CPUE=0. 86	
•Common bully	•Common bully	•Common bully	•Common bully
•Lonfin eel	•Longfin eel	•Longfin eel	•Longfin eel
•Shortfin eel	•Shortfin eel	•Giant kokopu	•Shorfin eel
•Perch	•Perch		•Inanga
	•Giant kokopu		•Koaro
			•Giant kokopu

* Note: Giant kokopu have been collected from the Lake George/Uruwera catchment (pers. comm. A. Hicks, Environment Southland)

** Likely community based on fish records from Freshwater River catchment obtained from NZ Freshwater Fish Database (NIWA).

In the CDRP dataset, a number of non-indigenous fish species were found to be widespread in the North Island. We therefore conducted an ordination of fish presence/absence data for only the South Island lakes (Figure 12). The first two axes of the ordination of fish presence/absence data explained 48. 3% of the variation in the South Island fish communities. Axis 1 described a gradient of fish communities largely defined by the presence/absence of smelt, goldfish, brown trout and estuarine species. As the Southland lakes contained none of these species, this gradient was not informative in terms of distinguishing the lakes. Axis 2 mainly explained the presence/absence of giant kokopu in relation to the above species. Therefore, The Reservoir, Lake Vincent and the proposed pristine fish community in the lakes of the Freshwater Creek catchment were distinguished by the presence of giant kokopu, whereas Lake George/Uruwera reflected the absence of giant kokopu and the presence of perch. However, giant kokopu have been collected from the Lake George/Uruwera catchment, suggesting that they do use the lake (pers. comm. A. Hicks, Environment Southland). Thus, the fish communities of the Southland lakes containing giant kokopu were most similar to those in the West Coast lakes, Ship Creek, Poerua and Mahinapua (Figure 12). Apart from the absence of koaro, the fish community of Ship Creek Lagoon reflects the pristine community postulated for the lakes in the Freshwater Creek catchment.

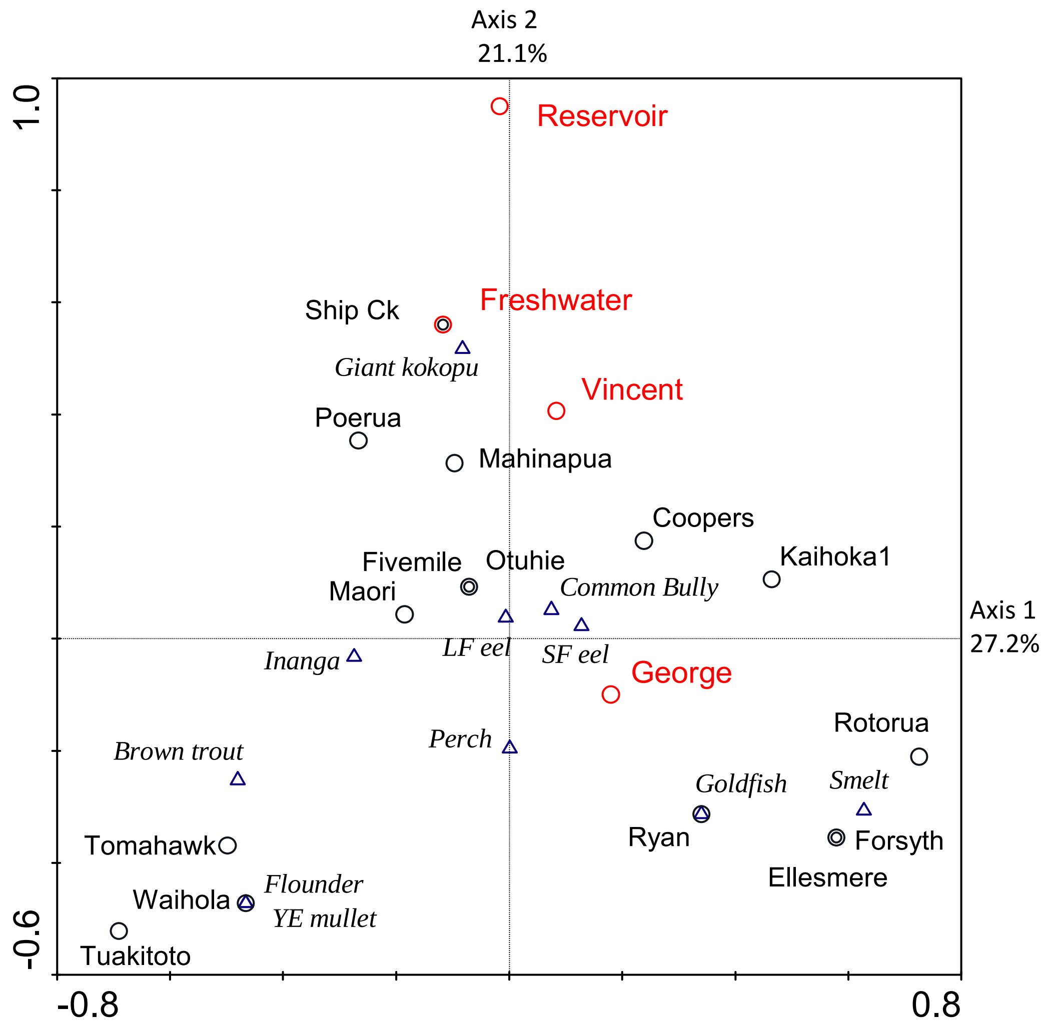

Figure 12. Ordination diagram (correspondence analysis on presence/absence) of fish taxa for 20 South Island shallow coastal lakes. Red labels and circles represent Southland lakes. Black circles represent other lakes. Only lakes similar to the Southland lakes are labelled. Freshwater indicates likely community present in Lakes Sheila and Calder, based on data for Freshwater Creek, Stewart Island/Rakiura, from the NZ Freshwater Fish Database. Triangles and text in italics represent fish taxa.

In summary, the mainland Southland lakes have relatively low native and non-indigenous fish diversity. The lakes with perch have low native fish CPUE. Lakes Vincent and The Reservoir are important in that they contain the nationally declining giant kokopu. All the lakes contain the nationally declining longfin eel.

5.7. Ecological integrity

New Zealand freshwater ecological integrity has been defined as the composite of ecological nativeness, pristineness, diversity and resilience (Schallenberg *et al*. 2011). While an objective index of ecological integrity has not yet been developed for shallow lakes, three of the experts who conducted the sampling of the lakes in the 2004-2008 CDRP campaign were independently asked to rank all the lakes in terms of each expert's interpretation of the lakes' ecological integrity. The ranking exercise was carried out after site visits but before data analysis. The rankings of the experts were highly correlated, with R^2s of around 0. 80 and so this information appears to have some interpretive validity.

The experts generally ranked the Southland lakes as having moderate ecological integrity, with Lake George/Uruwera having the highest integrity, followed closely by Lake Vincent and then The Reservoir (Table 13; lowest ranks indicate highest ecological integrity). Some of the factors that resulted in such moderate rankings included the presence of perch and low native fish CPUEs (Lakes George/Uruwera and Vincent), high nutrient loads from substantially developed catchments (all lakes), presence of the non-indigenous macrophyte *Elodea candensis* (Lake Vincent and The Reservoir), and high phytoplankton biomass (the Reservoir).

Table 13. Expert assessment of ecological integrity of the Southland lakes sampled in 2004.

Lake	**Average rank** out of 41 lakes	**Percentile** of average rank
George/Uruwera	17. 2	33
Vincent	19. 1	40
The Reservoir	28. 3	60

Note: Lowest rank indicates highest ecological integrity. Averages are from three experts' rankings of 41 lakes surveyed. Rankings were not influenced by analyses or data collected, only by site visits and observations of the catchments, characteristics of the water and the aquatic fauna and flora present.

6. KNOWLEDGE GAPS

This report is a first attempt at an ecological interpretation of Southland shallow coastal lakes. It is based on limited information from one-off samplings at the end of summer. Almost nothing is known about the temporal variation of water quality and ecological characteristics of these lakes throughout the year or across years. The data used do however provide a holistic view of the aquatic health of the lakes (*e. g.* water quality, phytoplankton, zooplankton, macrophytes, benthic macroinvertebrates and fish) and account for some of the spatial variation within the lakes (two open water sites and three littoral sites per lake).

Regular monitoring of the lakes would fill in knowledge gaps concerning temporal variation in these lakes. For example, in 2000 Lake Vincent had a much higher chl-a level than in 2004 and 2008. This is unusual for a lake whose catchment has undergone agricultural intensification. Annual monitoring of zooplankton and macrophytes in this lake could provide insight as to whether this lake undergoes regime shifts. Similarly, the phytoplankton biomass in The Reservoir has increased in the past 12 years, while the macrophyte distribution is sparse and patchy. Thus this lake may be vulnerable to regime shifts as a result of increasing nutrient loading from the catchment.

While Lake George/Uruwera is so shallow that it is not likely to temporarily vertically stratify, nothing is known about whether Lakes Vincent and The Reservoir undergo temporary vertical stratification. Such stratification could lead to periods of bottom water anoxia, macrophyte die offs and enhanced internal nutrient loading. Thus, late summer vertical temperature and oxygen profiles from the deepest sites in these lakes would be informative.

Nothing is known about the longer term environmental changes that have occurred in these lakes. For example, Lake George/Uruwera is known to have been affected by historical high sediment loads, but how much infilling has occurred and how current rates of infilling compare to historical rates is unknown. Similarly, it is not known whether Lake George/Uruwera, The Reservoir or Lake Vincent have undergone regime shifts in the past. Thus, palaeolimnological studies could be quite useful in revealing the historical conditions of these lakes, placing their current conditions in useful historical contexts.

The presence of *Echyridella menziesi* (kākahi) and *Daphnia carinata* in some of these lakes suggest that these lakes might exhibit some ecological resilience to the effects of eutrophication. However, little is known about the temporal and spatial variation in densities of these potentially keystone organisms in these lakes and their potential abilities to mitigate effects of nutrient and sediment loading. Similarly, it is important to know if these organisms are likely to be vulnerable to current and future conditions in the lakes.

Finally, Lakes Sheila and Calder are pristine shallow lakes. While we now have some knowledge about their condition and biodiversity values, we know little about their functioning. For example, does the lack of exotic fish result in different energy flow pathways in such indigenous freshwater systems? While primary productivity in Lake Calder is likely to be limited by low pH, alkalinity, and solute concentrations, what limits primary productivity in Lake Sheila? How vulnerable are such pristine lakes to nutrient enrichment?

These are some knowledge gaps which if addressed would greatly enhance our understanding of the functioning of southern shallow coastal lakes.

7. SUMMARY AND MANAGEMENT IMPLICATIONS

The Southland lakes examined in this report are in a moderate-to good ecological condition in comparison to shallow coastal lakes around New Zealand, which generally have been heavily impacted by agricultural land use and the introductions of non-indigenous species. The lakes examined here have only one moderately invasive macrophyte (*Elodea canadensis*) and one non-indigenous fish (perch). While *E. canadensis* probably has virtually no negative impact on the lakes in which it occurs, the presence of perch is probably detrimental to native fish and may even affect water quality.

A key aspect of future successful management of these lakes would be to prevent the introductions of other non-indigenous species into the lakes. A threat to these lakes is the invasive macrophyte *Potamogeton crispus*, which is already found on the south coast, in the Waiau Lagoons, and was detected in this survey in Lake Sheila. Propagules of this macrophyte can be readily transported by waterfowl, making management of its spread difficult if not impossible.

Probably the greatest threat to the water quality and ecology of these lakes would be the collapse of macrophyte communities, as has occurred in numerous other shallow lakes. Macrophyte collapses in shallow lakes and regime shifts to turbid plankton-dominated states are correlated with the percentage of pasture in the catchment and the presence of invasive macrophytes and fish (Schallenberg & Sorrell 2009). The relatively good macrophyte communities in the Southland lakes play key roles in regulating water quality, providing important ecological habitats in these lakes, and contributing to the high diversity of macroinvertebrate communities. It would therefore be prudent to have the macrophyte communities assessed annually to determine their spatial extent within the lakes, species composition (including invasive status), and depth of their colonisation and cover over time.

Summarising the information in this report, Table 14 lists the key ecological values of the four lakes along with threats to these values, monitoring that could be undertaken to provide useful information about potential changes in lake condition, and knowledge gaps. The knowledge gaps indicate research areas to improve understanding of ecological processes in the lakes that relate specifically to the identified values. Our advice concerning Lake Brunton is limited due to the paucity of information available on this lake.

In addition to the knowledge gaps identified in Table 14, a historical environmental context is also lacking for these lakes. For example, although historical sediment loads to Lake George/Uruwera are known to have been high, we have no information on the degree of sediment infilling that occurred or on the condition of the lake’s macrophytes prior to that time. Palaeo-limnological investigations based on analyses of sediment cores is increasingly being used to determine environmental histories of shallow coastal lakes and their catchments (*e. g.* Woodward & Shulmeister 2005; Cosgrove 2011; Schallenberg *et al*. 2012) and such studies can be quite useful for identifying risk factors and setting restoration targets (Schallenberg & Cadmus 2010a,b; Schallenberg 2012.).

Table 14. Summary of key values, threats, suggested monitoring and knowledge gaps for the mainland lakes.

Lakes	Key values	Threats	Suggested monitoring	Knowledge gaps
George/ Uruwera	• Intact riparian areas • Presence of macrophytes • No non-indigenous macrophytes • Presence of giant kokopu (in catchment) • Presence of *Daphnia carinata*, *Echyridella menziesi* and isopods (*Astridotea lacustris*) • High diversity/abundance of macroinvertebrates	• Decline or loss of macrophytes • Increase in suspended sediment • Phytoplankton probably N-limited • Increase in cyanobacterial dominance • Introduction of perch • Introduction of non-indigenous macrophytes	1. Annual monitoring of macrophyte biomass at fixed transects. Could be done by boat using a dredge. 2. At macrophyte transects, also monitor sediment infilling rates and oxic layer depth 3. Monitor water quality in August, October, December, February, April.	• Factors limiting macrophyte growth • Dynamics and role of *Daphnia* in maintaining water quality • Distribution of *Echyridella* and its role in maintaining water quality • Effect of perch on native fish abundance
Vincent	• Native macrophyte diversity and biomass • Low phytoplankton biomass • Presence of giant kokopu and *Echyridella menziesi* • High diversity/abundance of macroinvertebrates	• Return to high phytoplankton biomass (*e. g.* in March 2000) • High nitrate concentrations • Phytoplankton probably P-limited • Presence of perch • Presence of *Elodea canadensis* and possible future introduced macrophytes	1. Monitor water quality in August, October, December, February, April. 2. Survey potential sites of nutrient influx and monitor water quality at these sites before during and after rainfall events. 3. Monitor macrophyte species and cover at fixed transects every five years.	• Factors limiting phytoplankton growth • Effect of perch on native fish abundance
The Reservoir	• Presence of macrophytes • High water clarity • High native fish abundance • No non-indigenous fish	• High phytoplankton biomass is trending upward • Change in phytoplankton species to smaller cells	1. Monitor water quality monthly. Collect temperature oxygen profiles from deepest site. During	• Factors limiting phytoplankton growth • Potential internal nutrient load

Lakes	Key values	Threats	Suggested monitoring	Knowledge gaps
	• Presence of giant kokopu	• Low macrophyte biomass • Reduction in water clarity • Bottom water anoxia during calm periods leading to internal nutrient loading • Lake flipping • Presence of *Elodea canadensis* and possible future introduced macrophytes	blooms, determine dominant phytoplankton species. 2. Survey potential sites of nutrient influx and monitor water quality at these sites before during and after rainfall events. 3. Annual monitoring of macrophyte biomass at fixed transects. Could be done by boat using a dredge.	
Brunton	• Intact riparian areas • Presence of seagrasses	• High nitrate concentration • Sediment loading • Extended periods of high salinity	1. Monitor water quality over an opening/closing cycle (particularly when lake near full). 2. Collect data on opening and closing times of the lake. 3. Survey potential sites of nutrient influx and monitor water quality at these sites before during and after rainfall events. 4. Conduct fisheries surveys to identify fisheries values	• Water quality dynamics • Source of high nitrate concentration

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