Estimates of Reference Conditions for Southland's Shallow, Lowland Lakes

Marc Schallenberg PhD[1], Dave Kelly PhD[2]

1: Hydrosphere Research Ltd
2: Cawthron Institute

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Executive summary

Reference condition is the condition of and ecosystem prior to significant human disturbance or alteration. It is useful for lake management and restoration to know the degree of departure of lakes in their current condition from their likely reference conditions. This provides an idea of the degree of anthropogenic degradation that a lake has undergone.

Freshwater ecological integrity (EI) is a concept that encompasses nativeness, pristineness, diversity and ecological resilience. Lakes with high EI should have a high proportion of their biota made up of native species, should exhibit pristine water quality and ecological functioning, should have an appropriate level of biotic and functional diversity and should embody a degree of resilience to perturbations. The framework of EI can be used to assess the current and likely reference condition of lake ecosystems.

This report uses reference condition thresholds, based on 35 lowland lakes from around New Zealand, developed using the EI framework to assess the degree of departure from reference condition of six shallow, lowland Southland lakes. Data from the lakes was collected in 2012 and 2013. The analysis shows that Lakes Sheila and Calder on Stewart Island/Rakiura are typical reference condition lakes whereas Lakes Murihiku, Vincent, George/Uruwera and The Reservoir depart in various ways and to various degrees from reference conditions.

Key nativeness indicators used were the percentage of fish species that are native, the percentage of macrophyte species that are native, and the percentage of macrophyte cover that is attributable to native macrophyte species. The key pristineness indicators used were water column concentrations of total nitrogen, total phosphorus and phytoplankton biomass (chlorophyll *a*), in addition to the trophic level and the nitrogen loading rate from the catchment. Unfortunately, no diversity indicators were related to EI and, so no reference condition thresholds could be determined for diversity. The resilience indicator used was the ratio of dissolved inorganic nitrogen: total phosphorus in the water column. This variable indicate the degree of balance/imbalance between nitrogen and phosphorus availability and, thus, the vulnerability to cyanobacterial blooms and to excessive nitrogen loading.

The mainland Southland lakes were found to depart to varying degrees from reference conditions in terms of nativeness, pristineness and resilience. In terms of a holistic view of EI, Lake Murihiku departs most, followed by The Reservoir. Both these lakes have issues with non-native species, eutrophication and The Reservoir has a very low DIN:TP ratio. Lakes Vincent and George also depart from reference condition, but less than the other lakes. These lakes also have issues with non-native species, but because they have healthy macrophyte communities, the degree of eutrophication is not as great as in the other lakes. However Lake George does have a low DIN:TP ratio. The Stewart Island/Rakiura reference lakes, Lake Sheila and Calder, meet all the proposed reference condition criteria.

Because the reference condition thresholds are not exclusive thresholds (i.e. some non-reference lakes do meet each of the criteria), to be classified as a reference lake, a lake should meet all the proposed reference condition criteria.

This analysis places the Southland lakes in a context of historical anthropogenic alteration and provides a list of useful indicators for monitoring the future trajectories of the EI of the lakes. It also allows for the prioritisation of the lakes in terms of investment in management and restoration activities. Finally, the analysis indicates which aspects of the lakes have degraded most and, therefore, deserve the most pressing attention.

CONTENTS

1. BACKGROUND AND OBJECTIVES

1.1 SCOPE OF THE REPORT

This report addresses the condition of shallow coastal Southland lakes. To be able to describe the current condition, it is helpful to understand the likely natural, pre-impacted condition of lakes, also known as the reference condition. This can be ascertained in a number of different ways. For example, sediment cores from lakes can contain micro- and macrofossils as well as other biological and geochemical indicators which if interpreted carefully can inform on likely historical and pre-historical conditions. This approach is lake-specific and involves considerable expertise and time. In contrast, the approach used in this report relies on data on the current bio-physical condition of a number of shallow coastal lakes reflecting a wide range of anthropogenic disturbance in the catchment or some other indicator of ecological condition. Relationships exist between key indicators and the degree of disturbance or the ecological integrity of the lakes and, where clear relationships exist, the least impacted lakes may cluster or converge on restricted ranges of the indicator variables. This information can be used to deduce thresholds or ranges of indicator values that reflect minimally impacted, or reference, conditions.

Previous work has been undertaken to determine reference condition in New Zealand shallow coastal lakes (Schallenberg in press), and this information is used in this report to illustrate the current condition of Southland shallow coastal lakes in relation to an inferred reference condition applicable to the lakes. Measurements and data were collected from six Southland shallow lakes in 2012 and 2013 and this information is used to determine departures of the lakes from reference conditions.

In addition, this report discusses important processes and aquatic organisms that relate to ecological conditions in shallow Southland lakes. The indicators discussed in this report are recommended for use in monitoring, managing and restoring these shallow lakes.

1.2 THE LAKES

Note that the data presented in Section 1 are updated from similar data presented in Schallenberg & Kelly (2012). The data presented here supersede the previous estimates provided in the earlier report.

1.2.1 LAKE GEORGE/URUWERA

Lake George/Uruwera is a shallow, lowland, dune lake west of Colac Bay/Oraka. The lake comprises part of the Lake George/Uruwera Wildlife reserve and drains areas of protected native vegetation (the Longwood Mountains and the Owen Conservation Project), pasture and fringing wetlands (Figure 1; Table 1). Historically, gold mining in the lake's catchment resulted in substantial sediment infilling of the lake. The protection and restoration of the land on the lake margins is resulting in the regeneration of native vegetation. The lake is known as a local stronghold for giant kokopu.

The lake has a substantial freshwater inflow in relation to its volume, resulting in a short theoretical water residence time of 19 days (Table 1). Rapid flushing indicates that the lake is strongly influenced by any catchment activities resulting in the mobilisation of sediment and nutrients. This is supported by the high estimated nitrogen (N) and phosphorus (P) loading values for the lakes (Table 1).

Table 1. Morphometric, hydrological and catchment data for Lake George/Uruwera, Southland. Catchment data are from the Land Cover Database 2 (Ministry for the Environment). Nitrogen (N) and phosphorus (P) loading estimates are from the CLUES model (http://www. maf. govt. nz/environment-natural-resources/water/clues), as reported in Kelly et al. (2013).

Lake George/Uruwera	
Surface area (ha)	90.81
Maximum depth (m)	2
Volume (10^6 m^3)	0.605*
Water residence time (days)	19*
Catchment area (km^2)	29.1
Nitrogen load (t/y)	4.506
Areal nitrogen load (t/ha/y)	0.050
Phosphorus load (t/y)	0.553
Areal phosphorus load (t/ha/y)	0.006
% catchment in pasture	26
% catchment in native vegetation	70
% catchment in exotic forest	4

* 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).

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

Table 2 shows the data available for key ecological indicators of lake ecological integrity for Lake George/Uruwera, which are used for analyses in this report. The data for the year 2000 were collected by Environment Southland, whereas the rest of the data were collected by the authors of this report.

Table 2. Lake health indicator values for Lake George/Uruwera used in this study. See Section 2.2. for details.

Variable	2000	2004	2012	2013	Average*
Total nitrogen (mg m^3)	1100	434	1395	434	915
Total phosphorus (mg m^3)	74	27	111	32.5	71.8
TLI		4.8	4.9	3.3	4.1
Chlorophyll *a* (mg m^3)		6	17	2.2	9.6
DIN:TP		0.4	0.18	1.48	0.83
% macrophytes species native			100	100	100
% macrophyte cover native			100	100	100
% fish species native		67			67

* average is for 2012 and 2013, except where data were unavailable for those years.

1.2.2 LAKE MURIHIKU

Lake Murihiku is a small, very shallow lake laying in peatlands to the west of Invercargill. Although the catchment area is extremely small, with no obvious surface inflows to the lake (Table 3; Fig. 2), the water residence time is only 28 days, indicating strong coupling between the catchment land use and the conditions in the lake. It must be noted that because of the low topographic relief in the catchment, catchment boundaries are difficult to determine with accuracy. For example, the extensive wetlands to the north west of the lake may influence the lake, but they have been excluded from our catchment analysis due to surface topography. Although most of the lake margin is comprised of flaxes and other native vegetation, the rest of the catchment is used for agriculture. This results in fairly high estimated N and P loads to the lake (Table 3).

Table 3. Morphometric, hydrological and catchment data for Lake Murihiku, Southland. Catchment data are from the Land Cover Database 2 (Ministry for the Environment). Nitrogen (N) and phosphorus (P) loading estimates are from the CLUES model (http://www. maf. govt. nz/environment-natural-resources/water/clues), as reported in Kelly et al. (2013).

Lake Murihiku	
Surface area (ha)	5.73
Maximum depth (m)	1.3
Volume (10^6 m^3)	0.049*
Water residence time (days)	28*
Catchment area (km^2)	0.6
Nitrogen load (t/y)	1.232
Areal nitrogen load (t/ha/y)	0.215
Phosphorus load (t/y)	0.116
Areal phosphorus load (t/ha/y)	0.020
% catchment in pasture	91
% catchment in native vegetation	9.2
% catchment in exotic forest	0

* 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).

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

Table 4 shows the data available for key ecological indicators of lake ecological integrity for Lake Murihiku, which are used for analyses in this report. The data were collected by the authors of this report.

Table 4. Lake health indicator values for Lake Murihiku used in this study. See Section 2.2 for details.

Variable	2013
Total nitrogen (mg m^3)	2093
Total phosphorus (mg m^3)	235
TLI	6.2
Chlorophyll *a* (mg m^3)	27.9
DIN:TP	1.87
% macrophytes species native	100
% macrophyte cover native	100
% fish species native	67

1.2.3 THE RESERVOIR

The Reservoir is a dune reservoir located near Slope Point and Haldane Bay, which resulted from the damming of a small coastal creek. The outlet of the lake is sometimes regulated by the landowner. While the headwaters of the lake are indigenous forest, most of the lake's small catchment is in intensive agriculture including dairying (Figure 3; Table 5). The inflow volume to the lake and its volume together determine it intermediate theoretical water residence time of 55 days, suggesting that in-lake processes could influence the lake's water quality and ecology.

Table 5. Morphometric, hydrological and catchment data for The Reservoir, Southland. Catchment data are from the Land Cover Database 2 (Ministry for the Environment). Nitrogen (N) and phosphorus (P) loading estimates are from the CLUES model (http://www. maf. govt. nz/environment-natural-resources/water/clues), as reported in Kelly et al. (2013).

The Reservoir	
Surface area (ha)	35.53
Maximum depth (m)	5
Volume (10^6 m^3)	0.592*
Water residence time (days)	55*
Catchment area (km^2)	5.7
Nitrogen load (t/y)	3.083
Areal nitrogen load (t/ha/y)	0.087
Phosphorus load (t/y)	0.268
Areal phosphorus load (t/ha/y)	0.008
% catchment in pasture	73
% catchment in native vegetation	26
% catchment in exotic forest	0.3

* 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).

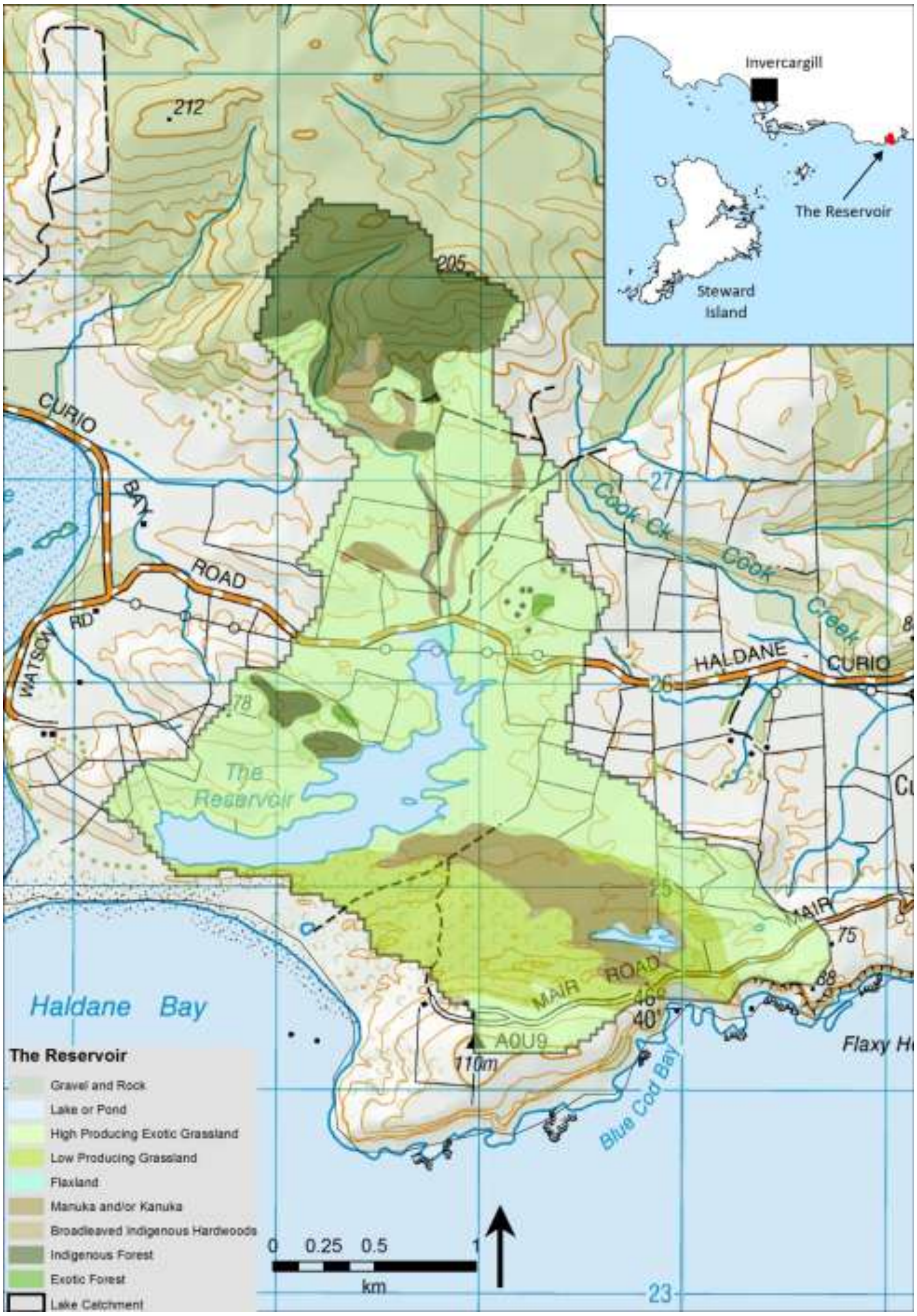

Figure 2. Location of The Reservoir, Southland. Catchment land use information is from the Land Cover Database 2 (Ministry for the Environment).

Table 6 shows the data available for key ecological indicators of lake ecological integrity for the Reservoir, which are used for analyses in this report. The data for the year 2000 were collected by Environment Southland, whereas the rest of the data were collected by the authors of this report.

Table 6. Lake health indicator values for The Reservoir used in this study. See Section 2.2 for details.

Variable	2000	2004	2012	2013	Average*
Total nitrogen (mg m^3)	925	615	630	535	583
Total phosphorus (mg m^3)	46	21	36	38.8	37.4
TLI		4.7	5.1	4.3	4.7
Chlorophyll *a* (mg m^3)	5	10	20	2.5	11.3
DIN:TP		0.9	0.39	0.14	0.27
% macrophytes species native			83	67	75
% macrophyte cover native			19	53	36
% fish species native		100			100

* average is for 2012 and 2013, except where data were unavailable for those years.

1.2.4 LAKES SHEILA AND CALDER

Lakes Sheila and Calder are situated in the Freshwater River catchment of Stewart Island/Rakiura. The lakes are located on opposite sides of Freshwater River, within an extensive unmodified wetland complex (Figure 4). The lakes are quite different in their hydrology. Whereas Lake Sheila has a moderate inflow and has a relatively short theoretical water residence time, Lake Calder which appears to be seepage-fed and, therefore, has a longer theoretical water residence time than Lake Sheila (Tables 7 and 8). Lake Calder has a higher elevation that Lake Sheila, suggesting that it might be perched – it does not appear to be connected to Freshwater Creek by surface water flows. The hydrological data in Tables 7 and 8 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 7. Morphometric, hydrological and catchment data for Lake Sheila, Stewart Island/Rakiura. Catchment data are from the Land Cover Database 2 (Ministry for the Environment). Nitrogen (N) and phosphorus (P) loading estimates are from the CLUES model (http://www. maf. govt. nz/environment-natural-resources/water/clues), as reported in Kelly et al. (2013).

Lake Sheila	
Surface area (ha)	14.12
Maximum depth (m)	6.6
Volume (10^6 m^3)	0.163*
Water residence time (days)	30*
Catchment area (km^2)	1
Nitrogen load (t/y)	0.515
Areal nitrogen load (t/ha/y)	0.036
Phosphorus load (t/y)	0.023
Areal phosphorus load (t/ha/y)	0.0016
% catchment in pasture	0
% catchment in native vegetation	100
% catchment in exotic forest	0

* 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).

Table 8. Morphometric, hydrological and catchment data for Lake Calder, Stewart Island. Catchment data are from the Land Cover Database 2 (Ministry for the Environment). Nitrogen (N) and phosphorus (P) loading estimates are from the CLUES model (http://www. maf. govt. nz/environment-natural-resources/water/clues), as reported in Kelly & Schallenberg (2013).

Lake Calder	
Surface area (ha)	4.12
Maximum depth (m)	6.7
Volume (10^6 m^3)	0.091*
Water residence time (days)	69*
Catchment area (km^2)	0.3
Nitrogen load (t/y)	0.182
Areal nitrogen load (t/ha/y)	0.044
Phosphorus load (t/y)	0.023
Areal phosphorus load (t/ha/y)	0.006
% catchment in pasture	0
% catchment in native vegetation	100
% catchment in exotic forest	0

* 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).

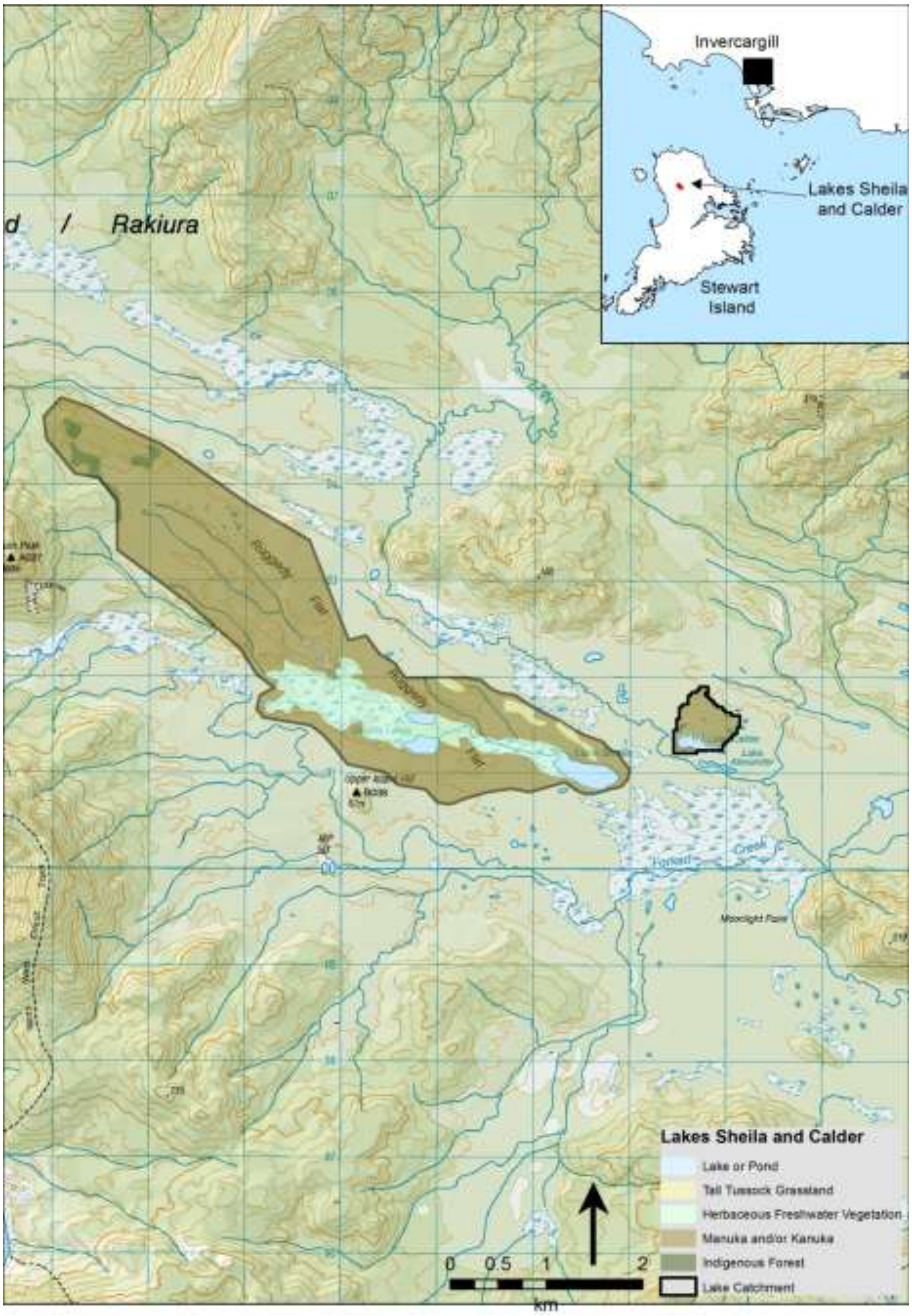

Figure 3. Location of Lakes Sheila (left) and Calder (right) and their catchments, Stewart Island/Rakiura. Catchment land use information is from the Land Cover Database 2 (Ministry for the Environment).

Tables 9 and 10 show the data available for key ecological indicators of lake ecological integrity for Lakes Sheila and Calder, which are used for analyses in this report. The data were collected by the authors of this report.

Table 9. Lake health indicator values for Lake Sheila used in this study. See Section 2.2 for details.

Variable	2012	2013	Average
Total nitrogen (mg m^3)	265	240	253
Total phosphorus (mg m^3)	2	19.5	10.8
TLI	2.5	2.8	2.65
Chlorophyll *a* (mg m^3)	2.2	0.9	1.55
DIN:TP	4.75	0.131	3.03
% macrophytes species native	100	100	100
% macrophyte cover native	100	100	100
% fish species native		100	100

Table 10. Lake health indicator values for Lake Calder used in this study. See Section 2.2 for details.

Variable	2012
Total nitrogen (mg m^3)	220
Total phosphorus (mg m^3)	6.5
TLI	2.9
Chlorophyll *a* (mg m^3)	1.5
DIN:TP	1.31
% macrophytes species native	100
% macrophyte cover native	100
% fish species native	100*

* assumed based on Lake Sheila fish community.

1.2.6 LAKE VINCENT

Lake Vincent is a dune lake located between the Mataura River mouth and Waipapa Point (Figure 5). It drains a small catchment dominated by intensive agriculture, including dairying (Table 11). Freshwater inflows and lake volume result in an intermediate theoretical water residence time of 49 days, suggesting that in-lake processes influence water quality and the ecology of the lake.

Table 11. Morphometric, hydrological and catchment data for Lake Vincent, Southland. Catchment data are from the Land Cover Database 2 (Ministry for the Environment). Nitrogen (N) and phosphorus (P) loading estimates are from the CLUES model (http://www. maf. govt. nz/environment-natural-resources/water/clues), as reported in Kelly et al. (2013).

Lake Vincent	
Surface area (ha)	17.21
Maximum depth (m)	5
Volume (10^6 m^3)	0.287*
Water residence time (days)	49*
Catchment area (km^2)	3.1
Nitrogen load (t/y)	2.733
Areal nitrogen load (t/ha/y)	0.159
Phosphorus load (t/y)	0.064
Areal phosphorus load (t/ha/y)	0.004
% catchment in pasture	97
% catchment in native vegetation	0.1
% catchment in exotic forest	2.7

* 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).

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

Table 12 shows the data available for key ecological indicators of lake ecological integrity for Lake Vincent, which are used for analyses in this report. The data for the year 2000 were collected by Environment Southland, whereas the rest of the data were collected by the authors of this report.

Table 12. Lake health indicator values for Lake Vincent used in this study. See Section 2.2 for details.

Variable	2000	2004	2012	2013	Average*
Total nitrogen (mg m^3)	662	563	670	515	593
Total phosphorus (mg m^3)	26	15	19	22.5	20.8
TLI		3.8	3.9	3.3	3.6
Chlorophyll *a* (mg m^3)	13	1	1.5	0.4	0.95
DIN:TP		3	3.29	0.84	2.07
% macrophytes species native			86	67	76.5
% macrophyte cover native			77	75	76
% fish species native		80			80

* average is for 2012 and 2013, except where data were unavailable for those years.

1.3 OBJECTIVES

This report aims to achieve four main objectives in relation to the scope of the report discussed in Section 1.1:

- To compile indicators of lake ecological condition/integrity that are useful for determining the degree of departure of lakes from their reference state.
- To employ a methodology based on data from 35 shallow lowland lakes around New Zealand to quantify the relative departure of six shallow Southland lakes from their inferred reference conditions
- To discuss some biotic drivers of ecological integrity in Southland lowland lakes
- To make recommendations on indicators to help monitor, manage and restore Southland lowland lakes.

2. METHODS

2.1 ANALYTICAL APPROACHES

This report employs a broad definition of ecological integrity to assess reference condition and departures from reference condition. The definition of freshwater ecological integrity (EI) derives from Schallenberg et al. (2010) and includes the core components: nativeness, pristineness, diversity and resilience. Schallenberg et al. (2010) suggest some indicators for the different components of EI that could be used to assess EI for lakes. Drake et al. (2010) used an extensive dataset collected from around 40 shallow lowland lakes to examine relationships between some of the lake EI indicators and human pressure gradients. Drake et al. (2010) also employed an expert assessment approach to quantify the EI of shallow lowland lakes, and these authors found that the expert assessments were relatively consistent among experts and were strongly correlated to both human pressure gradients and lake EI indicators. This expert assessment ranking it addition to measurement of the percentage of each lake's catchment that is in native vegetation are two independent estimates of EI used in this report to establish reference conditions for shallow lowland lakes.

This was done by Schallenberg (in press) for 35 freshwater lowland lakes sampled from Northland to Campbell Island, which is substantially the same dataset employed by Drake et al. (2010). The reference condition thresholds and ranges derived by Schallenberg (in press) were compared to data collected from six Southland lakes in 2012 (Schallenberg & Kelly 2012) and again in 2013.

2.2 DATA SOURCES

A variety of data sources were used in this report.

- The dataset of Drake et al. 2010 comprises around 35 shallow, freshwater, lowland lakes, including Lakes George/Uruwera, Lake Vincent and The Reservoir. The data cover fish, macrophytes, invertebrates, plankton, zooplankton, water quality and catchment land use. The lake data were collected during single samplings in mid-late summer.
- The dataset of Schallenberg & Kelly (2012) comprises the Southland lakes, George/Uruwera, Vincent, Brunton, Sheila, Calder and The Reservoir. Data collections were similar to Drake et al. (2010), although fish were not sampled. Fish data for some of the lakes were obtained from Environment Southland (A. Hicks, unpubl. data).
- The dataset of Schallenberg (in press) combined data from Drake et al. (2010) and data for Lakes Sheila and Calder from Schallenberg & Kelly (2012).
- A sampling campaign was again undertaken in the summer of 2013 to collect more data on the Southland lakes already sampled and to include Lake Murihiku in the dataset (M. Schallenberg and D. Kelly, unpubl. data). Fish sampling was undertaken in this campaign for Lake Sheila. Fish data for Lake Murihiku was provided by Environment Southland (A. Hicks, unpubl. data).
- Data on catchment nitrogen loading and catchment land use for the Southland lakes in this study were obtained from Kelly et al. (2013)

3. RESULTS AND DISCUSSION

3.1 USEFUL INDICATORS OF LAKE CONDITION AND TREND

3.1.1 INIDICATORS RELATED TO ECOLOGICAL INTEGRITY AND CATCHMENT MODIFICATION

Reference condition can be inferred by establishing whether relationships exist between indicators of ecological condition and indicators of catchment modification. If a positive correlation exists, then a definition of reference condition whereby lakes in the highest percentile of ecological condition and catchment native vegetation could be defined as modern reference lakes, reflecting conditions similar to those prior to anthropogenic impacts on lakes. Schallenberg (in press) utilised the 90th and 80th percentiles of the lakes to define "strict" and "relaxed" reference conditions for New Zealand lowland shallow lakes (Fig. 6).

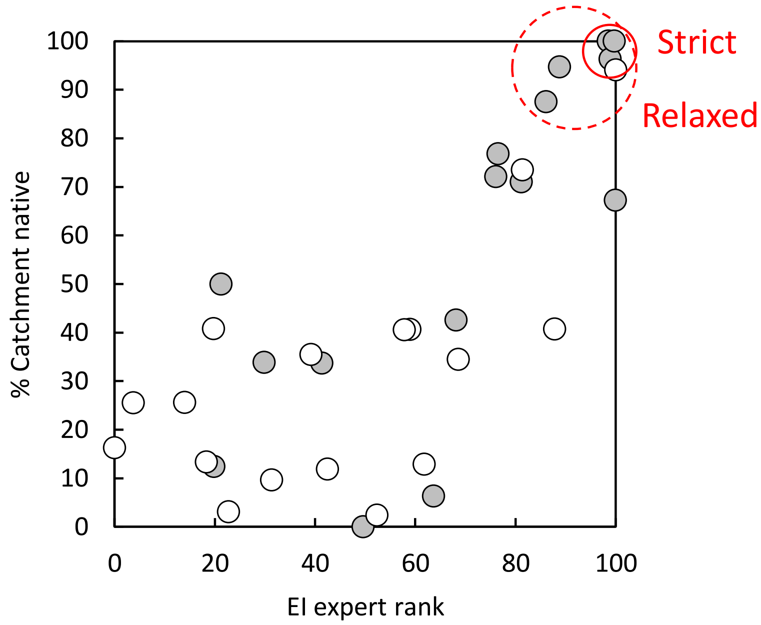

Figure 6. Relationship between two indicators of reference condition in shallow freshwater lakes, the percentage of catchment in native vegetation and the ecological integrity of the lake as determined by expert assessment (see Drake et al. 2010). Red circles demarcate potential reference lakes, "strict" reference lakes (encompassing the 90th percentiles of both indicators) and "relaxed" reference lakes (encompassing the 80th percentiles of both indicators). Filled symbols represent South Island lakes and open symbols represent North Island lakes. From Schallenberg (in press).

The reference lakes determined from this analysis include:

Strict	Relaxed
Six Foot Lake (Campbell Island)	Lake Wilkie (Catlins)
Ship Creek Lagoon (South Westland)	Lake Pounui (Wairarapa)
"Maori" Lake (South Westland)	
Lake Otuhie (Northwest coast of South Island)	
Lake Sheila (Stewart Island)/Rakiura	
Lake Calder (Stewart Island)/Rakiura	

These lakes are considered to be in good ecological condition both because their catchments have substantial cover of native vegetation and because they were ranked highest in terms of ecological integrity (EI) by scientists who visited all the lakes (see Drake et al. 2010). Thus, the conditions in these lakes may be useful in determining reference conditions for New Zealand lowland shallow lakes in general. Their utility in this regard depends on there being strong relationships between measures of EI and both native vegetation cover in the catchment and EI expert rankings. The following section describes the relationships and thresholds defining reference conditions as determined by this methodology and described fully in Schallenberg (in press).

3.1.2 INDICATORS OF NATIVENESS

Schallenberg et al. (2010) suggested a number of potentially useful indicators of nativeness of key lake biotic communities. Schallenberg (in press) tested a number of these indications in relationships against the two indicators of reference condition: ecological integrity and % catchment in native vegetation. In general, these relationships are not linear, but rather suggested polygons whereby the lower limit of percentage nativeness is positively related to indicators of reference condition. Nativeness thresholds for reference condition were set at 100% because no tolerance of invasive species is appropriate under reference conditions due to the extreme impacts that non-native species can have on lake ecosystems (Champion et al. 2002; Closs et al. 2004). In terms of nativeness, Lake Pounui (Wairarapa) was an outlier because although it was in near pristine condition, it had some non-native aquatic macrophytes at the time of sampling. Lake Wilkie (Catlins) maintained a high ecological integrity score despite scoring poorly in terms of native fish (it contained none) because the lake is a seepage lake and is heavily influenced by peatlands, resulting in a naturally low pH of 4.6, which may be too low for native fish reproduction. Neither of these outlier lakes are from the strict reference group and, therefore, they don't compromise the nativeness threshold as determined by the strict reference lakes.

Recommended nativeness thresholds and abilities of the thresholds to differentiate non-reference lakes from reference lakes are shown in Table 13. There was no relationship between "native fish catch per unit effort" and indicators of ecological integrity and, therefore, no threshold could be determined for that indicator of nativeness.

Table 13. Nativeness reference condition thresholds for shallow freshwater lakes. The percentage of non-reference lakes excluded by the threshold is a measure of the strength of the threshold in distinguishing reference lakes from non-reference lakes. Outliers are reference lakes that fall outside the deemed thresholds. Grey-shaded boxes indicate there is no relationship between the nativeness indicator and indicators of reference condition and, therefore, no threshold is proposed. From Schallenberg (in press).

Indicator	Units	Range for all lakes	Range for reference lakes	Threshold	% non-reference lakes excluded	Outliers
% native fish species	%	33-100	100	100	69 %	Wilkie
% native macrophyte species	%	0-100	75-100	100	53 %	Pounui
% native macrophyte cover	%	0-100	90-100	100	44 %	Pounui
Native fish CPUE	catch/effort	0-274	4-80			none

The percentage of native fish species in the fish community is considered to be a moderately effective indicator of nativeness and EI. While all strict reference lakes (90th percentile) had 100%

native fish species, 31% of non-reference lakes also had 100% native fish species present. So the indicator is robust with respect to certainty in the threshold, but it is not an exclusive indicator of EI.

Figure 7 shows the percentage native fish species in Southland lakes in relation to the nativeness threshold. Lake Sheila and The Reservoir had 100% native fish communities at the times of sampling, whereas lakes Murihiku, Vincent and George had some exotic fishes, moving them away from the reference condition. Yellow perch (*Perca fluviatilis*) is the main exotic fish species in shallow Southland lakes and this fish has detrimental effects on native fishes in these lakes, as reflected in the native fish catch per unit effort (Schallenberg & Kelly 2012).

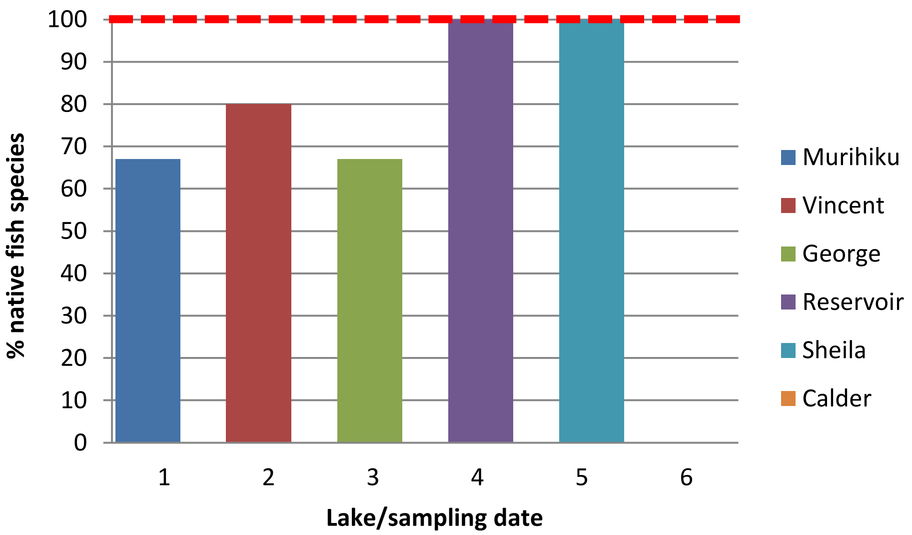

Figure 7. Percentage of fish species that are native, by lake. No fish data were available for Lake Calder, however this lake probably had 100% native fish present. The dashed red line is the threshold for reference condition (100%) as determined by Schallenberg (in press). This threshold was considered to be moderately effective at assessing reference condition: 100% of reference lakes at the 90th percentile achieved the threshold, but 31% of non-reference lakes also achieved the threshold.

The percentage of native macrophyte species in the macrophyte community is a slightly less effective indicator of nativeness and EI. While all strict reference lakes (90th percentile) had 100% native macrophyte species, 47% of non-reference lakes also had 100% native macrophyte species present. So, like percentage native fish species, this indicator is robust with respect to certainty in the threshold, but it is not an exclusive indicator of EI.

Figure 8 shows the percentage native macrophyte species in Southland lowland lakes, in relation to the reference condition threshold. Only The Reservoir and Lake Vincent had non-native macrophytes (*Elodea Canadensis* and *Ranunculus trichophyllus*) moving them away from reference condition. Although they are non-native species, these species are not considered to have a high invasiveness potential and generally do not dominate the macrophyte communities of New Zealand lakes in which they occur (Closs et al. 2004). These species were absent from Lakes George/Uruwera and Murihiku.

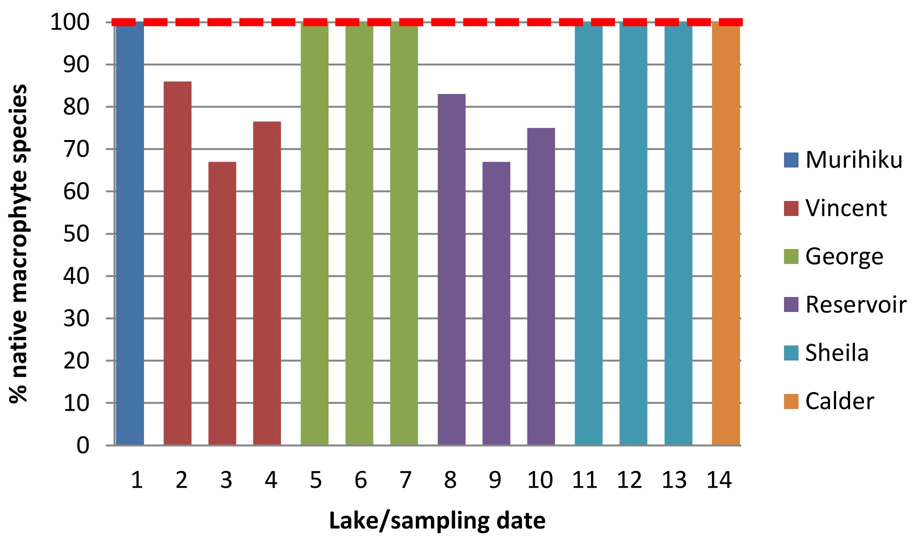

Figure 8. Percentage of macrophyte species that are native, by lake. Where there are three bars per lake, the bar to the left represents data from 2012, the middle bar represents data from 2013 and the bar on the right represents the mean of the 2012 and 2013 data. Lake Murihiku was only sampled in 2013 and Lake Calder was only sampled in 2012. The dashed red line is the threshold for reference condition (100%) as determined by Schallenberg (in press). This threshold was considered to be a moderately effective at discriminating reference condition: 100% of reference lakes at the 90th percentile achieved the threshold, while 47% of non-reference lakes also achieved the threshold.

The third useful indicator of nativeness is an indicator known as percentage native macrophyte cover. This indicator is calculated as the amount of macrophyte cover attributable to native species and assesses the potential dominance of native vs non-native species. This turned out to be a less effective indicator of nativeness and EI in the lakes studies. While all strict reference lakes (90th percentile) had 100% native macrophyte cover, 56% of non-reference lakes also had 100% native macrophyte species present. So, like percentage native fish species, this indicator is robust with respect to certainty in the threshold, but it is not an exclusive indicator of EI.

Figure 9 shows the percent native macrophyte cover for Southland lakes in relation to the reference condition threshold. The Reservoir shows significant incursions of non-native macrophytes, while cover of non-native species is more restricted in Lake Vincent.

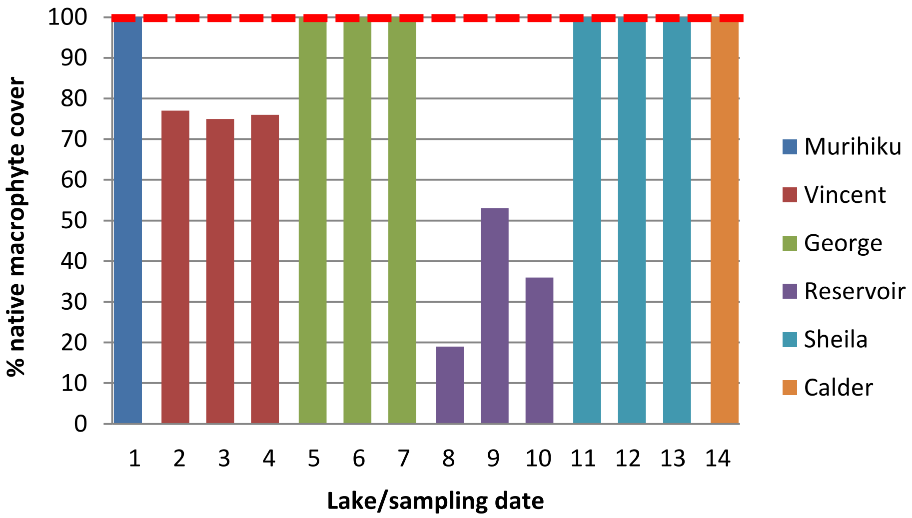

Figure 9. Percentage of lake bed macrophyte cover attributed to native macrophytes, by lake. Where there are three bars per lake, the bar to the left represents data from 2012, the middle bar represents data from 2013 and the bar on the right represents the mean of the 2012 and 2013 data. Lake Murihiku was only sampled in 2013 and Lake Calder was only sampled in 2012. The dashed red line is the threshold for reference condition (100%) as determined by Schallenberg (in press). This threshold was considered to be a weak discriminator of reference condition: 100% of reference lakes at the 90th percentile achieved the threshold, while 56% of non-reference lakes also achieved the threshold.

The departures from reference condition for the three nativenenss indicators for the six southland lakes can be summed to show an overall departure from nativeness reference condition (Figure 10). No weightings have been given to the three indicators, so nativeness of the macrophyte communities is more influential and fish nativeness in this analysis. The Reservoir shows the greatest departure from reference condition followed by Lake Vincent. Lakes George/Uruwera and Murihiku depart somewhat from reference conditions and Lakes Sheila and Calder are reference lakes, showing no departure from nativeness reference conditions.

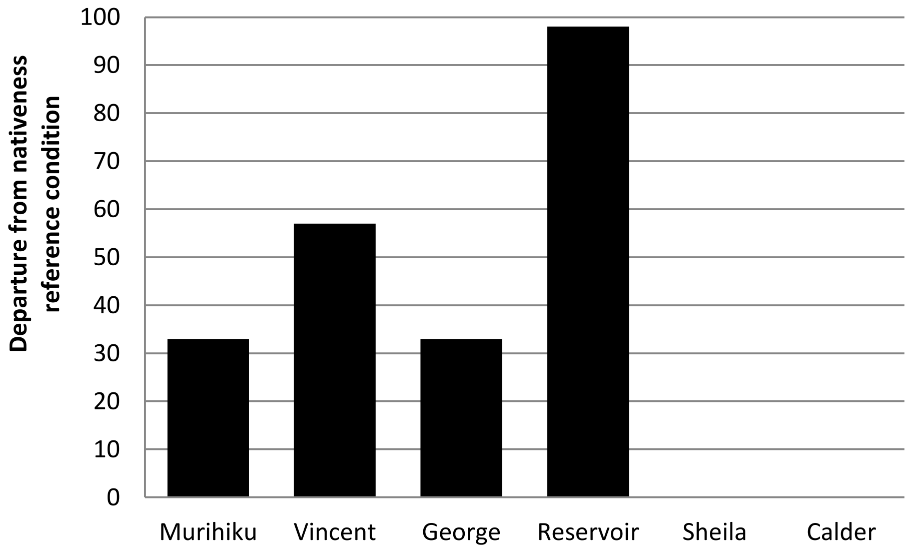

Figure 10. Departures from nativeness reference condition (sum of percentages) for Southland lowland lakes.

3.1.3 INDICATORS OF PRISTINENESS

Indicators of pristineness are mainly physico-chemical variables related to nutrient and sediment enrichment of the lakes. Many of these can effectively distinguish pristine lakes from degraded lakes because they correlate strongly with EI and the percentage of the catchment in native vegetation.

The strict reference lake, Sixfoot Lake (Campbell Island), is a consistent pristineness outlier due to its high levels of nutrients and chlorophyll *a*. This pristine lake was eutrophic when sampled and exhibited high levels of phytoplankton productivity (M Schallenberg, unpubl. data).

The recommended reference condition thresholds and their abilities to differentiate pristine from degraded shallow freshwater lakes are shown in Table 14. Strict and relaxed reference condition thresholds sometimes differ substantially. Note that many potential indicators of pristineness showed no clear relationships with EI or the percentage of the catchment in native vegetation. Thus, no reference condition thresholds could be determined for those indicators, which appear to be of little use in setting general reference conditions for shallow lowland lakes.

Table 14. Pristineness reference condition thresholds for shallow freshwater lakes. The percentage of non-reference lakes excluded by the threshold is a measure of the strength of the threshold in distinguishing reference lakes from non-reference lakes. Outliers are reference lakes that fall outside the deemed thresholds. Grey-shaded boxes indicate there is no relationship between the pristineness indicator and indicators of reference condition and, therefore, no thresholds are proposed. From Schallenberg (in press).

Indicator	Units	Range for all lakes	Range for reference lakes (relaxed)	Threshold (relaxed)	% non-reference lakes excluded (relaxed)	Outliers
Total nitrogen	µg/L	151-3672	235-277 (235-692)	≤ 277 (≤ 692)	86 % (42 %)	Sixfoot, Wilkie
Total phosphorus	µg/L	2-492	2-11.7 (2-23)	≤ 11.7 (≤ 23)	64 % (43 %)	Sixfoot
TLI		2-492	1.8-3.5 (1.8-4.4)	≤ 3.5 (≤ 4.4)	64 % (38 %)	Sixfoot
Chlorophyll a	mg/L	1-116	0.7-3.2 (0.7-5.7)	≤ 3.2 (≤ 5.7)	57 % (46 %)	Sixfoot
Nitrogen loading	t/ha/y			≤ 0.086*	45 %*	none
Macrophyte cover	%	0-100	31-98 (12-98)			Sixfoot
Dissolved organic carbon	mg/L	3-34	4.0-10.4 (4.0-23)			none
Euphotic depth	m	0.6-12.1	1-6.7 (1-6.7)			none
%ETO (species)	%	0-21	0-13.6 (0-14.3)			none
%ETO (abundance)	%	0-14	0-13.5 (0-13.5)			none
Humic absorbance per unit dissolved organic carbon	abs/mg/L	0.02-0.75	0.14-0.29 (0.14-0.39)			none
Macrophyte depth limit	m	0.1-11.9	0.4-6.0 (0.4-6.0)			none
Pest fish species	count	0-4	0*			none

* Re-calculated after Kelly et al. (2013) for South Island and Steward Island lakes (no estimate included for Sixfoot Lake).
** Reference lakes displayed no range

The concentration of total nitrogen (TN) in lake water is considered to be an effective indicator of pristineness and EI. While 83% of strict reference lakes (90th percentile) had TN concentrations equal to or less than the strict reference condition threshold, 14% of non-reference lakes also had TN concentrations below this level. So the indicator is quite robust with respect to certainty in the threshold and as an indicator of EI. However, the pristine Sixfoot Lake on Campbell Island was eutrophic at the time of sampling, exceeding the TN reference condition threshold set by Schallenberg (in press) as shown in Table 14.

Figure 11 shows the TN concentration in the Southland lakes in relation to both the strict and relaxed pristineness reference condition thresholds. Lakes Murihiku and George/Uruwera exceed both thresholds, with Lake Murihiku showing extreme departure from reference condition. Lake Vincent and The Reservoir both exceed the strict reference condition threshold, while the reference lakes, Sheila and Calder were below the threshold, exhibiting reference conditions.

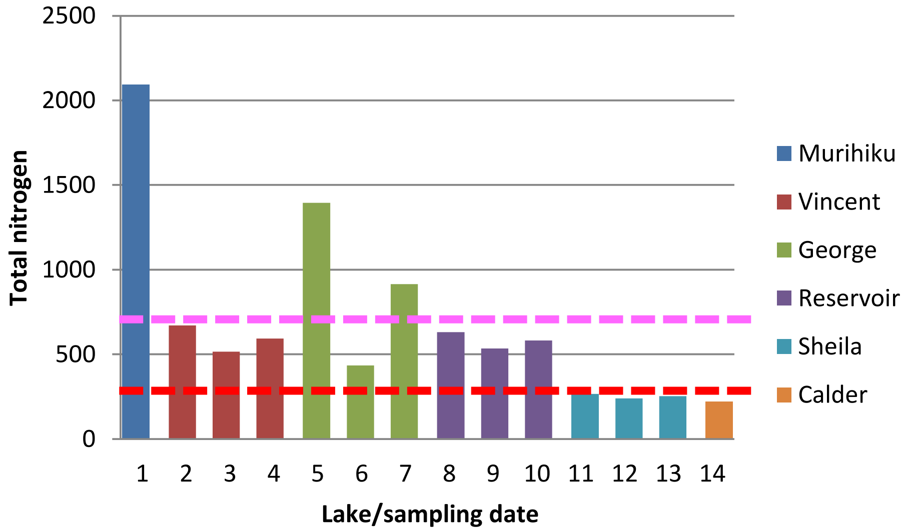

Figure 11. Lake water total nitrogen concentration (µg/L), by lake. Where there are three bars per lake, the bar to the left represents data from 2012, the middle bar represents data from 2013 and the bar on the right represents the mean of the 2012 and 2013 data. Lake Murihiku was only sampled in 2013 and Lake Calder was only sampled in 2012. The dashed red line is the threshold for strict reference condition (90th percentile; 277 mg/L)) and the pink dashed line is the relaxed reference condition (80th percentile; 692 mg/L) as determined by Schallenberg (in press). This threshold was considered to be a robust discriminator of reference condition: 83% of reference lakes at the 90th percentile achieved the threshold (Sixfoot Lake was an outlier), while 14% of non-reference lakes also achieved the threshold.

The concentration of total phosphorus (TP) in lake water is considered to be a moderately effective indicator of pristineness and EI. While 83% of strict reference lakes (90th percentile) had TP concentrations equal to or less than the strict reference condition threshold, 36% of non-reference lakes also had TN concentrations below this level. So the indicator is quite robust with respect to certainty in the threshold and as an indicator of EI, but is not effective at distinguishing lakes that are not in reference condition from those that are. The pristine Sixfoot Lake on Campbell Island was eutrophic at the time of sampling, exceeding the TP reference condition threshold set by Schallenberg (in press) as shown in Table 14.

Figure 12 shows the TP concentration in the Southland lakes in relation to both the strict and relaxed pristineness reference condition thresholds. Again, Lakes Murihiku and George/Uruwera exceed both thresholds, with Lake Murihiku showing extreme departure from reference condition. The Reservoir also slightly exceeds the relaxed reference condition threshold, while Lake Vincent only slightly exceeds the strict reference conditions threshold, indicating that in terms of TP, Lake Vincent is close to the reference condition. On average, both reference lakes, Lakes Sheila and Calder, were below the TP reference condition thresholds.

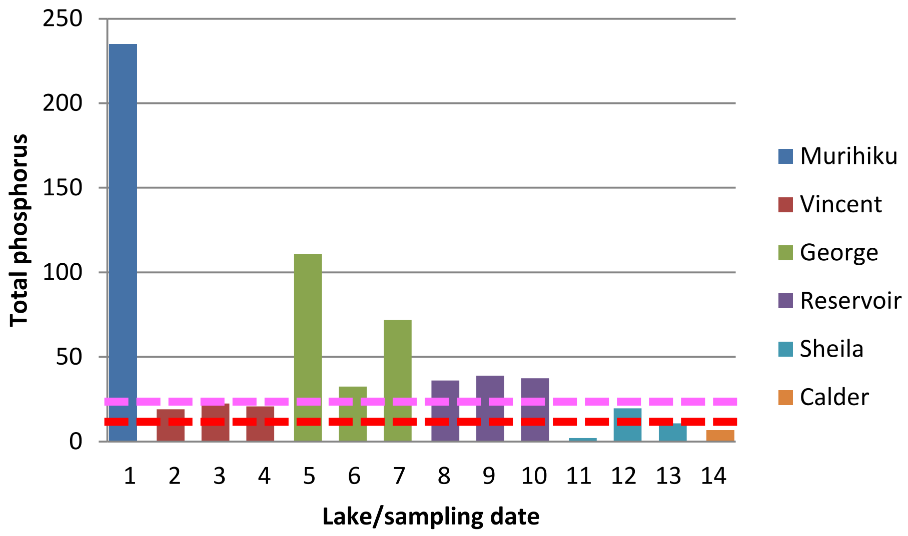

Figure 12. Lake water total phosphorus concentration (µg/L), by lake. Where there are three bars per lake, the bar to the left represents data from 2012, the middle bar represents data from 2013 and the bar on the right represents the mean of the 2012 and 2013 data. Lake Murihiku was only sampled in 2013 and Lake Calder was only sampled in 2012. The dashed red line is the threshold for strict reference condition (90th percentile) and the pink dashed line is the relaxed reference condition (80th percentile) as determined by Schallenberg (in press). This threshold was considered to be a moderate discriminator of reference condition: 83% of reference lakes at the 90th percentile achieved the threshold (Sixfoot Lake was an outlier), while 36% of non-reference lakes also achieved the threshold.

Given that effective reference condition thresholds were derivable for both TN and TP, it follows that the trophic level index (TLI) was also a moderately effective indicator of pristineness and EI. While 83% of strict reference lakes (90th percentile) had TLI levels equal to or less than the strict reference condition threshold, 36% of non-reference lakes also had TLI levels below this level. So the TLI indicator is quite robust with respect to certainty in the threshold and as an indicator of EI, but is not effective at distinguishing lakes that are not in reference condition from those that are. The pristine Sixfoot Lake on Campbell Island was eutrophic at the time of sampling, exceeding the TLI reference condition threshold set by Schallenberg (in press) as shown in Table 14.

Figure 13 shows the TLI levels for the Southland lakes in relation to both the strict and relaxed pristineness reference condition thresholds. Note that the TLI index is made up of $\log_{10}$-transformed data, which compresses high values and expands low values, in comparison to untransformed data. Again, Lake Murihiku far exceeds both of the TLI reference condition thresholds, while The Reservoir also exceeds the both thresholds. Lake George/Uruwera exceeds the strict TLI reference condition threshold (on average), whereas Lake Vincent varies about the strict threshold. Both reference lakes, Lakes Sheila and Calder, were below the TLI reference condition thresholds.

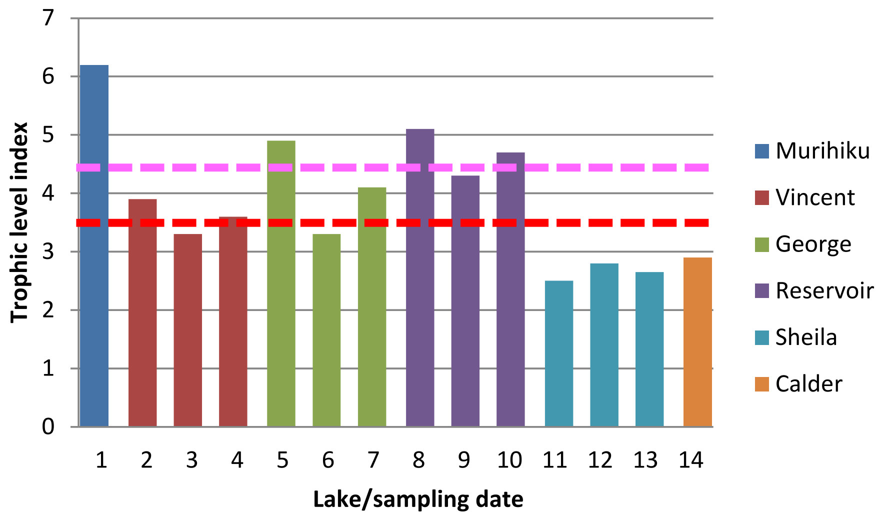

Figure 13. Lake water trophic level index (TLI), by lake. Where there are three bars per lake, the bar to the left represents data from 2012, the middle bar represents data from 2013 and the bar on the right represents the mean of the 2012 and 2013 data. Lake Murihiku was only sampled in 2013 and Lake Calder was only sampled in 2012. The dashed red line is the threshold for strict reference condition (90th percentile) and the pink dashed line is the relaxed reference condition (80th percentile) as determined by Schallenberg (in press). This threshold was considered to be a moderate discriminator of reference condition: 83% of reference lakes at the 90th percentile achieved the threshold (Sixfoot Lake was an outlier), while 36% of non-reference lakes also achieved the threshold.

Phytoplankton biomass in the water column of the lakes, as indicated by chlorophyll *a* concentration, was also a moderately effective indicator of pristineness and EI. While 83% of strict reference lakes (90th percentile) had phytoplankton biomass levels equal to or less than the strict reference condition threshold, 43% of non-reference lakes also had TLI levels below this level. So the TLI indicator is quite robust with respect to certainty in the threshold and as an indicator of EI, but is not effective at distinguishing lakes that are not in reference condition from those that are. The pristine Sixfoot Lake on Campbell Island was eutrophic at the time of sampling, exceeding the chlorophyll *a* reference condition threshold set by Schallenberg (in press) as shown in Table 14.

Figure 14 shows the chlorophyll *a* levels for the Southland lakes in relation to both the strict and relaxed pristineness reference condition thresholds. Lake Murihiku far exceeds both of the phytoplankton biomass reference condition thresholds, while The Reservoir and Lake George/Uruwera also exceed both the thresholds. Lake Vincent and the two reference lakes, Lakes Sheila and Calder, were below the phytoplankton biomass reference condition thresholds.

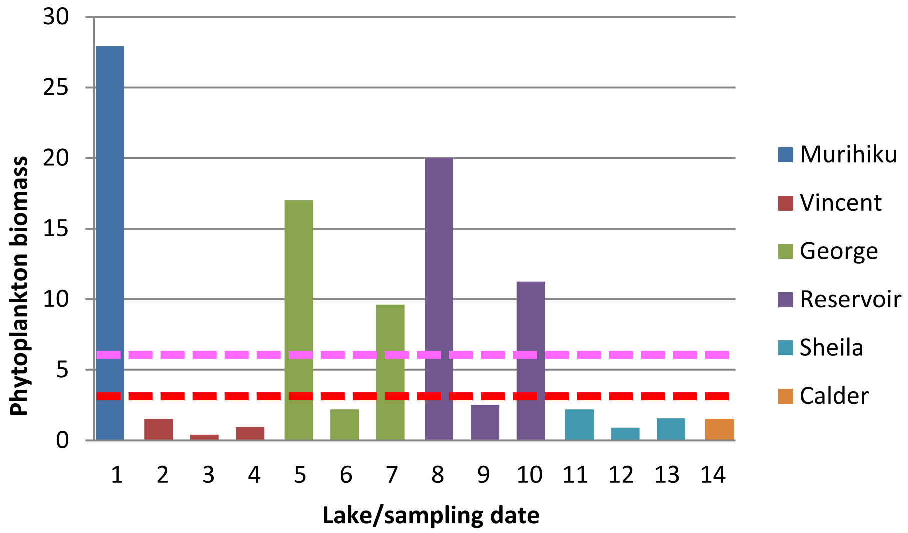

Figure 14. Lake phytoplankton biomass (chlorophyll *a* concentration; μg/L), by lake. Where there are three bars per lake, the bar to the left represents data from 2012, the middle bar represents data from 2013 and the bar on the right represents the mean of the 2012 and 2013 data. Lake Murihiku was only sampled in 2013 and Lake Calder was only sampled in 2012. The dashed red line is the threshold for strict reference condition (90th percentile) and the pink dashed line is the relaxed reference condition (80th percentile) as determined by Schallenberg (in press). This threshold was considered to be a moderate discriminator of reference condition: 83% of reference lakes at the 90th percentile achieved the threshold (Sixfoot Lake was an outlier), while 43% of non-reference lakes also achieved the threshold.

The rate of nitrogen loading to a lake reflects the input rate of nitrogen from the catchment to the lake. CLUES is a national-scale model developed by NIWA using land cover data to estimate the N losses/load from catchments. The CLUES-estimated N loading rate (per hectare of lake surface area), was found to be a weak indicator of pristineness and EI (Schallenberg in press). However, Kelly et al. (2013) recalculated CLUES estimates for South Island lakes and Clues N load estimates for the reference lakes Sheila and Calder were substantially revised downward. I have recalculated the N loading threshold based on revised CLUES N-load estimates for five reference lakes to be 0.086 t/ha/y. Thus, 100% of strict reference lakes (90th percentile) had CLUES N loading estimates equal to or less than the strict reference condition threshold while 55% of non-reference lakes also had estimated N-loading rates below this level (Table 14). So the CLUES estimated N load indicator appears to be robust with respect to certainty in the threshold and as an indicator of EI, but is not effective at distinguishing lakes that are not in reference condition from those that are.

Figure 15 shows the CLUES estimated N loading rates for the Southland lakes in relation to the strict pristineness reference condition threshold. Lakes Murihiku and Vincent substantially exceed the reference condition threshold, while The Reservoir just barely exceeds the threshold. Lake George and the reference condition lakes (Sheila and Calder) are below the reference condition threshold.

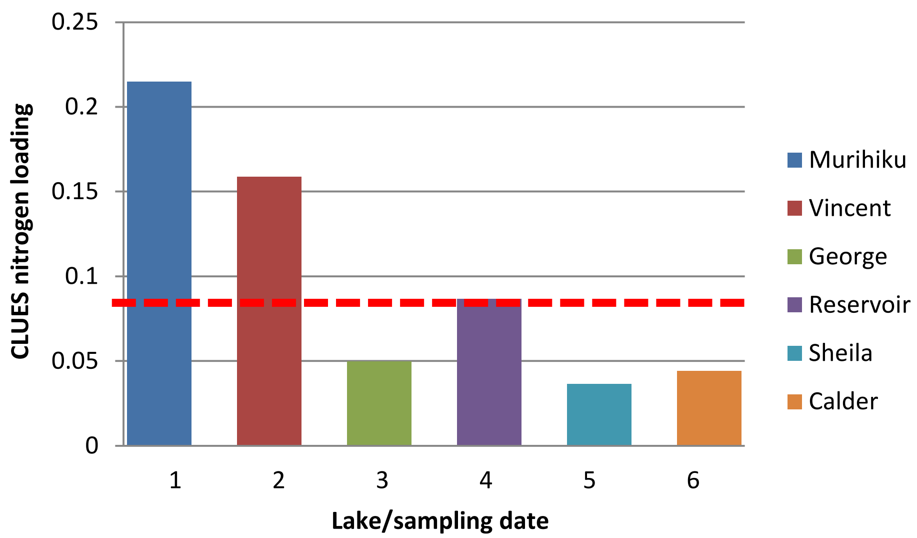

Figure 15. Areal catchment nitrogen loading rate (derived from the CLUES model; t/ha/y), by lake. The dashed red line is the threshold for strict reference condition (90th percentile). This threshold was considered to be a weak discriminator of reference condition: 100% of reference lakes at the 90th percentile achieved the threshold, while 55% of non-reference lakes also achieved the threshold.

3.1.4 INDICATORS OF DIVERSITY

Schallenberg (in press) found no relationships between measures of biological diversity and indicators of reference condition in the shallow lakes. Therefore no diversity thresholds can be defined to establish expected community diversities in reference lakes (Table 15).

Diversity may exhibit unimodal relationships along disturbance gradients (Flöder & Sommer 1999), but neither were such relationships observed in the dataset. The analysis shows that reference lakes had widely varying diversities and that the main anthropogenic changes to lakes have little effect on overall diversity. This may be due to the introduction of non-native species in many lakes. However the influence of non-native species on such diversity relationships is complex because their presence in lakes often leads to the loss of native species (Champion et al. 2002; Closs et al. 2004).

Table 15. Diversity and reference condition in shallow freshwater lakes. Grey-shaded boxes indicate no relationships between the diversity indicator and indicators of reference condition and, therefore, no thresholds are proposed.

Indicator	Units	Range for all lakes	Range for reference lakes	Threshold	% non-reference lakes excluded	Outliers
Native fish	species richness	0-5	0-5			
Native macrophytes	species richness	0-11	1-7			
Metazooplankton	species richness	0-9	0-8			

Phytoplankton	species richness	13-37	14-25			
Rotifers	species richness	1-17	5-11			
Benthic invertebrates	species richness	3-32	6-28			

3.1.5 INDICATORS OF ECOLOGICAL RESILIENCE

Schallenberg et al. (2010) found it challenging to define indicators of ecological resilience for lakes. Schallenberg (in press) found that three indicators could be useful in defining reference condition thresholds or ranges. However, data for two of the indicators (cyanobacterial cell density and food chain length) were not available for the Southland lakes which are the focus of this report. The only available indicator of resilience was the ratio of the water column concentrations of dissolved inorganic nitrogen to total phosphorus (DIN:TP), which is an indicator of the balance between nitrogen and phosphorus availability to phytoplankton. The DIN:TP ratio is an accurate indicator of nitrogen or phosphorus limitation in lakes (Morris & Lewis 1988; Abell et al. 2010; M. Schallenberg, unpubl. data). Lakes with large internal phosphorus loads (e.g. resulting from sediment anoxia) should have very low DIN:TP ratio, favouring N-fixing cyanobacteria. Under such conditions, where nitrogen fixers can outcompete other algae, cyanobacteria can form nuisance blooms, competing against other phytoplankton and macrophytes for light. Many cyanobacteria taxa also produce toxic metabolites which can result in the death of wildlife such as fish, freshwater mussels, etc.

Schallenberg (in press) found that the three indicators of resilience showed weak relationships with indicators related to reference condition and the thresholds did not differentiate reference lakes from degraded lakes very well (Table 16). Reference lakes tended to have intermediate DIN:TP ratios (between 1.2 and 4.75), indicating that they had a relatively balanced supply of N and P, except Sixfoot Lake, which had a ratio of DIN:TP ratio of 0.3, indicating an excess of phosphorus.

Table 16. Resilience reference condition thresholds and range for shallow freshwater lakes. The percentage of non-reference lakes excluded by the threshold or range is a measure of the strength of the threshold/range in distinguishing reference lakes from non-reference lakes. Outliers are reference lakes that fall outside the proposed thresholds/range. From Schallenberg (in press).

Indicator	Units	Range for all lakes	Range for reference lakes	Threshold	% non-reference lakes excluded	Outliers
Cyanobacteria	cells/mL	<500-891000	<500 - 1000	≤ 1000	65 %	Wilkie
Food chain length	trophic levels	2.99-4.64	3.06-3.86	≤ 3.86	35 %	none
DIN:TP		0.003-73	1.2-4.75	1.2-4.75*	38 %	Sixfoot

The ratio of DIN:TP in the water column of lakes appears to be a moderate indicator of ecological resilience and EI. 83% of strict reference lakes (90th percentile) had DIN:TP ratios within the range of the strict reference condition threshold (Sixfoot lake was an outlier), while 62% of non-reference lakes also had DIN:TP ratios within the reference lake range (Table 16). So the DIN:TP ratio appears to be fairly robust with respect to certainty in the threshold and as an indicator of EI, but is not effective at distinguishing lakes that are not in reference condition from those that are.

Figure 16 shows the DIN:TP ratios for the Southland lakes in relation to the strict pristineness reference condition threshold. Only lake George/Uruwera and The Reservoir fall outside the range of DIN:TP reference conditions, indicating that they have an oversupply of P relative to N, which could reflect conditions favouring N-fixing cyanobacteria. Lakes Murihiku and Vincent fell within the reference DIN:TP range as did the reference lakes, Sheila and Calder.

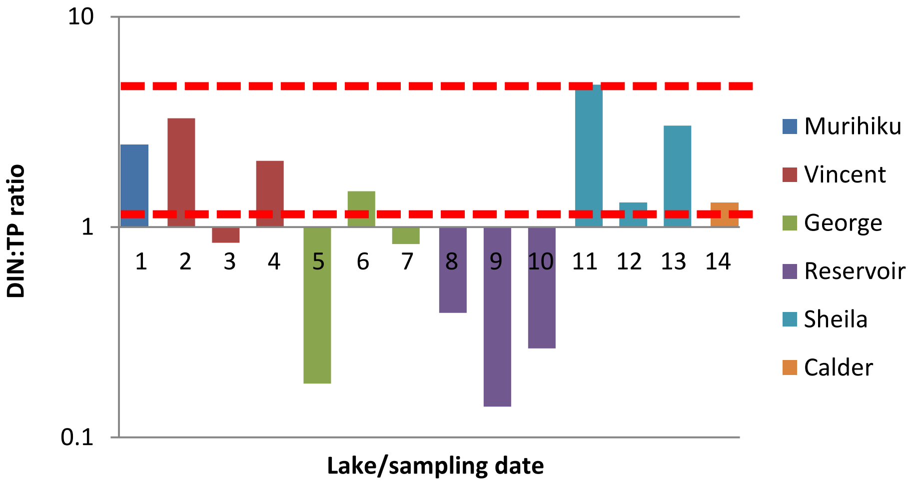

Figure 16. The balance between nitrogen and phosphorus available to phytoplankton (DIN:TP), by lake. Note the logarithmic scale on the y-axis. Where there are three bars per lake, the bar to the left represents data from 2012, the middle bar represents data from 2013 and the bar on the right represents the mean of the 2012 and 2013 data. Lake Murihiku was only sampled in 2013 and Lake Calder was only sampled in 2012. The dashed red lines indicate the range for strict reference condition (90th percentile) as determined by Schallenberg (in press). This range was considered to be a moderate discriminator of reference condition: 83% of reference lakes at the 90th percentile fell within the range (Sixfoot Lake was an outlier), while 38% of non-reference lakes also fell within the range.

3.1.6 OVERALL ECOLOGICAL INTEGRITY IN RELATION TO REFERENCE LAKES

Schallenberg (in press) identified nine useful indicators of EI and use these to set thresholds which distinguish reference condition from conditions of degradation. The indicators and thresholds were related to three of the four main components of EI: nativeness, pristineness and resilience (no indicators of diversity were found to be useful to determine reference conditions). Departures of the Southland lakes from the reference conditions could then be determined individually.

To examine departures from reference condition in a holistic way, a multivariate analysis of EI indicators was undertaken for the Southland lakes and all reference lakes as determined by Schallenberg (in press). Ordinations of the lakes and indicator variables are shown in Figures 17 and 18. Axis 1 of the PCA in Figure 17 represents 67% of the variation in the dataset and can be interpretated as a eutrophication gradient (47% of variation). Axis 2 explains 20% of the variance in the data and appears to reflect a nativeness/resilience gradient (20%) where macrophyte nativeness and DIN:TP are positively correlated to one another and both are negatively correlated with fish nativeness. Axis 3 of the PCA, shown as the y-axis in Figure 18, explains 13% of the variation and can be interpreted as nativeness gradient where the percentages of native fish and native macrophytes are strongly correlated. In our view, the gradients of nativeness and resilience are not optimally extracted from the dataset by the PCA analysis.

Most of the reference lakes group in a tight cluster in the ordination space and the space defined by this cluster defines reference condition for Southland lakes. Sixfoot Lake (Campbell Island) falls well outside the reference lake cluster because the lake was eutrophic at the time of sampling, a condition that may have reflected high use of the lake by marine mammals (sea lions) and waterfowl (albatross, skuas, petrels, etc.). While this condition may reflect a pre-historic (pre-human-influence) reference condition for New Zealand coastal lowland lakes, it was deemed not to be relevant to reference conditions for mainland shallow lowland lakes, which currently experience far less influence by marine mammals and birds than they once experienced. Lake Pounui (Wairarapa) is the only reference lake on the North Island and, as such, has been more vulnerable to invasive macrophytes than South Island lakes. Thus, despite its high ecological values and integrity, Lake Pounui has some non-native macrophytes and, therefore, is not deemed to be a good model for Southland reference conditions.

Therefore, reference condition for Southland lakes can be described within quite narrow parameters. Reference condition reflects low trophic state (including TN, TP, phytoplankton biomass and N loading) and intermediate DIN:TP ratios. The relationship with a high degree of nativeness is demonstrated on the 3rd axis (13% of variance explained) where native macrophytes and native fish correlate strongly (Fig. 18).

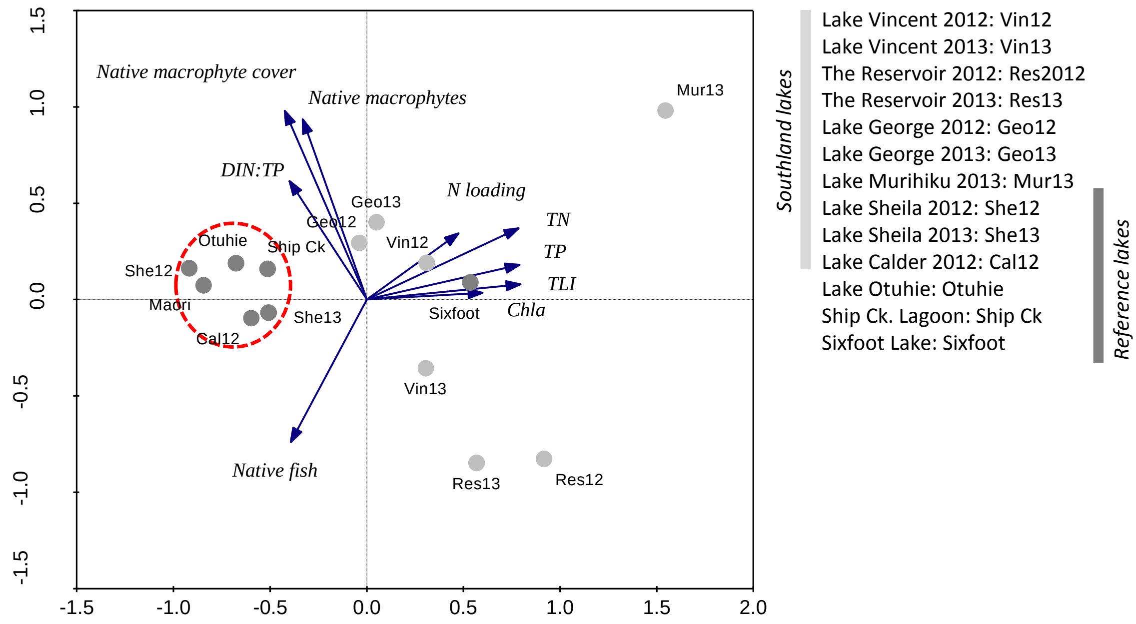

Figure 17. Ordination plot showing relationships between reference lakes (dark grey circles) and Southland lakes (light grey circles), based on nativeness, pristineness and resilience indicators of ecological integrity. The x-axis is Axis 1 and explains 47% of the variation and can be interpreted as a gradient of pristineness and nativeness. The y-axis is Axis 2 and explains 20% of the variation and can be interpreted as a gradient of DIN:TP and nativeness.

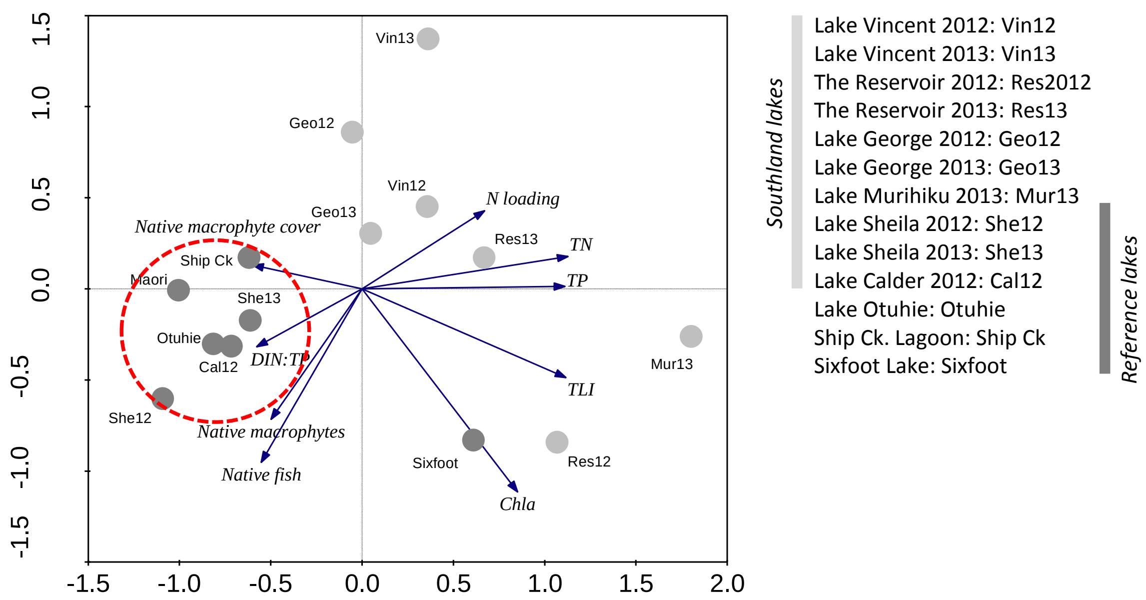

Figure 18. Ordination plot showing relationships between reference lakes (dark grey circles) and Southland lakes (light grey circles), based on nativeness, pristineness and resilience indicators of ecological integrity. The x-axis is Axis 1 and explains 47% of the variation and can be interpreted as a gradient of pristineness and nativeness. The y-axis is Axis 2 and explains 13% of the variation and can be interpreted as a gradient of nativeness and phytoplankton biomass.

In terms of Southland lakes, Lake Murihiku has the largest departure from reference condition due to its high trophic state and the presence of non-native fish (perch). It's DIN:TP ratio is still within the range of reference condition lakes. The Reservoir is the next degraded lake, with relatively high trophic state and the presence of non-native macrophytes and a high contribution to total macrophyte cover by these non-native species (*E. canadensis* and *R. trichophyllus*). The two lakes with the best macrophyte cover, Lakes Vincent and George/Uruwera, are less degraded, but in Fig. 18, Lake Vincent is shown to depart substantially from nativeness, as it has both non-native fish (perch) and non-native macrophytes (*E. canadensis and R. trichophyllus*).

According to this analysis, in terms of ecological integrity, the gradient in Southland lakes from highest integrity to lowest integrity is as follows: Lake George/Uruwera, Lake Vincent, The Reservoir, Lake Murihiku.

4 SUMMARY OF REFERENCE CONDITION THRESHOLDS FOR SOUTHLAND LOWLAND LAKES

In this report, thresholds defining reference condition were derived from Schallenberg (in press) who analysed mid-to-late summer data for 35 New Zealand lowland shallow lakes. The framework of ecological integrity (EI) as defined by Schallenberg et al. (2010) was used to select potentially useful indicators; however, not all indicators tested were useful for deriving reference conditions because some variable showed not clear relationships with EI. The determination of reference condition within the EI framework requires that indicators from each of the three EI components (nativeness, pristineness and resilience) be achieved.

The most useful indicators and their thresholds defining reference condition are presented in Table 17. While some of the thresholds were very effective at delimiting conditions of reference lakes, no threshold successfully excluded all non-reference lakes. In other words, no single indicator can be used to conclude whether a lake reflect its reference condition or not. In practice, a reference lake will be one that meets all of the criteria in Table 17.

Table 17. Summary of reference conditions for Southland lakes based on Schallenberg (in press). * indicates indicators for which recent data were not available for Southland lakes and, therefore, the thresholds for reference conditions were not tested against recent data for Southland lakes. Apart from the CLUES nitrogen loading estimates, the data used to derive these thresholds were collected in mid-to-late summer (they are not annual means).

Indicator (units)	Southland reference condition
Nativeness	
Percentage native macrophyte species	100%
Percentage native fish species	100%
Percentage of macrophyte cover that is due to native species	100%
Pristineness	
Total nitrogen (μg/L)	≤ 227
Total phosphorus (μg/L)	≤ 11.7
Trophic level index	≤ 3.5
Phytoplankton biomass (μg/L, as chlorophyll *a*)	≤ 3.2
CLUES nitrogen loading (kg/ha/y)	≤ 86
Resilience	
Ratio of dissolved inorganic nitrogen: total phosphorus	Between 1.2 and 4.75
Cyanobacteria cell density (cells/mL)*	≤ 500 cells/mL
Food chain length (δ^{15}N units)*	≤ 3.86

The indicators proposed here are worth discussing in some detail. While Southland lakes are less prone to invasion by non-native species due to Southland's remoteness from many of the distribution ranges of many of these species, a few non-native species have invaded or been stocked into some of the lakes examined in this report and some of these species have the potential to impact the ecological integrity of lake ecosystems. For example, perch have been introduced into Lakes George, Vincent and Murihiku. Perch are known to feed voraciously on zooplankton, invertebrates and fish during their various developmental phases (Kattel 1999; Burns et al. 2013). Schallenberg & Kelly (2012) considered it likely that the low native fish abundances (catch per unit effort) recorded in Lakes George and Vincent were a result of the presence of perch. In contrast, the native fish abundance in The Reservoir, which does not have perch, was much higher. There is evidence that the zooplanktivory of perch can suppress zooplankton grazing to the extent that phytoplankton blooms (including cyanobacterial blooms) can be facilitate by the presence of perch (Burns et al. 2013). Thus, the presence of perch can have far-reaching effects on the ecological integrity of shallow lakes.

Two species of non-native macrophytes have been found in the Southland lakes analysed here. The two species are *Elodea canadensis* (Canadian pondweed) and *Ranunculus triphyllus*. Generally, neither of these species is as invasive as noxious macrophytes such as *Egeria densa* or *Ceratophyllum dermersum* (hornwort). While these macrophytes will displace native species which inhabit the parts of the littoral zones where these species flourish, as long as the non-native macrophytes do not become dominant in the lakes, they can provide some ecological benefits to lakes by encouraging sedimentation, by inhibiting sediment resuspension, by competing with phytoplantkon for nutrients and by providing habitat for invertebrates and fish. However, these benefits must be weighed against the potential competitive effects these non-native species can have on native macrophytes, potentially reducing native biodiversity if they extirpate native species from lakes.

Indicators of trophic state have long been used in monitoring and management to track the degree of nutrient enrichment of lakes. Total phosphorus, total nitrogen and phytoplankton biomass (as chlorophyll *a*) are the key indicators in most trophic state indices and this report further illustrates the utility of these variables as key indicators of EI and departure from reference condition. The availability of phosphorus may generally be a key driver of phytoplankton biomass and productivity while the availability of nitrogen may be more closely related to the health of macrophyte communities in lakes (Kelly et al. 2013). The reference condition thresholds for total nitrogen and phosphorus proposed here (mid-to-late summer values of 277 and 11.7 μg/L, respectively) compare to the mean annual thresholds of 531 and 32 μg/L, suggested to maintain acceptable levels of ecological integrity in shallow coastal lakes (Kelly et al. 2013). The reference threshold for TLI proposed here is 3.5, which places the reference condition threshold for shallow lowland lakes at the mid-point of the mesotrophic category (Burns et al. 2000).

The one indicator EI used in this analysis that was not measured in lakes is the CLUES-estimated N loading rate, which was derived from a catchment model based on catchment land use and nitrogen export coefficients. This indicator was related to EI and gave a reference condition threshold N load of 86 kg N/ha/y. While all the reference lakes, which had largely unmodified catchments, met this criterion, many other catchments in which lakes did not exhibit high EI also met this criterion. This shows that while catchment land use is an important aspect of lake EI, other in-lake factors are also important. Lake Vincent has a surprisingly high nitrogen load (well above the reference condition threshold; Fig. 15) for a lake which maintains a relatively low TLI and phytoplankton biomass (Figs. 13 and 14). As Schallenberg & Kelly (2012) suggested, this lake might be in a vulnerable state due to excessive nitrogen loads.

No indicators of biotic community diversity were related to EI and as a result, no reference condition thresholds related diversity could be proposed. While biodiversity is a key value of ecosystems and freshwater biota is among the most threatened with respect to biodiversity, the species richness of a wide range of communities did not relate to catchment disturbance or EI in the dataset upon which the current analyses were based. So, unfortunately, reference condition thresholds for this important component of EI were elusive.

Finally, the concept of ecological resilience has not been well defined in the limnological literature. Schallenberg et al. (2010) and Schallenberg (in press) have defined some preliminary indicators of lake ecological resilience, but the only one for which recent data from Southland lakes was available was the DIN:TP ratio, which should represent the degree to which N and P availability are balanced or unbalanced in the lake. Here a range of DIN:TP ratios is proposed to reflect shallow, lowland lake reference condition. Values falling substantially above the range may have excessive nitrogen loads, while values falling substantially below the range may have either excessive phosphorus loads, substantial sediment resuspension issues, or internal phosphorus loading. Unbalanced DIN:TP conditions could compromise the EI of the lake and lead to episodic algal blooms and/or macrophyte collapse. Lake George/Uruwera and The Reservoir both had DIN:TP ratios below the reference range. Schallenberg (in press) also that cyanobacterial cell densities and food chain length were related to EI and proposed reference condition thresholds for these indicators. Unfortunately no recent data from Southland lakes were available to examine how well the proposed reference condition thresholds might work for Southland lakes.

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APPENDIX A: LAKE OUTSIDE THE SCOPE OF THIS REPORT

LAKE BRUNTON

Lake Brunton is an intermittently closed and open lake/lagoon (ICOLL) located near Waipapa Point and was considered outside the scope of this study due to intermittent marine influences. While its catchment is low-lying and is almost entirely intensively farmed (Figure 1), it is surrounded by a narrow margin of wetlands. Upstream from Lake Brunton, former wetlands have been converted to pasture, although some small ponds persist. The ICOLL is very shallow and has a short theoretical water residence time and a high nitrogen load (Table 1). The effects of nutrient inputs are somewhat moderated by the opening and closing of this ICOLL to the sea, which occurs naturally.

Table 2 shows the data available for key ecological indicators of lake ecological integrity for Lake Brunton. The data were collected by the authors of this report.

Table 2. Morphometric, hydrological and catchment data for Lake Brunton, Southland. Catchment data are from the Land Cover Database 2 (Ministry for the Environment). Nitrogen (N) and phosphorus (P) loading estimates are from the CLUES model (http://www. maf. govt. nz/environment-natural-resources/water/clues), as reported in Kelly et al. (2013).

Lake Brunton	
Surface area (ha)	25.84
Maximum depth (m)	3.3
Volume (10^6 m^3)	0.287*
Water residence time (days)	9.5*
Catchment area (km^2)	16
Nitrogen load (t/y)	12.626
Aerial nitrogen load (t/ha/y)	0.489
Phosphorus load (t/y)	0.839
Aerial phosphorus load (t/ha/y)	0.032
% catchment in pasture	87
% catchment in native vegetation	10.4

* 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).

Figure 1. Location of Lake Brunton, Southland. Catchment land use information is from the Land Cover Database 2 (Ministry for the Environment).

Table 2. Lake health indicator values for Lake Brunton. See Section 2.2 for details.

Variable	2012
Total nitrogen (mg m^3)	595
Total phosphorus (mg m^3)	27
TLI	4
Chlorophyll *a* (mg m^3)	1.5
DIN:TP	6.33
% macrophytes species native	100
% macrophyte cover native	100
% fish species native	