SALT ECOLOGY

Lake George
Broad Scale Habitat Mapping 2019

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EXECUTIVE SUMMARY

BACKGROUND

This report summarises the results of broad scale habitat mapping of Lake George (Uruwera) conducted on 12 March 2019. Lake George is a small shallow coastal freshwater lake in central Southland. It is one of several shallow lakes in Environment Southland's long-term State of the Environment (SoE) monitoring programme. The primary purpose of the 2019 survey was to determine whether there have been any substantive changes in aquatic macrophyte cover and species dominance compared with previous surveys, and to assess broad changes in previously mapped aquatic margin vegetation. The findings are compared with previous SoE studies and considered within the context of related investigations that have sought to understand the ecological health and potential drivers of degradation in Southland lakes.

KEY FINDINGS

The 2019 survey revealed no substantive change in macrophyte cover since the last broad scale survey was undertaken in 2013. In 2019, the lake water body and aquatic margin of Lake George comprised an area of 146ha, of which the lake itself was 104ha. The aquatic margin (42ha) was dominated by jointed wire rush and smaller areas of fringing vegetation comprising toetoe, flax, wire rush and tall fescue. Submerged macrophytes were present across 87ha (83%) of the lake body, with an average macrophyte cover of 43% being the highest recorded to date.

The macrophyte community was dominated by charophytes (*Chara corallina, Chara fibrosa, Nitella hookeri*), with a variety of other native species commonly present including native milfoils (*Myriophyllum triphyllum*), horse's mane (*Ruppia polycarpa*), blunt pondweed (*Potamogeton ochreatus*) and the low growing turf species *Lilaeopsis ruthiana*. No invasive non-indigenous plant species were recorded. During lake bed sampling, freshwater bivaves were noted to be widespread, indicating well oxygenated conditions at the lake bed.

The well-developed and relatively diverse native plant community present in 2019 is consistent with the previously categorised 'excellent' condition reported in other studies. However, the submerged macrophyte cover (43%) is below the >50% threshold suggested in overseas studies as being necessary to ensure a clear water state, and may indicate that the lake is susceptible to changing from its current condition.

Current data shows that phytoplankton biomass (indicated by chlorophyll-a) and water column nutrient concentrations are already relatively high, and place Lake George in the 'eutrophic' category, according to thresholds developed for New Zealand. The lake also remains susceptible to impacts from water level decreases, primarily from drainage to reduce flooding and facilitate farming on surrounding land, or from changes in land use (such as pine plantation plantings) that could alter current water inflows and quality. Since 2013, 4.7ha of native scrub has been converted to low-producing pasture within the 200m margin, with associated channelisation and drainage.

RECOMMENDATIONS

In order for ES to maintain Lake George in its current macrophyte-dominated state, the following is recommended as a minimum:

- Develop appropriate nutrient load guidelines for the lake that will maintain the lake at close to maximum macrophyte potential and hence ensure a clear water state.
- Determine whether current nutrient loads meet the guidelines and, as necessary, undertake investigations to identify primary sources and reduce loads.
- Continue the current water quality sampling programme and undertake an in-depth analysis of the water quality data, to consider trends over time and potential explanatory variables, especially given the high nutrient concentrations evident.
- Undertake similar broad scale surveys at intervals of ca 5 years, in part to monitor macrophyte diversity and cover, but also to keep a check on the spread of establish non-indigenous macrophytes and the occurrence of new incursions.

Beyond these specific recommendations, if ES intend to take actions to maintain or improve the state of Lake George, and minimise the risk of degradation, we emphasise the importance of defining appropriate management objectives. This will help to define and optimise a long-term monitoring programme accordingly, in order to track changes in the state of the lake, and the effectiveness of any management initiatives. The design of any such monitoring programme should target the key stressors on the lake, and identify the data needs, methods, resolution and frequency required to detect changes in catchment pressures and responses in lake ecology within a time frame appropriate for effective management.

It is recommended that a desktop review of the current long-term sampling design be conducted prior to undertaking any further broad scale habitat monitoring, incorporating key lake attributes and supporting monitoring indicators that Environment Southland are currently developing.

1. INTRODUCTION

1.1 BACKGROUND

Environment Southland (ES) has a State of the Environment (SoE) monitoring programme to assess the ecological health of the region's coastal and estuarine environment, which includes several shallow coastal lakes. ES's interest in the health of these lakes reflects that they are often poorly flushed, and are in highly modified catchments whose primary land use is agriculture. As such, the lakes are both sensitive and susceptible to a range of associated stressors such as described in Table 1.

To manage lake health, ES require robust information on the impact of these stressors. This includes knowledge of intensification or changes in catchment land use, modification of lake margin habitat, altered drainage or flow conditions, and inputs of non-point source contaminants. Of particular concern are eutrophication from nutrient enrichment, and effects from fine-sediment input such as smothering of lake-bed habitat and increased water turbidity, which may in turn result in the loss of submerged macrophytes. Submerged macrophytes are important structuring elements in shallow lakes due to their ability to maintain high water clarity, which may markedly affect lake environmental conditions (Kelly et al. 2013). Shallow lake studies from overseas indicate that submerged macrophyte cover needs to be >50% to ensure a clear water state (Jeppesen et al. 1994, Kosten et al. 2009, Tatrai et al. 2009, Blindow et al. 2002, cited in Robertson & Stevens 2013a).

Charophyte dominated vegetation represents the optimum state for most shallow lakes because species in this group enhance water clarity and reduce phytoplankton growth. This effect is caused by processes such as sediment trapping and reduced sediment resuspension (Van den Berg et al. 1998), and efficient nutrient immobilisation within charophyte meadows (Blindow 1992; Kufel & Kufel 2002). Also, because charophytes are heavily calcified and rarely grow to the water surface in lakes deeper than 1m, they seldom interfere with boating and swimming activities. Many charophyte species also remain green in winter and therefore possibly cause less oxygen depletion during winter than annual submerged plants (Robertson & Stevens 2013a).

Submerged macrophyte losses related to nutrient enrichment generally result from the shading of plants by phytoplankton blooms, epiphytic overgrowth, or excessive growths of tall macrophytes. These mechanisms cause light limitation of plants and their ultimate collapse, in a process termed 'flipping' (Schallenberg & Sorrell 2009), which in some cases can be difficult to reverse, as the internal loading of sediment-bound nutrients and re-suspension of lake bed materials stabilise the new turbid-phytoplankton dominated state.

Because of the strong connection between intensified catchment land use and increased sediment and nutrient inputs, maintenance of the clear-water state of macrophyte dominated shallow lakes is commonly used as a measure to assess shallow lake health and the success of management initiatives. This focus reflects that the loss of aquatic macrophytes and the important ecological functions they fulfil, and development of a lake ecosystem dominated by phytoplankton and susceptible to algal blooms and water quality degradation, is an undesirable outcome.

1.2 SHALLOW COASTAL LAKE MONITORING

To date, the ecological status of six Southland coastal lakes and lagoons has been assessed as part of SoE broad scale monitoring conducted between 2009 and 2014, namely Lake George, Lake Vincent, Lake Brunton, The Reservoir, Waiau Lagoon and Waituna Lagoon (e.g. Robertson & Stevens 2009a,b; Stevens & Robertson 2012; Robertson & Stevens 2013a, b, c, d). Other Southland lakes have also been included as part of other monitoring and research projects conducted for ES (e.g. Schallenberg & Kelly 2012, Burton et al. 2015). Additionally, in recent years ES has undertaken regular (typically monthly) surface water quality monitoring at many lakes and has also undertaken one-off bathymetric surveys at some of them. The aims of the past assessments have been varied but in essence have sought to broadly determine the ecological status of each lake, and changes over time. Several related studies have utilised the Lake Submerged Plant Indicators (LakeSPI) method (e.g. Clayton & Edwards 2006) to assess the ecological condition of lakes in Southland or more broadly (e.g. Burton et al. 2015). The method is based on the assumption that native plant species and high plant diversity represent a healthier lake or better lake condition, while invasive plants are ranked for undesirability based on their displacement potential and degree of measured ecological impact. However, Robertson and Stevens (2013a) noted limitations in the use of the LakeSPI sampling methodology in shallow coastal lakes, and recommended broad scale mapping to provide a more comprehensive spatial assessment of submerged macrophytes and aquatic margin habitat.

Table 1. Summary of key stressors affecting shallow coastal lakes in Southland (modified from Stevens & Robertson 2012)

	Key Ecological Stressors Affecting Shallow Coastal Lakes
Sedimentation	Because shallow lakes are a sink for sediments, their natural cycle is to slowly infill with fine muds and clays. In the last 150 years, with catchment clearance, wetland drainage, and land development for agriculture and settlements, many NZ shallow systems have begun to infill rapidly. Today, average sedimentation rates in our shallow lakes are typically 10 times or more higher than before humans arrived. The input of catchment-derived fine sediments can smother lake bed habitats, increase water turbidity, and lead to shading and loss of ecologically important aquatic macrophytes.
Eutrophication (Nutrients)	Excessive nutrient enrichment of shallow lake ecosystems, particularly with phosphorus and to a lesser extent nitrogen, stimulates the production and abundance of fast-growing algae, such as phytoplankton and short-lived macroalgae (e.g. filamentous species), at the expense of rooted aquatic macrophytes. Maintenance of a healthy aquatic macrophyte community in shallow lakes is beneficial to overall ecosystem health, and the presence of macrophytes has been shown to be important for modifying nutrient concentrations and reducing the potential for algal blooms. Nutrient thresholds required to maintain macrophyte growth in shallow lakes are difficult to predict, as the response depends on site-specific variables such as depth, substrate type (particularly mud content), humic content, wind exposure, water residence time, and water column mixing. However, at high nutrient concentrations, submersed macrophytes may be absent and a lake can become phytoplankton dominated.
Toxic Contamination	In the last 60 years, New Zealand has seen a huge range of synthetic chemicals introduced to lakes through land runoff, industrial discharges and air pollution. Many of them are toxic in minute concentrations. Of particular concern are polycyclic aromatic hydrocarbons (PAHs), trace metals, polychlorinated biphenyls (PCBs), and pesticides. These chemicals collect in sediments and may accumulate in fish and shellfish, potentially causing risks to humans and freshwater life. While the above contaminants are a particular issue in urban catchments, lakes in agricultural and horticultural catchments may also be exposed to compounds such as biocides and various trace metals (e.g. cadmium and zinc derived from fertiliser use).
Habitat Loss	Shallow lakes support many different habitat types including macrophyte beds, emergent aquatic plants (rushlands, herbfields, reedlands etc.), forested wetlands, shellfish, and a wide variety of substrate types ranging from unconsolidated cobble, gravel, sand, and mud to stable bedrock. The continued health and biodiversity of shallow lake systems depends on the maintenance of high-quality habitat. Loss of habitat and habitat diversity negatively affects fisheries, animal populations, filtering of water pollutants, and the ability of shorelines to resist storm-related erosion. Within NZ, habitat degradation or loss is common place with the major causes cited as human pressures on margins, drainage, reclamation, pest and weed invasion, reduced flows (damming and irrigation), over-fishing, polluted runoff, wastewater discharges, and excessive nutrient and sediment inputs.
Invasive species	Historic introductions of non-indigenous plants and animals, either accidental or deliberate, have led to a range of negative effects on the values of shallow lakes. Ecological effects include loss of biodiversity, changes in the composition of ecological communities, and functional changes to recipient ecosystems. In addition, more direct impacts on people can arise, such as loss of amenity value and physical interference with commercial activities (e.g. clogging of hydropower station intakes). In shallow lakes around NZ many internationally notorious plant and animal pests are already established, such as the macrophytes *Lagarosiphon major* and *Elodea canadensis*; however, some of the more remote and isolated lakes still remain free of such invaders.

1.3 PURPOSE AND SCOPE OF THIS REPORT

As part of ES's ongoing monitoring programme, Salt Ecology was contracted to undertake follow-up broad scale synoptic surveys of five previously sampled lakes (Lake George, Lake Vincent, Lake Brunton, The Reservoir, Waiau Lagoon) in late summer 2019. The surveys were restricted in scope compared with the earlier SoE studies; their primary purpose was to undertake broad scale mapping of submerged and emergent aquatic macrophytes to determine whether there have been any substantive changes in macrophyte cover and species dominance compared with previous surveys, and to assess broad changes in previously mapped aquatic margin vegetation.

This report summarises the results of a survey of Lake George (Uruwera; Fig. 1) conducted on 12 March 2019, and compares the findings with the previous SoE studies of Robertson and Stevens (2013a) and Burton et al. (2015). Results are also considered within the context of related investigations that have sought to understand the ecological health and potential drivers of degradation in Southland lakes (e.g. Schallenberg & Kelly 2012; Kelly et al. 2013; Kelly et al. 2016).

2. BACKGROUND TO LAKE GEORGE

Robertson and Stevens (2013a) provide background information on Lake George, which in turn reflects a summary by Schallenberg and Kelly (2012), although some of the information (e.g. lake depth and area, catchment area, nutrient and sediment loads) differs among the two studies. An overview of this background is paraphrased or repeated verbatim in the text below, and updated with information from more recent studies.

Lake George is a small shallow dune lake located in central Southland near Colac Bay, which Robertson and Stevens (2013a) estimated to have a lake bed of 105ha surrounded by 45ha of aquatic margin vegetation. The lake is situated within the Lake George/Uruwera Wildlife reserve and drains a catchment consisting of a mixture of protected lands, pasture (ca 50%) and fringing wetlands (see Fig. 1). Historical gold mining activities in the lake's catchment are reported by Schallenberg and Kelly (2012) to have resulted in sediment infilling of the bed. The lake is bordered by sand-dunes to the south and although some of Southland's coastal lakes have an intermittent connection to the sea, Lake George is 10m above sea level and not subject to seawater intrusion.

Several small coastal creeks enter the lake, the largest near the northern end, and the outlet is situated at the south western end. The lake's shallow depth (mean depth ~0.8m, maximum depth ~1.4m), and moderate freshwater inflows to the lake result in a relatively short theoretical water residence time of approximately 19 days (Schallenberg & Kelly 2012). Accordingly, flushing is expected to be relatively high.

Schallenberg and Kelly (2012) considered Lake George to be of high value due to its intact riparian areas, presence of macrophytes dominated by charophytes, the absence of non-indigenous macrophyte species, and a high diversity and abundance of macroinvertebrates, including several species of interest due to their rarity or functional importance (e.g. freshwater bivalves). Burton et al. (2015) applied the LakeSPI method to Lake George in 2014, and categorised the lake as being in 'excellent' ecological condition with an index value of 96%. This high score is close to its maximum scoring potential of 100%, which reflects the lake's well-developed and relatively diverse native plant community.

Similarly, Kelly et al. (2016) compared lake condition for four surveys (2004-2013) using a four point ecological integrity index that accounts for water quality and native fish attributes in addition to macrophytes. They also scored Lake George as 'excellent' (the top scoring category) with respect to the species and cover of native macrophytes. However, water quality and native fish attributes scored lower ratings (Good, Fair), with the water quality rating being highly variable among four years that were compared. Among the fish biota Kelly et al. (2016) described nationally declining longfin eel and giant kokopu (in the catchment), as well as exotic perch.

Among the threats identified for Lake George are the decline or loss of macrophytes, an increase in suspended sediment, and increase in cyanobacterial (blue-green algae) dominance, introduction of perch, introduction of non-indigenous macrophytes, and water level fluctuations due to storm events or modifications to the outlet channel.

Figure 1. Location of Lake George

3. METHODS

3.1 GENERAL APPROACH

The March 2019 broad scale survey was undertaken by three Salt Ecology staff, supported by a local boat and skipper (Chris Owen, Southern Waterways). All sampling was undertaken from the boat or by wading along the lake margins. While the survey focus was on delineating the spatial extent, cover and dominant species present within the aquatic macrophyte community, a limited point-in-time assessment was also made of some key field measures of water quality, and samples were collected for sediment quality analysis. Terrestrial margin and emergent vegetation was additionally mapped from aerial photographs, to provide a coarse resolution comparison with the 2013 survey.

The study focused on some key indicators of lake ecological health (Table 2), and a comparison of those indicators (where data were available) with the 2013 survey and other regional or national studies that have included Lake George. Most of these indicators relate to the trophic state of the lake system. For example, as described by Robertson & Stevens (2013a), nutrient-poor oligotrophic shallow lakes are likely to have the entire lake sediment surface covered by macrophytes, in particular charophytes. A more diverse assemblage (including milfoils, pondweeds, turf plants, and emergent plants) develops as the level of enrichment increases. Once nutrients reach eutrophic levels however, shallow lakes are characterised by a reduction in macrophyte species richness, the development of bare areas, an eventual decline in macrophyte growth to low levels or a complete absence, and an accompanying increase in nutrients and phytoplankton. Some New Zealand studies have provided threshold levels for chl-a, nutrients and water clarity that are linked to the level of enrichment and a lake's trophic state (Burns et al. 1999, Burns et al. 2000, NPS-FW 2014).

Table 2. Shallow lake ecological health indicators assessed in the 2019 survey.

Attribute	Rationale
Macrophytes	
Total lake bed cover	Shallow lakes with low nutrient status (oligotrophic and mesotrophic) may have the entire lake bed covered by macrophytes, with the cover decreasing as a lake becomes increasingly nutrient enriched and eutrophic.
Assemblage species richness and composition	Macrophytes in shallow lakes with low nutrient status will often be dominated by a cover of charophytes, and change to a more diverse and productive community as the level of enrichment rises, including milfoils, pondweeds, turf plants, and emergent plants. As enrichment increases, epiphytic plants may become more prevalent and macrophyte abundance may decline.
Maximum colonisation depth	The depth at which macrophytes grow may be restricted by increasing water turbidity (resulting from fine sediments and/or phytoplankton) and hence decreased light penetration for photosynthesis. Hence, maximum colonisation depth (MCD) is potentially a simple proxy measure of macrophyte abundance in deeper lakes, although this metric is only useful in shallow lakes if the MCD is less than the bottom depth.
Geographic origin	The occurrence of non-indigenous macrophyte species is a threat to a lake's ecosystem. The richness and cover of native vs invasive non-indigenous macrophytes is a simple indicator of a lake's 'nativeness'.
Water and sediment quality	
Secchi depth visibility	Field indicator of water clarity and potential for light penetration into the water column.
Water column chlorophyll-a (chl-a)	Field measure that provides a proxy indicator for phytoplankton biomass.
aRPD (apparent Redox Potential Discontinuity) depth	A subjective measure of the enrichment state of sediments according to the depth of visual transition between oxygenated surface sediments and deeper deoxygenated sediments (characterised by a change from lighter coloured to darker grey/black sediments).
Water and sediment nutrients	Total nitrogen (TN) and total phosphorus (TP) concentrations help to characterise the trophic status of shallow lakes.
Sediment total organic carbon	Indicator or organic matter accumulation in the sediment.
Sediment trace metals and metalloids	Indicators of trace contaminant inputs from catchment sources.

3.2 FIELD-BASED MACROPHYTE AND SEDIMENT ASSESSMENT

Macrophyte data were collected along six transects that zig-zagged backwards and forwards from shore to shore along the length of the Lake, with each transect positioned approximately 200m apart (Fig. 2). At specific stations along each transect (see Fig. 2), the following was conducted:

1. A camera attached to a surface monitor was slowly lowered to the lake bed and each macrophyte species present and its estimated percent cover were recorded.
2. Simultaneous with the camera drop, a custom-built sampling hoe on a telescopic pole (extendable to 6m) was used to collect macrophytes and associated sediment. The sampler had a 20x20cm flat bottom, two 20cm high enclosed sides and a supported open back. The front section, which digs into the sediments, was pointed. Typically, three samples were collected while the boat drifted during each camera drop. Based on the three samples combined:
    a. Sediment type was classified into predefined categories based on those used in the National Estuary Monitoring Protocol (Appendix 1).
    b. The depth of the apparent redox potential discontinuity (aRPD) layer was recorded if visible.
    c. The estimated relative prevalence of different macrophyte species was used as a proxy for their percent cover using categories in Fig. 3 as a guide.
    d. Representative photographs were taken.
3. Camera and macrophyte sample data were combined to provide a single percent cover value for each species at each sampling station, which reflected the consensus of two observers.
4. Water depth was recorded using a combination of boat depth sounder and sounding pole.

Sampling stations were selected on the basis of transition boundaries in macrophyte species or prevalence identified during the 2013 survey, with a particular focus being to identify any areas where macrophyte boundaries (between presence and absence) had expanded or contracted in the latest survey. Sample station data were recorded electronically in a template that was custom-built using Fulcrumapp software (www.fulcrumapp.com). Pre-specified constraints on data entry (e.g. with respect to data type, minimum or maximum values) ensured that the risk of erroneous data recording was minimised. Each sampling record created in Fulcrum generated a GPS position for that record.

In addition to the detailed assessment described for each sampling station, the camera and hoe method were also used at intermediate points, and the estimated macrophyte cover for each species at each point was recorded directly onto laminated A3 maps of the lake. Where emergent vegetation was visible, the approximate boundaries were drawn onto the map.

3.3 WATER AND SEDIMENT QUALITY

Water and sediment sampling were conducted at each of three stations (A3, C2, E3) (see Fig. 2). Quantitative water quality measurements were made in situ using a YSI Pro10 multimeter (pH, salinity, dissolved oxygen, temperature) and a Delrin Cyclops-7F fluorometer with chlorophyll optics and Databank datalogger. These measurements were made ~20cm below the water surface, and ~20cm above the sediment surface, with care taken not to disturb bottom sediments before sampling. The thermocline depth, represented by abrupt changes in temperature, was recorded if present. A modified secchi method was used to obtain a rough field estimate of water clarity. To supplement the synoptic field assessment of water quality, a summary was made of water quality data collected by ES in 2000 (reported in Schallenberg & Kelly 2012) and subsequently from two sites in the lake between March 2013 and June 2019. The ES data included a greater suite of water quality variables, such as nutrients, but not all are reported here. For comparison with the field meter salinity data, conductivity data (units mS/cm) reported in previous studies or in the ES dataset were converted to an approximate salinity value using the formula: salinity = [conductivity^1.0878]*0.4665).

At each of the same stations where synoptic water quality measurements were made, three sediment subsamples were collected (to ~20mm depth) and composited into a single sample (~250g). Samples were stored chilled or frozen and sent to a laboratory (RJ Hill Laboratories) for analysis of: particle grain size in three categories (% mud <63µm, sand <2mm to ≥63µm, gravel ≥2mm); organic matter (total organic carbon, TOC); nutrients (total nitrogen, TN; total phosphorus, TP); and trace metals or metalloids (cadmium, Cd; chromium, Cr; copper, Cu; lead, Pb; nickel, Ni; zinc, Zn; mercury, Hg; arsenic, As). Details of laboratory methods and detection limits are provided in Appendix 2.

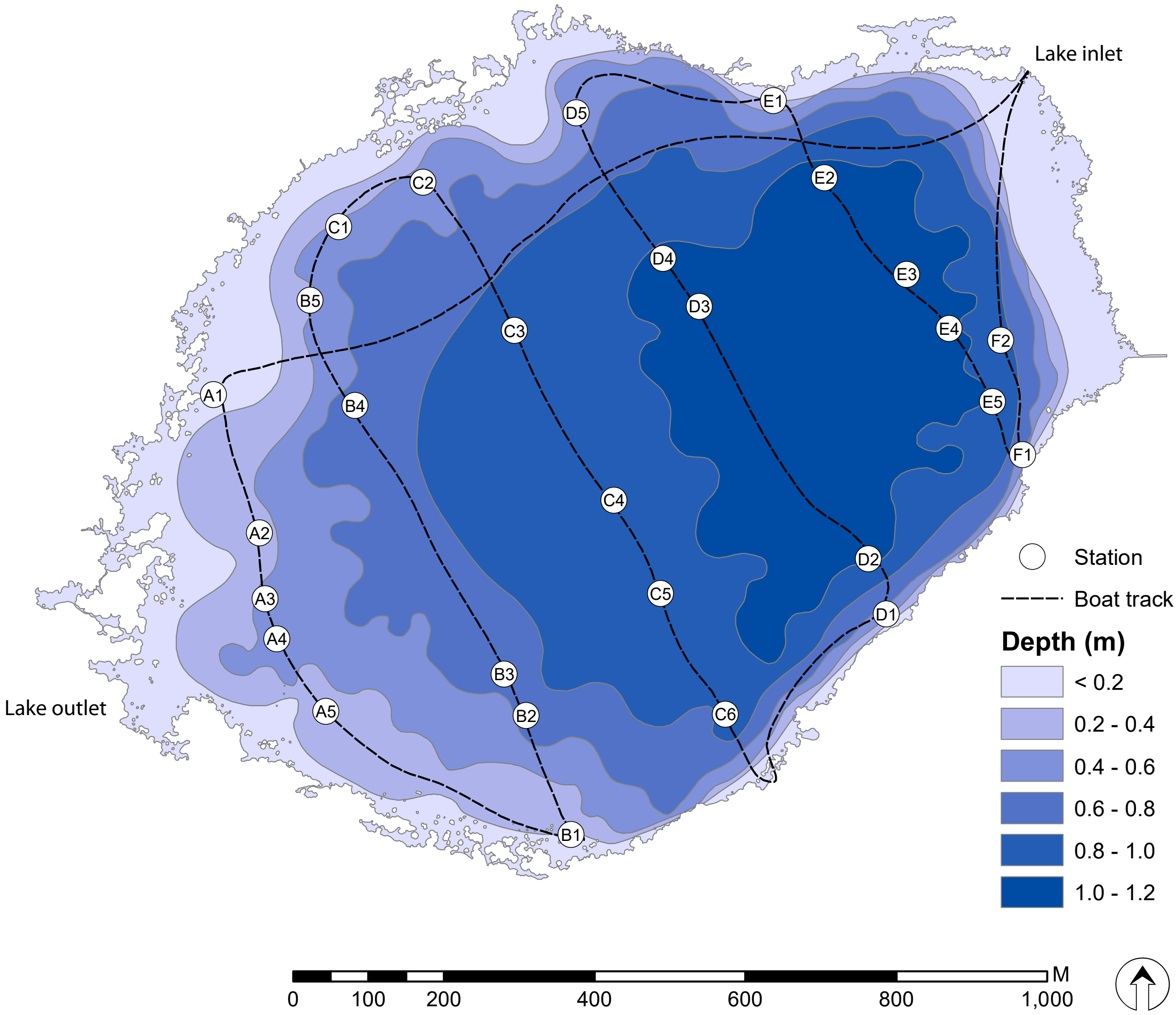


Figure 2. Sampling transects and stations where detailed assessment was undertaken. Sediment and water quality measurements were made at stations A3, C2 and E3. Depth bands were compiled from data provided by ES and Thompson (2016).

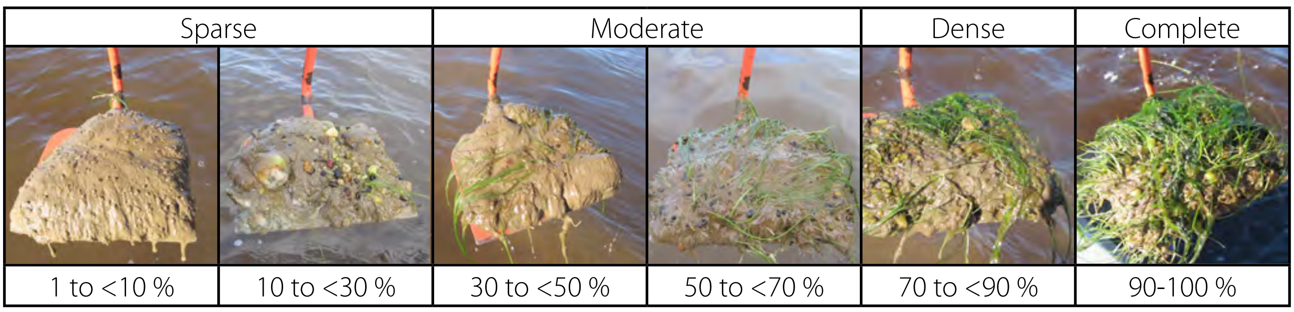


Figure 3. Visual rating scale for percentage cover estimates.

3.4 DATA, QA/QC, MAPPING AND ANALYSIS

The lake mapping approach was based on the broad scale habitat methods described in the National Estuary Monitoring Protocol, that has previously been applied to Southland coastal lakes and lagoons (e.g. Stevens & Robertson 2012). Broad scale habitat features visible on aerial photographs were digitised into ArcMap 10.6 shapefiles using a Wacom Cintiq21UX drawing tablet, and combined with field notes on the laminated aerials, and georeferenced Fulcrum data and photographs to produce habitat maps showing dominant substrata and macrophytes. Macrophyte data are expressed in two ways

i. The percent of the lake body with ≥1% macrophyte cover, grouped based on defined bands of percent cover (e.g. Fig. 3). This reflects the overall spatial area within the lake where macrophytes were growing regardless of plant density, and replicates the approach of Robertson and Stevens (2013a).

ii. Total weighted % macrophyte cover. This reflects the total area of macrophyte cover within the lake incorporating plant density and area. It is calculated by: Sum (cover estimate x area)/total lake area x 100. It replicates the approach taken by Schallenberg and Kelly (2012) and was used with the raw data (Appendix 3) to calculate the percent cover of selected dominant species.

Following the field survey, sediment samples sent to RJ Hill were tracked using standard Chain of Custody forms, and results were transferred electronically to avoid transcription errors. Fulcrum field data were exported to Excel, together with data from the sediment analyses. To minimise the risk of subsequent data manipulation errors, Excel sheets for the different data types were imported into the software R 3.5.3 (R Core Team 2019) or into ArcMap, for analysis as described below. To ensure accurate and consistent outputs across the surveys, standardised coding methods in R and ArcMap were used for producing data summaries. For the mapping data, a suite of GIS scripts ensured attributes were consistently named, geometries were valid, and there was no duplication, gaps or overlaps in digitising.

For trace metals, sediment concentrations were interpreted in relation to ANZG (2018) sediment quality guidelines. The Default Guideline Value (DGV) and Guideline Value-High (GV-high) specified in ANZG are thresholds that can be interpreted as reflecting the potential for 'possible' or 'probable' ecological effects, respectively. Until recently, these thresholds were referred to as Interim Sediment Quality Guideline low (ISQG-low) and Interim Sediment Quality Guideline high (ISQG-high) values, respectively.

3.5 COMPARISONS WITH PREVIOUS STUDIES

Previous studies against which we compare the 2019 data (in particularly for water quality and macrophytes), and use as context for explaining our key findings, were as follows:

- 2000: March 2000 synoptic water quality data collected by ES and summarised by Schallenberg and Kelly (2012).
- 2004: March 2004 synoptic water quality, macrophyte, plankton, invertebrate and fish data, described by Drake et al. (2011), with data summarised by Schallenberg and Kelly (2012).
- 2012: March 2012 synoptic water quality, macrophyte, plankton and invertebrate data collected by Schallenberg and Kelly (2012).
- 2013: February 2013 synoptic water quality and macrophyte data collected using broad scale methods and reported in Robertson and Stevens (2013a).
- 2014: November 2014 synoptic LakeSPI assessment of macrophytes reported in Burton et al. (2015).
- 2012-2019 ES water quality data (see Table 4).

4. KEY FINDINGS

4.1 LAKE DEPTH CHARACTERISTICS

The maximum lake depth recorded in 2013 and 2019 was 0.8m, compared with 1.2m measured during the ES depth profiling survey (see Fig. 2). The ES survey data shows the deepest parts of the lake (>1m depth) in the northeastern section to comprise ca 18% of the lake area.

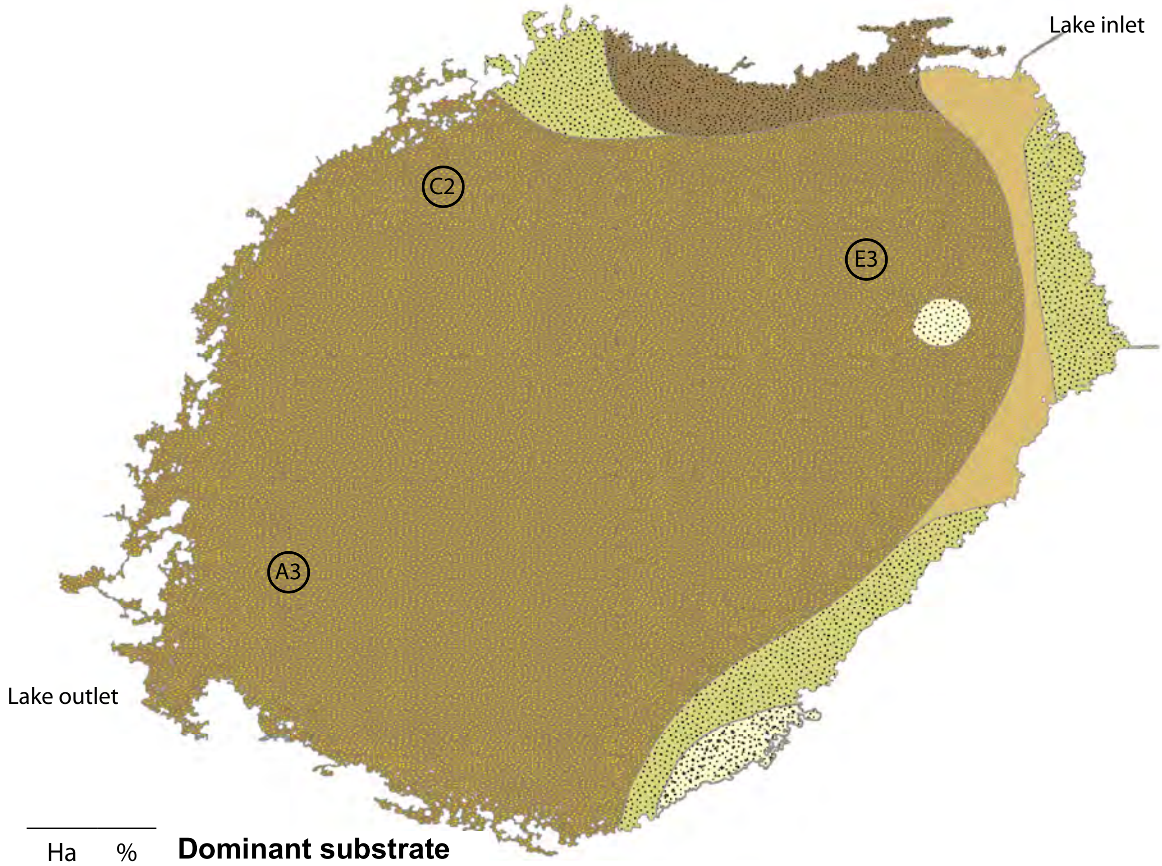
4.2 LAKE SEDIMENTS

4.2.1 Sediment type

Based on the subjective classification of sediment type, supported by quantitative laboratory validation, an estimated 91% of the lake bed consisted of muddy sediments (e.g. >25% mud) of which 86.2ha was classified as very soft mud (e.g. >50% mud) (Fig 4). Areas classified as primarily coarser sandy or gravel sediments were restricted to the northern and eastern lake margins. The quantitative laboratory analyses revealed that composite sediment samples taken from the three locations had a mud content ranging from 49% at the southern station to 75% at the northern end (Table 3, Fig. 5).

4.2.2 Sediment enrichment and contaminants

Sediments from the southern (A2) and western



Ha	%	Dominant substrate
0.4	0	Firm sand
1.2	1	Firm sand/gravel field
8.5	8	Firm muddy sand
3.8	4	Soft sandy mud
86.2	83	Very soft sandy mud
3.9	4	Firm mud

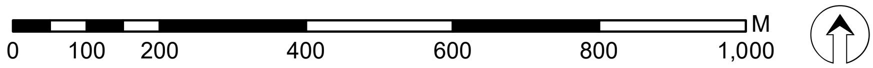


Figure 4. Substratum map and summary statistics of Lake George sediment classes. Percentages shown are of the total lake area of 104ha. A3, C2, and E3 are sediment sampling stations.

Table 3. Sediment sample analyses based on composite samples from each of three sampling stations at Lake George. Grain size classes are as described for Fig. 5. Trace contaminants compared to ANZG (2018) sediment quality guideline values (see note 1)

Station	Mud %	Sand %	Gravel %	aRPD mm	TOC %	TN mg/kg	TP mg/kg	As mg/kg	Cd mg/kg	Cr mg/kg	Cu mg/kg	Hg mg/kg	Ni mg/kg	Pb mg/kg	Zn mg/kg
A3	49.2	50.8	<0.1	3	4.00	3100	460	1.3	0.080	19.0	11.7	0.05	10.7	6.5	46
C2	60.2	39.8	<0.1	10	3.40	2300	460	1.4	0.064	21.0	11.4	0.05	10.5	5.2	38
E3	75.1	24.9	<0.1	>150	1.64	1300	290	0.7	0.045	11.6	5.8	0.03	6.7	2.8	28
						ANZG DGV		20	1.5	80	65	0.15	21	50	200
						ANZG GV-high		70	10	370	270	1	52	220	410

Note 1. Brown shading represents contaminants whose concentration was less than half of the Default Guideline Value (DGV) for possible ecological effects, whereas green shading reflects concentrations of more than half of the DGV but less than the threshold.

(C2) stations were moderately elevated in terms of total nitrogen (TN) and total organic carbon (TOC), probably reflecting root mass or detrital material from macrophytes, or catchment inputs (Table 3). Assessment of aRPD was not particularly useful as an indicator of enrichment status as it could only be reliably determined in 5 of 29 observations made. Furthermore, where visible, the aRPD ranged from 3mm (i.e. black anoxic sediment near the surface) to > 150mm (i.e. clean sediment). The more enriched locations may have corresponded to areas where there was localised degradation of organic matter. However, in general, this indicator may not be suitable in freshwater systems, for reasons described by Robertson and Stevens (2013a), and may have limited value in the context of any future monitoring or investigations. Trace metal and metalloid levels were low in all Lake George samples, generally being considerably less that ANZG Default Guideline Values for 'possible' ecological effects. Hence, despite evidence from other regions that agriculture and horticulture can lead to soil contamination with trace metals due to land use practices such as fertiliser application (Gaw et al. 2006; Lebrun et al. 2019), these results strongly suggest that there are no significant sources of such contaminants in the Lake George catchment. It is possible that other types of trace contaminants could be present (e.g. agricultural biocides); however, a comprehensive assessment in this respect was not part of the present focus.

4.3 LAKE WATER QUALITY

Readily available water quality data are summarised in Table 4. Lake George waters are well oxygenated with no water column stratification present. The latter will reflect the shallow depth of the lake and the regular turnover of the water column by wind. Water clarity varied between 0.4m and the bottom (0.8m) at the time of the survey, which appears fairly typical considering the ES dataset summary in Table 4. It appears that the water column can be relatively clear at times, with a maximum horizontal secchi disk clarity value of 3.18m record and lowest turbidity reading of 0. As a measure of phytoplankton biomass, chl-a values were moderate at the time of the survey (mean 6.8. ± 0.3mg/m^3) and almost half the relatively high long-term mean determined from ES data. Of interest is that several very high chl-a readings (up to 90mg/m^3) have been recorded over the last year. The ES data also reveal occasional more recent spikes in nutrient concentrations (TN and TP), but even mean values measured since April 2012 are indicative

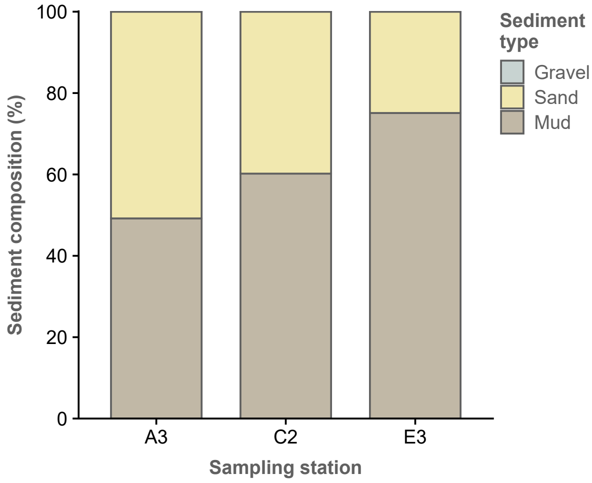


Figure 5. Sediment grain size based on composite samples from each of three sampling stations at Lake George. Grain size is classified into three broad categories: mud <63 µm (i.e. silt and clay); sand 63µm to ≤2 mm; and gravel >2 mm.

Table 4. Water quality summary comparing various parameters across different years. Data sources are described in Section 3.5.

Analyte	2000 (Mar)	2004 (Mar)	2012 (Mar)	2013 (Feb) Surface	2013 (Feb) Bottom	2019 (Mar) Surface				2019 (Mar) Bottom				ES April 2012 - July 2019 Surface			
				Range	Range	n	Range	Mean	SE	n	Range	Mean	SE	n	Range	Mean	SE
Chl-a (mg/m^3)	-	6.20	4.00	-	-	3	4.8-5.8	5.20	0.32	2	6.5-7.0	6.8	0.25	74	0.25-90	11.9	2.37
DO (g/m^3)	-	-	-	10.9-11.6	10.9-11.6	3	8.6-10.3	9.7	0.56	2	9.7-9.8	9.7	0.05	68	4.0-13.6	10.8	0.19
DO (%saturation)	-	-	-	102-114	102-114	3	89-110	102	6.50	2	102-103	102.5	0.50	68	37-115	98	1.20
pH	7.7	-	-	-	-	3	8.5-9.3	8.8	0.23	2	8.4	8.5	0.16	74	6.4-7.9	7.36	0.03
Salinity (psu)	-	0.07	0.07	0.10	0.10	3	0.10-0.13	0.11	0.01	2	0.10-0.10	0.10	0.00	68	0.06-0.14	0.08	0.00
Secchi (m, vertical)	-	0.30	-	>0.7		3	0.4->0.8	0.6	0.12	3	-	-	-	38	0.10-2.18	0.64	0.07
Secchi (m, horiz)	-	-	-	-	-	-	-	-	-	-	-	-	-	22	0.15-3.10	1.16	0.14
Temperature (^{O}C)	-	-	-	17.3-18.1	17.3-18.1	3	17.3-18.2	17.8	0.30	2	18.0-18.2	18.1	0.10	68	3.0-20.0	11.5	0.60
TN (g/m^3)	1.1	0.434	0.460	-	-	-	-	-	-	-	-	-	-	74	0.2-3.6	0.7	0.06
TP (g/m^3)	0.07	0.027	0.033	-	-	-	-	-	-	-	-	-	-	74	0.01-0.23	0.04	0.01
TSS (g/m^3)	-	-	-	-	-	-	-	-	-	-	-	-	-	50	1.2-198.0	19.7	5.38
Turbidity (NTU)	-	-	21	-	-	-	-	-	-	-	-	-	-	20	0-218	40.3	14.57

Where multiple values are summarised, the standard error (SE) of the mean and relevant sample size (n) are indicated if available.

of moderate nutrient enrichment according to thresholds described for New Zealand lakes (NPS-FW 2014). Given these indicators of water column enrichment, it would be of value to undertake a more in-depth analysis of the water quality data to consider trends over time, and potential explanatory variables.

4.4 LAKE VEGETATION

4.4.1 Terrestrial margin

The vegetation in the terrestrial margin comprised an area of 116ha, which was dominated (ca 65%) by regenerating or established native scrub and forest (Fig. 6). Grassland comprised ca 30% of the remaining landuse with 4.7ha of native scrub cleared and converted to low producing grassland since 2013.

4.4.2 Lake aquatic margin and macrophytes

The lake water body and aquatic margin comprised an area of 146ha, of which the lake itself was 104ha. The breakdown of dominant vegetation classes and main species in this area are shown in Fig. 7, with Fig. 8 showing aquatic margin vegetation and lake

	LCDB Class (Terrestrial Margin)	Ha	%
5	Transport Infrastructure	1.4	1.2
21	River	0.2	0.1
40	High Producing Exotic Grassland	29	25.3
41	Low Producing Exotic Grassland	5.0	4.3
51	Gorse and/or Broom	4.4	3.8
52	Manuka and/or Kanuka	20.4	17.6
54	Broadleaf Indigenous Hardwoods	54.7	47.1
71	Exotic Forest	0.5	0.4

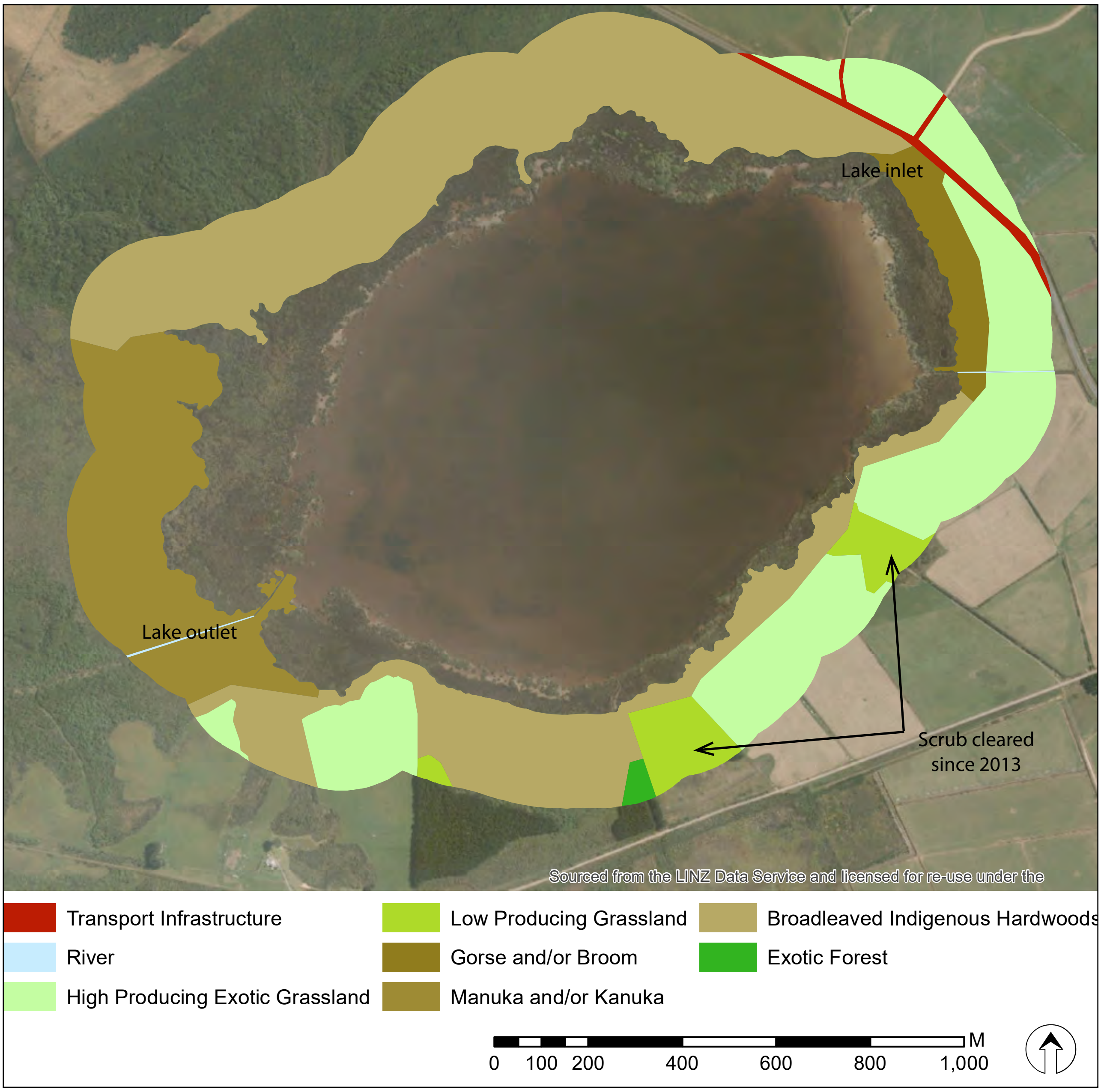


Figure 6. Landuse map and summary statistics for the 200m terrestrial margin of Lake George based on LCDB cover classes. Percentages shown in the data table are of the total terrestrial margin area of 116ha.

Aquatic Margin Dominant Class	Ha	%
Tussockland (*Cortaderia*)	2.3	5.5
Rushland (*Apodasmia*)	39.8	94.5
Total	42	100

Lake Body Dominant Class	Ha	%
Charophyte (*Chara, Nitella*)	84.1	80.9
Seagrass (*Ruppia*)	2.1	2.0
Turf plants (*Lilaeopsis*)	0.5	0.5
<1% vegetated	17.2	16.6
Total	104	100

macrophyte percentage cover. A summary of the key attributes of the lake macrophyte assemblage is provided in Table 5. Raw data are provided in Appendix 3, with a description of the macrophyte species recorded in Appendix 4.

As described previously in 2013, the aquatic margin was dominated by jointed wire rush *Apodasmia similis* and fringing toetoe (*Cortaderia* sp.), flax, and tall fescue (Fig. 7). In 2019, submerged macrophytes were present (at ≥1%) across 87ha (83%) of the lake body, with an estimated total macrophyte cover of 43% being the highest recorded to date (Table 5). The most dense cover was in the central lake area, with the lake shore margins supporting few macrophytes (generally <1% cover) (Fig. 7). A total of 8 macrophyte

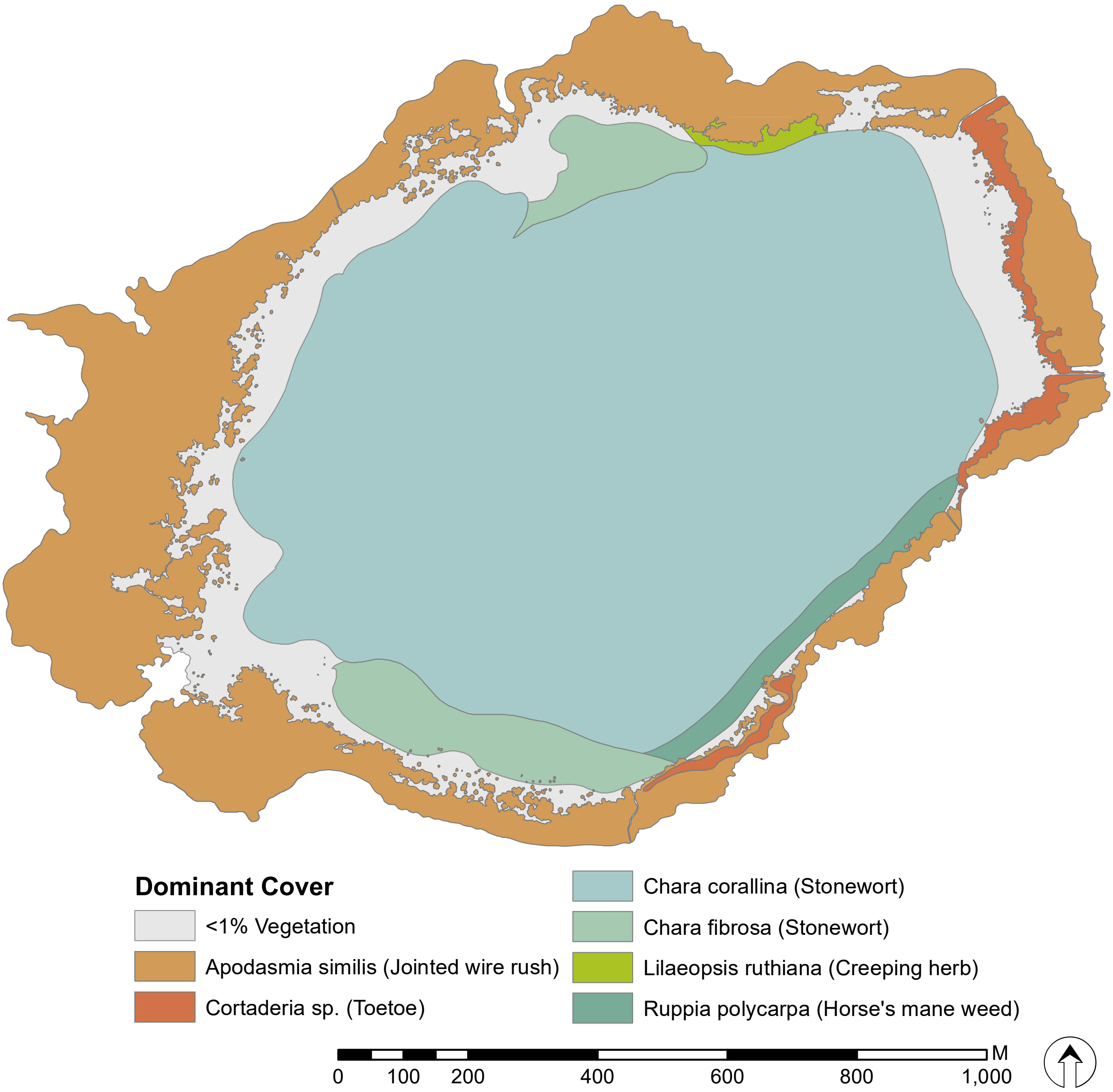


Figure 7. Map of dominant vegetation classes and summary statistics for the main species in Lake George, including the aquatic margin. Percentages shown in the data table are of the total area of 146ha.

species were recorded in 2019 which, with minor exceptions, were the same species recorded in 2013. Fewer species were recorded in the earlier surveys (Table 5), but this probably reflects the different sampling methodologies used.

No non-indigenous species have been recorded to date. Native charophytes, mainly *Chara corallina*, and to a lesser extent *Chara fibrosa* and *Nitella hookeri*, dominated the macrophyte assemblage, being present in 87ha of the lake water body in 2019, with the estimated total cover of charophytes being 32% (Appendix 3). The deepest parts of the lake consisted almost exclusively of charophytes, probably reflecting the tolerance of these species to low light. Co-occurring with the charophytes, but relatively patchy, were blunt pondweed *Potamogeton ochreatus*, at an estimated total cover of ca. 8%, and the milfoil *Myriophyllum triphyllum*. Also present was horse's mane (*Ruppia polycarpa*). The most conspicuous species around the shallow lakeshore margin was *Lilaeopsis ruthiana*.

Freshwater mussel and sparse cover of charophytes in soft mud substrate from the central basin of Lake George

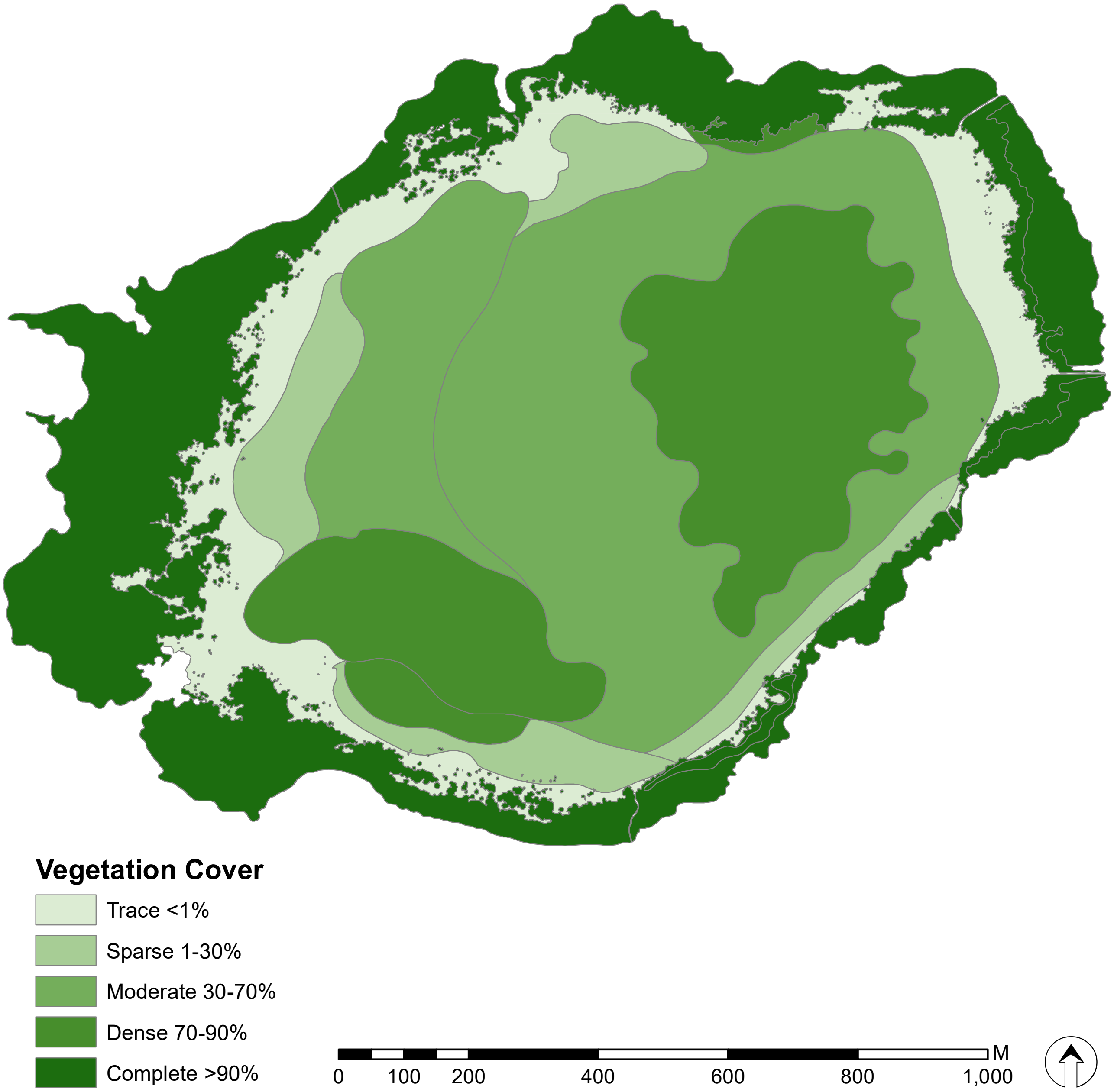


Figure 8. Vegetation percentage cover classes in Lake George, including the aquatic margin.

Table 5. Summary of attributes of Lake George macrophytes in 2019 compared with other years. Data sources as described in Section 3.5. Macrophyte % cover is based on the 104ha lake area excluding emergent rushland.

Note that survey methods used in 2004, 2012 and 2014 (transect sampling) differed from the lake-scale mapping approaches in 2013 and 2019. As such, differences should be interpreted with caution as they may reflect sampling variation.

Macrophyte attribute	Mar 2004	Mar 2012	Feb 2013	Nov 2014	Mar 2019
% of lake with >1% macrophyte cover	-	-	81	-	83
Total weighted macrophyte % cover	0.5	36	34	-*	43
Percent cover native	100	100	100	100	100
Maximum colonisation depth	-	-	0.8 (max depth)	1.4 max depth)	0.8 (max depth)
Total no. species	3	3	8	9	8
Species list:					
Chara corallina			x	x	x
Chara fibrosa			x	x	x
Lilaeopsis ruthiana	x	x	x	x	x
Myriophyllum triphyllum	x	x	x	x	x
Nitella claytonii				x	
Nitella hookeri	x	x	x	x	x
Nitella tricellularis				x	
Potamogeton ochreatus			x	x	x
Ruppia polycarpa			x	x	x
Ruppia megacarpa			x		
Unidentified macrophyte turf					x

**Note: Burton et al. (2015) did not report total % cover in 2014 but state a % cover range of 51-95% on the 5 transects sampled.*

5. SYNTHESIS AND RECOMMENDATIONS

5.1 SYNTHESIS OF KEY FINDINGS

The 2019 survey revealed no substantive change in macrophyte cover since the last broad scale survey was undertaken in 2013. As in previous surveys, the aquatic margin (42ha) was dominated by jointed wire rush *Apodasmia similis* and smaller areas of fringing vegetation comprising toetoe (*Cortaderia* sp.), flax, jointed wire rush and tall fescue. Submerged macrophytes were present (at ≥1%) across 87ha (83%) of the lake body. The estimated total weighted macrophyte percent cover was 43%, the highest recorded to date.

The macrophyte community was dominated by charophytes (*Chara corallina, C. fibrosa, Nitella hookeri*), with a variety of other native species commonly present including native milfoils (*Myriophyllum triphyllum*), horse's mane (*Ruppia polycarpa*), blunt pondweed (*Potamogeton ochreatus*) and the low growing turf species *Lilaeopsis ruthiana*. No invasive non-indigenous plant species were recorded. During lake bed sampling, freshwater bivalves were noted to be widespread, indicating well oxygenated conditions at the lake bed.

Current data shows that phytoplankton biomass (indicated by chlorophyll-a) and water column nutrient concentrations are already relatively high, and place Lake George in the 'eutrophic' category, according to thresholds developed for New Zealand.

The well-developed and relatively diverse native plant community present in 2019 is consistent with the previously categorised 'excellent' condition reported in Robertson & Stevens (2013a) and Burton et al. (2015). However, the submerged weighted macrophyte cover (43%) is below the >50% threshold suggested in overseas studies as being necessary to ensure a clear water state, and may indicate that the lake is susceptible to changing from its current condition.

The loss of macrophyte cover due to storm events is a natural stressor, but in Lake George this is potentially mitigated by the widespread presence of seed producing native species, which means it is likely to recover quickly from storm driven fluctuations (Burton et al. 2015). Phytoplankton proliferation in response to elevated nutrient inputs is also a potential driver of change. Schallenberg and Kelly (2012) estimated a strong catchment influence (i.e. high predicted nutrient load inputs) but concluded that the absence of a phytoplankton dominated community was likely explained by the relatively short retention time in the lake. Restricted light due to lake turbidity and macrophyte growth may also contribute to limited phytoplankton. A review of the catchment loads used by Schallenberg and Kelly (2012) indicates that the lake catchment area and associated nutrient loads were previously overestimated with the revised 2019 loads being approximately half those previously estimated (see Appendix 5 for details). Despite this, nutrient concentrations are still sufficiently high to fuel phytoplankton blooms and their conclusion that the relatively short retention time in the lake is the primary factor limiting the establishment of a phytoplankton dominated community is still considered valid.

The lake also remains susceptible to impacts from water level decreases, primarily from drainage to reduce flooding and facilitate farming on surrounding land, or from changes in land use (such as pine plantation plantings) that could alter current water inflows and quality. Since 2013, 4.7ha of native scrub has been converted to low-producing pasture within the 200m margin, with associated channelisation and drainage.

5.2 RECOMMENDATIONS

Various studies have been undertaken in Lake George over the past decade focusing on many different aspects of lake ecology, with recommendations made for ongoing assessment. While not coordinated in any way, the different studies have made generally similar monitoring recommendations. Schallenberg and Kelly (2012) highlight that key aspects to monitor and manage are the maintenance and enhancement of lake macrophyte communities, controlling the impacts of agricultural land uses in their catchments, and preventing the spread of invasive pest species into Southland lakes. Specific to Lake George, Robertson and Stevens (2013a) recommend a staged approach involving:

- Developing specific nutrient and sediment load guidelines to maintain the lake at close to maximum macrophyte potential and hence ensure a clear water state;
- Defining current nutrient and sediment loads;
- Identifying primary load sources and developing monitoring and management plans to manage loads to meets guideline levels;
- Regularly monitoring for invasive aquatic plants.

Burton et al. (2015) recommend continued work to understand and mitigate any threats to long term lake ecological condition because the shallow nature of these lake systems makes them particularly vulnerable to change over a short time frame.

In addition to the above, it is recommended that current water quality monitoring continue, and that ES schedule similar broad scale surveys at intervals of ca 5 years, in part to monitor macrophyte diversity and cover, but also to keep a check on the spread of established non-indigenous macrophytes and the occurrence of new incursions.

Beyond these specific recommendations, if ES intend to take actions to maintain Lake George in its current macrophyte dominated state, and minimise the risk of degradation, we emphasise the importance of defining appropriate lake management objectives. This will help to define and optimise a long-term monitoring programme accordingly, in order to track changes in the state of the lake, and the effectiveness of any management initiatives. The design of any such monitoring programme should target the key stressors on the lake, and identify the data needs, methods, resolution and frequency required to detect changes in catchment pressures and responses in lake ecology within a time frame appropriate for effective management.

It is recommended that a desktop review of the current long-term sampling design be conducted prior to undertaking any further broad scale habitat monitoring, incorporating key lake attributes and supporting monitoring indicators that Environment Southland are currently developing.

6. REFERENCES CITED

ANZECC 2000. Australian and New Zealand guidelines for fresh and marine water quality. Australian and New Zealand Environment and Conservation Council, Agriculture and Resource Management Council of Australia and New Zealand.

ANZG 2018. Australian and New Zealand Guidelines for Fresh and Marine Water Quality. Australian and New Zealand Governments and Australian state and territory governments, Canberra ACT, Australia. Available at www.waterquality.gov.au/anz-guidelines.

Blindow I 1992. Decline of charophytes during eutrophication: comparison with angiosperms. Freshwater Biology 28: 9–14.

Blindow I, Hargeby A, Andersson G 2002. Seasonal changes of mechanisms maintaining clear water in a shallow lake with abundant Chara vegetation. Aquatic Botany. 72:315–334.

Burns NM, Rutherford JC, Clayton JS 1999. A Monitoring and Classification System for New Zealand Lakes and Reservoirs. Lake and Reservoir Management 15(4): 255-271.

Burns NM, Bryers G, Bowman E 2000. Protocol for Monitoring Trophic Levels of New Zealand Lakes and Reservoirs. Lakes Consulting Client Report: 99/2, prepared for the Ministry for the Environment, March 2000. 122p.

Burton T, Wells R, Taumoepeau A 2015. Assessment of three lowland Southland lakes using LakeSPI: Lake George, Lake Vincent, and The Reservoir. NIWA Client Report No. HAM2014-119, prepared for Environment Southland, April 2015. 20p.

Clayton J, Edwards T 2006. Aquatic plants as environmental indicators of ecological condition in New Zealand lakes. Hydrobiologia 570(1): 147-151.

Gaw SK, Wilkins AL, Kim ND, Palmer GT, Robinson P 2006. Trace element and ΣDDT concentrations in horticultural soils from the Tasman, Waikato and Auckland regions of New Zealand. Science of The Total Environment 355(1): 31-47.

Jeppesen E, Søndergaard M, Kanstrup E, Petersen B, Eriksen RB, Hammershøj M, Mortensen E, Jensen JP, Have A 1994. Does the impact of nutrients on the biological structure and function of brackish and freshwater lakes differ? Hydrobiologia, 275/276, 15–30.

Kelly D, Shearer K, Schallenberg M 2013. Nutrient loading to shallow coastal lakes in Southland for sustaining ecological integrity values2375. 41 p.

Kelly D, Schallenberg M, Waters S, Shearer K, Peacock L 2016. A calibrated ecological health assessment for Southland lakes2832. 56 p.

Kosten S, Kamarainen A, Jeppesen E 2009. Climate-related differences in the dominance of submerged macrophytes in shallow lakes. Global Change Biology, 15, 2503–2517.

Kufel L, Kufel I 2002. Chara beds acting as nutrient skinks in shallow lakes - a review. Aquatic Botany 72: 249–260.

Lebrun JD, Ayrault S, Drouet A, Bordier L, Fechner LC, Uher E, Chaumont C, Tournebize J 2019. Ecodynamics and bioavailability of metal contaminants in a constructed wetland within an agricultural drained catchment. Ecological Engineering 136: 108-117.

NPS-FW 2014. National Policy Statement for Freshwater Management 2014 (Amended August 2017). Ministry for the Environment. 47p.

R Core Team 2019. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Robertson BM, Stevens LM 2009a. Lake Brunton: Synoptic survey, macrophyte mapping and vulnerability assessment. Wriggle Coastal Management report, prepared for Environment Southland. 17p.

Robertson BM, Stevens LM 2009b. Waituna Lagoon 2009: Macrophyte (*Ruppia*) Monitoring. Wriggle Coastal Management report, prepared for Department of Conservation. 19p.

Robertson BM, Stevens LM 2013a. Lake George - Broad Scale Habitat Mapping 2013. Wriggle Coastal Management report, prepared for Environment Southland. 26p.

Robertson BM, Stevens LM 2013b. The Reservoir - Broad Scale Habitat Mapping 2013. Wriggle Coastal Management report, prepared for Environment Southland. 27p.

Robertson BM, Stevens LM 2013c. Lake Vincent - Broad Scale Habitat Mapping 2013. Wriggle Coastal Management report, prepared for Environment Southland. 27p.

Robertson BM, Stevens LM 2013d. Lake Brunton Broad Scale Habitat/Macrophyte Mapping 2013. Wriggle Coastal Management report, prepared for Environment Southland. 20p.

Schallenberg M, Sorrell B 2009. Regime shifts between clear and turbid water in New Zealand lakes: Environmental correlates and implications for management and restoration. New Zealand Journal of Marine and Freshwater Research 43(3): 701-712.

Schallenberg M, Kelly D 2012. Ecological condition of six shallow Southland lakes. Cawthron Report No. 2198, prepared for Environment Southland. 43p.

Stevens LM, Robertson BM 2012. Waiau (Te Waewae) Lagoon 2012: Fine Scale Monitoring and Macrophyte Mapping. Wriggle Coastal Management report, prepared for Environment Southland. 19p.

Tatrai I, Boros G, Gyorgy A, Matyas K, Korponai J, Pomogyi P. Havasi, M, Kucserka T 2009. Abrupt shift from clear to turbid state in a shallow eutrophic, biomanipulated lake. Hydrobiologia, 620, 149–161.

Thompson C 2016. Bathymetric Surveys: Lake George, Lake Vincent, The Reservoir, Survey Report. TrueSouth Survey Services Ltd, Invercargill, July 2016. 6p.

Van den Berg MS, Coops H, Meijer ML, Scheffer M, Simons J 1998. Clear water associated with a dense Chara vegetation in the shallow and turbid Lake Veluwemeer, The Netherlands. In: Jeppesen, E., Søndergaard, M., Søndergaard, M., Christoffersen, K. (Eds.), The Structuring Role of Submerged Macrophytes in Lakes. Springer, New York, pp. 339–352.

APPENDICES

APPENDIX 1. VEGETATION AND SEDIMENT CLASSES

VEGETATION

Tussockland: Vegetation in which the cover of tussock in the canopy is 20-100% and in which the tussock cover exceeds that of any other growth form or bare ground. Tussock includes all grasses, sedges, rushes, and other herbaceous plants with linear leaves (or linear non-woody stems) that are densely clumped and >100 cm height. Examples of the growth form occur in all species of *Cortaderia, Gahnia,* and *Phormium*, and in some species of *Chionochloa, Poa, Festuca, Rytidosperma, Cyperus, Carex, Uncinia, Juncus, Astelia, Aciphylla,* and *Celmisia*.

Rushland: Vegetation in which the cover of rushes (excluding tussock-rushes) in the canopy is 20-100% and where rush cover exceeds that of any other growth form or bare ground. A tall grasslike, often hollow-stemmed plant, included in rushland are some species of *Juncus* and all species of *Apodasmia (Leptocarpus)*.

SEDIMENT

Rock field: Land in which the area of residual rock exceeds the area covered by any one class of plant growth-form. They are named from the leading plant species when plant cover is ≥1%.

Boulder field: Land in which the area of unconsolidated boulders (>200mm diam.) exceeds the area covered by any one class of plant growth-form. Boulder fields are named from the leading plant species when plant cover is ≥1%.

Cobble field: Land in which the area of unconsolidated cobbles (20-200 mm diam.) exceeds the area covered by any one class of plant growth-form. Cobble fields are named from the leading plant species when plant cover is ≥1%.

Gravel field: Land in which the area of unconsolidated gravel (2-20 mm diameter) exceeds the area covered by any one class of plant growth-form. Gravel fields are named from the leading plant species when plant cover is ≥1%.

Sand: Granular beach sand with no conspicuous fines evident when sediment is disturbed i.e. a mud content <1%. Classified as firm sand if an adult sinks <2 cm, soft sand if an adult sinks >2 cm, or mobile when characterised by a rippled surface layer from tidal currents or wind-generated waves.

Muddy sand (Low mud content): A sand/mud mixture dominated by sand with a low mud fraction (e.g. 1-10%), the mud fraction conspicuous only when sediment is mixed in water. Granular when rubbed between the fingers. Classified as firm if you sink 0-2 cm when walking, soft if you sink 2-5cm, or mobile when characterised by a rippled surface layer.

Muddy sand (Moderate mud content): A subjective division may be applied where the sand/mud mixture remains dominated by sand, but has an elevated mud fraction (i.e. 10-25%). Granular when rubbed between the fingers, but with a smoother consistency than muddy sand with a low mud fraction, the mud fraction visually conspicuous when walking on it. Classified as firm if you sink 0-2 cm when walking, soft if you sink 2-5cm, or mobile when characterised by a rippled surface layer.

Sandy mud (High mud content): A mixture of mud and sand where mud is a major component (i.e. >25%-50% mud). Sediment rubbed between the fingers is primarily smooth/silken but retains a granular component. Sediments generally soft and only firm if dried out or another component e.g. gravel prevents sinking. Classified as firm if you sink 0-2 cm when walking, soft if you sink 2-5cm, or very soft if you sink >5cm.

Sandy mud (Very high mud content): A mixture of mud and sand where mud is the dominant component (e.g. >50% mud). Sediment rubbed between the fingers may retain a slight granular component but is primarily smooth/silken. Sediments generally very soft and only firm if dried out or another component e.g. gravel prevents sinking. Classified as firm if you sink 0-2 cm when walking, soft if you sink 2-5cm, or very soft if you sink >5cm.

Mud (>90% mud content): A strongly mud dominated substrate with sand a minor component. Smooth/silken when rubbed between the fingers. Sediments generally very soft and only firm if dried out or another component e.g. gravel prevents sinking. Classified as firm if you sink 0-2 cm when walking, or soft if you sink >2 cm.

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APPENDIX 2. RJ HILL ANALYTICAL METHODS

Summary of Methods

The following table(s) gives a brief description of the methods used to conduct the analyses for this job. The detection limits given below are those attainable in a relatively clean matrix. Detection limits may be higher for individual samples should insufficient sample be available, or if the matrix requires that dilutions be performed during analysis.
Unless otherwise indicated, analyses were performed at Hill Laboratories, 28 Duke Street, Frankton, Hamilton 3204.

Sample Type: Sediment

Test	Method Description	Default Detection Limit	Sample No
Individual Tests			
Environmental Solids Sample Drying*	Air dried at 35°C Used for sample preparation. May contain a residual moisture content of 2-5%.	-	1-21
Environmental Solids Sample Preparation	Air dried at 35°C and sieved, <2mm fraction. Used for sample preparation. May contain a residual moisture content of 2-5%.	-	1-21
Dry Matter for Grainsize samples (sieved as received)*	Drying for 16 hours at 103°C, gravimetry (Free water removed before analysis).	0.10 g/100g as rcvd	1-21
Total Recoverable digestion	Nitric / hydrochloric acid digestion. US EPA 200.2.	-	1-21
Total Recoverable Phosphorus	Dried sample, sieved as specified (if required). Nitric/Hydrochloric acid digestion, ICP-MS, screen level. US EPA 200.2.	40 mg/kg dry wt	1-21
Heavy metals, trace As,Cd,Cr,Cu,Ni,Pb,Zn,Hg	Dried sample, <2mm fraction. Nitric/Hydrochloric acid digestion, ICP-MS, trace level.	0.010 - 0.4 mg/kg dry wt	1-21
Total Organic Carbon and Total Nitrogen*	Catalytic Combustion (900°C, O_2), separation, Thermal Conductivity Detector [Elementar Analyser]	-	1-21
3 Grain Sizes Profile as received			
Fraction >/= 2 mm*	Wet sieving with dispersant, as received, 2.00 mm sieve, gravimetry.	0.1 g/100g dry wt	1-21
Fraction < 2 mm, >/= 63 µm*	Wet sieving using dispersant, as received, 2.00 mm and 63 µm sieves, gravimetry (calculation by difference).	0.1 g/100g dry wt	1-21
Fraction < 63 µm*	Wet sieving with dispersant, as received, 63 µm sieve, gravimetry (calculation by difference).	0.1 g/100g dry wt	1-21

APPENDIX 3.
A) SUMMARY DATA ON DOMINANT VEGETATION

Class & Dominant Cover	Subdominant 1	Subdominant 2	Subdominant 3	Ha	%
AQUATIC MARGIN				42.1	100
Tussockland				2.3	5.8
Cortaderia sp.	*Phormium tenax*	*Apodasmia similis*		2.3	
Rushland				39.8	94.5
Apodasmia similis				1.8	
Apodasmia similis	*Cortaderia sp.*	*Phormium tenax*	*Plagianthus divaricatus*	38.0	

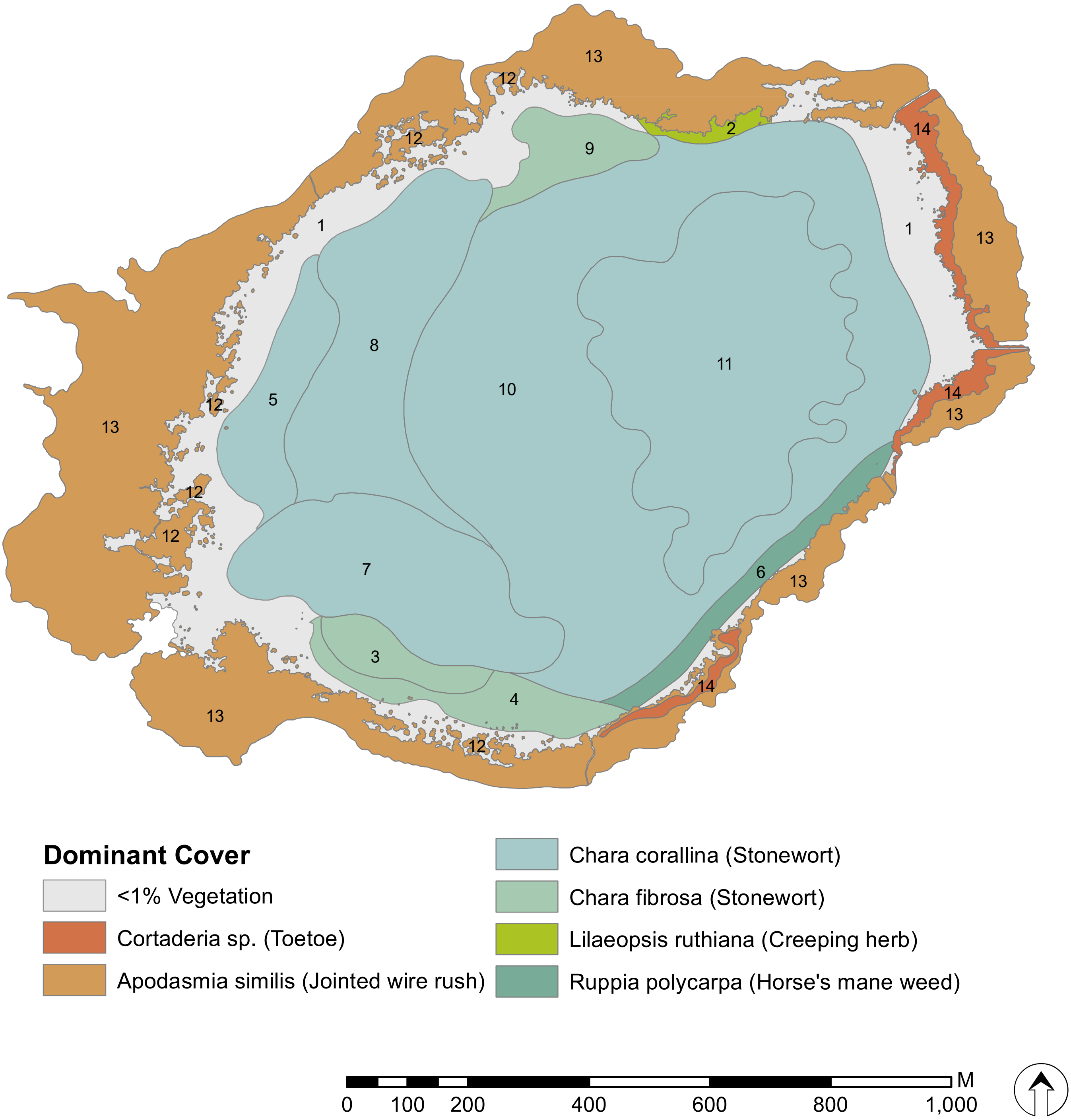
Class & Dominant Cover	Subdominant 1	Subdominant 2	Subdominant 3	Ha	%
LAKE BODY				104	100
Charophyte				84.1	80.9
Chara corallina	*Chara fibrosa*	*Potamogeton ochreatus*	*Myriophyllum triphyllum*	10.3	
	Potamogeton ochreatus	*Myriophyllum triphyllum*	*Ruppia polycarpa*	67.1	
Chara fibrosa	*Chara corallina*	*Potamogeton ochreatus*		2.7	
	Potamogeton ochreatus			1.7	
	Ruppia polycarpa	*Myriophyllum triphyllum*		2.4	
Macrophyte				2.1	2.0
Ruppia polycarpa	*Chara fibrosa*	*Nitella hookeri*		2.1	
Turf plants				0.5	0.5
Lilaeopsis ruthiana	*Chara fibrosa*			0.5	
<1% vegetation				17.2	16.6

B) POINT ESTIMATES FROM STATIONS SHOWN IN FIG. 2 OF MAIN REPORT

Sample Station	NZTM North	NZTM East	Depth (m)	Sediment type	aRPD (mm)	Bare space	*Chara corallina*	*Chara fibrosa*	*Lilaeopsis ruthiana*	*Myriophyllum triphyllum*	*Nitella hookeri*	*Potamogeton ochreatus*	*Ruppia polycarpa*	Unidentified turf
A1	4853536	1203922	0.3	vsSMvh	5	100	0	0	0	0	0	0	0	0
A2	4853266	1203988	0.4	vsSMvh	-	88	5	0	0	1	0	5	1	0
A3	4853138	1203998	0.4	vsSMvh	3	50	40	2	0	0	0	5	3	0
A4	4853781	1203969	0.35	vsSMvh	-	5	0	95	0	0	0	0	0	0
A5	4853585	1204040	0.35	vsSMvh	-	30	0	68	0	0	0	2	0	0
A6	4853471	1204097	0.3	vsSMvh	-	85	0	14	0	0	0	1	0	0
B1	4853372	1204122	0.3	vsSMvh	-	90	4	4	0	0	0	2	0	0
B2	4820855	1206443	0.6	vsSMvh	-	10	10	0	0	40	0	40	0	0
B3	4853800	1204266	0.35	vsSMvh	-	15	30	0	0	25	0	30	0	0
B4	4820809	1206246	0.6	vsSMvh	150	30	35	0	0	5	0	30	0	0
B5	4852979	1204094	0.4	vsSMvh	-	96	1	0	0	1	0	1	1	0
C1	4853097	1204080	0.4	vsSMvh	-	30	15	40	0	0	0	15	0	0
C2	4820582	1206370	0.7	vsSMvh	-	40	58	0	0	0	0	2	0	0
C3	4820555	1206480	0.75	vsSMvh	150	50	48	0	0	1	0	1	0	0
C4	4827328	1206153	0.75	vsSMvh	-	60	35	0	0	1	0	4	0	0
C5	4820583	1206648	0.7	vsSMvh	-	70	28	0	0	0	0	2	0	0
C6	4853330	1204587	0.3	fMSl	-	50	0	35	0	0	0	15	0	0
D1	4853165	1204819	0.55	fMSl	-	90	0	2	0	0	0	0	8	0
D2	4820475	1206932	0.8	vsSMvh	-	30	64	0	0	1	0	5	0	0
D3	4820435	1206734	0.8	vsSMvh	-	25	70	0	0	0	0	5	0	0
D4	4820788	1206667	0.6	vsSMvh	-	25	25	0	0	0	0	50	0	0
D5	4853473	1204431	0.3	fMSm	-	97	0	1	0	1	0	0	1	0
E1	4853213	1204711	0.4	fMvh	-	10	0	1	89	0	0	0	0	0
E2	4820518	1206848	0.72	vsSMvh	-	30	50	0	0	0	0	20	0	0
E3	4820567	1207002	0.8	vsSMvh	10	20	65	5	0	0	4	6	0	0
E4	4820513	1207056	0.78	fMSl	-	60	25	0	0	0	0	15	0	0
E5	4853578	1204952	0.4	fMvh	-	95	0	0	0	0	1	0	0	4
F1	4853673	1204981	0.5	sSMvh	-	50	15	0	0	15	0	15	5	0
F2	4820558	1207121	0.65	vsSMvh	-	40	25	0	0	10	0	25	0	0

NOTES:
f=firm, s=soft, vs=verysoft, MS=muddy sand, SM=sandy mud, l=1-10%mud, m=>10-25%mud, h=>25-50%mud, vh=>50%mud

C) GIS SUMMARY MAP AND DATA



Id	Depth (m)	Class	DomHab	SubDom1	SubDom2	SubDom3	SubDom4	PctCvr	FieldCode	Spp_PctCvr	ha	%
1	<0.2	<1% vegetated						<1	bare	-	17.2	12%
2	<0.2	Turf plants	*Lilaeopsis ruthiana*	*Chara fibrosa*				80	liru chfi	79 1	0.5	0%
3	0.2-0.4	Charophyte	*Chara fibrosa*	*Potamogeton ochreatus*				80	chfi pooc	78 2	1.7	1%
4	0.2-0.4	Charophyte	*Chara fibrosa*	*Chara corallina*	*Potamogeton ochreatus*			5	chfi chco pooc	2 2 1	2.7	2%
5	0.2-0.4	Charophyte	*Chara corallina*	*Potamogeton ochreatus*	*Myriophyllum triphyllum*	*Ruppia polycarpa*		5	chco pooc mytr rupo	2 1 1 1	3.7	3%
6	0.2-0.4	Macrophyte	*Ruppia polycarpa*	*Chara fibrosa*	*Nitella hookeri*			5	rupo chfi niho	3 1 1	2.1	1%
7	0.4-0.6	Charophyte	*Chara corallina*	*Potamogeton ochreatus*	*Ruppia polycarpa*	*Chara fibrosa*		80	chco pooc rupo chfi	40 15 15 10	9.5	6%
8	0.4-0.6	Charophyte	*Chara corallina*	*Chara fibrosa*	*Potamogeton ochreatus*	*Myriophyllum triphyllum*		60	chco chfi pooc mytr	34 15 15 1	10.3	7%
9	0.4-0.6	Charophyte	*Chara fibrosa*	*Ruppia polycarpa*	*Myriophyllum triphyllum*			5	chfi rupo mytr	2 2 1	2.4	2%
10	0.8-1.0	Charophyte	*Chara corallina*	*Potamogeton ochreatus*	*Myriophyllum triphyllum*			40	chco pooc mytr	30 7 3	35.3	24%
11	1.0-1.2	Charophyte	*Chara corallina*	*Potamogeton ochreatus*	*Myriophyllum triphyllum*			80	chco pooc mytr	60 14 1	18.6	13%
12	Emergent	Rushland	*Apodasima similis*					100	lesi	100	1.8	1%
13	Emergent	Rushland	*Apodasima similis*	*Cortaderia* sp.	*Phormium tenax*	*Plagianthus divaricatus*	*Festuca arundinacea*	100	lesi cosp phte pldi fear	80 5 5 5 5	38.0	26%
14	Emergent	Tussockland	*Cortaderia sp.*	*Phormium tenax*	*Apodasima similis*	*Plagianthus divaricatus*	*Festuca arundinacea*	100	cosp phte lesi pldi fear	40 30 20 5 5	2.3	2%
											146	100%

The Spp_PctCvr column shows percent cover for each species in the same order as listed in the FieldCode column.

APPENDIX 4. MACROPHYTE DESCRIPTIONS

Species	Type	Status
Lilaeopsis ruthiana	Turf	Native

L. ruthiana is a submerged vascular turf macrophyte, rooted in substrate. It is a creeping herb with cylindrical septate leaves (2-5cm long). It is vegetatively similar to *L. novae-zelandiae*, but leaves are often finer with paler septa. Like *Ruppia*, it is rhizome creeping. Plants are widespread in damp margins of waterways.

Species	Type	Status
Myriophyllum triphyllum	Emergent	Native

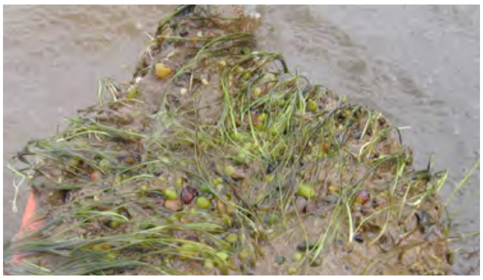
M. triphyllum is a widespread submerged perennial milfoil species. Plants grow to 3m tall, and have emergent and submerged leaves. Emergent leaves are reddish, ovate, entire or lobed. Submerged leaves are 10-15mm long, finely pinnate in whorls. Plants have small reddish flowers and globular fruit.

Species	Type	Status
Potamogeton ochreatus (Blunt pondweed)	Emergent	Native

P. ochreatus is a common pondweed species, tolerant of slightly brackish as well as fresh water. It survives low light and temperatures, and prefers high nutrient water. It forms dense mats of vegetation up to the water surface. It germinates in autumn, grows vigorously in spring, and dies off in the late summer. Decaying plant matter can make the water enriched and encourage nuisance algal mats near the sediment surface.

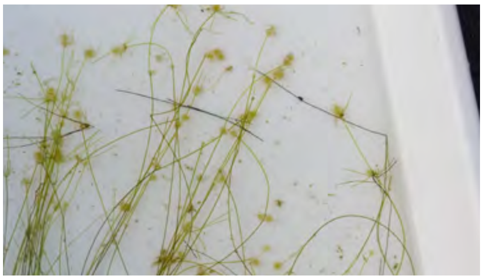
Species	Type	Status
Ruppia polycarpa (Horse's mane weed)	Emergent	Native

R. polycarpa is a surface-flowering, submerged, aquatic annual or perennial herb. Stems grow to 50cm long, depending on water depth. Vegetative buds (turions) can be formed in some ephemeral habitats. It grows in fresh to hypersaline coastal lakes, lagoons and estuaries and is relatively common in the 0-1.5m depth range (depending on water clarity). It grows in sandy sediments, and has distinctive flowers terminal on white stalks.



Species	Type	Status
Nitella sp.	Charophyte	Native

Nitella is a widespread bottom-dwelling, green charophyte algal species that superficially resembles flowering aquatic plants. It sometimes creates dense carpets on freshwater or slightly saline lagoon beds, reaching depths of 30m in some clear lakes. It is a long stringy looking plant without leaves. Stems "pop" if squeezed.



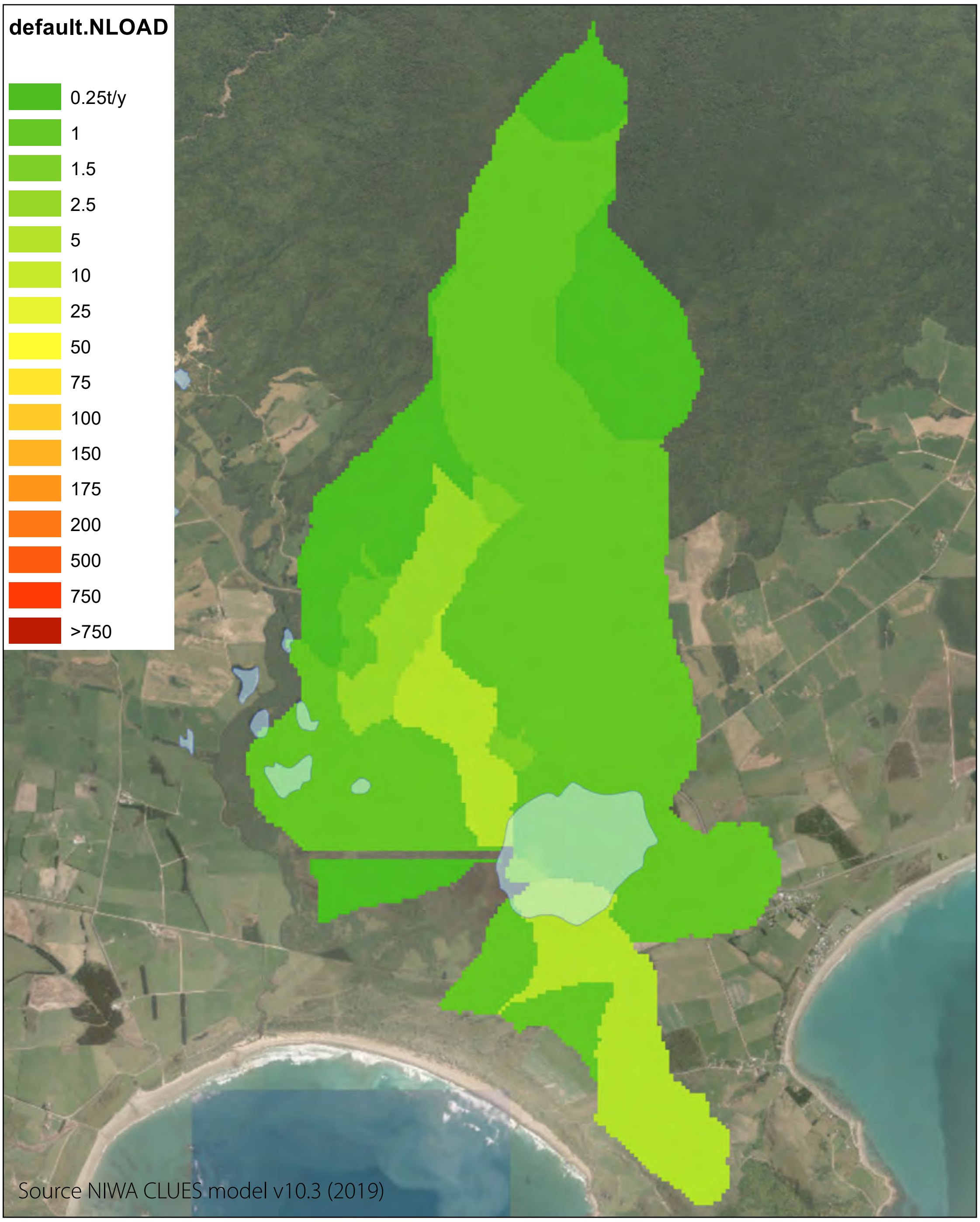
Species	Type	Status	
Chara corallina *C. corallina* is a widespread submerged bottom-dwelling green charophyte algal species, that superficially resembles flowering aquatic plants. Plants are stout and crisp with turgid segments and pinched nodes, pale to bright green. The conspicuous antheridia (male sex organs) are spherical and bright orange or yellow when mature. There are no stem divisions. It is widespread in the North and South Islands.	Charophyte	Native	
Chara fibrosa *C. fibrosa* is a relatively common bottom dwelling, grey-green charophyte algal species. Many small spines grow from a central stem (generally <0.5m) with reproductive organs found near the stem, surrounded by spines. Oospores are black. It is most common in shallows <2m.	Charophyte	Native	
Apodasmia similis (Oioi or jointed wire rush) Formerly *Leptocarpus similis, A. similis* is a rush with dark-banded wire-like slightly zigzagging stems. It is a coastal rush but it is also found around peat bogs and hot springs. It flowers from October to December and bears fruit from December to March.	Emergent shoreline	Native (endemic)	
Juncus edgeriae (Wiwi or Edgars rush) *J. edgeriae* is very common in coastal to alpine areas (1600 m.a.s.l.) but is mainly coastal to montane. It usually grows in open shrubland, fringing wetlands, and in seasonally damp sites. It is often found invading pasture and in urban areas. It fllowers from October to December and fruits from November to April.	Emergent shoreline	Native	
Carex secta (Purei or niggerhead) *C. secta* is a tussock-forming sedge, found throughout the North, South and Stewart Islands. It is widespread in suitable wetlands from coastal to montane wetlands. It flowers from October to November and fruits from October to December.	Emergent shoreline	Native (endemic)	

APPENDIX 5. CATCHMENT OVERVIEW

Lake George	2019
Catchment Area (ha)	1555
Lake area (ha)	104
Maximum depth (m)	1.4
TN Load (t/y)*	7.6
TP (t/y)*	0.39
TSS (kt/yr)*	0.08
N Areal Load (mg/m²/d)	20.0
P Areal Load (mg/m²/d)	1.0
TSS Areal Load (g/m²/d)	0.2

* Source NIWA CLUES model v10.3 (2019)

Note: Schallenberg and Kelly (2012) reported a 2912ha catchment area (information provided by Environment Southland), a lake area of 90.8ha, maximum depth of 2.0m, and TN & TP load estimates of 17t/yr & 0.76t/yr respectively.



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