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Determining reference conditions for New Zealand lakes

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Cover: Lake Sheila – a reference condition lake on Stewart Island/Rakiura. *Photo: Marc Schallenberg*.

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CONTENTS

Appendix 1

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Abstract

Lake restoration benefits by being guided by clear environmental targets, which can be informed by robust information about the natural, unimpacted state of the lake ecosystem. This study uses two approaches to establish appropriate reference or pre-human conditions for New Zealand's shallow- and deep-water lakes and for brackish lakes and lagoons. A survey-calibration approach was used, which primarily included multi-lake survey data that had been analysed within an ecological integrity framework. In addition, a palaeolimnological approach was used, which inferred reference conditions for New Zealand lakes from chronologies reconstructed from lake sediment cores. The combination of these two approaches provided a number of qualitative and quantitative benchmarks for reference conditions for the three lake classes. In general, reference conditions for all three lake classes exhibited low chlorophyll *a* and nutrient levels, a dominance of native flora and fauna, low levels of cyanobacteria, and extensive macrophyte beds. In addition to these, brackish lakes and lagoons with the least anthropogenic impact exhibited a deeper extent of macrophyte beds, benthic macroinvertebrate diversity and a decreased diversity of phytoplankton species. Additional attributes for minimally impacted deep lakes included low rotifer and phytoplankton diversity, high macrophyte diversity, and high ratios of dissolved inorganic nitrogen to total phosphorus concentrations (DIN:TP), suggesting P limitation of phytoplankton growth. Quantitative limits defining reference conditions were derived for most of these attributes. The limitations and complementarities of the two approaches are discussed, as well as ways in which the methodologies could be further developed to provide more diverse and accurate estimates of lake reference conditions.

Keywords: New Zealand lakes, reference conditions, survey-calibration approach, palaeolimnological studies, ecological integrity framework

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1. Introduction

Humans have had a major impact on the New Zealand environment ever since Polynesian people first arrived c. 700 years ago. The impact of fires on the landscape increased during Polynesian occupation, resulting in substantial deforestation and land clearance, whilst the arrival of Europeans in the late 18th and early to mid-19th centuries initiated a rapid phase of land use change. Palaeolimnological studies from New Zealand (Schallenberg & Saulnier-Talbot 2016) and elsewhere (Kidwell 2015) have also revealed that the period of intensification of land use since the 1950s, which is known as 'The Great Acceleration', has had widespread limnological effects.

Independent scientists, the Ministry for the Environment and regional councils have documented the decline in the water quality of lakes and rivers (PCE 2004, 2013; Verburg et al. 2010; Ballantine & Davies-Colley 2014; MfE & Statistics New Zealand 2015) and the worsening state of native freshwater biodiversity (Joy 2009; Goodman et al. 2014; Weeks et al. 2015). However, there is now increasing interest in maintaining and conserving the water quality and ecological integrity (EI) of lakes that are in a relatively good condition, and in restoring lakes that are deemed to be in an unacceptably degraded state, as evidenced by the publication of a special issue on the restoration of aquatic ecosystems in the *New Zealand Journal of Marine and Freshwater Research* in 2010 (Volume 43(3)).

The effective management of lakes requires appropriate environmental goals and targets (Higgins & Duigan 2009), which are often presented in regional plans and national policy statements. However, management targets are often not consistent, having been set in different ways. For example, some regional councils use toxicity-based guidelines (e.g. ANZECC 2000, NPSFM 2017) to set water quality targets, while others aim for conditions measured at some point in the past. The latter approach can be viewed as arbitrary or pragmatic, because the historical baseline does not account for the full degree of anthropogenic degradation that has occurred.

The restoration of ecosystems from a degraded state also requires environmental targets and goals to be set. However, such targets are again often pragmatic, arbitrary or misguided because of a lack of understanding of the conditions of the ecosystems prior to human disturbance. Some advances are being made in this area though. For example, a handbook on wetland restoration in New Zealand contains two chapters on the use of palaeoecological techniques to enable restorers to infer the historical environmental conditions of the wetlands (Schallenberg & Cadmus 2010a, b). This allows those undertaking a wetland restoration to incorporate information on the natural, unimpacted state (or 'reference condition') of the wetland into their restoration targets.

Although palaeolimnology is a useful tool for assessing historical lake conditions, it has not been used extensively for management or restoration in New Zealand. This may be because this approach can be quite expensive and time-consuming, and because there are limitations on the types and ranges of environmental conditions that can be inferred. Furthermore, it can be difficult to infer quantitative conditions using palaeolimnological techniques if no statistical models that relate environmental conditions to fossil biological proxy assemblages are available.

Thus, a key issue for those involved in managing and restoring lakes remains how to quantify the reference condition for a lake and how to quantify the lake's departure from that reference state (Higgins & Duigan 2009).

1.1 Reference condition

The term 'reference condition' has been used in the ecological literature to refer to an ecosystem that has not been affected by human activities. Stoddard et al. (2006) considered that there are four different applications of this term: i) a minimally disturbed condition; ii) a historic condition; iii) the least disturbed condition; and iv) the best attainable condition. In this report, the definition of Lee et al. (2005) is used whereby 'reference condition' is the EI of an ecosystem immediately prior to its first anthropogenic impacts.

In New Zealand, different anthropogenic impacts can be attributed to the period of Māori occupation v. the European phase of settlement, and much work has been done to assess the impacts of early Māori on the landscape (e.g. McGlone & Wilmshurst 1999; McWethy et al. 2009).

Various approaches can be used to estimate the reference conditions for lakes, including the examination of existing undisturbed lakes, and the use of palaeolimnology, expert knowledge, deterministic modelling and historical/archival information. In this report the strengths and limitations of two approaches for determining lake reference conditions are discussed, and information from these two approaches is gathered to infer the reference conditions for three types of New Zealand lakes: shallow freshwater lakes, coastal lakes and lagoons, and deep lakes.

1.2 Ecological integrity

EI is a concept that equates anthropogenic impacts with reductions in ecological values (Schallenberg et al. 2011). Thus, the concepts of EI and reference condition are related.

Schallenberg et al. (2011) defined EI for the New Zealand freshwater context. They argued that there are four essential components to the EI of freshwater ecosystems:

1. **Nativeness** – The degree to which the structural components of an ecosystem represent the native biota that are, or would have been, representative of the region.
2. **Pristineness** – The degree to which functional, structural and physicochemical components of an ecosystem reflect the processes that would be expected in an unmodified ecosystem. Pristineness also requires that the natural connectivity within and between ecosystems is maintained.
3. **Diversity** – The degree of taxonomic diversity or taxonomic richness of an ecosystem. Diversity may also include the evenness of species, i.e. how biomass is distributed among the constituents of biological communities, as measured by diversity indices.
4. **Resilience** – The degree to which structural and functional components of an ecosystem can return the ecosystem to its stable state after a perturbation. Resilience relates to an ecosystem's self-renewal capacity and long-term viability.

EI is a complex, normative concept that is not easily measured. According to Schallenberg et al. (2011), lakes with high EI must exhibit high values in all four components. Therefore, ideally, any measurement of EI should integrate metrics from each of the EI components. Schallenberg et al. (2011) also suggested a number of variables or indicators that could be used to quantify each of the four components of EI, and Özkundakci et al. (2014) modelled the integrated EI for 24 deep New Zealand lakes. However, no other attempts have been made to calculate EI from its four components for New Zealand lakes.

Despite its complexity, EI is a concept that seems to be amenable to subjective assessment by people with a good knowledge of the structure and functioning of lakes. For example, Drake et al. (2009, 2010) reported that there was a high correlation between the independent EI rankings of 43 New Zealand lakes by three experts (r^2 = c. 0.80), despite these only being based on site visits and prior to any analysis of the data collected. Thus, the average rank of the 43 lakes was proposed as a robust assessment of the EI of these lakes. This EI assessment also correlated well with measures of the water quality and biotic characteristics of the lakes, as well as the inferred anthropogenic (e.g. catchment development, modelled nitrogen and phosphorus loading) and invasive species pressure scores. However, the measured lake variables were poorly correlated with the pressure variables (e.g. catchment land use, invasive species). Therefore, Drake et al.

(2010) concluded that the expert assessment technique seems to effectively assess, integrate and weight the various EI components in an intuitive manner, which appears to be difficult to replicate using statistical modelling.

Practical use of the concept of EI requires that all four components be quantifiable in relation to some condition, which could be either the reference condition or some other desired or preferred condition. Alternatively, Schallenberg et al. (2011) suggested that EI could be normalised to quantifiable ecological tipping points – i.e. points along disturbance gradients where rapid (i.e. catastrophic) regime shifts occur in lakes. Thus, reference condition is not the only endpoint that could be used for EI assessments. However, this concept does appear to hold a persistent, intrinsic appeal for many people with an interest in lake management, conservation and restoration (Schallenberg et al. 2011).

1.3 Objectives

The main objective of this study was to determine whether reference conditions for New Zealand lakes could be inferred using two different approaches.

The survey-calibration approach used contemporary, New Zealand-wide data on recent lake conditions of a wide variety of ecological variables to infer pristine/reference conditions for three classes of lakes: shallow freshwater lakes, brackish lakes and lagoons, and deep lakes.

The palaeolimnological approach analysed the results of published and unpublished palaeolimnological studies that specifically reconstructed historical in-lake conditions (as opposed to the historical condition of catchments and catchment vegetation) using the same three classes of New Zealand lakes and lagoons.

Based on the findings from both approaches, a suite of evidence-based, reference conditions for the three classes of New Zealand lakes are proposed. The two approaches are compared and further work to address persistent knowledge gaps concerning lake reference conditions is suggested.

2. Methods

2.1 Survey-calibration approach

The survey-calibration approach uses a space-for-time substitution, whereby the historical trajectory of changes in lake condition is inferred by examining variation in attributes across a range of lakes, from those that are minimally disturbed to those that are clearly degraded. Thus, relationships between lake attributes and EI were investigated across a range of lakes and, where these relationships were found to be monotonic, interpolation or extrapolation was used to obtain meaningful information about reference condition.

Lakes that were considered to exhibit the highest EI were deemed to be in reference condition. EI was estimated using two independent measures: the percentage of loss of natural vegetation from the catchment and expert assessments of EI based on visits to the lakes. The positions of the reference condition lakes within the multi-lake relationships allowed determination of the reference condition limits for the various attributes tested. Validation of the limits was carried out by calculating how well the limits could independently distinguish reference lakes from non-reference lakes in the dataset.

2.1.1 Data sources

Three separate datasets were used in this analysis:

- For **shallow freshwater lakes and brackish lakes and lagoons**, the dataset from Drake et al. (2010) was used. This dataset comprised a one-off sampling of up to 46 shallow lakes and lagoons over a 4-year period. Lakes were sampled at the end of summer (between February and April) and were located from Northland to Campbell Island / Motu Ihupuku. Sampling was intensive, with multiple sites per lake being sampled for physicochemistry (46 lakes), phytoplankton (46 lakes), zooplankton (46 lakes), macrophytes (41 lakes), benthic invertebrates (41 lakes) and fish (41 lakes). This provided a comprehensive assessment of the ecological condition of the lakes using standardised methodologies. To complement this dataset, data for two lakes on Stewart Island / Rakiura were also obtained from Schallenberg & Kelly (2012), to provide additional data on unmodified lakes. These lakes were sampled at the same time of year and using the same methodologies as the 46 shallow lakes (although fish were not sampled).
- For **deep lakes**, a dataset compiled by Özkundakci et al. (2014) was used. This dataset also contained comprehensive information on physicochemistry, phytoplankton, zooplankton, macrophytes, benthic invertebrates and fish. However, unlike Drake et al. (2010), these data were gleaned from different sources using a variety of methodologies and were often presented as means that had been calculated from data collected over time. Ecological integrity was also assessed differently between the two studies (see section 2.1.2).

Due to the different data sources for shallow lakes/lagoons and deep lakes, there were some differences in the variables that were available for the analyses. All of the lakes that were used in the survey-calibration approach are listed in Appendix 1.

2.1.2 Determining reference lakes

Previous assessments of lake ecological integrity (Drake et al. 2010; Ozkundakci et al. 2014) provided an opportunity to set criteria to distinguish lakes that were close to reference condition from those that were not. To determine which lakes in the nationwide lake surveys most closely reflected reference conditions, two independent indicators of EI that had previously been assessed for the lakes were plotted against each other. The indicators used were lake 'ecological integrity' and '% catchment in native vegetation' (obtained from the New Zealand Land Cover Database II; Drake et al. 2010; Özkundakci et al. 2014). From the biplot of these EI indicators, lakes with the highest EI for both indicators were deemed to be lakes reflecting reference conditions. This pre-classification allowed the testing of other, independent lake attributes to determine whether the attributes could distinguish reference lakes from non-reference lakes. Attributes that could do this successfully were then considered relevant attributes for defining specific reference conditions for New Zealand lakes.

For the shallow lakes, EI was determined as the average ranking of lakes in the survey by three experienced freshwater scientists who had sampled all of the lakes, as described in section 1.2. For the deep lakes, EI was modelled as described in Özkundakci et al. (2014): 12 significant regression models were used to rank the study lakes according to their in-lake condition values; weightings were then applied to these ranks to correct for differences in data availability for the different variables, before calculating the sum of ranks for all EI variables.

By correlating '% catchment in native vegetation' with 'ecological integrity', lakes could be selected that represented both high catchment and within-lake integrity. These lakes were considered to reflect reference conditions (Fig. 1).

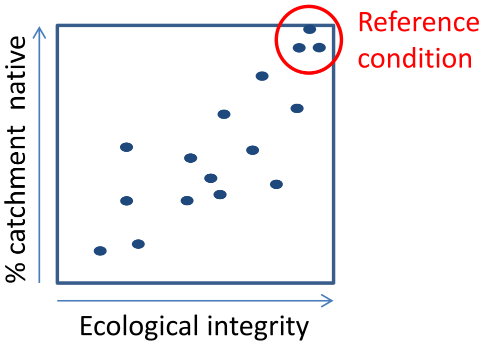

Figure 1. Schematic diagram showing the attribution of reference condition to selected lakes.

2.1.3 Analysis by lake class

In recognition of the fact that not all lakes should have similar reference conditions due to the effects of different degrees of vertical mixing, different salinities and different lake depths, reference conditions were identified separately for three classes of lakes: shallow freshwater lakes, brackish lakes and lagoons, and deep lakes.

The influences of latitude and associated biogeographic effects were not dealt with a priori. However, these are illustrated on all graphs by using different data markers for North Island lakes and South Island lakes.

2.1.4 Selection of ecological integrity metrics (key condition variables)

The reference lakes for the different lake classes were selected using correlation analysis, as described in section 2.1.2. To quantify in-lake reference conditions for different environmental and ecological variables, number of key indicator variables that reflect EI were analysed. These variables were based on those proposed in Schallenberg et al. (2011), according to data availability, and represented all four components of EI (i.e. nativeness, pristineness, diversity and resilience; see section 1.2).

2.1.5 Determining reference condition limits

Lakes that were deemed to be in a reference condition were used to indicate the reference condition limit for the lake attributes (Fig. 2). This limit should encompass all lakes in the reference condition and, if statistically robust, should exclude all lakes that are deemed to have departed from the reference condition and become degraded.

The robustness of the reference condition limit was quantified by calculating the percentage of degraded lakes that were distinguished from the reference lakes by the limit.

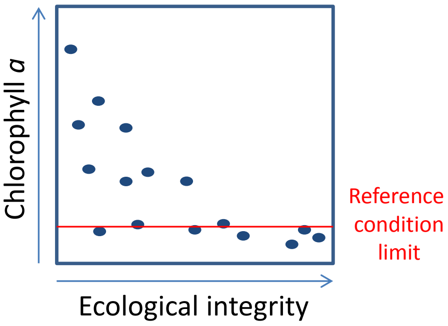

Figure 2. Determination of a reference condition limit with the survey-calibration method, using the concentration of chlorophyll a as an example attribute.

2.2 Palaeolimnological approach

Palaeolimnological reconstructions using lake sediment cores have been carried out extensively in New Zealand to determine the (pre)history of land clearance, and the effects of land use change and fires on the landscape (e.g. McGlone & Wilmshurst 1999; McWethy et al. 2009). However, relatively few palaeolimnological studies have been carried out specifically to reconstruct the (pre)historical/reference conditions for lakes.

The palaeolimnological approach used here involved examining published and unpublished palaeolimnological studies that specifically provided insights into the conditions of lakes prior to human and/or European influence. These studies generally inferred historical changes in lake conditions due to anthropogenic hydrological and land use changes. As in the survey-calibration approach, the lakes examined in these studies were separated into the following three classes: shallow freshwater lakes, brackish lakes and lagoons, and deep lakes.

Most of the information on reference conditions and temporal trends obtained from the palaeolimnological studies was qualitative. Therefore, brief historical narratives based on the palaeolimnological data and interpretations were first constructed and then general trends and patterns were extracted from the independent studies.

3. Reference conditions for lakes according to the survey-calibration method

3.1 Shallow freshwater lakes

Shallow lakes differ functionally from deeper lakes in that they tend to be vertically mixed throughout the year, although weak stratification can occur briefly. Consequently, the water column is not separated from the lake bed by a dark, cold layer of water during summer, leading to a strong coupling between processes occurring in the sediments and in the water column. Furthermore, the entire water column warms up in the summer, resulting in high rates of productivity and nutrient cycling. Shallow lakes often tend to exhibit clear waters because they are dominated by aquatic macrophytes; however, during high winds they may develop turbid waters due to the resuspension of sediments.

Shallow lowland lakes often lie at the bottom of catchments, where the soils tend to be richer. Consequently, agricultural land use is usually present and often dominant in their catchments, which can lead to high nutrient and sediment loads entering these lakes, which are generally in a degraded state (Drake et al. 2009, 2010; Schallenberg & Kelly 2012). The 34 shallow freshwater lakes surveyed as part of this dataset were located throughout the lowlands of New Zealand, from Northland to Campbell Island/ Motu Ihupuku. These lakes were polymictic and, for the most part, had a maximum depth of < 10 m. In addition, all of them had a specific conductivity below 600 µS/cm (salinity < 0.32 psu or < 0.29 ppt) at the time of sampling.

3.1.1 Reference lakes

In selecting the 34 shallow lowland lakes for this survey, special effort was made to include a number of minimally impacted lakes (Drake et al. 2009, 2010; Schallenberg & Kelly 2012), which were deemed to have > 90% native land cover in their catchments. These lakes were found on Campbell Island/Motu Ihupuku, on Stewart Island/Rakiura, in The Catlins, on the West Coast of the South Island, in the Tasman District and in Wairarapa.

There was a positive relationship between '% catchment in native vegetation' and 'ecological integrity', and the minimally impacted lakes were clearly differentiated from the degraded lakes (Fig. 3). However, to determine whether small differences in the reference lake criteria could lead to substantial differences in reference condition limits observed in the data, two groups of reference lakes were differentiated:

1. The 'Tier 1' reference group – a group of lakes that lay within the 90th percentile for both indicators, which included Six Foot Lake (Campbell Island/ Motu Ihupuku), Ship Creek Lagoon (South Westland), 'Maori' Lake (South Westland), Lake Pounui (Wairarapa), Lake Sheila (Stewart Island/Rakiura) and Lake Calder (Stewart Island/Rakiura).
2. The 'Tier 2' reference group – a group of lakes that lay within the 80th percentile for both indicators, which included the above lakes plus Lake Wilkie (The Catlins) and Lake Otuhie (Tasman).

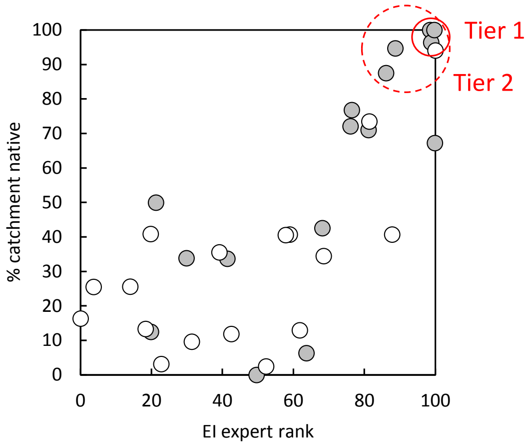

Figure 3. Relationship between the two indicators of reference condition in shallow freshwater lakes: the percentage of the catchment in native vegetation and the ecological integrity (EI) of the lake as determined by expert assessment (see Drake et al. 2010). Red circles demarcate potential reference lakes, with 'Tier 1' reference lakes encompassing the 90th percentiles of both indicators and 'Tier 2' reference lakes encompassing the 80th percentiles of both indicators. Filled symbols represent South Island lakes and open symbols represent North Island lakes.

Figure 3 shows that North Island lakes and South Island lakes occupied similar EI ranges, without distinct clustering. Therefore, North Island and South Island lakes were pooled in the following analyses.

3.1.2 Nativeness limits

For the nativeness component, a limit of 100% native species was deemed appropriate as a reference condition because many non-native species are known to negatively impact the ecology of lakes (Champion et al. 2002; Closs et al. 2004). Therefore, instead of an empirical determination of Tier 1 and Tier 2 reference lakes, all reference lakes were deemed to have 100% native species composition.

Figure 4 shows the relationships between various indicators of nativeness and the two indicators of reference condition ('ecological integrity' and '% catchment in native vegetation').

As can be seen, the relationships in Fig. 4 are not linear, but rather suggest data polygons or envelopes, whereby the lower limit of nativeness is positively related to the indicators of reference condition, while the upper limit is independent of the indicators. Such relationships indicate complex biophysical relationships between variables whereby other, extraneous factors potentially mediate the relationships.

All of the reference lakes achieved the 100% nativeness score except Lake Pounui (Wairarapa). This lake has a largely intact catchment and was deemed to have a high EI at the time of sampling. However, there was a low biomass and % cover of the non-indigenous macrophyte *Elodea canadensis* in Lake Pounui at the time of sampling. It should also be noted that Lake Wilkie (The

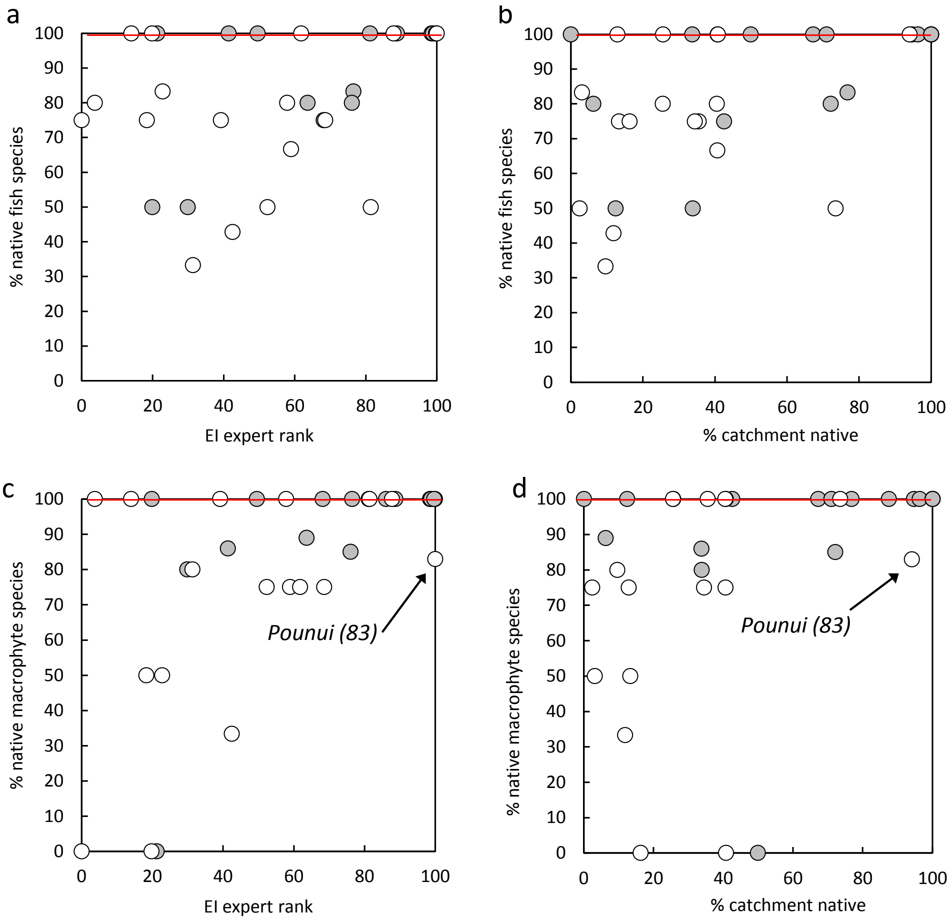

Figure 4. Correlations between measures of nativeness (*y*-axes) and indicators of reference condition (*x*-axes) in shallow freshwater lakes. Red lines are proposed reference condition limits (see Table 1). Reference lakes that fall outside the limit are indicated on the graphs. Filled symbols represent South Island lakes and open symbols represent North Island lakes.

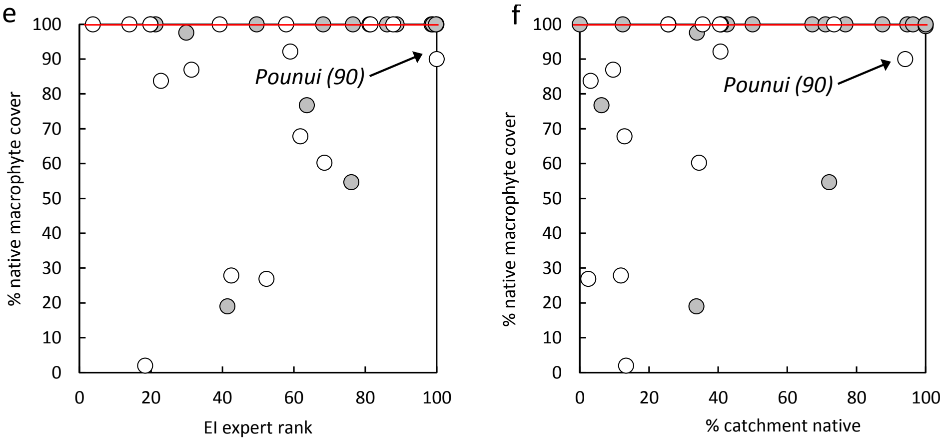

Figure 4 *continued.*

Catlins) was deemed to have a high EI score despite containing no native fish due to it being a seepage lake that is heavily influenced by surrounding peatlands, resulting in a naturally low pH of 4.6, which may be too low for native fish reproduction (Rowe & Graynoth 2002).

The recommended nativeness limits and the abilities of these limits to differentiate non-reference lakes from reference lakes are shown in Table 1. There was no relationship between 'native fish catch per unit effort' and the indicators of reference condition and, therefore, no reference condition limit could be determined for that indicator of nativeness.

Table 1. Nativeness reference condition limits for shallow freshwater lakes. The percentage of non-reference lakes excluded by the limit is a measure of the strength of the limit in distinguishing reference lakes from non-reference lakes. Outliers are reference lakes that fall outside the deemed limits. '–' indicates that there was no relationship between the nativeness and reference condition indicators and, therefore, no limit is proposed. No Tier 2 limit was set for nativeness (see text).

INDICATOR	UNIT	RANGE FOR ALL LAKES	RANGE FOR REFERENCE LAKES	LIMIT	% NON-REFERENCE LAKES EXCLUDED	OUTLIERS
% native fish species	%	33–100	100	100	69%	Lake Wilkie
% native macrophyte species	%	0–100	75–100	100	56%	Lake Pounui
% native macrophyte cover	%	0–100	90–100	100	44%	Lake Pounui
Native fish catch per unit effort (CPUE)	Catch/effort	0–274	4–80	–	–	N/A

3.1.3 Pristineness limits

Pristineness indicators consist mainly of physicochemical variables related to nutrient and sediment enrichment. Some of these variables are useful for distinguishing pristine lakes from degraded lakes because they correlate strongly with 'ecological integrity' and '% catchment in native vegetation' (Fig. 5).

Six Foot Lake (Campbell Island / Motu Ihupuku) is a consistent outlier in terms of pristineness due to its high levels of nutrients and chlorophyll *a*. This undoubtedly pristine lake was eutrophic when sampled and exhibited high rates of phytoplankton productivity (unpubl. data). It is possible that the high levels of nutrients in the water column of Six Foot Lake arise from marine nutrient subsidies provided by the high densities of marine biota (sea lions, albatross, petrels etc.) observed at the lake and in its catchment. The absence of macrophytes in the lake at the time of sampling may have resulted from high light attenuation due to the influence of peat staining and particulate matter in the water column and to the extreme winds that the lake is subject to, which may prevent macrophyte colonisation and competition with phytoplankton for nutrients. It is also possible that the remoteness of Campbell Island / Motu Ihupuku, and the intense prevailing southerly and westerly weather may have prevented the colonisation of Six Foot Lake by freshwater macrophyte flora to date, contributing to the eutrophic condition of the lake.

The recommended reference condition limits and the strength of their abilities to differentiate pristine from degraded shallow freshwater lakes are shown in Table 2. Note that because of the non-linear nature of many of these relationships, a shift in the acceptance criteria from > 90th percentile (Tier 1) to > 80th percentile (Tier 2) can result in a doubling (or greater) of the limit distinguishing pristine from non-pristine lakes.

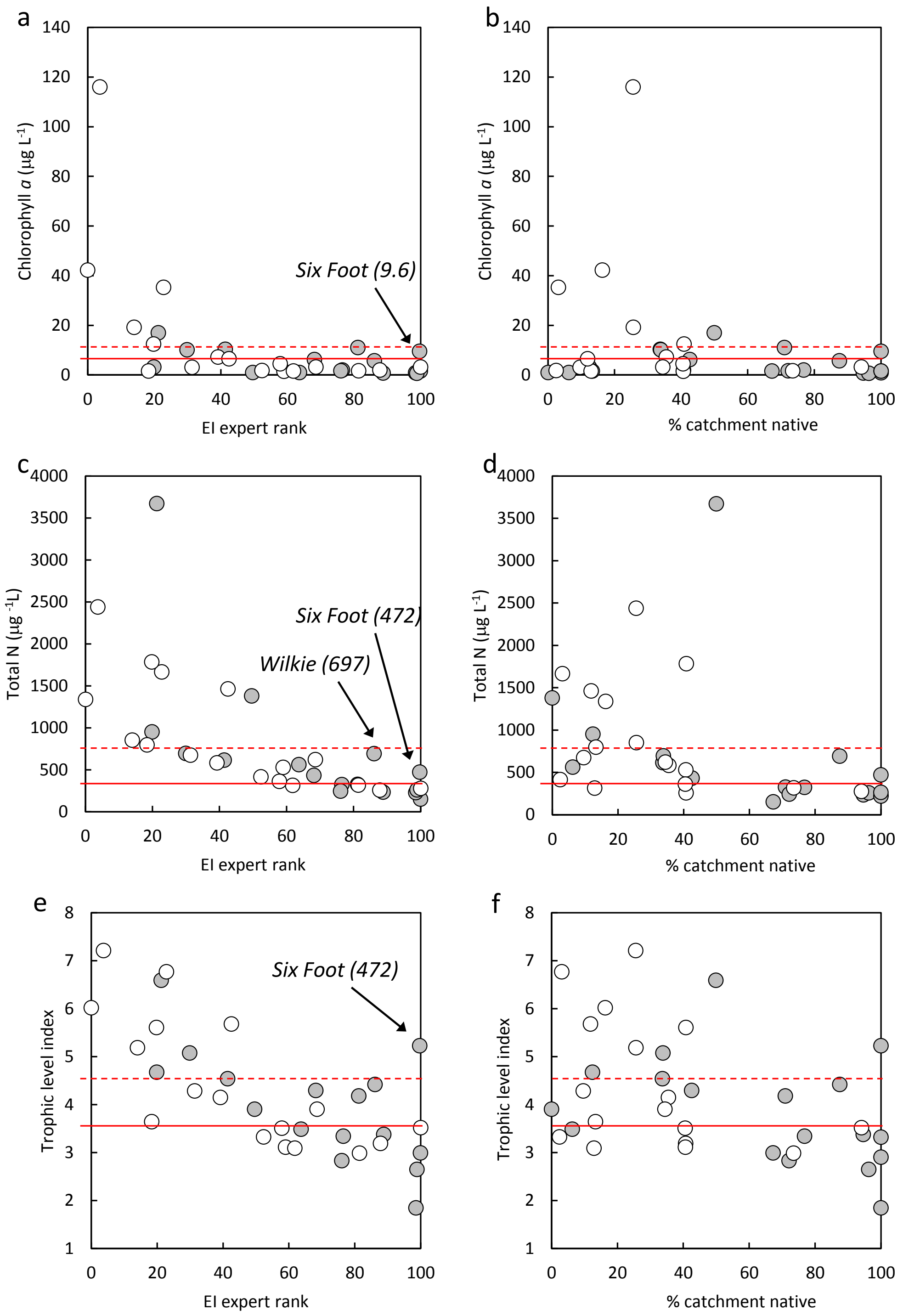

Figure 5. Correlations between measures of pristineness (*y*-axes) and indicators of reference condition (*x*-axes) in shallow freshwater lakes. Red lines are proposed pristineness reference condition limits for Tier 1 (solid lines) and Tier 2 lakes (see Table 2). Reference lakes that fall outside the limits are indicated on the graphs. Filled symbols represent South Island lakes and open symbols represent North Island lakes.

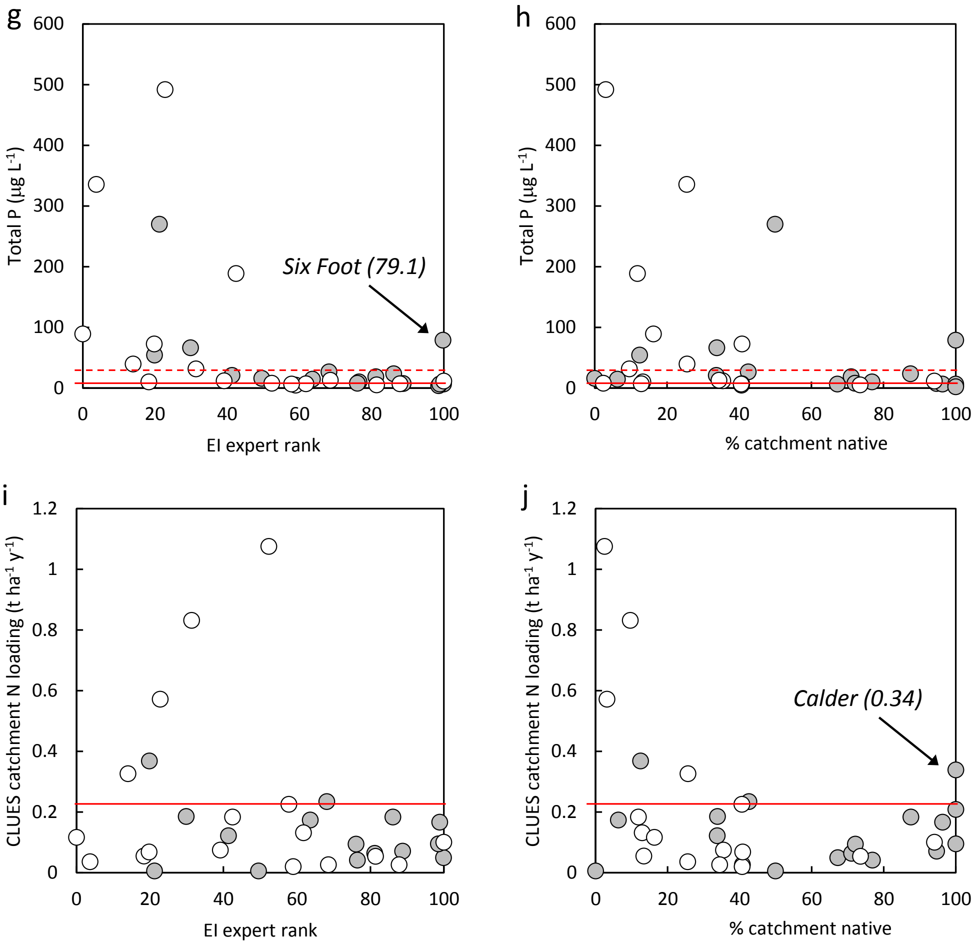

Figure 5 *continued.*

Table 2. Pristineness reference condition limits for shallow freshwater lakes. The percentage of non-reference lakes excluded by the limit is a measure of the strength of the limit in distinguishing reference lakes from non-reference lakes. Outliers are reference lakes that fall outside the deemed limits. '–' indicates that there was no relationship between the pristineness and reference condition indicators and, therefore, no limit is proposed.

INDICATOR	UNIT	RANGE FOR ALL LAKES	RANGE FOR REFERENCE LAKES TIER 1 (TIER 2)	LIMIT TIER 1 (TIER 2)	% NON-REFERENCE LAKES EXCLUDED (RELAXED)	OUTLIERS
Total nitrogen	µg/L	151–3672	235–277 (235–692)	≤277 (≤692)	86% (42%)	Six Foot Lake, Lake Wilkie
Total phosphorus	µg/L	2–492	2.0–11.7 (2.0–23.0)	≤11.7 (≤23.0)	64% (43%)	Six Foot Lake
Trophic Level Index		1.8–7.2	1.8–3.5 (1.8–4.4)	≤3.5 (≤4.4)	64% (38%)	Six Foot Lake
Chlorophyll *a*	mg/L	1–116	0.7–3.2 (0.7–5.7)	≤3.2 (≤5.7)	57% (46%)	Six Foot Lake
Nitrogen loading	t/ha/y	0.006–1.080	0.10–0.21 (0.10–0.21)	≤0.21 (≤0.21)	26% (26%)	Lake Sheila
Macrophyte cover	%	0–100	31–98 (12–98)	–	–	N/A
Dissolved organic carbon	mg/L	3–34	4.0–10.4 (4.0–23.0)	–	–	N/A
Euphotic depth	m	0.6–12.1	1.0–6.7 (1.0–6.7)	–	–	N/A
% Ephemeroptera, Trichoptera and Odonata taxa	%	0–21	0.0–13.6 (0.0–14.3)	–	–	N/A
% Ephemeroptera, Trichoptera and Odonata abundance	%	0–14	0.0–13.5 (0.0–13.5)	–	–	N/A
Humic absorbance per unit dissolved organic carbon	Abs/mgC$^{/}$/L	0.02–0.75	0.14–0.29 (0.14–0.39)	–	–	N/A
Macrophyte depth limit	m	0.1–11.9	0.4–6.0 (0.4–6.0)	–	–	N/A
Pest fish species	Count	0–4	0*	–	–	N/A

* Reference lakes displayed no range.

3.1.4 Diversity limits

There were no relationships between measures of biological diversity and indicators of reference condition in the shallow lakes dataset. Therefore, no diversity limits were proposed to distinguish lakes in a reference condition (Table 3).

Diversity often exhibits unimodal relationships along disturbance gradients (Flöder & Sommer 1999). However, such relationships were not observed here either. The dataset indicated that lakes in a reference state had widely varying diversities and that the main anthropogenic changes to lakes that have occurred in New Zealand have had little effect on their diversity. This may be due to the introduction of non-native species in many of these lakes, although the influence of non-native species on such diversity relationships is also complex because while they contribute to diversity, their effects also often lead to the extirpation of native species (Champion et al. 2002; Closs et al. 2004). Therefore, the relationship between diversity and reference condition remains complex and the analyses presented here were unable to elucidate any direct or indirect effects in shallow lowland lakes.

Table 3. Diversity reference condition limits for shallow freshwater lakes. '–' indicates that there was no relationship between the pristineness and reference condition indicators and, therefore, no limit is proposed.

INDICATOR	UNIT	RANGE FOR ALL LAKES	RANGE FOR REFERENCE LAKES	LIMIT	% NON-REFERENCE LAKES EXCLUDED	OUTLIERS
Native fish	Species richness	0–5	0–5	–	–	N/A
Native macrophytes	Species richness	0–11	1–7	–	–	N/A
Metazooplankton	Species richness	0–9	0–8	–	–	N/A
Phytoplankton	Species richness	13–37	14–25	–	–	N/A
Rotifers	Species richness	1–17	5–11	–	–	N/A
Benthic invertebrates	Species richness	3–32	6–28	–	–	N/A

3.1.5 Resilience limits

Three indicators of ecological resilience were included in this analysis:

1. An indicator of the balance between nitrogen (N) and phosphorus (P) availability (i.e. the ratio of dissolved inorganic N to total P, DIN:TP). This is an accurate indicator of N or P limitation in lakes (Morris & Lewis 1988; Abell et al. 2010; M. Schallenberg, unpubl. data). Lakes with large internal P loads (e.g. as a result of sediment anoxia) would be expected to have very low DIN:TP ratios and would, therefore, be favourable environments for the proliferation of N-fixing cyanobacteria.
2. The density of cyanobacterial cells in the lake. N-fixing cyanobacteria can form nuisance blooms due to their ability to convert atmospheric nitrogen gas into available N. Many taxa are also able to migrate upward in the water column, competing effectively with other phytoplankton and macrophytes for light. Many cyanobacteria taxa also produce toxic metabolites, which can result in the death of wildlife such as fish and freshwater mussels.
3. The length of the food chain, as determined by stable nitrogen isotope analysis.

All three indicators of resilience showed relationships with the reference condition indicators, although all of these relationships were relatively weak (Fig. 6) and the limits did not effectively differentiate reference lakes from degraded lakes (Table 4).

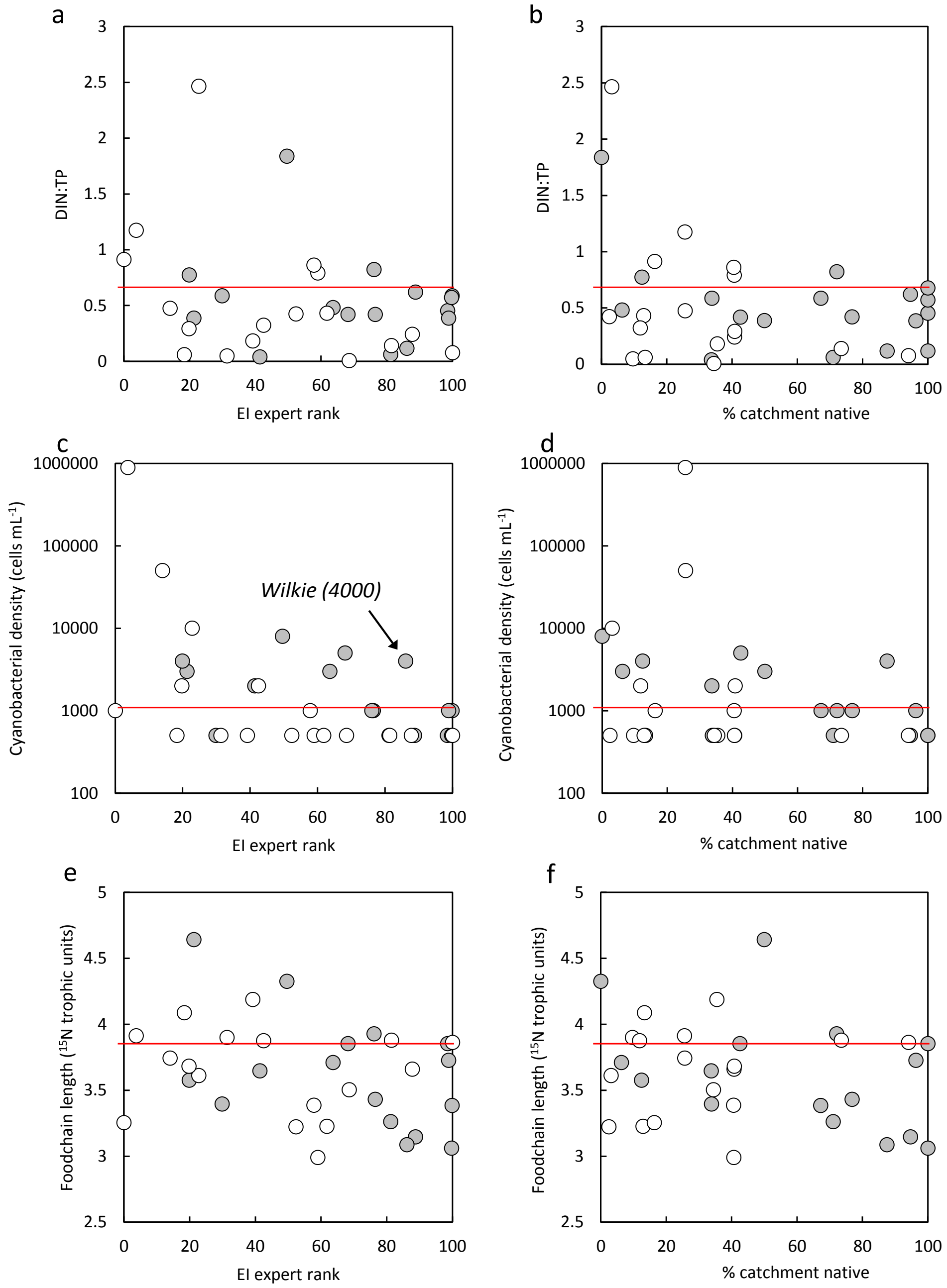

Figure 6. Correlations between measures of resilience (*y*-axes) and indicators of reference condition (*x*-axes) in shallow freshwater lakes. DIN:TP is the ratio of dissolved inorganic nitrogen to total phosphorus measured in the water column. Red lines are proposed reference condition limits (see Table 4). Reference lakes that fall outside the limits are indicated on the graphs (arrows). Filled symbols represent South Island lakes and open symbols represent North Island lakes. There was no difference in the limit for Tier 1 and Tier 2 reference lakes.

Table 4. Resilience reference condition limits for shallow freshwater lakes. The percentage of non-reference lakes excluded by the limit is a measure of the strength of the limit in distinguishing reference lakes from non-reference lakes. Outliers are reference lakes that fall outside the proposed limits. There was no difference in the limits for Tier 1 and Tier 2 reference lakes.

INDICATOR	UNIT	RANGE FOR ALL LAKES	RANGE FOR REFERENCE LAKES	LIMIT	% NON-REFERENCE LAKES EXCLUDED	OUTLIERS
Cyanobacteria	Cells/mL	<500–891 000	<500–1000	≤1000	65%	Lake Wilkie
Food chain length	Trophic levels	2.99–4.64	3.06–3.86	≤3.86	35%	None
DIN:TP*		0.01–2.46	0.08–0.68	≤0.68	29%	None

* Ratio of dissolved inorganic nitrogen to total phosphorus.

Reference lakes tended to have low DIN:TP ratios (e.g. < 1), indicating that phytoplankton growth was more likely to be N-limited than P-limited in these lakes. Low DIN:TP ratios could imply that internal P-loading is relatively high in these shallow lakes, that rates of N loading from their catchments are relatively low, and that denitrification and/or macrophyte uptake may maintain low DIN levels in the water column.

Lakes in a reference condition tended to have low cyanobacterial densities, with the exception of Lake Wilkie (The Catlins), which is a seepage lake that is affected by acid drainage from a peat bog and so was found to be an outlier.

The analyses also showed that lakes that were closer to reference condition had food chain lengths that were shorter than those of more degraded lakes by around one trophic level. The absence of vertebrate top predators such as perch and salmonids in reference lakes results in naturally shorter food chains than those in more degraded lakes, which are more likely to have such introduced predators.

3.1.6 Proposed reference condition for shallow freshwater lakes

The above analyses provide a clear picture of the likely typical reference condition for New Zealand shallow freshwater lakes in terms of some of their specific attributes. Aspects of nativeness, pristineness and resilience were informed by the analysis; however, no clear information on biodiversity of aquatic organisms could be obtained because diversity was not monotonically related to the two reference condition indicators used. The strongest relationships and most informative limits are presented in Table 5.

The approach developed here and in Schallenberg et al. (2011) proposes that lakes that are in a reference condition should meet all of the appropriate reference criteria across the four components of EI (although, in this case, diversity could be excluded). Thus, a shallow lowland lake that fits all of the limit criteria in Table 5 could be considered to be in a reference condition typical for this type of lake. Note, however, that some apparently pristine lakes may fail to meet some of these criteria due to certain atypical factors, such as additional marine nutrient subsidies, being subject to extreme climatic conditions or biogeographic isolation (e.g. Six Foot Lake); the presence of non-native macrophyte species (Lake Pounui); and factors related to poor

Table 5. Summary of the most useful limits for discriminating between reference condition and degraded shallow lowland lakes. Note: Only limits that discriminated at least 50% of the non-reference lakes are included.

INDICATOR	UNIT	RANGE FOR ALL LAKES	RANGE FOR REFERENCE LAKES TIER 1 (TIER 2)	LIMIT TIER 1 (TIER 2)	% NON-REFERENCE LAKES EXCLUDED	OUTLIERS
Nativeness						
% native fish species	%	33–100	100	100	69%	Lake Wilkie
% native macrophyte species	%	0–100	100	100	56%	Lake Pounui
Pristineness						
Total nitrogen	µg/L	151–3672	235–277 (235–692)	≤277 (≤692)	86%	Six Foot Lake, Lake Wilkie
Total phosphorus	µg/L	2–492	2.0–11.7 (2.0–23.0)	≤11.7 (≤23.0)	64%	Six Foot Lake
Trophic Level Index		2–492	1.8–3.5 (1.8–-4.4)	≤3.5 (≤4.4)	64%	Six Foot Lake
Chlorophyll *a*	mg/L	1–116	0.7–3.2 (0.7–5.7)	≤3.2 (≤5.7)	57%	Six Foot Lake
Diversity						
No relationships						
Resilience						
Cyanobacteria	Cells/mL	< 500–891 000	< 500–1000	≤1000	65%	Lake Wilkie

hydrological connectivity and low pH (Lake Wilkie). Thus, some of the lakes that were deemed to be in a reference condition based on expert assessment and catchment condition fail the reference condition test described in Table 5.

3.2 Brackish lakes and lagoons

Brackish lakes and lagoons are influenced by the marine environment, not only in terms of their salinity, but also often in terms of tidal lake level variations, flushing and mixing. Even minor marine influences can have major impacts on the structure and functioning of lake ecosystems (Schallenberg et al. 2003). Therefore, the reference condition for brackish lakes and lagoons was assessed separately from shallow freshwater lowland lakes.

Unfortunately, comprehensive ecological data only exist for ten such systems in New Zealand, somewhat limiting the conclusions that can be drawn from the following analyses.

3.2.1 Reference lakes/lagoons

The two indicators of reference condition showed a moderate degree of correlation with each other for the brackish lakes and lagoons dataset (Fig. 7). Based on this correlation, Five Mile Lagoon (South Westland) was considered to be the only system that reflected the reference condition for this class of lakes/lagoons, and so it is considered a high priority to undertake further surveys in catchments with high native forest cover. Furthermore, since only one system was deemed to be in a reference state, there is only one tier of inferred reference condition and no range of reference conditions available. Therefore, the following analysis of reference state limits for brackish lakes/lagoons should be considered preliminary.

A comparison of the EI indicators from the North and South Island brackish lakes/lagoons indicated that the brackish lakes and lagoons of the two islands did not exhibit distinct groupings. Therefore, North and South Island brackish lakes/lagoons were pooled for subsequent analyses.

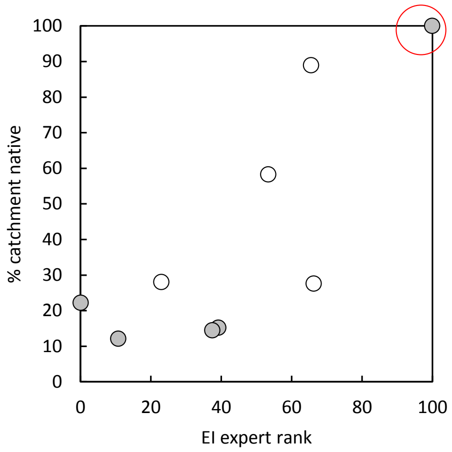

Figure 7. Correlation between the two measures of reference condition in brackish lakes and lagoons: the percentage of the catchment in native vegetation and the ecological integrity (EI) of the lake as ranked by three experts based on site visits and sampling. The red circle demarcates the potential reference lake/lagoon (Five Mile Lagoon). Filled symbols represent South Island lakes/lagoons and open symbols represent North Island lakes/ lagoons.

3.2.2 Nativeness limits

As with shallow freshwater lakes, a limit of 100% native species was deemed appropriate as a reference condition because many non-native species are known to negatively impact the ecology of lakes (Champion et al. 2002; Closs et al. 2004). Therefore, instead of an empirical determination of Tier 1 and Tier 2 reference brackish lakes/lagoons, all reference brackish lakes/ lagoons were deemed to have 100% native species composition.

Brackish lakes and lagoons exhibited a relatively narrow range of macrophyte and fish nativeness. This is probably due to the highly dynamic nature of these systems in terms of water level, salinity and turbidity, which may challenge the survival of many of the native (and non-native) species found in freshwater lakes. Consequently, the relationships between nativeness and the two indicators of reference condition were relatively weak in these systems (Fig. 8), with none of the relationships indicating useful limits for distinguishing reference condition (Table 6). As with freshwater shallow lakes, a nativeness limit of 100% native macrophyte species was deemed appropriate as the reference condition for such systems.

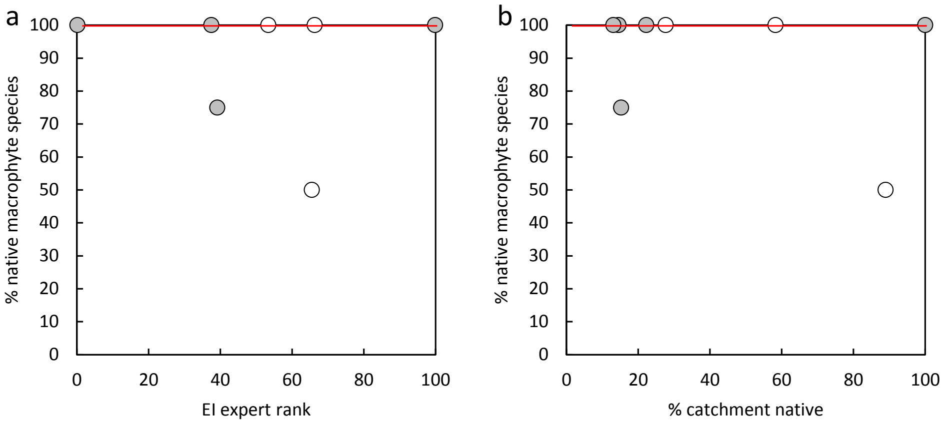

Figure 8. Correlation between the percentage of native macrophyte species and the two indicators of reference condition in brackish lakes and lagoons. Red lines are proposed reference condition limits (see Table 6). Filled symbols represent South Island lakes and open symbols represent North Island lakes.

Table 6. Nativeness reference condition limits for shallow brackish lakes and lagoons. '–' indicates that there was no relationship between the nativeness and reference condition indicators and, therefore, no limit is proposed.

INDICATOR	UNIT	RANGE FOR ALL LAKES	LIMIT	% NON-REFERENCE LAKES EXCLUDED	OUTLIERS
% native macrophyte species	%	50–100	100	29%	None
% native fish species	%	57–100	–	–	N/A
% native macrophyte cover	%	83–100	–	–	N/A
Native fish catch per unit effort (CPUE)	Catch/effort	1.5–283.0	–	–	N/A

3.2.3 Pristineness limits

Pristineness indicators consist mainly of physicochemical variables, although some bioindicators can also be related to physicochemical and habitat conditions in lakes (see Schallenberg et al. 2011). A number of relationships were revealed between the pristineness indicators and reference condition indicators (Fig. 9). Unfortunately, since only one of the brackish lakes and lagoons was in a pristine or reference condition, the dataset provides no indication of the variability among reference lakes/lagoons. Nevertheless, some relationships are suggested and some provisional limits can be inferred from the data (Fig. 9 & Table 7).

As expected, indicators of nutrient enrichment showed clear relationships with both of the indicators for reference condition. In addition, in brackish lakes and lagoons, a benthic macroinvertebrate indicator of pristineness (the percentage of the macrobenthic community abundance comprising ephemeropterans, trichopterans and odonates or '% ETO'), the depth limit of macrophytes, and the percentage macrophyte cover in the systems also correlated with indicators related to reference condition (Fig. 9 & Table 7).

Upper Lake Onoke (Wairarapa) appeared to be an outlier with regard to 'macrophyte maximum depth' (Fig. 9k and 9l). This lake had a higher macrophyte maximum depth limit than the pristine Five Mile Lagoon, despite not being considered in pristine condition. This is probably due to the moderate, natural humic acid staining that occurs in Five Mile Lagoon, which restricts light penetration and euphotic depth compared with Upper Lake Onoke. Therefore, natural humic acid staining must be accounted for when considering appropriate reference conditions in relation to water clarity/transparency and euphotic depth.

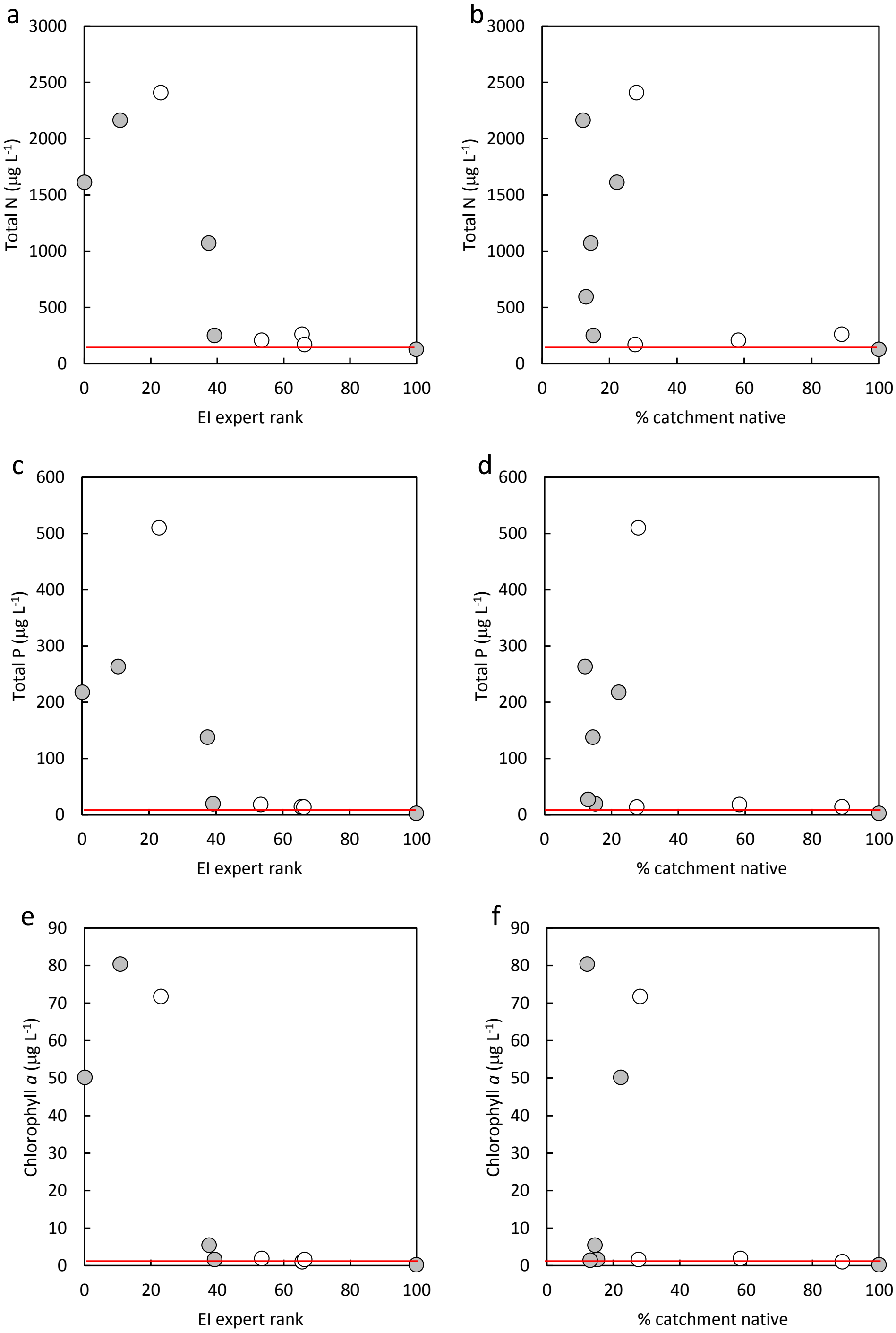

Figure 9. Correlations between various measures of pristineness and the two indicators of reference condition in brackish lakes and lagoons. Red lines are proposed reference condition limits (see Table 7). Filled symbols represent South Island lakes and open symbols represent North Island lakes. %EPT is the percentage of the benthic macroinvertebrate abundance made up of the sum of Ephemeroptera, Plecoptera and Odonata.

The reference condition limits for pristineness indicators effectively differentiated the reference condition lake from the non-reference condition lakes. However, the dataset for brackish lakes and lagoons is too small to capture the variability that exists among such systems. Therefore, caution should be used in utilising the proposed reference condition limits for lakes/lagoons of this class.

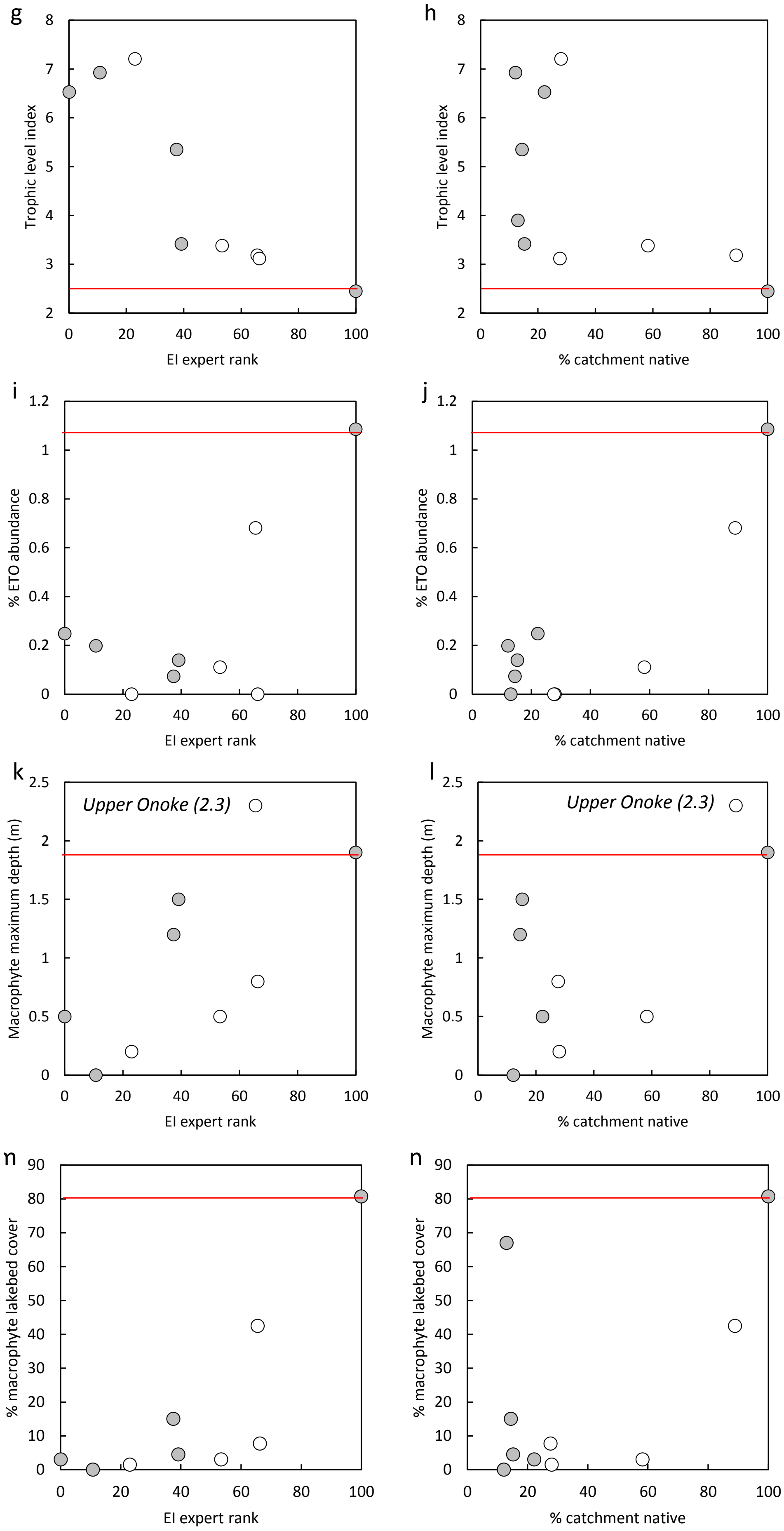

Figure 9 *continued.*

Table 7. Pristineness reference condition limits for brackish lakes/lagoons. The percentage of non-reference lakes excluded by the limit is a measure of the strength of the limit in distinguishing reference lakes from non-reference lakes. '–' indicates that there was no relationship between the nativeness and reference condition indicators and, therefore, no limit is proposed. Limits are based on only one lake and are, therefore, preliminary.

INDICATOR	UNIT	RANGE FOR ALL LAKES	LIMIT	% NON-REFERENCE LAKES EXCLUDED	OUTLIER
Chlorophyll *a*	µg/L	0.3–80.4	≤0.3	100%	None
Total nitrogen	µg/L	128–2163	≤128	100%	None
Total phosphorus	µg/L	2.4–510.0	≤2.4	100%	None
Trophic level index		2.5–7.2	≤2.5	100%	None
% Ephemeroptera, Trichoptera and Odonata abundance (%ETO)	%	0.0–1.1	≥1.1	100%	None
Macrophyte depth limit	m	0.2–2.3	≥1.9	88%	Upper Lake Onoke
Nitrogen loading		0.02–3.24	–	–	N/A
Macrophyte cover	%	0–81	–	–	N/A
Dissolved organic carbon	mg/L	2.7–18.0	–	–	N/A
Euphotic depth	m	0.3–4.9	–	–	N/A
% ETO (species)	%	0–20	–	–	N/A
Humic absorbance per unit dissolved organic carbon	Abs/mgC/L	0.05–0.34	–	–	N/A
Pest fish species	No.	0–2	–	–	N/A

3.2.4 Diversity limits

Unlike for the shallow freshwater lakes, diversity indicators were correlated with the indicators of reference condition for brackish lakes and lagoons (Fig. 10). The reference lake, Five Mile Lagoon, had a low phytoplankton diversity (assessed in late summer) and a high benthic invertebrate diversity compared with the other lakes. However, both Whakaki Lagoon (Hawke's Bay) and Lake Onoke also had low phytoplankton diversities. Both of these systems were characterised by high turbidity due to suspended inorganic sediments at the time of sampling, which contrasts with the clear but humic-stained water of Five Mile Lagoon. The low phytoplankton diversity in these turbid lakes supports the previous finding that high levels of inorganic turbidity may limit phytoplankton diversity (Duthie & Stout 1986), potentially confounding stimulatory effects of anthropogenic perturbations (e.g. increased nutrient loading) on phytoplankton diversity (Fig. 10). The higher benthic invertebrate diversity that was observed in Five Mile Lagoon suggests that reference condition systems contain diverse benthic habitats, with macrophyte beds covering a substantial proportion of the lake/lagoon bed. The diversity reference condition limits derived from the data in Fig. 10 are shown in Table 8.

3.2.5 Resilience limits

The presence and high abundance of cyanobacteria in the water column of lakes is considered to be an indicator of potential instability in lake functioning due to the ability of cyanobacteria to form blooms, and the ability of some species to fix N from the atmosphere and produce toxic metabolites. Cyanobacteria can dominate under conditions of strong N limitation (e.g. high P availability); therefore, a lack of cyanobacteria suggests a degree of resilience to cyanobacterial blooms in the system.

Cyanobacterial abundance in the water column of brackish lakes and lagoons correlated well with the two indicators of reference condition (Fig. 11). This clear pattern indicates that an appropriate cyanobacterial limit for brackish reference systems is 'below detection limit' or, in the case of this data analysis, < 500 cells/mL (Table 9).

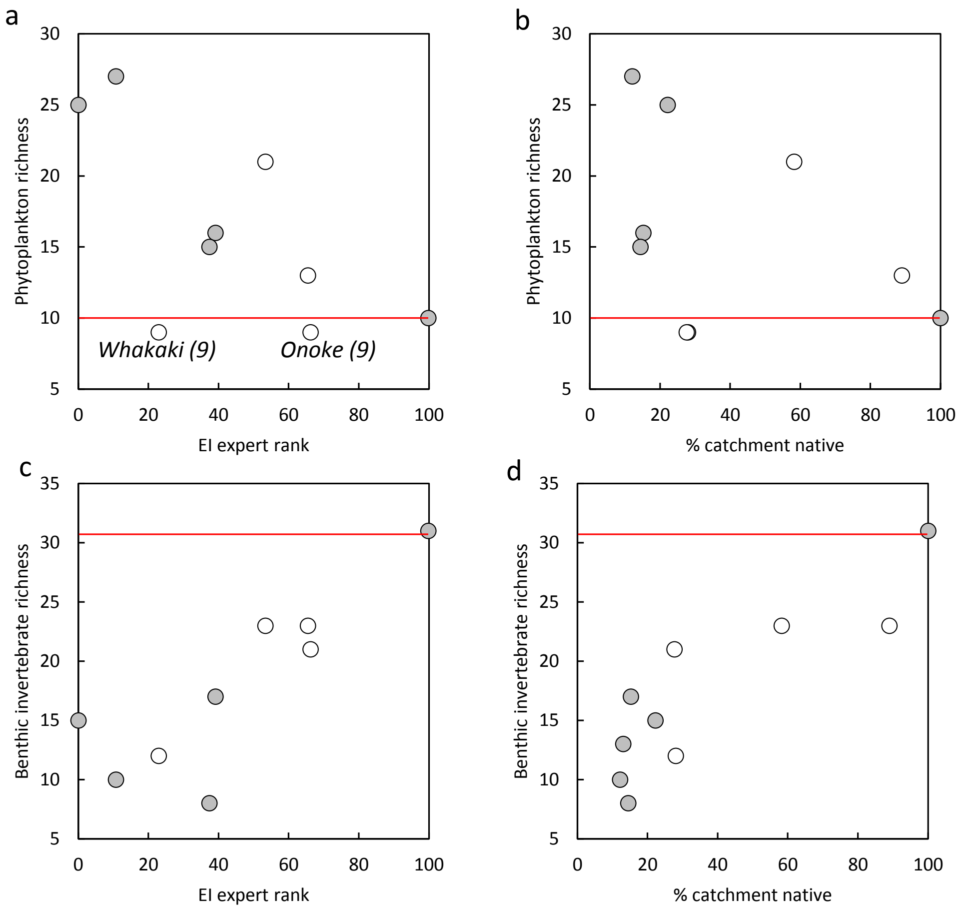

Figure 10. Correlations between measures of diversity and the indicators of reference condition in brackish lakes and lagoons. Red lines are proposed reference condition limits (see Table 8). Outliers are indicated on the graphs. Filled symbols represent South Island lakes and open symbols represent North Island lakes.

Table 8. Diversity reference condition limits for brackish lakes and lagoons. The percentage of non-reference lakes excluded by the limit is a measure of the strength of the limit in distinguishing reference lakes from non-reference lakes. '–' indicates that there was no relationship between the diversity and reference condition indicators and, therefore, no limit is proposed. Outliers are non-reference lakes/lagoons that have similar indicator values to the reference lake/lagoon. Since limits are based on only one lake, they are considered preliminary.

INDICATOR	UNIT	RANGE FOR ALL LAKES	LIMIT	% NON-REFERENCE LAKES EXCLUDED	OUTLIERS
Benthic invertebrates	Species richness	8–31	≥31	100%	None
Phytoplankton	Species richness	9–27	≤10	75%	Whakaki Lagoon, Lake Onoke
Metazooplankton	Species richness	2–5	–	–	N/A
Macrophytes	Species richness	0–4	–	–	N/A
Rotifers	Species richness	3–8	–	–	N/A
Native fish	Species richness	2–5	–	–	N/A

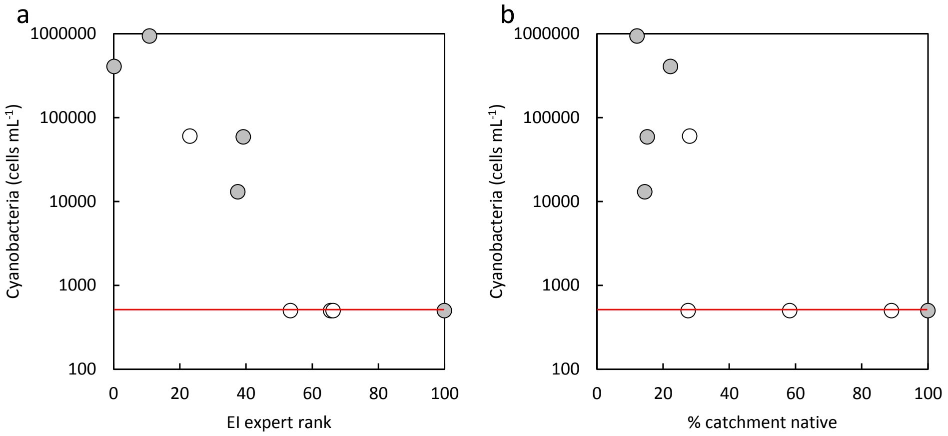

Figure 11. Correlations between cyanobacterial cell density and indicators of reference condition in brackish lakes and lagoons. Red lines are proposed reference condition limits (see Table 9). Filled symbols represent South Island lakes and open symbols represent North Island lakes.

Table 9. Resilience reference condition limits for brackish lakes and lagoons. The percentage of non-reference lakes excluded by the limit is a measure of the strength of the limit in distinguishing reference lakes from non-reference lakes. '–' indicates that there was no relationship between the resilience and reference condition indicators, and so no limit is proposed. Outliers are reference lakes that fall outside the deemed limits. Since limits are based on only one lake, they are considered preliminary.

INDICATOR	UNIT	RANGE FOR ALL LAKES	LIMIT	% NON-REFERENCE LAKES EXCLUDED	OUTLIERS
Cyanobacteria	Cells/mL	<500–940 000	<500	56%	None
Food chain length	Trophic levels	3.4–4.2	–	–	N/A
DIN:TP*		0.16–1.05	–	–	N/A

* Ratio of dissolved inorganic nitrogen to total phosphorus.

3.2.6 Proposed reference condition for brackish lakes/lagoons

The above analyses of brackish lakes and lagoons yielded a number of potentially useful limits for distinguishing reference condition from degraded conditions in such systems, the most useful of which are summarised in Table 10. These analyses identified reference condition limits for three of the four main components of EI: pristineness, diversity and resilience.

The approach developed here and in Schallenberg et al. (2011) proposes that lakes that are in a reference condition should meet all appropriate reference criteria across the four components of EI (although, in this case, diversity could be excluded). Five Mile Lagoon was the only lake examined here that was identified as being in reference condition, based on expert assessment and the amount of native catchment vegetation. This is also the only lake in the dataset that met all of the specific, quantitative reference condition criteria summarised in Table 10 – the other lakes met some of the reference criteria but not all of them.

3.3 Deep lakes

Vertical density stratification affects the fundamental functioning of lakes. Thus, lakes that are deep enough to undergo seasonal vertical stratification are functionally different from polymictic (not seasonally stratified) and meromictic (permanently stratified) lakes. Deep, seasonally stratified lakes have zones of productivity and decomposition within the water column and sediments, which are separated and defined by light, temperature and density gradients.

Table 10. Summary of the most useful limits for discriminating between reference condition and degraded brackish lakes and lagoons. Since these limits are derived based on only one reference condition lake, they are considered preliminary.

INDICATOR	UNIT	RANGE FOR ALL LAKES	LIMIT	% NON-REFERENCE LAKES EXCLUDED	OUTLIERS
Nativeness					
No relationships					
Pristineness					
Chlorophyll *a*	µg/L	0.3–80.0	≤0.3	100%	None
Total nitrogen	µg/L	128–2163	≤128	100%	None
Total phosphorus	µg/L	2.4–510.0	≤2.4	100%	None
Trophic Level Index		2.5–7.2	≤2.5	100%	None
% Ephemeroptera, Trichoptera and Odonata abundance (%ETO)	%	0.0–1.1	≥1.1	100%	None
Macrophyte depth limit	m	0.2–2.3	≥1.9	88%	Upper Lake Onoke
Diversity					
Benthic invertebrates	Species richness	8–31	≥31	100%	None
Phytoplankton	Species richness	9–27			
	≤10	75%	Whakaki Lagoon, Lake Onoke		
Resilience					
Cyanobacteria	Cells/mL	<500–940 000	≤500	56%	None

The differences in the biological and physicochemical characteristics of the open waters are enhanced during the summer months, when vertical mixing of the water column is restricted due to surface heating causing a vertical density gradient, whereas the water column is blended into one mixed layer after autumn cooling, when the lake 'turns over'. Thus, the coupling between benthic and pelagic processes is generally weaker in deep lakes than in shallow lakes. For these reasons, the reference condition for deep lakes was analysed separately from shallow lakes and brackish lakes and lagoons.

3.3.1 Reference lakes

There was a weak relationship between the two indicators of reference condition ('ecological integrity' and '% catchment in native vegetation') in deep lakes (Fig. 12). None of the lakes sampled were within the 90th percentile of either indicator variable and so the criterion for the selection of deep reference lakes was further relaxed to include lakes within the 74th percentiles (Tier 2 limits). Using this criterion, four South Island lakes were selected as provisionally representing a reference condition for deep lakes: Lakes Ohau (Canterbury), Wanaka (Otago), Wakatipu (Otago) and Pukaki (Canterbury). Some North Island lakes were also considered to have high EI, but their catchments had been substantially modified, disqualifying them from selection into the group of lakes exhibiting the reference condition.

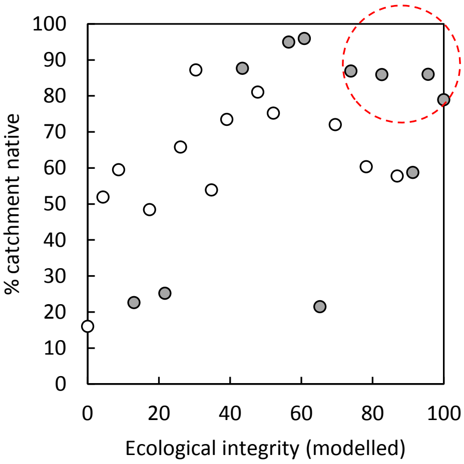

Figure 12. Correlation between the two measures of reference condition for deep lakes: the percentage of the catchment in native vegetation and the ecological integrity (EI) of the lake (scaled from 0 to 100%), as modelled in Özkundakci et al. (2014). The red circle demarcates potential Tier 2 reference lakes. Filled symbols represent South Island lakes and open symbols represent North Island lakes.

It should be noted that none of these proposed reference lakes should be considered to be in a pristine condition because all have undergone modifications to their functioning: Lakes Pukaki and Ohau are part of the Waitiaki hydroelectric scheme, and Lakes Wanaka and Wakatipu are part of the Clutha hydroelectric scheme. Lake Pukaki is particularly heavily modified because dams have raised its water level by 46 m, additional inflows have been diverted into the lake, and its current operating range (i.e. water level) spans 13.8 m. Lakes Ohau, Wakatipu and Wanaka are affected by downstream dams, which restrict or prevent the migration of native diadromous fish. All of the reference lakes also contain non-native salmonids, which have some impact on lake food webs (Rowe & Graynoth 2002).

3.3.2 Nativeness limits

No nativeness indicators were related to 'ecological integrity' or '% catchment in native vegetation' in the modelled deep lakes and, therefore, no limits defining nativeness reference condition could be determined (Table 11). However, the reference condition should always reflect 100% native communities due to the substantial alterations to ecosystem functioning that are caused by many non-native species (Champion et al. 2002; Closs et al. 2004). Therefore, this analysis considers that any departure from 100% native species composition constitutes a significant actual or potential departure from reference condition.

Table 11. Nativeness reference condition limits for deep lakes. '–' indicates that there was no relationship between the resilience and reference condition indicators and, therefore, no limit is proposed. Outliers are reference lakes that fall outside the deemed limits.

INDICATOR	UNIT	RANGE FOR ALL LAKES	RANGE FOR REFERENCE LAKES	LIMIT	% NON-REFERENCE LAKES EXCLUDED	OUTLIERS
Native macrophyte species	%	4–25	12–13	–	–	N/A
Native macrophyte condition index	%	13–93	14–81	–	–	N/A
Native macrophyte diversity score		1.2–5.0	2.3–5.0	–	–	N/A
Native fish species	%	1–5	1–4	–	–	N/A
Ratio of native:exotic fish species		0.3–4.0	1.3–2.0	–	–	N/A

3.3.3 Pristineness limits

Five pristineness indicator variables showed relationships with the indicators of reference condition (Fig. 13). These pristineness indicators were mainly related to eutrophication and water clarity. Schwarz et al. (2000) listed the diffuse light attenuation coefficients for a number of New Zealand lakes, providing sufficient data to allow the analysis of light attenuation as an indicator of pristineness. Unfortunately, however, although there were strong positive relationships between Secchi depth and both of the reference condition indicators, no information was available on the Secchi depths for the reference lakes and, therefore, no limit for reference condition could be determined for this indicator of water clarity (Fig. 13 & Table 12). Most of the indicators of pristineness are physicochemical variables. However, 'macrophyte maximum depth limit' is also considered an indicator of pristineness as this bioindicator integrates water clarity variations over time (Schwarz et al. 2000).

The presence of naturally occurring glacial flour and chromophoric dissolved organic matter (CDOM; also known as dissolved humic acids) can substantially reduce water clarity and macrophyte depth limits in pristine lakes. Thus, while reductions in water clarity are typical of degraded lakes, the influences of glacial flour and CDOM can reduce water clarity in relatively pristine lakes. Therefore, due to the presence of natural light attenuating substances, water clarity does not correlate strongly with indicators of EI in the deep lake dataset. For example, one of the reference lakes, Lake Pukaki, is so turbid as a result of glacial flour that no macrophytes have been reported in it. Lake Ohau is also affected by glacial flour, but macrophytes are present in the lake to a maximum depth of 22 m.

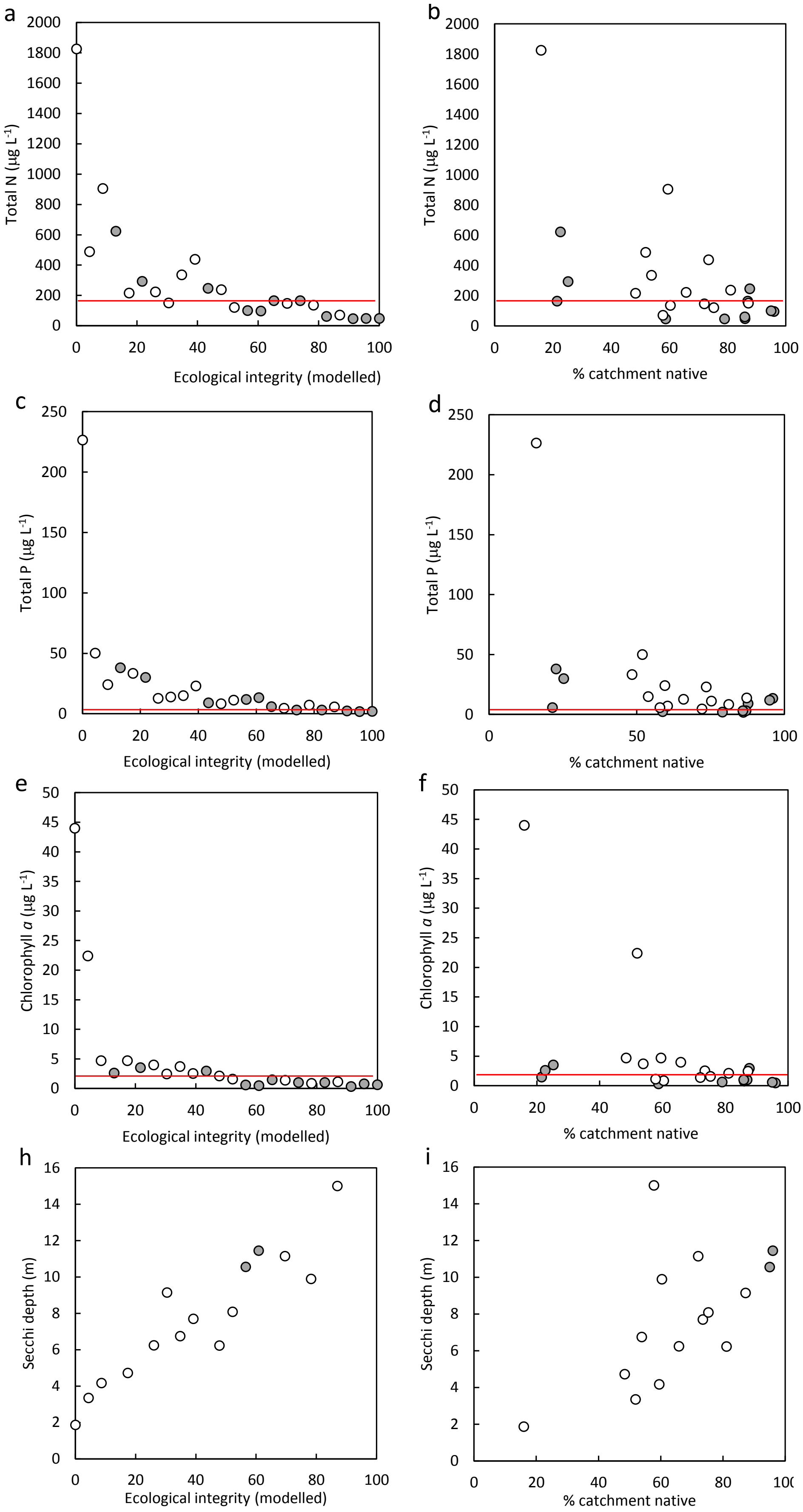

Figure 13. Correlations between measures of pristineness (*y*-axes) and indicators of reference condition (*x*-axes) in deep lakes. Red lines indicate proposed reference condition limits (see Table 12). Reference lakes that fall outside these limits are indicated on the graphs. Filled symbols represent South Island lakes and open symbols represent North Island lakes.

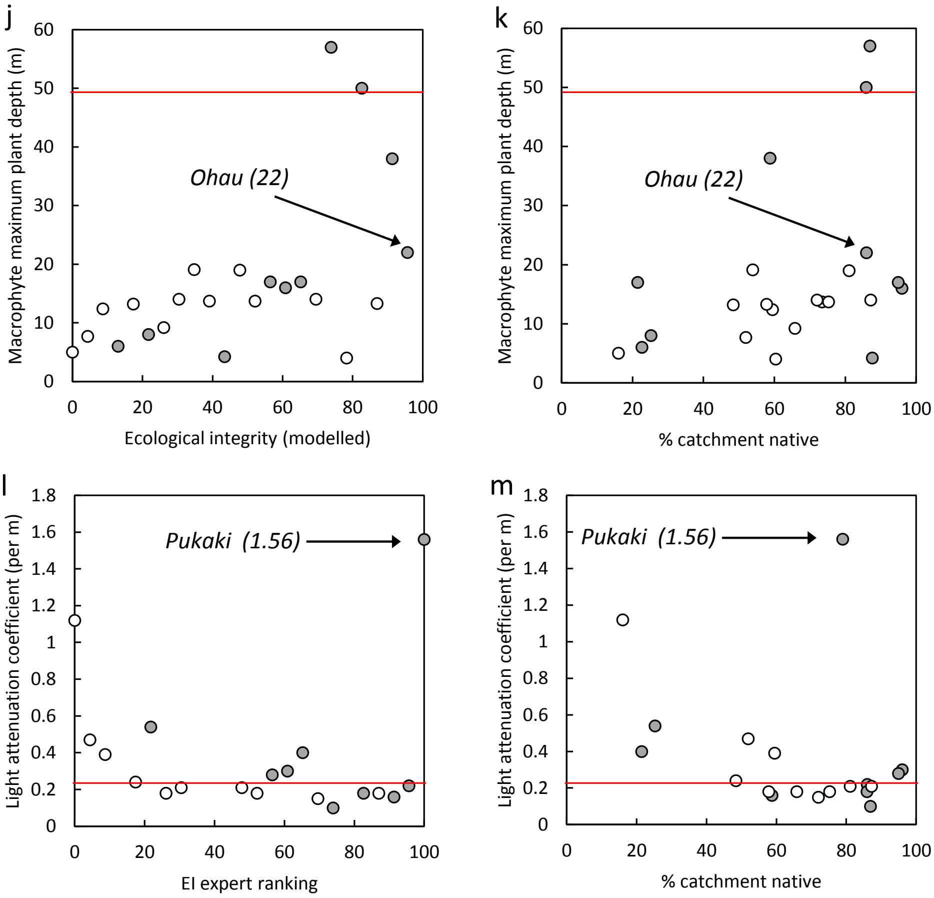

Figure 13 *continued.*

Table 12. Pristineness reference condition limits for deep lakes. The percentage of non-reference lakes excluded by the limit is a measure of the strength of the limit in distinguishing reference lakes from non-reference lakes. '–' indicates that there was no relationship between the resilience and reference condition indicators and, therefore, no limit is proposed.

INDICATOR	UNIT	RANGE FOR ALL LAKES	RANGE FOR REFERENCE LAKES	LIMIT	% NON-REFERENCE LAKES EXCLUDED	OUTLIER
Macrophyte depth limit	m	4–57	50–57	≥50*	100%	Lake Ohau, Lake Pukaki
Total phosphorus	µg/L	1.8–227.0	1.8–3.1	≤3.1	79%	
Chlorophyll *a*	µg/L	0.3–44.0	0.6–1.0	≤ 1	67%	
Total nitrogen	µg/L	46–1826	47–164	≤ 164	47%	
Light attenuation	per m	0.10–1.56	0.10–0.22	≤ 0.22	47%	Lake Pukaki
Secchi depth	m	1.9–15.0	4.7–15.0	–	–	–
N load	mg/m^2/y	109–13 418	666–6264	–	–	–
P load	mg/m^2/y	4–1178	53–491	–	–	–
LakeSPI score[†]		18–90	26–80	–	–	–
Invasive macrophyte index score	%	4–92	11–69	–	–	–
Invasive fish index score		0–92	0–73	–	–	–

[*] For lakes unaffected by glacial flour or chromophoric dissolved organic matter (CDOM). Lakes shallower than this should have macrophytes inhabiting the deepest basins.

[†] Lake Submerged Plant Indicators score.

The presence of CDOM in lakes also increases light attenuation (Rae et al. 2001) and decreases macrophyte maximum depth limits. Unfortunately, however, the relationship between humic staining and EI could not be assessed due to a lack of lakes with high CDOM concentrations in the dataset.

For lakes not affected by glacial flour and CDOM, the data suggested that a reference condition limit for 'macrophyte maximum depth limit' could be set at 50 m. By contrast, in reference lakes that are affected by glacial flour and CDOM, macrophyte depth limits will be reduced, but these will likely be lake specific and directly determined by the concentrations of glacial flour and CDOM in the lakes.

3.3.4 Diversity limits

Unlike for shallow freshwater lakes, some indicators of diversity were correlated with indicators of reference condition for deep lakes. The selected reference condition lakes tended to have lower diversities of phytoplankton and rotifers, and a higher diversity of macrophytes than the degraded lakes (Fig. 14). Lake Pukaki appears to be an outlier in terms of rotifer diversity and Lake Ohau appears to be an outlier in terms of macrophyte diversity. It is possible that the presence of glacial flour could have influenced the departures of these lakes from the overall trends. Macrophytes have not been reported in Lake Pukaki, probably due to the extremely sedimentation rate due to high inputs of glacial flour (see section 3.3.3) and the large lake level operating range (for hydroelectricity generation). Thus, this particular lake is not informative in terms of establishing a general reference condition for deep lakes with respect to macrophyte depth distributions.

The paucity of data available means that the diversity relationships shown in Fig. 14 and Table 13 are weak, and so the limits should be considered provisional until more data become available.

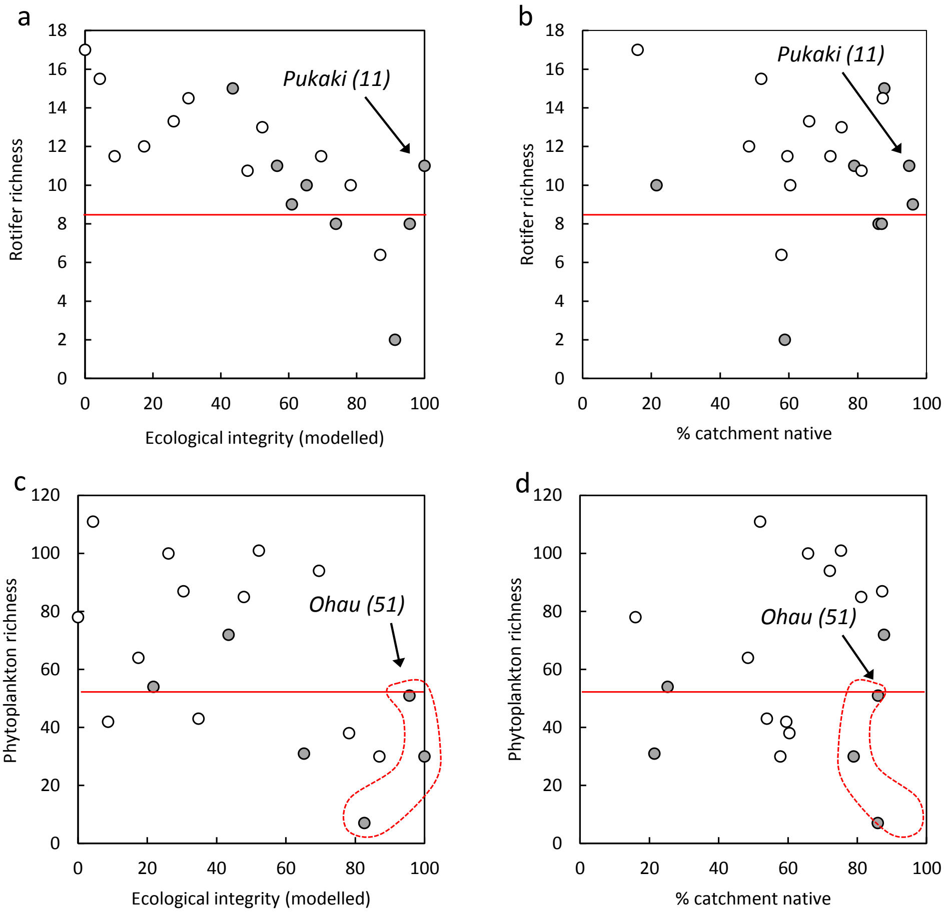

Figure 14. Correlations between measures of diversity (*y*-axes) and the indicators of reference condition (*x*-axes) in deep lakes. Red lines are proposed reference condition limits (see Table 13). Reference lakes that fall outside these limits are indicated on the graphs. The proposed reference lakes are enclosed in a red dashed envelope. Filled symbols represent South Island lakes and open symbols represent North Island lakes.

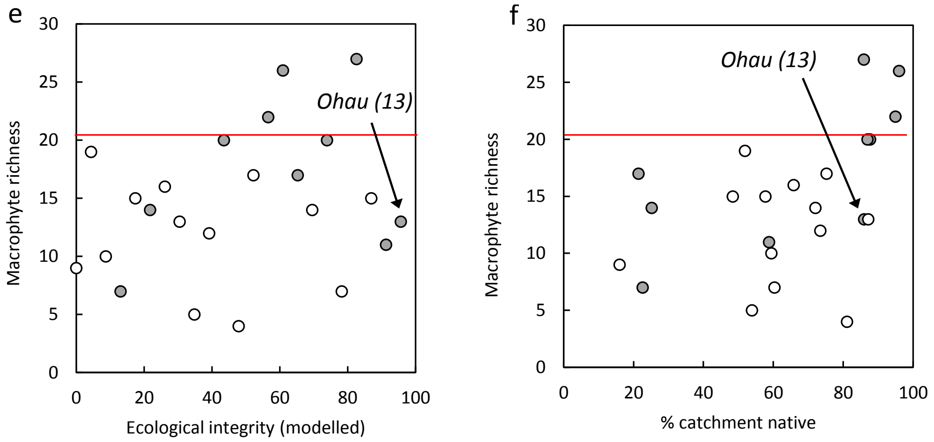

Figure 14 *continued.*

Table 13. Diversity reference condition limits for deep lakes. The percentage of non-reference lakes excluded by the limit is a measure of the strength of the limit in distinguishing reference lakes from non-reference lakes. '–' indicates that there was no relationship between the diversity and reference condition indicators and, therefore, no limit is proposed. Outliers are reference lakes that fall outside the deemed limits.

INDICATOR	UNIT	RANGE FOR ALL LAKES	RANGE FOR REFERENCE LAKES	LIMIT	% NON-REFERENCE LAKES EXCLUDED	OUTLIERS
Rotifer species	No.	2–17	8*	≤8	92%	Lake Pukaki
Macrophyte species	No.	7–27	14–17	≥20	85%	Lake Ohau
Phytoplankton species	No.	7–111	7–51	≤51	64%	
Fish species	No.	1–8	1–7	–	–	N/A
Benthic invertebrate taxa	No.	1–86	1–52	–	–	N/A

* With the exception of Lake Pukaki, the reference lakes for which data were available had a rotifer species richness of 8.

3.3.5 Resilience limits

The only resilience indicator that correlated with the two indicators of reference condition was the ratio of DIN:TP, which is indicative of the nutrient limitation status of lakes (Fig. 15 & Table 14). A DIN:TP ratio that is close to 1 implies a balanced availability of N and P to phytoplankton (Morris & Lewis 1988; M. Schallenberg, unpubl. data). The DIN:TP ratio of the selected reference lakes tended to be higher than that of degraded lakes, exceeding a limit of DIN:TP = 6, which indicates that phytoplankton growth rates in the reference lakes is likely to be P limited. This potentially also reflects low levels of P loading (internal and external), low levels of denitrification and efficient N recycling within the water columns of these lakes. Therefore, a high DIN:TP ratio potentially reflects a high resilience to cyanobacterial blooms and a lack of internal P loading - conditions which may increase the resilience of lakes to eutrophication.

No other indicators of resilience were available for the deep lakes dataset.

3.3.6 Proposed reference condition for deep lakes

The analyses presented above suggest a number of limits that could be indicative of reference condition for deep lakes. The most useful indicators reflect three of the four components of EI: pristineness, diversity and resilience. No relationships were identified between indicators of nativeness and reference condition. A summary of the most useful indicators and their proposed limits demarcating reference condition are presented in Table 15. It should be noted that since none of the proposed reference lakes are unmodified and Lake Pukaki can be considered heavily modified, the reference condition limits proposed here are probably not strict enough for deep glacial lakes. Furthermore, since all of the reference lakes are deep glacial lakes, the proposed limits probably do not strictly apply to smaller lakes and lakes not of glacial origin (e.g. volcanic lakes).

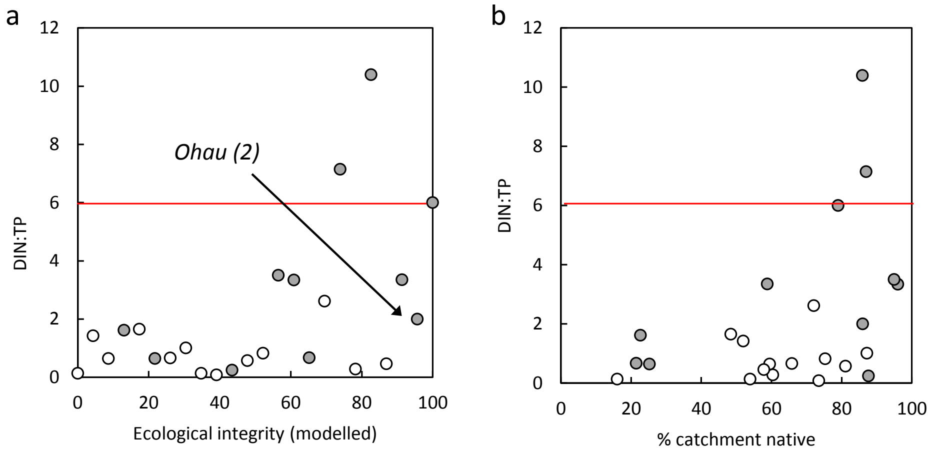

Figure 15. Correlations between a measure of resilience (the ratio of dissolved inorganic nitrogen to total phosphorus (DIN:TP) in the water column) and two indicators of reference condition (*x*-axes) in deep lakes. Red lines indicate the proposed reference condition limit (see Table 14). Reference lakes that fall outside this limit are indicated on the graphs. Filled symbols represent South Island lakes and open symbols represent North Island lakes.

Table 14. Resilience reference condition limits for deep lakes. The percentage of non-reference lakes excluded by the limit is a measure of the strength of the limit in distinguishing reference lakes from non-reference lakes. Outliers are reference lakes that fall outside the deemed limits.

INDICATOR	UNIT	RANGE FOR ALL LAKES	RANGE FOR REFERENCE LAKES	LIMIT	% NON-REFERENCE LAKES EXCLUDED	OUTLIERS
DIN:TP*		0.09–10.40	6.0–10.4	≥6	100%	Lake Ohau

* Ratio of dissolved inorganic nitrogen to total phosphorus.

Table 15. Summary of the most useful limits for discriminating between reference condition and degraded deep lakes.

INDICATOR	UNIT	RANGE FOR ALL LAKES	RANGE FOR REFERENCE LAKES	LIMIT	% NON-REFERENCE LAKES EXCLUDED	OUTLIER
Nativeness						
No relationships						
Pristineness						
Macrophyte depth limit	m	4–57	50–57	≥50*	100%	Lake Ohau
Total phosphorus	µg/L	1.8–227.0	1.8–3.1	≤3.1	79%	
Chlorophyll *a*	µg/L	0.3–44.0	0.6–1.0	≤1	67%	
Diversity						
Rotifers	Species richness	2–17	8[†]	≤8	92%	Lake Pukaki
Macrophytes	Species richness	7–27	14–17	≥20	85%	Lake Ohau
Phytoplankton	Species richness	7–111	7–51	≤51	64%	
Resilience						
DIN:TP[‡]		0.09–10.40	6.0–10.4	≥6	100%	Lake Ohau

* For lakes unaffected by glacial flour or chromophoric dissolved organic matter (CDOM). Lakes shallower than this should have macrophytes inhabiting the deepest basins.

[†] With the exception of Lake Pukaki, the reference lakes for which data were available had a rotifer species richness of 8.

[‡] Ratio of dissolved inorganic nitrogen to total phosphorus.

4. Reference conditions of lakes according to palaeolimnological studies

Palaeolimnological techniques examine and interpret sediments that have been deposited sequentially and have built up over time on lake beds. These sediments contain indicators (often termed 'proxies') that can be used to infer environmental conditions at the time of deposition on the lake bed. A number of considerations must be taken into account to accurately reconstruct palaeoenvironments using lake sediments. Firstly, strata in cores of lake bed material must be accurately aged, usually through careful radioisotopic dating of appropriate materials or by using indicators in the core material that derive from known dates (e.g. the presence of *Pinus radiata* pollen grains can indicate the time of first pollen production of local pine trees). Secondly, the depositional environment must allow a continuous record of deposition to occur – the erosion of previously sedimented materials greatly complicates interpretation. Thirdly, the indicators or proxies must not migrate or decompose substantially within the sedimentary environment. Finally, bioturbation (the disturbance and mixing of sediment layers by organisms) must be absent or minimised in the depositional environment. If these conditions are met, palaeolimnological techniques can be useful for reconstructing past environmental conditions and, thus, also lend themselves to the determination of the reference conditions for lakes.

Palaeolimnology has been practised in New Zealand for several decades. Previous studies have reconstructed catchment vegetation and anthropogenic changes in land cover (e.g. McWethy et al. 2009), while other studies have reconstructed the impacts of human disturbance on lake conditions (e.g. phytoplankton biomass and community structure, and eutrophication), including inferring conditions within the lakes prior to human and European influence.

Below, the results of these studies are summarised, focusing on the reconstructions of lake conditions just prior to Māori and European influence.

4.1 Shallow freshwater lakes

4.1.1 Lake Waihola

Lake Waihola is a shallow (c. 2 m maximum depth) coastal lake in South Otago, which has a surface area of 5.4 km^2. It is tidal and occasionally receives saline water from its tidal connection to the Taieri Estuary. Although this lake contains macrophytes throughout, it is subject to substantial wind-induced sediment resuspension. Schallenberg et al. (2012) obtained sediment cores from the deepest basin of the lake and undertook a sediment dating analysis from the mid-Holocene to the present. Their study revealed numerous changes in the lake over that time period. During the mid-Holocene, the lake had estuarine characteristics and extensive beds of the estuarine bivalve *Austrovenus stutchburyi*, indicating that the mean salinity must have been at least 14 ppt. This contrasts with the salinity of the lake today, which is too fresh for *A. stutchburyi*, but allows freshwater mussels (*Echyridella menzeisii*) to inhabit it. Diatom analysis confirmed that there has been a gradual decrease in salinity from c. 4000 years ago to the present.

Schallenberg et al.'s (2012) study also examined the rates of sediment infilling, which were shown to have increased by c. 30× since European settlement of the catchment c. 160 years ago. This represents a dramatic increase in the influence of erosion, and the flows of sediment and nutrients from the catchment to the lake since the 1850s. The drainage of a significant proportion of a large wetland area that used to buffer the lake from its catchment and reduce water velocities through the system has undoubtedly also affected the condition and functioning of this lake ecosystem. For example, the once extensive wetlands probably contributed more humic acids to the water of the lake. The authors compared their reconstruction of the changes in sediment infilling rates with infilling rates of other estuaries and coastal lakes around New Zealand, and found that the increase in sediment infilling calculated from the Waihola core is roughly consistent with changes in infilling rates due to European land use changes that have been calculated by other researchers for estuaries and coastal lakes elsewhere in New Zealand.

4.1.2 Lake Taumatawhana

Lake Taumatawhana is a very small (c. 1 ha) dune lake situated on the central Aupouri Peninsula of Northland. The lake is at least 4500 years old, and its present hydrology is regulated by seepage, precipitation and evaporation. Today, the catchment of the lake is dominated by *Leptospermum* scrub, with scattered *Coprosma* spp., *Pomaderris* spp., cabbage trees (*Cordyline australis)* and exotic wattles (*Acacia* spp.) on the eastern side of the catchment, and by pasture on the northern, western and southern sides of the catchment. *Pinus radiata* plantations can also be found on some of the drier hilltops in the region (Striewski 1999).

Elliot et al. (1995) carried out a suite of physicochemical measurements, and pollen and charcoal analyses based on sediment strata from a core that was obtained from the deepest part of the lake (6.5 m depth). They found that the sediment characteristics reflected a very clear abrupt transition from a long period of fine sediment deposition and arboreal pollen deposition, to coarser sediment with high charcoal content beginning c. 900 years before present (ybp). This change in sediment characteristics was considered to reflect a period of intense soil erosion and vegetation change in the catchment as a result of Polynesian settlement in the area. Following this, the sediment grain size (but not pollen or charcoal) briefly reverted to conditions prior to this time, but then another phase of intense soil erosion (reflected by all sediment parameters) began c. 550 ybp, which intensified c. 400 ybp and continued to be indicated in even the most recent sediments.

4.1.3 Lake Emma and Maori Lakes East

Lake Emma and Māori Lakes East are small, shallow lakes in the uplands of South Canterbury. Analysis of cores from the Lake Emma indicated that prior to human influence, the lake was an oligotrophic, clear water lake, with a macrophyte community that was dominated by *Isotetes* sp. and *Nitella*. (Woodward et al. 2014). However, in response to apparent effects of vegetation burning in the catchment by early Māori, water level rose (Woodward et al. 2014) and *Chara* sp. became a component of the macrophyte community. The period of initial European influence (farming) in the catchment resulted in a number of rapid changes to the lake, including an increase in lake productivity and a loss of charophytes from the lake, the dominance of a chironomid species that is associated with eutrophic conditions, and an increase in the planktonic alga *Botrycoccus* sp., which is also indicative of an increase in lake productivity. An increase in turbidity at this time is also suggested by the appearance of statoblasts of the bryzoan *Plumatella* sp., which is a filter-feeding organism.

In around the 1950s, the waters of Lake Emma became less turbid and less productive, possibly in response to less frequent burning of the catchment vegetation, less use of superphosphate fertiliser in the catchment or the invasion of the lake by the exotic macrophyte *Elodea canadensis,* which was the dominant macrophyte in the lake in 2007 (De Winton 2008). The presence of dense beds of this exotic macrophyte may have reduced the availability of nutrients for phytoplankton and initiated a recovery to a relatively clear water state from its inferred pre-1950s state of high turbidity and low macrophyte abundance. Note however, that Lake Emma recently exhibited classic regime shifting behaviour (Schallenberg & Sorrell 2009), alternating between a clear water and turbid state within a period of 1–2 years (De Winton 2008).

The state of the lake's macrophyte community in 2007 was characterised by a Lake Submerged Plant Indicators (LakeSPI) score of 37 (native condition index = 45; invasive condition index = 69), which is much lower than its inferred reference condition LakeSPI value of 100 (native condition index = 100; invasive condition index = 0; de Winton 2008).

The chronology of the sediment cores from Māori Lakes East was problematic; however, there was also evidence that the water level increased after Māori arrived and deforested the catchment. In both lakes, the impacts of European arrival were considered minor compared with the impacts on the lakes of forest clearance associated with Māori arrival (Woodward et al. 2014).

4.2 Brackish lakes/lagoons

4.2.1 Waituna Lagoon

Waituna Lagoon is a barrier bar lagoon or intermittently closed and open lake/lagoon (ICOLL) in Southland, which has been subject to managed openings to the sea for the last c. 100 years. This lagoon alternates between being a freshwater lake and a tidal lagoon with a salinity near that of sea water (Schallenberg et al. 2010).

Cosgrove (2011) undertook a palaeolimnological study to determine the natural opening regime of the lake and to assess whether the dominant macrophytes in the lagoon at present (the seagrasses *Ruppia polycarpa* and *R. megacarpa*, and the freshwater macrophyte *Myriophyllum triphyllum*) were also present prior to manipulation of the hydrology of the ICOLL.

While radiosiotopic dating of the core was difficult, some chronological inferences were made based on indicator pollen in the core. The opening and closing of the lagoon occurred at a far lower frequency prior to management of the water level of the ICOLL, suggesting that natural opening was a rare occurrence, but one that had a large influence on the ICOLL. Thus, the results indicated that the alternate states of freshwater v. marine influence were stronger and more persistent, but less frequent prior to onset of management of the ICOLL opening.

Cosgrove (2011) also found pollen grains of the macrophytes that are currently dominant in sediment that pre-dated anthropogenic management of the ICOLL, suggesting that these macrophytes were a natural component of the ICOLL ecosystem and have not appeared in the ICOLL as a result of water level management.

4.2.2 Lake Waihola

Lake Waihola is a coastal lake in South Otago, which receives occasional saline inputs from the Taieri Estuary. A palaeolimnological investigation of this lake is described in section 4.1.1 above.

4.2.3 Lake Forsyth (Wairewa)

Lake Forsyth (Wairewa) is a shallow (< 4 m deep), brackish barrier bar lagoon or ICOLL located in Canterbury. Woodward & Shulmeister (2005) analysed a core from the lake and reconstructed its environmental history from the mid-Holocene to the present time. They found that the lake was a tidal estuary until the 1840s, at which time a permanent gravel barrier bar formed across its mouth and it became a seepage lake, which resulted in major changes to its salinity and water levels. The gravel barrier began to be opened mechanically as early as 1866, which marked the start of a period of lake level management whereby the gravel barrier was opened to alleviate the flooding of low-lying farmland – a practice that continues to the present day. Thus, a major natural change occurred in this system (shift from tidal estuary to coastal seepage lake) at the onset of European settlement in the area, making it difficult to establish a meaningful and appropriate reference condition for this system.

4.2.4 Lake Ellesmere (Te Waihora)

Lake Ellesmere (Te Waihora) is a large (c. 200 km^2), shallow (< 3 m deep) eutrophic ICOLL located southwest of the Banks Peninsula (Canterbury). Kitto (2010) obtained sediment cores from the deepest basin in Lake Ellesmere (Te Waihora) with the aim of describing the lake's environmental history, hydrology and catchment. This lake is c. 7500 years old and has undergone extensive changes during its past, including at least one natural temporary diversion of the Waimakariri River into the lake. Unfortunately, the chronological information in the cores from Lake Ellesmere (Te Waihora) provided by ^{210}Pb, ^{137}Cs, ^{14}C and indicator pollen was difficult to reconcile, making it impossible to arrive at a definitive chronology of the core. However, it was concluded that the lake was a relatively stable environment between c. 500 ybp and European settlement in the early 1800s, which was characterised by eutrophic, freshwater conditions, with a higher water level and a larger surface area than the current ICOLL.

Following European settlement in the area in the 1870s, the deforestation of Banks Peninsula resulted in increased sediment infilling and turbidity. The salinity then increased from around 1901, when the barrier bar began to be regularly opened by the local farming community to maintain a lower water level, allowing an increased marine influence on the lake. This marked the start of a major transition from a deeper, low-nutrient, freshwater lake to a shallower, brackish, nutrient-enriched lagoon (Kitto 2010). This transition was completed in 1968, when a powerful storm resulted in the uprooting of the remaining macrophyte beds and the resuspension of lake bed sediments, drastically reducing the water clarity. Since this time, significant macrophyte beds have not been able to re-establish in the lake and increasing nutrient loading from intensifying land use now fuels regular phytoplankton blooms, resulting in a supertrophic status.

4.2.5 Wainono Lagoon

Wainono Lagoon is a barrier bar lake/lagoon in South Canterbury. Its hydrology was altered in 1910 by the construction of a device traversing the barrier bar that enhances outflow to the sea. Schallenberg & Saulnier-Talbot (2016) obtained sediment cores from the centre of the lake to ascertain how the lake changed in response to the arrival of European settlers, and the subsequent development of the catchment for agriculture and its recent intensification. The authors analysed diatom and macrofossil proxies for environmental change, as well as a number of physicochemical attributes of the sediment strata, and obtained sediment core chronologies from ^{210}Pb and ^{137}Cs analyses.

This study showed that the lake underwent major transformations from a predominantly freshwater coastal lake containing freshwater diatoms, charophytes, *Ruppia* spp. and the freshwater zooplankton *Daphnia* spp. in the early years of European colonisation, to a devegetated, eutrophic, brackish lagoon with high phytoplankton biomass that was represented largely by coastal diatoms and a hypertrophic status by the 2000s. Salinisation and sediment infilling rates increased in the 20th century, but the main degradation and loss of EI occurred between the 1970s and the present day. This reflects an ecological trajectory whereby the lake initially showed ecological resistance to hydrological and land use pressures, but then appears to have undergone a rapid ecological regime shift in the past 30–40 years. This trajectory is similar to those inferred for many other coastal lakes/lagoons in New Zealand and elsewhere, and the rapidity of change inferred in Wainono Lagoon in the latter half of the 20th century mimics the pattern of rapid degradation that has been widely reported in similar systems around the world – known as 'The Great Acceleration' (Kidwell 2015).

4.3 Deep lakes

4.3.1 Lakes Tūtira and Rotonuiaha

Lakes Tūtira (surface area = 1.8 km^2, maximum depth = 42 m) and Rotonuiaha (surface area = 0.44 km^2, maximum depth = 30 m) are located in northern Hawke's Bay. These lakes are located in steep hill terrain with highly erodible soils. Both lakes have been affected by deforestation, agriculture, volcanic eruptions, and severe climatic and seismic events (Orpin et al. 2010). Wilmshurst (1997) obtained 6-m-long cores from the deepest sites in each lake and analysed these for pollen, charcoal and tephra markers to obtain chronologies and sedimentation histories. These analyses indicated that sediment infilling rates have increased since pre-human times

(Table 16). Burning of the catchments by early Māori increased the sediment infilling rates of these lakes by c. 60–65% in this highly erodible terrain. European land use changes then led to c. 4- to 5-fold additional increases in the sediment infilling rates.

Table 16. Mean sediment infilling rates during different periods of occupation in Lakes Tūtira and Rotonuiaha (after Wilmshurst 1997).

LAKE	SEDIMENT INFILLING RATE (mm/y)		
	PASTURE (EUROPEAN)	BRACKEN (POLYNESIAN)	FOREST (PRE-HUMAN)
Tūtira	13.8	2.7	1.7
Rotonuiaha	10.5	2.6	1.7

4.3.2 Lake Grasmere

Grasmere is a 15-m-deep glacial lake situated 600 m a.s.l. near Cass, Canterbury. The lake has a surface area of 0.67 km^2, and has inlet streams and an outlet. The catchment is predominantly tussock grassland, c. 50% of which is grazed. A stand of mountain beech (*Fuscospora cliffortioides*) is in the catchment, which was the dominant vegetation in the catchment prior to the arrival of the first Māori, who instigated large-scale changes in the vegetation by burning the area.

Recent data indicate that this lake is oligotrophic (Verburg et al. 2010). However, since the 1970s the lake has been described as mesotrophic, eutrophic and supertrophic based on various indicators (Schakau 1993). Stark (1981) described the presence of extensive macrophyte beds that were dominated by the invasive *Elodea canadensis* down to 7 m depth. This macrophyte was also recorded in neighbouring Lake Sarah in 1934–35 (Flint 1938) and may have been in Lake Grasmere at that time.

Schakau (1991; 1993) obtained a 3.26-m-long sediment core from Lake Grasmere and carried out a range of investigations, including the analysis of fossil chironomids, zooplankton and plant pigments. This showed that environmental conditions varied markedly between the pre-human period and c. 6000 ybp. Productivity was relatively high in pre-human times, but possibly not as high as during Polynesian times or post-European settlement of the area.

Schakau (1993) found that the productivity of the lake was relatively high following Polynesian arrival, as reflected in the high organic matter, pigment, diatom, chironomid larvae and cladoceran contents of the sediments. Macrophyte growth was also probably extensive during this time, as indicated by the high densities of macrophyte-associated chironomids and cladocerans. Nutrient inputs could have been relatively high as a result of burning of the catchment vegetation and subsequent soil erosion.

The sediments of the early Polynesian period were succeeded by sediments that contained lower organic matter and pigment concentrations, and animal fossil densities, and a shift in the cladoceran and diatom contents that indicated greater productivity in the open waters as opposed to in the macrophyte beds.

The youngest sediments, which represent the post-European era, again had higher pigment concentrations, and higher densities of diatoms and cladocerans, indicating a return to relatively high productivity, as described by Schakau (1993):

> *The uppermost 6 cm [of sediments] were deposited after the arrival of the European settlers as shown by the presence of* Pinus *pollen in the sediments.* Chironomus *and in the Chydoridae,* Chydorus, *were the dominant faunal components. Both species can occur in abundance in more eutrophic lakes and their increased proportion in the top sediments might indicate changed trophic conditions in the lake as a result of the activities of the European settlers. But even with a possible increase in the productivity of the lake, the low organic matter content of the sediments in this zone indicated that the mineral sediment accumulation remained relatively large during*

> *this period, possibly caused by human-induced erosion (McSaveney & Whitehouse, 1989). The appearance of* Diatoma elongatum *in the top sediments might point to a rise of the water level to its present depth in this zone (possibly caused by further damming of the lake by the New Ribbonwood Fan).*

The first appearance of *Pinus radiata* pollen combined with ^{14}C dating suggested that the average modern sediment infilling rate was c. 0.46 mm/y (since 1857).

4.3.3 Lake Pupuke

Lake Pupuke is a crater lake that has a surface area of 1.1 km^2 and a maximum depth of 57 m. Based on recorded historical information, the lake had become eutrophic by the 1920s and has experienced nuisance macrophyte proliferations in its littoral zone since 1895. Augustinas et al. (2006) obtained an 84-cm-long core from the site of maximum depth and used a range of palaeolimnological measurements and proxies to interpret recent environmental changes in the lake. The sediment core was dated using ^{210}Pb, indicator pollen and known dates of the addition of the algicide copper sulphate, which could be clearly seen in sediment copper profiles.

Their study showed that the modern mean sediment accumulation rate based on ^{210}Pb was 4.45 mm/y. The basal 4 cm of the core contained no exotic pollen grains, indicating that it pre-dated European modification of the surrounding landscape, which is thought to have commenced in the 1840s. Analysis of elemental ratios in the core indicated that anthropogenic sediment erosion has contributed little to the sediment load of the lake. However, the ratios of total organic carbon to total nitrogen (TOC:TN) and stable carbon isotopes confirmed that eutrophication occurred immediately upon conversion of the catchment to dairying in the 1840s and again in c. 1935 (which was corroborated by the recorded use of algicide in the lake at that time). These inferences were supported by changes in the diatom community from one dominated by *Cyclotella stelligera*, to a community that was increasingly dominated by eutrophic species. Changes in the diatom community structure were used to infer changes in the lake trophic state, and the use of diatom transfer functions developed for New Zealand lakes inferred that the pre-European condition of the lake reflected the conditions shown in Table 17.

Table 17. Diatom-inferred water quality for Lake Pupuke (after Augustinas et al. 2006). Trophic states are also indicated, as calculated by Burns et al. (2000).

WATER QUALITY VARIABLE	IMMEDIATE PRE-EUROPEAN CONDITION (c. 1813)	PEAK SINCE 1840	NOTE
Chlorophyll *a* (µg/L)	4 (mesotrophic)	8 (eutrophic)	Mean isothermal concentration
Total phosphorus (µg/L)	10 (mesotrophic)	25 (eutrophic)	Mean annual concentration
Dissolved reactive phosphorus (µg/L)	2	6	Mean isothermal concentration
pH	7.7	8.0	Mean annual level

4.3.4 Lake Okaro

Lake Okaro is a small, deep, supertrophic, volcanic crater lake located in the Bay of Plenty region. Wood et al. (2008) collected a 36-cm-long sediment core from the deepest part of Lake Okaro (maximum depth = 15 m, surface area = 0.33 km^2). Their analysis focused on the historical presence and community structure of cyanobacteria in the lake. The sediment core was dated using the distinctive Tarawera tephra layer, which was deposited in 1886, and the chronology of the core was also calibrated against ^{210}Pb dates from another core taken from the same site. A number of cyanobacterial taxa were germinated from sediments dating back to 1886 and DNA fragments from a number of cyanobacteria were also found throughout the core, indicating that cyanobacteria have been a component of the phytoplankton community in this lake since this time. While the species diversity that was determined by germination and the presence of DNA increased upcore, this pattern could be due to diagenetic processes and so may not necessarily indicate increases in recent years. The authors also found that some species that were germinated from old sediment produced cyanobacterial toxins in culture and that species that are known to produce toxins were present throughout the core since 1886.

4.3.5 Lake Rotorua, North Island

In 1978, a 104-cm-long core was collected from a depth of 20 m in Lake Rotorua, which was analysed for diatoms and phytoplankton pigments (Rawlence 1984). The core was dated using the distinctive Tarawera Tephra layer deposited in 1886, which constituted the bottom of the core below a depth of 82 cm. Rawlence (1984) found that both the concentration of chlorophyll *a* and the density of diatoms waxed and waned since 1886, but there were clear peaks in each near the top of the core, consistent with eutrophication as a result of sewage discharges and agricultural intensification in the catchment at the time. The diatom community also became more diverse during this era. Rawlence (1984) also found that the variability in pigment concentration and diatom density increased upcore, which he interpreted as indicating that the phytoplankton biomass became more variable as eutrophication proceeded. *Melosira granulata* dominated the diatom community until c. 1965, when other diatoms began to dominate the phytoplankton community, including *Melosira granulata* var. *anguistissima*, which prefers eutrophic conditions.

4.3.6 Lake Rotoiti, North Island

Rawlence (1985) obtained two 40-cm-long cores from a depth of 60 m in Lake Rotoiti and analysed these for diatoms and phytoplankton pigments. Again, the cores were dated using the Tarawera tephra layer, which was deposited in 1886. Since that time, chlorophyll *a* has shown a relatively gradual increase, with a large peak observable at a depth of 3–4 cm, which corresponds to the early to mid-1960s. The density of diatoms in this lake also peaked near the top of the cores (at 6 cm), but at a slightly earlier date than the concentration of pigments (4 cm). Lake Rotoiti was slower to respond to sewage inputs and changes to the catchment than Lake Rotorua and was classified as oligo-mesotrophic at the time of sampling (whereas Lake Rotorua was classified as eutrophic).

4.3.7 Lake Clearwater

Lake Clearwater is a small lake with a maximum depth of 19 m, in the uplands of South Canterbury. Sediment cores from this lake indicated that deforestation associated with Māori arrival resulted in increased water levels and increased transport of catchment soils into the lake (Woodward et al. 2014). Difficulties in developing a robust chronology and a clear reconstruction from the sediment core in this lake was probably due to its retrieval from near the shoreline as opposed to the depositional basin.

4.4 Palaeolimnology-inferred reference conditions for lakes

A summary of inferences concerning the reference conditions for lakes based on these palaeolimnological studies is presented in Table 18.

Table 18. Reference conditions for shallow freshwater lakes, brackish lakes and lagoons, and deep lakes as inferred from palaeolimnological studies. Unless otherwise stated, interpretations are compared with modern conditions.

PRE-POLYNESIAN CONDITION	PRE-EUROPEAN CONDITION	LAKES/LAGOONS INTERPRETED
Shallow freshwater lakes		
• Very low rates of sediment and nutrient inputs from the catchment • Very low productivity and turbidity • Extensive native macrophyte beds dominated by *Nitella* sp. (Lake Emma)	• Low rates of sediment and nutrient inputs from the catchment • Low productivity and turbidity • Shift in macrophyte community to mixed charophytes (Lake Emma)	• Lake Waihola • Lake Taumatawhana • Lake Emma
Brackish lakes/lagoons		
• Less frequent openings of barrier bars where they existed; deeper lakes with lower salinity (Lake Ellesmere (Te Waihora) • More pronounced and persistent marine and freshwater phases, or an absence of marine influences (Lake Waituna, Lake Ellesmere (Te Waihora)) • Presence of extensive macrophyte beds (seagrasses and/or freshwater macrophytes) • Very low rates of sediment and nutrient inputs from the catchment	• Less frequent openings of barrie bars where they existed • More pronounced and persistent marine and freshwater phases, or an absence of marine influences (Lake Waituna, Lake Ellesmere (Te Waihora)) • Presence of extensive macrophyte beds (seagrasses and/or freshwater macrophytes) (Lake Ellesmere (Te Waihora), Wainono Lagoon) • Eutrophic but relatively clear water • Low rates of sediment and nutrient inputs from the catchment (Lake Ellesmere (Te Waihora), Lake Waihola) • Freshwater system as indicated by diatoms and/or the presence of *Daphnia* spp. (Wainono Lagoon, Lake Waihola)	• Lake Waihola • Waituna Lagoon • Lake Ellesmere (Te Waihora) • Wainono Lagoon
Deep lakes		
• Oligotrophic • Very low rates of sediment and nutrient inputs from the catchment	• Oligotrophic to mesotrophic (Lake Pupuke) • Slightly increased (but still low sediment and nutrient inputs from the catchment • Slightly increased (but still low) levels of phytoplankton • Clear water and presence of macrophyte beds • Increase in macrophyte productivity (Lake Grasmere)	• Lake Tutira • Lake Rotonuiaha • Lake Grasmere • Lake Pupuke

5. Strengths and limitations of the two approaches

5.1 Survey-calibration approach

The overall aim of this study was to quantify the pre-human or pre-European reference conditions for New Zealand lakes. Both the survey-calibration and the palaeolimnological approaches were able to detect changes in the EI of New Zealand lakes due to anthropogenic impacts. However, the survey-calibration approach successfully established quantitative limits describing reference conditions for a number of key variables. This method was useful for determining general or average reference conditions for the three classes of lakes, but the presence of outliers indicated that characteristics that are specific to individual lakes in the dataset sometimes influence reference conditions in particular ways (e.g. Six Foot Lake, Lake Pukaki). This conclusion was supported by the examination of historical reconstructions of sediment cores in lakes using palaeolimnological techniques, which suggested that lake-specific characteristics often play a role in determining how lakes respond to anthropogenic pressures over time. They also undoubtedly influence the consistency of reference conditions across lakes because variation in natural factors that affect water clarity can result in large differences in macrophyte distributions and other key drivers and indicators of lake condition.

For the shallow freshwater and brackish lakes, a strength of the survey-calibration approach applied in this study was the fact that all lakes were sampled at a similar time of year, by the same researchers, using the same methodologies. In addition, the dataset exhibited excellent national coverage, and very intensive and comprehensive sampling of the lakes was undertaken to cover a wide range of EI indicators. The EI scores were also robust and somewhat independent from the indicator data, as they were obtained by averaging the assessments of three experts who visited the lakes and assessed EI based on their experience prior to analysing the data. By contrast, for the deep lakes dataset, EI was modelled based on some of the indicator data and so the scores were not statistically independent from some of the indicator data. However, a strength of the deep lakes dataset was that it contained temporally averaged data for variables for which time series were available.

While the survey-calibration approach yielded some useful quantitative results, the method as used in this study also had a number of limitations that should be considered when interpreting reference condition limits.

The shallow freshwater lake, and brackish lake and lagoon data were obtained from single samples collected at the end of summer. Therefore, the method did not account for temporal variability in the data for these classes of lakes. Furthermore, only one brackish lake/lagoon in the dataset was deemed to reflect reference condition, which limited the robustness of the reference limits.

A three-class lake typology (shallow freshwater lakes, brackish lakes and lagoons, and deep lakes) was applied to improve the specificity of the method and the accuracy of the limits. However, this typology may have been too generalised for detecting useful trends in some indicators. Therefore, as data become available on a wider range of lakes, more detailed lake classification systems, such as the Freshwater Ecosystems of New Zealand database (Leathwick et al. 2010), may be used to further stratify the reference condition limit analyses conducted here. This could enable limits to be determined for subgroups of lakes, such as those influenced by natural turbidity (e.g. glacial flour, CDOM).

The survey-calibration approach used in this report also relied on general trends, and so outlier lakes that did not fit the general trends were excluded from the limit analyses. At this stage, it is not possible to predict which new lakes these generalised limits will or will not apply to, and although suggested confounding factors have been discussed where possible, these remain to be tested against an expanded dataset.

5.2 Palaeolimnological approach

An important strength of the palaeolimnological approach was that it attempted to assess the reference condition for individual lakes, regardless of how typical they were. However, this also meant that although some general trends were apparent within the groups of lakes and some useful information on reference conditions could be gleaned from the various studies, few quantitative limits could be generalised across lakes due to the qualitative nature of the descriptions of reference conditions.

As with the survey-calibration approach, a three-class lake typology was applied to improve the reliability of the method. However, the shallow freshwater and brackish lake classes contained few lakes within them, making generalised inferences difficult. Furthermore, palaeolimnology depends on the effective dating of sediment strata, which is more problematic for shallow lakes as a result of issues such as sediment erosion (resuspension), discontinuous sedimentation and bioturbation of the sediment layers. Thus, this approach generally lends itself to studies on deep lakes, although some exceptions do exist (e.g. Schallenberg et al. 2012).

Most of the palaeolimnological studies examined in this report were only able to provide qualitative information on reference conditions. However, this approach can also provide quantitative data if statistical hindcasting models (e.g. transfer functions) can be applied to microfossil data, such as reconstructed diatom or chironomid assemblages. A number of transfer functions currently exist for New Zealand lakes and these pave the way for more quantitative applications of palaeolimnological techniques. For example, Cochran (2002) provided a diatom transfer function for reconstructing salinity levels from fossil diatom assemblages, Reid (2005) provided diatom transfer functions for reconstructing chlorophyll *a*, total nitrogen (TN) and total phosphorus (TP) levels from fossil diatom assemblages, and Woodward & Shulmeister (2006) provided a chironomid transfer function for reconstructing temperature and chlorophyll *a* levels from fossil chironomid assemblages. Transfer functions were used in Augustinas et al.'s (2006) study on Lake Pupuke to hindcast quantitative estimates of the pre-European reference condition for the lake, which allows us to compare the findings with the limits derived from the survey-calibration method for deep lakes. This comparison indicates that the reference condition for Lake Pupuke fell outside the limits demarcating a generalised reference condition for deep lakes, indicating that Lake Pupuke is an outlier in relation to the proposed limits. This is not surprising, as the deep lake dataset encompassed many South Island glacial lakes and these comprised all of the reference lakes. By contrast, Lake Pupuke is a crater lake in the Auckland region and consequently would have quite different reference conditions. This highlights the important differences between lakes within the classes used in this report and emphasises that caution should be exercised if applying the reference condition limits to lakes outside this dataset.

Fossil pigment analysis has been used successfully to reconstruct phytoplankton communities from phytoplankton pigments preserved in lakes sediments. However, when Gall & Downes (1997) trialled this approach on four central North Island lakes, they found that the pigments appeared to have decomposed downcore, rendering interpretations difficult because different pigments likely have different long-term stabilities in the sedimentary environment. Thus, this approach may not yield useful results in all lakes.

5.3 Comparison of the two approaches

The palaeolimnological studies examined provided fairly consistent qualitative interpretations of reference conditions for the three classes of lakes and of changes to their ecology resulting from human impacts. This approach also confirmed many of the findings concerning reference conditions that were inferred by the survey-calibration approach (e.g. lake productivity, turbidity, importance of macrophytes) and, in addition to this, provided information that complemented that obtained by the survey-calibration approach. For example, the palaeolimnological approach yielded information on reference condition macrophyte and phytoplankton community structures, and on reference condition opening regimes. In principle, the survey-calibration approach could also analyse changes and limits for these indicators, but the data to do this were lacking in the present study.

The two approaches complement one another in that the survey-calibration approach yields quantitative average reference condition limits based on multi-lake datasets, while the palaeolimnological approach yields mostly qualitative data that are specific to individual lakes. For example, the survey-calibration approach can be used to provide reference condition limits for variables such as %ETO, benthic invertebrate richness, phytoplankton richness and macrophyte depth limits for lakes. The palaeolimnological approach can complement this information by providing specific information on the types of benthic invertebrates, phytoplankton and macrophytes that inhabited a lake when it was in its reference condition.

While the palaeolimnolgical approach has tended to provide qualitative information in the past, the increasing use of statistical transfer functions (e.g. Reid 2005) is allowing more quantitative inferences to be made about variables such as trophic state and salinity. This information will not only be useful for understanding the historical trajectories of specific lakes but will also allow some of the general reference condition limits obtained by the survey-calibration method in this report to be tested.

6. Summary and Conclusions

One of the main anthropogenic impacts on freshwaters is eutrophication, or the enrichment of waters with plant nutrients, which results in increased aquatic algal densities, plant biomass and productivity (Ansari et al. 2011). It is, therefore, not surprising that the analyses presented in this report also showed that the main impact of human settlement on New Zealand's shallow freshwater lakes, brackish lakes and lagoons, and deep lakes has been eutrophication. In New Zealand freshwaters, eutrophication either co-occurred with, or has led to, other forms of degradation of the EI of lakes, including changes in biodiversity, the introduction of non-native species and an increase in the vulnerability of lakes to regime shifts (Schallenberg & Sorrell 2009), culminating in persistent algal and cyanobacterial blooms in many lakes.

An understanding of the reference conditions for lakes can help with their management or restoration, because this information can be used both to quantify the current degree of departure of lakes from their reference conditions, and to provide aspirational goals for lake management and restoration (Higgins & Duigan 2009; Schallenberg et al. 2011). Although many of the anthropogenic effects on lakes are obvious to those who are experienced and familiar with these systems, the task of imagining and then quantifying the reference conditions for lakes can be difficult. Within the context of the EI framework (Schallenberg et al. 2011), the two approaches used in this study yield useful and complementary information on the likely reference conditions for lakes (Table 19), the quantitative limits for most of which are presented in tables within this report.

Table 19. General reference conditions for the three classes of lakes used in this study based on a combination of the survey-calibration and palaeolimnological approaches. Unless otherwise stated, interpretations are compared with modern conditions. Proposed quantitative reference condition limits can be found in tables in section 3.

SHALLOW FRESHWATER LAKES	BRACKISH LAKES AND LAGOONS	DEEP LAKES
Lower chlorophyll *a* and nutrient levels	Lower chlorophyll *a* and nutrient levels	Lower chlorophyll *a* and nutrient levels
Lower nutrient inputs	100% native flora and fauna	100% native flora and fauna
100% native flora and fauna	More extensive and deeper macrophyte beds	More extensive and deeper macrophyte beds
Low levels of cyanobacteria	Increased diversity of benthic macroinvertebrates	Lower rotifer and phytoplankton diversity
More extensive macrophyte beds	Decreased diversity of phytoplankton species	Greater macrophyte diversity
	Low levels of cyanobacteria	High ratios of dissolved inorganic nitrogen to total phosphorus (DIN:TP), suggesting strong P limitation
	Fewer openings of barrier bars (in intermittently closed and open lakes/ lagoons; ICOLLs)	
	Either more pronounced and persistent alternating marine and freshwater phases, or no marine influence (in ICOLLs)	

Both the survey-calibration and the palaeolimnological approaches used in this report have limitations, as discussed in section 5. However, there is scope to substantially advance both of the approaches to provide more detailed and refined estimates of reference conditions. For example, if sufficient data become available, multivariate statistical modelling could be applied to the survey-calibration approach, which would allow the examination of covariates (e.g. water residence time, temperature, glacial v. volcanic origin). In addition, the inclusion of community data would allow specific community structures related to reference conditions to be determined (e.g. phytoplankton community and size structure, benthic invertebrate community structure).

Similarly, more sophisticated palaeolimnological analyses could provide more quantitative information on reference conditions. This could be achieved by applying currently available transfer functions (e.g. Reid 2005; Woodward & Shulmeister 2006) to appropriate microfossil communities recorded in sediment cores, and by developing new transfer functions for new 'proxy' communities (e.g. cladocerans, charophyte oocytes) and for specific lake classes (e.g. humic-stained lakes, turbid lakes, geothermally-influenced lakes).

The analyses presented here are preliminary and so the reference condition limits presented should be considered provisional. However, the simple analyses that were undertaken provide initial benchmarks for the reference conditions for New Zealand lakes, and also show that there is significant potential to further our understanding of lake reference conditions with further data collection and the types of analyses advocated above.

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Appendix 1

List of lakes included in the survey-calibration approach

LAKE	REGION	% CATCHMENT IN NATIVE VEGETATION	ECOLOGICAL INTEGRITY (EXPERT ASSESSMENT)
SHALLOW FRESHWATER LAKES			
Lake Calder*	Stewart Island/Rakiura	100	N/A
Coopers Lagoon/Muriwai	Canterbury	0	49.6
Lake George	Southland	43	68.2
Lake Humuhumu	Northland	41	87.8
Kaihoka Lakes (south)	Tasman	67	99.9
Kaihoka Lakes (north)	Tasman	71	81.2
Lake Kaiiwi	Northland	73	81.4
Kaitoke Lake	Manawatu	3	22.8
Lake Mahinapua	Westland	77	76.5
‘Maori’ Lake*	South Westland	100	98.5
Lake Marahau	Wanganui	10	31.3
Lake Ngatu	Northland	41	59.0
Oingo Lake	Hawke’s Bay	13	18.3
Lake Otuhie*	Tasman	95	88.8
Lake Papaitonga/Waiwiri	Horowhenua	41	19.8
Lake Poerua	Westland	72	76.1
Lake Pokorua	South Auckland	26	14.0
Lake Pounui*	Wairarapa	94	100.0
The Reservoir	Southland	34	41.4
Lake Rotokawa	Northland	13	61.8
Lake Rotorua	Kaikoura	50	21.2
Runanga Lake	Hawke’s Bay	26	3.7
Lake Ryan	Westland	34	29.9
Shag Lake	Northland	35	39.2
Lake Sheila*	Stewart Island/Rakiura	100	N/A
Ship Creek Lagoon	South Westland	96	98.9
Six Foot Lake*	Campbell Island/Motu Ihupuku	100	99.7
Spectacle Lake	Northland	16	0.0
Tomarata Lake	Northland	41	57.8
Lake Tuakitoto	Otago	12	19.9
Lake Vincent	Southland	6	63.6
Lake Waiparera	Northland	34	68.6
Lake Waitawa/Forest	Horowhenua	12	42.5
Lake Whatihua	South Auckland	2	52.3
Lake Wilkie*	The Catlins	88	86.1
BRACKISH LAKES AND LAGOONS			
Lake Brunton	Southland	13	N/A
Lake Ellesmere (Te Waihora)	Canterbury	12	11.0
Five Mile Lagoon*	South Westland	100	100.0
Lake Forsyth (Waiwera)	Canterbury	22	0.0
Lake Onoke	Wairarapa	28	66.0
Tomahawk Lagoon (west)	Otago	14	37.0
Upper Lake Onoke	Wairarapa	89	66.0
Lake Waihola	Otago	15	39.0

*Indicates lakes deemed to be Tier 2 reference lakes.

Continued on next page

Appendix 1 continued

LAKE	REGION	% CATCHMENT IN NATIVE VEGETATION	ECOLOGICAL INTEGRITY (EXPERT ASSESSMENT)
Lake Wairarapa	Wairarapa	58	53.0
Whakaki Lagoon	Hawke's Bay	28	23.0
DEEP LAKES			
Lake Alexandrina	Canterbury	65	21.0
Lake Coleridge	Canterbury	91	59.0
Lake Hayes	Otago	22	25.0
Lake Johnson	Otago	13	23.0
Lake Kaiiwi	Northland	39	73.0
Lady Lake	Westland	43	88.0
Lake Manapouri	Southland	61	96.0
Lake Ohau*	Canterbury	96	86.0
Lake Ōkareka	Rotorua Lakes	26	66.0
Lake Okaro	Rotorua Lakes	0	16.0
Lake Ōkataina/Te Moana i kataina ā Te Rangitakaroro	Rotorua Lakes	30	87.0
Lake Pukaki*	Canterbury	100	79.0
Lake Pupuke	Auckland	9	60.0
Lake Rotoiti/Te Roto kite ā Ihenga i ariki ai Kahu	Rotorua Lakes	4	52.0
Lake Rotomā	Rotorua Lakes	70	72.0
Lake Rotomahana	Rotorua Lakes	17	48.0
Lake Taharoa	Northland	78	60.0
Lake Tarawera	Rotorua Lakes	52	75.0
Lake Taupo (Taupomoana)	Waikato	87	58.0
Lake Te Anau	Southland	57	95.0
Tikitapu/Blue Lake	Rotorua Lakes	48	81.0
Lake Waikere	Waikato	35	54.0
Lake Wakatipu*	Otago	74	87.0
Lake Wanaka*	Otago	83	86.0

*Indicates lakes deemed to be Tier 2 reference lakes.