

Shallow coastal lakes in New Zealand: current conditions, catchment-scale human disturbance, and determination of ecological integrity

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Abstract We present the results of an effort to develop a national-scale predictive model to describe the current condition of shallow, coastal New Zealand lakes. Comprehensive biological, physical and chemical data from 45 shallow, coastal lakes are compared to catchment-level disturbance indices (indigenous vegetation loss, nutrient loading, invasive species) derived by New Zealand's Waters of National Importance (WoNI) Programme. Few strong relationships were identified, but some general patterns were

evident: lakes in disturbed catchments tended to have a higher trophic state, higher pH, reduced light penetration, lower submerged macrophyte cover, smaller food webs, lower rotifer diversity, and a larger proportion of introduced fish species. We discuss these patterns in the context of “ecological integrity” (EI), a subjective descriptor used in WoNI and other management programmes. A lack of historical data and difficulties in quantifying “integrity” remain persistent challenges for linking science with management for EI. Relationships between the WoNI indices and measured limnological conditions were not strong enough to build a predictive, nationally relevant model for estimating the EI. However, we present an alternative method for estimating EI based on expert assessment; expert assessment EI was significantly correlated to both WoNI pressure indices and many of the limnological variables measured here.

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Introduction

Shallow temperate lakes, when compared to deeper lakes, tend to be warmer and more productive on a volume basis, have photic zones that usually extend to the sediment surface, and frequently do not stratify. As

a result, the flora and fauna supported by shallow lakes are very different from those supported by nearby deep lakes. Under natural conditions, most temperate shallow lakes were probably clear and supported a diversity of emergent macrophytes (Mitchell, 1971; Scheffer, 2004). Today, as a result of anthropogenic degradation, many shallow lakes are turbid and have lost their populations of aquatic macrophytes (e.g. Lake Ellesmere, New Zealand Brooks & Hamilton, 2009). Declining water quality, drainage, eutrophication and catchment disturbances such as development, loss of natural vegetation and poor agricultural practices are changing the fundamental ecology of shallow lakes in much of the world. In response to this, a number of governments are developing large-scale management strategies that target conservation of shallow lakes (e.g. the European Union's Water Framework Directive, Moss, 2007). The multi-year, interdisciplinary study presented here was undertaken to develop an understanding of the basic ecology and degradation of New Zealand's shallow, coastal lakes, and the information generated will contribute to a national-scale management plan for these ecosystems.

Shallow, coastal lakes and lagoons are a highly impacted and frequently overlooked component of New Zealand's collective freshwater resource. There are approximately 900 lakes in New Zealand that are >2 ha in area, <10 m in estimated or measured depth, and within 25 km of the coast (Fig. 1). These ecosystems provide important habitat for native fishes (e.g. *Anguilla* spp. and *Galaxias* spp.), invertebrates (e.g. *Paranephrops planifrons*), native aquatic plants (e.g. *Ruppia* spp.) and waterfowl (e.g. *Tadorna variegata*). In addition, their position at the interface between land and sea suggests that they may play an important role in the landscape by regulating nutrients and materials export from their catchments. For example, within catchments depositional areas generally occur as slope decreases near the coasts (i.e. in higher order rivers; Vannote et al., 1980). Lakes in low-gradient coastal areas will increase the water residence time and fine sediment deposition at a catchment scale, and these conditions facilitate processes such as denitrification. But coastal lakes are also relatively susceptible to species introductions, increased nutrient and sediment loading, and hydrologic alterations because they tend to be accessible to people and are catchment focal points for sediments, nutrients and other pollutants.

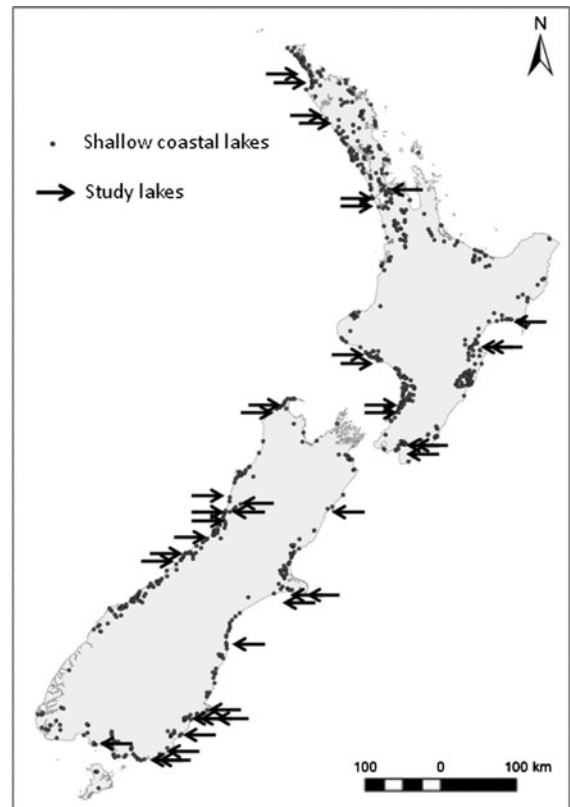


Fig. 1 Locations of the approximately 900 known shallow, coastal lakes in New Zealand (lakes in the Subantarctic Islands and Chatham Islands are not shown), and the 44 of the 45 study lakes in this study—the 45th study lake was on Campbell Island, in the Subantarctic

In New Zealand, the ecological monitoring of lakes (e.g. that conducted by regional councils) tends to focus on relatively large, deep lakes due to greater public interest (Hamill, 2006). With a few exceptions, shallow coastal lakes have received relatively little attention in environmental science, management and conservation. Today, shallow coastal lakes in New Zealand tend to be relatively productive with high nutrient and chlorophyll *a* concentrations, especially when compared to deeper, higher lakes (e.g. Hamill, 2006). Those in relatively undisturbed catchments tend to have clear water and support dense growths of native submerged macrophytes, consistent with shallow lakes in other part of the world (Scheffer, 2004). Also consistent with global patterns, shallow coastal lakes in disturbed catchments of New Zealand are frequently turbid, a result of increased sediment inputs from catchment disturbance and wind-driven

sediment resuspension due to the loss of submerged macrophytes (c.f. Scheffer et al., 1993).

Relatively, little is known about the natural conditions of shallow coastal lakes in New Zealand. We might expect these systems to be naturally more productive than other New Zealand lakes because of their position towards the bottom of catchments and because they frequently support seabirds and anadromous fishes which can import marine-derived nutrients that may increase productivity when water residence time is sufficiently long (e.g., Holtham et al., 2004). Oligotrophy is regarded as desirable for large, deep New Zealand lakes, but may not be the natural condition of many shallow coastal lakes and, therefore, may not be an appropriate target condition for the management or restoration of these systems. Furthermore, landscape-scale heterogeneity in catchment geology, vegetation and lake water residence times may lead to considerable variation between lake ecosystems even when lakes are ostensibly similar or physically near to each other. These considerations present significant challenges for describing “natural” or reference conditions for lake conservation and management.

New Zealand’s Waters of National Importance (WoNI) programme, led by the Department of Conservation, identifies water bodies that encompass the largest possible range of biodiversity and the highest degree of “ecological integrity” (EI) for conservation protection (Leathwick & Julian, 2007). Rivers, lakes and wetlands are ranked for conservation management using the best available data and CAR management principles. CAR refers to comprehensive, adequate, and representative management principles—a generally applicable approach for large-scale management of parks or other natural lands (e.g. Task Force on Marine Protected Areas, 1999) first developed in Australia. Complex models incorporating a range of factors assumed to be associated with aquatic degradation (termed human pressures) are used to predict the condition of each catchment. In support of this goal, the WoNI programme has produced a national database of human pressure indices that estimate the severity of specific human disturbances at the catchment scale. Proposed key pressures on lakes (disturbance indices) are: the proportion of the catchment that has lost native vegetation cover, the proportion of the catchment that is impervious (e.g. area under roads

or buildings), interruptions in hydrological connectivity (dams), nitrogen and phosphorus inputs and the presence of non-native fish or aquatic plants (De Winton et al., 2009).

The overarching aims of this study were to: (i) collect representative data from a nationally representative set of shallow, coastal lakes, (ii) identify relationships between WoNI pressure indices and the measured lake characteristics and (iii) evaluate the relationships between pressures and lake conditions as a basis of a predictive model of lake EI, based on pressure indices. We also test an alternative approach for quantifying EI which utilises expert assessment techniques, and we test this approach against the disturbance indices and lake condition variables quantified in this study.

Methods

We measured 40 physical, chemical and biological variables (Table 1) in a nationally representative set of 45 shallow coastal lakes (Fig. 1) including 15 dune lakes, 15 riverine lakes, two peat lakes, and nine coastal lagoons. The Fresh Water Ecosystems of New Zealand (FWENZ) database was used to select lakes that conformed to the following criteria: (1) they had a measured or estimated maximum depth ≤ 10 m, (2) they were usually located within 25 km of the coast and (3) they had average salinities <10 . The lakes were chosen to represent the lowland regions of New Zealand (Fig. 1) and to span a wide range of trophic states within each region (Appendix A in Electronic supplementary material). Each lake was sampled once in late summer (February or March) between 2004 and 2008.

WoNI human pressure (disturbance) indices

Six human pressure indices were derived from databases and/or GIS-based models:

(1) Impervious area in catchments—the percent of the lake catchment area covered by impervious surfaces (roads, buildings, etc.) divided by lake area (De Winton et al., 2009). (2) Native vegetation removal in catchments—the percent of the catchment converted to non-native forest or pasture (De Winton et al., 2009). (3) Lake N loading—annual total N

Table 1 Lake characteristics measured in this study

Lake condition variables measured	
Physical	Fish
Measured max depth (m)	Native catch per unit effort (CPUE)
Hydrologically altered (yes/no)	Exotic catch per unit effort (CPUE)
	% Native species
Water quality	Macrophytes
Conductivity $\mu\text{S}/\text{cm}$	% Cover (exotic + native)
pH	Simpson index
Turbidity (NTU's)	Weighed Simpson index
Water colour (absorbance at 440 nm)	Alternated macrophyte-phytoplankton states
Cl (ppm)	Macroinvertebrates, Rotifers, Metainvertebrates (each group analysed separately)
Ca (ppm)	Density
Mg (ppm)	Evenness
Dissolved organic carbon (ppm)	Diversity indices
Chlorophyll <i>a</i> (ppb)	Richness
Total N (mg/m^3)	
Total P (mg/m^3)	
Total N/total P	
Trophic level index (TLI)	
Nitrate–nitrite N ($\text{NO}_3\text{-N}$; mg/m^3)	
Ammonium N ($\text{NH}_4\text{-N}$; mg/m^3)	
Soluble reactive phosphorus (SRP; mg/m^3)	
Euphotic depth, Z_{eu} (m)	
PAR attenuation coefficient (K_d)	
Known incidence of cyanobacterial blooms (yes/no)	

loads (kg/year) from tributary streams were derived using the Catchment Land Use for Environmental Sustainability model (CLUES; <http://www.maf.govt.nz/mafnet/rural-nz/sustainable-resource-use/clues/>). N contributions to tributary streams were calculated based on catchment sediments, point-sources, rainfall, and drainage for areas of each of the following land use categories: native and exotic forest coverage, pasture (classified as dairy, deer, sheep and beef), hill and high country. Pasture weightings were derived from stocking densities provided to OVERSEER, an Ag-Research/Ministry for the Environment/fertiliser industry joint model that calculates N losses from pastoral land uses. Annual N loading was then adjusted by area and water residence time (in days, calculated by the FWENZ model) to weight each lake by its potential capacity to assimilate or retain nutrients (e.g. Ahlgren et al., 1988). (4) Lake P loading—annual lake P loads (kg/year) were also

calculated for tributary streams using the CLUES model. Using CLUES, P loading is a function of catchment % coverage of the following types: pasture (dairy and other), non-pasture, vegetation type (forests, scrub), sediment load, and point sources. Annual P loading values were also adjusted for lake area and water residence time. (5) Invasive macrophyte pressure was calculated with the aquatic weed risk assessment method (AWRAM; Champion & Clayton, 2000). Lake scores are equal to the highest-scoring or “weediest” invasive macrophyte present based on records in the Freshwater Biodata Information System (FBIS). Invasive macrophyte scores were only available for 17 of the 45 study lakes. (6) Invasive fish pressure was derived from the New Zealand freshwater fish database using a scoring system developed by Wilding & Rowe (2008). Invasive fish scores were available for 29 of the 45 lakes.

Sample collection and analyses

A suite of variables potentially indicative of shallow lake EI (as described by Schallenberg et al., 2010) were measured.

Water quality

Sampling of physico-chemical variables and plankton was undertaken at two or three sites in each lake. In situ lake measurements included: specific conductivity, Secchi depth, temperature, and light profiles. Specific conductivity and temperature 1 m below the lake surface were measured using an YSI 85 multiprobe. Underwater light profiles were determined using a LICOR underwater LI-192SA PAR sensor (2π), so that PAR was measured from at least 5 depths. Water samples were collected from the top <1.5 m of open water (above any macrophytes) using a 1.5-m long, 150-mm diameter, tube sampler with a closure. Samples were collected into a clean 20 l bucket, from which a 5 l subsample was immediately obtained and stored in the dark, at ambient temperature for up to 5 h until processing. Subsamples were then processed for analyses of phytoplankton, turbidity, nutrients, dissolved organic carbon, pH, and water colour. Laboratory facilities were not available at several of the most remote field sites and water samples from those lakes were processed within 24 h. Zooplankton was quantitatively sampled at two sites in each lake by one of two methods depending on depth. At sites <1.5 m deep, water was collected using the integrated tube sampler and a known volume of the lake water was then passed through a 50- μm mesh net. At sites >1.5 m deep, zooplankton was collected by vertical hauls through the whole water column using the same net. Zooplankton samples were preserved in 2% formalin.

Benthic invertebrates

Triplicate grab samples were collected from two locations along a littoral zone transect (5–10 m from shore) and a sublittoral zone transect (~50 m offshore) in triplicate with either a Wisconsin Grab (2004, 0.1 m²) or with a Ponar dredge (2004–2008, 0.0225 m²). Material from the triplicate benthic grabs at each site was pooled, sieved through a 400- μm

mesh sweep net, and preserved in 70% isopropanol for taxonomic analysis.

Fish

Surveys were conducted at three shoreline locations using two trapping methods. At each site, two lines of 10, baited gee-minnow traps (mesh size ~5 mm) were deployed overnight, extending perpendicular from the shoreline. Three 10-m fyke nets were also deployed overnight at each site in each lake. In several very small lakes, only one to two trap lines and fyke nets were deployed. Fish were identified, counted, fork-lengths were recorded, and fin clips were collected from 10 individuals of each species when possible. Fish tissue samples (lateral muscle and/or caudal fin) were frozen as soon as possible (usually within 5 h) for N and C isotope analyses. For eels, both muscle and fin tissues were collected from fish caught in the first 14 lakes, and a relationship between muscle and fin isotopic signatures was developed (linear regression $P < 0.05$, $r^2 = 0.67$). Following this (for the remaining 31 lakes), only fin tissue was collected from eels and the statistical relationship was used to convert fin isotope values to muscle values.

Food web collections

Macrophyte material and invertebrates for stable isotope analysis were obtained at three sites per lake from littoral areas of wadeable (<1.2 m) depth using a 400- μm sweep net, and using Ponar grabs in deeper areas. Between 5 and 10 individuals of the most common invertebrate taxa were sorted into 25-ml vials filled with lake water, left overnight to allow gut contents to clear and then frozen. Terrestrial detritus (e.g., leaves, wood) was obtained from the dominant species along the lake shore, and submerged detritus (coarse benthic organic matter) was collected using a sweep net. Detritus samples were washed to remove invertebrates. Fine benthic organic matter samples were obtained using a Ponar grab by collecting surface sediment samples from littoral (5–10 m offshore) and sublittoral (50 m offshore) areas. Seston was filtered onto ashed, 0.45- μm glass fibre filters until clogged and then frozen for C and N isotope determination.

Submerged macrophytes

These were surveyed at each of three sites in each lake via standardised diving survey methods (Braun-Blanquet cover estimates) during 2004–2005 field seasons, but due to logistical constraints were surveyed from the lake surface using either an underwater viewer (wadeable depths) or grab samples at unviewable depths during the 2007 and 2008 field seasons. Macrophyte cover and species composition were quantified at 5 m intervals on 50 m transects at each site.

Laboratory methods

Water quality

Subsamples were passed through GF/F filters and filters were frozen for chlorophyll *a* and phaeophytin determinations using a Turner Model 450 fluorometer. Whole water and filtrate (passed through acid washed Whatman GF/F filters) was frozen for determination of total N (TN), total P (TP), soluble reactive P (SRP), nitrate + nitrite-N ($\text{NO}_3\text{-N}$) and ammonium-N ($\text{NH}_4\text{-N}$) using a Skalar San System autoanalyser, wet peroxide digestions for total nutrients, and standard colorimetric methods. Turbidity was measured on unfiltered water samples using a Hach 2100A turbidity meter. Filtrate was collected after filtration through 0.45- μm Millipore nitrocellulose membrane filters for the determination of chloride, calcium and magnesium ion concentrations, dissolved organic carbon concentration and water colour. Chloride was measured by flow injection analysis using a Foss Tecator FIASTAR 5000. Ca and Mg were measured using a Varian SpectrAA 220FS flame ionisation atomic absorption spectrophotometer. Dissolved organic C (DOC) was measured as non-purgable dissolved organic carbon on a Shimadzu TOC-V CSH analyser, and colour was measured as light absorbance at 440 nm using a 10-cm quartz cell in a Shimadzu Mini 1240 UV-vis spectrophotometer. Metazooplankton and rotifers were identified and enumerated using taxonomic guides by Chapman & Lewis (1976), Stemberger (1979) and Streble & Karuter (1988).

Benthic invertebrates were identified to the lowest taxonomic level possible—in some cases, this was species, but some groups were identified only to phylum (nematodes), class (oligochaetes and mites),

or family (dipterans). Subsamples were separated using a barrel splitter. At least 25% of each entire sample was identified and at least 100 individuals of the most abundant taxa were counted. Although the proportion of each sample that was identified and counted varied, this approach should standardise estimates of diversity. Invertebrates were identified using keys by Winterbourn & Gregson (1981) and Thorp & Covich (1991).

Food web (isotope) analyses

Macrophyte samples were freeze-dried and homogenised with a mortar and pestle for isotopic analysis. Whole invertebrates (typically >5 individuals, fewer for some rare taxa) were freeze-dried, homogenised and lipids extracted. Invertebrates such as snails and caddisflies were removed from cases or shells prior to processing. Surface sediments were treated with 5% HCl to remove carbonate deposits (e.g. snail shells), freeze-dried, and processed as for macrophytes. Fish muscle and fin tissue was freeze-dried, and processed as for invertebrates. Lipids were extracted from all animal tissues on a Dionex ASE 200 Accelerated Solvent Extractor (Dionex Corporation, Sunnyvale, California) using 100% dichloromethane. $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ were determined by mass spectrometry on a Finnigan MAT Delta Plus Continuous Flow Mass Spectrometer (Thermo Finnigan, San Jose, California, USA). Results are reported as the relative difference between the sample and international standards of C and N (Pee Dee Belemnite for C, and air for N) with an analytical precision of 0.1%. All isotope analyses were performed at the Water and Aquatic Sciences Research Unit, University of Victoria, BC, Canada.

Expert site assessments of EI

EI ranks were determined after all field work was completed (2008), but prior to any data analysis other than calculation of means. Three freshwater ecologists involved in this project (two career ecologists and one senior technician) who had visited and surveyed most or all of the study lakes independently ranked all lakes from 1 (highest integrity) to 45 (lowest integrity) using their own conceptions of “ecological integrity” and without consulting datasets. Because the correlation

between the three rankings was high ($r^2 \approx 0.79$), the rankings were averaged for further analyses.

Quantitative analyses

Multivariate analyses such as those used here are subject to the problems of co-linearity (between variables, predictors and responses) and testing multiple hypotheses with the same data, which unless corrected for, increases the likelihood of falsely identifying non-significant relationships as significant (type I error). We acknowledge these limitations, but note that our analyses are exploratory in nature.

Standard deviations tended to increase with mean values of conductivity, nutrient and ion concentrations, chlorophyll *a* and phaeophytin (although coefficients of variation did not). These data were transformed (ln) to conform to the assumptions of regression and correlation analysis. All fish density and catch per unit effort calculations were adjusted for trap numbers and number of nights (rather than hours) deployed.

Diversity indices

We calculated both Shannon (H') and Simpson (D) diversity indices for benthic invertebrates, metazooplankton, rotifers (usually identified to genus or species, nauplii excluded) and aquatic macrophytes (to species). Data were composited from the three sites in each lake prior to diversity index calculations.

A modified Simpson index was calculated for submerged macrophytes, weighted to reflect a negative influence of non-native macrophyte species. Lower Simpson index values indicate higher diversity. Simpson indices here were calculated using native species, and weighted as follows: a weight of 0.25 was added to the Simpson index when non-aggressive exotic species were present, 1.00 was added when aggressive exotic species (*Ceratophyllum demersum*, *Egeria densa*, and *Lagarosiphon major*) were present, and 3.00 was added when no submerged macrophytes at all were observed (as in highly disturbed lakes such as Ellesmere and Spectacle).

Trophic level index (TLI)

Trophic level index (TLI) is a composite metric developed for lakes based on nutrient and chlorophyll

Table 2 Trophic states based on trophic level index (TLI) and the corresponding nutrient enrichment descriptions, as described by Burns et al. (1999)

TLI	Trophic state	Nutrient enrichment description
<1	Ultra-microtrophic	Practically pure
1–2	Microtrophic	Very low
2–3	Oligotrophic	Low
3–4	Mesotrophic	Medium
4–5	Eutrophic	High
5–6	Supertrophic	Very high
>6	Hypertrophic	Extremely high

a concentrations and Secchi depth. TLI is calculated by logarithmically transforming TN, TP, Secchi depth (Z_{sd}) and chlorophyll *a* data, so that each parameter is scored on a similar scale (after Burns et al., 1999). The average of the four component scores is the TLI. Trophic state classes are defined based on TLI ranges (Table 2). The formulae for the four component indices are:

$$\begin{aligned}
 TL_N &= -3.61 + 3.01\log(\text{TN}) \\
 TL_P &= 0.218 + 2.92\log(\text{TP}) \\
 TL_S &= 5.10 + 2.27\log(1/Z_{sd} - 1/40) \\
 TL_C &= 2.22 + 2.54\log(\text{chlorophyll } a)
 \end{aligned}
 \tag{1}$$

Food web structure

Metrics of food web structure were calculated from stable isotope ratios of C and N according to the methods described by Layman et al. (2007). $\delta^{13}\text{C}$ versus $\delta^{15}\text{N}$ isotope biplots were used to calculate food chain length (corrected for 3.4‰ $\delta^{15}\text{N}$ per trophic level), trophic span, mean nearest neighbour distance, and total convex hull area (Layman et al., 2007).

Boosted regression tree analysis

Boosted regression tree (BRT) models were constructed using the WoNI pressure indices as multivariate predictors of each of 27 measured lake variables as responses, which were selected based on correlation and preliminary boosted regression tree analyses (Drake et al., 2009). BRT models were fitted using R software version 2.3-1, using gbm package version

1.5–7 plus custom code developed by Elith et al. (2008). We used BRT to identify variables with the greatest explanatory power. BRTs are of particular value in controlling overfitting (Elith et al., 2008), a common problem in small datasets, such as the one in this study.

Results

Current conditions of shallow coastal lakes in New Zealand

This study produced a complex, national-scale data set describing physical, chemical and biological conditions in 45 shallow, coastal lakes in New Zealand (Fig. 1; Table 3, Appendix A in Electronic supplementary material). Most of the lake catchments in this study were degraded to some extent, as reflected in the WoNI indices (Appendix A in Electronic supplementary material). On average, ~60% of native vegetation had been removed from the catchments, varying from 0% (most on the west coast of the South Island, Appendix A in Electronic supplementary material) to 100% removal. Loss of native vegetation usually equates to establishment of pastureland, non-native forest or other agriculture. The average impervious area in the catchments of this study was 3.7%, and varied from 0 to 21.8%. Lake N and P loading index values (adjusted for water residence time) varied by several orders of magnitude from 0 to 66,000 for N and 0 to 2,900 for P.

Some indicators of lake degradation measured here include TLI and euphotic depth (Z_{eu}), the depth to which 1% of light entering the lake's surface penetrates. Although we sampled each lake only once, our estimates of TLI were strongly correlated to TLIs of a subset of lakes for which long-term data were available ($r^2 = 0.81$, $n = 27$; data obtained from Sorrell et al., 2006). The average TLI of the lakes in this study

was relatively high at 4.3 (eutrophic, Table 2) and values ranged from 1.8 (microtrophic; Lake Tawharekiri, Westland) to 7.2 (hypertrophic; Whakaki Lagoon and Runanga Lake in Hawke's Bay). Average Z_{eu} in the lakes was 3.8 m, and varied from 0.3 m (Lake Ellesmere, Canterbury) to ~12.0 m (Lakes Kaiwi and Ngatu in Northland, and Coopers Lagoon in Canterbury). Although Coopers Lagoon lies in one of the most disturbed catchments of this study (100% of native vegetation removed), the lake was characterised by very clear water and a relatively low TLI of 3.4 (Appendix A in Electronic supplementary material). N and P loading indices were, in fact, quite low in Coopers Lagoon, probably a result of a small catchment size (~1,000,000 ha, one of the smallest catchments in this study).

We identified a total of 20 metazooplankton taxa. Those found in abundances of >100 individuals l^{-1} in at least one lake were *Calamoecia lucasi*, *Boeckella hamata*, *Gladioferens pectinatus*, Calanoid copepods, *Bosmina* spp., *Ceriodaphnia* spp., and *Chydorus* spp. At least 44 rotifer taxa were identified, the most abundant (found in at least one lake at >1,000 individuals l^{-1}) were in the genera *Filinia*, *Gastropus*, *Keratella*, *Polyarthra*, *Synchaeta*, and *Trichocerca*. At least 77 taxa of benthic invertebrates were identified, and the most common were *Potamopyrgus antipodarum*, calanoid copepods, *Paracorophium excavatum*, *Chironomus* spp., and *Oligochaeta*. We identified 26 species of native macrophytes in the study lakes, the most common being *Nitella hookerii*, *Chara fibrosa*, *Myriophyllum triphyllum* and *Typha orientalis*.

New Zealand supports a relatively low diversity of freshwater fishes. We caught a total of 18 species, 10 of which are native. Most lakes contained at least one of the three most common native species: bullies (*Gobiomorphus cotidianus*), longfin eels (*Anguilla dieffenbachia*) or shortfin eels (*A. australis schmidtii*). We caught inanga (*Galaxias maculatus*) in 13 lakes, smelt

Table 3 Ranges and averages of selected water quality variables in the 45 lakes in this study

	pH	Ca (ppm)	Mg (ppm)	DOC (ppm)	Chl <i>a</i> (ppb)	TN (mg/m ³)	TP (mg/m ³)	NO ₃ -N (mg/m ³)	NH ₄ -N (mg/m ³)	SRP (mg/m ³)
Mean	7.4	13.90	19.50	10.69	13.21	808.72	76.18	29.27	45.37	13.29
Min	4.6	0.50	0.48	0.00	0.30	127.97	2.38	0.20	1.47	0.10
Max	9.2	83.00	188.67	33.80	116.00	3672.00	510.25	1061.93	640.47	226.96

(*Retropinna retropinna*) in seven lakes, giant kokopu (*G. argenteus*) in six lakes, and banded kokopu (*G. fasciatus*) in two lakes. Triplefin (*Ruanoho whero*) were found in Lake Onoke (Wairarapa) only. We caught a maximum of five native species in any lake. The lakes supporting five species of native fishes were Kaitoke (Manawatu), Waipouri (Otago), Onoke (Wairarapa), Mahinapua and Ship Creek (West Coast). No fish were caught in Lake Wilkie (Otago), a peat lake with a pH of 4.6. Non-native mosquito fish (*Gambusia affinis*) were found in four of the warm, northern lakes, and invasive, predatory perch (*Perca fluviatilis*), were caught in 11 study lakes representing all but the northern regions of New Zealand. Our surveys detected invasive fishes in 28 of the 45 study lakes and invasive macrophytes in 30 of the 45 study lakes. Two lakes, Ellesmere (Canterbury) and Spectacle (Northland), supported no submerged macrophytes at all, and Whakaki (Hawke's Bay) supported only invasive macrophytes.

Food web area (convex hull area, after Layman et al., 2007), a measure of the variability of N and C isotope values in whole lake food webs, varied from 4.6 units in hypertrophic Lake Papaitonga (Manawatu), to 45.9 units in the Reservoir (Southland)—dam-formed, eutrophic lake. Other lakes with food web areas greater than 40 units (suggesting they should be more pristine) were Kaihoka 2 (Golden Bay), in a relatively undisturbed catchment, and Shag Lake (Northland) with relatively high WoNI nutrient loading and native vegetation removal values.

Relationships between the current conditions of shallow coastal lakes and indices of catchment disturbance

Correlation analyses: redundancy and co-linearity in variables

The WoNI pressure indices were statistically independent among the lakes of this study except N load and P load which were strongly positively correlated ($r = 0.93$) and the invasive fish index which was positively correlated with N and P load ($r = 0.55$ and 0.57 , respectively).

We used Pearson's correlation analysis to identify relationships between variables and to reduce the number of redundant variables in subsequent multivariate analyses. For example, the Cl, Ca and Mg ion

concentrations co-varied strongly (average $r \sim 0.86$), so concentrations were summed by molar concentration to produce one variable (ions). Chlorophyll *a* concentration, phaeophytin concentration and light attenuation coefficient (K_d) also co-varied (average $r = 0.74$). Phaeophytin is a product of chlorophyll *a* degradation ($r = 0.82$) so we used chlorophyll *a* only in the multivariate analyses. Although chlorophyll *a* and K_d covaried ($r = 0.73$), we retained both in the multivariate analyses because these variables may be decoupled in shallow lakes affected by wind-induced sediment re-suspension. In addition chlorophyll *a* and K_d are distinct, viable alternatives for monitoring programmes.

TLI co-varied with many other measured variables including native fish CPUE ($r = 0.48$), % macrophyte cover ($r = -0.56$), macrophyte weighted Simpson's index ($r = 0.31$), pH ($r = 0.48$), DOC ($r = 0.60$), K_d ($r = 0.57$) and metazooplankton biomass ($r = 0.38$), but none of these relationships were strong enough to warrant removal of TLI or its covariates. Because the components of TLI did not co-vary strongly in our dataset, we tested their predictive powers separately in addition to composite TLI. Native fish CPUE determined in this study co-varied weakly ($0.30 < r < 0.50$) with % macrophyte cover, chlorophyll *a*, TN, TP, TLI, macroinvertebrate density, and meta-zooplankton and rotifer diversity, but again the relationships were not strong enough to warrant removal of any of these covariates.

Relationships between WoNI pressure indices and measured lake condition variables

Indigenous vegetation removal was correlated with six of the measured variables (Table 4), N load was correlated with four variables, P load was correlated with five variables, and catchment impervious area was only weakly correlated with rotifer diversity and macroinvertebrate richness. Surprisingly, WoNI invasive fish indices were not correlated with fish survey data collected in this study (% native fish or native fish CPUE), possibly due to the small number of available WoNI invasive fish index values (29). Native fish CPUE was, however, correlated with several water quality variables including salinity (brackish lakes tended to contain more invasive fishes), K_d and food web $\delta^{15}\text{N}$ range. Rotifer diversity tended to be higher in lakes with less impervious area

Table 4 Summary of Pearson correlation coefficients ≥ 0.30 relating the WoNI pressure indices to measured variables

WoNI pressure index	Ln conductivity	Ions (Ca + Cl + Mg ppm)	pH	Colour (absorbance at 440 nm)	Chlorophyll <i>a</i> (ppb)	Ln TN (mg/m ³)	Ln TP (mg/m ³)	Rotifer diversity (Simpson index)	Macro-invertebrate richness	d ¹⁵ N range (consumers only ‰)	Macrophyte diversity (weighted Simpson index)
Catchment impervious area								-0.34	-0.32		
Indigenous vegetation removal	0.34		0.71	-0.47	0.30	0.56	0.47				
N load	0.55	0.62			0.47						0.51
P load	0.49	0.53			0.56			-0.33			0.40
Invasive macrophytes					-0.45	-0.43	-0.38				
Invasive fishes		0.45								0.38	0.46

Threshold of significance ($\alpha = 0.05$) of Pearson r for $N = 45$ is 0.2875

in the catchment, but this was a weak relationship (Table 4). Diversity of benthic invertebrates and zooplankton was not correlated with any of the WoNI pressure indices and was not clearly related to lake condition. The diversity of native macrophytes tended to be higher in lakes with low nutrient loads, and a low diversity of native macrophytes was associated with the presence of non-native fishes.

Boosted regression tree analyses

BRT results were similar to correlation analyses with few strong relationships identified. Using the four WoNI indices for which values were available for all lakes (native vegetation removal, N load, P load and imperviousness) we found that the WoNI indices could only be predicted by % native fish species, pH, chlorophyll *a*, and TLI (Table 5).

Expert assessment of ecological integrity

The EI rankings of the lakes, determined independently by three freshwater scientists, were similar to each other (average $r^2 = 0.79$) and averaged rankings were correlated with 11 of the measured variables including TLI ($r = 0.75$, Fig. 2) and two of the WoNI indices (Table 6). EI rank was strongly correlated with the % native vegetation removed from the catchment ($r = 0.78$, Fig. 2) and weakly correlated with the invasive fish index ($r = -0.30$). In every case where EI rank was correlated with a measured variable (Pearson's > 0.30 , Table 6) the relationship conformed to expectations. For example, high EI rank (poor condition) was positively correlated with trophic status, and negatively correlated with Simpson's diversity index value for macrophytes (high EI rank (poor condition) = low macrophyte diversity]. The exception may be the correlation between EI rank and colour (Pearson's correlation = -0.30), for which no expectation was formulated. This consistency suggests that, in general, the correlations are biologically meaningful. In addition, the BRT multivariate analysis showed that EI rank was the response variable most strongly predicted by the WoNI pressure indices (Table 5). The nine study lakes with EI rank above the 20th percentile had an average of 8.4% of their catchments in pasture, while the 80% of lakes below the 20th EI

Table 5 Cross-validated correlations of BRT models built using WoNI pressure indices (native vegetation removal, imperviousness, N load and P load) as predictors

Measured variable	Cross-validated correlation with the 4 WoNI pressure indices (BRT modelled)
Native fish species % in this survey	0.302
Native fish CPUE (common bully + shortfin + longfin individuals)	0.235
Benthic inverts Piliou evenness	−0.045
Macrophyte weighed Simpson index	0.098
pH	0.653
Colour	0.031
K_d	0.231
TN:TP/Redfield N:P	0.204
Food web mean distance to centroid	0.115
$\delta^{15}\text{N}$ range of consumers	0.058
Chlorophyll <i>a</i>	0.360
TLI	0.421
Expert assessment	0.772

A value of 0 indicates that no model could be fitted, and negative values indicate that the model diverged during cross validation and did not fit satisfactorily. Good correspondences (>0.3) are bold, and 15 variables with 0 correlation are not shown

rank percentile had an average of 57% of their catchments in pasture.

Trophic level index was reflected in the expert assessment EI rankings, although a larger range of rank values was seen in lakes with intermediate TLI (>3 and <5 , Fig. 2A). The standard deviation of assessed EI values in intermediate TLI lakes, however, was actually lower than the lakes with low TLI (<3) or high TLI (>5) (Table 7). A combination of factors is likely responsible for this: first, sample size varied between the categories (e.g. only 6 lakes had a TLI <3). Second, lakes that are not clearly pristine or extremely degraded may be more difficult to assess because of the multiple factors that contribute to lake condition. Third, TLI alone does not fully describe lake condition, for example, six-foot Lake on Campbell Island is essentially pristine, yet had an unexpectedly high TLI (~ 5.2), probably due to marine nutrient input from birds and marine mammals.

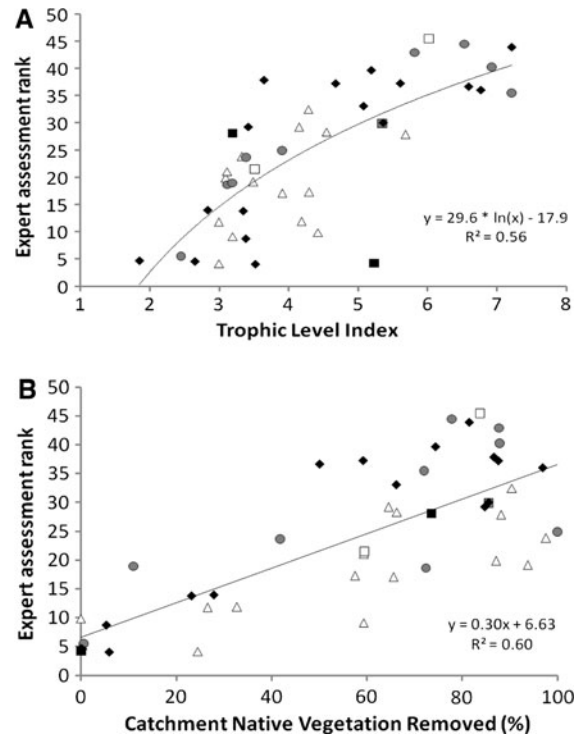


Fig. 2 **A** Expert assessment rank reflects TLI (Table 2), a composite measure of TN, TP, chlorophyll *a* and Secchi depth. TLI values >6 indicate hypertrophy. **B**. Expert assessment EI rank was positively related to the WoNI Native Vegetation Removal index. In both panels, lake types are designated by symbols: *open square* peat lakes, *filled triangle* are dune lakes, *filled circle* lagoons and *filled diamond* are riverine lakes; three unclassified lakes are designated by *filled square*

Discussion

Physical, biological, and chemical data from 45 shallow, coastal New Zealand lakes

This project was New Zealand's first national-scale examination of shallow coastal lakes, and the resulting dataset (Appendix A in Electronic supplementary material) is unique. Although these data do not represent reference conditions, they comprise a comprehensive snapshot of conditions in shallow coastal lakes in 2004–2008. The physico-chemistry, primary producer communities, consumer communities and food web structures, along with the WoNI pressure indices of the 45 study lakes varied considerably, reflecting a range of natural conditions and degradation. Many of the variables were correlated with expert assessments of lake EI. In general, our

Table 6 Correlates of EI rank (average rank of three EI assessments by experts who had visited the lakes)

Measured variable	Correlation (Pearson's) with EI rank
Macrophyte cover (%)	-0.48
Macrophyte Simpson's index	0.43
Ln electrical conductivity	0.42
TLI	0.75
pH	0.67
Colour	-0.30
K_d	0.34
Chlorophyll <i>a</i>	0.52
Ln TN	0.59
Ln TP	0.49
DOC	0.33
% Fish species native	-0.34
CPUE native eels and bullies	0.32
% Native vegetation removal	0.78
WoNI pressure index	
Exotic fish WoNI pressure index	-0.30

Lowest rank equated to the highest EI (best condition)

results show that shallow coastal lakes in New Zealand are very productive and most are invaded by non-native fishes and macrophytes. The few lakes located in national parks and other protected areas tended to be less productive (mesotrophic range) and supported fewer invasive species. Although we lack a historical perspective (data) on the current conditions of New Zealand's shallow coastal lakes, the results of this study suggest that a majority of shallow coastal lakes outside of the conservation estate in New Zealand are in poor condition due to human activities.

Trophic status (TLI; Burns et al., 1999) is a useful indicator of overall lake condition because it is a composite measure of nutrient concentrations, chlorophyll *a* standing stocks and water clarity. The mean TLI of the study lakes was 4.3 (eutrophic) and seven

of the 45 lakes were super- or hypertrophic (Appendix A). All seven of the lakes with TLI > 7 were located in catchments supporting intensive agriculture. Only six of the 45 lakes examined were mesotrophic or oligotrophic (TLI < 3). Of these, five were located on the relatively pristine, high-rainfall West Coast of the South Island and one was located in Northland (Appendix A in Electronic supplementary material). Although coastal lakes may be naturally more productive than inland lakes, our results indicate that intensive agriculture in lowland areas [e.g., increasing rates of fertiliser application in most of New Zealand (Parfitt et al., 2006) and increasing stocking rates of dairy cows] contributes to the high trophic status of New Zealand's shallow, coastal lakes.

Relationships between the condition of shallow coastal lakes and WoNI pressure indices

The WoNI pressure indices were correlated with many measured lake condition variables in expected ways, although the relationships were usually not strong. For example, lakes in highly modified catchments tended to have higher chlorophyll *a* concentrations, higher pH, reduced light penetration, lower % macrophyte cover (exotics and natives), larger proportions of exotic fish species, smaller food webs (seen in BRT analyses only) and lower rotifer diversities. But important exceptions to these patterns indicate that caution must be exercised when relying on general patterns for managing specific lakes. For example, one of the most pristine lakes in the dataset, Six-foot Lake on Campbell Island, was hypertrophic—ostensibly a result of a high natural nutrient influx mediated by seabirds and marine mammals using the lake and its catchment. Such high densities of seabirds and marine mammals were not observed in the North or South Island lakes, but this example illustrates a potentially large range in trophic state in undisturbed lakes.

A strong regionality in the data was evident and confounded some analyses. For example, the West Coast South Island lakes were, on average, in better condition than lakes in the other regions of New Zealand (data not shown). The West Coast supports the least agriculture, the lowest human population densities, and the largest area of land contained within the conservation estate (e.g. national parks) of all New Zealand coastal areas. West Coast lakes

Table 7 Statistics describing the relationships between low, medium and high TLI to expert assessed EI rank

TLI	No. of lakes	Expert assessed EI range	Standard deviation of expert assessed EI
1–3	6	4.1–21.0	4.28
3–5	24	4.1–37.8	0.51
>5	15	4.2–45.6	0.77

generally have a lower trophic state than those in other parts of New Zealand. Lakes in this region, however, do not necessarily reflect reference conditions for all New Zealand lakes because their low trophic state may be partially attributable to non-anthropogenic, regional characteristics such as high rates of precipitation and high hydrological flows.

Are the WoNI pressure indices useful for predicting the EI of shallow coastal lakes?

The high degree of variability within the 45 lakes of this study, conceptual difficulties in describing and quantifying “integrity” in shallow coastal lakes, and difficulties in linking field measurements and EI have, to date, precluded the development of an EI model with predictive capabilities. Of all the measured lake condition variables, only pH and TLI were correlated with WoNI pressure indices using the BRT approach (Table 5). These correlations were not informative enough for development of a predictive multimetric model. The lack of predictive power may be a result of the limited sample size (45 lakes) and the complex nature of ecosystems which often exhibit nonlinear dynamics and system memory effects (Scheffer et al., 1993). But the lack of strong relationships in this data set also illustrates the point that shallow lakes are highly variable, unique ecosystems that may best be assessed on a case-by-case basis rather than with generalised, national-scale, predictive models.

Most assessments of EI depend upon first quantifying reference conditions (e.g. Søndergaard et al., 2005), but the extent of anthropogenic degradation makes this difficult in most parts of the world. Related conservation programmes in Europe (The Water Framework Directive; WFD) and the US (Environmental Monitoring and Action Plan; EMAP) include directives for the quantification of human impacts on surface waters. The European Union’s WFD is the more comprehensive of these programmes and requires member states to assess the ecological status of surface waters. Within the framework, a population of >400 lakes is available with which to assess reference condition (e.g. Phillips et al., 2003) by classifying lakes and building empirical models based on the reference lakes within each lake type. If degraded conditions prevail within a lake type, a model is developed to quantify the

relationship between anthropogenic stress and ecological response. A WFD-type methodology may eventually be applicable for management of New Zealand lakes, but will require the improvement of existing databases such as the Freshwater Biodata Information System (FBIS, also currently under development), and the development of new databases such as the one produced by this study.

An alternative approach for assessing the EI of New Zealand’s shallow coastal lakes

A possible solution to the problems described above is the adoption of a more inductive approach for determining Lake EI. We found strong relationships between EI rank (inductively determined by three researchers) and measured limnological condition variables as well as the WoNI pressure indices. Thus, expert site assessments in combination with the collection of essential field data (e.g., pest fish and weed species, water chemistry) could be a useful approach for EI assessment.

Expert assessment approaches are used in the USA and Europe (Horner et al., 1986; Wallin & Solheim, 2005). Member states of the European Union Water Framework Directive use expert judgement to describe reference conditions for aquatic ecosystems when it is not possible to use modelling or spatial comparisons (Wallin et al., 2003). Expert assessment has also been used in New Zealand for producing environmental pressure estimates on rivers (e.g. Leathwick & Julian, 2007) and lakes (De Winton et al., 2009) and for incorporating cultural perspectives and values into river management and decision making in New Zealand (Tipa & Tierney, 2006).

The EI ranks determined independently by three experts in this study were very similar to each other (average $r^2 = 0.79$) suggesting a common, intuitive understanding of existing lake conditions, and probable departures from individual, pristine, reference conditions. It is interesting to note that the EI ranks determined by expert assessment were more strongly correlated with measured limnological variables than any of the WoNI pressure indices (Tables 4, 6). Similarly, the EI ranks were more closely correlated with the WoNI pressure indices than any measured lake variables (Table 5; Fig. 2). Expert assessments may (i) integrate many potentially interacting processes and factors that are difficult to capture with

one-point-in-time or infrequent limnological measurements and statistical analyses, (ii) incorporate the benefits of years of research experience, (iii) integrate lake and landscape characteristics and (iv) include an understanding of time-related processes, interactions and non-linear processes that models based solely upon limited data may not capture.

Science and management face significant challenges in determining appropriate target conditions for the conservation, management and restoration of New Zealand's shallow coastal lakes. First, very few historical data from shallow coastal lakes are available. Second, unimpacted reference sites are rare in many regions. Third, new data collections at the national scale are labour intensive and costly and, therefore, struggle to capture natural variability. Nevertheless, the need to make informed management decisions about aquatic resources continues to increase with growing human populations and land use intensification. Our results suggest that if EI determination is to be integral to policy development and management, it will require expansion of national-scale datasets, and it may be useful to incorporate expert site assessments into the model.

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