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LakeSPI critical appraisal for monitoring Waikato Lakes

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LakeSPI Critical Appraisal for Monitoring Waikato Lakes

Invasive oxygen weed, *Lagarosiphon major* (M. Schallenberg)

Hydrosphere Research Report 2018-01 prepared for the Waikato Regional Council by:

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Executive Summary

The Waikato Region has around 100 named lakes and despite water quality being routinely measured in many of them, little is known about the broader ecological health of these lakes. The LakeSPI index is an indicator of lake macrophyte community health and The Waikato Regional Council has commissioned many LakeSPI assessments on the region's lakes since 1981. The purpose of this report is to explore whether LakeSPI is a robust ecological indicator of lake health.

LakeSPI and trophic state data was provided by the Waikato Regional Council for this analysis. Our critical appraisal of the LakeSPI indicator broadly follows published evaluation guidelines for ecological indicators, focusing on the conceptual relevance, response variability and interpretation and utility of the index. We also critically evaluate some of the abilities of the LakeSPI index originally promoted by the index's developers.

The Waikato LakeSPI data was only weakly correlated with TLI (trophic level index), both when assessed among the Waikato lakes and within some of the lakes (i.e. over time). This indicates that the information about lake condition provided by LakeSPI is not strongly linked to the drivers of lake trophic state and, therefore, LakeSPI information provides another conceptual dimension with which to assess lake health. This can be especially useful for assessing shallow lakes, which are challenging for TLI to accurately assess due to strong benthic-pelagic coupling (e.g., wind-induced sediment resuspension, high rates of benthic primary productivity, etc).

Macrophytes are important components of most lake ecosystems. Therefore, LakeSPI undoubtedly has some relevance to lake functioning. However, because LakeSPI is a complex index derived from many different measurements and estimates of the macrophyte community, the specific interpretation of the functional significance of LakeSPI is complicated. For example, LakeSPI focuses on certain characteristics of the macrophyte community such as the presence and cover of invasive species, the diversity of native species, the depth distributions and percentage cover of both native and invasive communities, and the height of invasive species. When these, and other, assessments are amalgamated into the LakeSPI index, interpretation of the index can be challenging. This difficulty is somewhat ameliorated by also considering the two sub-indices which comprise LakeSPI: the Native Condition Index and the Invasive Impact Index. However, as common with multicomponent indices, they are normative, conveying high-level information about attributes that are human constructs, not fundamental processes. Normative indices reflect attributes that have complex definitions, often reflecting human perspectives on ecosystem structure and function (e.g., ecosystems health, ecosystem integrity, etc.), which incorporate human values. Thus, normative indices can be useful for management, but careful consideration must be given to how such indices align with monitoring and planning goals and with the lake values that managers must ultimately manage lakes for. For example, the LakeSPI index considers invasive macrophytes to have only negative impacts on lakes – potential ecosystem services afforded by non-native species are not valued in LakeSPI.

When LakeSPI assessments are carried out at intervals of ≤ 5 years, LakeSPI assessments can be very useful in tracking potentially complex temporal dynamics of aspects of the macrophyte community of a lake. Important features of lake temporal dynamics such as whether the macrophyte communities show slow, rapid and/or non-linear changes over time can be shown and, thus, inferences about ecological resistance, resilience, tipping points and hysteresis in relation to pressure gradients can be made. If concomitant information on pressures is available, then tipping points or thresholds between alternate stable states may be defined. Such information should be very useful to lake managers.

However, we argue that LakeSPI is not so much a robust indicator of specific pressure gradients in lakes, but is more accurately a measure of the departure of a lake's macrophyte community from that expected to have occupied the lake prior to European arrival in New Zealand (prior to European influences on lake ecology). This role of LakeSPI depends strongly on a calibration of the modern-day LakeSPI assessment scores against estimates of pristine LakeSPI scores. The calibration procedure is not appropriately explained and justified in the documentation supporting the method and, therefore, the calibration procedure may be a weakness in the LakeSPI methodology.

Being a measure of departure from reference conditions, LakeSPI is a useful tool for lake restoration when achieving the "pre-European" condition of the macrophyte community (or an approximation thereof) is the restoration goal. In such circumstances, LakeSPI scores are direct measure of restoration progress or success.

The decision about which measures are included in an index is a subjective decision. As with many ecological indices, the amalgamation of multiple measurements into the index creates advantages and disadvantages when it comes to interpretation. Careful thought must be given as to whether the individual measures that contribute to LakeSPI or its amalgamated index scores are better aligned to the Waikato Regional Council's monitoring and planning goals. Further analysis of individual metrics of the index may yield deeper understanding of the index's information value and how it best aligns to management goals.

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1. Introduction

There are around 100 named lakes in the Waikato Region, including peat lakes, riverine lakes, dune lakes, lakes of volcanic origin and run-of-the-river reservoirs. Many of the region's lakes have been impacted by land use, drainage, vegetation clearance, sediment and nutrient inputs and the impact of invasive flora and fauna. As such, many of the lakes are now degraded or degrading and are in poor condition. Lake ecological functioning, cultural values and ecosystem services including recreational activities such as kayaking, sailing, swimming and gamebird hunting are negatively affected by poor lake condition.

While water quality is monitored in a number of lakes, the broader issue of the ecological health/integrity of Waikato lakes is largely uncertain and few tools are available to provide an integrated assessment of lake health/integrity. One of the tools available is the macrophyte-based indicator, Submerged Plant Indicator or LakeSPI (Clayton and Edwards 2006). LakeSPI is a lake health monitoring protocol and bioindicator, carried out by aquatic botanists at the National Institute of Water and Atmospheric Research (NIWA). It is based on assessments by SCUBA divers of lake macrophyte communities and coverage, including information about the native and invasive macrophyte communities, native diversity, depth distributions and percentage cover.

Lake macrophyte communities are assessed in many countries to determine ecological condition or "lake health" and to assess the conservation value of lakes. For example, in the United Kingdom, information on macrophyte communities is recorded for over 4000 sites and in the USA a variety of government and community environmental organisations survey and quantify lake macrophyte communities (Duker & Palmer 2009). In the USA, the Nature Conservancy and the Vermont Biodiversity Project jointly developed a classification scheme for standing waters based on macrophyte communities (Langdon et al. 1998). And in Sweden, submerged and floating macrophytes are used for water quality assessment and conservation prioritisation of the country's lakes (Willén 2009). The attention given to aquatic plants as indicators of ecological condition and conservation value acknowledges the important and diverse structural and functional ecological roles that macrophytes play in lake ecology (Pokorný & Květ 2004).

Ideally, the monitoring of aquatic plant communities should provide valuable information for identifying policy responses and making resource management decisions by complementing information obtained from water quality monitoring. The Waikato Regional Council has LakeSPI assessments dating back to 1981 and it is now timely to evaluate the suitability of this ecological indicator for its lakes monitoring program.

LakeSPI has been promoted to answer a wide range of lake management questions (Clayton & Edwards, 2006) and the Waikato Regional Council specifically posed the following questions for consideration in this report:

Lake condition generally

- **Is the overall condition of a lake improving or declining?**
- How can I prioritise lakes in my region?

Are lakes in this region or area improving or declining?

- **Is the water clarity improving or deteriorating for this lake/lakes in this region?**
- **What is the rate of this improvement or decline?**
- **Is the lake condition typical for a lake of this type (in this region)?**

Invasive alien plants

- **How pervasive has alien plant invasion been in this lake? How many invasive species are there? Which species are present?**
- What is the current regional or national distribution and relative abundance of alien plant species in lakes?
- **How vulnerable is this lake to (further) impact from invasive plant species? What sorts of impacts are possible?**

Native plant communities

- **What is the quality of the native plant communities in this lake? Is there a good diversity of native plant communities or have they been largely or entirely replaced by invasive alien species?**
- Are there lake attributes (e.g., native plant communities) that require special management? What type of management would be needed?
- **How do the existing plant communities in a lake/group of lakes compare to pre-European/ pre-human times?**

Restoration goals

- **What would be the appropriate restoration goals for water clarity and plant communities given the lake type and its current state?**

The Waikato Regional Council has indicated that the above questions in bold font are those of greatest relevance for this review of the LakeSPI indicator, although the other questions will also be discussed, but in less detail.

2. Scope

2.1 Framework for critical appraisal of indicators

The structure of this review is based on the evaluation guidelines for ecological indicators proposed by Jackson et al. (2000). Although these guidelines have not been adopted by the Waikato Regional Council, they provide a useful framework for critically reviewing the LakeSPI. The four key issues that the guidelines relate to are: (1) conceptual relevance, (2) feasibility of implementation (3) response variability, and (4) interpretability and utility. It was agreed that (2) would be outside the scope of this review and is therefore not discussed in detail.

(1) Conceptual Relevance

Indicators must provide information that is relevant to societal concerns about ecological condition and they should clearly pertain to one or more identified assessment questions, which should directly relate to management decisions. Often, the selection of a relevant indicator is obvious from the assessment question and from professional judgement.

Guideline 1: Relevance to the Assessment

Proposed indicators must be responsive to an identified assessment question and should provide information useful to a management decision. For indicators requiring multiple measurements (indices or aggregates), the relevance of each measurement to the management objective should be identified. In addition, indicators should be evaluated for their potential to contribute information in the context of a suite of potential indicators designed to address multiple assessment questions. The ability of a proposed indicator to complement other indicators at other scales and levels of biological organization should also be considered. Some redundancy with existing indicators may be permissible.

Guideline 2: Relevance to Ecological Function

Indicators must be conceptually linked to the ecological function of concern. A conceptual model can be useful if an indicator is an index and, in this case, the relevance of each index component to ecological function and to the index should be described. A description of the principal stressors that are presumed to impact the indicator should be provided, as well as an indication of the resulting ecological response.

(3) Response Variability

The numerical values of useful indicators should co-vary with stressor or condition gradients. However, indicators may show variability due to a number of sources of variation including measurement error and natural spatial and temporal variation (stochasticity). Some types of variation must be isolated and quantified in order to interpret indicator responses. If an indicator is composed of multiple measurements, variability should be evaluated for each measurement as well as for the resulting indicator.

Guideline 8: Estimation of Measurement Error

The collection, transportation and analysis of ecological samples and data generates errors that can obscure the ecological signal of an indicator. Estimates of variation due to human and instrument error should be reported for the indicator.

Guideline 9: Temporal Variability - Within the Field Season

Within-field season indicator variability should be estimated and evaluated. An optimal time frame, or index period reduces extraneous temporal variability (noise). The use of a specific index period should be considered and the variability within the index period should be estimated and evaluated.

Guideline 10: Temporal Variability – Inter-annual

Inter-annual variation in indicator values attributable to weather, succession, population cycles or other natural inter-annual variations should be examined to ensure that indicators provide an accurate estimate of ecological condition.

Guideline 11: Spatial Variability
For regional-scale assessments, indicator responses to various environmental conditions should be consistent across the monitoring region. Sites within the reporting region having similar ecological conditions should exhibit similar indicator results. If spatial variability occurs due to regional differences in physiography or habitat, either indicators should be normalized across the region, or the reporting should be divided into more homogeneous units.

Guideline 12: Discriminatory Ability
An indicator should be able to discriminate sites along a condition gradient. Extraneous variability must not dominate the ecological signal in the indicator data.

(4) Interpretation and Utility
Useful ecological indicators must produce results that are understood and accepted by scientists, policy makers, and the public. Statistical limitations of an indicator's performance should also be understood and accounted for. Ranges of indicator values must be calibrated so that they indicate acceptable, marginal, and unacceptable ecological states. Finally, indicator data should be presented so that their relevance for specific management decisions and public acceptability is understood.

Guideline 13: Data Quality Objectives
The efficacy of indicator data should be evaluated in relation to program data quality objectives and constraints. How sample size, monitoring duration, and other variables affect the precision and confidence levels of reported results should be described, as well as how these variables may be used to optimize indicator assessment. Statistical power curves can be used to determine the effects of different optimization strategies on indicator performance.

Guideline 14: Assessment Thresholds
Stressor-response relationships should be understood so that thresholds and ranges of acceptable and unacceptable ecological condition can be determined and documented. Indicator thresholds can be determined based on documented thresholds, regulatory criteria, historical records, experimental studies, or other information. Thresholds should include safety margins accounting for stochasticity and other "risk" factors.

Guideline 15: Linkage to Management Action
Indicators should provide relevant information to support management decisions. Policy-makers and resource managers should be able to understand the implications of indicator results for stewardship, regulation, or research. Indicators should exhibit the following characteristics: responsiveness to a specific stressor, linkage to policy, relevance for cost-benefit assessments, limitations and boundaries of application, and public understanding and acceptance.

It is appreciated that the National Institute of Water & Atmospheric Research is currently in the process of producing an updated version of the user manual. However, the Waikato Regional Council considers the evaluation of LakeSPI in relation to the currently available documents appropriate because the documents were used to inform decisions about monitoring of the Waikato lakes using LakeSPI.

2.2 Data Sources

Currently, the Waikato Regional Council carries out regular water quality monitoring in 12 lakes. In addition to the datasets for these lakes, water quality samples were also taken from about 50 lakes in the Waikato Region at irregular time intervals between 1980 and 2016.

The latest LakeSPI assessment in the Waikato Region encompassed a total of 65 lakes. The Waikato Regional Council aims to revisit particular lakes for LakeSPI assessments every 5 years and more lakes will be added to the list every year as part of the ongoing "data deficient lakes survey" that aims to fill knowledge gaps of lakes that have never been assessed systematically.

The LakeSPI index (LSI) dataset used for this analysis included submerged plant data for 43 Waikato lakes (133 samples in total), with entries dating back to 1981. In addition to LSI, components of the LakeSPI index were also analysed, including: Native Condition Index (NCI), Invasive Impact Index (III), lake maximum depth, maximum depth of natives, maximum depth of charophyte meadows, maximum depth of invasives and maximum height (length) of invasives. LakeSPI data was recorded for each sample site, most often with 5 sampled transects (sites) per lake. Therefore, we averaged LakeSPI indices from all sampling sites within a lake, resulting in one overall index value per lake, per sampling event. The LakeSPI metrics that constitute the LakeSPI indices are maximum values, again recorded per site. Thus, when analysing the metrics, the maximum values per lake were used. Assessments with no submerged vegetation present (LakeSPI index = 0) were not included in the principal components analysis of LakeSPI variables; as a result, data from only 13 lakes with 51 assessments in total were used for these analyses.

TLI was calculated for all lakes that had corresponding LakeSPI data using both TLI3 (Σ (TLc + TLp + TLn)/3) and TLI4 (Σ (TLc + TLs + TLp + TLn)/4) equations using the statistical equation outlined in Burns et al. (2000). TLI scores for the year immediately preceding each LakeSPI sampling date were averaged and used in this analysis so as to minimise the potential influence of unusual one-off water quality samples, thus giving a more typical TLI score to compare with corresponding LakeSPI samples. In total, the dataset used for all comparisons of TLI (and TLI components) with LakeSPI indices (and components) comprised 75 samples across 30 lakes.

Temporal analysis of LakeSPI indices was undertaken using lakes for which there were ≥ 5 LakeSPI assessments through time, resulting in a dataset comprising 7 lakes and a total of 96 samples. Temporal comparisons of corresponding LakeSPI and TLI data used the same ≥ 5 assessment threshold, resulting in 3 lakes with a total of 38 samples. The LakeSPI methodology was formalised in 2006. Assessments of LakeSPI prior to 2006 were calculated from earlier lake vegetation survey data (Edwards et al. 2007), however it is unclear how the accuracy of retrospective LakeSPI assessments compares to the accuracy of more recent LakeSPI assessments. Presumably, the retrospective assessments are less accurate because they didn't adhere specifically to the LakeSPI sampling protocols as outlined in Clayton & Edwards (2006).

Finally, the data requirements for the comparison between the most recent LakeSPI and TLI data were that data had to be the most recent recorded sampling event. Lakes with the most recent assessment occurring more than 20 years ago were excluded from the analysis. This resulted in a dataset of 30 lakes with 30 total samples.

The metadata relating to the different data sets used for the different analyses are presented in Table 1.

Table 1. Metadata for the different analyses used in this report.

Analysis	*Data Requirements*	*# of Lakes*	*# of Samples*
LakeSPI Correlation and PCA	LakeSPI variables, excluding samples with no submerged vegetation (i.e. LakeSPI = 0)	43	133
TLI correlation and PCA	TLI variables averaged from the year prior to each LakeSPI sample (when corresponding data are available)	30	75
TLI and LakeSPI correlation	LakeSPI and TLI variables (averaged from the year prior to each LakeSPI sample) when corresponding data are available	TLI3: 30 TLI4:27	TLI3: 75 TLI4:60
TLI and LakeSPI correlation (only latest samples)	LakeSPI and TLI3 variables (averaged from the year prior to each LakeSPI sample) using only the most recent sample for each lake	30	30
Redundancy Analysis	LakeSPI and TLI variables (averaged from the year prior to each LakeSPI sample) excluding samples that lack all submerged vegetation (i.e. LakeSPI = 0)	51	13
TLI and LakeSPI regression Serpentine East, North, South			Serp East: 14 Serp North: 17 Serpt South: 7
LakeSPI indices over time	Lakes with >=5 LakeSPI samples	7	Otamatearoa: 6 Parkinson: 5 Rotoroa (Ham): 23 Serp East: 20 Serp North: 18 Serp South: 17 Waahi: 7
Seasonal Variability	Spring samples with corresponding Autumn samples taken in the same year.	7	13
Spatial Variability	Peat lakes and other shallow lakes	Peat: 11 Shallow: 14	Peat: 11 Shallow: 14

3. Conceptual relevance of LakeSPI

3.1 Relevance to assessment needs

Submerged macrophyte communities play key roles in lake functioning (Pokorný & Kvêt 2004), especially in shallow lakes (Scheffer 2004), including supporting lake productivity and biodiversity and in sediment stabilisation. Macrophytes also provide important ecosystem services to lakes, mainly in relation to ecological support and regulation, but also in support of waterfowl provisioning and cultural ecosystem services (Schallenberg et al. 2013).

While their importance in regulating water quality has also been highlighted (Schallenberg & Sorrell 2009; Schallenberg et al. 2017), specific macrophyte indicators are absent from the National Objectives Framework (e.g., MfE 2017) and often absent from regular national-scale lake reporting (e.g. MfE 2015, but see Verburg et al. 2010). However, Waikato Region's Shallow Lakes Management Plan (WRC 2014a, b) acknowledges the importance of macrophytes in the health of Waikato shallow lakes by including LakeSPI monitoring, in addition to nutrient monitoring, as an important lake assessment tool.

Particularly relevant to this review are Objective 6 and Strategy 6.1 in the Waikato Regional Council (WRC) Shallow Lakes Management Plan (WRC 2014a), which are:

Objective 6: *Sufficient information is collected from shallow lakes to assess and report upon their condition (WQ and ecological health), and to assess the effectiveness of WRC's policy and planning framework and shallow lake management programmes.*

Strategy 6.1: *WRC's water quality and environmental indicator monitoring programmes are reviewed to ensure that they are adequate for SOE reporting, reporting upon the effectiveness of shallow lakes management & restoration programmes, and NPS reporting (i.e. monitoring shallow lakes with eutrophic or better WQ).*

The following section explores the conceptual relevance of the LakeSPI indicator in relation to the objectives and strategies of the WRC's Shallow Lakes Management Plan.

3.1.1 What is LakeSPI?

LakeSPI (Submerged Plant Indicator) is a biological indicator developed to assess "the departure of lake submerged vegetation from an expected or potential state, based on a range of ubiquitous vegetation features common to the majority of New Zealand lakes" (McDonald et al. 2013). LakeSPI is also used to monitor the ecological condition of New Zealand Lakes through the presence or absence of native and invasive submerged plants. Three indices are produced, pertaining to: (1) the condition of native submerged plants (Native Condition Index; NCI), (2) the impact of invasive submerged plants on the lake (Invasive Impact Index; III) and (3) the overall LakeSPI index (LSI) which relates to the ecological health of the lake (Clayton & Edwards 2006). Sometimes in the LakeSPI literature NCI and LSI are referred to as scores rather than indices. While these terms are synonymous, in this report we use the term index in relation to these metrics because they aggregate different scores. Higher NCI and LSI are taken to represent a healthier lake, while a higher III is representative of a degraded lake with poorer ecological health. Metrics relating to native plant condition such as the maximum depth of natives and charophyte meadows, the native plant ratio and scores calculated for native diversity and distribution are combined with invasive metrics such as invasive plant ratio, maximum invasive plant height and metrics calculated for invasive impact, invasive depth impact and nature of invasive cover. These are combined to give an overall LakeSPI index number (Figure 1), which is calibrated for each lake and scaled to a percentage such that a LakeSPI of 100 corresponds to a pristine lake condition (Clayton & Edwards 2006).

LakeSPI is intended to compliment other lake assessment attributes that can vary on short time scales (e.g., water quality grab sampling, which can be strongly affected by wind conditions immediately prior to sampling) by using macrophyte indicators, which integrate environmental conditions related to plant growth over a period of time prior to sampling. The integration time is not specified, but it is recommended that LakeSPI be assessed at 5-yearly intervals (Clayton & Edwards 2006). The method does not detect special or unusual vegetation features that represent specific ecological values such as unique community assemblages or populations of threat-status species (McDonald et al. 2013).

Although macrophyte community health is a normative concept (incorporating values and estimates of reference conditions), LakeSPI scores can be compared across lakes because the index scores are scaled in relation to the maximum potential scores for each lake (i.e., how close a lake is to its best possible condition). Conceptually, the quantification of departure from reference condition and the scaling of the index scores to allow across-lake comparisons is attractive for lake health assessment and reporting. However, the calibration of LakeSPI to lake-specific reference conditions involves the use of some assumptions, including:

(1) native plant species and high plant diversity represent healthier lakes or higher lake condition;
(2) invasive plant species are undesirable due to their potential to displace natives and to adversely affect ecological condition;
(3) maintaining an exotic plant community in good condition is preferable to total collapse of the vegetation community leading to algal dominance;
(4) the deeper the submerged plants are able to grow, the better the ecological condition of the lake;
(5) sites surveyed in a lake are representative samples of the wider submerged plant community in that lake (McDonald et al. 2013).

Specific calibration assumptions are applied via the use of lake depth (using a depth calibration table in Clayton & Edwards 2006), which dictates a maximum scoring potential for the LakeSPI metrics, where maximum scores are set to reflect the “pre-European” condition of the macrophyte community of each lake (Clayton & Edwards 2006). Sometimes other information is used to adjust the calibration to reference conditions, including: (1) corrections for naturally turbid waters (Clayton & Edwards 2006), (2) historical information (where available) on macrophyte communities prior to substantial human impacts (Edwards et al. 2007; 2010), and (3) expert opinion (Edwards et al. 2010), which presumably could include consideration of the influence of other factors that can affect macrophyte distribution in lakes such as substrate type, water colour, etc. Thus, the important calibration step is somewhat subjective, relying on expert knowledge embodied in the depth calibration table and sometimes in other corrections/adjustments.

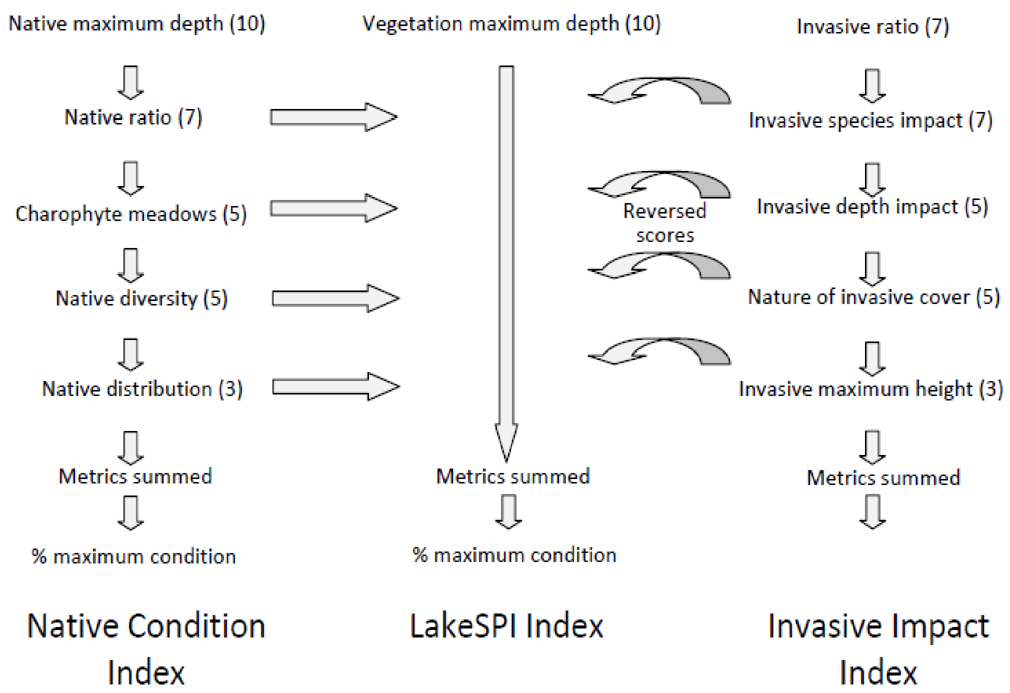

Figure 1. Flow diagram of features used to calculate Native Condition Index, Invasive Impact Index and LakeSPI Index. Source: McDonald et al. (2013).

The calibration step also involves scaling the results as a percentage change from reference condition and this scaling of the information to a percentage imposes a certain dispersion of the data. In LakeSPI, calibration is undertaken to help lake managers make useful comparative assessments (i.e., comparison with reference condition and also comparison among lakes). However, a number of assumptions used for calibration and percentage scaling can be seen as weaknesses of the method in generating robust and/or reproducible assessments of macrophyte community health.

LakeSPI aggregates a number of different sets of data and metrics relating to the macrophyte community (Figure 2) and, as a result, LakeSPI is influenced by a number of different measurements, scores, calibrations and transformations. Thus, the information amalgamated is likely to be multi-dimensional. In the following section, we examine the correlation structure among different components of the LakeSPI index and the LakeSPI index, itself. The analyses are based on data for the Waikato lakes.

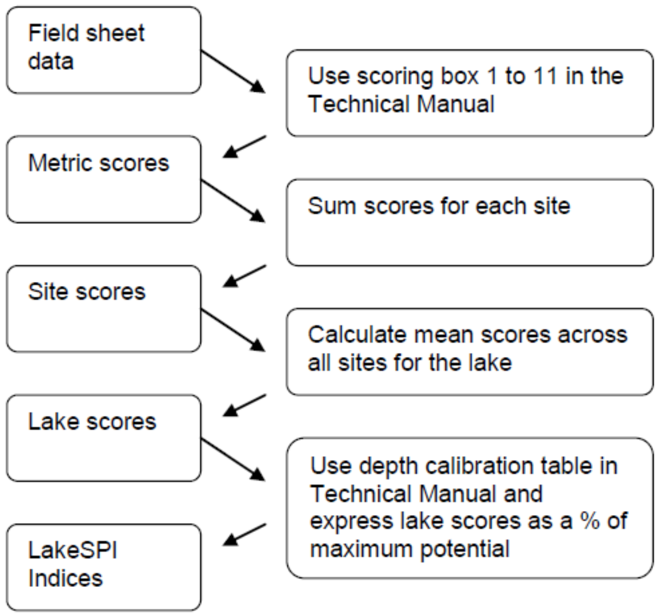

Figure 2. Flowchart showing calculation steps in deriving LakeSPI scores. Source: McDonald et al. (2013).

First, we look at the correlation structure between the scored metric components of LakeSPI, the sub-indices, and the overall LakeSPI index (Table 2). This correlation matrix uses data from all assessed transects (not averaged for each lake) and shows strong correlation structure and redundancy within the invasive components, but weaker correlation structure among the native components. The native:invasive ratio is more strongly correlated with the invasive components, indicating that information from the invasive plant community may have a strong influence on the ratio and on the LakeSPI index as well. The strong inter-correlations among invasive scores suggests that a reduction in the number of invasive assessments carried out in the Waikato Lakes may be feasible without affecting the LakeSPI or III to a great extent. For example, the estimation of invasive cover alone is almost perfectly correlated with the III (r = 0.97), suggesting that the estimation of other invasive scores and attributes contributes little additional information to the III and LakeSPI assessments. Table 2 indicates that in the Waikato Lakes, the LakeSPI score is more strongly influenced by the invasive component scores than by the native component scores.

To calculate a LakeSPI score for a lake, the calculated index values for each transect in the lake are averaged. The resulting lake-wide LakeSPI index scores are reported for individual lake assessments and are used when comparing macrophyte communities among lakes. As expected from the negative weighting of invasive macrophytes in LakeSPI, the LakeSPI index is strongly positively correlated with the NCI (r = 0.93) and strongly negatively correlated with III (r = -0.82) in the Waikato lakes (Table 3).

Table 2. Pearson correlation matrix of LakeSPI component metrics, sub-indices, and the LakeSPI index scores. Data are from transects assessed in Waikato Regional Council lakes and excluded transects where LakeSPI was zero (transect was devegetated). $N = 598$ samples. Where $0.50 \leq r < 0.70$, cells are shaded yellow. Where $0.70 \leq r < 0.90$, cells are shaded orange. Where $0.90 \leq r < 1.00$, cells are shaded red.

	Plant max depth	*Native max depth*	*Charophyte meadow*	*Native diversity*	*Native distribution*	*Native-Invasive Ratio*	*Invasive species impact*	*Invasive max depth*	*Invasive height*	*Invasive cover*	***Native Condition Index***	***Invasive Impact Index***	***LakeSPI***
Plant max depth	1.00												
Native max depth	0.46	1.00											
Charophyte meadow	0.19	0.70	1.00										
Native diversity	0.00	0.50	0.46	1.00									
Native distribution	0.33	0.50	0.45	0.24	1.00								
Native-Invasive Ratio	-0.45	0.22	0.41	0.36	0.00	1.00							
Invasive species impact	0.49	-0.09	-0.31	-0.22	0.03	-0.88	1.00						
Invasive max depth	0.38	-0.12	-0.30	-0.20	0.03	-0.88	0.86	1.00					
Invasive height	0.50	-0.06	-0.25	-0.18	0.12	-0.86	0.92	0.87	1.00				
Invasive cover	0.50	-0.02	-0.21	-0.17	0.13	-0.90	0.88	0.92	0.91	1.00			
Native Condition Index	-0.38	0.34	0.54	0.59	0.06	0.88	-0.75	-0.75	-0.74	-0.74	1.00		
Invasive Impact Index	0.48	-0.12	-0.32	-0.25	0.05	-0.95	0.95	0.95	0.94	0.97	-0.82	1.00	
LakeSPI	-0.44	0.16	0.39	0.35	-0.03	0.95	-0.92	-0.93	-0.91	-0.93	0.91	-0.97	1.00

During the LakeSPI assessment, macrophyte depth distributions are measured (i.e. lake maximum depth, charophyte maximum depth, native maximum depth and invasive maximum depth) and invasive macrophyte height measurements are made. These measurements provide the opportunity to assess the influence of measured data (prior to converting to metric scores/calibration) on the LakeSPI indices. The correlation matrix in Table 3 again highlights the strong influence of invasive macrophyte measures on the LakeSPI indices within the Waikato Lakes dataset. It is interesting to note that the effect of native macrophytes becomes more strongly related to LSI after scoring and aggregating the data, as is indicated by the higher correlation of NCI than III vs LSI in Table 3. Nevertheless, the maximum invasive height and maximum invasive depth are strongly correlated with LSI, III and even NCI, whereas the correlations with charophyte and native maximum depths are weaker. The moderately strong negative correlation between lake maximum depth and LSI is curious and may be related to the calibration against lake depth that is undertaken within LakeSPI calculation procedure (Clayton & Edwards 2006; McDonald et al. 2013). If the calibration is valid, deeper lakes in the Waikato Region exhibit poorer macrophyte health in relation to reference conditions. This should be verified.

Table 3. Pearson correlation matrix of measured LakeSPI variables, sub-indices and the LakeSPI index. Data are from Waikato Regional Council lakes and excluded samples where LakeSPI was zero (lakes were devegetated). *N* = 133 samples, 43 lakes. NCI – Native condition index. III – Invasive Impact Index. LSI – LakeSPI index. Yellow shading indicates 0.05 ≥ *P* > 0.01, orange shading indicates 0.01 ≥ *P* > 0.001 and red shading indicates P ≤ 0.001.

	Lake max depth	*Max depth natives*	*Max depth charophyte meadows*	*Max depth invasive*	*NCI*	*III*	*LSI*	*Max invasive height*
Lake max depth	1.00							
Max depth natives	-0.07	1.00						
Max depth charophyte	-0.13	0.92	1.00					
Max depth invasive	0.78	0.17	0.08	1.00				
NCI	-0.49	0.29	0.36	-0.56	1.00			
III	0.48	-0.01	-0.10	0.79	-0.67	1.00		
LSI	-0.42	0.17	0.25	-0.63	0.93	-0.82	1.00	
Max invasive height	0.66	0.04	-0.04	0.80	-0.58	0.79	-0.67	1.00

The correlation structure in Table 3 can be visualised in the principle components analysis biplot shown in Figure 3, where the strong gradient of native condition index and invasive impact index dominate axis 1. This axis is correlated both to the LakeSPI index and to the maximum depth of invasives, but is poorly correlated to the maximum depth of natives and charophytes.

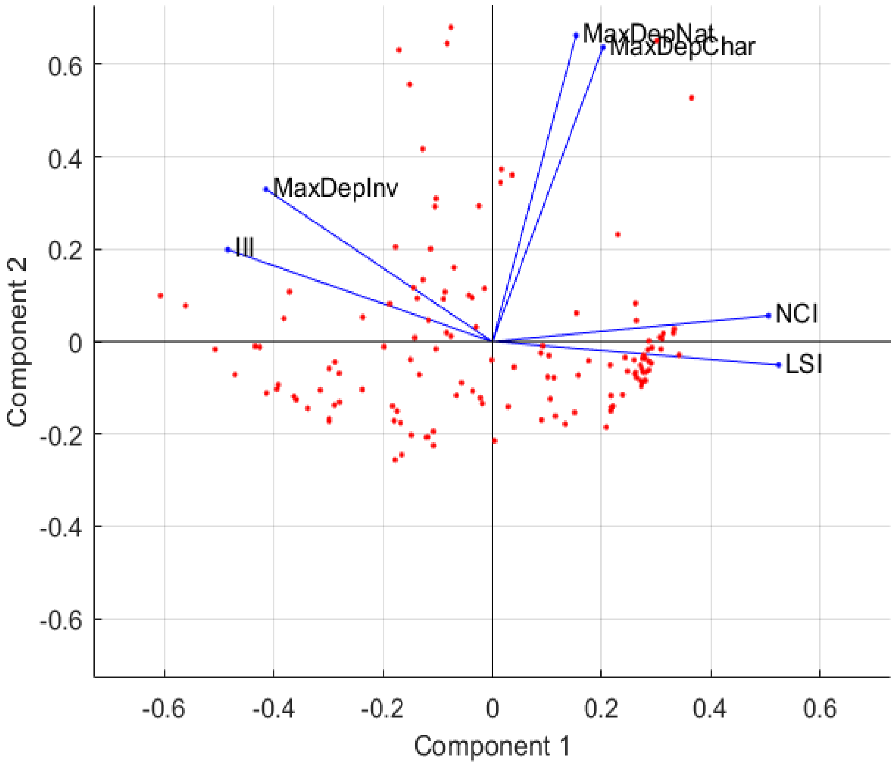

Figure 3. Principal components analysis of LakeSPI variables LakeSPI Index (LSI), Native Condition Index (NCI), Invasive Impact Index (III), Maximum depth of Invasives, Maximum depth of Natives and Maximum depth of Charophytes. This analysis is based on the correlation matrix in Table 3.

3.1.2 Relationship to trophic level index (TLI)

To assess the conceptual relevance of LakeSPI as a lake monitoring tool, it is important to discern how LakeSPI fits into the set of freshwater values for which lakes are monitored. While many values of lakes may be identified, such as fisheries, mahinga kai, swimming, nutrient sequestration, etc., generally water quality is the only value formally monitored in New Zealand lakes or mandated by central government (MfE 2017). The National Objectives Framework specifies national guidelines for chlorophyll a, total nitrogen and total phosphorus, three of the four components of the trophic level index (TLI; Burns et al. 2000). The TLI also includes Secchi depth (water clarity) but this is specified mainly for lakes > 10 m depth because wind-induced sediment resuspension can interfere with assessment of the trophic state of polymictic lakes. For such lakes, the TLI3 is often used as a more reliable measure of trophic state (TLI3 omits water clarity).

WRC monitors water quality using TLI in a number of Waikato lakes. A key question regarding the relevance of LakeSPI monitoring in the context of the Waikato Shallow Lakes Management Plan is: does LakeSPI provide similar or complementary information to TLI? In this section, we explore the relationship between TLI and LakeSPI in the WRC lakes dataset to help answer this question.

First, we examine the correlation structure among component TLI variables and the TLI indices to help understand the meaning of TLI in the monitored set of Waikato lakes. Table 4 shows that TLI3 and TLI4 are very strongly correlated in this dataset and that variation in TLI in the Waikato lakes is related mainly to total phosphorus (TP) and chlorophyll *a* (Chl *a*), with Secchi depth being weakly correlated and total nitrogen (TN) showing the poorest correlation to TLI.

Table 4. Pearson correlations among TLI indices and TLI components in Waikato lakes. N = 75 samples, 30 lakes. Yellow shading indicates $0.05 \geq P > 0.01$, orange shading indicates $0.01 \geq P > 0.001$ and red shading indicates $P \leq 0.001$.

	Log Chl a	*Log TN*	*Log TP*	*Log Secchi*	*TLI4*	*TLI3*
Log Chl *a*	1					
Log TN	0.39	1				
Log TP	0.88	0.46	1			
Log Secchi	-0.77	-0.30	-0.8	1		
TLI4	0.92	0.62	0.95	-0.9	1	
TLI3	0.92	0.68	0.94	-0.75	0.99	1

The principle component analysis biplot in Figure 4 visually shows the correlation structure among the TLI variables and indices, highlighting the strong correlations of TP and Chl *a* with trophic state and the weak correlation of trophic state with TN.

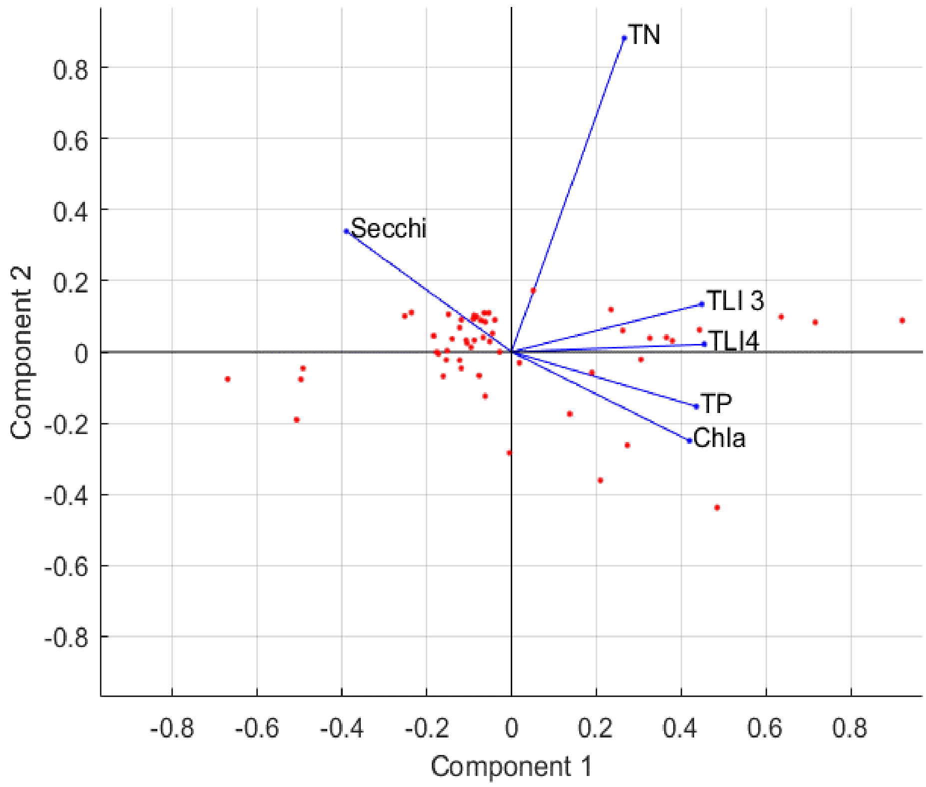

Figure 4. Principal Components Analysis of TLI components and indices: Secchi depth, TN, TP, Chla, TLI3 and TLI4. The biplot is based on the correlation matrix in Table 4.

3.1.3 The relationship between LakeSPI and TLI among Waikato lakes

To examine relationships between LakeSPI and TLI, we rationalised how best to compare the data. TLI scores for the year immediately preceding each LakeSPI sampling date were averaged and used in this analysis so as to minimise the potential influence of unusual, one-off water quality measurements, thus giving an annual mean TLI score to compare with corresponding LakeSPI samples. Setting up the comparison in this way accounts for the ability of macrophytes to integrate environmental conditions over time (Clayton & Edwards 2006). Devegetated lakes (LakeSPI = 0; includes lakes with <10% macrophyte coverage) were included in this analysis to see if the condition of devegetation was related to trophic state.

Figure 5 shows the relationships between the LakeSPI indices and TLI3 (4A) and TLI4 (4B) water quality indicators. It is apparent that there are no substantial trends between these indices within the Waikato lakes dataset, despite there being large ranges in both LakeSPI and TLI indicators. However, the graphs show that none of the lakes with a TLI below 4.3 were devegetated whereas many lakes with a TLI ranging from 4.3 – 8 were devegetated (i.e., with a LakeSPI index of 0). Within the TLI range of 4.5 to 5.5, distinct clusters of high NCI and LSI scores occurred while the III scores tended to be more variable. The clustering was due to multiple samples taken from some frequently sampled lakes, which returned a large number of similar scores. Therefore, we removed most of the samples from these frequently sampled lakes, leaving only the most recent single sample from each lake (Figure 6).

The lack of relationships between LakeSPI and TLI in these analyses indicates that LakeSPI is not an accurate indicator of trophic state in these lakes. Thus, LakeSPI potentially provides information about the state of health of the lakes that is complementary to TLI.

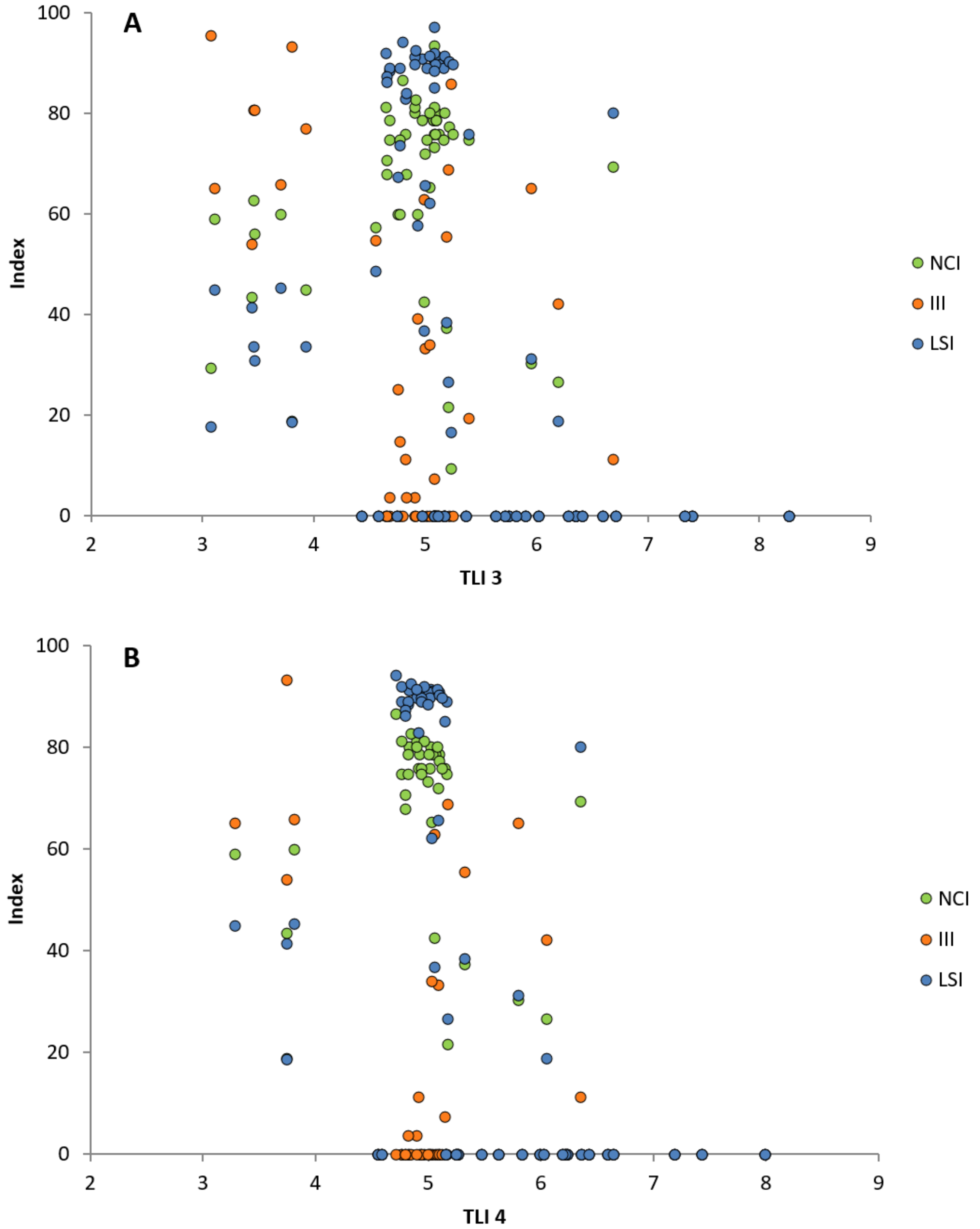

Figure 5. (A) LakeSPI indices Native Condition Index (NCI), Invasive Impact Index (III) and LakeSPI Index (LSI) samples with corresponding lake TLI3 values (*n* = 75 samples, 30 Lakes) and **(B)** with corresponding lake TLI4 values (*n* = 60, 27 lakes).

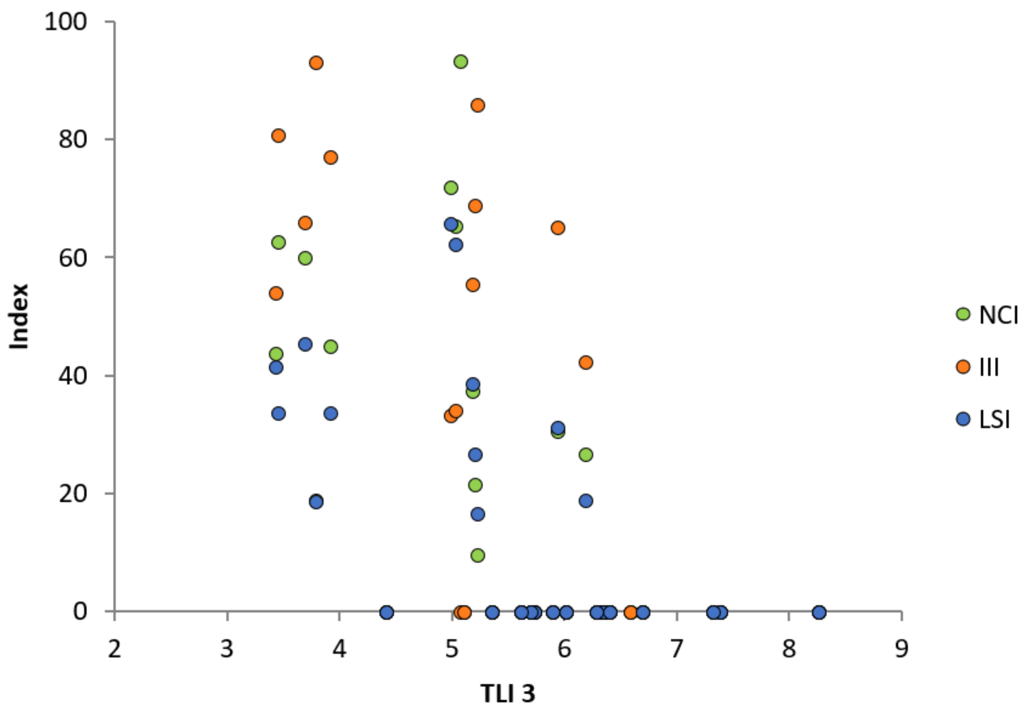

Figure 6. LakeSPI indices Native Condition Index (NCI), Invasive Impact Index (III) and LakeSPI Index (LSI) with corresponding lake TLI3 values using only the most recent sample for each lake (*n* = 30, 30 lakes).

The correlation matrix in Table 5 confirms that there are only weak statistical relationships between the TLI indices and the III and the LSI.

Table 5. Correlations between TLI and LakeSPI variables. Yellow shading indicates 0.05 ≥ *P* > 0.01, orange shading indicates 0.01 ≥ *P* > 0.001 and red shading indicates P ≤ 0.001.

	Log Chla	*Log TN*	*Log TP*	*Log Secchi*	*TLI4*	*TLI3*	*Lake max depth (m)*	*Max depth natives*	*Max depth charophyte meadows*	*Max depth invasive*	*Native Condition Index*	*Invasive Impact Index*	*LakeSPI Index*
Log Chla	1.00												
Log TN	0.54	1.00											
Log TP	0.83	0.52	1.00										
Log Secchi	-0.56	-0.46	-0.64	1.00									
TLI4	0.91	0.78	0.91	-0.75	1.00								
TLI3	0.93	0.76	0.92	-0.64	0.99	1.00							
Lake max depth (m)	-0.10	-0.37	-0.24	0.44	-0.38	-0.26	1.00						
Max depth natives	-0.37	-0.54	-0.37	0.49	-0.60	-0.48	0.15	1.00					
Max depth charophyte meadows	-0.38	-0.15	-0.32	0.40	-0.36	-0.34	-0.11	0.65	1.00				
Max depth invasive	-0.51	-0.61	-0.45	0.49	-0.57	-0.58	0.74	0.49	0.23	1.00			
Native Condition Index	0.15	0.37	-0.02	0.08	0.03	0.17	-0.52	-0.09	0.29	-0.71	1.00		
Invasive Impact Index	-0.52	-0.49	-0.31	0.15	-0.30	-0.50	0.48	0.34	0.05	0.88	-0.86	1.00	
LakeSPI Index	0.38	0.43	0.16	0.01	0.13	0.36	-0.45	-0.24	0.06	-0.82	0.93	-0.97	1.00

The correlation structure among the two sets of indices and their components shown in Table 5 was further explored via redundancy analysis (Figures 7 & 8). The biplots illustrated the weak correlations between TLI and LakeSPI indices. Only TN, Chl *a* and TLI3 correlated with the primary LakeSPI axis in the redundancy analysis using TLI3 and its components (Figure 7). When TLI4 and its components were tested, there were no strong correlations with the LakeSPI gradient (primary axis; Figure 8).

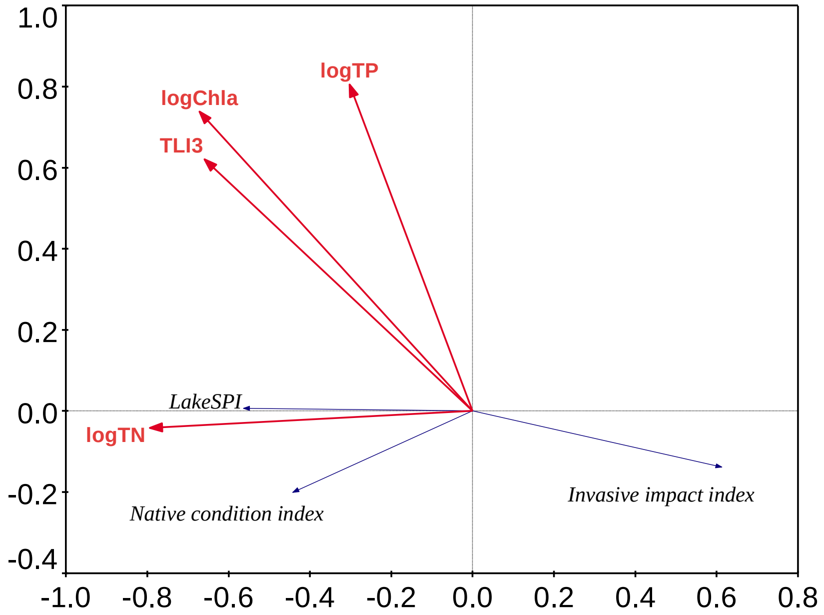

Figure 7. Redundancy analysis of Native Condition Index (NCI), Invasive Impact Index (III) and LakeSPI Index (LSI) with TLI3, Chl*a*, TN and TP, after removing samples that lack any submerged vegetation (*n* = 51, 13 lakes)

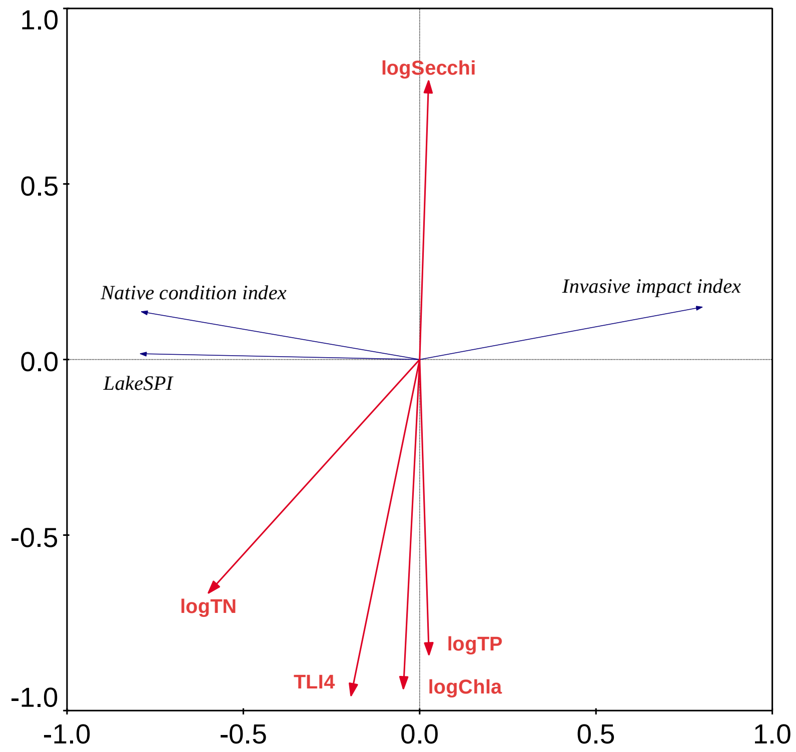

Figure 8. Redundancy analysis of TLI4, Chl*a*, Secchi depth, TN and TP with Native Condition Index (NCI), Invasive Impact Index (III) and LakeSPI Index (LSI) having removed samples that lack all submerged vegetation (*n* = 40, 11 lakes)

3.1.4 The relationship between LakeSPI and TLI for individual Waikato lakes

We demonstrated above that relationships between LakeSPI and TLI among Waikato lakes were weak at best. However, inter-lake differences and variation may obscure these relationships to some extent. WRC commissioned multiple LakeSPI assessments over time in a number of lakes for which TLI data also exist. Therefore, we compared within-lake relationships between TLI and LakeSPI for the three Serpentine Lakes because these have enough data to warrant comparisons (≥ 5 data points).

In Serpentine East, the TLI range is relatively restricted and there is little evidence that TLI and LakeSPI indices correlate over time (Figure 9).

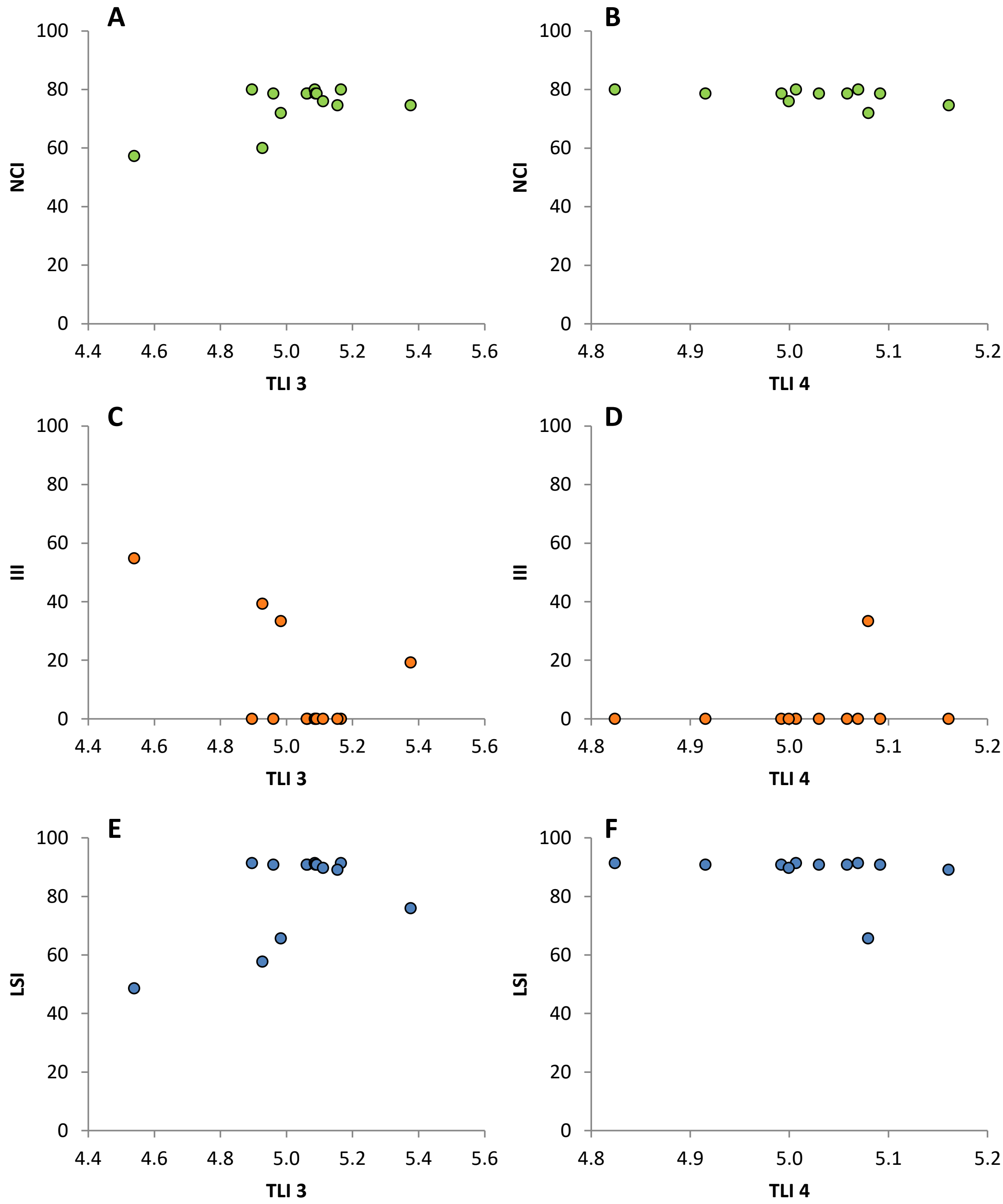

Figure 9. Relationships between TLI indices and LakeSPI indices in Lake Serpentine East (N = 14)

In Lake Serpentine North, the TLI range was greater due to one high TLI measurement in May 2014 (Figure 10). This outlier suggests that NCI may have decreased in association with the higher TLI measurement, however more data across the TLI range would be required to confirm such a relationship in this lake. Other than that, there were no indications of relationships between TLI and LakeSPI indices in this lake.

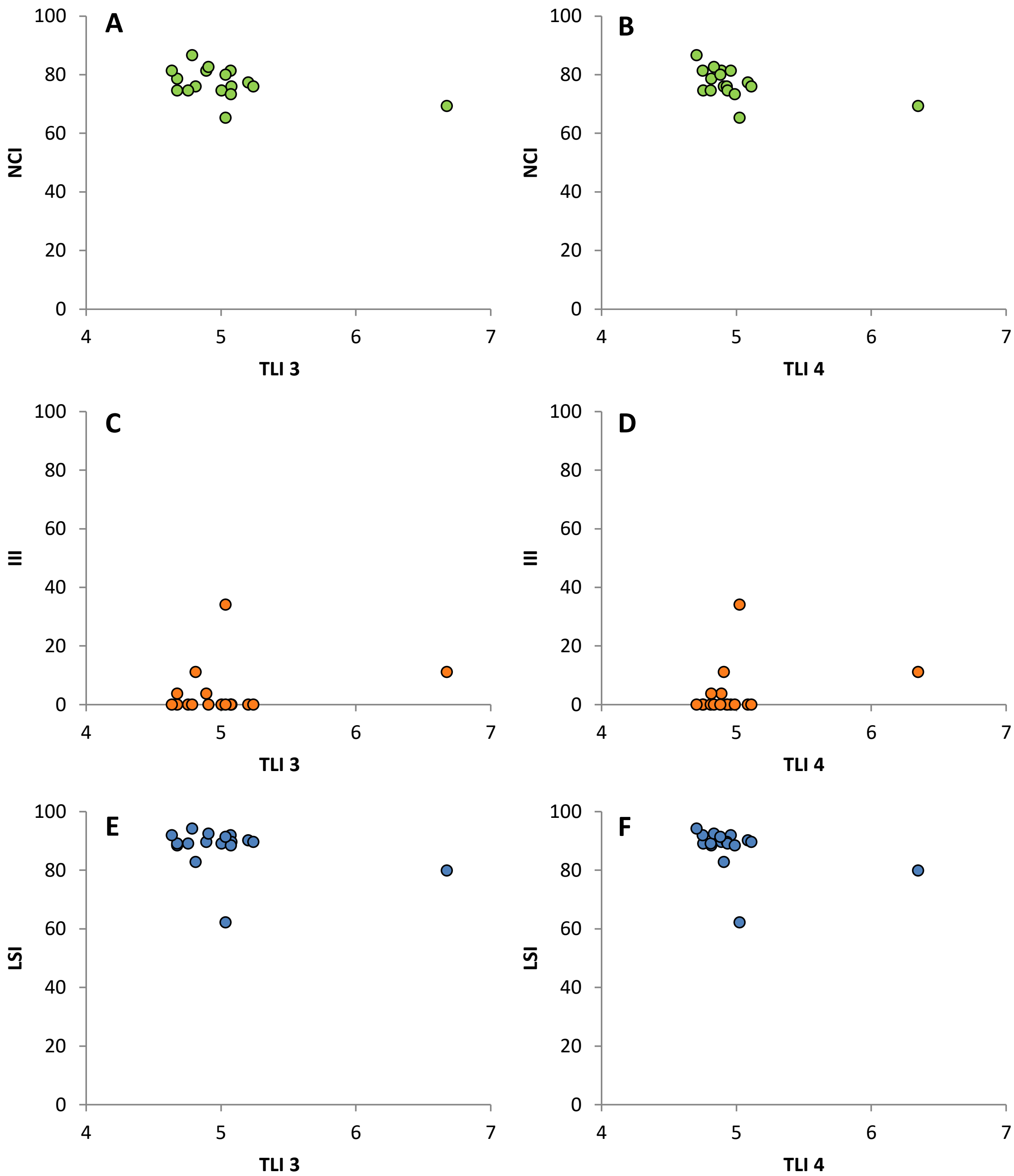

Figure 10. Relationships between TLI indices and LakeSPI indices in Lake Serpentine North (*N* = 17)

The TLI range in Serpentine South was more restricted than in Serpentine North (Figure 11), however there appeared to be strong negative relationships between TLI3 and both NCI and

LSI in this lake. For further discussion of relationship between TLI and LakeSPI in the Serpentine Lakes, see the text associated with Figures 15 to 17.

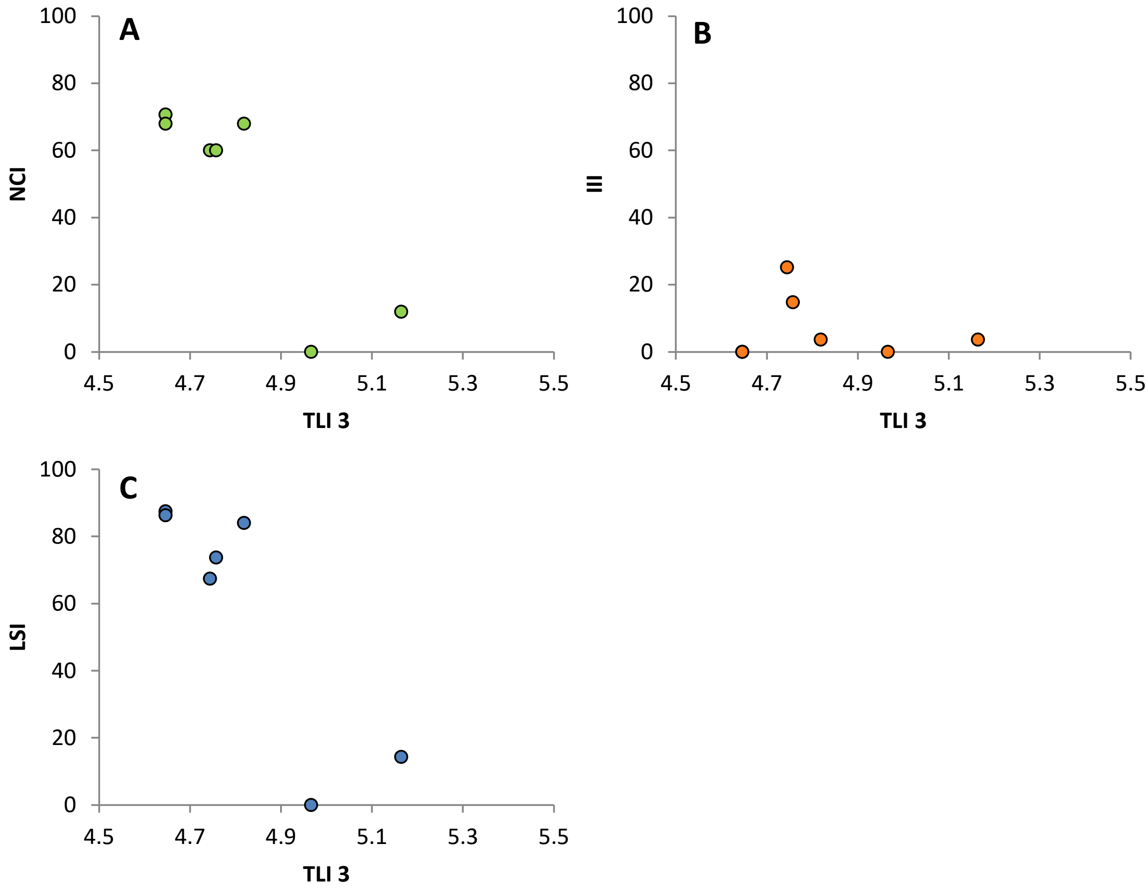

Figure 11. Relationships between TLI3 and LakeSPI indices in Lake Serpentine South (N = 7)

3.1.5 Prediction of LakeSPI from TLI variables

The rather poor correlations we found between LakeSPI indices and lake trophic state strongly suggest that the LakeSPI captures information about the condition and health of the Waikato lakes that indicators of trophic state do not effectively capture. To test this further, we used multiple linear regression to explore whether routinely measured trophic state variables along with lake depth could together predict the LakeSPI index values for Waikato lakes. We used the multiple regression coefficient (R^2) and model F values as the attributes for model selection and we used subset selection to produce 2- and 3-parameter models with the highest R^2 and F values. Due to the small number of independent variables available, we tested all possible models.

Fifty-eight percent of the variation in III, 38% of the variation in the NCI, and 34% of the variation in the LakeSPI index could be explained by simple statistical models based on trophic state variables and depth (Table 6). These models confirm that, while some correlations do exist, there is limited redundancy among LakeSPI and trophic state variables and that trophic state variables together with lake depth do not adequately predict or explain variation in

LakeSPI and its constituent indices. This is inconsistent with the implication in Clayton and Edwards (2006) that LakeSPI is a cheaper substitute for the trophic level index for monitoring lake water quality. In the Waikato lakes, these indices largely correlate with different lake health gradients, principally the occurrence and dominance of exotic macrophyte species.

Table 6. Multiple linear regression models for predicting LakeSPI indices from trophic state variables in Waikato lakes. *N* = 70, 23 lakes.

	Intercept	*X1*	*X2*	*X3*	*F*	R^2
Native Condition Index	181.7	Log Max Depth (-61.3 ***)	Log TP (-58.4 ***)		21	0.38
Invasive Impact Index	-48.6	Log Depth (78.7 ***)	Log Chl *a* (-70.8 ***)	Log TP (63.7 ***)	30.7	0.58
LakeSPI Index	209.5	Log Depth (-77.2 ***)	Log Chl *a* (38.8 *)	Log TP (-97.0 ***)	11.4	0.34
	192.7	Log Max Depth (-70.4 ***)	Log TP (-59.1 ***)		14.4	0.3

3.2 Relevance to ecological function

The importance of submerged macrophyte communities to lake ecology, and especially shallow lake ecology, has been demonstrated exhaustively (e.g., Pokorný & Květ 2004; Scheffer 2004). Their importance in providing various ecosystem services is also well known (Schallenberg et al. 2013). They play important roles in supporting aquatic biodiversity, in habitat provision, in lake physico-chemical regulation, and macrophytes are considered a key constituent of healthy lake ecosystems (Duker & Palmer 2009; Willén 2009; WRC 2014a).

The LakeSPI index is designed to facilitate the assessment and monitoring of the health of submerged macrophyte communities in New Zealand lakes. However, a strong focus on native macrophyte biodiversity is embedded in the LakeSPI index, such that the presence of any of the 10 invasive macrophyte species identified results in a discounting of lake health within the index's algorithm. Thus, any positive ecological role that invasive macrophytes have in maintaining lake functioning (e.g., contributions to the lake food web; Kelly & Hawes (2005); Bickel & Closs (2007)) is not accounted for in the LakeSPI index.

While the invasion of lakes by invasive macrophytes can have negative consequences for lake ecological function (e.g., Lake Omapere, Lake Tutira), the impact of macrophyte invasion in some lakes has not necessarily been catastrophic for ecosystem functioning (to date). Non-native macrophytes with a low invasive impact (Clayton & Edwards 2006), may provide benefits to ecosystem function (e.g., habitat provision, sediment stabilisation, nutrient sequestration), especially in comparison to a non-vegetated state. While LakeSPI puts a strong weighting on the benefit of native macrophyte cover and biodiversity, it also accounts for some ecological benefits attributable to low-impact invasive species. In ecology it is increasingly being acknowledged that species distributions are dynamic and that a core function of ecosystems is to adapt to species invasions, be they natural or anthropogenic

(Theodoropoulos 2003). In this regard, LakeSPI's relative weighting of the ecological benefits of native vs invasive species may underestimate the functional ecological value of some low-impact non-native macrophyte species by giving a high weighting to native species, due to their local biodiversity values.

Clayton and Edwards (2006) specifically promoted LakeSPI as a tool for monitoring temporal changes in the macrophyte community. We analysed the temporal dynamics of LakeSPI indices for lakes where sufficient data (≥ 5 LakeSPI assessments in the same lake) were available. Seven lakes (96 assessments in total) fitted this criterion and below we have plotted the three LakeSPI indices NCI, III and LSI over time for each of the seven lakes. For the three Serpentine Lakes, TLI3 data were also overlain on the graph to illustrate how temporal LakeSPI dynamics related to trophic state dynamics.

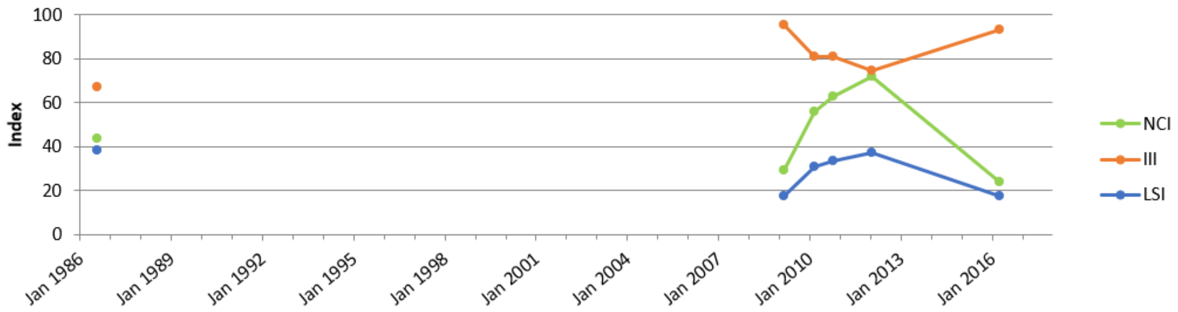

Figure 12. Native Condition Index (NCI), Invasive Impact Index (III) and LakeSPI Index (LSI) vs time for Lake Otamatearoa. The breaks in the lines indicate a gap of more than 5 years

A long-term trend is difficult to discern for Lake Otamatearoa (Figure 12), although when sampling frequency was higher, between 2009-2016, a consistent decrease in III coupled with a substantially higher NCI occurred over a 4-year period from 2009-2012. The trend then reversed and, by 2016, all indices had returned to near 2009 levels, confirming the unsuccessful attempt to eradicate hornwort from the lake between 2009 and 2011 (WRC 2014b). Thus, LakeSPI appears to be a useful indicator for tracking the effectiveness of macrophyte eradication attempts and potentially other restoration and management actions aimed at changing the macrophyte community and/or cover.

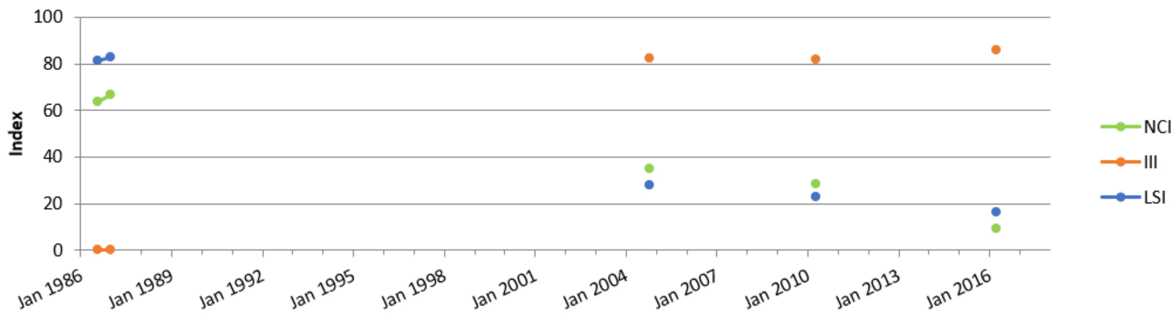

Figure 13. Native Condition Index (NCI), Invasive Impact Index (III) and LakeSPI Index (LSI) vs time for Lake Parkinson. Gaps of > 5 years occurred between all LakeSPI assessments

The LakeSPI data for Lake Parkinson show that the lake had recovered from nuisance *Egeria densa* and pest fish proliferations by the time the first LakeSPI assessment was carried out in 1986 (WRC 2014b; Figure 13). However, between 1986 and 2004 the lake entered a state of high invasive impact and poor native condition, reflecting the reintroduction of *E. densa* to the lake after 1996 (WRC 2014b). Grass carp were introduced to the lake in 2008 to control *E. densa* (B. Wilson, pers comm.), but this appears to have failed. From 2004 to 2016, LakeSPI sampling was undertaken every 6 years showing a continual decline in lake condition throughout this period. These data clearly show that the macrophyte community of Lake Parkinson underwent major degradation between 1986 and 2004, that the restoration attempt by the addition of grass carp in 2008 failed, and that the lake has continued to degrade since 2004, showing no sign of recovery.

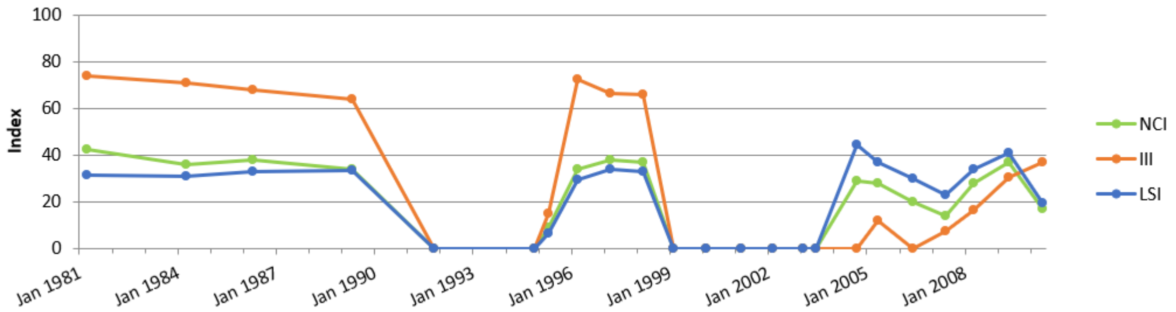

Figure 14. Native Condition Index (NCI), Invasive Impact Index (III) and LakeSPI Index (LSI) vs time for Lake Rotoroa (Hamilton Lake)

LakeSPI indices showed that Lake Rotoroa underwent at least two devegetation episodes - one between 1991 and 1996 and the other between 1999 and 2004 (Figure 14). The first devegetation was probably the result of herbicide use in the lake to control *Lagarosiphon*, *Elodea* and *Egeria* (WRC 2014b). The LakeSPI data show that the lake had recovered between 1996 and 1999 to a condition similar to that during the pre-devegetated period (1981 to 1990), with invasive macrophytes dominanting. However, after the second devegetetation in 1999, the native macrophyte community recovered faster and to a greater extent than the invasive macrophyte community. However, invasive impact continued to increase toward the end of the time series (2010). This information clearly shows a dynamic of alternative stable states occurred in this lake and that recovery trajectories differed after the two devegetated states. The recovery of native macrophytes in 2005 showed resilience of the native macrophyte community to devegetation events, but this resilience seemed to be eroding as invasive macrophytes again began to dominate the macrophytes community toward the end of the time series (2010).

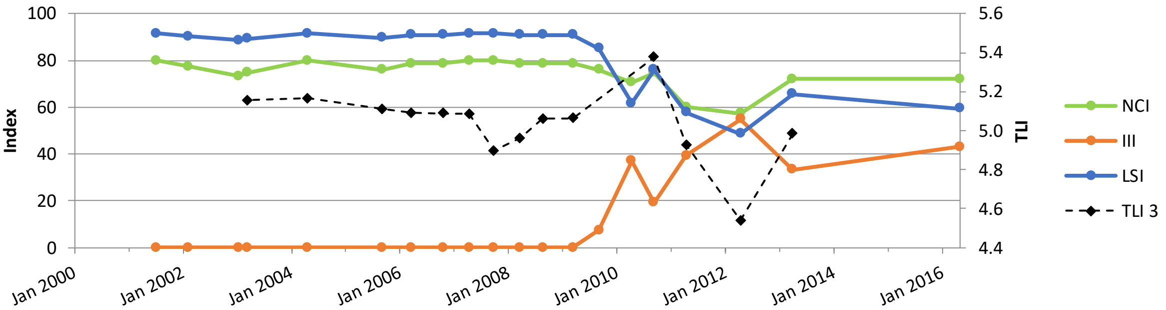

Figure 15. Native Condition Index (NCI), Invasive Impact Index (III) and LakeSPI Index (LSI) vs time for Lake Serpentine East. TLI3 scores are shown on the right hand vertical axis

The LakeSPI data for Serpentine East indicates that the lake was in a near pristine state with no invasive plant impact until 2009, when a macrophyte invasion occurred and invasive impact began to rise (Figure 15). The lake showed ecological resistance as the degradation reversed slightly before appearing to stabilise, with the native condition index remaining higher than the invasive impact index. However, subsequently, the LakeSPI index continued to gradually decline. The TLI data for this lake indicate that the trophic state became destabilised in association with the macrophyte invasion, with increasing variability in TLI apparent after the invasion. In this case, there has been no clear, consistent increase or decrease in TLI with the invasion or with the marked decline in LakeSPI scores.

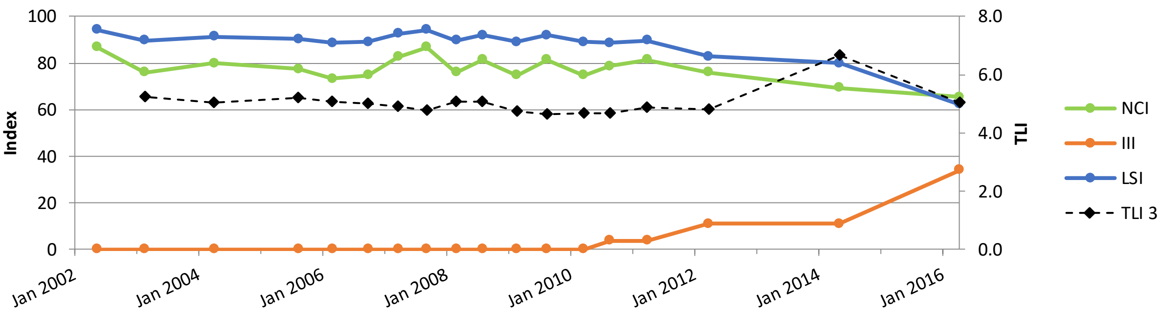

Figure 16. Condition Index (NCI), Invasive Impact Index (III) and LakeSPI Index (LSI) vs time for Lake Serpentine North. TLI3 scores are shown in the right hand vertical axis

The LakeSPI data for Serpentine North show a consistent, gradual degradation of macrophyte values, beginning with an invasion in 2010 (Figure 16). The TLI in this lake was very stable until 2014, when it showed a shift from eutrophic to hypertrophic conditions. However, the TLI recovered to pre-2014 levels in 2016, but the temporary shift to hypertrophic conditions may have affected a further decline in LakeSPI observed in 2016. The LakeSPI data for this lake suggest that the lake is at risk of flipping to a devegetated state in the near future. The data indicate that this lake should be monitored more closely and potentially interventions to reduce further invasive macrophyte proliferation should be considered. The data from 2016 show that TLI re-stabilised, suggesting that the invasive macrophytes may be compensating for the decline in the NCI, with respect to maintaining water clarity and phytoplankton biomass. However, the data from Serpentine East suggest that TLI could again be destabilised in the future if the III remains at 20, or higher.

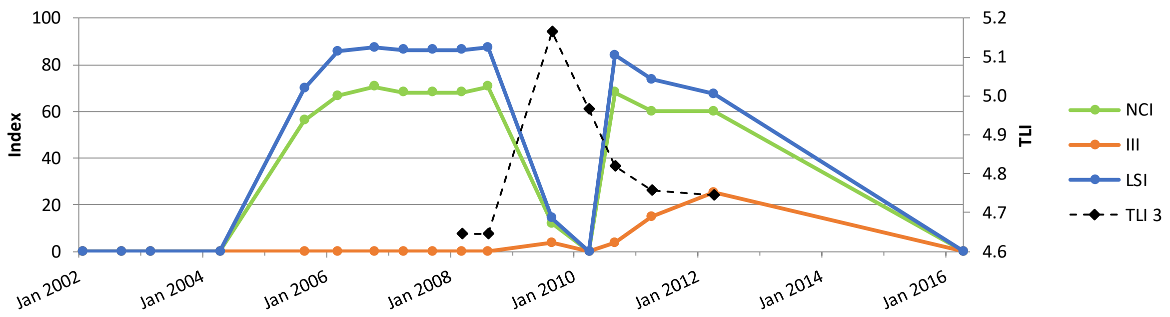

Figure 17. Native Condition Index (NCI), Invasive Impact Index (III) and LakeSPI Index (LSI) vs time for Lake Serpentine South. TLI3 scores are shown on the right hand vertical axis

Lake Serpentine South is another lake that has undergone devegetation events, but has also shown resilience and the ability to recover (Figure 17). The first recovery in 2005 was by the native macrophyte community. The second devegetation event seems to have facilitated invasion by invasive macrophytes. The impact of the invasives between 2012 and 2016 (the third vegetation collapse) is unknown as no LakeSPI surveys were carried out between these dates. It is possible that the invasive macrophytes facilitated the macrophyte collapse in the lake recorded in 2016, though this is unconfirmed. The TLI data showed a small jump in TLI (half a TLI unit) coinciding with the 2010 and 2016 devegetations and with the severe reduction in LakeSPI scores at the time. The LakeSPI data clearly show that this lake undergoes regime shifts with devegetated states, but also that the lake has shown resilience to these events. How invasive macrophyte dynamics affect the macrophyte dynamics and regime shifting behaviour of this lake will require more investigation.

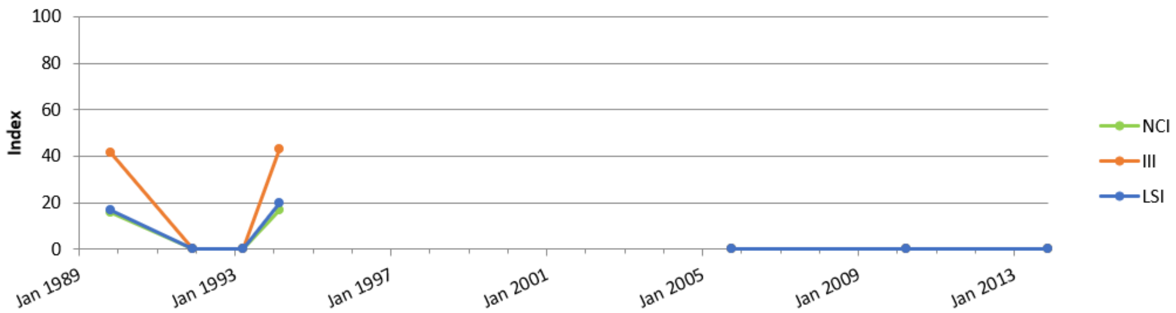

Figure 18. Native Condition Index (NCI), Invasive Impact Index (III) and LakeSPI Index (LSI) vs time for Lake Waahi. Breaks in the line indicate gaps of more than 5 years

The LakeSPI data for Lake Waahi show that the macrophyte community in the lake was poor in the early 1990s, undergoing a temporary collapse in 1992 (Figure 18). Native macrophytes were struggling in this lake at the time. The lake has been devegetated since at least 2005.

The data shown in these graphs illustrate that the III scores generally oppose those of the NCI and the LSI. However, in association with devegetation events, the behaviour of the three indices (and their trends) are generally positively associated. This is probably due to the overwhelming effect of cover estimations on the NCI and III, such that when cover declines or increases rapidly in relation to devegetation events, the covers of both native and invasive macrophytes are similarly affected. This appears not to be the case when lakes are in a vegetated state.

The above examples show that records of temporal dynamics of LakeSPI indices can illustrate a range of macrophyte community dynamics. This information complements TLI information because LakeSPI dynamics only sometimes synchronise with trophic state dynamics (e.g., Lake Serpentine South). At other times, LakeSPI provides information on lake ecological structure and functioning not captured by TLI (e.g., Lake Serpentine East).

The long LakeSPI time series also provide important information on the ecological resistance and resilience of the macrophyte communities and on the linearity or non-linearity of temporal trends (i.e., the tendency toward catastrophic collapse vs gradual change). This type of information can be useful for prioritising lakes for monitoring and/or restoration. However, LakeSPI information should be considered in relation to the assumptions and limitations of the LakeSPI architecture and methodology.

4. LakeSPI response variability

A feature of good ecological indicators is their ability to provide information of value (signal) while having a low susceptibility to bias (confounding effects) and random error (noise). We have noted that LakeSPI indices show patterns in variation over a substantial scale (0 to 100 percent) and can exhibit good interannual stability across multiple assessments of the same lake, suggesting that LakeSPI can exhibit a high signal to noise ratio.

4.1 Estimation of measurement error

Because assessing LakeSPI is technically complex, involving substantial expertise, few practitioners exist and NIWA appears to be the sole provider of LakeSPI assessments. Therefore, it appears that LakeSPI assessors have been highly trained practitioners, suggesting that between-assessor error or bias was low. Indeed, NIWA carried out simultaneous comparisons of LakeSPI assessments by two independent field teams and found that the coefficient of variation between assessment teams assessing the same 10 sites in Lake Okataina was 2.1% for the three LakeSPI indices (Clayton & Edwards 2006). Independent transect selection and LakeSPI assessment of the entire lake yielded a coefficient of variation of 6% between the teams. Although this test of between-assessor error was only carried out in one lake, the results were remarkably consistent, suggesting that as long as NIWA continues to assess LakeSPI, between-assessor variability should be acceptably small.

4.2 Seasonal variability

The WRC LakeSPI data included some assessments which were carried out in different seasons of the same year – some in autumn and some in spring. We analysed these LakeSPI data to determine whether assessments in different seasons could show significant error or systematic differences in LakeSPI scores.

The two-tailed T-test in Table 7 shows that there is no significant systematic difference between the spring and autumn LakeSPI assessments, indicating that the LakeSPI method provides consistent results in spring and autumn (t = 0.85, P = 0.41). However, interestingly, the variance in LakeSPI scores among the 13 assessments in 7 lakes was much higher in autumn than in spring, suggesting that there could be greater discriminatory power in the LakeSPI indices if measured in autumn.

Table 7. Students t-tests of corresponding autumn and spring LakeSPI index values from the same year. *N* = 13 samples, 7 lakes.

	Autumn	*Spring*
Mean	76.04	83.74
Variance	826.15	246.84
Observations	13.00	13.00
Hypothesized Mean Difference	0.00	
df	19.00	
t Stat	-0.85	
P(T<=t) one-tail	0.20	
t Critical one-tail	1.73	
P(T<=t) two-tail	0.41	
t Critical two-tail	2.09	

4.3 Temporal variability across years

The multi-year LakeSPI data from 7 lakes shown in Figures 12 to 18 shows clearly that LakeSPI indicators are able to reveal periods of stability as well as periods of rapid and marked change in macrophyte communities. This indicates that the data obtained on the macrophyte communities are both sensitive and reproducible across time.

4.4 Spatial variability

Guideline 11 of Jackson et al. (2000) indicates that useful ecological indicators must either give consistent estimates of condition across pressure gradients within the monitored geographical region or they should be able to be normalised so that physiogeographical differences within the region don't bias assessments of ecological condition. LakeSPI attempts to calibrate each lake to derive an estimate of departure from the lake's pristine reference condition using a lake maximum depth transformation (see Table 4, Clayton & Edwards 2006). In this way, the LakeSPI indicator attempts to normalise for inherent difference in potential maximum LakeSPI scores.

Nevertheless, we did analyse for potential differences associate with lake depth and associated with peat vs non-peat lakes in the Waikato lakes dataset. We found in our correlation analyses (Table 3) that lake maximum depth correlated significantly with LakeSPI indices (negatively with NCI and LSI and positively with III). Because LakeSPI indices are calibrated for differences in lake depth, these results may be affected by that calibration, where the calibration may overcompensate for the hypothesised depth effect on maximum potential LakeSPI scores. The possibility that the depth calibration is not accurate and potentially introduces bias should be investigated further, but is beyond the scope of this report.

We found no evidence of a bias in LakeSPI scores among shallow peat lakes vs shallow, non-peat lakes (Figure 20), however this analysis is inconclusive because of the high proportion of peat lakes that are devegetated.

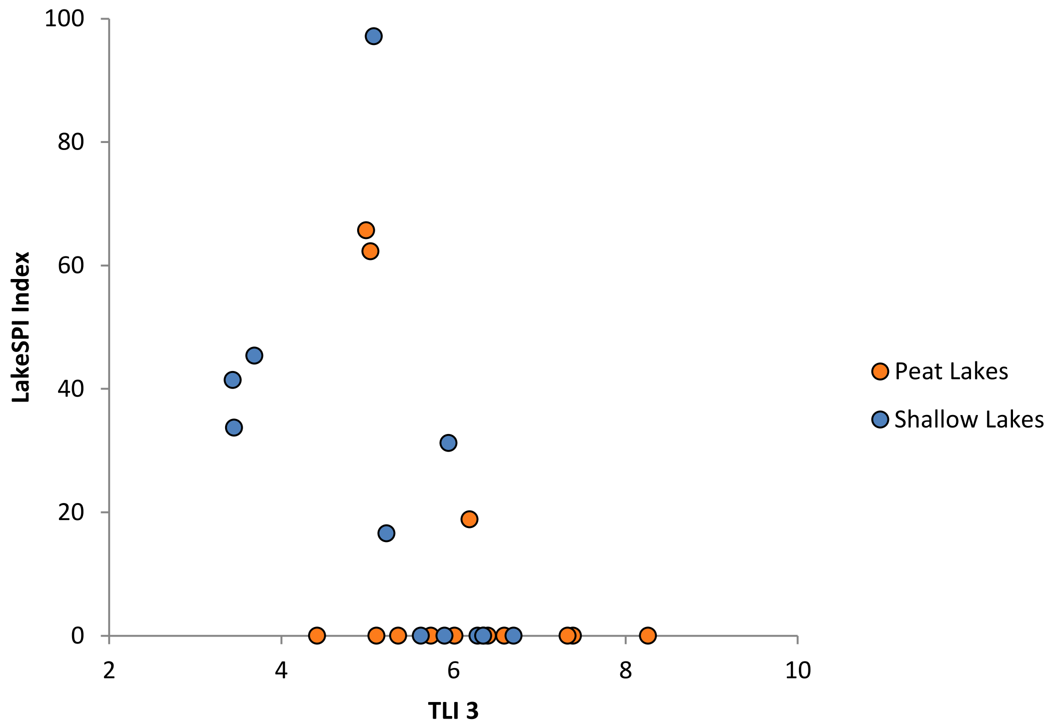

Figure 20. TLI3 and LakeSPI Index from the most recent data for each lake (taken to be the most recent sample from a lake within the last 10 years) (Shallow, non-peat lakes *n* = 11; Shallow, peat lakes *n* = 14).

Our conclusion concerning potential group biases in LakeSPI indices for lakes in the Waikato region is that there is the potential of bias related to lake depth and that this is potentially due to the calibration procedure used in LakeSPI. Due to their naturally reduced water clarity, LakeSPI may yield biased results for peat lakes, but because of a lack of data, more investigation is required before such a bias can be confirmed.

4.5 Discriminatory ability

A useful ecological indicator should be sensitive to known pressure gradients (Jackson et al. 2000). We have shown that LakeSPI is weakly correlated to TLI, indicating that it isn't strongly linked to drivers of TLI in Waikato lakes. We have been unable to test its relationship to other pressure gradients such as fish community composition (i.e., herbivory), lake level perturbation, or substrate suitability, due to a lack of available data.

This raises the issue of whether LakeSPI should be considered an ecological indicator coupled to explicit pressure gradients or whether it should be more appropriately considered an important attribute of lake ecosystem condition and health that responds in a complex way to multiple stressors. The latter perspective acknowledges that the macrophyte community may be a driver of lake condition, not just a response indicator. In this regard, the lack of strong correlations between pressure gradients and LakeSPI may not undermine its utility in monitoring lake ecosystem health. Clayton & Edwards (2006) stated that LakeSPI's aim was, "[to] assess the effects of catchment and water management on a lake and the impact of aquatic weed invasion in a lake.”. However, a more appropriate perspective on the purpose of LakeSPI is probably that stated by McDonald et al. (2013), which is “to measure the departure of lake submerged vegetation from an expected or potential state, based on a range of ubiquitous vegetation features common to the majority of New Zealand lakes.”.

5. Interpretation and utility of LakeSPI

A useful ecological indicator must be understandable and acceptable by scientists, policy makers, and by the public. In some cases, statistical limitations may need to be carefully considered when interpreting or employing an ecological indicator in a management context.

5.1 Data quality objectives

In the examination and exploration of WRC's LakeSPI data, certain issues related to data and the treatment of data in the LakeSPI method became apparent. Some of these are discussed below.

LakeSPI is a complex index, itself the product of two complex indices. Therefore, LakeSPI should not be considered a standard lake attribute or indicator of a pressure gradient, but rather it is a complex indicator of a suite of lake macrophyte community attributes. It combines different types of information about macrophytes into a normative assessment of lake condition which focuses on the negative biodiversity impacts of invasive macrophyte species, native macrophyte diversity, and on the importance of macrophyte cover to lake health. Therefore, the interpretation of variation in LakeSPI indices and their drivers is likely to be complicated and related to multiple stressors. For example, the relationship of LakeSPI to lake trophic state in the Waikato lakes is weak. Drivers other than those affecting nutrient concentrations and water clarity are likely to play important roles in determining LakeSPI scores in the Waikato lakes.

Because LakeSPI is a measure of departure from a pristine reference condition, calibration to a reference condition for each lake is required. The LakeSPI calibration procedure may rely on a number of additional factors and sources of information and the calibration is not clearly explained or justified in the LakeSPI documentation.

We found that LakeSPI assessments carried out repeatedly in the same lake at frequencies ≤ 5 years provided interesting information about lake macrophyte dynamics, which could be useful in a lake management context. Unfortunately, the WRC have not employed a consistent sampling interval for all lakes and most of the Waikato lakes have been sampled infrequently. The recommended sampling interval for LakeSPI assessments is 5-yearly (Clayton & Edwards 2006), but more frequent assessments provide a better understanding of lake dynamics, especially pressure tipping points and sudden regime shifts. Figure 21 shows a frequency histogram of the mean interval between assessments for lakes that have been assessed more than once, illustrating that the majority of Waikato lakes were assessed less frequently than the 5-yearly assessment frequency recommended by Clayton & Edwards (2006). In addition, 27 lakes in the WRC dataset were assessed only once. While there may be justifications for assessment frequencies exceeding the 5-yearly recommended frequency,

Figure 21 suggest that a review of LakeSPI sampling frequency may be required to improve the utility of LakeSPI data for managing lake health in the Waikato region.

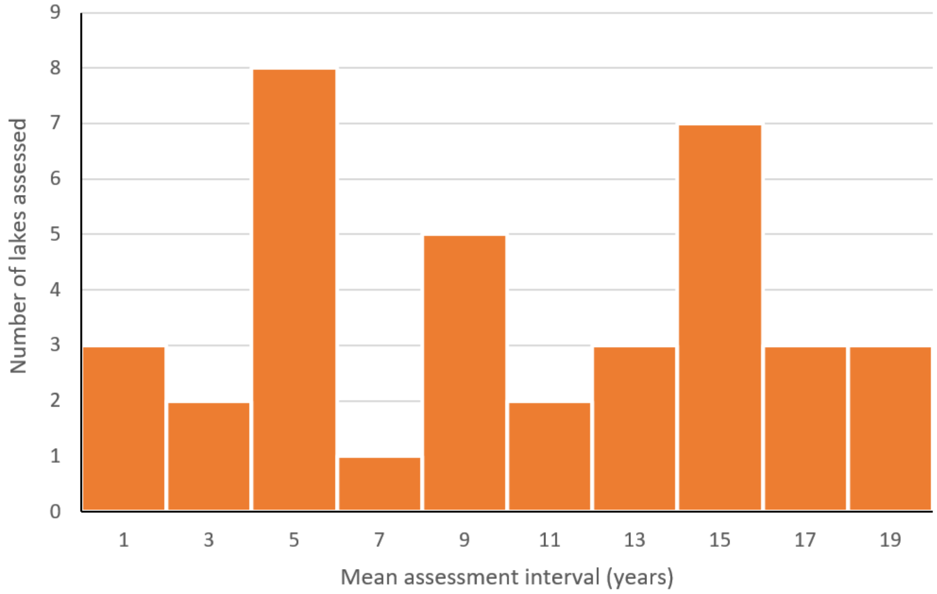

Figure 21. Frequency histogram showing the mean assessment interval for LakeSPI assessments in Waikato lakes that have been assessed more than once. Twenty-seven lakes have been assessed only once (data not shown)

5.2 Assessment of thresholds

Pressure-response relationships in lakes can sometimes be non-linear, exhibiting pressure thresholds, hysteresis and alternative stable states (Scheffer 2004). From a management perspective, understanding such relationships is important because they can reveal the presence of tipping points and the potential for rapid, catastrophic change in ecosystem structure and function. Therefore, useful ecological indicators should provide information capable of revealing such dynamics and allowing the identification of inherent tipping points in lake ecosystems.

We have shown that LakeSPI indices are useful for showing both gradual and rapid change in lake macrophyte communities when LakeSPI assessments are carried out ≤ 5-yearly. For example, the LakeSPI datasets indicate that Lakes Rotoroa (Hamilton Lake), Serpentine South and Waahi have alternated between vegetated and non-vegetated states, whereas Lakes Otamatearoa, Parkinson, Serpentine East and Serpentine North showed more gradual changes in macrophyte community dynamics. Similarly, the dynamics of native and invasive macrophyte influence on the lakes can be determined with the LakeSPI sub-indices, which discriminate the influences of invasive and native species.

A careful analysis of the drivers of such dynamics could lead to the determination of pressure-response relationships for the macrophyte communities in these lakes and the identification of pressure tipping points, where these relationships are non-linear.

As discussed above, our analysis of the relationship between LakeSPI and trophic state in the Waikato lakes shows that trophic state (and drivers of trophic state) are only weakly related to LakeSPI, suggesting the LakeSPI is influenced by multiple stressors. Factors that influence invasive macrophytes, native macrophyte diversity and pressures that reduce macrophyte cover and distributional ranges in lakes (e.g., water level variation, water clarity, herbivore pressure, macroalgae and periphyton blooms) are likely to influence LakeSPI dynamics. Thus, LakeSPI tipping points are probably determined by interactions between multiple stressors and may be difficult to define accurately. However, in some cases, a single driver may exert a very strong impact (e.g., invasion by *E. densa*, invasion by herbivorous and benthic fish; Schallenberg & Sorrell 2009) and in such cases, the identification of LakeSPI tipping points may be more straight forward.

6. Conclusions and linkage to management actions

Ecological indicators are often selected as simple-to-measure attributes that clearly link pressure gradients to important ecological attribute responses. To be useful for management, the attribute responses should reflect key values. LakeSPI doesn't align closely to this definition of an indicator, although it has characteristics in common with ecological indicators. The attributes assessed by LakeSPI are primarily related to invasive macrophyte proliferation, native macrophyte diversity and macrophyte cover and distributions. The pressures that drive these attributes are generally more complex than, for example, the pressures that drive chlorophyll *a* in lakes. In addition, the index nature of LakeSPI, which amalgamates different features of lake macrophyte communities (e.g., diversity, cover, distribution, invasiveness, nativeness, etc.), results in a complexity which is not easy to relate to a simple value or attribute to be managed. Despite this complexity, LakeSPI and its component indices have been touted as useful indicators of lake health in relation to catchment and water management (Clayton & Edwards 2006). We agree that LakeSPI does have some value as a pressure-response indicator, but that it should be used carefully in this regard due to its complexity.

Lake macrophyte communities play important structural and function ecological roles and also provide important ecosystem services (Schallenberg et al. 2013). Macrophytes not only provide habitat for many other lake taxa, the macrophyte community in itself is an important component of lake biodiversity which is often threatened by invasive species within the Waikato region. The macrophyte community also plays important regulatory roles in lakes and the presence/absence and specific characteristics of macrophyte communities can be seen as drivers of lake health, as well as responses to other drivers. Thus, the indicator potential of LakeSPI may be further complicated by the fact that macrophyte community characteristics (or the lack of macrophytes) can determine other important aspects of lake health. We agree with McDonald et al. (2013), who emphasised the importance of LakeSPI not so much as an ecological indicator of pressures, but as a measure of the departure of macrophyte communities from pristine, reference condition. Thus, its main strength is a measure of change in ecosystem structure, which has implications for ecosystem function, although the links to altered ecosystem function and further structural changes can be complex.

While measuring changes in a key lake community, LakeSPI provides and integrates much useful ecological information and can be a useful tool for lake managers, complementing TLI monitoring. This is especially relevant for shallow lakes which have strong benthic-pelagic coupling, and which present challenges to trophic state monitoring due to wind-induced sediment resuspension and the importance of benthic primary productivity, neither of which are effectively accounted for in TLI monitoring. However, due to lake-specific calibration and normalisation, among-lake analysis of relationships between LakeSPI and other absolute measures of lake pressures (e.g., nutrient loading) and attributes (e.g., water clarity) are likely to be weak and of limited management value. This is not necessarily a shortcoming of LakeSPI because such pressures and attributes may be more easily and directly measured by other methods.

The LakeSPI index is also a potentially useful restoration tool because (1) the method sets an explicit "pre-European" LakeSPI score and (2) the score itself is a measure of proximity to a potential restoration endpoint (i.e., the estimated "pre-European" condition).

In summary, while LakeSPI may not be an ideal pressure indicator, it is a useful indicator of macrophyte community departure from a reference condition. In this regard, LakeSPI is likely to align with lake values related to biodiversity, habitat provision, functional regulation, water quality and cultural and recreational values. However, the complexity of the index means that the links to these values may not be direct or easily quantified. Nevertheless, trophic indices are not ideal for monitoring shallow lake health and LakeSPI provides a useful tool to complement TLI, particularly in these lakes. Finally, the calibration of LakeSPI scores makes them particularly useful for lake restoration because a "pre-European" condition is explicitly set and measuring the departure from that condition was a design goal of the LakeSPI index. However, neither the quantitative basis for the calibration nor the calibration method have been explicitly described or validated for LakeSPI, to date.

7. Critical appraisal of questions related to the LakeSPI index

Clayton and Edwards (2006) posed a number of management questions covering lake condition, plant condition and restoration goals that LakeSPI could aid in answering. To assess the relevance of LakeSPI as an ecological indicator for Waikato Lakes, the questions are specifically examined in the following section, using all existing Waikato LakeSPI data, as appropriate. The questions that were posed are in italics and those in bold font were those that were considered to be within the scope of this report.

Lake condition generally

Q: Is the overall condition of a lake improving or declining?

A: LakeSPI can contribute to an understanding of the overall condition of the lake and whether this condition is improving or declining. However, LakeSPI and the macrophyte communities of lakes should not be the sole indicators of overall lake condition or health, which should include a wider range of values. The definition of overall condition for lakes may vary from lake-to-lake depending on the values inherent in the lakes. In considering

the contribution of LakeSPI to overall condition, the assumptions and limitations of the LakeSPI indicator should be taken into account as well as the design of the indicator, which gives strong opposite weightings to native vs invasive macrophyte species. Such a weighting within the LakeSPI index will not capture aspects of ecosystem function and ecosystem services that can be provided by non-native species. This report shows that time series of LakeSPI data do show useful information related to key lake ecosystem dynamics and temporal assessments of sufficient frequency (ideally 5-yearly or less) can reveal the trajectories of aspects of macrophyte dynamics over time.

Q: How can I prioritise lakes in my region?
A: LakeSPI data of high temporal frequency illustrate aspects of the resistance and resilience of the macrophyte communities over time. They also provide information on the temporal dynamics, highlighting whether lakes tend to undergo catastrophic macrophyte collapses, gradual changes and whether or not tipping points may exist in the macrophyte-system dynamics. Such information can be useful in prioritising Council resources for lake monitoring and/or restoration actions.

LakeSPI is also a measure of departure from a reference condition and, therefore, is not an absolute measure of condition. The degree of departure from a pristine reference condition may provide useful information for prioritising council resources for lake monitoring or restoration. In contrast TLI is an absolute measure of trophic state and doesn't reflect the departure from a reference condition.

LakeSPI data specifically on the health of the native macrophyte community and on the impact of invasive macrophytes can assist managers to prioritise lakes in terms of protecting native biodiversity and preventing the spread of invasive species. These issues are discussed in more detail in the sections on invasive alien plants and native plant communities, below.

Q: Are lakes in this region or area improving or declining?
A: Yes the index is useful for trend analysis of macrophyte condition, if assessments are carried out at ≤ 5-yearly intervals.

Q: Is the water clarity improving or deteriorating for this lake/lakes in this region?
A: While LakeSPI contains components closely related to water clarity (e.g., maximum depth of macrophyte distributions), these are combined with other metrics in the calculation of the LakeSPI indices. The focus on native vs. invasive species in LakeSPI may also dilute the relationship of the LakeSPI index to water clarity. LakeSPI does contain raw information on macrophyte depth distributions and this information could be analysed independently to understand water clarity in lakes. However, macrophyte distributions can also be related to factors other than water clarity, such as substrate suitability and herbivore pressure. Therefore, water clarity would better assessed by regular direct measurement.

Q: What is the rate of this improvement or decline?
A: See above. LakeSPI is not a recommended measure of water clarity.

Q: Is the lake condition typical for a lake of this type (in this region)?
A: LakeSPI uses lake depth to calibrated scores to a "pre-European" reference condition. Although LakeSPI scores are not normalised to specific regions, simple quantile analysis of LakeSPI data from within a region would provide an indication of how the LakeSPI score for a particular lake, or lake types, relates to scores from other lakes in the region.

<u>*Invasive alien plants*</u>

Q: How pervasive has alien plant invasion been in this lake? How many invasive species are there? Which species are present?
A: A LakeSPI assessment collects information on individual invasive species, including which species are present, estimated cover, their depth distribution, and heights. Therefore, the Invasive Impact Index is a good indicator of the general prevalence of invasive species in lakes.

Q: What is the current regional or national distribution and relative abundance of alien plant species in lakes?
A: LakeSPI wasn't specifically designed for this purpose. The guidance on selecting transects is not optimal for specifically surveying invasive plant incursions. Please contact the NIWA LakeSPI group for their thoughts on how effective LakeSPI data could be for this.

Q: How vulnerable is this lake to (further) impact from invasive plant species? What sorts of impacts are possible?
A: Devegetated states may facilitate the establishment of invasive species in lakes (e.g., Serpentine South, Figure 17). However, apart from revealing devegetation potentials, in general, LakeSPI probably gives little insight into the vulnerability of lakes to invasive plant incursions. In lakes that have invasive macrophytes, LakeSPI time series data of appropriate frequency are useful for showing the dynamics of invasive impact over time. This can reveal aspects of ecological resistance and resilience and sensitivity to invasive impact, which may help predict future trajectories of invasive impact.

A key aspect to invasive impact dynamics is the tendency for proliferations of certain invasive macrophyte species, such as *Egeria densa* (Schallenberg & Sorrell 2009), to suddenly collapse, leaving the lake in a devegetated state. *Ceratophyllum demersum* (hornwort) and *Hydrilla verticillata* may also cause this type of dynamic in some New Zealand lakes.

LakeSPI doesn't specifically assess invasion risk from neighbouring lakes, however the data that the LakeSPI assessment provides on invasive species presence in lakes could be used to develop a risk assessment of transfer of invasive species. For example, three variables could be used to develop a crude index of invasion risk and potential impact: (1) the III, (2) the distance between lakes of interest, and (3) the NCI. For any pair of lakes, a high risk of invasion and impact would occur if a lake with a high NCI score were situated close to a lake with a high III score.

Furthermore, an analysis of lakes that are free of any exotic macrophyte species could indicate that certain lake types may be more impacted by invasives than others. This

information might be useful in lake biodiversity management and surveillance, which might aim to safeguard lakes with native macrophyte communities which are poorly represented by lake type in the region.

<u>*Native plant communities*</u>

Q: What is the quality of the native plant communities in this lake? Is there a good diversity of native plant communities or have they been largely or entirely replaced by invasive alien species?

A: One of the goals of designing LakeSPI was to assess native macrophyte diversity (Clayton & Edwards 2006). The Native Condition Index has a specific diversity metric which is assessed in relation to five macrophyte communities, such as charophytes, pondweeds, etc. These are not reported to species level. The native diversity metric is scored (0 to 5) and this metric can therefore provide some specific information on the diversity of the native plant communities (but not species). The Native Condition Index combines this diversity information with other information on the native macrophyte communities, thereby giving a broader perspective on the quality of the native macrophyte communities.

Q: Are there lake attributes (e.g., native plant communities) that require special management? What type of management would be needed?

A: While the five native plant communities assessed in LakeSPI are given equal weighting under their contribution to native diversity, special consideration is given to deep-water charophyte communities (> 11 m) and deep-water pondweed, milfoil and isoetes communities (all > 5 m), because these are deemed to be (1) resistance to displacement by invasive species and (2) sensitive to reductions in water clarity (Clayton & Edwards 2006). Thus, reduction of the maximum depth extent of these communities make make them more vulnerable to displacement by invasive species. Therefore, the maximum depth to which these communities grow in lakes can be considered both an early warning indicator of a loss of water clarity as well as a potential indicator of invasion risk. The management of water clarity by benthivorous fish removal, water level management, installation of wave barriers, enhancement of phytoplankton grazers, etc. might be feasible to safeguard water clarity and these deep-water communities. The forthcoming book called, "The Lake Restoration Handbook: New Zealand perspectives" by Hamilton et al. (Springer-Verlag) should provide further information related to management and restoration techniques that could help safeguard deep-water native macrophyte communities.

LakeSPI is not recommended for the assessment of rare plant communities because the surveys conducted to assess LakeSPI are not exhaustive and are not designed specifically to assess the presence of rare species or communities (Clayton & Edwards 2006). However, LakeSPI information indicating that a lake is free of exotic macrophytes could signal to lake managers that such lakes could benefit from special management and protection to try to prevent incursions of invasive species.

Q: How do the existing plant communities in a lake/group of lakes compare to pre-European/ pre-human times?

A: LakeSPI incorporates a calibration of the current condition of a lake's macrophyte community to its estimated condition in "pre-European" times. The calibration method

varies in different descriptions of the LakeSPI method, but it always includes two factors: (1) a correction for lake depth and (2) the adjustment of LakeSPI by excluding invasive species from the calculation (Clayton & Edwards 2006). Other factors that are sometimes used to determine the "pristine" or maximum potential LakeSPI score include: (1) naturally impaired water clarity (Clayton & Edwards 2006), (2) the use of historical macrophyte records where available (e.g., Edwards et al. 2007, 2010), and (3) the use of expert opinion (e.g., Edwards et al. 2010).

The scaling of the current LakeSPI scores in relation to "pre-European", pristine conditions relies on some assumptions. The accuracy of the scaling and calibration procedures have not been adequately demonstrated to date.

Restoration goals

Q: What would be the appropriate restoration goals for water clarity and plant communities given the lake type and its current state?
A: LakeSPI estimates a departure from reference condition, not an absolute condition. Therefore, LakeSPI is well suited to informing restoration goals, assuming that the reference condition has been accurately estimated. As stated above, LakeSPI's relationship to water clarity is not simple or direct and, therefore, as a tool, it is best suited to restoration goals related to restoring the native macrophyte community.

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9. References

Bickel TO, Closs GP. (2007) Fish distribution and diet in relation to the invasive macrophyte *Lagarosiphon major* in the littoral zone of Lake Dunstan, New Zealand. *Ecology of Freshwater Fish* **17:** 10-19.

Burns N, Bryers G, Bowman E. (2000) Protocols for monitoring trophic levels of New Zealand lakes and reservoirs. Report SMF 5090. Ministry for the Environment, Wellington, New Zealand. 138 p.

Clayton J, Edwards T. (2006) LakeSPI: a method for monitoring the ecological status of New Zealand lakes. NIWA Technical Report v.2. NIWA, Hamilton, New Zealand. 77 p.

Duker L, Palmer M. (2009) Methods for assessing the conservation value of lakes. Pp. 166-199 *in* PJ Boon & CM Pringle (*eds*) Assessing the conservation value of fresh waters. Cambridge University Press, Cambridge, U.K. 293 p.

Edwards T, Clayton J, de Winton M. (2007) The condition of 41 lakes in the Waikato Region using LakeSPI. Environment Waikato Technical Report 2007/35. Waikato Regional Council, Hamilton, New Zealand. 45 p.

Edwards T, de Winton M, Clayton J. (2010) Assessment of the ecological condition of lakes in the Waikato Region using LakeSPI - 2010. Environment Waikato Technical Report 2010/24. Waikato Regional Council, Hamilton, New Zealand. 99 p.

Hamilton, D, Collier, K, Howard-Williams, C, Quinn J (*eds*) Lake Restoration Handbook: A New Zealand Perspective. Springer. [in press]

Jackson LE, Kurtz JC, Fisher WS. (2000) Evaluation Guidelines for Ecological Indicators. U.S. Report EPA/620/R-99/005. Environmental Protection Agency, North Carolina, USA. 109 p.

Kelly DJ, Hawes, I. (2005) Effects of invasive macrophytes on littoral zone productivity and foodweb dynamics in a New Zealand high-country lake. *Journal of the North American Benthological Society* **24:** 300–320.

Langdon R, Andrews J, Cox K, et al. (1998) A classification of the aquatic communities of Vermont. Report prepared by the Vermont Aquatic Classification Workgroup for the Nature Conservancy and the Vermont Biodiversity Project. Burlington, Vermont, USA.

McDonald A, de Winton M, Edwards T. (2013) Lake submerged plant indicators (LakeSPI) survey version 1. Inventory and monitoring toolbox: freshwater ecology. Report DOCDM-996172. Department of Conservation, Wellington, New Zealand. 22 p.

MfE (2017) Clean Water. Proposed amendments to the National Policy Statement Freshwater Management 2014. Ministry for the Environment, Wellington, New Zealand. 96 p.

MfE (2015) Environment Aotearoa 2015: Data to 2013. New Zealand's Environmental Reporting Series. Ministry for the Environment, Wellington, New Zealand. 131 p.

Pokorný J, Květ J. (2004) Aquatic plants in lake ecosystems. Pp. 309-340 *in* PE O'Sullivan & CS Reynolds (*eds*) The lakes handbook: limnology and limnetic ecology. Blackwell Publishing, Oxford, U.K. 699 p.

Schallenberg M, de Winton M, Verburg P, Kelly DJ, Hamill KD, Hamilton DP. (2013) Ecosystem Services of Lakes. Pp. 203-225 *in*: Ecosystem services in New Zealand: condition and trends. J Dymond (*ed*). Manaaki Whenua Press, Lincoln, New Zealand. 538 p.

Schallenberg M, Hamilton DP, Hicks AS, Robertson HA, Scarsbrook M, Robertson B, Wilson K, Whaanga D, Jones HFE, Hamill K. (2017) Multiple lines of evidence determine robust nutrient load limits required to safeguard a threatened lake/lagoon system. *New Zealand Journal of Marine and Freshwater Research* **51**: 78-95.

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

Scheffer M. (2004) The ecology of shallow lakes. Springer-Verlag, Heidelberg, Germany. 357 p.

Theodoropoulos DI. (2003) Invasion biology: critique of a pseudoscience. Avvar Books, Blythe, California, USA. 236 p.

Verburg P, Hamill K, Unwin M, Abell J. (2010) Lake water quality in New Zealand 2010: Status and trends. National Institute of Water and Atmospheric Research (NIWA) Client report HAM2010-107. Prepared for the Ministry for the Environment. Wellington, Ministry for the Environment. 54 pp.

WRC (2014a) Waikato Region shallow lakes management plan volume 1. Waikato Regional Council, Hamilton, New Zealand. 50 p.

WRC (2014b) Waikato Region shallow lakes management plan volume 2. Waikato Regional Council, Hamilton, New Zealand. 221 p.

Willén E. (2009) System Aqua – a Swedish system for assessing nature conservation values of fresh waters. Pp. 200-217 *in* PJ Boon & CM Pringle (*eds*) Assessing the conservation value of fresh waters. Cambridge University Press, Cambridge, U.K. 293 p.