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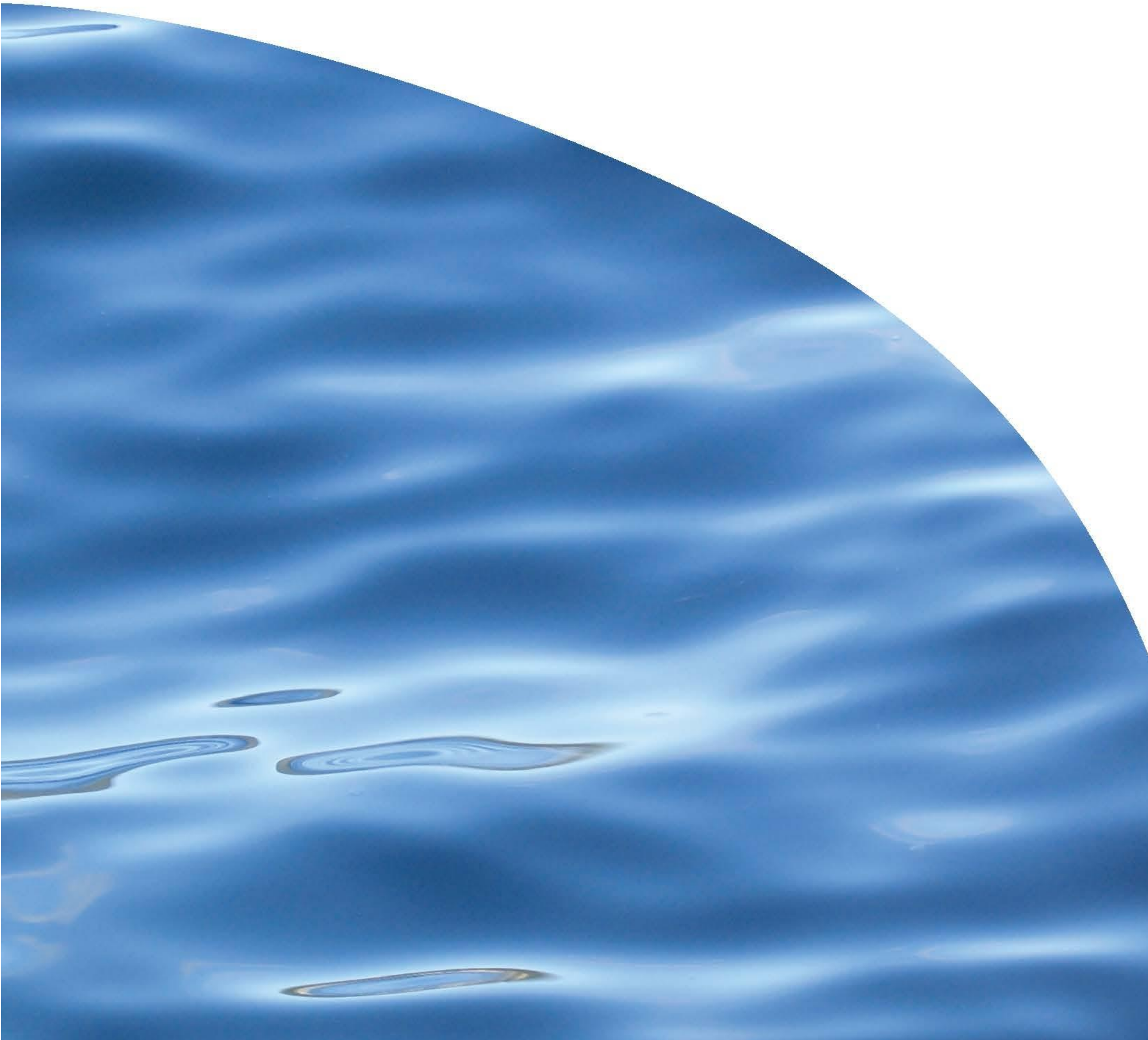
NUTRIENT MANGEMENT FOR NORTHLAND'S DUNE LAKES



NUTRIENT MANGEMENT FOR NORTHLAND'S DUNE LAKES

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Prepared for the Northland Regional Council

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EXECUTIVE SUMMARY

Background

The Northland region has some of the most outstanding examples of coastal dune lakes in New Zealand, with some of the few remaining lowland lakes with high water quality on the North Island. Management of their conservation, recreational and cultural values requires an understanding of their vulnerability to different human-induced pressures, including nutrient load from land uses in their catchments. The implementation of the National Policy Statement for Freshwater Management 2014 (NPS-FM) requires regional authorities to establish and implement limits to protect water quality and ecological values of waterbodies in their region.

Land use in coastal areas of Northland includes agriculture and plantation forestry, intermixed with significant areas of native forest and dune scrubland vegetation. The effects of land use can be cyclical, particularly in relation to forest harvest cycles and agricultural rotation. Northland Regional Council (NRC) has initiated measures as part of the development of their new (second-generation) regional plan for the management of water quality in dune lakes. Presently NRC regularly monitor twenty-seven high value lakes for water quality status and trend, as well as ecological health attributes (*e.g.*, lake macrophytes, macroinvertebrates).

A framework for evaluating the ecological status of dune lakes has been developed by NIWA in conjunction with NRC, and is based on a range of ecological attributes (water quality, macrophytes, invasive species, riparian condition). From this classification, NRC have identified 12 of these dune lakes as outstanding for their region, and are considering the development of individual catchment management plans to manage the health and resilience of these systems. However, there is still limited understanding of water quality targets required to maintain these high values, recognising there are a broad range of lake types (*e.g.*, seasonally stratifying and polymictic lakes varying in their connectivity to groundwaters).

Study Objectives

The present study focused on understanding nutrient relationships with key ecological values of dune lakes, and testing existing land-use tools for predicting nutrient losses to dune lakes. The work comprises a first assessment of estimating nutrient concentrations, loading rates, and associated ecological response for these lakes.

The specific objectives of this study were:

- to undertake analyses of the relationship between in-lake nutrient concentrations with specific indicators of ecological integrity (*e.g.* macrophytes, water clarity, macroinvertebrate indices)
- to test the use of existing catchment land-use management tools such as CLUES in their ability to predict catchment nutrient loading in relation to in-lake nutrient concentrations in dune lakes

- to evaluate groundwater linkages for a limited set of window lakes and demonstrate how groundwater could be accounted for in calculating nutrient loads
- to evaluate the relative importance of nitrogen (N) or phosphorus (P) limitation for different dune lake systems in regards to potential lake restoration measures
- to make recommendations on nutrient targets to protect values for different classes of dune lakes for maintaining ecological values.

Approach

The study consisted of a modelling approach to estimate total nitrogen (TN) and total phosphorus (TP) loads to 27 dune lakes in Northland, and calibrate model outputs with existing water quality data. There are only limited environmental monitoring data for nutrient loading from lake tributaries in this region; therefore, a catchment modelling approach using the national CLUES (Catchment Land Use for Environmental Sustainability) model was used to estimate nutrient loads to the lakes. Nutrient loads were calibrated to median annual total nitrogen (TN) and total phosphorus (TP) concentrations for the lakes from monitoring data collected between 2009 and 2014.

Key Findings

Moderately strong statistical relationships were observed between TN and TP loads calculated using the CLUES model and in-lake nutrient concentrations. The relationships were improved by transforming nutrient loads with Vollenweider regression models, which took into account lake physical features (*e.g*. depth, water residence time). The TN and TP loading models derived for shallow and deep lakes modelled separately yielded the strongest statistical power, which explained between 41 to 49% of the variation of in-lake TN and TP concentrations. These results support that deep (seasonally stratifying) and shallow (polymictic) lakes be considered separately in relation to managing nutrient loads. However, the performance of the CLUES load Vollenweider models was poorer than observed for lakes from other regions (*e.g*., Canterbury high country lakes, South Island coastal lakes), where CLUES TP Vollenweider models explained between 75–80% of between-lake variation. This finding suggests a degree of caution in utilising the CLUES model for establishing lake-specific N and P load targets for dune lakes due to its lesser predictive performance. Future work on factors not accounted for in our CLUES Vollenweider modelling such as groundwater hydrogeology, internal recycling, denitrification, and waterbird sources of phosphorus could improve the overall load predictions for dune lakes, and increase confidence in the load model predictions.

The relationship between in-lake nutrient status with other ecological integrity variables was explored to identify potential water quality targets to be included in NRC's new regional plan. We focused our analyses around ecological responses to variation in median annual TN and TP because of their inclusion in Appendix 2 of the NPS-FM (NOF ecosystem health attributes). These therefore are the most relevant nutrient parameters to establish water quality targets within the regional water plan. They provide good linkage with catchment load models that predict annual loads of TN and TP. There were strong statistical relationships between in-lake nutrient status and ecological integrity variables, such as chlorophyll-*a* (chl-*a*), water clarity, and macrophyte and macroinvertebrate community indices. As with load modelling, separate models for deep and shallow lakes yielded greater statistical performance. Stronger statistical relationships occurred with TP than TN, but TN appeared to be important for some macrophyte community indices. Ecological variables with the strongest relationships with in-lake nutrient status included chl-*a*, water clarity (Log Secchi), macrophyte depth limit, macroinvertebrate ETO (Insects of the orders Ephemeroptera, Tricopetra, and Odonata), macroinvertebrate diversity, and the LakeSPI native index. Based on these regression analyses, ecological variable targets (and associated TN and TP concentrations) are recommended, based on protecting and maintaining good ecological integrity.

Ecological variable relationships with lake trophic status were also considered in regards to bands set out in the National Objectives Framework (NOF) for annual median TN and TP for New Zealand lakes. There was a reasonably consistent pattern of differing bands for TN and TP associated with the ecological variables targets, with TP more often required to be within a more protective band to achieve the set target. For instance, based on our regression functions, lakes classified as B-band lakes for TP would be classified as C-band lakes for median chl-*a*, and similarly C-band lakes for TP were often D-band lakes for median chl-*a*. Alternatively there was reasonable correlation between NOF bands for TN and chl-*a*. This has important implications for target setting under the NRC regional plan, suggesting that a higher[1] TP NOF band will be required to achieve the intended ecological targets, including chl-*a*, visual clarity, macrophyte depth limit, and macroinvertebrate diversity. In nearly all cases ecological variables and trophic status was better for deep lakes, and therefore TN and TP band targets were recommended to be more stringent to protect higher water quality and ecological values (*e.g*., high water clarity and more extensive macrophytes). The data set used in this study was too limited to draw strong conclusions in relation to specific threshold loads or concentrations that would lead to step changes such as macrophyte community collapse. Macrophytes appeared to more progressively decline with nutrient concentration range, rather than approach a threshold for collapse.

High N:P ratios and a greater occurrence of P limitation in nutrient bioassays would suggest that P or co-limitation is most prevalent in the dune lakes, which likely contributes to stronger statistical relationships of TP loading with ecological variables. However, in several instances strong relationships were found with TN, particularly for macrophyte community indices. This could be in response to species-specific tolerances of soluble N forms (*e.g.* nitrate, ammonium) for some species. Macrophytes are considered critical in the ecology of shallow lakes in maintaining clear-water conditions, and lake water quality. Given the roles of both N and P in lake water quality, and maintaining macrophytes, it would be prudent to manage both nutrients. However, the expected likelihood P limitation in most of the dune lakes considered could help guide prioritisation of lake remediation measures; e.g. controlling P losses to lakes showing indications of P limitation.

[1] Meaning a higher attribute state in terms of A-D ratings, lower in terms of phosphorus concentration

Recommendations

Overall, results from the nutrient models provided useful information about the relationships between nutrient status and key measures of the ecological integrity of the dune lakes. Catchment modelling provided a moderate degree of confidence in using the CLUES models (Vollenweider transformed) for predicting in-lake nutrient status, but further work is recommended on improving load model predictions before it is used to set lake-specific loading targets. This could be focused on better understanding groundwater loads, internal nutrient cycling, and inputs from waterbirds.

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1. INTRODUCTION

The Northland region has some of the most outstanding examples of coastal dune lakes in New Zealand. These include some of the few remaining lowland lakes with high water quality on the North Island. Management of their conservation, recreational and cultural values requires an understanding of their vulnerability to different human-induced pressures, including nutrient loads from land use in their catchments. Northland Regional Council (NRC) is in the process of developing a new regional plan for promoting the sustainable management of Northland's natural and physical resources. Improving the state and management of water in Northland's lakes, particularly dune lakes, is a key priority in the plan development project.

The implementation of the National Policy Statement (NPS) for Freshwater Management 2014 (NPS-FM) requires regional authorities to establish and implement limits to protect water quality and ecological values of waterbodies in their region. In Northland, as in many parts of New Zealand, the primary land uses involve agriculture and forestry, which pose challenges for managing water quality in lakes with very small catchment areas, in some instances comprised of a single farm or forestry block. The management of nutrient losses from adjacent lands is expected to be a critical component of maintaining ecological and other (recreational, aesthetic) values of lakes. As such, understanding ecological responses of waterbodies to nutrient loading is essential for setting nutrient loads for lakes and for the conservation of freshwater ecosystems.

Management of nutrient inputs to waterbodies to achieve concentration targets has been an ongoing priority for management agencies in New Zealand and internationally for decades. However, the current focus of establishing nutrient load limits to protect ecological and other values is likely to be a greater challenge because it relies on a thorough understanding of relationships between nutrient generation, transport pathways, and loading, as well as receiving water quality and how water quality influences the ecological integrity (EI) of these waterbodies. While there is reasonable understanding of relationships between loading and in-lake nutrient concentrations, the relationships between in-lake processes and biological feedbacks (*e.g.*, phytoplankton production, macrophyte uptake, zooplankton grazing) is complex (*e.g.* Lijklema 1994; Søndergaard *et al.* 2003; Abell *et al.* 2011; Jeppesen *et al.* 2007; Moss *et al.* 2013).

<u>Northland dune lakes</u>

The Northland region contains a large number of lakes, most of which are associated with sand deposits within dunes shaped by aeolian processes during relatively recent geological history. The Freshwater Ecosystems of New Zealand database (FENZ) classifies 3821 lakes that are greater than one hectare in area occurring across the North and South islands and some of the smaller outlying islands (Leathwick *et al.* 2010). FENZ identifies 240 lakes within Northland region, of which 179 are listed as dune lakes. A further 188 dune lakes[2] of less than one hectare have also been identified for the region (Champion & de Winton 2012). Geoformation attributes of lakes (i.e., how the lake basin was formed), such as dune lakes and volcanic crater lakes, are linked to functional and landscape attributes that influence ecological processes (e.g., elevation, connectivity to groundwaters, lake basin morphometry, and climatic patterns). Thus geoformation is often used as a surrogate feature for classifying lakes (*e.g*. Irwin 1975; Livingston *et al*. 1986).

On an international basis, dune lakes constitute a rare environment class with the only known occurrences in New Zealand, Australia, Madagascar, and the south-eastern coast of the USA (Porter 2009; Champion & de Winton 2012). The greatest abundance occurs along the west coast of the North Island of New Zealand, particularly through Northland but extending southward through to the Wellington region. There are also smaller pockets of dune lakes along the West Coast of the South Island extending as far as Southland, but far less numerous than in the North Island. In Northland, three larger clusters of dune lakes occur through dune areas of the Pouto Peninsula located on the western side of Kaipara Harbour, the Apouri Peninsula along Ninety Mile Beach, and the Kai-iwi lakes north-west of Dargaville along the west coast.

In addition to their uniqueness, Northland dune lakes represent a large proportion of warm, lowland New Zealand lakes with relatively good water quality (Sorrell *et al*. 2006; Verburg *et al*. 2010). Verburg *et al*. (2010) compared water quality for each region and showed 14 Northland lakes were either oligotrophic or mesotrophic, compared with only one lake each within Auckland and Waikato regions (areas with similar temperatures and elevations to Northland).

1.1. Dune lake typology

A functional classification for defining freshwater management units (FMUs) of Northland lakes was recently proposed (Hughes *et al*. 2015). It aimed at grouping lakes with similar ecological structure and responses to management intervention measures. This classification was expected to form the basis for lake management classes, and aid in more streamlined planning measures within the Northland's new Regional Water Plan. The proposed classification provided a framework by which water quality and ecological integrity relationships are examined in this study. The proposed FMU classification identifies two key attributes by which lakes are considered for classification; specifically lake depth and geomorphic formation.

[2] Waterbodies less than 1 ha in open-water area may be considered ponds or wetlands by some regions

1.1.1. Lake depth

There is strong recognition that lake water depth is a key functional driver of water quality in New Zealand lakes (Snelder *et al*. 2006; Drake *et al*. 2011). The morphometry of the basin is a key variable in determining the mixing regime of a lake, and the prevalence of thermal stratification over seasonal cycles. In the FENZ environmental classification, mixing regime was regarded as having fundamental importance for New Zealand lakes (Snelder *et al*. 2006). The importance of basin depth has been recognised for influencing mixing regimes, lake volume, hydraulic residence times (*i.e*, water turnover) and the extent and biotic composition of littoral zones.

Analysis of the variation in key water quality parameters amongst 26 Northland dune lakes identified two functional depth classes, based on maximum lake depths (Hughes *et al*. 2015):

- Shallow polymictic dune lakes— less than10 m maximum depth
- Deep seasonally stratifying dune lakes— greater than 10 m maximum depth.

Based on this analysis it was recommended that FMUs for the dune lakes in the Northland Region should include classification by depth.

1.1.2. Lake hydrogeology and groundwater connectivity

Hydrogeology of dune lakes is considered an important factor controlling their ecology and water quality dynamics through the manner by which the lakes connect to surface and groundwater flow paths. Champion and de Winton (2012) reported on a comprehensive geomorphic classification system for dune lakes as part of a process of assessing the ecological status of 82 dune lakes in the Northland region. This classification system considers various attributes around the formation of the lake basin, connection with underlying groundwaters (*e.g*., perched or window as defined below), and the nature of sedimentary layers that comprise its immediate surface water catchment.

Classification followed that of Timms (1982) which can be broken into six classes as follows (from Champion & de Winton 2012):

1. Perched lakes in deflation hollows—perched in leached dunes, in deflation hollows in elevated leached dunes where organic material has sealed the basin floor and provided humic (tea-stained) water. Twenty-two lakes are tentatively assigned to this class.
2. Swamp associated perched lakes—similar to Class 1 but close to the sea, associated with extensive swamps. Seven lakes are assigned to this class.

3. Window lakes-—water-table window lakes in a drowned valley or interdune basin, fed by springs with clear water character. Nineteen lakes are tentatively assigned to this class.
4. Dune contact lakes— waterbodies where· at least one shore is in contact with a coastal dune, often but not exclusively humic. Seventeen lakes are assigned to this class.
5. Marine contact lakes—freshwater lakes with marine contact, where there may be intermittent connection with the sea. Waitahora Lagoon is the only example of this lake class.
6. Ponds in frontal sand dunes—ponds where wind erodes sand to form deflation hollows. Although common on the west coast, only one, Te Arai, is identified in lake strategy.

Subsequent analyses aimed at assessing the variation in key water quality parameters amongst 26 Northland dune lakes did not demonstrate any significant variation amongst the geomorphic classes tested (Hughes *et al.* 2015). However, due to the expected differences in groundwater connectivity between the different geomorphic classes, Hughes *et al*. (2015) recommended that management of FMUs would at least need to consider the entire extent of groundwater recharge area in managing dune lakes. These planning measures would not necessarily require further subdivision of FMUs by geomorphic class, but could nevertheless consider planning and policy measures appropriate to the different geomorphic types. Therefore, classification of FMUs by geomorphic type was not recommended.

1.2. Purpose of this project

This project is aimed at quantifying relationships between nutrient loads, nutrient status, and the ecological condition of dune lake in the Northland region. A framework for classifying the ecological status of dune lakes has been developed by NIWA in conjunction with NRC (Champion & de Winton 2012). This framework is based on a range of ecological attributes (water quality, macrophytes, invasive species and riparian condition). From this classification, NRC have identified 12 dune lakes as outstanding for their region, and implemented individual catchment plans to manage their health and resilience. However, there is still limited understanding of water quality targets required to maintain these high values, recognising there are a broad range of lake types (*e.g*., seasonally stratifying and polymictic[3] lakes varying in their hydrology and connectivity to ground waters). This report comprises a first assessment of estimating nutrient concentrations, associated loading rates, and their associated ecological response for lakes in these dune lakes.

[3] Polymictic lakes are lakes that mix frequently, usually due to wind-formed waves, and are often shallow lakes that remain thermally stratified only over short periods (e.g. weeks)

The specific objectives of this study were:

1. To undertake analyses of the relationship between in-lake nutrient status and specific indicators of ecological integrity of dune lakes (*e.g.* macrophytes, water clarity, macroinvertebrate indices).
7. To test the use of existing catchment land-use management tools such as CLUES in their ability to predict catchment nutrient loading in relation to in-lake nutrient status in dune lakes.
8. To evaluate groundwater linkages for a limited set of window lakes and show how groundwater nutrient sources could be accounted for in calculating nutrient loads.
9. To evaluate the relative importance of nitrogen (N) or phosphorus (P) limitation for different lake systems in regards to guiding policy and lake restoration measures.
10. To recommend nutrient targets for different classes of dune lakes for maintaining ecological values in relation to concentration bands described in the National Objectives Framework attributes for lakes.

The analyses of nutrient status and load relationships with ecological integrity indicators was structured to take into account FMU classes proposed in Hughes *et al*. (2015).

1.3. Ecological theory of nutrient loading to lakes

1.3.1. Indicators of lake nutrient status

Relationships between lake properties and their catchments have been the subject of extensive scientific investigation (*e.g.* Rasmussen *et al.* 1989; Schallenberg & Sorrell 2009). Advances in spatially-explicit information *(*GIS and remote sensing) have allowed for the development of catchment models for a number of indicators of key anthropogenic catchment pressures such as nutrients and fine sediment. These pressures are known to be related to the Ecological Integrity (EI) and functioning of lakes (Woods *et al.* 2006; Leathwick *et al.* 2010). Understanding the relationships between these catchment pressures and in-lake response variables, as well as identifying critical pressure thresholds (*e.g.* regime shifts, *sensu* Scheffer *et al.* 2001) could better inform lake management.

Management of freshwaters is complex with a multitude of stressors interacting to affect their functioning, such as invasive species, land use change, physical habitat alteration, and water abstraction. Ecological integrity (EI) is an appealing concept for considering freshwater ecosystem management because it integrates a wide range of parameters relating to the structure and function of the ecosystems. Assessments of EI have traditionally been based on biological indicators and processes (*e.g.* Angermeir & Karr 1994), but increasingly, physical and chemical variables are being used to complement biological integrity assessments (Barbour *et al.* 2000; Moss *et al.* 2003; Søndergaard *et al.* 2005).

A comprehensive review by Schallenberg *et al.* (2011) defined New Zealand freshwater EI as a composite of four components: nativeness, pristineness, diversity and resilience, with a list of potential indicators or metrics for defining each of these components. Schallenberg *et al.* (2011) identified a number of key indicators in relation to nutrient loading stressors, which included:

- trophic level index and its components
- aquatic macrophytes
- water clarity
- macroinvertebrates.

Below we provide a brief summary of these key response variables and their known relationships with nutrient loading.

Trophic level index and components

The trophic level index (TLI) integrates measures of key nutrients, algal biomass and water clarity to provide an overall score of lake water quality (Burns *et al.* 2000). Partly because of its ease of measurement and widespread applicability, it has been widely used in classifying New Zealand lakes, and has been linked to nutrient loading and catchment land use (Hamill 2006). The TLI has four component parts: Total Nitrogen (TN), Total Phosphorus (TP), Secchi depth and chlorophyll-*a (*chl-*a)*. In some instances TLI is calculated excluding the Secchi depth component (called TLI3), particularly in shallow lakes where Secchi depth exceeds maximum lake depth.

Total N and TP are used as indicators of nutrient availability in many lake quality assessment schemes (Moss 2007), and TN is a strong predictor of lake productivity in northern hemisphere temperate lakes (Vollenweider 1976). Chlorophyll-*a* concentration in the water is a measure of phytoplankton biomass, and can be a robust indicator of nutrient enrichment (Moss 2007). However, variation in biomass-specific pigment content (*e.g*. chl-*a* content per cell) and community composition may, to some extent, decouple relationships between chl-*a* concentrations and phytoplankton biomass.

Secchi depth (or Secchi disk transparency) is a measure of water clarity that integrates factors such as suspended sediment, phytoplankton biomass, and water colour (chromophoric dissolved organic matter). Its use in the TLI is primarily as a further measure of eutrophication, so confounding clarity conditions should be considered as to its useful inclusion.

TLI scores are not necessarily an indicator of pristine water quality. Pristine lakes may exhibit high TLI scores due to high natural nutrient loads (shallow lakes situated on fertile plains, water bird nutrient loading, *etc*.) or naturally low water clarity (high levels of suspended sediments, peat staining of water, *etc*.). Trophic lake index variables often vary seasonally and, therefore, TLI measurements are made on a monthly basis and reported as an annual mean (Burns *et al.* 2000). Shallow lakes can exhibit high temporal variability in the components of TLI due to the entrainment of bottom sediment into the water column in windy conditions. Concentrations of inorganic suspended sediments can be used to correct TLI for sediment re-suspension effects (Burns *et al.* 2000), or the Secchi parameter can be excluded from the TLI equation.

Aquatic macrophytes

Aquatic macrophytes are strongly linked with nutrient loads due to their sensitivity to either increased phytoplankton abundance (reducing light availability), or epiphytic growth on macrophytes. There is a strong relationship between the maximum depth to which macrophytes grow and water clarity across a wide range of lakes (Schwarz *et al.* 2000), indicating a sensitivity to changes affecting water clarity. The depth to which macrophytes grow defines the littoral zone of lakes, which is generally the zone of highest productivity and biodiversity values. Therefore, substantial reductions in macrophyte depth limits and water clarity have direct impacts on lake ecological integrity. The maximum depth of submerged plants is used in the LakeSPI (lake submerged plant indicator) monitoring method as a measure of ecological condition in lakes (Clayton & Edwards 2006). However, macrophyte depth limits may not be applicable to shallow lakes in which macrophytes either inhabit the entire lakebed or are completely absent.

Native aquatic macrophyte diversity is probably the most well-documented indicator, and is widely used as a component of the LakeSPI methodology (*e.g.* Clayton & Edwards 2006). It is not well understood how macrophyte richness is related to nutrient loading, although there is increasing recognition of N concentration sensitivity for some species (Moss *et al.* 2013).

Water clarity

Water clarity is a key indicator for nutrient enrichment of lakes because of its links to phytoplankton biomass, and light availability for aquatic macrophytes. Large and/or persistent compression of the euphotic zone by phytoplankton blooms or fine suspended sediment can contribute to, or even cause, catastrophic collapse of keystone plant communities (Burkholder & Cuker 1991; Scheffer *et al*. 2001) including in numerous shallow lakes in New Zealand (Gerbeaux & O'Connor 1992; Schallenberg & Sorrell 2009). The euphotic depth (depth in the lake to which 1% of surface irradiance can penetrate) is related to the maximum depth of macrophyte growth. Euphotic depth is assessed by using a sensor to measure depth profiles of photosynthetically active radiation (PAR). Other surrogate measures of clarity can include Secchi disk measurements, turbidity (measurement of light scattering in water), and concentrations of particulates in water (*e.g.* total suspended solids). The euphotic depth can be assessed in any lake but can vary markedly over time in response to seasonality, floods, algal blooms and wind disturbance. Excessive variation in, or consistent reductions in, the euphotic depth over time can indicate that macrophyte communities are at risk of collapse because of diminishing light intensity.

Macroinvertebrates

The macroinvertebrate communities of dune lakes comprise a diverse array of insect and other invertebrate fauna (Ball *et al*. 2009). Generally, the diversity of sublittoral and littoral zone macroinvertebrates remains quite stable throughout the year (Talbot & Ward 1987; Kelly & McDowall 2004). However, macroinvertebrate diversity has been shown to relate to nutrient status of lakes. Although the relationship was non-linear with the main response occurring at the super-eutrophic end of the nutrient gradient (Timms 1982). Weatherhead and James (2001) also showed that littoral invertebrates were strongly influenced by physical gradients of depth and exposure. Kelly and Hawes (2005) demonstrated that community composition of macroinvertebrates can be related to invasive macrophytes.

Recent work by Kelly *et al*. (2013) and Schallenberg and Kelly (2014) has shown that composition of the macroinvertebrate community, particularly of the insect orders Ephemeroptera, Trichoptera, and Odonata (ETO), were sensitive to variation in nutrient loads to small and medium-sized lakes on the South Island. It was thought that this response may have been mediated by changes in aquatic plant cover and extent.

1.3.2. Internal nutrient cycling

One aspect to consider for management of nutrients in lakes is the potential for recycling of accumulated sedimentary nutrients (*e.g.* from macrophyte decay and phytoplankton settling) back into the water column. The processes, also referred to as 'internal loading', can greatly increase annual loads of phosphorus in conjunction with external sources in some lakes (*e.g.* Howard-Williams & Kelly 2003; Gibbs 2011). Internal nutrient cycling processes are enhanced by anoxic conditions near the sediment water interface. Such conditions are facilitated by extended (seasonal) thermal stratification of the water column (*e.g.* Vant 1987; Burger *et al.* 2007).

For small to medium-sized lakes (as is the focus of this study), it is more common for lakes with maximum depths of greater than 10 m to thermally stratify for extended periods during summer (*e.g.,* October–April) depending on wind mixing and tributary inflow dynamics. Seasonally stratifying lakes are vulnerable to internal loading when organic inputs (*e.g.* settling phytoplankton) to lake-bottom are high, thereby increasing oxygen demand in the hypolimnion (bottom waters). As a result, internal loading related to bottom-water anoxia occurs more often in eutrophic (nutrient rich) lakes, while the pattern of significant oxygen depletion in lakes having relatively low surface water production (*i.e.* low chlorophyll) is uncommon (Verburg *et al.* 2010). Management focusing on preventing internal loading is of high priority, as once these negative feedback processes start they can be difficult to halt. Poor water quality (*e.g.* bottom water anoxia, high nutrient status) can remain even after external nutrient loads are diminished. Maintaining lake nutrient status in the oligotrophic–mesotrophic range is therefore a priority for minimising risk of internal loading processes establishing in deeper lakes.

Shallow lakes (*i.e.* lakes with maximum depths < 10 m) tend to respond to nutrients in a different manner to deep lakes, and thus have their own ecology and management challenges (Scheffer 2004; Scheffer *et al*. 1993). Because of the high rates of water column mixing in shallow lakes, there are frequent interactions between the lake water column and sediments. Phosphorus contained in lake sediment and pore-water can be recirculated to the water column during periods when wave action disturbs the deeper anaerobic sediment layers (Jensen *et al.* 1992a). This process is mediated by water column temperatures, with nutrient (P) concentrations in shallow lakes often being highest during summer (*e.g.* Gibbs & White 1994)—the opposite of that usually observed in thermally stratified lakes (Scheffer 2004).

Phosphorus is often considered the primary nutrient to be controlled in shallow lakes as it can be absorbed by the lake sediment and released to the water column during sediment resuspension events. This internal loading can delay the restoration of lake P concentrations by many years despite a reduction in external P inputs (Jeppesen *et al.* 1991; Knuuttila *et al.* 1994; Perrow *et al.* 1994; Søndergaard *et al.* 2005). In some cases, low N:P ratios from internal P loads can increase the incidence of cyanobacterial blooms of some species that are capable of nitrogen fixation (Noges *et al.* 2007). Shallow, highly polluted lakes can have long recovery periods following a reduction in external P loading because of the large amounts sedimentary P that can be recirculated (Bostrom *et al.* 1982; Jeppesen *et al.*1991).

Submerged macrophytes are a key consideration in regards to nutrient recycling in shallow lakes. Not only are they a very important structural element for lake habitats (Kelly & McDowall 2004), they also prevent bed disturbance and resuspension, thereby stabilising the clear-water state (Scheffer *et al.* 1993). Thus, the aim of shallow lake management is often to sustain or restore macrophyte communities to maintain the lake's clear-water state. Loss of macrophyte communities from nutrient enrichment of lakes can occur in a number of ways, including: sustained phytoplankton blooms, epiphyton growth, or intensive growths of tall macrophytes (Scheffer 2004). All of these mechanisms generally result in shading of macrophyte communities reducing light availability potentially resulting in their ultimate collapse, through a process termed 'flipping' (Schallenberg & Sorrell 2009). In some cases the loss of macrophytes can be permanent, with internal loading of nutrients from sediments and resuspension of lake bed materials generating turbidity to stabilise the ecosystem in its new turbid, phytoplankton-dominated state.

Management actions to reduce external nutrient loading can be counteracted by these internal lake processes once lakes have flipped, preventing the re-establishment of a macrophyte-dominated state (Carpenter 2003, Scheffer 2004). Consequently, management actions in shallow lakes focused on preventing the loss of macrophytes is a priority, as once a lake becomes enriched, it is a very difficult, lengthy (years), and costly process, if possible at all, to return it to its former (better) water quality state.

2. CATCHMENT NUTRIENT LOAD MODELLING

Nutrient load studies can be conducted either by collecting time series measurements of inflow concentrations and inflow volumes, or by using complex catchment models to predict inflow concentrations and volumes. In Northland, because of the ephemeral nature of stream inflows to dune lakes, there is limited information on the nutrient inflows to these lakes, and a considerable proportion of inflow is likely to occur as subsurface flow. As such, there are very limited data on which to base calculation of annual N and P loads. Consequently, a modelling approach is needed to estimate nutrient loads for these lakes, using existing information on current land use and leaching losses, and water quality monitoring data.

A pilot study was conducted to evaluate the use of an existing catchment land-use tool for predicting nutrient loads to dune lakes. The national Catchment Land Use for Environmental Sustainability[4] (CLUES) model (Woods *et al.* 2006), has been used for predicting loads to small and medium-sized lakes in other regions with some success (Kelly *et al*. 2013, 2014). Mean annual nutrient load predictions were made using the CLUES model standardised to Land Cover Database 4 (Landcare Research 2014) for 27 dune lakes for which long-term water quality data sets are available. The lakes are located in the Pouto Peninsula, Apouri Peninsula, and Kai-iwi lakes areas. These lakes varied in their land cover attributes; importantly, in the relative proportions of their catchment areas used for agriculture and forestry activities. These contrasting attributes provided a range of land uses and nutrient losses to assess against in-lake response measures.

Vollenwider models were used to calibrate predicted annual TN and TP loads with in-lake mean annual TN and TP concentrations for the 27 dune lakes. Considerable scientific investigation has been conducted into relating lake water quality with catchment loading characteristics (Vollenweider 1976,1982). Vollenweider's models relate the inflow nutrient loads with lake water quality, taking into account properties known to be related to nutrient cycling, including the lake volume, depth and water residence time for the lake. Vollenweider models were used to fit regression models with water quality data used to verify model performance (Vollenweider 1982). Limited data availability on stratification patterns and seasonal variability meant it was beyond the scope of this study to develop system-specific deterministic models for the Northland lakes with more complex models, such as DYRESM (Özkundakci *et al.* 2011).

This modelling procedure brings together catchment, water quality, and ecological information across the gradient of catchment nutrient loading, and recommends possible approaches to using this information for setting nutrient concentration targets and nutrient loads for dune lakes. The diagram below (Figure 1) provides an overview

[4] http://www.mpi.govt.nz/environment-natural-resources/water/clues

of the modelling approach, indicating the input data, modelling, and other assessments undertaken.

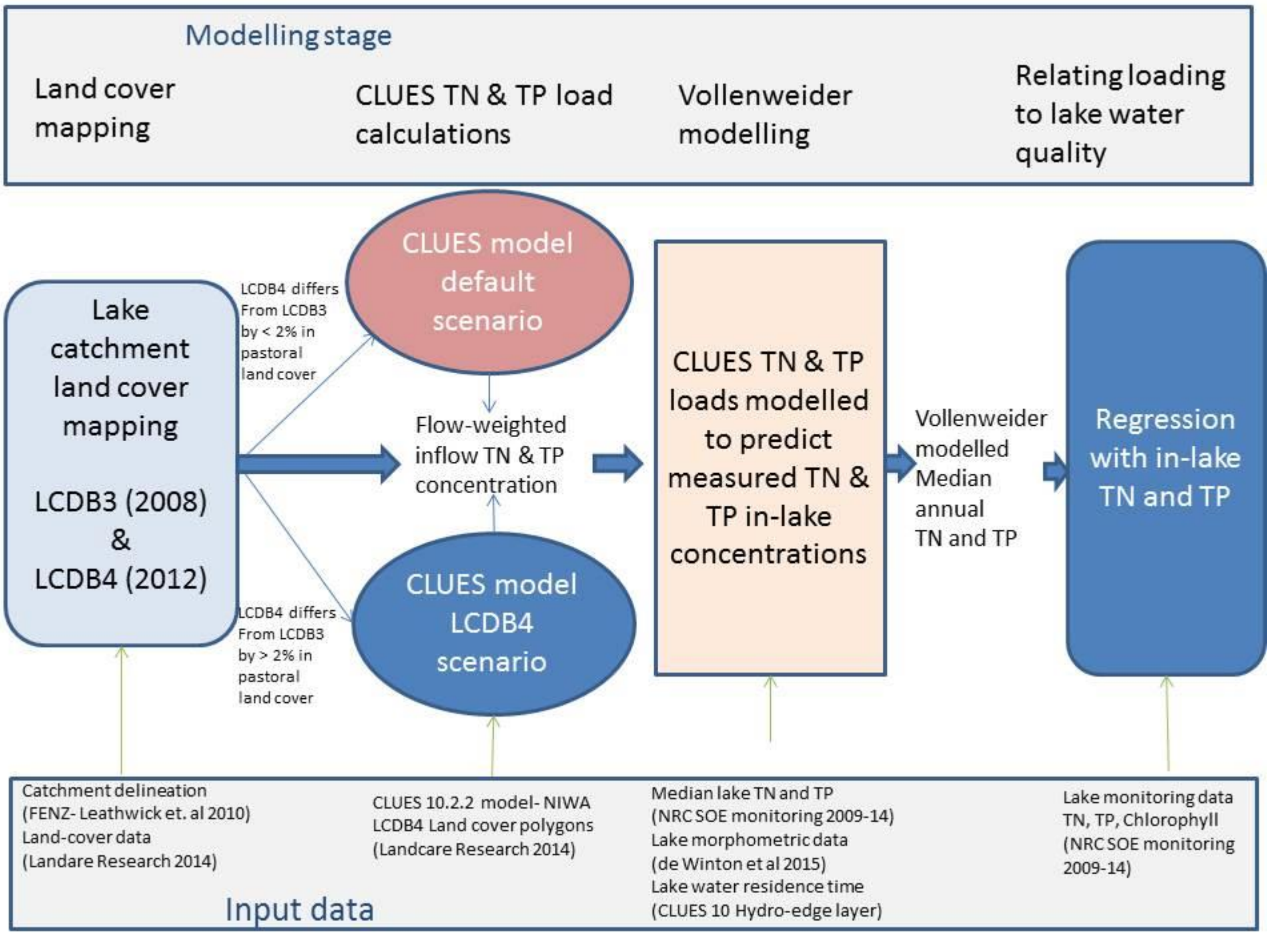


Figure 1. Diagram of the stages of modelling processes followed in this study and associated input and output data for the modelling components.

2.1. Land cover mapping

Lake catchment localities and land cover maps are shown in Figures 2 to 6, and a table of the proportional coverage using the Land Cover Database (LCDB v4.0) land cover categories is provided in Appendix 1. Lake catchment areas were derived from the Freshwater Ecosystems of New Zealand (FENZ; Leathwick *et al.* 2010) and overlaid with land cover information from Land Cover Database version 4.0 (Landcare Research 2014).

The 27 study lakes varied in their land cover attributes; importantly, in the relative proportions of their catchment areas in agriculture, forestry, native forest or native vegetation classes, thereby providing a gradient of nutrient loading to assess against in-lake response measures.

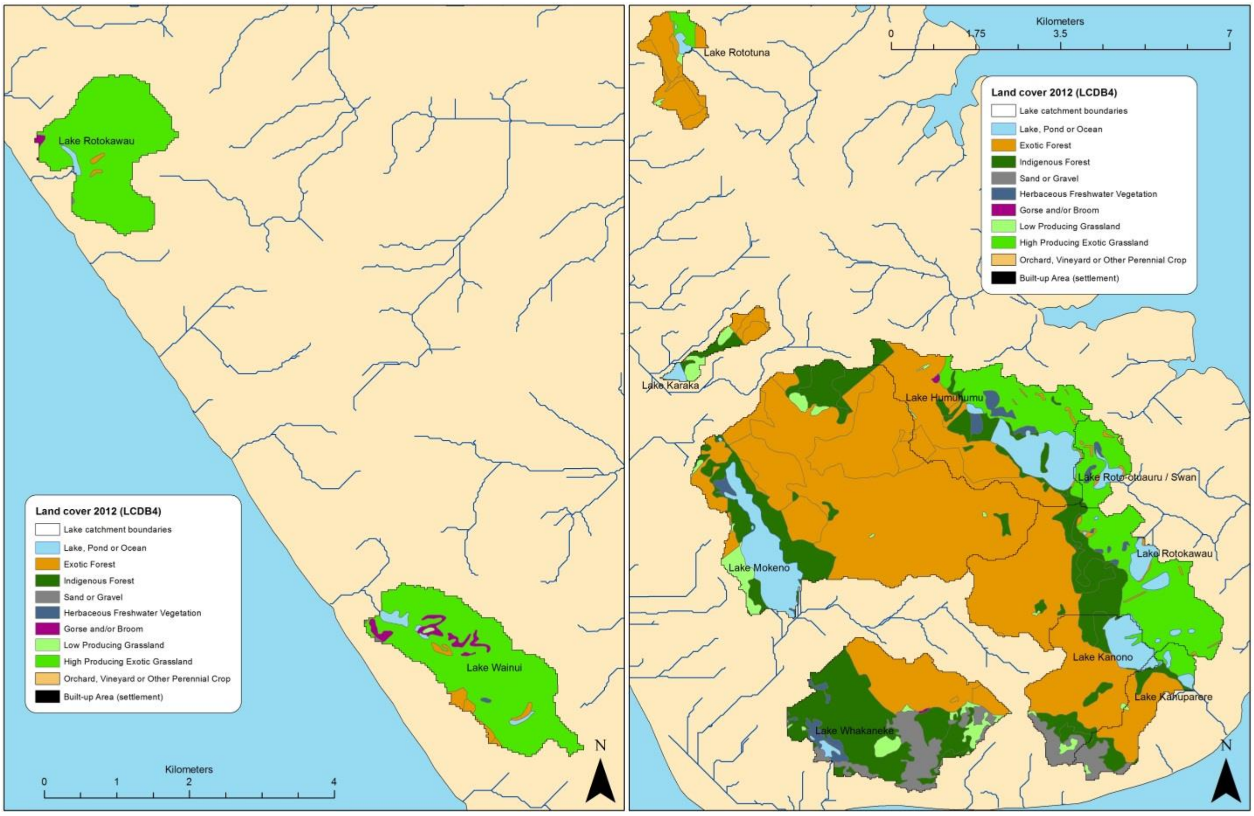


Figure 2. Lake catchment land-cover vegetation (Land Cover Database version 4.0) for nine dune lakes in the Pouto Peninsula, Northland.

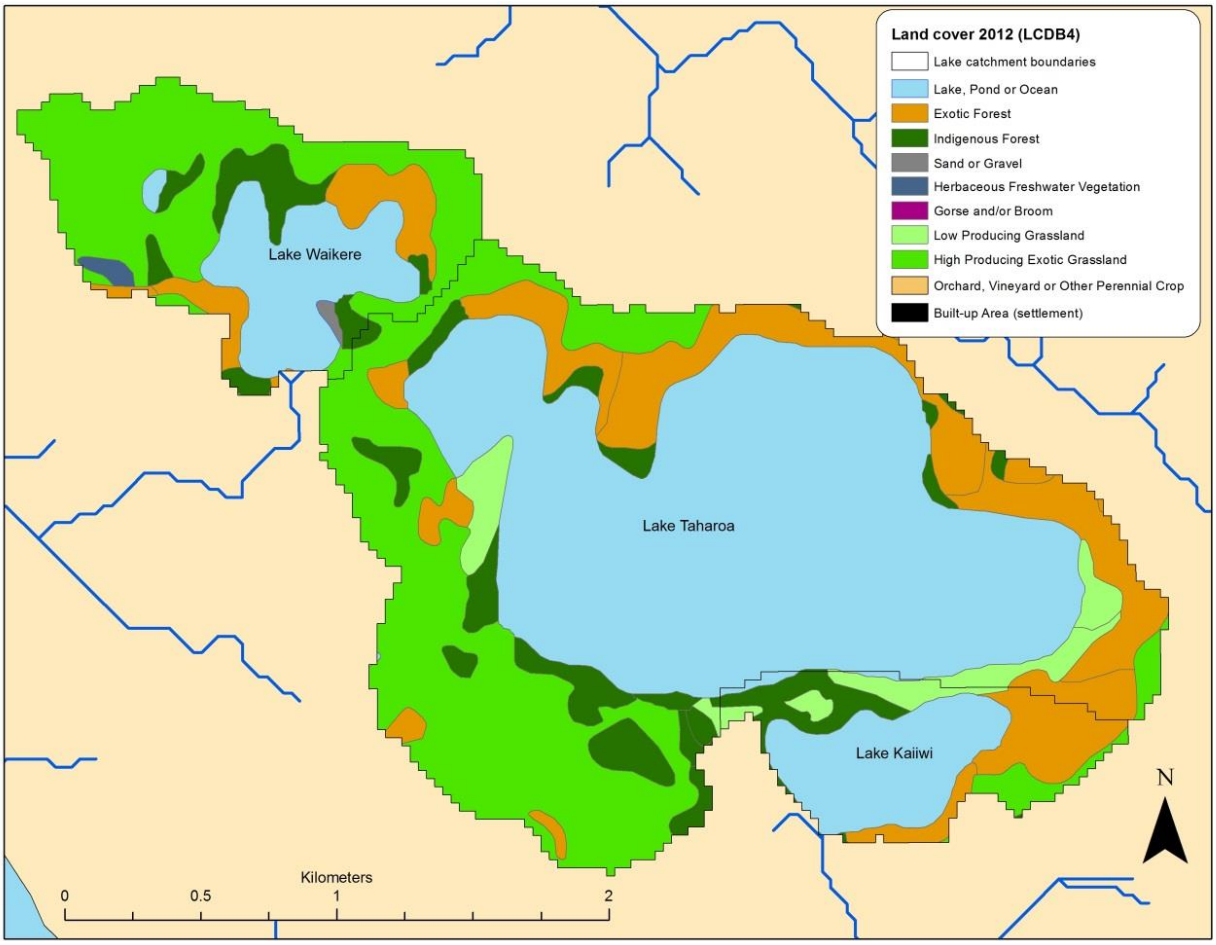


Figure 3. Lake catchment land-cover vegetation (Land Cover Database version 4.0) for three lakes in the Kai-iwi lakes, Northland.

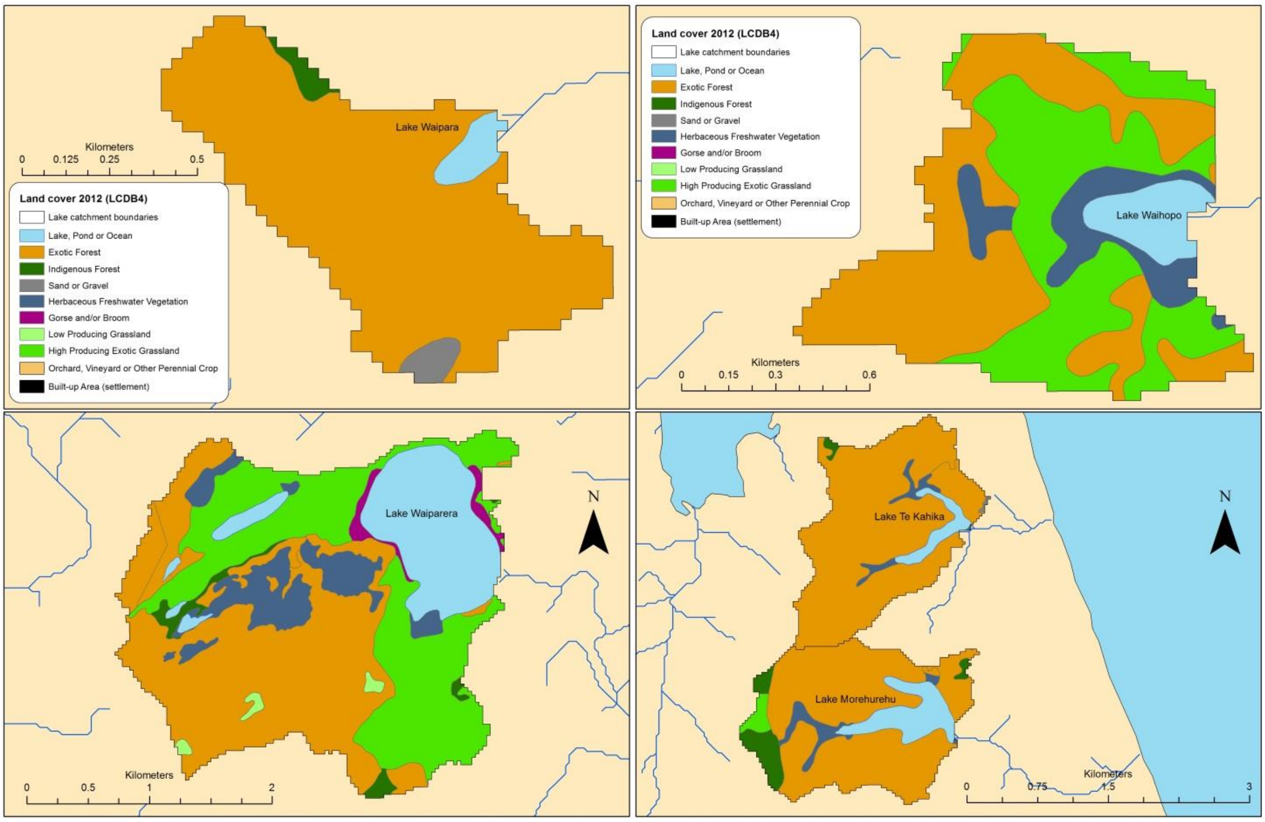


Figure 4. Lake catchment land-cover vegetation (Land Cover Database version 4.0) for five lakes in Northern Apouri Peninsula, Northland.

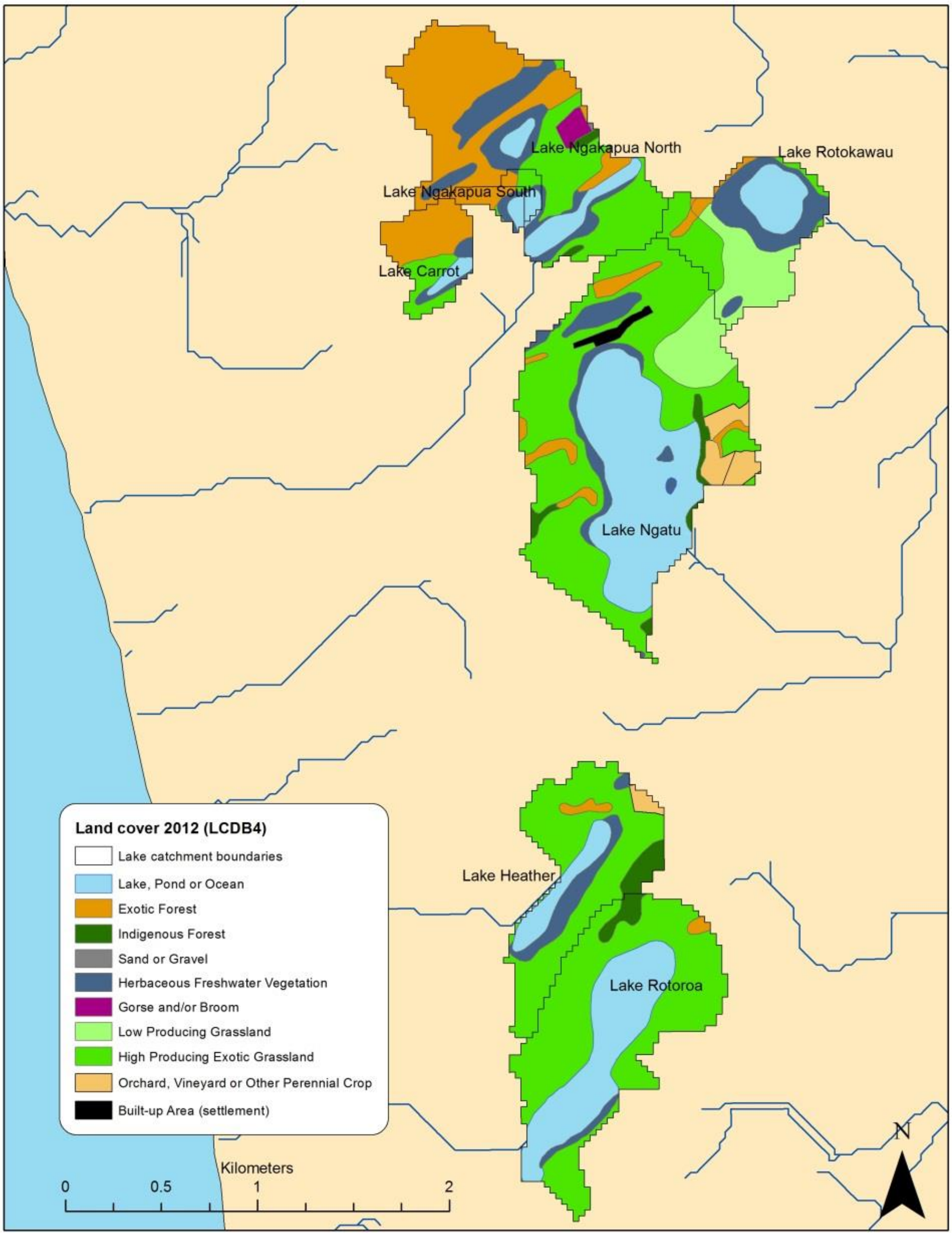


Figure 5. Lake catchment land-cover vegetation (Land Cover Database version 4.0) for seven lakes in the Southern Apouri Peninsula, Northland.

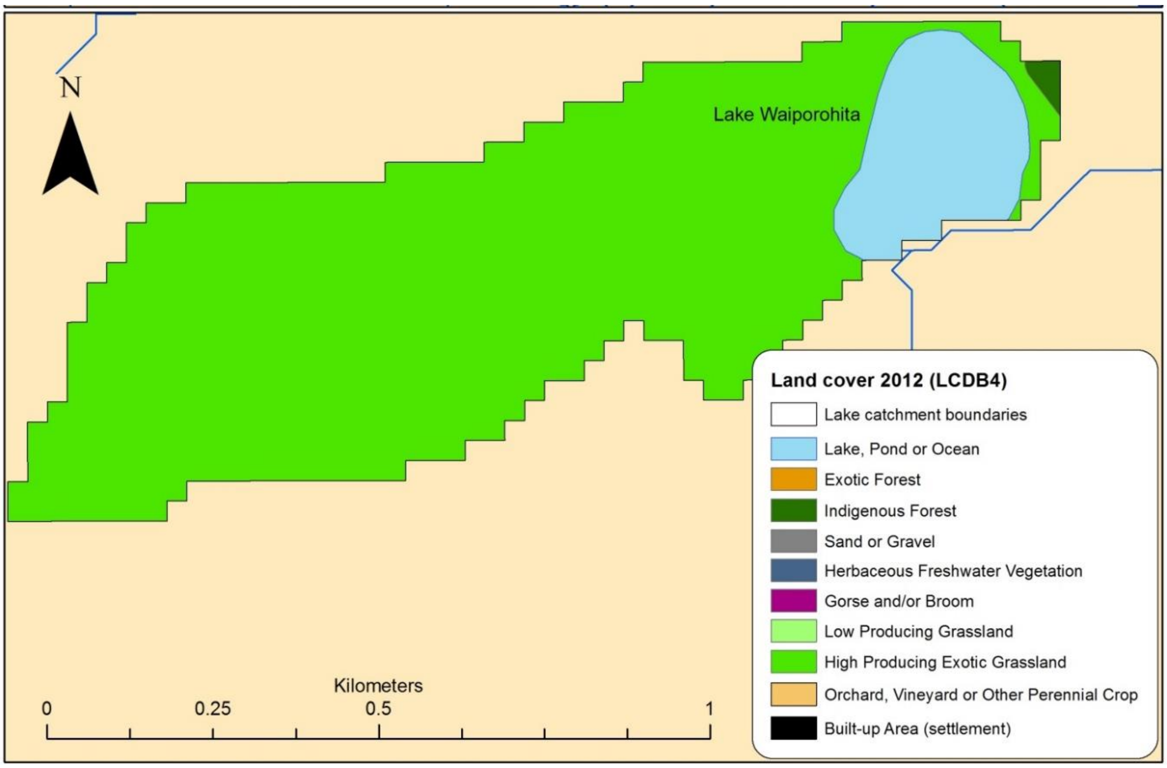


Figure 6. Lake catchment land-cover vegetation (Land Cover Database version 4.0) for Lake Waiporohita, Karikari Peninsula, Northland.

2.2. Calculating nutrient loads to lakes

Annual loads (tonnes / annum) of TN and TP to the lakes were estimated using a nutrient transport model combined with the regionally-based hydrological regression model, CLUES version 10.2.2 (Woods *et al.* 2006). Total Nitrogen and TP loadings generated by this model reflect the effects of various land uses such as production forestry, low-intensity grazing, high-intensity grazing, dairy farming, horticulture and urban development and take into account upstream retention by lakes and wetlands.

Catchment land-use in the 27 lake catchments was compared between the Land Cover Database version 3 (LCDB v3.0—Ministry for the Environment 2012) on which the present CLUES version 10.2.2 is based, and the latest land cover information in Land Cover Database version 4 (LCDB v4.0—Landcare Research 2014). This comparison was used to determine which lakes required updated CLUES land-use scenarios based on more recent land cover information. The following simple rule was applied: lake catchments that had land cover of agriculture or forestry classes differing between LCDB v3.0 and LCDB v4.0 by greater than 2% of the total catchment area were updated by running LCDB v4.0 land-use scenarios. This was done in ARCMap 10.1 using the CLUES polygon tool to trace the updated LCDB v4.0 land cover. In some cases alternative scenarios needed to be run when the digital elevation stream model poorly fit the lake drainage area. As a result of updating land-use cover or stream networks, alternative LCDB v4.0 land-use scenarios were run for the following lakes; Karaka, Ngatu, Kai-iwi, Taharoa, and Rotokawau (Pouto).

The CLUES model produced an overall estimate of TN and TP load in tonnes per annum, by summing the TN and TP loads for the inflows of each lake. Mean annual inflow TN and TP concentrations were calculated by dividing tributary inflows by the mean annual flow obtained from the CLUES model hydro-edge function. Mean annual aerial loads of TN and TP were calculated by dividing the total annual load (kg/y) by the area of the lake (ha).

Direct deposition of N and P to the lake surface in rainfall was also incorporated into estimates of annual nutrient loads. Annual estimates of rainfall (in mm/y) were obtained from contour maps of the Northland region of mean annual precipitation between 2004–2014 (NIWA Climate Database). Mean concentrations of TN and TP in rainfall were not readily available for Northland sites, and overall there has been very little monitoring conducted on N and P content of rainwater in New Zealand. Therefore, average nutrient concentrations had to be obtained from data for other regions, with the most extensive data source being from three sites in the Lake Taupo catchment between 2004–05 (Vant & Gibbs 2006). Methods for that study included daily collection of rainwater samples on days having significant rainfall events. Rainwater analyses were conducted for various forms of soluble and total N and P, but only TN and TP concentrations were used in the calculation of loads for Northland. Rain samplers were specifically designed to exclude particulate deposition. Mean rainfall concentrations over the two-year study were calculated as follows: for TN, 440 mg N/m^3, and for TP, 35.4 mg P/m^3 (Vant & Gibbs 2006). These concentrations were multiplied by annual rainfall over the entire lakes surface to determine annual TN and TP atmospheric loads.

2.3. Vollenweider modelling

To test and verify the accuracy of the predicted nutrient loadings from the CLUES model and their applicability to lakes in the Northland dune lakes, the model predictions were correlated against lake water quality conditions in 27 lakes for which routine water quality data was available (Table 1).

Vollenweider models were used to transform the predicted inflow nutrient loading rates (from CLUES) into predicted in-lake TN and TP concentrations. Vollenweider (1982) found that annual average TP and TN concentrations in lakes (TP_{Lake} and TN_{Lake} in mg m^{-3}) could be estimated from lake flushing rates and inflow concentrations according to equations 1 to 4 (Vollenweider 1976,1982). Two sets of Vollenweider equations derived for South Island shallow lakes (Kelly *et al*. 2013) and deep lakes (Özkundakci *et al.* 2014) were tested:

Shallow lakes (from Kelly *et al*. 2013):

$$TP_{Lake} = 3.018\left[TP_{Inflow}/\left(1+\sqrt{\tau}\right)\right]^{0.723} \tag{1}$$

$$TN_{Lake} = 158\left[TN_{Inflow}/\left(1+\sqrt{\tau}\right)\right]^{0.2} \tag{2}$$

Deep lakes (from Özkundakci *et al.* 2014):

$$TP_{Lake} = 1.55\left[TP_{Inflow}/\left(1+\sqrt{\tau}\right)\right]^{0.82} \tag{3}$$

$$TN_{Lake} = 5.34\left[TN_{Inflow}/\left(1+\sqrt{\tau}\right)\right]^{0.78} \tag{4}$$

Where TP_{Inflow} and TN_{Inflow} are the annual average inflow concentrations of P and N, respectively (mg m^{-3}), and τ is the hydraulic retention time of the lake (y). TP_{inflow} and TN_{inflow} were derived from the flow-weighted average nutrient concentrations from the CLUES catchment model output (see above) and used to calculate an annual mean discharge to the lake. The multiplier (a) and exponent (b) terms for the functions were optimised for the 27 Northland dune lakes using a non-linear regression model in the statistical program 'R'. The regression model uses the measured values of TN_{Lake} and TP_{Lake} from monitoring data (median of the annual averages for the years 2009 to 2014). For TP, an additional Vollenweider-type model was also considered (Brett & Benjamin 2008) that included a term for lake mean depth, as below:

$TP_{Lake} = TP_{inflow} / [1+ (v \mid / Z_{mean})]$

Where v is a constant optimised to fit the TP_{lake} data for the 27 Northland dune lakes.

Parameters used in calibrating Vollenweider models, including lake volume, hydraulic residence time (|), mean depth (Z_{mean}), and fetch were obtained from a recent NIWA bathymetric survey for 25 dune lakes (de Winton *et al.* 2015). This excluded lakes Kapoai and Whakaneke, for which bathymetric data reported in the FENZ lakes geo-database were used (Leathwick *et al.* 2010).

2.3.1. Nutrient retention

Net nutrient retention estimates (*i.e.* the portion of the nutrient load retained in the lake basin) are often calculated by using estimates of particle settling times and water residence times. The retention factor for phosphorus (R_P) was calculated using the retention model of Vollenweider (1976):

$$R_P = \frac{\nu_p}{(\nu_p + q_a)}$$

where v_P is the apparent settling velocity of P (m y^{-1}) and q_a is the areal water load in m y^{-1}. However, because there was no information on settling rates for any of the study lakes, we estimated the retention rates using relationships between inflow and outflow nutrient concentrations, by the following equations:

R_{TP} = [Mean TP_{inflow}]/ [$TP_{Lake} \times Q_{out}$]
R_{TN} = [Mean TN_{inflow}]/ [$TN_{Lake} \times Q_{out}$]

Where mean TP_{inflow} and TN_{inflow} is the flow-weighted inflow concentration calculated in CLUES, TP_{lake} and TN_{Lake} are the surface TN or TP concentrations of lake water calculated as the mean of measured data for lake surface samples. Q_{out} is the lake surface outflow calculated using the sum of the data of the 'MEANQ' field in the 'HYDROEDGE' layer in CLUES for the lake outlet stream reach.

Table 1. Lake morphometric data, CLUES (Catchment Land Use for Environmental Sustainability) nutrient loads, and median (2009–2015) total nutrient concentrations and turbidity for 27 Northland dune lakes used in the nutrient loading modelling study. P = phosphorus, N =nitrogen.

Lake	Lake Area (ha)	Max. depth (m)	Residence time (y)	Catchment area (ha)	CLUES N-Load (kg/ha/y)	CLUES P-Load (kg/ha/y)	Median in-lake total-N (mg/m^3)	Median in-lake total-P (mg/m3)	Median in-lake Chl-*a* (mg/m3)	Median in-lake Secchi (m)
Apouri										
Carrot	3.7	7.9	0.84	20	61.2	7.4	537	20.0	6.3	3.1
Heather	13.0	6.8	0.81	58	75.4	1.5	322	13.0	4.9	3.1
Morehurehu	45.1	14.9	2.23	316	19.9	1.5	467	12.5	2.1	1.8
Ngakapua N.	4.4	8.3	0.36	100	17.5	1.0	498	12.0	5.1	3.5
Ngakapua S.	10.4	5.5	0.88	8	92.2	11.2	541	16.0	6.6	2.7
Ngatu	58.0	6.3	1.66	172	15.5	1.1	828	9.0	4.0	3.1
Rotokawau	17.2	3.4	1.51	46	10.2	1.2	670	13.5	4.8	2.5
Rotoroa	34.9	7.3	1.16	97	21.1	0.6	820	13.0	3.8	2.2
Te Kahika	17.7	11.1	0.67	302	31.1	1.5	296	3.5	0.8	2.7
Waihopo	11.5	3.7	0.32	104	101.1	10.9	565	15.0	3.7	2.5
Waipara	2.5	4.4	0.26	65	78.8	3.2	452	14.0	2.6	2.5
Waiparera	117	5.2	1.02	704	9.0	0.5	818	25.5	12.3	1.9
Karikari										
Waiporohita	7.4	3.5	0.35	62	69.8	14.9	811	33.5	15.6	2.2
Kai-iwi										
Kai-iwi	30.7	15.7	0.60	485	30.8	1.9	363	7.0	2.0	7.0
Taharoa	222	38.8	10.60	423	6.8	0.5	130	2.0	0.8	10.1
Waikere	32.4	29.5	4.00	118	10.1	0.7	208	4.0	1.8	9.1
Pouto										
Humuhumu	137	15.2	2.18	879	20.7	2.1	312	11.0	6.5	3.8
Kahuparere	7.0	7.6	0.16	257	114.8	8.5	379	14.0	8.4	3.0
Kanono	81.4	15.6	3.16	499	21.8	1.7	350	17.0	7.7	2.5
Kapoai	2.5	9.0	0.05	252	422.7	75.5	2255	129.0	64.4	0.6
Karaka	13.7	5.8	0.80	96	34.7	3.2	494	29.0	18.1	1.7
Mokeno	176	6.5	0.49	2194	17.9	1.3	1070	32.5	8.9	1.9
Rotokawau	27.3	13.0	0.18	1489	105.2	6.4	358	8.5	2.4	6.0
Rototuna	7.4	4.0	0.13	189	53.8	2.5	733	31.0	17.2	2.5
Roto-otuauru	19.6	5.4	0.11	1026	64.5	5.6	937	47.5	17.5	2.0
Wainui	5.3	10.5	0.15	324	534.0	22.5	367	15.0	2.5	4.2
Whakaneke	22.2	3.2	0.05	885	119.5	10.1	648	67.0	25.1	1.0

2.4. Lake Ecological Integrity response variables

All ecological monitoring data sets available for the Northland dune lakes were used for examining the relationships between EI and nutrient concentrations.

A number of physico-chemical and biological indicators were then selected to assess relationships with nutrient loading (see Schallenberg *et al.* 2011). Physico-chemical data for the lakes were obtained from NRC State of the Environment monitoring of 27 dune lakes collected between 2009 and 2015. This included mean annual concentrations of TP, TN, chl-*a*, ammonium-N, dissolved inorganic nitrogen, total suspended solids, and Secchi depth measured at quarterly intervals. The TLI (Burns *et al*. 2000) has been widely used in New Zealand to determine the trophic state of lakes. Values of TLI were determined from annual mean surface water concentrations of chl-*a*, TN and TP (TLI) and excluded Secchi depth, as is often the case with shallow lakes. Water clarity measurements, consisting of Secchi disk depth, turbidity, and TSS were available for most lakes.

Submerged macrophyte community data for projects undertaken by NRC were compiled from NIWA's LakeSPI database (http//www.lakespi.niwa.co.nz). The database collated information about submerged macrophytes for 25 of 27 dune lakes sampled between 2009 and 2014 for which water quality data was available. Key metrics including the LakeSPI native condition score, invasive condition score, and overall LakeSPI score were used in the analyses. Submerged macrophyte depth limits have also been found to be useful indicators in relation to the nutrient status of lakes and have been used in analyses (Schwarz *et al*. 2000; Drake *et al*. 2011; Kelly *et al*. 2013).

Benthic macroinvertebrate community data were obtained from several sources of historical benthic macroinvertebrate surveys. These included data from one dune lake sampled in March 2006 (Humuhumu; Drake *et al*. 2009), ten Apouri Peninsula lakes sampled in November 2008 (Ball *et al*. 2009), one dune lake sampled in March 2013 (Waikere; DOC unpublished data) and eight dune lakes sampled in August 2015 (NRC unpublished data). Survey methods differed slightly between years, with collections in 2008 being semi-quantitative using a single sweep net sample, versus in 2006, 2013 and 2015 where sampling was done quantitatively by taking triplicate ponar grab (0.025 m^2 area) samples. Because of the inclusion of semi-quantitative data, only proportional composition metrics could be calculated across the whole data set. Benthic macroinvertebrate metrics included the calculation of taxa richness, the proportion of the community comprised of the insect orders Ephemeroptera, Trichoptera, and Odonata (ETO%), and overall community Shannon diversity score (H'). Macroinvertebrate data from the most recent monitoring event was used so as to align with the water quality data record, but for some lakes this was outside of 2009-2015, which could affect correlations with water quality data.

2.4.1. Analyses

Linear regression analyses were used to relate water quality variables with Vollenweider-transformed TN and TP loads for the lake set. A small number of outlier lakes were identified in the data set in some regression functions, and accordingly were omitted from regression models. The reason for omitting outliers is discussed in subsequent sections. All analyses were conducted using Systat version 10 statistical software (SPSS Inc, Chicago, USA). Regression slopes, significance (P-values) and coefficients of determination (r-squared values) are reported for all significant regressions.

Stepwise linear regression was used to interrogate relationships between multiple water quality variables and response ecological variables. An automated linear model selection procedure was used to look at the relationships between multiple water quality variables and response ecological variables. Analyses were conducted with the R package glmulti (Calcagno 2013) which finds the best model among all possible candidate models based on the Akaike Information Criterion (AIC).

3. RESULTS OF CLUES MODEL WATER QUALITY COMPARISONS

3.1. Nutrient loading and water quality relationships

CLUES model predictions of TP inflow concentrations were positively related to in-lake TP concentrations in the 27 lake data set ($P = 0.050$, $r^2 = 0.13$; Figure 7a). In this regression, predicted inflow TP usually exceeded in-lake P, as demonstrated by most points falling below the 1:1 fit line (regression slope 0.18, Figure 7a). This was evident for all of the lakes except for lakes Rototuna, Swan and Kapoai, which had the highest TP concentrations of the dune lakes in this study.

Higher TP loadings relative to in-lake concentrations are expected for dune lakes, indicating some degree of in-lake uptake of P (*e.g.*, by macrophytes) and a high degree of P retention. Dune lakes have low flow-through rates, frequently have no lake outlets, and therefore retention of nutrients (particularly particulate-bound P) in the lake is high. Lakes in which in-lake TP exceeded the predicted load concentrations tended to occur in those with the highest in TP concentrations. This could be due to an under-prediction of TP export by CLUES at higher TP concentrations; however, it is more likely that internal recycling of P (*e.g.* resuspension from sediments) was the primary cause for this. For example, Swan Lake has had grass carp introduced for the control of an invasive macrophyte (hornwort), which has likely resulted in more rapid P recycling that would tend to increase in-lake TP concentrations. Lake Kapoai has undergone a collapse in its aquatic macrophytes, and is now recovering following riparian restoration measures that included fencing and stock exclusion (Ministry for the Environment 2005).

A positive relationship was also apparent between predicted CLUES TN loading with in-lake TN concentrations; however, the strength of this relationship was weak and non-significant ($P = 0.261$, Figure 7b). Unlike the CLUES TP predictions, there were a greater number of instances where the CLUES TN loading predictions were less than the measured lake TN concentrations. The longer residence times of and high nutrient retention in dune lakes generally results in greater recycling of materials so it is not unexpected that in-lake concentrations could exceed those predicted from inflows. Furthermore, because the CLUES model does not explicitly account for groundwater N inputs to lakes, predicted CLUES loads could be smaller than actual loads.

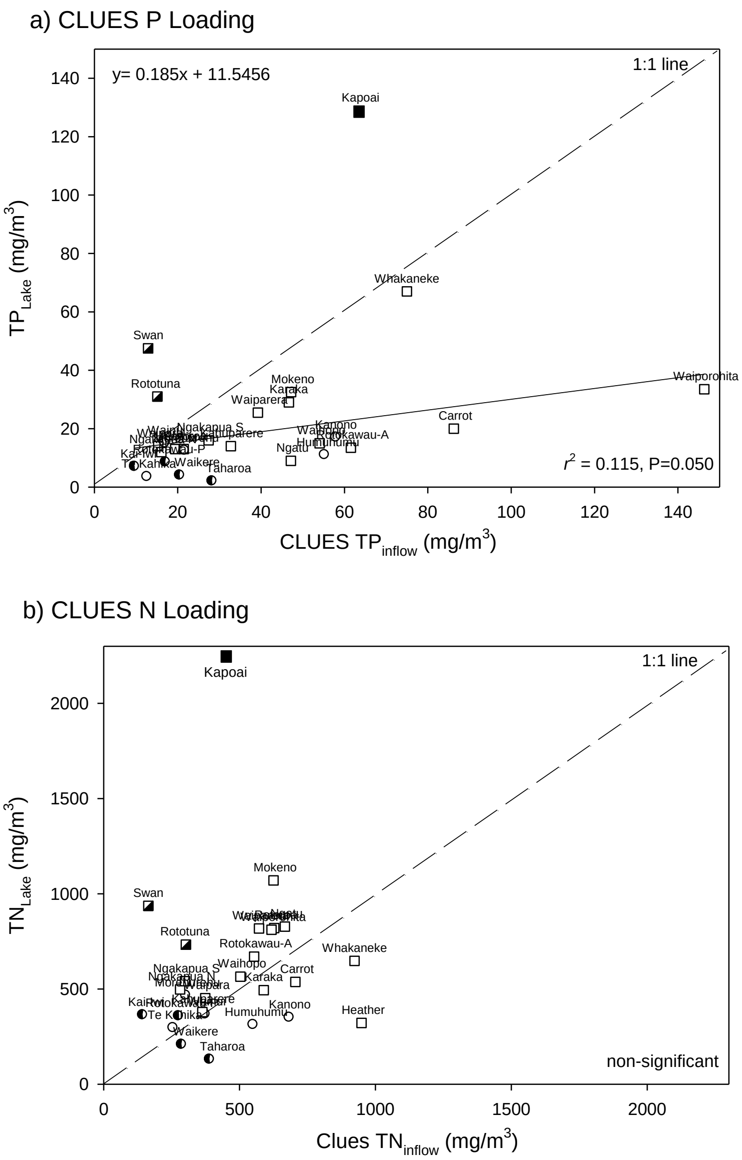


Figure 7. Predicted inflow total nitrogen (TN) and total phosphorus (TP) concentrations (from CLUES) compared with in-lake TN and TP measurements in 26 Northland dune lakes. Note that Lake Kapoai (in-lake values 2,255 mg TN/m³ and 129 mgTP/m³) was removed from regression and further Vollenweider analyses due to it being considered an outlier in the model.

3.1.1. Vollenweider phosphorus models

Better relationships between predicted loading and in-lake concentrations were obtained using the Vollenweider models that transform CLUES TP_{inflow} predicted concentrations to in-lake TP concentrations using a water residence time correction. Although most models were significant, the models that were optimised to the Northland lakes had the greatest statistical power and significance. Models derived previously for a national deep-lake data set (Özkundakci *et al.* 2014) and a South

Island shallow-lake data set (Kelly *et al.* 2013) yielded reasonably good linear fits, but less statistically significant results (Figure 8a and b).

For all regressions the closer the fit to 1:1 (a = 1.0) the better the relationship between predicted TP and lake measurements. The Kelly *et al.* (2013) model derived for South Island shallow coastal lakes had a regression slope of 0.665, indicating some slope bias and a tendency to under-predict in-lake TP in lakes with higher TP. The Özkundakci *et al* (2014) model slope also under-predicted in-lake TP in higher ranges (Figure 8b).

Vollenweider models that were optimised to the combined lake data set or with deep and shallow lakes fitted to the model separately had the greatest statistical power. Optimised Vollenweider models had slopes between 0.675 and 1.45 (Figure 8e and f). The model for shallow and deep lakes optimised separately provided better statistical power, explaining 41% of the variation in median in-lake TP amongst the lake-set. A alternative model that incorporated mean depth of the lake in addition to residence time (Brett & Benjamin 2008), was the most statistically significant ($P < 0.0001$, $r^2 = 0.449$), with a slope of 0.785 (Figure 8d). Because depth has been found to be such an important factor relating to the nutrient status of the dune lakes (Hughes *et al.* 2015), we suggest that this particular model, which incorporates a continuous depth function, may perform best. For the other models, depth was accounted for by calculating regression functions for shallow and deep lakes in separate Vollenweider models (Figure 8f). However, this appears not to have been as effective.

Overall, the performance of the TP Vollenweider models would provide support that CLUES TP load estimates provide reasonable estimates of TP loads to the Northland dune lakes, with nearly half the variation in the data explained just by implementing a simple model incorporating residence time and mean depth of the lake.

Other factors such as macrophyte nutrient uptake and wind-wave re-suspension (in shallow lakes) can have a large influence on in-lake TP concentration, and can affect the loading to in-lake nutrient relationships. It is therefore unlikely that perfect fit would occur for simple models. Considering that these ‘other’ influences have not been assessed, the TP Vollenweider models for the Northland lakes are viewed as being just ‘moderately’ good. It was beyond the scope of this investigation to account for such dynamics, as this would require detailed information on lake nutrient cycling that is not presently available.

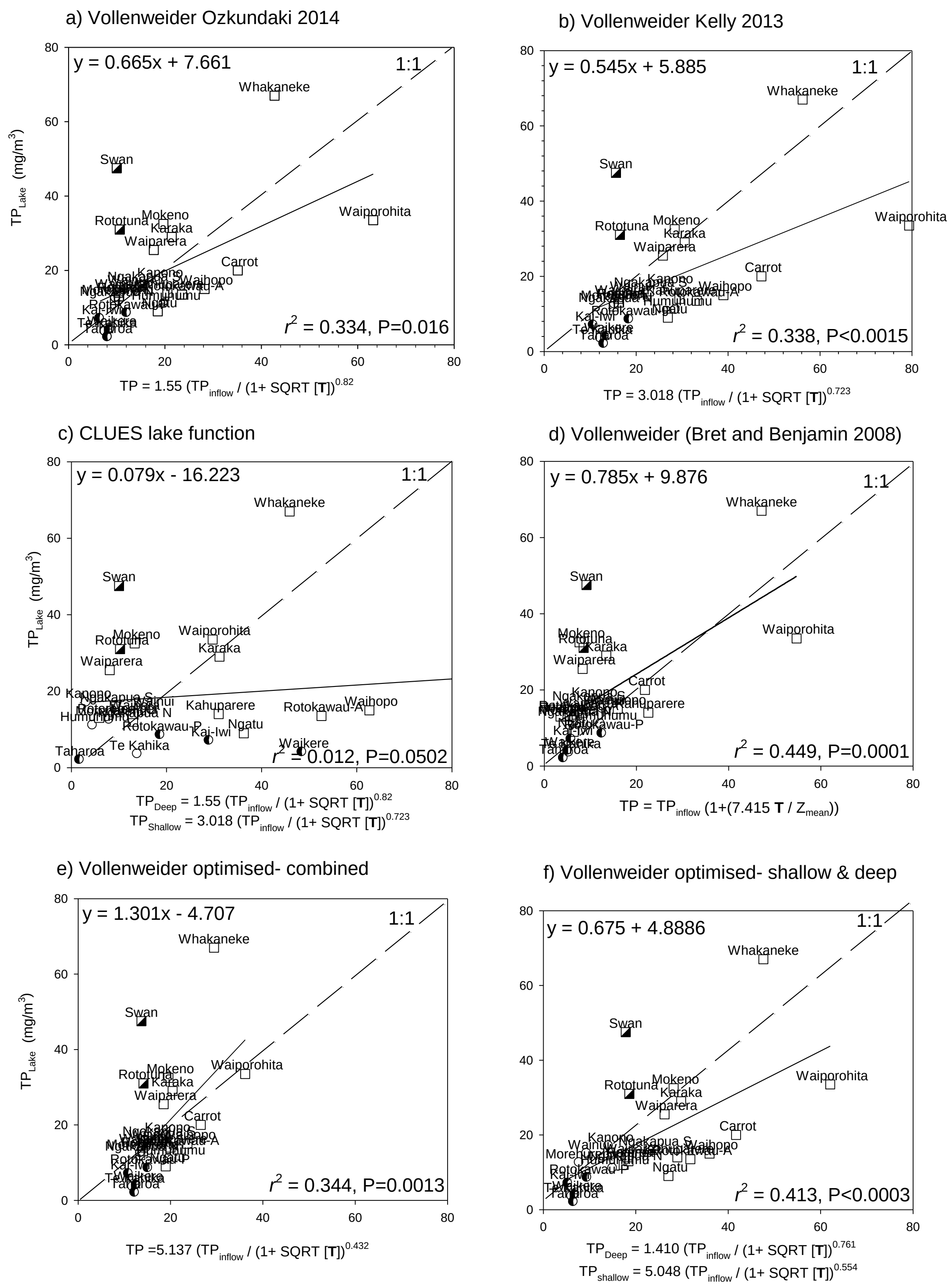


Figure 8. Relationships between in-lake total phosphorus (TP) concentrations and six Vollenweider models that predicted TN concentrations based on CLUES model TN inflow concentrations for 26 Northland dune lakes. Dune lake classes are shown by symbols: deep-window = half-filled circles, deep-perched = hollow circles, shallow-window = half-filled squares, shallow-perched = hollow squares. Note that Lake Kapoai was omitted from the model as an outlier.

3.1.2. Vollenweider nitrogen models

Vollenweider models relating CLUES-predicted TN loading to in-lake TN concentrations were in some instances significant, but overall had poorer predictive power and significance than the TP models. Use of previously derived models (*e.g.* Kelly *et al.* 2013; Özkundakci *et al.* 2014) tended to under-predict in-lake TN concentrations in the dune lakes, although these were non-significant and therefore functions are not depicted on graphs (Figure 9a, 9b). This suggests that either the degree of internal lake N uptake or de-nitrification was considerably less for the dune lakes (giving higher in-lake TN), or that the CLUES model is under-predicting N loss from the catchment. We would expect a greater proportion of nitrogen to be delivered to the dune lakes in groundwater, and this may have been poorly captured by the CLUES model. With longer residence times of dune lakes, is quite possible that retention and recycling of N is greater and therefore these previously derived models for South Island lakes would be less appropriate. Longer retention time is known to be associated with higher nutrient status (Harrison *et al.* 2009). The relatively poor understanding of hydraulic retention times for dune lakes could have contributed to poorer correlations observed in Vollenweider functions. The nutrient attenuation function that is part of the CLUES model (Figure 9c) had poor correlation between predicted in-lake nutrient status and median in-lake TN concentrations.

Vollenweider models were optimised to the Northland dune lakes using either the combined lake set, or with deep and shallow lakes modelled separately; both had a significant predictive power (Figure 9d,9e), however the separate deep and shallow model explained a greater proportion of the variation in in-lake TN (r^2 =0.418). There was very little slope bias in either of the models with slopes of 0.865 and 0.814, respectively. The function for just the shallow dune lakes appeared to be a poorer fit in the overall model, and had an atypically narrow data range of predicted TN. The CLUES predictions for most of the deep lakes were better. The relatively strong relationship between predicted TN and in-lake TN concentrations indicates the CLUES model provides a reasonable prediction of catchment N loads to deep lakes.

Lake Kapoai was omitted as an outlier in the model, as it had atypically high in-lake nutrient concentrations (2250 mg/m^3 median between 2009–2014) based on a small number of sampling events. This was nearly double that of any other lake in the dataset, and is thought to be linked with recycling of nutrients from benthic sources following collapse of macrophytes in the lake. Other lakes that poorly fit the regression functions included lakes Heather and Swan, both of which have had grass carp introduced as a control measured for exotic weeds. This has likely increased internal nutrient recycling and affected the relationship between catchment loading to in-lake concentration.

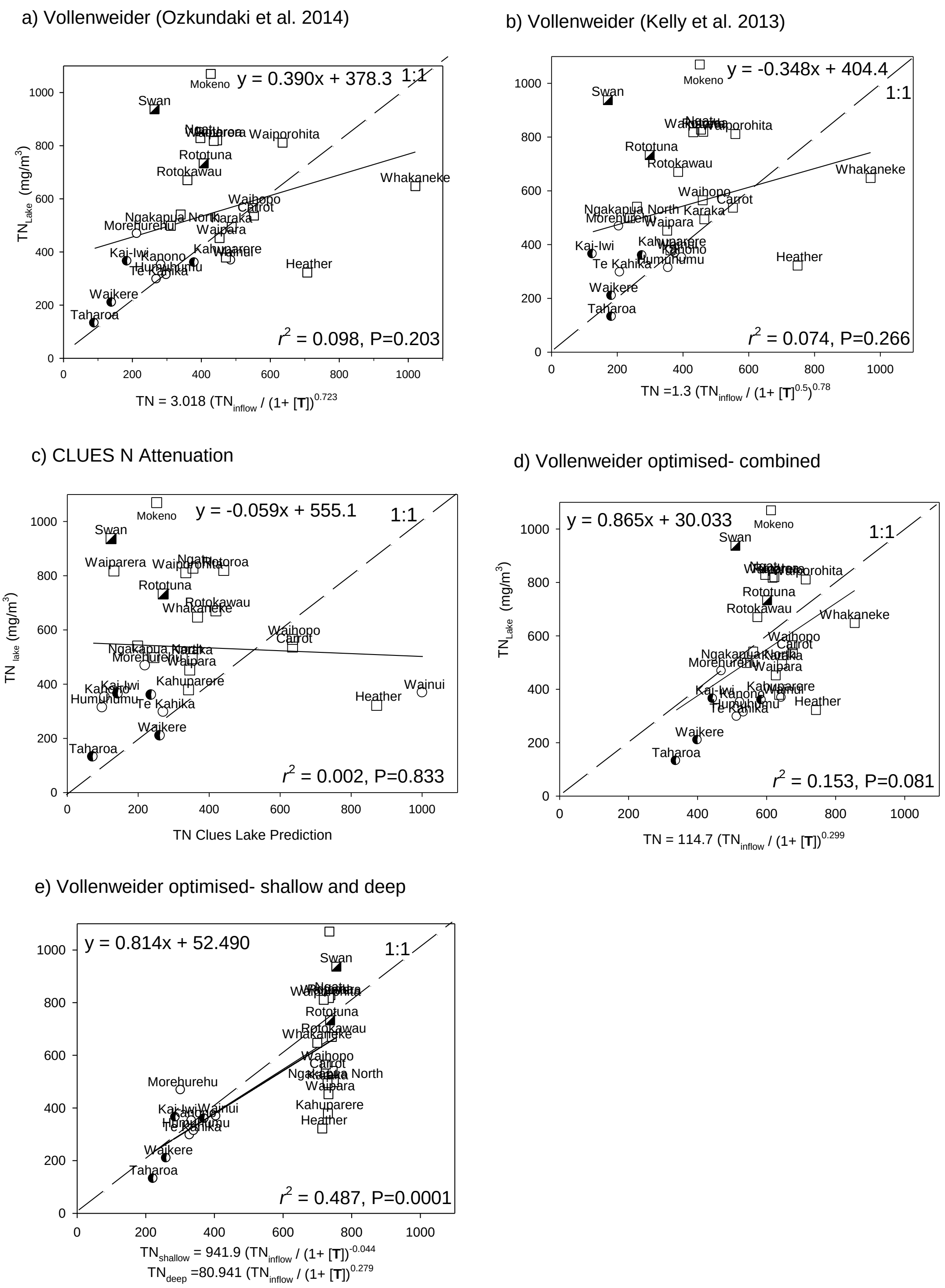


Figure 9. Relationships between in-lake total nitrogen (TN) concentrations and five Vollenweider models that predicted TN concentrations based on CLUES model TN inflow concentrations for 26 Northland dune lakes. Dune lake classes are represented by symbols: deep-window = half-filled circles, deep-perched = hollow circles, shallow-window = half-filled squares, shallow-perched = hollow squares. Note that Lake Kapoai was omitted from the model as an outlier.

3.2. Groundwater load estimates

Because of the likely importance of groundwater connectivity to dune lakes, additional scenarios were conducted exploring potential groundwater nutrient loads to the dune lakes and the effects this would have on Vollenweider model predictive power. The scenarios were focused only on nitrogen loads in groundwater and excluded phosphorus estimates because of the high degree of uncertainty regarding P solubility in the differing dune catchment soil types. The scenarios were limited to nine window lakes for which previous hydrogeology investigations quantitatively modelled annual surface and groundwater inflow rates (Jacobs 2014). These lakes were expected to have the greatest degree of groundwater influence, and therefore might also be expected to have nutrient loads under-predicted by the CLUES model, which is predominantly focused on surface water runoff sources. Unfortunately, there was no present monitoring data available for groundwater nutrient concentrations in any of the dune lake catchments considered.

Three scenarios were considered for estimating groundwater dissolved inorganic nitrogen (DIN) concentration, which were then multiplied by the annual groundwater yield to calculate groundwater annual load. In all cases, the estimated groundwater yield was taken from hydrogeology model estimates of groundwater inflow rates (Jacobs 2014). The DIN concentrations were determined as follows:

1. Scenario 1: 'CLUES DIN' — Groundwater N concentrations were equal to the estimated mean-annual CLUES inflow TN concentration multiplied by the ratio of dissolved to particulate nitrogen (DIN:TN) calculated from monitoring data for the particular dune lake between 2009-14.
2. Scenario 2: '2x CLUES DIN' — Groundwater concentrations were equal to twice the above concentration of scenario 1.
3. Scenario 3: 'Regional CLUES DIN' — Groundwater DIN concentrations for the lake were the regional average (for Pouto and Kai-iwi regions separately) of scenario 1, recognising regional aquifer inputs to the lakes.

The inclusion of a groundwater N loading fraction meant that groundwater comprised between 0% (Rototuna) and 26% (Humuhumu) of the total N catchment load to the lakes, depending on the particular groundwater scenario considered (Table 2). As expected, the proportion of groundwater inflow yield greatly affected these predicted groundwater contributions, with lakes having higher proportional groundwater yield having much greater groundwater N loads. Based on these predicted yields and concentration ranges, groundwater loads were predicted to contribute appreciably to the total catchment load in four lakes, specifically Humuhumu, Kai-iwi, Taharoa, and Waikere. For the remaining five Pouto lakes, groundwater contributions were predicted to only be around 1% or less of the total catchment load.

Table 2. Hydrological and nitrogen load statistics for nine Northland dune lakes for which surface and three groundwater nitrogen load scenarios were considered.

		Proportional water yield[1]			Surface water N Loads		Groundwater N Loads		
Lake	[1]Water Yield m³/d	Direct Rainfall %	Surface Runoff %	Ground water %	CLUES Runoff T N/yr	Direct Rainfall T N/yr	Scenario1 T N/yr (% total load)	Scenario 2 T N/yr (% total load)	Scenario 3 T N/yr (% total load
Kai-iwi	7011	60	10	30	26.8	0.686	0.048 (5.5)	0.104 (11.2)	0.043 (4.9)
Taharoa	10916	74	9	18	204.2	0.336	0.052 (3.6)	0.116 (7.7)	0.064 (4.4)
Waikere	2158	60	33	8	29.7	0.148	0.006 (1.9)	0.014 (4.4)	0.006 (1.8)
Humuhumu	9337	49	12	40	139.57	2.222	0.431 (13)	1.046 (26.6)	0.332 (10.3)
Rotokawau (Pouto)	1814	59	34	7	25.7	2.582	0.012 (0.4)	0.025 (0.9)	0.012 (0.4)
Kanono	4200	57	42	2	77.1	1.313	0.009 (0.5)	0.024 (1.4)	0.006 (0.4)
Kahuparere	562	37	60	3	7.3	0.807	0.002 (0.2)	0.004 (0.5)	0.002 (0.2)
Rototuna	434	45	55	0	8.9	0.436	0.000 (0.0)	0.000 (0.0)	0.000 (0.0)
Roto-otuauru (Swan)	1366	42	28	30	17.2	1.029	0.017 (1.5)	0.045 (3.9)	0.037 (3.2)

[1] Statistics taken from Jacobs (2014) estimates of water yields

Vollenweider N models optimised to the Northland dune lake datasets were recalculated considering the additional groundwater N loads and groundwater inflow rates. Plots of predicted versus observed in-lake TN from the new Vollenweider model indicated that there were only minor improvements in predictive power obtained by including groundwater loads (Figure 10). The relatively minor effect of groundwater loads on the total N load likely resulted because hydraulic inflow rates also increased, thus decreasing hydraulic residence time and affecting Vollenweider in-lake TN values. Therefore, there was an appreciable increase of in-lake TN concentration associated with the groundwater loads only for scenarios in which groundwater concentration was substantially elevated over surface water inflows. Such was the case for the '2x CLUES DIN' scenario 2.

Interestingly, the Vollenweider N model predictions were reasonably stronger for the subset of nine window dune lakes in comparison to the entire 26-dune lake dataset. The Vollenweider N model performed well even for the default scenario where no groundwater load component was added, with a large portion of the variance in median in-lake TN explained by the model ($r^2 = 0.681$). The greatest improvement in the Vollenweider model predictions were for groundwater loads calculated under the regional groundwater concentration average scenario, which slightly improved on the variation explained in median in-lake TN concentration ($r^2 = 0.681$). However, it should be noted that all groundwater load scenario models were significant, and performed well by comparison to models that included load predictions for all 26 dune lakes. This could suggest that inaccuracy of N load predictions by CLUES could be as poor (or worse) for perched lakes, which are not thought to be influenced as strongly by groundwater inflows. Alternatively other processes (*e.g*. internal loading, denitrification) could be more significant factors influencing in-lake TN concentration. Therefore, inclusion of more detailed groundwater load information will not necessarily improve the overall nitrogen load model predictions that are based on CLUES, and other means of quantifying nitrogen loads to some lakes may have to be pursued.

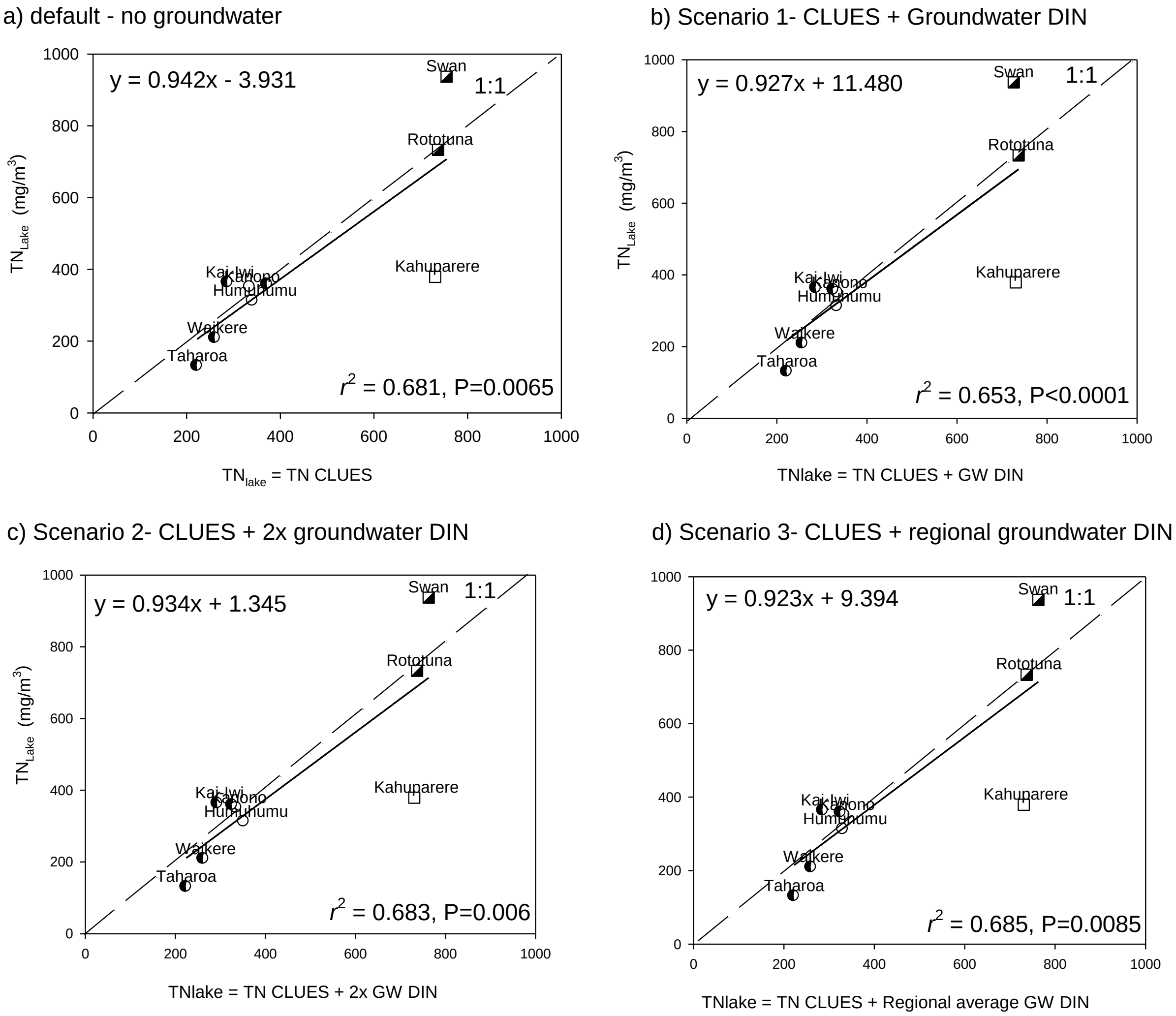


Figure 10. Relationships between median in-lake total nitrogen (TN) concentrations and four Vollenweider models that predicted TN concentrations based on CLUES model and three groundwater N load scenarios calculated for 9 Northland dune lakes. The graph panels are (a) default- no groundwater loads, (b) scenario 1- CLUES DIN loads, (c) scenario 2- 2x CLUES DIN loads, and (d) scenario 3-CLUES regional average DIN loads. Dune lake classes are represented by symbols: deep-window = half-filled circles, deep-perched = hollow circles, shallow-window = half-filled squares, shallow-perched = hollow squares.

3.3. Other factors

3.3.1. Internal nutrient cycling

Internal cycling of nutrients between sedimentary and water column pools of nutrients is not explicitly accounted for in Vollenweider model predictions and this is a potential weakness of the modelling process. Legacy accumulations of P-rich sediment could likely be having an effect by recycling of nutrients back into the water column. Therefore, although there was a good relationship between TP model estimates and measured in-lake concentrations, it is likely the CLUES load estimates may be underestimating actual loads. This has likely contributed to the under-predictions of in-lake TP concentrations by Vollenweider models for some lakes, particularly those with the highest nutrient status where internal recycling may have been relatively more important. Modelling of internal P and N loads to the lakes was beyond the scope of this investigation, and would likely require greater site-specific data on lake sediment characteristics.

Denitrification of water column and/or sedimentary-bound N to gaseous nitrogen (another form of internal recycling) is also not explicitly accounted for in our Vollenweider modelling. Denitrification is facilitated by anoxic conditions in the water column or sediment pore water that can cause nitrogen to be removed from the system, and therefore may account for lakes in which TN surface water loads over-predict in-lake TN concentrations (Burgin & Hamilton 2007). We observed a greater proportion of lakes for which TN loads were over-predicted relative to in-lake TN, suggesting that denitrification losses could have accounted from some of these CLUES over-predictions. Further work on lake-specific denitrification would be needed to better quantify these processes.

3.3.2. Waterbird contributions

The contribution from waterbirds to lake nutrient loads is sometimes raised as an issue of concern in for dune lakes. In particular, large numbers of Canada geese, swans and other water birds contribute directly to N and P loads and indirectly to nutrient cycling during the period the birds spend on or nearby the lake.

There has been limited research in New Zealand undertaken on the degree that water bird excreta can alter the trophic status of freshwater lakes. Data on waterbird contribution to nutrient loads was estimated in case studies based on estimates of the daily TN and TP load per bird for the Rotorua lakes (Don & Donovan 2002), and their estimates were based on overseas research (*e.g.* Manny *et al.* 1994). Annual estimates of loads per birds from Don and Donovan (2002) were subsequently used to calculate annual loads of TN and TP to the Ashburton lakes (Canterbury region) in a set of lakes for which seasonal water bird counts had been collected (Kelly *et al.* 2014).

Based on estimates from Canterbury high-country lakes, waterbird faecal source contribution to annual N and P catchment loads were relatively minor, TN load is likely to be only minimally influenced by the presence of water birds. On average water birds contributed 2.5% of the annual nutrient load to these small lakes, which had high waterbird populations (excess of 400 birds/ha in some lakes). Waterbird contribution to annual TP load was greater (mean of 9.3% for eight lakes), however most (> 90%) of the TP load was from catchment sources. Lakes with small (< 20 ha) undeveloped catchments are likely to be the most affected by inclusion of waterbird contributions to TP loads. Based on this pattern of nutrient susceptibility, it is possible that some of the dune lakes could have their TP annual load affected by waterbird sources, should they have small catchment areas combined with high waterbird populations.

The inclusion of waterbird loading could account from some under-prediction of annual TP loads and improve the overall model performance in the dune lake datasets. Winter bird counts are conducted annually at some lakes nationally (coordinated by DOC) and these could potentially provide a surrogate index for the numbers of water birds (and species) using lakes across Northland. However, more extensive seasonal data would be needed to provide the level of accuracy used for calculating annual loads as in the Ashburton lakes pilot study. Based on raw counts, there was a high degree of seasonal variability between lakes, and therefore a seasonal monitoring programme would best inform abundances of waterbirds for estimating nutrient loads in dune lakes unless there was little evidence for seasonal variation.

4. LAKE NUTRIENT STATUS RELATIONSHIPS WITH ECOLOGICAL INTEGRITY INDICATORS

4.1. Physico-chemical parameters

There were strong relationships between chl-*a* and in-lake median TN and TP concentrations (Figures 11 and 12). Between-lake variation in median TP concentration explained approximately 83% of the variation in chl-*a* for shallow lakes, and 46% for deep lakes. Given the previously documented connection between TP and chl-*a* concentrations (*e.g.* Dillon & Rigler 1974; Rigler 1982), it is not surprising TP values would provide a strong fit with lake chl-*a*. However, the slope of this relationship was steeper than might be expected by the NOF TP and chl-*a* classification, which tended to give lower band classifications for TP than for chl-*a*. This meant that several of the lakes classified as B-band lakes for TP under the NOF framework (Ministry for the Environment 2012) would be classified as C-band lakes for median chl-*a*, and similarly C-band lakes for TP were D-band lakes for median chl-*a*. This has some important connotations for target setting under the NRC regional plan, suggesting that lakes with a lower grade for TP may have to be targeted to achieve the intended targets for median chl-*a*. Only the three Kai-iwi lakes (deep-window lakes) were within the A-band, and achieved this for both TP and chl-*a*, suggesting these lakes have the highest water quality for the region's lakes.

A few lakes fell markedly outside the 95% confidence intervals for the TP chl-*a* function; notably the deep lakes Humuhumu and Kanono, and the shallow lakes Karaka, Rototuna and Kahuparere. These lakes comprised some of the higher chl-*a* lakes in the data set (including Kapoai which has been discussed as having recently 'flipped'), and all had higher chl-*a* than would be expected based on median in-lake TP. This suggests a degree of concern for these lakes, which appear to more effectively cycle water column P into phytoplankton standing stock, and could mean greater risk of degrading water clarity and macrophyte values.

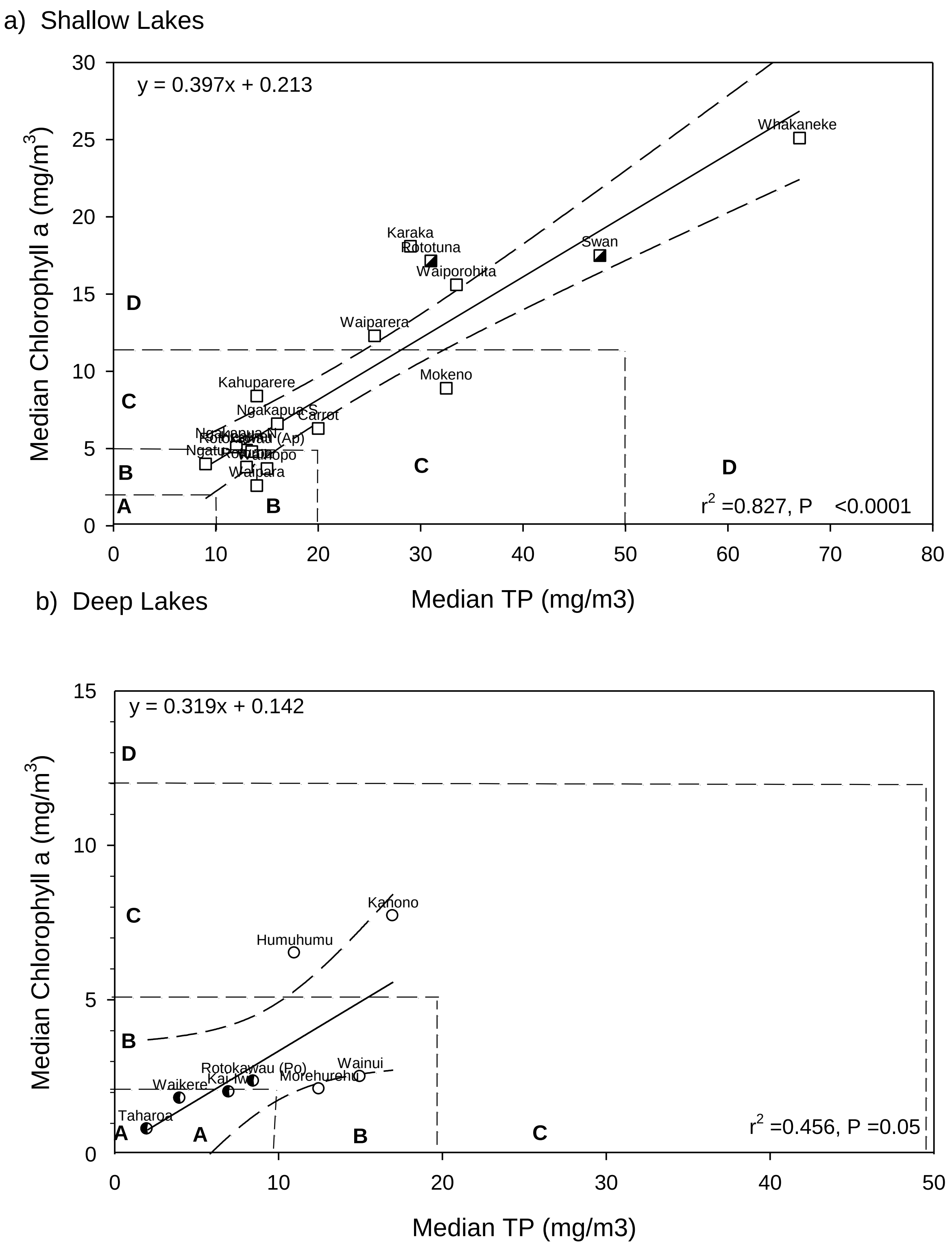


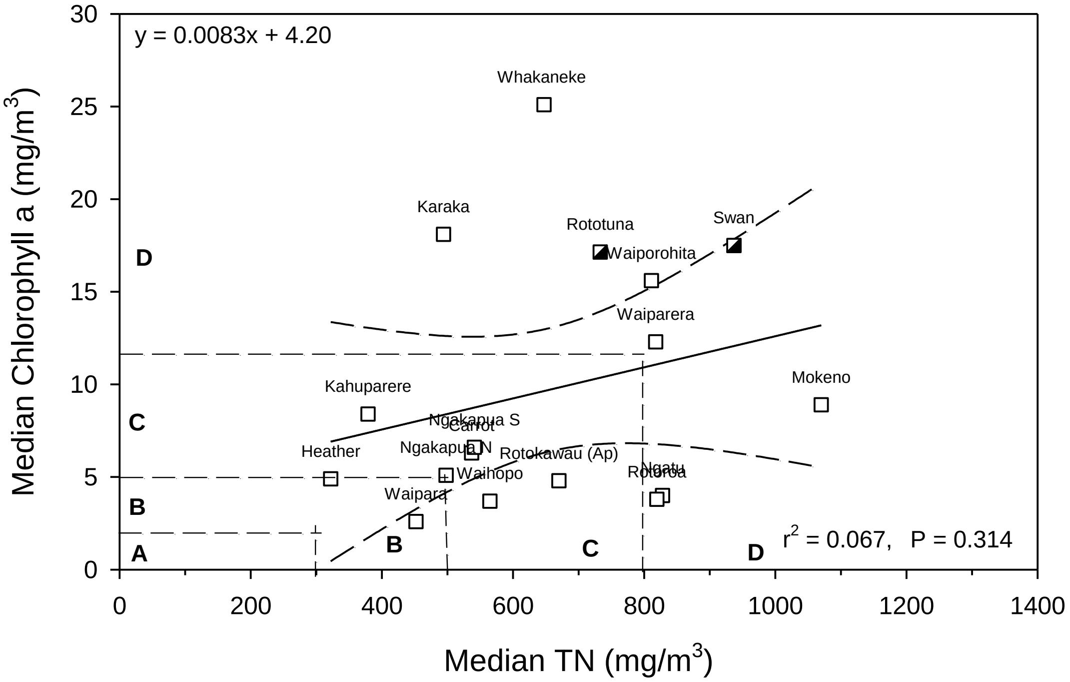
Figure 11. Relationships between median in-lake chlorophyll concentration and median total phosphorus (TP) for 26 Northland dune lakes of (a) shallow, or (b) deep lake classes. Also depicted are the NOF classification bands from A –D (Ministry for the Environment 2012) for TP and chlorophyll-*a* median. Dune lake classes are represented by symbols: deep-window = half-filled circles, deep-perched = hollow circles, shallow-window = half-filled squares, shallow-perched = hollow squares. Note that lakes Kapoai and Te Kahika were excluded from the plot due to being considered outliers.

There was a weaker relationship of in-lake TN with median chl-*a* as indicated by lower deviation explained by the regression models (shallow lakes $r^2 = 0.712$, deep lakes not significant), and wider 95% confidence intervals of the fitted-function (Figure 12). As with the TP relationship, lakes within particular TN NOF bands could fit into several alternative chl-*a* bands. However, opposite to the trend for TP, more often lakes were in higher TN bands than for chl-*a* bands, suggesting weaker correspondence between TN and in-lake chl-*a*. Of the most extreme examples, the Apouri lakes Ngatu and Rotoroa both had TN in excess of the NOF national bottom line (> 800 mg N/m^3), but had chl-*a* within the B-band. The overall poorer fit between TN and chl-*a*, and poorer correspondence of bands indicates that chl-*a* concentration was less dependent on N concentration of the lakes.

There were a few instances in which there was particularly greater chl-*a* than TN, and this appeared to occur for the same lakes as for TP, specifically the deep lakes Humuhumu and Kanono, and the shallow lakes Karaka, Rototuna and Kahuparere. Again, these lakes both had higher than expected chl-*a* based on their nutrient concentrations. This is a cautionary sign of physico-chemical conditions contributing to higher than expected chl-*a* and poorer water clarity (examined subsequently).

There is some uncertainty as to the extent to which lake foodweb structure can affect nutrient to chlorophyll relationships, and consequently also affect how individual lakes fitted the chl-*a* functions. The prevalence of zooplanktivorous fish in some of the lakes considered in this study has been shown to affect zooplankton biomass, and therefore potentially grazing rates of zooplankton on phytoplankton (Jeppesen *et al.* 2000). However, in their study reduced zooplankton biomass did not appear to manifest itself with cascading trophic level effects of atypically high chl-*a* concentrations. It is also worth noting that the nature of the lake foodweb can affect chlorophyll-nutrient relationships and is therefore a further variable to consider in a management context.

a) Shallow Lakes



b) Deep Lakes

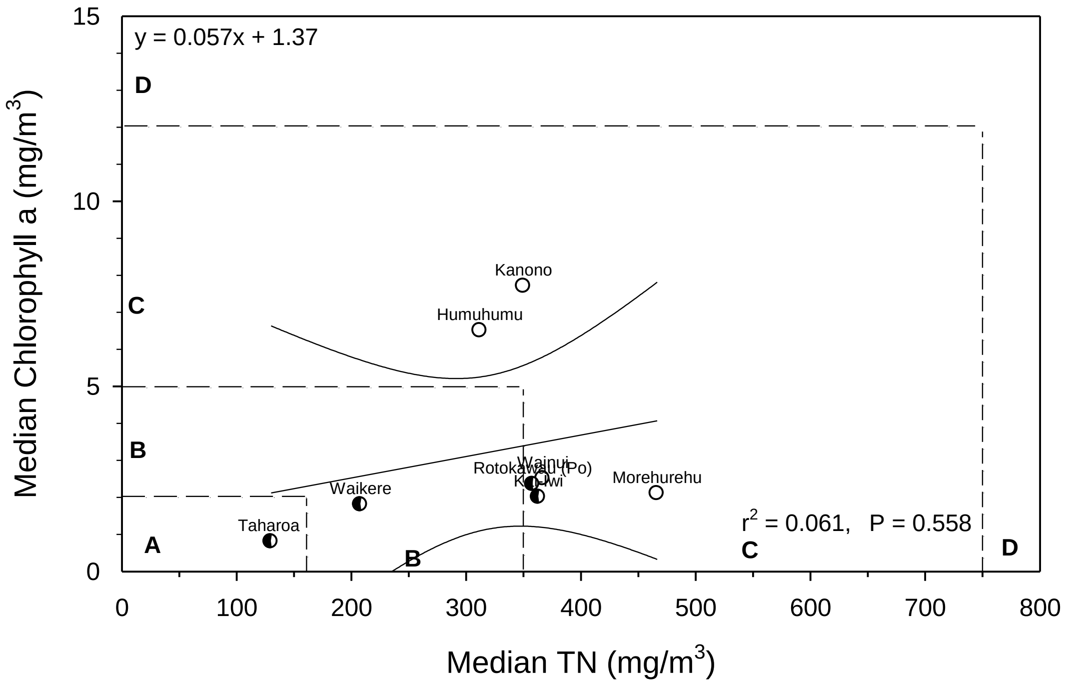


Figure 12. Relationships between median in-lake chlorophyll concentration and median total nitrogen (TN) for 26 Northland dune lakes of (a) shallow, or (b) deep lake classes. Dune lake classes are represented by symbols: deep-window = half-filled circles, deep-perched = hollow circles, shallow-window = half-filled squares, shallow-perched = hollow squares. Note that lakes Kapoai and Te Kahika were excluded from the plot due to being considered outliers.

4.2. Nutrient ratios

Nutrient ratios of TN:TP provide an indication of the nutrient limitation status at the times the lakes were sampled (Figure 13). The TN:TP ratios near 7 (Redfield ratio by mass) indicate that supply of N and P are roughly balanced in relation to the demands of macrophyte and algal growth. Departures from these thresholds could suggest that primary productivity in the systems is increasingly limited by either N (< 7) or P (> 7), with single nutrient limitation more likely to occur when the ratios are > 14 (P-limited) or < 3.5 (N-limited). Note that ratios within the ranges of TN:TP of 7 can suggest either productivity is co-limited by both N and P, or in cases where nutrient concentrations are potentially in excess, that no limitation may occur.

For all lakes, the TN:TP ratios (calculated from annual medians) indicated some degree of P limitation, with 26 of 27 lakes having ratios > 14 indicative of strong P limitation (Figure 13). This trend was similar for both shallow and deep lakes, despite the tendency for shallow lakes to have greater TP concentrations due to wind-resuspension of lakebed sediments and therefore lower ratios of TN:TP.

Nutrient limitation status was also assessed in short-term bioassay experiments for 25 of the lakes during winter 2014 and the summer of 2015 (Gibbs *et al.* 2014). Outcomes of these short-term bioassay results in terms of being either N, P or co-limited (N+P) are shown above nutrient ratio bars, with bolded results indicating the same result in both winter and summer bioassay trials (Figure 13). Results would tend to support inferences from nutrient ratio data that a large proportion of the dune lakes are P limited. However there was a much larger number of instances in which co-limitation by both N and P occurred (N+P), or where there was no response of added nutrients in the bioassays (*i.e.*, lakes that were not limited by N or P). Lake Kanono was the only lake to have been found to be limited only by N, which also had the lowest TN:TP ratio of the dune lakes.

Inferring nutrient limitation is complex. The TN:TP ratio is often used to indicate nutrient status because it incorporates both dissolved and bound nutrient fractions, and is more stable. We only used annual averages of TN:TP to infer the limiting nutrients, because current loading models can only calculate annual loads. The nutrient ratios can vary seasonally as processing and internal loading rates vary with changes in water temperature. Results from short-term bioassay experiments in both winter and summer were supportive of inferences from nutrient ratios, which highlight the importance of P in controlling phytoplankton growth in many of the dune lakes. However, concentrations of soluble nutrient fractions (dissolved inorganic nitrogen [DIN] and soluble reactive phosphorus [SRP]) are also important in determining nutrient bioavailability. Limitation by a single nutrient does not suggest that only the single nutrient is important to lake water quality dynamics, but it can provide information on prioritising management intervention and guide restoration and management measures to get the greatest improvements in water quality. The prevalence of P limitation in New Zealand lakes has also been reported in other studies (Abell *et al.* 2010).

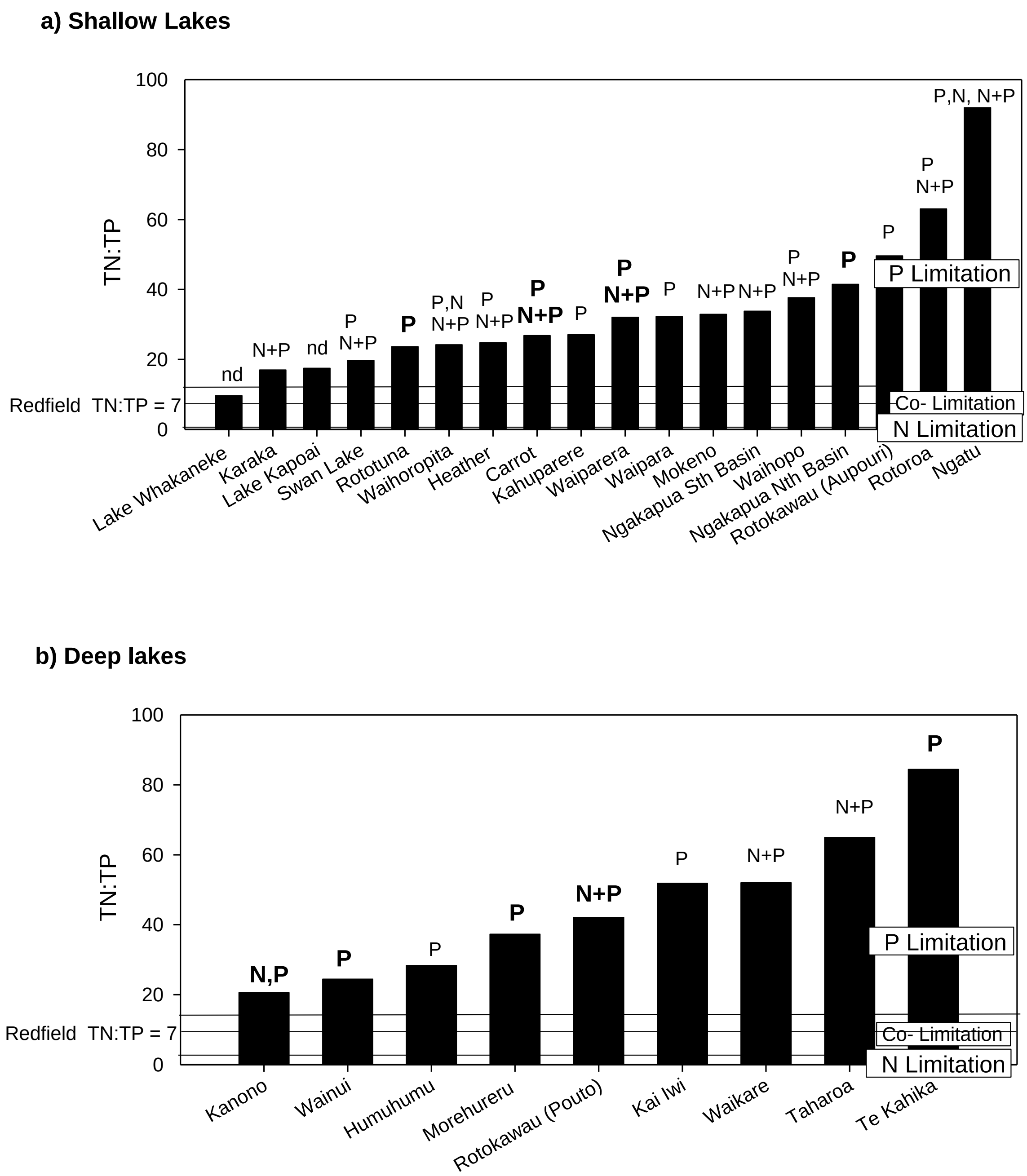


Figure 13. Nutrient limitation assessment using total nitrogen: total phosphorus (TN:TP) ratios and dissolved inorganic nitrogen: total phosphorus (DIN:TP) ratios of in-lake concentrations for 27 Northland dune lakes. Nutrient limitation status, either by P or N limitation, is indicated by TN:TP ratios diverging from 7 (< 3.5 = N limitation; 3.5 to 14 = co-limitation; >14 = P limitation) or DIN:TP ratios diverging from 1 (< 0.5 = N limitation; 0.5 to 1.5 = co-limitation; >2 = P limitation). Also shown are results from short-term bioassays of N, P, and N+P limitation with bold indicating identical results on both winter and summer trials (Gibbs 2015). nd = not done.

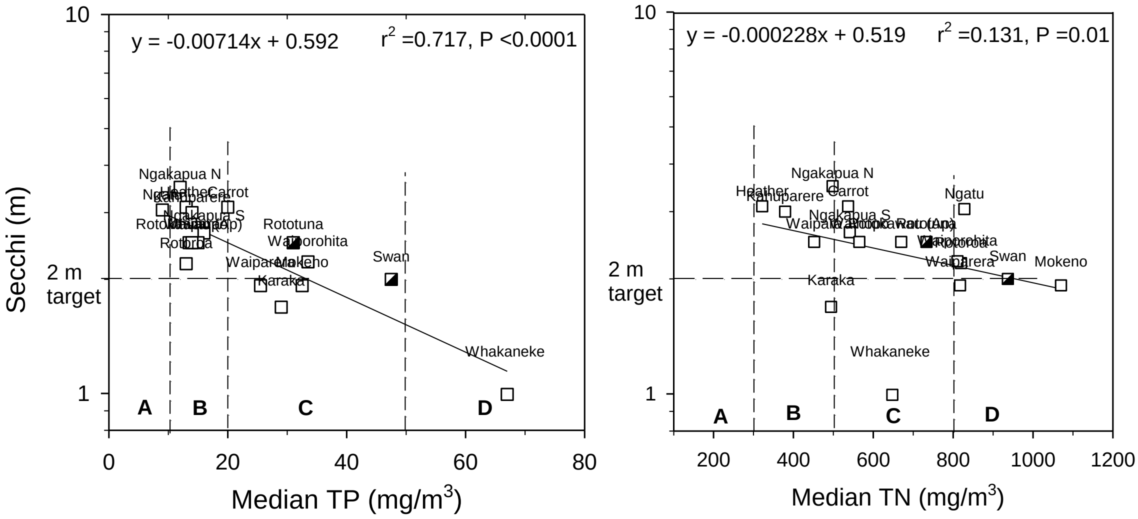
4.3. Visual clarity

Significant relationships were observed between lake visual clarity, measured as Secchi depth, and in-lake TP and TN concentrations (Figure 14). Secchi depth log transformed was most highly correlated with TP (r^2 = 0.717 shallow lakes, r^2 = 0.725 deep lakes). Given the strong relationship between TP and chl-*a*, this indicates turbidity is most likely to be associated with phytoplankton biomass. Other light absorbing compounds such as humic dissolved organic matter (DOM) can also affect Secchi depth, and may also contain some particulate-bound N and P. Relationships between TN and Secchi depth were weaker (shallow lakes r^2 = 0.131) , and non-significant for deep lakes. Because TN was only moderately correlated with phytoplankton biomass, it is probable this contributed to its weaker relationship with visual clarity. Some lakes did not fit the TN and TP loading relationship for Secchi depth; shallow lakes Whakaneke and Karaka and the deep lake Morehurehu fell below the regression line. These lakes had higher than expected chl-*a* in comparison to TN and TP, which may explain the lower than expected clarity in the lakes.

Visual clarity is a key ecological indicator in lakes because it relates to so many ecological functions including photosynthesis of aquatic plants, zonation of aquatic macrophytes, and feeding by visually foraging fish and invertebrates (Donahue & Molinos 2009). For the Northland dune lakes, the ranges of visual clarity were very different between deep and shallow lakes, and therefore examining the two lake classes separately appears to be a very useful approach.

Clarity ranges for sustaining ecological values are also different between the two lake depth classes. For shallow lakes, where nutrient ranges were higher, Secchi depth was largely confined to between 0.8-3 m, whereas in the deep lakes it ranged between 2-11 m. Based on the nutrient ranges and their relationship with visual clarity, we would see an effective minimum clarity (Secchi depth) for shallow lakes of around 2 m, corresponding to the mid C-band for TP (30 mgP/m^3) and the lower C-band TN (800 mgN/m^3). This is the TP and TN band that many of the shallow lakes currently are situated in. For deep lakes, greater light penetration is required to sustain macrophyte communities over a larger depth range. It is difficult to set a single target value for clarity for deep lakes due to the large range in visual clarity distances amongst the lakes. Potentially a minimum could be established around the mid-B-band (where many lakes sit); this would correspond to a Secchi depth of approximately 3 m. This may not be sufficiently stringent for some lakes, and consideration could be given to a second clarity minimum for lakes with outstanding aquatic plant values and be set closer to the mid A-band of TP, which would correspond to a clarity of approximately 7 m.

a) Shallow Lakes



b) Deep Lakes

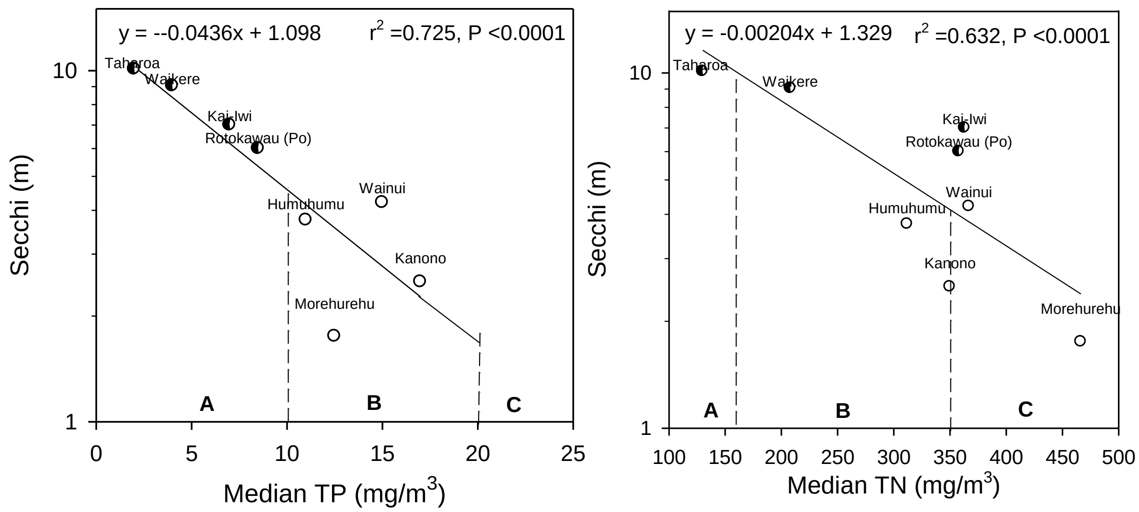


Figure 14. Relationships between the log Secchi depth and median annual total phosphorus (TP) and total nitrogen (TN) in 27 Northland dune lakes of a) shallow and b) deep lake classes. Dune lake classes are represented by symbols: deep-window = half-filled circles, deep-perched = hollow circles, shallow-window = half-filled squares, shallow-perched = hollow squares. Note that Lakes Kapoai and Te Kahika were excluded from the plot due to being considered outliers.

4.4. Aquatic macrophytes

Aquatic macrophyte communities are an important ecological component of small lakes, with the beds of some shallow lakes entirely covered by plant communities (Scheffer 2004). These communities provide essential habitat for macroinvertebrates and native fish (Kelly & McDowall 2004), and are frequently the focus of lake management and restoration (*e.g.* Howard-Williams & Kelly 2003; Schallenberg & Sorrell 2009).

We observed significant trends between in-lake TN and TP, and macrophyte community indices (Figure 15 and 16). Most notably, there was a significant negative trend in the bottom depth limit of macrophytes with TN and TP (*i.e.* Figure 16c and 17c). The trend between the macrophyte depth limit and TP was particularly strong (shallow lakes $r^2 = 0.670$, deep lakes $r^2 = 0.746$). TN was also strongly related to macrophyte depth limit in deep lakes ($r^2 = 0.882$), but less so for shallow lakes ($r^2 = 0.391$). Because both TN and TP loading were strongly correlated with chl-*a* and water clarity, it is likely this relationship reflects the influence of nutrient load on phytoplankton biomass and its effect on water clarity.

LakeSPI score was not significantly related to in-lake TN and TP in either the shallow or deep lakes sets, although there was a trend of declining LakeSPI score with increasing TN and TP in shallow lakes. For the deep lakes, the relationship was flat with the exception of Lake Morehurehu, which had a markedly lower LakeSPI score and moderately higher TN. The LakeSPI score is strongly weighted by the occurrence of exotic species (Clayton & Edwards 2006) therefore this index is less likely to correlate directly with nutrient loading. LakeSPI scores for the 18 shallow dune lakes were mostly in the moderate to high range. However, lakes in both these categories covered quite a wide range of in-lake TP and TN. This confirms that nutrient status is unlikely to be the only factor driving variation in LakeSPI scores. Generally, lakes with excess of 16 mg/m^3 in-lake TP were below the boundary between moderate-high LakeSPI conditions.

A sub-score of LakeSPI, the LakeSPI Native Score, based on the richness and cover of native species per lake, ranged between 0 (several lakes with no macrophytes) and 84 (Lake Waiporohita). In-lake TP showed a significant inverse relationship ($r^2 = 0.271$) with LakeSPI Native Score in shallow lakes, however this relationship was flat and non-significant for deep lakes ($P = 0.734$). TN relationships with LakeSPI native score were not significant for either shallow or deep lakes, although there was some decline with TN concentration in shallow lakes. Lakes Waiporohita, Rototuna, and Karaka appear to have higher native LakeSPI scores than the models would predict based on their TP concentrations. Although macrophyte richness has been observed to be influenced by TP (Jeppesen *et al*. 2007; Lauridsen *et al*. 2003), recent evidence suggests that it may also be strongly influenced by soluble N fractions and possibly TN (Moss *et al.* 2013). This could be related to differences in plant species nitrogen requirements for optimal growth. Overall, the models indicate the importance of co-management of TN and TP for maintaining macrophyte community richness and extent.

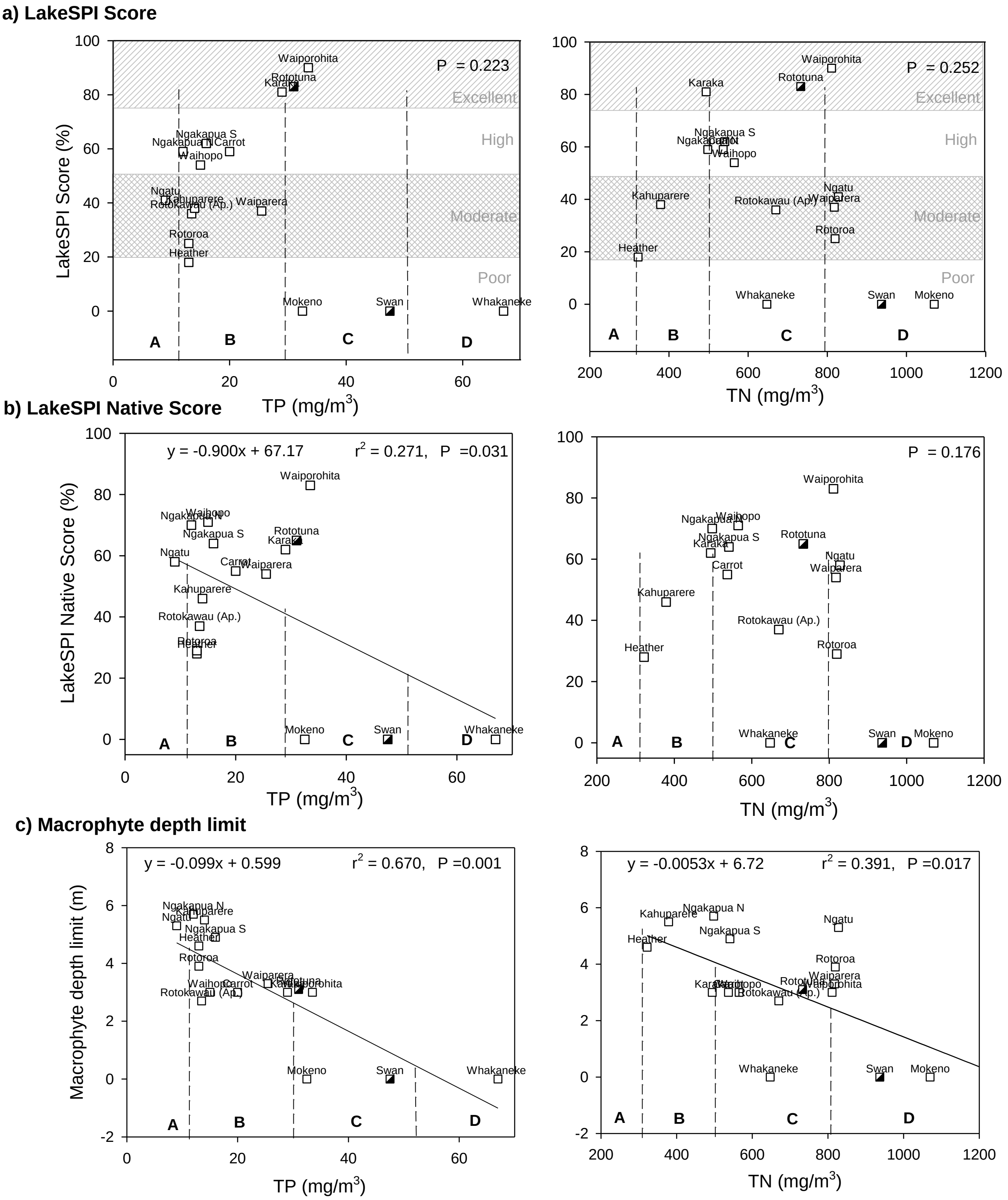


Figure 15. Relationships between total phosphorus (TP) and total nitrogen (TN) and three macrophyte community indexes in 16 shallow Northland dune lakes. Graph panels are for (a) LakeSPI Score, (b) LakeSPI Native Score and (c) macrophyte depth limits. Dune lake classes are represented by symbols: shallow-window = half-filled squares, shallow-perched = hollow squares.

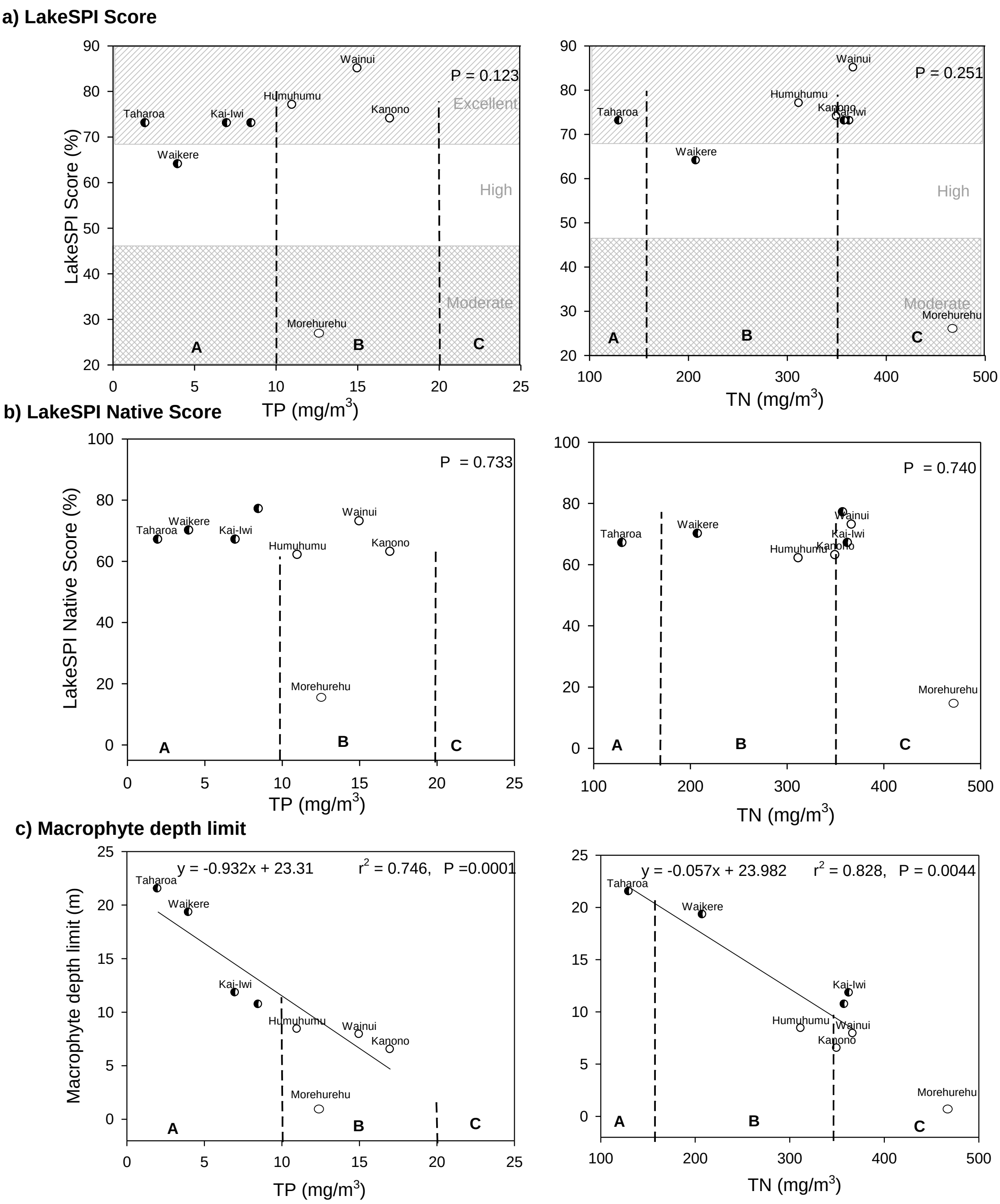


Figure 16 Relationships between total phosphorus (TP) and total nitrogen (TN) and three macrophyte community indexes in 8 deep Northland dune lakes. Graph panels are for (a) LakeSPI Score, (b) LakeSPI Native Score and (c) macrophyte depth limits. Dune lake classes are represented by symbols: deep-window = half-filled circles, deep-perched = hollow circles. Note that Lake Morehurehu (shown on plot) was excluded from regression calculations due to it being considered a statistical outlier.

Consideration could be given to setting either macrophyte depth limit targets or LakeSPI index targets in the NRC regional water plan for protection of aquatic habitat values. Other regional councils such as Canterbury have identified LakeSPI objectives in their Land and Water Regional Plan. For small–medium sized lakes, such as dune lakes, ECan cited a target LakeSPI score in the 'high' range (> 50%). Should NRC adopt a similar target for the regional water plan, based on the most recent monitoring data, seven of 9 deep lakes surveyed met this target, the exceptions being Morehurehu and Te Kahika. Lake Te Kahika was excluded from the macrophyte regression models due to its unusually low pH (< 4) which would preclude the growth of aquatic macrophytes. For shallow lakes, only seven of 15 lakes would meet a target LakeSPI of 'High' condition so this would be a more aspirational target. Should a less stringent target of 'Moderate' condition be considered, 12 of 16 lakes would presently meet this target. However, because the LakeSPI index is controlled by other environmental factors beyond nutrient status (*e.g.*, exotic weed incursion, herbivorous pest fish) a range of measures would need to be employed in combination to manage lakes for meeting LakeSPI targets.

It could be more sensible to identify macrophyte depth limit targets for dune lake categories under a regional plan for managing macrophyte values in relation to lake nutrient status. Macrophyte depth limits were highly correlated with lake nutrient status, and therefore are more likely to link directly with manging nutrient loads to dune lakes. The depth extent of macrophytes also relates to other important macrophyte community values such as the diversity of community types (Schwarz *et al.* 2000; Kelly & McDowall 2004) as well as the richness of species (Jeppesen *et al*. 2007; Moss *et al*. 2013). The nature of the relationships between macrophyte depth limits and lake nutrient status differed between shallow and deep dune lakes, and therefore separate depth limit targets would need to be considered for these two lake categories. We envisage targets of > 7 m for deep lakes and > 3 m for shallow as appropriate targets for the dune lakes given their present data ranges and relationships with nutrient status. Based on these regression functions (Figures 16c, 17c) this would correspond to nutrient concentrations in the NOF B-band for TP and C-band for TN for both shallow and deep lakes.

4.5. Aquatic macroinvertebrates

We observed significant trends between in-lake TN and TP, and macroinvertebrate community indices, although only for shallow lakes (Figures 15 and 18). There were rapid declines in macroinvertebrate richness, diversity, and the proportion of the community comprised of ETO taxa (*i.e.*, mayflies, caddisflies and dragonflies) with in-lake TP concentration in the shallow lake data set (Figure 17). Macroinvertebrate Shannon diversity index was the only index significantly related to in-lake TN concentration, but the other two both had declining trends. The observed declines in taxonomic richness (affecting all macroinvertebrate indices) occurred predominantly for more motile species such as caddisflies and dragonflies, which are typically associated with macrophyte beds. This pattern of decline, particularly in ETO taxa, has also been reported for a national set of shallow coastal lakes (Kelly *et al*. 2013; Schallenberg & Kelly 2014).

For deep category dune lakes, there were no obvious patterns for macroinvertebrate community indicators with the nutrient status of the lakes. Timms (1982) observed that macroinvertebrate community composition in a set of Rotorua lakes did not change in relation to lake trophic status until lakes were either eutrophic or greater nutrient status. That we observed no change in deep lakes could have arisen because these were all of a lower nutrient status than eutrophic, and that any significant community change only happens at nutrient concentrations above what was seen in the deep Northland lakes sampled.

Macroinvertebrates represent an important food-web linkage to other aquatic (fish) and riparian (waterbird) species inhabiting lakes, and appear to comprise a reliable indicator of nutrient status in shallow lakes. Whilst there are no national protocols or standards yet developed for lake macroinvertebrates, their inclusion as an indicator of biodiversity and food web health could be considered in a regional planning context for setting water standards as has been done for LakeSPI. This would need to be examined in greater detail to effectively provide a set macroinvertebrate community health index targets. Looking at regression functions of macroinvertebrate community indices, most of their declines occurs through the B-band for TP, whereas for TN the C-band appears to be where degraded conditions occur. This corresponds closely with macrophyte community indicators, and supports the finding that habitat provided by aquatic plants may play an important role in influencing macroinvertebrate community values (Kelly & McDowall 2004).

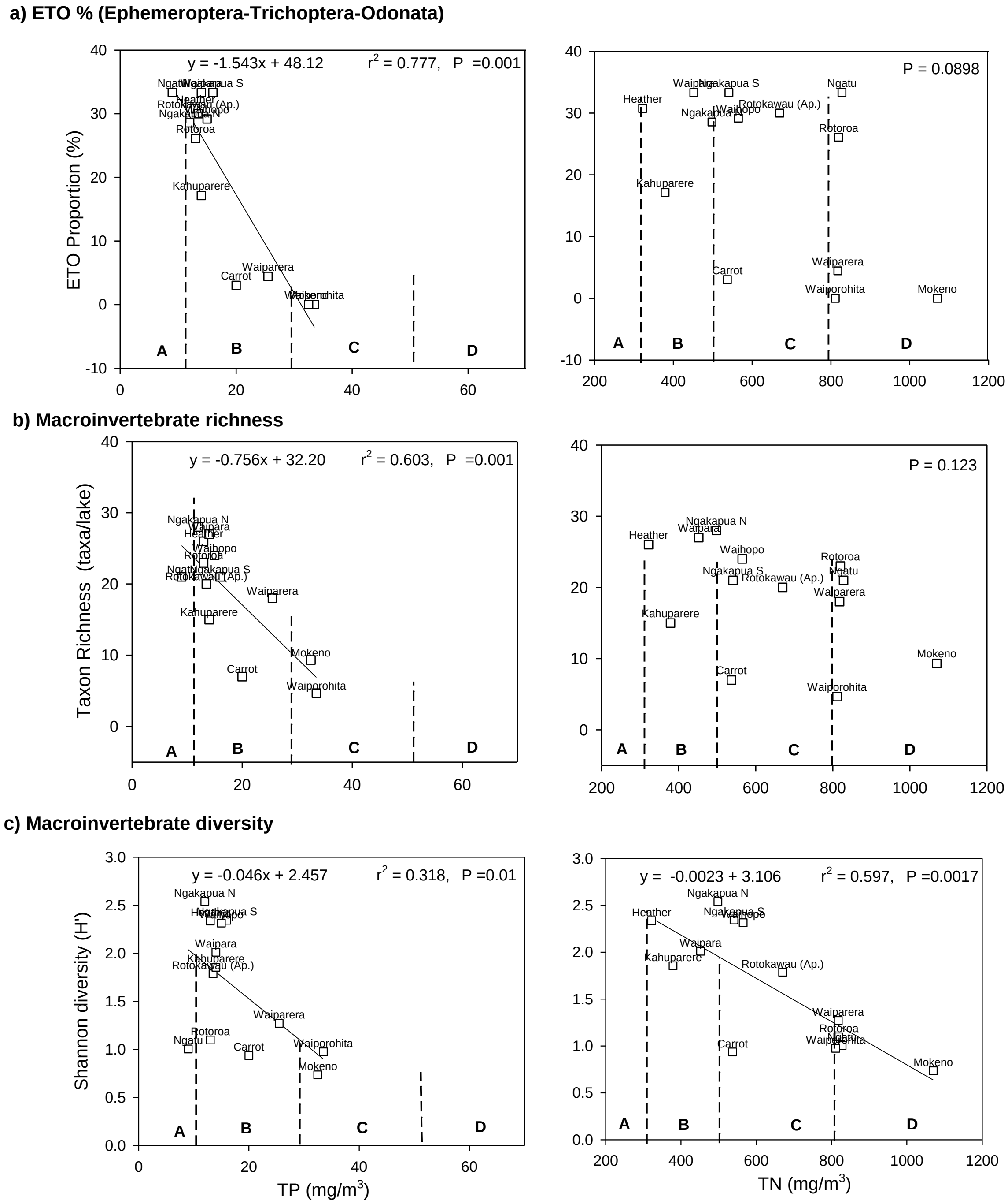


Figure 17. Relationships between total phosphorus (TP) and total nitrogen (TN) and three macroinvertebrate community indexes in 7 deep Northland dune lakes. Graph panels are for (a) ETO%, (b) Taxon richness and (c) Macroinvertebrate diversity. Dune lake classes are represented by symbols: shallow-window = half-filled squares, shallow-perched = hollow squares.

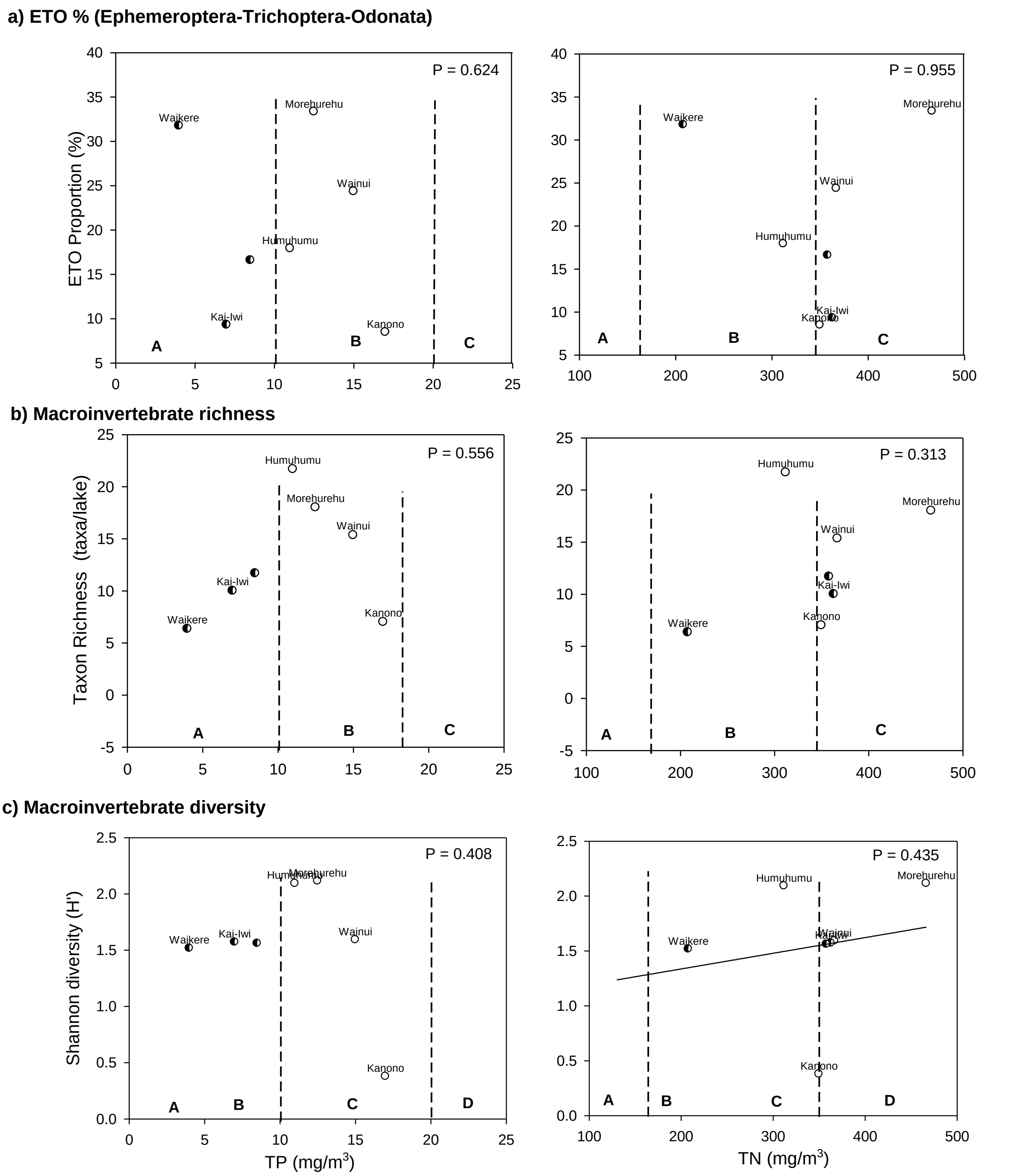


Figure 18. Relationships between total phosphorus (TP) and total nitrogen (TN) and three macroinvertebrate community indexes in 7 deep Northland dune lakes. Graph panels are for (a) ETO%, (b) Taxon richness and (c) Macroinvertebrate diversity. Dune lake classes are represented by symbols: deep-window = half-filled circles, deep-perched = hollow circles.

4.6. Limitations of the modelling

There is some uncertainty as to whether individual lakes will respond in the same manner to changes in nutrients over time, should they be subject to management measures that would alter nutrient loads to achieve management targets. The study found that the model had varying degrees of fit for individual lakes. Therefore, it is almost certain that some lakes will not respond in the exact manner as predicted by the nutrient concentration should it change over time. The type of response to changes in catchment nutrients is based on a generalised relationship between all of the 27 lakes and results can only be inferred for a specific lake.

To minimise this error we have excluded a few lakes clearly identified as outliers where the model performance did not appear to fit (up to two lakes for some models). The relatively small number of outliers provides support that the models have relatively wide generality to the dune lakes considered in this study. The study limited the selection of lakes to mainly small, shallow to medium-depth lakes, located at similar elevations and subject to similar climatic influences. Hence we might expect the nature of nutrient status and ecological structure to be relatively similar. It is unlikely there would be a similar result using a national lake data set. We have also derived the loading to in-lake concentration Vollenweider models separately for deep and shallow lakes, which might account for differences in seasonal stratification and mixing patterns amongst the lakes.

There was no water quality and flow data from tributary inflow streams. Additional inflow and outflow volume and nutrient concentration data would improve the performance of the CLUES catchment model and estimates of lake water residence time used in Vollenweider models.

Groundwater nutrient loads are not explicitly accounted for in CLUES predictions and this is a potential weakness of the modelling process, particularly for estimates of N loads. Although there was a reasonable relationship between TN model estimates and measured lake concentrations, it is likely the CLUES results without groundwater may be underestimating actual loads. However, exploration of groundwater input for a small number of window lakes suggested load predictions were relatively insensitive to groundwater load inputs unless groundwater nutrient concentrations were simulated to be much higher than surface water inflow predictions. Because Vollenweider models are based on inflow concentrations, large under-predictions in TN loads would only occur if groundwater concentrations were considerably greater than surface-water inflows, and this is likely to be infrequent in dune landscapes. Modelling of groundwater loads to the lakes was preliminary as very little data on groundwater N concentrations was available to support a more detailed assessment.

This study was completed at a whole-catchment level, so is not applicable at the farm or sub-catchment scale. The establishment of catchment-specific load limits will require finer scale investigations into allowable nutrient losses at a farm scale to meet the overall catchment targets. This was beyond the scope of this project, but the CLUES model does allow reach scale determination of nutrient loading. More detailed farm-scale OVERSEER modelling will inform the farm-based management required to meet objectives.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Relationships between nutrient loading and lake Ecological Integrity

The study has yielded useful analyses quantifying relationships between CLUES predicted annual nutrient loads and in-lake median TN and TP concentrations. Statistical relationships of loads with variation in in-lake TN and TP concentrations, were best identified by implementing separate models for shallow and deep lakes. Twenty-six Northland dune lakes were therefore subdivided according to maximum depths of either greater or less than 10 metres. Further exploration of in-lake nutrient status relationships with a range of ecological integrity indicators found that in-lake nutrient status was strongly related to chlorophyll-*a*, water clarity, macrophyte community composition and cover extent, and macroinvertebrate community structure. Summaries of the key findings of the study components are in the following sections.

5.1.1. Nutrient load modelling

This study has produced a model (Vollenweider transformed CLUES model) that identified useful relationships between TP loads and measured nutrient concentrations in dune lakes. Although other models derived for New Zealand lakes provided significant correlations (Kelly *et al.* 2013; Özkundakci *et al.* 2014), Vollenweider models calibrated to the dune lake water quality data yielded the greatest statistical power. The TN and TP loading models derived separately for shallow and deep lakes best explained the data distributions, likely linked to differences in lake mixing and thermal stratification cycles between deep and shallow lakes.

The TP loading model explained approximately 41% of the variation in measured in-lake TP concentrations in the 26-lake set, and the TN model explained 49% of the variation in TN concentration. The model coefficients and exponents were close to those published in the literature (*e.g.* Vollenweider 1982) providing reasonable confidence that the model is not over-fitted to the data. Consequently, CLUES TN and TP load models were thought to provide moderately accurate estimates of nutrient loads to the Northland dune lakes. Improvements in the models could be made with better knowledge of flow through rates (affecting hydraulic retention), as these were largely derived from surface water runoff models rather than field-measured inflows. The reasonable performance of the CLUES model in generating annual nutrient load predictions was unanticipated, because it is largely based on surface water nutrient transport and it is expected that a significant proportion of the lake inflows arrive as sub-surface flows not captured by the models. The CLUES model is likely to be predicting a greater proportion of nutrients delivered via surface waters, but some of these loads may actually occur in subsurface flows.

Further exploration considering the addition of groundwater loads was pursued for a subset of window lakes, which are presumed to be the lakes most affected by groundwater inflows not linked with their immediate surface water catchments. The inclusion of a groundwater loading term in annual load calculations made some improvement in Vollenweider model predictions, but these improvements were relatively minor. The greatest improvement in the model predictions were for groundwater loads calculated under a regional groundwater averaging scenario (for Pouto and Kai-iwi lakes separately), which slightly improved on the variation explained in median in-lake TN concentration ($r^2 = 0.681$). Interestingly, however, predicted in-lake TN concentration by the Vollenweider models was stronger for the subset of nine window lakes than it was for the larger 26-lake dataset. This could suggest that improved knowledge of groundwater loads may not necessarily improve overall model predictions made by CLUES. Future work aimed at better understanding groundwater nutrient concentrations would assist in interpreting groundwater inputs, as only the scenarios in which groundwater N concentrations greatly deviated from surface water concentrations revealed marked effects on the predicted in-lake TN concentration.

Overall, the performance of the CLUES model in predicting annual TN and TP loads aligned to in-lake concentrations were moderately lower than for other regions where this has been tested (Kelly *et al*. 2013, 2014). In Canterbury, the CLUES model Vollenweider function explained similar amounts of variation of in-lake TN ($r^2 = 49\%$) for a set of 27 high-country lakes, but CLUES TP predictions were much better (Kelly *et al*. 2014; TP model 73% variation explained versus 41% for dune lakes). This poorer performance in the P model for dune lakes may result because dune lakes receive a significant proportion of their inflow via subsurface flows, whereas P is predominantly transported in surface water flows bound to particulates. Similarly, Kelly *et al*. (2013) reported that the CLUES Vollenweider function could account for 80% of the variation of in-lake median TP for a South Island set of 18 coastal lowland lakes, most of which had permanent inflowing tributaries. This finding warrants a degree of caution in utilising CLUES for establishing lake-specific N and P load targets for dune lakes due to its lesser predictive performance compared with other regions.

Future work on other factors not accounted for in our CLUES Vollenweider modelling such as groundwater loads, internal nutrient loading from lake sediments, denitrification, and waterbird sources of P could improve the overall load predictions for dune lakes, and increase the confidence in load model predictions. Monitoring of in-lake nutrient cycling processes and obtaining seasonal waterbird counts for high bird population lakes could assist in quantifying these aspects, but these additional components were beyond the scope of this investigation.

5.1.2. Nutrient status relationships with other ecology variables

In-lake nutrient status was highly related with a number of key indictors used for characterising the ecological integrity of lakes (Schallenberg *et al*. 2011). We focused our analyses predominantly around ecological responses to variation in median annual TN and TP because these are the key nutrient parameters in the NOF (ecosystem health attributes), and therefore likely to be the appropriate nutrient parameters to establish water quality targets within the regional plan. These nutrient parameters also directly relate to load targets made by most catchment modelling tools (*e.g*., CLUES as trialled here) and are therefore likely to be most relevant to future management of nutrient load targets. It is possible that soluble nutrients (nitrate, ammonium, dissolved reactive phosphorus) are linked with ecological responses, but these were not considered in detail due to the wider aims of being most relevant to the NOF and catchment load targets.

Chlorophyll

There were strong relationships between chl-*a* and in-lake median TN and TP concentration, particularly for TP. Between-lake variation in median TP concentration explained approximately 97% of the variation in chl-*a* for shallow lakes, and 74% for deep lakes. This suggests nearly a direct relationship between nutrient status and chl-*a* for the dune lakes, and therefore the establishment of nutrient targets are likely to be very effective in achieving chl-*a* targets. However, differences in the regression functions meant that NOF TN, TP and chl-*a* classification bands did not directly align. This meant that several of the lakes classified as B-band lakes for TP would be classified as C-band lakes for median chl-*a*, and similarly C-band lakes for TP were often D-band lakes for median chl-*a*. This has important implications for target setting under the NRC regional plan, suggesting that a lower TP NOF band will be required to achieve the intended targets for median chl-*a*. Alternatively there was reasonable correspondence between NOF bands for TN and chl-*a*.

Visual clarity

Visual clarity of dune lakes, measured as Secchi depth, were strongly related with in-lake TP and TN concentrations, again most strongly with TP (r^2 = 0.831 shallow lakes, r^2 = 0.725 deep lakes). Given the strong relationship between TP and chl-*a*, turbidity is most likely to be associated with phytoplankton biomass. Other light-scattering or absorbing materials such as suspended sediment and coloured dissolved organic matter (CDOM) can affect Secchi depth, and may also contain some organically bound N and P. Relationships between TN and Secchi depth were weaker for shallow lakes (r^2 = 0.583), and non-significant for deep lakes. Data ranges for visual clarity were markedly different between deep and shallow lakes, and therefore examining the two lake classes separately appears to be the most relevant approach. Based on the nutrient ranges and their relationship with visual clarity, we would consider an effective minimum Secchi depth for shallow lakes to be around 2 m. However, this corresponded to different NOF TN and TP bands (as for chl-*a*) being at the mid C-band for TP (30 mgP/m^3) and the lower C-band TN (800 mgN/m^3). For deep lakes, greater light penetration is required to sustain macrophyte communities over a larger depth range. Although it is difficult to set a single target value for clarity for deep lakes due to the larger range in visual clarity (Secchi) distances amongst the deep dune lakes, potentially a minimum could be established around 3 m (Secchi depth), which corresponded to the mid-B-band at which many lakes sit. Consideration could be given to a clarity standard to specifically accommodate lakes with outstanding deep-water aquatic plant values (*e.g*. set closer to the mid A-band of TP, which corresponds to Secchi depth of around 7 m).

Macrophytes

Results from this study also identified strong statistical relationships for both TP and TN with macrophyte cover extent and LakeSPI native score. In terms of TN, this could be in response to plant species-specific tolerances of soluble N forms (*e.g.* nitrate, ammonium) for some species. Macrophytes are considered critical to the ecology of shallow lakes by maintaining clear water conditions and lake water quality. Given the roles of both N and P in lake water quality and maintaining macrophytes, it would be prudent to manage both nutrients.

Consideration could be given to targets for either LakeSPI index or macrophyte depth limit targets within NRC's Regional Water Plan for protection of aquatic habitat values. Other regional councils such as Canterbury have identified LakeSPI objectives in their plans, *e.g*. the Canterbury Land and Water Regional Plan. For dune lakes this might consist of a target LakeSPI score in the 'high' range (> 50%) for deep lakes, and potentially 'Moderate' condition (20–50%) for shallow lakes, which tended to have lower LakeSPI scores. Lower LakeSPI ranges for shallow lakes may be presumably due to the sensitivity of LakeSPI index to the prevalence of exotic species (rather than nutrient impacts), with shallow lakes being more vulnerable to the spread of exotic species over their entire extent. Based on the most recent monitoring data, 7 of 9 deep lakes surveyed would meet Canterbury's 'High' condition target and 12 of 16 lakes shallow lakes would presently meet their 'Moderate' condition target. However, because the LakeSPI index is controlled by other environmental factors beyond nutrient status (*e.g*., exotic weed incursion, herbivorous pest fish) a range of additional measures would need to be employed in combination to manage lakes for meeting LakeSPI targets.

Targets for macrophyte depth limits for dune lake categories could also be considered under a regional plan for maintaining macrophyte values in relation to lake nutrient status. Macrophyte depth limits were more highly correlated with lake nutrient status, and therefore more likely to link directly with manging nutrient loads to dune lakes. The depth extent of macrophytes also relates to other important macrophyte community values such as the diversity of community types (Schwarz *et al*. 2000; Kelly & McDowall 2004) as well as the richness of species (Jeppesen *et al*. 2007; Moss *et al*. 2013). The nature of the relationships between macrophyte depth limits and lake nutrient status differed between shallow and deep dune lakes, and therefore separate depth limit targets would need to be considered for these two lake categories. We envisage targets of > 7 m for deep lakes and > 3 m for shallow lakes as appropriate targets for the dune lakes given their present data ranges and relationships with nutrient status. Based on these regression functions (Figures 16c, 17c) this would correspond to nutrient concentrations in the NOF B-band for TP and C-band for TN for both shallow and deep lakes. Overall, from both a conservation and water quality management perspective, we would view the management of nutrients loads for the purpose of maintaining aquatic macrophytes communities as the key priority for these small dune lakes.

Macroinvertebrates

Macroinvertebrate community indices were significantly related to lake nutrient status, although only for shallow lakes. There were rapid declines in macroinvertebrate richness, diversity, and the proportion of the community comprised of ETO taxa with increasing in-lake TP concentrations. The macroinvertebrate Shannon diversity index was the only index significantly related to in-lake TN concentration. The observed declines in taxonomic richness (affecting all macroinvertebrate indices) occurred predominantly for more motile species such as caddisflies and dragonflies, which are typically associated with macrophyte beds. This pattern of decline supports results reported for a national set of shallow coastal lakes (Kelly *et al*. 2013, Schallenberg & Kelly 2014). For deep category dune lakes, there were no obvious patterns for macroinvertebrate community indicators with the nutrient status, possibly because major changes in macroinvertebrate communities occur at higher nutrient ranges than occurred in the deep dune lakes (Timms *et al*. 1982).

Macroinvertebrates represent an important food-web linkage to other aquatic (fish) and riparian (waterbird) species inhabiting lakes, and appear to comprise a reliable indicator of nutrient status in shallow lakes. Whilst there are no national protocols or standards yet developed for lake macroinvertebrates, their inclusion as an indicator of biodiversity and food web health could be considered in a regional planning context similar to LakeSPI. Looking at regression functions of macroinvertebrate community indices, most of their decline occurs through the B-band for TP, whereas for TN the C-band appears to be where degraded conditions occur. As macroinvertebrate sampling and analyses were part of a pilot investigation and considered only a subset of lakes, further examination is required to effectively recommend a set macroinvertebrate community health index targets for the dune lakes as part of the regional water plan.

5.1.3. Nutrient limitation

This investigation, and international literature, suggests a greater importance of P loading in driving the response of lakes to nutrient inputs. If lakes become N limited, conditions will favour dominance by N-fixing phytoplankton species, thereby making up for any deficit of N (*sensu* Schindler *et al.* 2008). High N:P ratios and a greater prevalence of P limitation in short-term nutrient bioassay results (Gibbs *et al.* 2014) would suggest that P or co-limitation was most prevalent in the dune lakes. This likely contributed to stronger statistical relationships of TP with other water quality variables.

Limitations to the modelling included relatively sparse monitoring data for calibrating model predictions of surface and groundwater inflows to high-country lake catchments. Additional work specific to these areas could assist the calibration of the lake models. Nevertheless, it appears that P loads largely control nutrient availability and productivity, and this has been the focus of managing nutrient loads to many lakes. Our modelling of Northland dune lakes would support this hypothesis to some extent, as TN loading models accounted for less variation in chl-*a* and other EI variables (*e.g.* macrophytes, clarity). Ratios of in-lake TN:TP for 25 of 27 lakes suggested that most were likely to have been phosphorus limited, but several indicated a degree of co-limitation.

An international study looking at the importance of N to water quality of shallow lakes, concluded that while chl-*a* and trophic status were more often controlled by P, macrophyte species composition and (in some cases) cover was related to TN concentrations (Moss *et al.* 2013). Results from this study also found a very strong TN relationship with macrophyte cover and richness. Because macrophytes are considered critical to the ecological functioning of shallow lakes and maintaining clear-water conditions, the management of both nutrients is clearly advocated (Moss *et al.* 2013; e.g. via nutrient uptake limiting phytoplankton production; trapping and enhanced deposition of suspended sediment).

5.1.4. Use of predicted nutrient loading models for setting catchment limits

Results from load modelling indicated predicted loads from the CLUES model followed general patterns of lake trophic status for the 26 dune lakes able to be tested. However there was greater unexplained variation in the developed Vollenweider relationships than for other regions. As such, the use of the CLUES model to inform lake-specific load targets should be considered with a degree of caution.

The loading model results could help inform decisions on estimating the proportional improvements in nutrient loading rates to achieve community water quality and ecological outcomes for the Northland dune lakes. This could be done on a lake-by-lake basis with some evaluation for individual lakes in terms of how well they fitted the Vollenweider regression functions. Some lakes, as discussed in the document, had sound explanations for not fitting the model due to known internal nutrient cycling issues (*e.g.*, Lake Kapoai), or atypical physico-chemistry (*e.g.*, Lake Te Kahika). Identification of required improvements (or allowable change) in catchment loads will vary depending on objectives but it would be the most sensitive value that will determine the specific TP and TN concentrations targets and associated loads.

Relationships between catchment loads and lake response variables (*e.g.* chl a) were mostly linear. Thus for management purposes TLI targets for lakes could be directly related to nutrient load targets, with allowances made for inflow concentration and lake water residence time. While the modelled relationships provide a means of developing load limits based on ecological values and water quality objectives, it is important to remember that the models only approximate environmental patterns. Therefore, information derived from the models should be the starting point when setting nutrient load targets, with further monitoring to support and to review decisions under an adaptive management framework.

The study has derived a useful approach for modelling relationships between catchment loads, in-lake nutrient concentrations, and lake ecological integrity for Northland dune lakes. Significant challenges are present in advancing scientific understanding to enable regional authorities to confidently engage with stakeholders on setting load limits for waterbodies. This is due to incomplete knowledge of how complex ecological systems respond to multiple stressors (*e.g.* nutrients and sediment), and because of the variability of scale at which decisions are often required (farm, sub-catchment, catchment, and regional scales). This study has enlarged that understanding at a sub-catchment and regional scale. It is also likely to increase confidence in community stakeholder engagement processes under the Northland Water Plan.

5.2. Recommendations for further investigation

Further work could be undertaken to improve the confidence and accuracy of the catchment models and lake ecological responses. These include:

- More detailed monitoring of hydrogeology to provide estimates of groundwater inflow yield and better estimate flow-through rates. This is the key parameter in the Vollenweider models.
- Monitoring, and modelling of groundwater sources of nutrients to the dune lakes. This ideally would address groundwater sources in a range of lake types (perched, dune contact, window) of both deep and shallow basin morphometry. Because of the clustering of lakes across Northland, this could be done in a regional basis (Apouri, Pouto, Kai-iwi) to better understand regional patterns of groundwater quality.
- Further research on in-lake nutrient processing, and the key drivers of these processes (*e.g.*, anoxia, sediment chemistry, macrophytes). Macrophyte nutrient uptake appeared to be a significant factor in some shallow lakes because of atypical TP loading–chl-*a* relationships. The extent of macrophyte nutrient processing would help to inform lake management.
- Investigations of the tolerance of macrophyte species to soluble N forms in dune lakes (and other lake types). The study was not able to investigate species-

specific responses to nutrient concentration changes. A reasonably long history of macrophyte data combined with in-lake concentrations could yield important insights on this.

- Predictions of TP loads by water birds for Northland lakes that experience high bird abundances. Seasonal bird count data for a range of lakes (and lake types) would be required for this assessment. Such work could improve the TP loading model, but it is expected that improvements in TN load predictions would be only minor (and should preferably focus on groundwater).

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8. APPENDICES

Appendix 1. Lake catchment proportional cover by LCDB v4.0 (Landcare Research 2014) land cover categories for 27 Northland dune lakes.

Lake	Lake catchment area (ha)	Native forest (%)	Gravel/rock/sand (%)	Wetland vegetation (%)	Lake/pond (%)	Exotic forest (%)	High producing exotic grassland (%)	Low producing grassland (%)	Orchard, Vineyard or Other Perennial Crop (%)	Built-up Area (settlement) (%)
Apouri Peninsula										
Lake Carrot	19.7	-	-	8.8	9.0	56.2	26.0	-	-	-
Lake Heather	57.7	5.9	-	11.8	12.6	2.3	64.9	-	2.6	-
Lake Morehurehu	316.1	6.9	0.0	4.3	12.3	74.3	2.3	-	-	-
Lake Ngakapua N.	99.5	1.0	0.1	18.2	10.0	43.8	26.9	-	-	-
Lake Ngakapua S.	8.0	-	-	15.6	28.3	40.4	15.7	-	-	-
Lake Ngatu	172.1	2.0	-	6.0	31.9	3.9	43.2	6.9	4.8	1.2
Lake Rotokawau	46.3	-	-	24.9	19.2	4.6	20.0	31.3	-	-
Lake Rotoroa	96.7	2.6	-	1.7	32.9	0.8	62.0	-	-	-
Lake Te Kahika	301.6	0.7	0.2	2.9	4.9	91.3	-	-	-	-
Lake Waihopo	104.4	-	-	10.2	6.5	45.9	37.4	-	-	-
Lake Waipara	64.6	1.7	2.3	-	3.6	92.4	-	-	-	-
Lake Waiparera	703.6	1.7	-	9.2	16.6	41.7	30.0	0.7	-	-
Karikari Peninsula										
Lake Waiporohita	61.6	0.4	-	-	11.2	-	88.4	-	-	-
wi Lakes										
Lake Kai-iwi	485.0	7.3	-	-	51.4	15.3	22.2	4.0	-	-
Lake Taharoa	422.8	6.6	-	-	51.6	14.1	24.5	3.2	-	-
Lake Waikere	118.5	10.5	0.6	1.1	27.8	11.2	48.8	-	-	-
Pouto Peninsula										
Lake Humuhumu	878.6	11.9	-	3.6	16.0	41.8	26.7	0.2	-	-

Lake	Lake catchment area (ha)	Native forest (%)	Gravel/rock/sand (%)	Wetland vegetation (%)	Lake/pond (%)	Exotic forest (%)	High producing exotic grassland (%)	Low producing grassland (%)	Orchard, Vineyard or Other Perennial Crop (%)	Built-up Area (settlement) (%)
Lake Kahuparere	257.1	17.8	15.1	0.0	6.5	46.2	13.5	0.9	-	-
Lake Kanono	499.5	17.8	8.6	-	15.4	55.5	1.0	1.7	-	-
Lake Kapoai	252.5	-	0.1	-	1.3	1.4	97.1	-	-	-
Lake Karaka	95.7	22.4	-	0.1	11.0	43.3	-	23.2	-	-
Lake Mokeno	2193.5	14.4	-	0.5	7.8	74.7	-	2.7	-	-
Lake Rotokawau	1488.7	17.1	2.9	0.4	8.1	46.4	24.5	0.6	-	-
Lake Rototuna	188.7	-	-	-	4.5	80.4	12.9	2.2	-	-
Lake Roto-otuauru-Swan	1026.2	10.3	-	3.8	15.3	36.4	34.0	0.2	0.1	-
Lake Wainui	323.8	-	0.2	0.2	2.6	9.0	87.7	0.3	-	-
Lake Whakaneke	885.2	45.9	15.3	3.6	0.9	29.0	-	5.2	-	-

1 ‘Native Forest’ includes LCDB v4.0 categories: Indigenous Forest, Manuka and/or Kanuka, Broadleaved Indigenous Hardwoods, Fernland
2 ’Tussock / alpine grassland / scrub’ includes LCDB v4.0 categories: Tall Tussock Grassland, Sub Alpine Shrubland, Matagouri or Grey Scrub, Alpine Grass/Herb-field
3 ‘Gravel / rock’ includes LCDB v4.0 categories: Gravel or Rock, Landslide
4 ‘Wetland vegetation’ includes LCDB v4.0 categories: Herbaceous Freshwater Vegetation
5 ‘Lake / pond’ includes LCDB v4.0 categories: Lake or Pond
6 ‘Exotic forest’ includes LCDB v4.0 categories: Exotic Forest, Mixed Exotic Shrubland, Deciduous Hardwoods, Gorse/Broom
7 ‘‘High producing exotic grassland’ includes LCDB v4.0 categories: High Producing Exotic Grassland
8 ‘Low producing grassland’ includes LCDB v4.0 categories: Low-Producing Grassland, Depleted Grassland
9 ‘Orchard, Vineyard or Other Perennial Crop” includes LCDB v4.0 categories: Orchard, Vineyard or Other Perennial Crop; Short rotational cropland
10 ’Built Up Area’ includes LCDB v4.0 categories: Built Up Area (Settlement)