Lake FMUs for Northland

Recommendations for Policy development

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Executive Summary

The National Policy Statement for Freshwater Management 2014 (NPS-FM) establishes objectives and policies that require regional councils to manage water in an integrated and sustainable manner within set water quality and water quantity limits. Councils must implement the NPS-FMs requirements through a regional plan that specifies objectives, policies and limits for the sustainable management of freshwater. In addition, the NPS-FM requires councils to set objectives for specific attributes that are specified by the National Objectives Framework (NOF) and must specify objectives above specified minima or 'national bottom lines'[1]. Councils must develop policies, which may include limits and other management actions, to achieve the specified freshwater objectives.

The NPS-FM recognises that the quantity and quality of water and associated values of freshwater varies between individual waterbodies. It is generally inappropriate to establish objectives that apply to all waterbodies within a region. As a result, the NPS-FM requires that regional councils establish a spatial framework of freshwater management units (FMUs) for managing water quality and quantity objectives specific to individual waterbodies or groups of waterbodies. The FMU comprises the waterbody (or group of waterbodies) and it's (their) catchment(s). The catchment is the land area that influences the waterbody's state, and activities within the catchment must be managed to achieve the objectives.

Northland Regional Council (NRC) is currently developing its second generation regional plan, in part, to give effect to the NPS-FM. The new plan will address water management at the regional scale by establishing default objectives, policies and limits and will form the basis for managing resource use and monitoring. The default plan provisions establish a generalised management framework that applies to the entire region, but which can be revised and refined over time to address catchment-specific water quality or quantity issues.

Northland has over 400 freshwater lakes, most of which are associated with sand deposits within dune systems of recent geological origin. Other lake types include volcanic, brackish and artificial lakes (dams and reservoirs). Many Northland lakes have high ecological, cultural and recreational values including a group of 12 lakes which are classified by the NRC as outstanding freshwater bodies.

This report outlines a proposed framework for the management of water quality and quantity in lakes in the Northland Region based on the delineation of FMUs following a two-step process.

The first step in defining FMUs for Northland's lakes is the definition of a Management Classification. The classification broadly discriminates variation in the characteristics of the water bodies that are relevant to management including their values, capacity for resource use and response to management interventions. Regional plan objectives for lakes will therefore be consistent within and vary between classes of the Management Classification. Objectives for a class will apply generally to all lakes in the class and be linked to values that are generally held for the management class. This requirement means that the Management Classification must discriminate variation in the current state of water quality of the region's lakes.

The proposed Management Classification broadly discriminates differences in dune lake water quality and functioning based on categories of maximum depth (deep, shallow), and geomorphology (window, perched). Maximum depth categories discriminate variation in water quality caused by differences in lake mixing patterns, thermal stratification, and

[1] See policies CA2 and CA3 , NPS-FM

interactions between surface-waters and nutrients associated with bed sediments. Geomorphic categories discriminate differences in the hydraulic connection between the lake and underlying regional aquifer systems.

The available water quality data for lakes in the Northland Region was analysed to assess the current water quality state. This analysis demonstrated that maximum lake depth is the single factor that most efficiently discriminated observed variation in the dune lake water quality. The analysis also indicated that 10 meters is the most effective threshold to define the deep and shallow lake classes. With the exception of clarity, the geomorphic categories (perched and window) did not significantly discriminate variation in water quality. However, depth and geomorphic interactions were significant in nearly all NOF and TLI water quality indicators.

The second step in defining FMUs was the identification of management zones, which are the land area consisting of catchments contributing to the water balance and contaminant loads of the lakes in each management class. Management zones provide a spatial framework for implementation of management actions to achieve water quality objectives established for lakes. Delineation of catchments for individual lakes depends on their management classification:

- For deep and shallow perched lakes, the management zones encompass the spatial extent of the surface water catchment draining to the lakes in both classes;
- For deep and shallow window lakes, the management zones consist of the spatial extent of the surface water catchments draining to the lakes plus the recharge area for hydraulically connected groundwater, up-gradient of the lakes.

It is noted the provisional management zones recommended in this report are based on currently available data. Assignment of individual lakes to a specific management class and delineation of individual lake catchments may be amended as additional information becomes available.

Limited data is available to characterise water quality in several lake types lakes defined by Champion and de Winton (2012), including volcanic, alluvial and artificial lakes. We have assumed that the major drivers of water quality these lake types will be similar to those identified for dune lakes, so these waterbodies can be managed under the proposed Management Classification on the basis of depth and geomorphic classification. Targeted monitoring and investigations may be required to validate this assumption.

The recommended approach acknowledges that water quality in window lakes is potentially influenced by recharge from spatially extensive regional aquifer systems whose boundaries extend beyond the immediate surface water catchment. In locations where multiple window lake occur, a common recharge area has been delineated where there is insufficient information available to reliably delineate the recharge area (or 'capture zone') for individual lakes.

We recommend that policies or other provisions established to manage lake water quality allow the provisional catchment of any particular dune lake to be modified if better information on its hydraulic connection to groundwater becomes available. Management zones based on surface water catchments may be refined using improved topographic data to better delineate the spatial extent of individual surface water catchments. Similarly, the catchments of window lakes may be further refined by collection and assessment of hydrogeological and water quality data which better characterise the nature of their hydraulic connection with regional aquifer systems and its contribution to lake water and nutrient balances and enable reliable delineation of recharge areas for individual lakes.

Ultimately, objectives and policies developed for the management of water quality in window lakes may discriminate management actions applicable to their surface catchments from those applying to their groundwater recharge areas. For example, management actions in surface catchments may include provisions related to matters such as stock access and riparian management, while management actions applying to groundwater recharge areas may be restricted to their contribution to cumulative nutrient inputs. Thus, inclusion of groundwater recharge areas in window lake management zones may be associated with additional management actions management actions to those applying to their surface water catchments over a geographic area larger (most likely relating to diffuse nutrient inputs). It is noted that it may be possible to exclude groundwater recharge areas from a sub-set of window lake catchments on the basis of geochemistry (e.g. reducing conditions in groundwater which remove nitrate). However, exclusion of recharge areas which make a more than minor contribution to overall lake nutrient budgets is unlikely to provide an effective framework for managing lake water quality.

Results of the analysis indicates that 8 of the 26 lakes currently monitored fail the NOF bottom line for one or more water quality attributes (including Total Nitrogen, median and maximum Chlorophyll-a). Although monitoring data is only available for a small number of lakes, and assuming the monitored lakes are representative of water quality at a regional-scale, it is inferred that there may be a significant number of lakes in the Northland Region which have a current water quality state below the national bottom line.

The Northland Regional Policy Statement (RPS) directs the NRC to set objectives and limits that are designed to improve the overall quality of fresh and coastal water with a particular focus on matters including an overall reduction in the Trophic Level Index status of the region's lakes. The analysis of water quality indicates that there is appreciable variability in water quality within individual management classes. The study was unable to identify consistent predictors of water quality variation other than the depth variable and was therefore not able to recommend a more detailed management classification that could further resolve regional differences in lake water quality. The use of the recommended management classification therefore involves establishing a single set of objectives and other plan provisions for all lakes in each management class, even though that class comprises lakes with a somewhat heterogeneous current state.

Water quality objectives for each management class would likely require an overall water quality improvement across the class. However, due to the heterogeneity of water quality in the classes, objectives that are appropriate to the class as a whole may meet the requirement to improve water quality is some or most lakes, but may allow a reduction of water quality in those lakes that currently have the best water quality in the class. This may be inconsistent with requirements of the RPS depending on whether it is interpreted as meaning that the water quality state is improved (or at least maintained) in **all** lakes or whether it is interpreted as applying generally (or "overall") to each Management Class. If the former interpretation is used, the inconsistency may be addressed by implementing policies that require maintenance of existing water quality state every lake. This would mean that where water quality currently exceeds the objectives established for a lake's class, the relevant objective would be to at least maintain the current quality. The former interpretation would reduce the certainty of plan provisions because the current state of a lake would need to be established before its objectives and policies can be defined. The former interpretation may also have implications for monitoring because progress toward objectives could not be assessed on the basis of a representative sample of lakes in each management class.

The following steps are recommended for delineating FMUs for managing lake water quality in the Northland Region:

1. Adopt the proposed four class Management Classification (Shallow-Perched, Deep-Perched, Shallow-Window, Deep-Window) as a conservative approach to managing regional lake water quality and quantity;

2. Define provisional catchments for individual lakes in the 'perched' classifications on the basis of surface water catchments defined in the FENZ database. Allow for redefinition of the provisional management zones if individual catchment boundaries are further refined by collection and analysis of additional high-resolution topographical data (e.g. Lidar imagery);

3. Define provisional catchments for window lakes based on surface water catchments defined in the FENZ database plus the estimated maximum extent of hydraulically connected unconfined aquifers defined in this report. Allow for redefinition of provisional catchment areas for individual or grouped window lakes by studies that characterise the nature and magnitude of groundwater/lake interaction and the spatial extent of contributing groundwater recharge areas. For any additional areas where window lakes are identified in the future (e.g. Aupouri Peninsula), catchments should be defined on a similar basis using available hydrogeological data to define the potential maximum spatial extent of hydraulically connected aquifers;

4. Undertake further investigations to characterise the potential groundwater contribution to lake nutrient budgets in individual window lakes. This will require investigation of the potential influence of groundwater hydrology and geochemistry on lake water quality. If investigations indicate lake nutrient budgets are relatively insensitive to inputs associated with groundwater inflows, the classification system may be able to be refined to a simple shallow and deep lake classification, at least in individual sub-regions; and,

5. Define management zones as comprising the spatial extent of surface water catchments and relevant groundwater recharge areas identified for lakes of each class.

For lakes for which a management classification has not been assigned (including lake types other than dune lakes) we recommend an initial depth classification (shallow/deep) is assigned based on the maximum depth attribute (MaxDepth) recorded on the FENZ database (or any other data sources available to quantify lake depth). In the absence of information to identify the potential for groundwater contribution to the lake water balance, the Management Classification should be assigned on the basis of the geomorphic class (perched/window) that has more stringent management controls for the relevant depth class. Provision should be made to enable this classification to be updated if additional information becomes available to characterise lake depth and/or connection to the regional groundwater system.

1 Introduction

1.1 National Policy Statement for Freshwater Management

The National Policy Statement for Freshwater Management 2014 (NPS-FM) contains objectives and policies that require regional councils to manage water in an integrated and sustainable manner within set water quality and water quantity limits. These limits must be established within a regional plan which specifies objectives, policies and limits for the sustainable management of freshwater.

The NPS-FM requires councils to identify community values that are associated with freshwater (for example environmental values such as recreation, and economic use values, namely contaminant assimilation and water supply) and to collect water quality and quantity information to assess the current state of water bodies within their regions. Taking into account both the current state of waterbodies and values associated with them, the NPS-FM requires councils to develop freshwater objectives that express numerically (where practicable) the intended environmental outcome(s) for a waterbody or group of waterbodies.

Under the NPS-FM, freshwater objectives must strike a balance between enabling water resource use and sustaining other values of water. However, they must also provide for overall maintenance or enhancement of regional water quality[2] and safeguard the life-supporting capacity of fresh water[3].

In addition the NPS-FM requires councils to set objectives that are above specified minima or 'national bottom lines'[4]. Councils must develop policies, which may include limits and other management actions, to achieve specified freshwater objectives[5]. Where objectives are not currently being achieved, the NPS-FM directs regional councils to determine how and over what timeframes, those goals are to be achieved[6].

1.2 Freshwater Management Units

The NPS-FM is based in the recognition that the quantity and quality of water and associated values it supports varies between individual waterbodies, so it is generally inappropriate to establish objectives which apply to all waterbodies within a region. As a result, the NPS-FM requires that regional councils establish a spatial framework of freshwater management units (FMUs) for managing water quality and quantity objectives to individual waterbodies or groups of waterbodies. The NPS-FM defines a FMU as a '*….water body, multiple water bodies, or any part of a water body determined by a regional council as the appropriate spatial scale for setting freshwater objectives and limits and for freshwater accounting and management purposes'*. A regional plan requires a spatial framework of FMUs that subdivides the region at an appropriate spatial scale for managing water quality and quantity.

Implicit in this definition is the idea that FMUs are to be established based on how water bodies, or parts of water bodies, are valued and function (i.e., respond to management). There is therefore interdependence between establishing FMUs and determining the values (objectives) for which they are to be managed.

[2] See Objective A2 and Policy A1, NPS-FM
[3] See Objective A1 and Policy B1, NPS-FM
[4] See policies CA2 and CA3 , NPS-FM
[5] See policies A1 and B1, NPS-FM
[6] See policies A2 and B6, NPS-FM

FMUs are a significant component of a regional plan because they provide a framework for applying different plan provisions[7] and management functions including;

1. setting freshwater objectives,
2. defining management actions, including water quality and quantity limits, to achieve the objectives,
3. accounting for resource use (within limits), and
4. monitoring progress towards, and the achievement of, freshwater objectives.

The FMU comprises the waterbody (or group of waterbodies) and it's (their) catchments. The catchment is the land area that influences the waterbody's state and, within which land use and land management activities can impact on water quality objectives. For example, the FMU defined for a lake may include both its surface water catchment plus the recharge area for any hydraulically connected aquifers which contribute to the water balance of the lake. Thus the area to which objectives, policies and rules for an individual waterbody apply may encompass a geographically extensive catchment area.

As a consequence, the scale of FMUs is a key consideration. Large FMUs may not provide sufficient resolution of values, community aspirations for water quality maintenance and enhancement, and current water quality state and subsequently may not provide plan provisions of sufficient specificity. By contrast, many independently defined and small FMUs may produce overly detailed plan provisions that may be difficult to justify and result in inefficient plan implementation. For example, application of the range of lake classification schemes reviewed by Champion and de Winton (2012) may result in a complex management framework, with large numbers of lake classes with limited distinction between individual classes (in terms of water quality).

Also of note when considering the scale of FMUs is the applicability of management actions to different types (or classes) of waterbodies. Functional characteristics of waterbodies (e.g. lake depth) can predispose them to be responsive to particular management actions. For example, deep lakes are characterised by having extended periods of thermal stratification that often result in biogeochemical processes occurring in their deeper areas (e.g., deoxygenation, phosphorus desorption, ammonification), and management actions aimed at managing these processes can be of great importance to managing their water quality and ecological health. Therefore, the grouping of FMUs by their functional attributes is an important consideration in determining appropriate policy responses in a regional plan.

1.3 Northland Regional Water Plan

The existing Regional Water and Soil Plan (RWSP) for Northland became operative in August 2004. This plan outlines a suite of objectives, policies and rules relating to the use, development and management of freshwater.

Northland Regional Council (NRC) is currently in the process of developing its second generation regional plan, in part to meet the council's obligations under the NPS-FM. The new plan will establish a default regional framework for managing water quality and quantity. Over time, the plan may be revised and refined to include catchment-specific provisions for areas in the region that are subject to significant water quality or quantity related issues.

[7] Plan provisions refers to objectives, polices, methods and rules that are defined in the regional plan.

A key requirement for NRC's new regional plan is a framework of FMUs that differentiates the region's water bodies in a manner that resolves differences in:

1. how they are valued by the community,
2. their capacity for use[8], and
3. how they need to be managed.

The framework must also be adaptable to future amendments to the NPS-FM.

This project has provided a logical basis for defining FMUs for the lakes in the Northland region-wide water plan. This report outlines a suggested approach for defining lake FMUs, and suggests that provision is made to allow some refinement of the proposed FMUs as improved information becomes available.

An important assumption of this report is that the framework of FMUs that are presented is to provide a basis for "default" plan provisions. Default plan provisions are a backstop set of provisions that apply region-wide in the absence of more specific provisions. In terms of lakes, NRC has identified a group of 12 lakes which are classified as outstanding freshwater bodies. These outstanding lakes will have individual management objectives and, potentially, plan provisions defined as part of a separate process to that which defines the regional "default" plan provisions for the remaining lakes.

The criteria for defining FMUs proposed in this report can be augmented or amended as improved information becomes available. For example, the exact extent and nature of interaction between groundwater and surface water is poorly characterised for a majority of lakes in the region. It is also important to acknowledge that decisions concerning the definition of FMUs and their associated objectives are not purely technical and are ultimately socio-political in nature, reflecting the mix and balance of values held for those water bodies. It is therefore important that the objectives for lake FMUs discussed in this report are considered only as <u>examples</u> of possible options. Furthermore, it is important that decisions concerning the definition of FMUs and associated objectives are undertaken in a transparent manner and their implications are considered by the decision-makers.

1.4 Report objectives

The overall objective of the report is to develop a recommended framework for the delineation of Freshwater Management Units (FMUs) for the management of water quality and quantity in freshwater lakes in the Northland Region.

1.5 Approach to defining FMUs

The FMUs were developed in two steps. The first step was to *classify* the region's lakes for management purposes. The region's lakes were represented as individual entities in a Geographic Information System (GIS) layer. As much as was possible, the lakes that are represented on this layer are assigned to a class so that the plan can be clear about the objectives that apply to all the region's lakes.

The second step involves assigning land areas to management zones. Management zones need to be defined so that management actions and limits that apply to them provide for the

[8] The amount of resource use that can be made by people while sustaining all competing values at some agreed level. In the context of water quality, the capacity for use is the capacity of the water body to dilute and/or assimilate contaminants derived from human uses, while sustaining all other values at desired levels. In the context of water quantity, the capacity for use is the rate at which water can be removed from the water body (or be diverted or dammed) while sustaining all other values at the desired level.

achievement of the most restrictive downstream objectives. For example, in some circumstances land may drain to a lake that is relatively resistant to the effects of nutrient concentrations. However, further downstream may be another lake that is more sensitive. In this case, management actions need to provide for the more stringent objective. Management zones clarify these important concepts (i.e. that policies and resource limits apply to use and development within contributing catchments and that policies and limits applying at any location must be consistent with the most restrictive downstream objectives).

1.6 Structure of this report

- Section 2 provides background on lakes in the Northland Region and outlines a proposed Management Classification for dune lakes;
- Section 3 provides analysis of available lake water quality data to test the application of the proposed Management Classification;
- Section 4 outlines a recommended approach for defining lake water quality FMUs in the Northland Region;
- Section 5 discusses the findings and recommendations.

Appendix A of this report provides a detailed analysis of available lake water quality data in the Northland region.

2 Northland Lakes

2.1 Background

The Northland region contains a large number of lakes, most of which are associated with sand deposits within dunes that were shaped by aeolian processes during the Holocene period (c. last 11,200 years [Augustinus et al., 2011]) and earlier in the Quaternary Period of glacial-interglacial past climate . 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 (>1 ha) within Northland Region (Leahtwick et al. 2010) of which 179 are listed as dune lakes. A further 188 dune lakes of less than one hectare have been identified for the region (Champion and de Winton 2012). An additional 45 waterbodies of man-made, volcanic, riverine, or wetland origin are identified in FENZ. These geoformation attributes of lakes are linked to functional and landscape attributes that influence ecological processes (e.g., elevation, connectivity to rivers and the coastal zone, lake basin morphometry, and climatic patterns), thus geoformation is often used 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 occurrences centred largely on New Zealand, Australia, Madagascar, and the South-Eastern coast of the USA. Within the Southern Hemisphere, the greatest abundance occurs along the West Coast of the North Island of New Zealand, particularly through Northland but extending southward to the Wellington region. There are also smaller numbers of dune lakes along the West Coast of the South Island extending as far as Southland. 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 Aupouri 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 dune lakes were either oligotrophic or mesotrophic, compared with only one lake each within Auckland and Waikato Regions, with similar temperatures and elevations to Northland.

2.2 Ecological Values

Biological communities of dune lakes can be distinctive owing to their historical isolation and lack of downstream seaward connectivity (Ball, Pohe and Winterbourn 2009). For example several of the Northland dune lakes contain genetically distinctive forms of dune lake galaxids and dwarf inanga derived from migratory ancestral inanga which would have occupied coastal stream basins prior to being isolated by dune movement (Rowe and Chisnall 1997). Seepage outlets and a lack of direct sea connection also means that many dune lakes do not contain diadromous predatory species such as shortfin eels, which tends to enhance populations of threatened galaxids and Northland mudfish. Several of the lakes do contain other threatened species such as migratory longfin eels (Allibone et al. 2010).

The abundance of dune lakes and associated wetlands, although discontinuous, collectively provide important habitat for a number of threatened and regionally significant birds including the Nationally Critical Australasian bittern and other rare species such as NZ dabchick, spotless crake and North Island fernbird (Conning & Holland 2003).. Other rare submerged aquatic plant species such as *Utricularia australis, a*nd *Thelypteris confluens* occur more widely in Northland lakes*.*

In relatively unmodified catchments (i.e., reference conditions), dune lakes typically have high ecological and human recreational values (Drake et al. 2009). They are typically clear, and have intermediate (mesotrophic) concentrations of dissolved nutrients. Submerged and emergent plant communities are usually present and provide habitat for diverse invertebrate fauna. Fish communities can vary quite substantially between lakes depending on their historical connectivity to upstream and downstream drainage networks. Lakes can range from having no fish species, to those having populations of diadromous species where connections to the sea are either present or intermittent.

Kakahi (freshwater mussels) are currently classified as threatened species in gradual decline (Hitchmough, 2007). While kakahi have been confirmed from three of Horizons lakes (Pauri, Dudding and Horowhenua), (L. Brown, pers comm.) it is highly likely that other lakes provide suitable habitat in Northland with their presence key to ecosystem services in Lake Omapere (e.g., filtering phytoplankton, improving clarity, regenerating macrophyte cover)*.* Longfin eels and inanga have also recently been classified as threatened species in gradual decline (Allibone et al 2010).

2.2.1 Outstanding Lakes

Part 1 of the Northland Lakes Strategy (Champion and de Winton, 2012) undertook an evaluation of ecological values in 76 lakes distributed across the Northland Region. Ecological values were assessed in terms of the following criteria:

- Habitat size
- Buffering
- Water quality

- Aquatic vegetation diversity
- Aquatic vegetation integrity
- Endangered species
- Presence of key species
- Connectivity

Each lake was scored in terms of these criteria and lakes ranked in terms of a cumulative ecological score. Of the lakes surveyed, 12 were rated as 'Outstanding' receiving an ecological score greater than 12 (out of a possible 20). Following completion of the Part 1 of the Northland Lakes Strategy, the NRC approved the addition of all 12 lakes classified as having an 'Outstanding' ecological score to the list of outstanding freshwater bodies, although they are yet to be ratified by inclusion in the RWSP. Lakes included in this list include:

- Lake Morehurehu
- Lake Wahakari
- Lake Waihopo
- Lake Waiporohita
- Lake Ngatu
- Lake Waikare (referred to as Waikere until recently)
- Lake Taharoa
- Lake Kai-Iwi
- Lake Humuhumu
- Lake Mokeno
- Lake Rotokawau
- Lake Kanono

Figure 1 shows the location of lakes included in the NRC list of outstanding freshwater bodies. As previously noted, management objectives for these lakes may be developed separately from the generic regional classification outlined in this report.

It is however noted that lakes included in this classification form a large component of the water quality data set available to assess the current state of lake water quality in the Northland Region. These lakes have therefore been utilised in the assessment of water quality outlined in the following section as being representative of lakes across the wider region for which no water quality data is currently available.

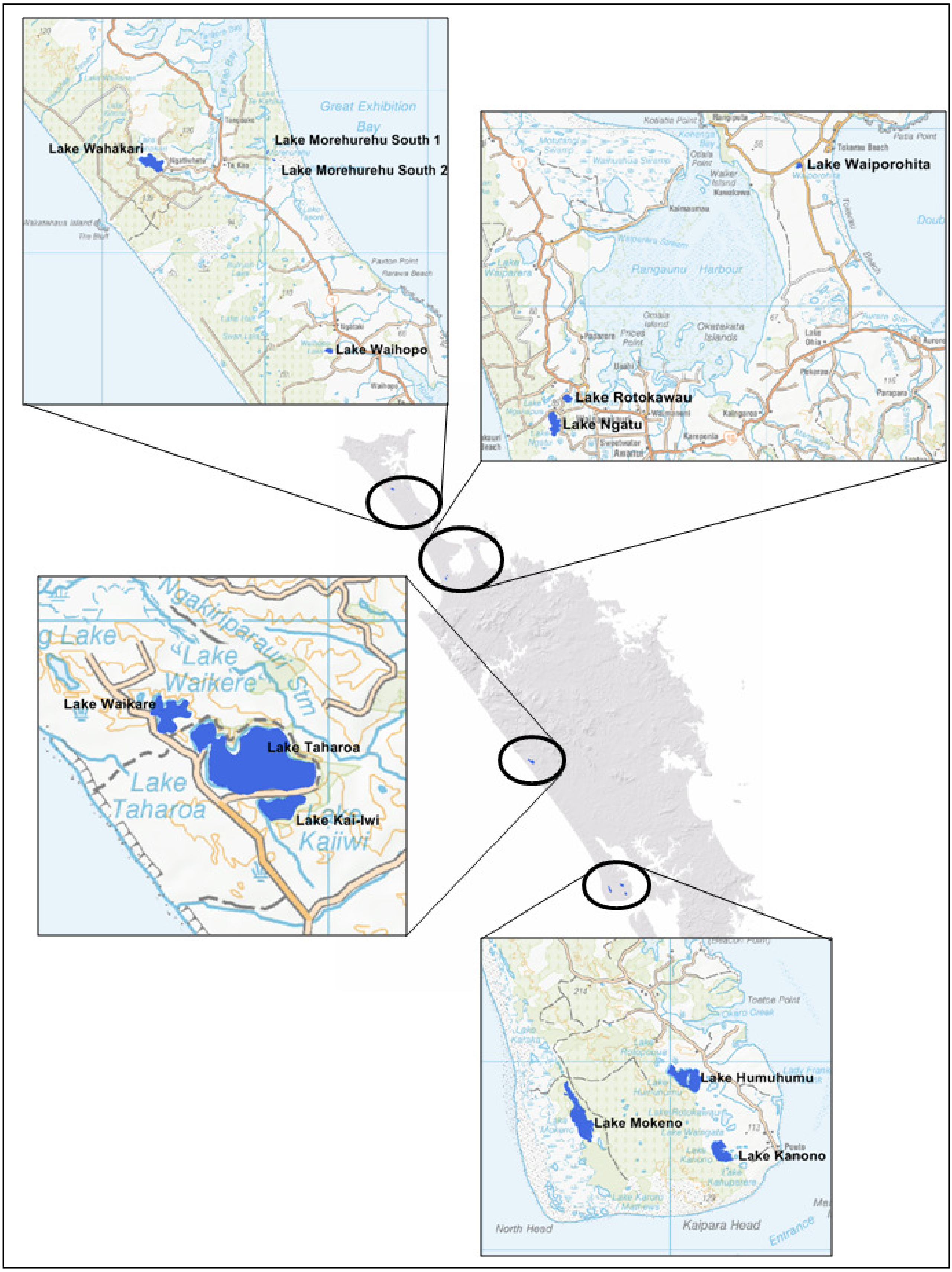

Figure 1. Outstanding lakes identified in the Northland Region

2.3 Management Classification of Northland's lakes

The first step in defining FMUs for Northland's lakes is the definition of a Management Classification. The classification should broadly discriminate variation in the functional characteristics of the water bodies that are relevant to management including their values, capacity for resource use and response to management interventions. Regional plan objectives for lakes will therefore be consistent within and vary between classes of the Management Classification. It is assumed that first and foremost, objectives and policies will be consistent with the Northland Regional Policy Statement which directs the Council to "*Improve the overall quality of Northland's freshwater, with a particular focus on reducing the overall Trophic Level Index status of the region's lakes…*". This requirement effectively sets the capacity for use of water bodies in each class. Objectives for a class will apply generally to all lakes in the class and be linked to values that are generally held for the management class. This requirement means that the Management Classification must discriminate variation in the current state of water quality of the region's lakes.

All lakes are distinct, but at some level similarities with regard to specific water quality and functional characteristics can be drawn between lakes. An appropriate Management Classification of lakes requires that lakes that share similar characteristics are grouped into alike classes. It is essential that this is done well, otherwise, the regional plan may mismatch lakes with respect to their water quality objectives and appropriate management interventions. Defining an appropriate classification is challenging because there are always differences between lakes and there must therefore be judgments about the level of detail (i.e., number of classes) versus the discrimination of differences that are meaningful from a management perspective. Increasing the number of classes provides for greater discrimination of differences and allows more specific policies. However, the addition of classes may be difficult to justify when data is limited and will increase the complexity of the planning framework.

There has been considerable scientific effort to developing environmental classifications of New Zealand freshwaters. At present, one main classification systems exists: the Freshwater Environments of New Zealand (FENZ) classification, which is a multivariate classification based on physical eco-typing but optimised against a spatial database of biological community data (Snelder 2006, Leathwick et al. 2008b). Variables driving the classifications were selected and weighted according to what was considered to drive the underlying ecology and function of different lake types. Additionally, biological databases were used to calibrate the physical environment typologies, with lakes optimised against a submerged macrophyte dataset (Snelder 2006).

2.3.1 Classifying lakes by depth

There is strong recognition that lake water depth is a key functional driver of water quality in New Zealand lakes (Drake et al. 2010). The morphometry of the basin is a key variable in determining the mixing regime of the lake, and the prevalence of thermal stratification over seasonal cycles. In the FENZ environmental classification, mixing regime was regarded as having fundamental importance for NZ lakes (Snelder et al. 2006). Important variables controlling mixing regime include wind strength, temperature, solar radiation and basin morphometry (including area of the lake and depth). The importance of basin depth is evident not only in manner in which lakes behave, but also in water quality objectives and indicators that are assigned to different lake classes. In addition to the importance of depth in controlling mixing regimes, basin morphometry also controls lake volumes, hydraulic residence times (i.e., flushing) and the extent and biotic composition of littoral zones (macrpohyte habitat).

2.3.1.1 Shallow Lakes

Shallow lakes respond to nutrients in a different manner to deep lakes, and thus have their own ecology and management challenges (reviewed in Scheffer 1984). In shallow lakes, wave bases can more easily stir up bottom-water, resulting in greater rates of water column mixing. Greater mixing results in greater physical resupply of nutrients from bed sediments, whilst also reducing water clarity. Phosphorus, which is stored in lake sediments, can be released to the water column during periods where wave action disturbs pore water from deeper anaerobic sediment layers or when sediment is physically recirculated into the water (Jensen et al. 1992a). This process is mediated by water column temperatures, with nutrient (phosphorus) concentrations in shallow lakes often being highest during summer (e.g. Gibbs 1994) — the opposite of that usually observed in stratified lakes due to thermal stratification (Scheffer 2004).

Submerged macrophytes are very important structuring elements in shallow lakes (Kelly & McDowall 2004), and may markedly affect the environmental conditions of a lake by their ability to facilitate a "clear-water state" of lower algal biomass (Scheffer & Jeppesen 1998). Shallow lake management often aims to sustain or restore macrophyte communities to maintain the clear-water state of shallow lakes. Loss of macrophyte communities can occur through numerous mechanisms including nutrient enrichment whereby excessive algal production occurs, either phytoplankton blooms and/or epiphyton growth, or intensive growth of undesirable (weedy) macrophytes. All of these mechanisms generally result in shading of macrophyte communities causing light limitation of low-growing plants and their ultimate collapse, in a process termed 'flipping' (Schallenberg & Sorrell 2009). Once lost, internal nutrient loading from sediments and re-suspension of lake bed materials reinforce the "turbid state" by feeding back into lower clarity and greater nutrient availability due to loss of a macrophyte carpet locking nutrients into sediment . In many cases management actions which lead to further reductions in external nutrient loading are counteracted by these internal lake processes, causing an inertia to re-oligotrophication and to the re-establishment of a macrophyte-dominated state (Carpenter 2004, Scheffer 2004).

2.3.1.2 Deep Lakes

Much of our understanding of lake responses to nutrient enrichment is based on patterns observed in deep lakes (Wetzel 1984). In deeper lakes, the physical properties of water are important. Reductions in density occur below and above approximately 4°C so that water of differing temperature has different density and will not readily mix. Hence during periods of greater insolation (summer), surface waters can heat more rapidly than deeper water, generating a density-driven gradient between upper and lower water. If waves are sufficiently deep, this process results in the water column becoming thermally stratified. If so, the epilimnion (surface layer) becomes physically separated by a thermocline (narrow zone of marked temperature change over depth) from the hypolimnion (bottom layer).

If thermal stratification is prolonged, bottom-waters become starved of oxygen which alters the chemical conditions at the sediment-water interface, encouraging the release of phosphorus as well as altering rates of nitrification and denitrification (e.g., Vant, 1987; Burger et al., 2007). The epilimnion effectively becomes starved of nutrients (phosphorus in particular as nitrogen is available atmospherically to phytoplankton), promoting low algal biomass during stratification. However, upon either cooling (reducing the density differences between top and bottom water) and/or greater windiness, internal nutrients held in bottom-waters can be returned to the well-lit surface and promoting an algal bloom. Hence, whilst spring external nutrient concentration are important in determining algal growth responses that occur over the summer season, internal nutrient release coupled with any external coeval inputs drive autumn primary production.

Deep lakes therefore differ fundamentally from shallow lakes, such that management objectives need to account for the risk of oxygen-consuming processes as decomposition and respiration driving higher algal and nutrient availability. Internal loading, can greatly increase annual loads of phosphorus above external inputs (*e.g.* Howard-Williams & Kelly 2003, Gibbs 2011).

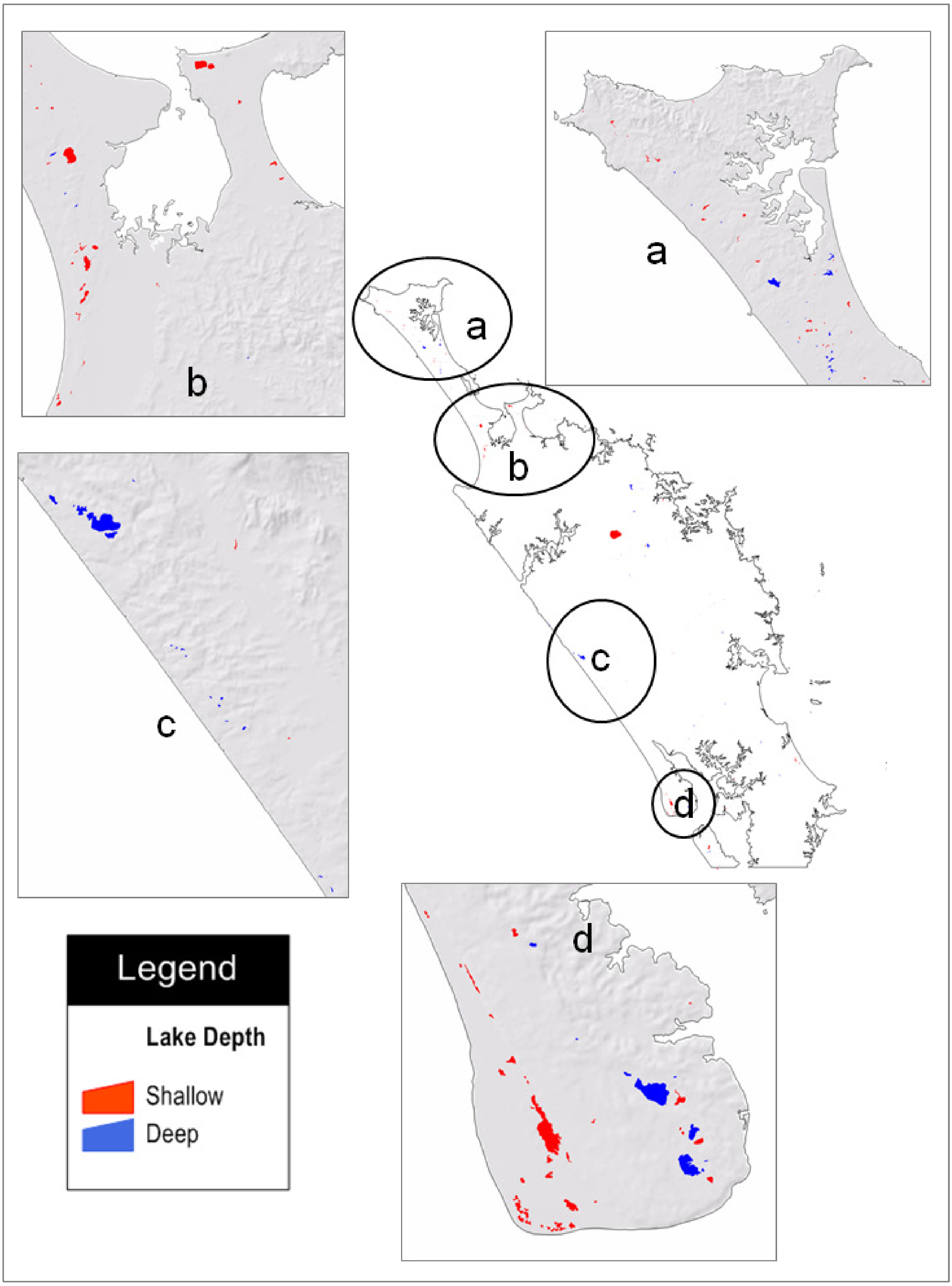

Figure 2. Classification of Northland Lakes by depth (shallow <10 m maximum depth, deep >10m maximum depth)

2.3.2 Geomorphic classes of dune lakes

Dune lakes typically result from partial blockage of stream valleys or in depressions formed by blown sand. Formation of these lakes predominantly occurs in two ways. Firstly, and more commonly is when wind-blown materials (sand) deposit in the basin of an existing stream draining to the sea, thereby flooding an upstream area as the outflow is blocked, often with associated existing wetland. Secondly, when an unconnected (i.e., no stream inflow) basin floods due to the reduction in subsurface drainage caused by the deposition of less permeable soil materials (e.g., clay, silt) within a depression, which generally occurs during episodic events such as large floods. Additionally, changes in sea level can mean that some depression lakes are now perched on older inland sequences of elevated dunes. The varying processes by which these lakes form affect the connection between the surface water body and subsurface groundwater, and have important implications for water quality management in these systems. Most dune lakes are thought to be relatively recent in formation, being less than 6,500 years old (Lowe & Green 1987), but Lake Taharoa is at least 50,000 years old (Mosley 2004).

Champion and de Winton (2015) 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 groundwater (e.g., perched or window), and the nature of sedimentary layers that comprise its immediate surface water catchment.

Classification followed that of Timms (1982) which can be broken into 6 classes as follows (from Champion and 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 provides humic (tea-stained) water.

2) Swamp associated perched lakes, - Similar to Class 1 but close to the sea, associated with extensive swamps.

3) Window Lakes - Water-table window lakes in a drowned valley or interdune basin, fed by springs with clear water character.

4) Dune contact lakes - waterbodies where· at least one shore is in contact with a coastal dune, often but not exclusively humic.

5) Marine contact lakes - Freshwater lakes with marine contact, where there may be intermittent connection with the sea. Waitahom 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. Shallow, small and often ephemeral, e.g. Lake Horahora (on the east coast) also would fit within this class.

According to Champion and de Winton (2012), primary dune lake classes could be further broken down into the dominant soil ages that comprise their surface water catchments. These differing sediment compositions could result in varying degrees of reducing conditions in groundwater flows, and affect denitrification and phosphorus retention along groundwater flow paths.

The dominant soil types in which each dune lake is formed can be divided into three ages from youngest to oldest:

1. Holocene (Pinaki sand series).
2. Upper Quaternary (Redhill and Houhora series).
3. Lower Quaternary (Te Kopuru and Tangitiki series).

For this study we have adopted a more simplistic geomorphic classification based on a simple distinction between 1) window lakes (i.e. those lakes with a hydraulic connection to the underlying regional aquifer system), 2) perched lakes (i.e. those which have a water balance dominated by runoff and shallow subsurface flow from their immediate surface water (topographical) catchments) and 3) other (i.e. non-dune) classifications (including volcanic, alluvial and artificial (dams and reservoirs)) based on the initial grouping of lake types by Champion and de Winton (2012). Adoption of this simplified classification reflects the limited availability of water quality datasets on which to test lake geomorphic effects on what quality patterns, with data available for only 28 lakes dune lakes. Assignment of geomorphic class to individual lakes was modified to incorporate the updated identification of window lakes outlined in Part 2 of the Northland Lake Strategy (Champion, 2014) as well as the results of water balance modelling undertaken by Jacobs (2014).

Figure 3 shows the geographical distribution of geomorphic lake classes utilised for this study.

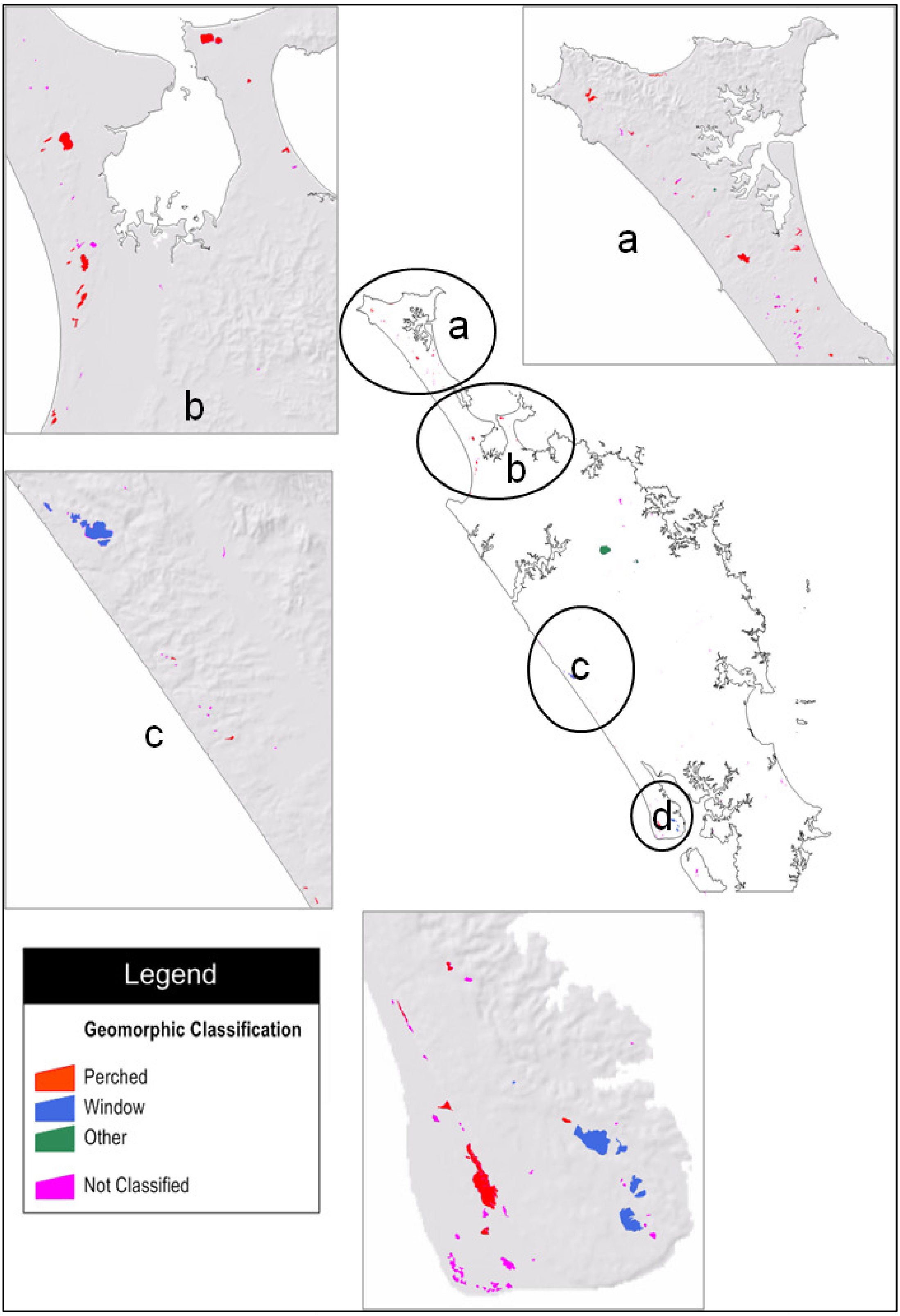

Figure 3. Geomorphic classification of Northland Lakes (based on lake types assigned by Champion and de Winton (2012), modified to incorporate updated identification of window lakes in Champion (2014) and SKM (2014))

2.3.3 Proposed Management Classification

From limnological theory above, an appropriate Management Classification is likely to require subdivisions of lake classes by depth and geomorphic character (groundwater connection). Depth classes must discriminate variation in water quality attributed to lake mixing and/or residence time on nutrient availability, to be warranted. Classes based on geomorphic character must discriminate differences in nutrient availability arising from differences in external loading to surface water, to be warranted (i.e., effects of differences in catchment area beyond the topographic boundaries and to total loading).

We propose a pragmatic choice of two lake depth classes based on a maximum depth threshold of 10 meters. It is subjected to detailed testing against observed water quality data at varying thresholds in the subsequent section of this report, alongside a range of additional factors (see Appendix A). The proposed Management Classification derived from this, builds on national recommendations for deep and shallow lake classes to be defined at 15 m depth for some water quality attributes of ecosystem health within the National Objectives Framework of the NPS. A modification to the national depth criterion is recommended here to better capture regional differences in Northland dune lake morphometry and/or climatic effects on water quality.

The previous studies of Champion and de Winton (2012 and 20154 suggests that dune lakes be classified into six primary geomorphic categories and three soil ages categories to produce a total of 18 dune lake classes for the Northland Region. This large number of geomorphic classes was deemed too extensive for effective policy development and unwarranted from the differences observed amongst twelve key water quality indicators. Whilst geomorphic differences were evident, their effect was complex. So, the key geomorphic features included in the proposed management classification relate to management rather than functional differences, that is the extent to which a lake's external nutrient loads are supplied by the immediate surface water drainage areas (perched lakes) or to a more extensive regional aquifer whose boundaries extend beyond the lake's surface water catchment (window lakes).

Given the limited data available to characterise water quality state and geomorphological characteristics for lakes other than dune lakes in the Northland Region, this report assumes that the major drivers of water quality in other lake classes will be the same as those identified for dune lakes and, consequently, these lakes can be managed under the Management Classification developed for dune lakes. Further work would be required to establish if additional Management Classification classes are justified for lakes which are not included in the dune lake classes.

The proposed Management Classification therefore comprises four classes; shallow perched, deep perched, shallow window and deep window. The subsequent section details the water quality data and analyses underpinning the proposed Management Classification for Northland dune lakes, demonstrating notable differences in water quality (current state) between the proposed classes.

2.3.4 Assignment of lakes to classes

Assignment of individual lakes to the proposed Management Classification utilised the geomorphic classes described in Section 2.3.3, combined with the maximum lake depth attribute (MaxDepth) recorded on the FENZ database. Classifications assigned to individual lakes are listed in Appendix 2.

Overall, of the 75 lakes evaluated by Champion and de Winton:

- 43 lakes were classified as Shallow-Perched lakes;
- 10 lakes were classified as Deep-Perched lakes;
- 3 lakes were classified as Shallow-Window lakes; and
- 9 lakes were classified as Deep-Window lakes.

Of the remaining 10 lakes which were unclassified, 3 do not have a FENZ MaxDepth attribute assigned, while the remaining 7 include the non-dune lake types (volcanic, alluvial and artificial). Potential options for classification of these lakes is further discussed in Section 5.

3 Analysis of water quality

3.1 Data

NRC regularly monitor 27 dune lakes in the Northland region. These lakes are sampled on a quarterly basis for a suite of physicochemical and ecological variables that indicate 'ecosystem health'. As part of this study, data resulting from the lake monitoring programme for the period 2009-2014 for 26 lakes were analysed (including an additional volcanic system, Lake Omapere). A 5-year period was thought to best capture the current state of the lakes, with consistent sampling and analytical methodology as well as sufficient observations from which to reliably determine 95^{th}% scores for several attributes (see below). The aims of the analysis were to characterise the water quality state of the 26 lakes and identify patterns that relate to underlying driving factors that could form the basis of the Management Classification.

In total quarterly lake water quality samples were analysed for 17 water quality variables (Table 1). The variables included three physical indicators Total Suspended Solids (TSS), Secchi depth (SD) and Temperature. TSS and SD are measures of water clarity that indicate the level of suspended organic (algae or phytoplankton) and inorganic material (eroded sediment) in the water column. Temperature affects thermal stratification in lakes, which coupled to lake morphological characteristics (e.g., maximum depth, volume, residence time), can result in variation in nutrient availability.

Water chemistry indicators represented nutrient availability in the water column. pH is an important aspect of water column physicochemical environment, which affects the solubility of toxins, and availability of nutrients. Conductivity (Cond) indicates differences in hydrogeology that can drive differences in nutrient supply. Dissolved oxygen (DO) indicates the availability of oxygen in either the upper (epilimnion) or entire water column. Total nutrients, both phosphorus (TP) and nitrogen (TN), record the total fraction of dissolved and particulate, organic and inorganic nutrients in the water column and indicate the likelihood of algal blooms and associated risks to water quality degradation. Ammoniacal nitrogen (NH_4-N) is a component of TN that is toxic to lake fauna at elevated concentrations. The variables TN, TP and NH_4-N are attributes associated with ecosystem health in the NOF.

Chlorophyll-a concentration (Chl-a) is an ecological measure of the abundance of lake phytoplankton (algal biomass). Phytoplankton abundance varies in response to both internal (in-lake) and external processes (nutrient supply from the catchment). Chl-a is an attribute associated with ecosystem health in the NOF. The variables of SD, Chlorophyll-a, TN and TP are combined in a single physiochemical indicator known as the Trophic Level Index (TLI; using the revision to SD in Burns et al. 2000). The TLI is a measure of the potential primary production or 'trophic state' of a lake. The TLI scores vary from less than one to seven with a score of one or less indicating low (ultra-microtrophic) nutrient availability and phytoplankton production and greater than six indicating very high (hypertrophic) conditions.

Table 1. Lake water quality variables included in this study (note that there are 17 parameters when different statistical measures of are accounted for (e.g., median and maxima))

Variable type	Variable	Abbreviation	Units
Physical	Total Suspended Solids	TSS	mg/m^3
	Secchi depth	SD	m
	Temperature	Temp	°C
Chemical	pH	pH	N/A
	Conductivity	Cond	mS/cm^{-1}
	Dissolved oxygen	DO	mg/L
	Total Phosphorus	TP	mg/m^3
	Total Nitrogen	TN	mg/m^3
	Ammoniacal Nitrogen (median and maximum)	NH_4-N	mg/m^3
Phytoplankton	Chlorophyll-a (median and maximum)	Chl-a	mg/L
Index	Trophic Level Index (and fout TLx)	TLI	N/A

3.2 Water quality analysis results

A detailed description of the assessment of lake water quality is provided in Appendix A. An underlying assumption of these analyses is that the water quality of the monitored lakes is representative of the large number of lakes across the Northland Region which are not currently monitored. For most of the analyses the median values of the water quality variables recorded at each lake in the period 2009-2014 were used to represent the most recent water quality conditions in each lake.

Summary statistics were generated for each indicator before being subjected to a Principal Component Analysis (PCA). This analysis indicates a majority of variation in lake water quality is aligned with a gradient in the TLI (e.g., nutrient availability, clarity and phytoplankton biomass).

The gradient in water quality across the monitored lakes was also strongly associated with variation in maximum lake depth (using measured maximum depths from a NIWA 2015 survey). Maximum lake depth explained statistically significant proportions of the variability in TLI, as well as all other water quality indicators except NH_4-N ($p<0.05$). Analysis of Variance (ANOVA) using two depth classes as the explanatory variable and a 10 m depth threshold demonstrated that the average TLI of deep and shallow dune lakes was significantly different ($p < 0.0001$). The depth classification also discriminated significant ($p < 0.05$) differences in the other relevant water quality indicators (i.e., TN, TP, Chl-a median, Chl-a max).

An analysis of the ability to discriminate water quality differences by maximum depth was undertaken, over a range of depths (5 to12 m, at one metre increments) to assist with the justification of a depth threshold. The analysis calculated the performance of classifications based on ANOVA r^2 values for all eight classifications defined using maximum depths of 5 to12 metres, across each of the six key water quality variables. For each interval, the mean of the r^2 values across the six variables was used to indicate the performance of the classification. The analysis indicated that a depth threshold of 9 to -10 meters was the optimal depth threshold, with r^2 variation from 0.20 to 0.42[9].

ANOVA also indicated that the geomorphic classification (i.e., perched and window lakes) did not explain variation in the majority of water quality variables tested ((excluding NH_4-N maxima and median, which varied very little across all 26 lakes, precluding the ability ot classify lakes on either indicator). The geomorphic classification did however explain significant differences in water clarity (SD and one of the component variables making up the TLI (Figure 6)).

Further exploratory analyses of potential drivers of variation in lake water quality were made using multiple linear regression. Summary water quality scores were regressed against 17 physical catchment (e.g. land use, geology) and in-lake characteristics (e.g. lake surface area and depth) obtained from FENZ and filtered to exclude collinearity. While caution is required in the application of model findings across the wider region, the assessment indicated that:

1. Shallower maximum depth is associated with higher nutrient concentration (TN, TP) and poorer water clarity;
2. Total phosphorus (TP) availability is linked to land use with catchments having greater proportions of exotic forestry and pasture cover, characterised by higher TP;
3. Total nitrogen availability (TN) was not significantly linked to land use but rather to lake morphometry, with higher TN concentration associated with shallower and larger lakes.
4. The only consistent factor or driver across all 10 water quality indicators tested was maximum depth. In all indicators the effect of changes to depth were also consistent; deeper lakes are associated with lower nutrient availability, lower algal biomass, greater clarity and lower TLI.

[9] An r^2 of 0.42 is of moderate predictive power but considerable for a single-factor linear model.

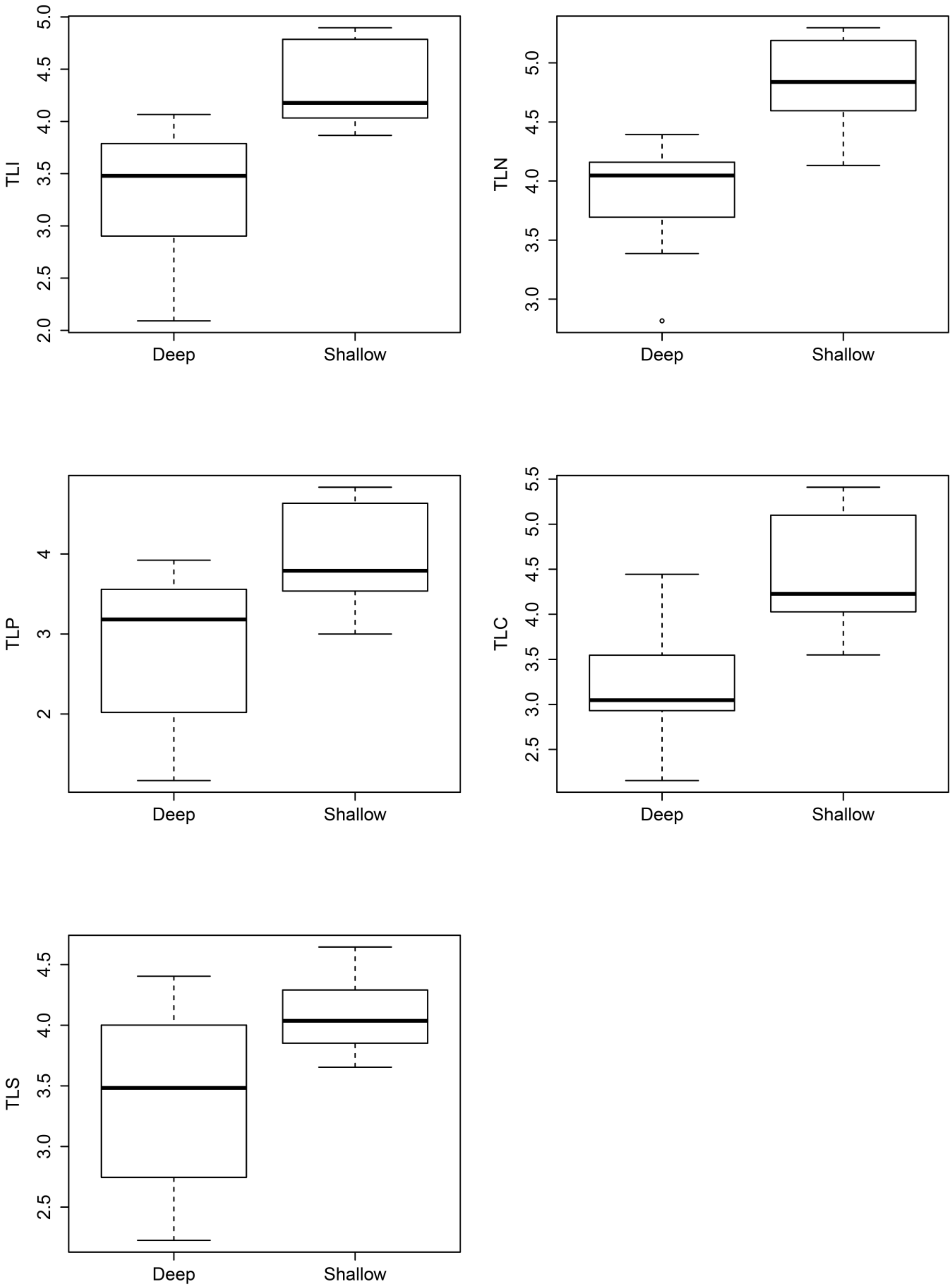

Figure 4. Distributions of site median (thick black line) and 95% (whiskers) values for total nitrogen (TN), total phosphorus (TP), maximum Chlorophyll-a (Chla max), median Chlorophyll-a (Chla median) and Secchi Depth (SD) for shallow and deep lakes where the depth threshold was 10 meters.

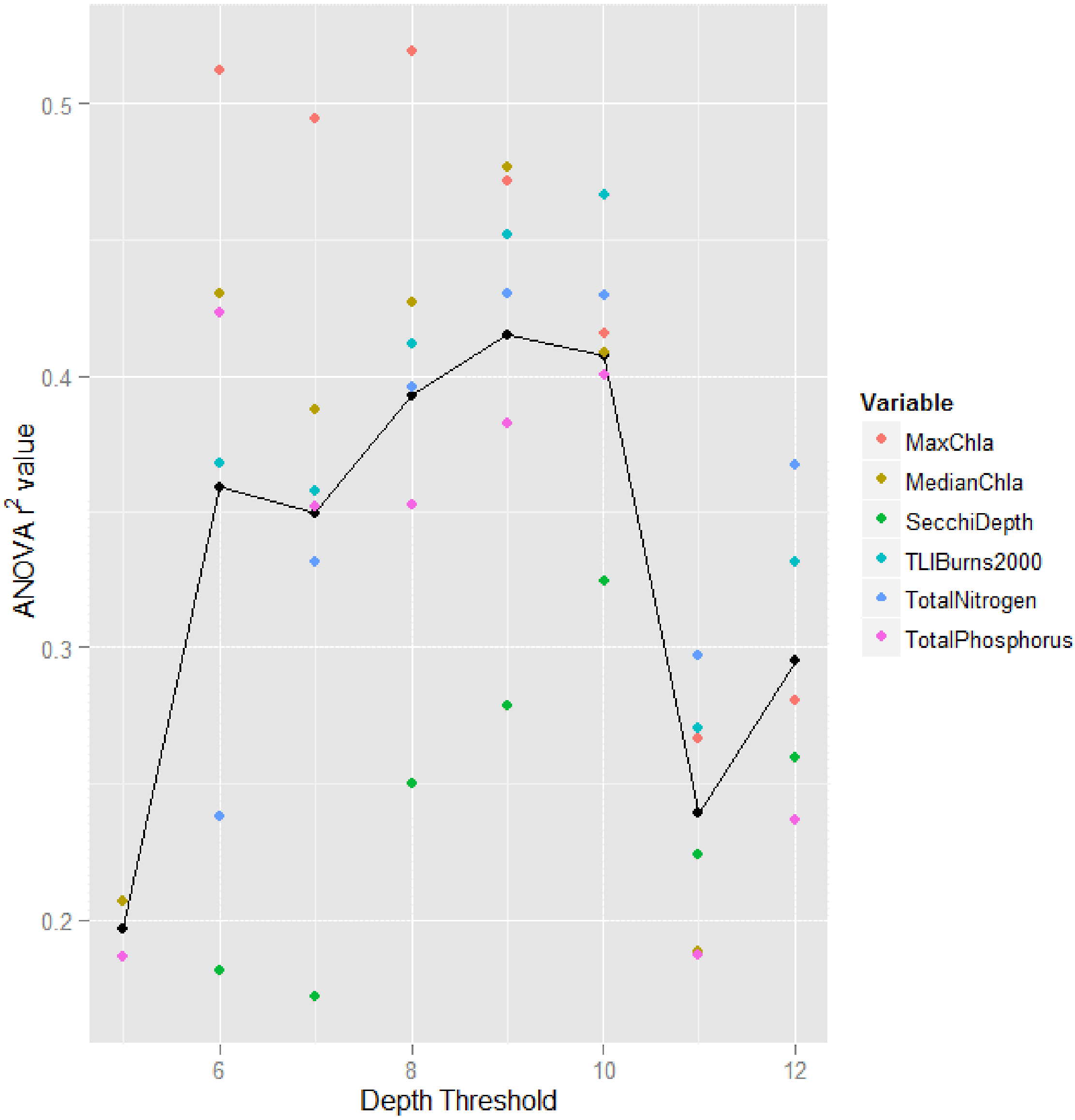

Figure 5. Results of tests of the performance classifications of lakes into Deep and Shallow classes using depth thresholds defined in increments of one meter from 5 to 12 m. An ANOVA test was performed on each water quality variable for each classification. The black line represents the mean r^2 values across the six variables that was used to indicate the overall performance of the classification at each threshold.

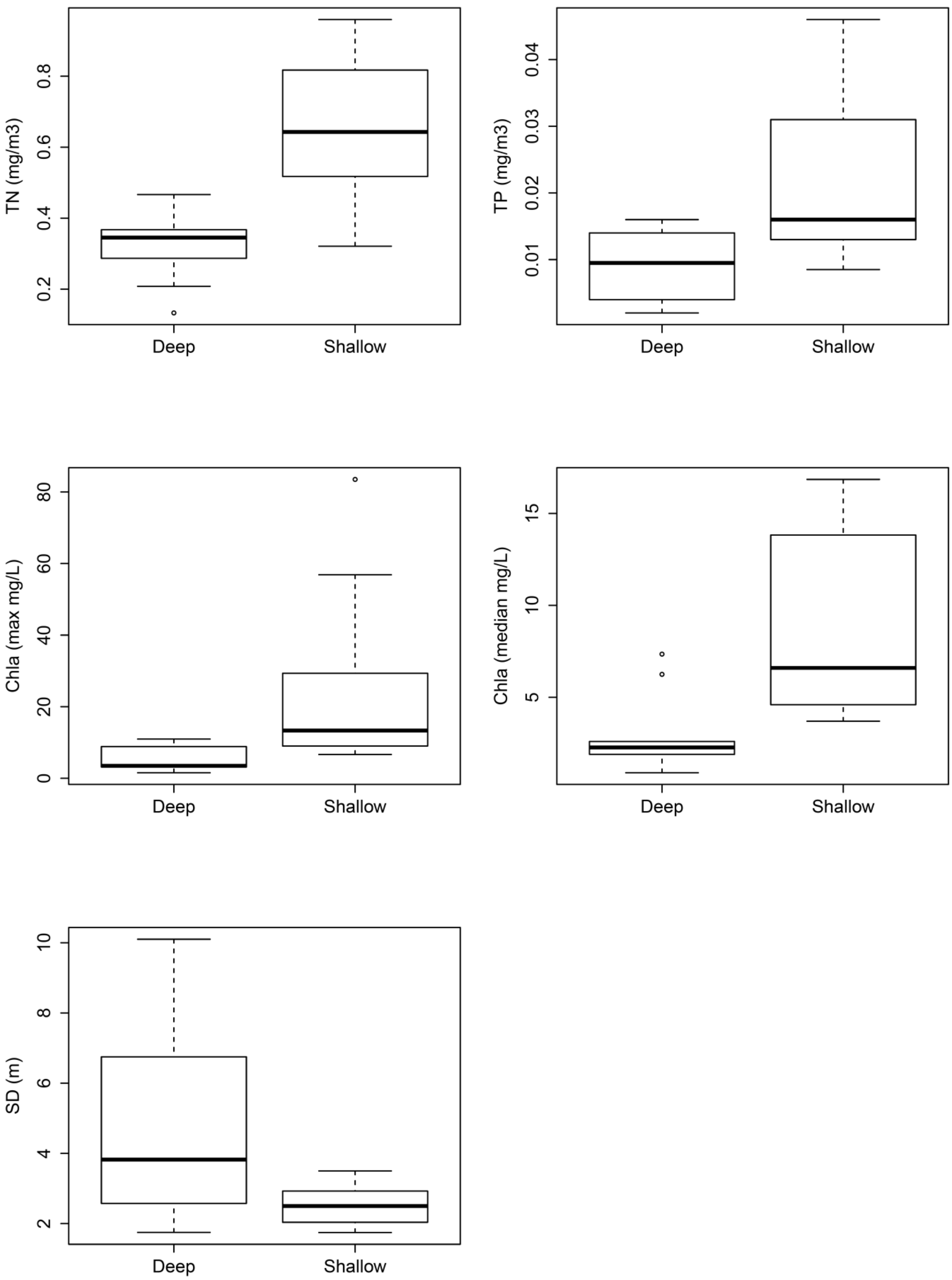

Figure 6. Distributions of site median (thick black line) and 95% (whiskers) values for total nitrogen (TN), total phosphorus (TP), maximum Chlorophyll-a (Chl-a max), median Chlorophyll-a (Chl-a median) and Secchi Depth (SD) between perched and window lakes.

3.3 Performance of the proposed Management Classification

All lakes are sensitive to water quality impacts associated with both internal recycling of nutrients and external inputs of nutrients and other contaminants from their catchments. The proposed Management Classification discriminates major differences in lake water quality and functioning based on these internal and external processes by classifying lakes by depth (deep, shallow), and geomorphology (window, perched).

The empirical water quality data analysis supports a maximum depth based classification of the region's dune lakes, reporting that maximum lake depth was the sole consistent factor linked to variation in observed lake water quality. Other physical characteristics of lakes (e.g., proportion of catchment area occupied by pasture or exotic forestry land cover) were associated with variation in water quality variables (e.g., TLI, TP, TLP, TLS, TLC, SC, Chl-a median and maximum) although these effects were not consistent. These and other analyses indicate, unsurprisingly, that factors other than depth also influence water quality. The analysis also indicates a maximum depth of 10 meters is the most effective threshold to define the deep and shallow classes that in turn reduce the variation in water quality between lakes, within those classes.

An alternative classification of the regions lakes into geographic sub-regions defined by Aupouri, Central, Kai-Iwi, and Pouto did not significantly discriminate variation in lake water quality. This indicates that a simple sub-regional classification would not provide a Management Classification that was as robust as the proposed depth based classification.

The classification of lakes on the basis of geomorphology into perched and window only explained significant differences in water clarity. The retention of the geomorphological component of the proposed management classification is nonetheless supported by the latter's relevance to the management of external inputs of dissolved nutrients, to both deep and shallow lakes connected to a regional aquifer system.

4 Lake water quality FMUs

This section outlines a suggested approach for defining a default regional framework of FMUs for management of lake water quality in the Northland Region, under the NPS-FM.

4.1 NPS-FM lake water quality objectives

The NPS-FM establishes a set of national objectives for freshwater management (the NOF). These objectives establish a common set of 'attributes' and associated bands (in effect water quality standards), which apply to all waterbodies (i.e., lakes, rivers) nationally. Attributes are defined in the NPS-FM to mean "*a measurable characteristic of freshwater including physical, chemical and biological properties, which support particular values*". Attribute bands are numeric values that define four water quality states (A, B, C and D bands). The NOF also defines a minimum acceptable state (also referred to as the *bottom line*) which establishes a minimum state that all waterbodies of a particular type must be managed to achieve, which is the boundary between the C and D bands.

The varying bands above the bottom line enable communities to identify the water quality state that is considered to sufficiently support the values (including ecological, aesthetic, recreational, and economic use values) applicable to that waterbody. The appropriate water quality states for individual waterbodies are established through the regional plan process, along with appropriate management actions (in the form of policies and/or rules) that will enable the desired water quality state to be maintained (or achieved where the current water quality state is below the desired state). The NPS-FM also provides for regional councils to establish a timeline for implementing management actions than will enable all waterbodies to meet the national bottom line.

It is important to note that the NOF establishes a minimum set of water quality objectives (i.e., standards) that apply to all waterbodies depending on type (the bottom line) and requires that water quality is maintained or improved *overall*. Regional councils may also establish water quality objectives for parameters not included in the NOF, which are considered appropriate for individual waterbodies.

The NPS-FM attributes that are relevant to lakes include Phytoplankton (Chl-a maxima and median), Total Nitrogen (TN median) and Total Phosphorus (TP) which contribute to, or indicate, trophic state, and Ammoniacal nitrogen concentrations to manage toxicity (NH4-N maxima and median). Attribute states for TN are expressed differently for seasonally stratified and brackish lakes as opposed to polymictic lakes. Attribute states for phytoplankton (expressed in terms of milligrams chlorophyll-a per cubic metre) and Ammoniacal nitrogen are based on annual median and annual maximum concentrations. Table 2 outlines the relevant bands for lake water quality attributes.

Table 2. NPS-FM NOF attributes and band criteria for lakes

<table>
<tr><th rowspan="2">Attribute</th><th rowspan="2">Units</th><th rowspan="2">Compliance Statistic</th><th rowspan="2">Lake Type</th><th colspan="4">Criteria for bands</th></tr>
<tr><th>A</th><th>B</th><th>C</th><th>D</th></tr>
<tr><td rowspan="2">Phytoplankton (chlorophyll-a)</td><td rowspan="2">mg/m^3</td><td>Annual Median</td><td></td><td>≤2</td><td>2< x ≤ 5</td><td>5< x ≤12</td><td>>12</td></tr>
<tr><td>Annual Maximum</td><td></td><td>≤10</td><td>10< x ≤25</td><td>25< x ≤60</td><td>>60</td></tr>
<tr><td rowspan="2">Total Nitrogen</td><td rowspan="2">mg/m^3</td><td rowspan="2">Annual Median</td><td>Seasonally stratified and brackish</td><td>≥160</td><td>160 < x ≤350</td><td>350< x ≤750</td><td>>750</td></tr>
<tr><td>Polymictic</td><td>≥300</td><td>300 < x ≤500</td><td>500< x ≤800</td><td>>800</td></tr>
<tr><td>Total Phosphorus</td><td>mg/m^3</td><td>Annual Median</td><td></td><td>≤10</td><td>10< x ≤20</td><td>20< x ≤50</td><td>>50</td></tr>
<tr><td rowspan="2">Ammoniacal nitrogen</td><td rowspan="2">mg/L</td><td>Annual Median</td><td></td><td>≤0.03</td><td>0.03< x ≤0.24</td><td>0.24< x ≤1.30</td><td>>1.30</td></tr>
<tr><td>Annual Maximum</td><td></td><td>≤0.05</td><td>0.05< x ≤0.40</td><td>0.40< x ≤2.20</td><td>>2.20</td></tr>
</table>

4.2 Current lake water quality state

The current state of water quality in the region's lakes was assessed from annual median values calculated from the last five years monitoring data (2009-14), the six-year median of annual maxima (see Appendix A for details). Results of this analysis were compared with NPS-FM NOF attributes bands and a water quality band was assigned for each water quality attribute for each of the individual monitored lakes (Table 3).

Table 3. Current state of Northland lake water quality state in terms of NOF attributes

Lake	FENZ ID	Management Classification	Total Nitrogen	Total Phosphorus	Chl-a	Chl-a	NH_4-N	NH_4-N
			Median	Median	Median	Max	Median	Max
Carrot	23690	Shallow perched	C	B	C	B	A	A
Heather	23682	Shallow perched	B	B	B	B	A	A
Humuhumu	50401	Deep window	B	B	C	A	A	A
Kahuparere	50371	Shallow window	B	B	C	B	A	A
Kai-Iwi	21918	Deep window	C	A	B	A	A	A
Kanono	50373	Deep window	B	B	C	B	A	A
Karaka	50320	Shallow perched	B	C	D	D	A	B
Mokeno	50314	Shallow perched	D	C	C	C	A	B
Morehurehu	24628	Deep perched	C	B	B	A	A	A
Ngakapuha (North Basin)	18717	Shallow perched	B	B	C	A	A	B
Ngakapuha (South Basin)	18718	Shallow perched	C	B	C	A	A	A
Ngatu	23691	Shallow perched	D	A	B	A	B	B
Omapere - Outlet	23721	Other Shallow	B	C	B	A	A	A
Rotokawau (Aupouri)	18719	Shallow perched	C	B	B	A	A	A
Rotokawau (Pouto)	50413	Deep window	B	A	B	A	A	A
Rotoroa	23681	Shallow perched	D	B	B	A	A	A
Rototuna	50345	Shallow perched	C	C	D	C	A	B
Swan	50403	Shallow window	D	C	D	C	A	A
Taharoa	21917	Deep window	A	A	A	A	A	A
Te Kahika	24633	Deep perched	B	A	A	A	A	A
Waihopo	24511	Shallow perched	C	B	B	A	A	A
Waikare	21926	Deep window	B	A	A	A	A	A
Wainui	17761	Deep perched	C	B	B	B	A	A
Waipara	19575	Deep perched	B	B	B	A	A	A
Waiparera	13467	Shallow perched	C	C	D	B	A	A
Waiporohita	24415	Shallow perched	D	C	D	C	A	A

The key findings of the water quality state assessment include:

- 5 lakes failed the NOF bottom line for TN (Swan, Rotoroa, Ngatu, Waiporohita and Mokeno);
- 5 lakes failed the NOF bottom line for median Chl-a (Karaka, Rototuna, Waiparera, Swan and Waiporohita);

- 1 lake failed the NOF bottom line for Chl-a maximum (Karaka);
- No lakes failed the NOF bottom lines for TP, median NH_4 or maximum NH_4;

Table 4 compares current lake water state to the NOF water quality bands assigned according to the Management Classification (reported as percentage of monitored lakes falling within each water quality band). Results of this assessment indicate:

- Chlorophyll-a (median) - 25% (1/4) of deep perched and 33% (2/6) of deep window lakes fall within the 'A' band. 31% (4/13) of shallow perched and 50% (1/2) of shallow window lakes exceed the NOF bottom line;
- Chlorophyll-a (maximum) - 46% (6/13) of shallow perched, 75% (3/4) deep perched and 83% (5/6) of deep window lakes fall within the 'A' band. 8% (1/13) of shallow perched lakes exceed the NOF bottom line;
- Total Nitrogen - 17% (1/6) of deep window lakes fall within the 'A' band. 31% (4/13) of shallow perched and 50% of shallow window lakes exceed the NOF bottom line;
- Total Phosphorus - 8% (1/13) of shallow perched, 25% (1/4) of deep perched and 67% (4/6) of deep window lakes fall within the 'A' band. No lakes exceed the NOF bottom line
- NH_4 (median) - 92% (12/13) of shallow perched and 100% of deep perched, shallow window and deep window lakes fall within the 'A' band. No lakes exceed the NOF bottom line; and
- NH_4 (maximum) - 62% (8/13) of shallow perched, 100% of deep perched and 100% of deep window lakes fall within the 'A' band. No lakes exceed the NOF bottom line.

The available data indicate that there is significant variability in water quality state within each Management Class. This variability confirms earlier inferences from linear modelling of the wide range of factors in addition to maximum depth, significantly linked to differences in lake water quality as described in Section 3.2 (and outlined in more detail in Appendix A).

Overall, the analysis indicates water quality in all deep perched and deep window lakes falls within the NOF 'C' state or better, while a sub-set of shallow perched and shallow window lakes are below the NOF bottom line for median Chl-a, maximum Chl-a and TN.

Table 4. Current state of Northland lake water quality based on the proportion of sites falling into the NPS-FM water quality bands for each class of the Management Classification. Percentage of sites exceeding the NPS-FM bottom line (i.e. D class) highlighted in red

Objective	State Band	Water Quality Management Class				
		Shallow perched	**Deep perched**	**Shallow window**	**Deep window**	**Volcanic**
		n = 13	n = 4	n = 2	n = 6	n=1
Chlorophyll-a (median)	A	0%	25%	0%	33%	0%
	B	38%	75%	0%	33%	100%
	C	31%	0%	50%	33%	0%
	D	**31%**	0%	**50%**	0%	0%
Chlorophyll-a (maximum)	A	46%	75%	0%	83%	100%
	B	23%	25%	50%	17%	0%
	C	23%	0%	50%	0%	0%
	D	0%	0%	0%	0%	0%
Total Nitrogen (median)	A	0%	0%	0%	17%	0%
	B	23%	50%	50%	67%	100%
	C	46%	50%	0%	17%	0%
	D	**31%**	0%	**50%**	0%	0%
Total Phosphorus (median)	A	8%	25%	0%	67%	0%
	B	54%	75%	50%	33%	0%
	C	38%	0%	50%	0%	100%
	D	0%	0%	0%	0%	0%
NH_4-N (median)	A	92%	100%	100%	100%	100%
	B	8%	0%	0%	0%	0%
	C	0%	0%	0%	0%	0%
	D	0%	0%	0%	0%	0%
NH_4-N (maximum)	A	62%	100%	0%	100%	0%
	B	38%	0%	100%	0%	100%
	C	0%	0%	0%	0%	0%
	D	0%	0%	0%	0%	0%

4.3 Definition of Lake Catchments

A management zone is an area where management actions (i.e., policies and rules) are applied to achieve lake water quality and quantity objectives for a particular lake class.

Management zones consist of all catchment areas of individual lakes or groups of lakes that are assigned to the same class under the management classification. For the purposes of this report the delineation of catchments for individual lakes depends on their management classification:

- For perched lakes, the catchment encompasses the spatial extent of the surface water catchment draining to the lakes;
- For window lakes, the catchment encompasses the spatial extent of the surface water catchment draining to the lake plus the recharge area for hydraulically connected groundwater, up-gradient of the lake.

Figure 7 shows a schematic illustration of the spatial extent of management zones for perched and window lakes. As illustrated, catchments for perched lakes are defined as the surface water catchment draining to the lake. In contrast, catchment areas for the window lake class comprise the surface water catchment of the lake plus the portion of the surrounding aquifer that is hydraulically connected to the lake and, therefore, contributes recharge to the lake (i.e. the 'capture zone' of the lake). Areas of aquifer system which do not contribute to the lake nutrient or water balance are excluded.

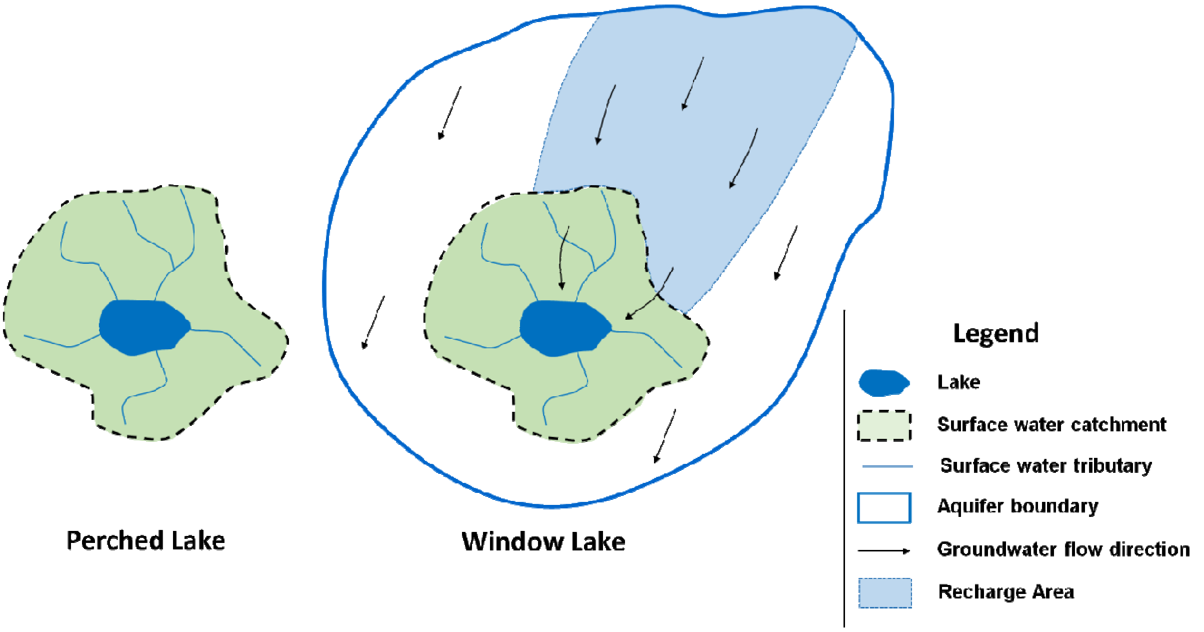

Figure 7. Schematic illustration surface water catchments and recharge areas for perched and window lakes.

This study has defined provisional surface water catchments for individual lakes based on the catchment boundaries delineated in the FENZ database. Figure 8 illustrates catchments for a selection of lakes across the Northland Region defined by the FENZ lake catchment boundaries. Provision should be made to allow these catchments to be refined as improved topographic information to better delineate catchment boundaries (e.g., Lidar surveys) become available.

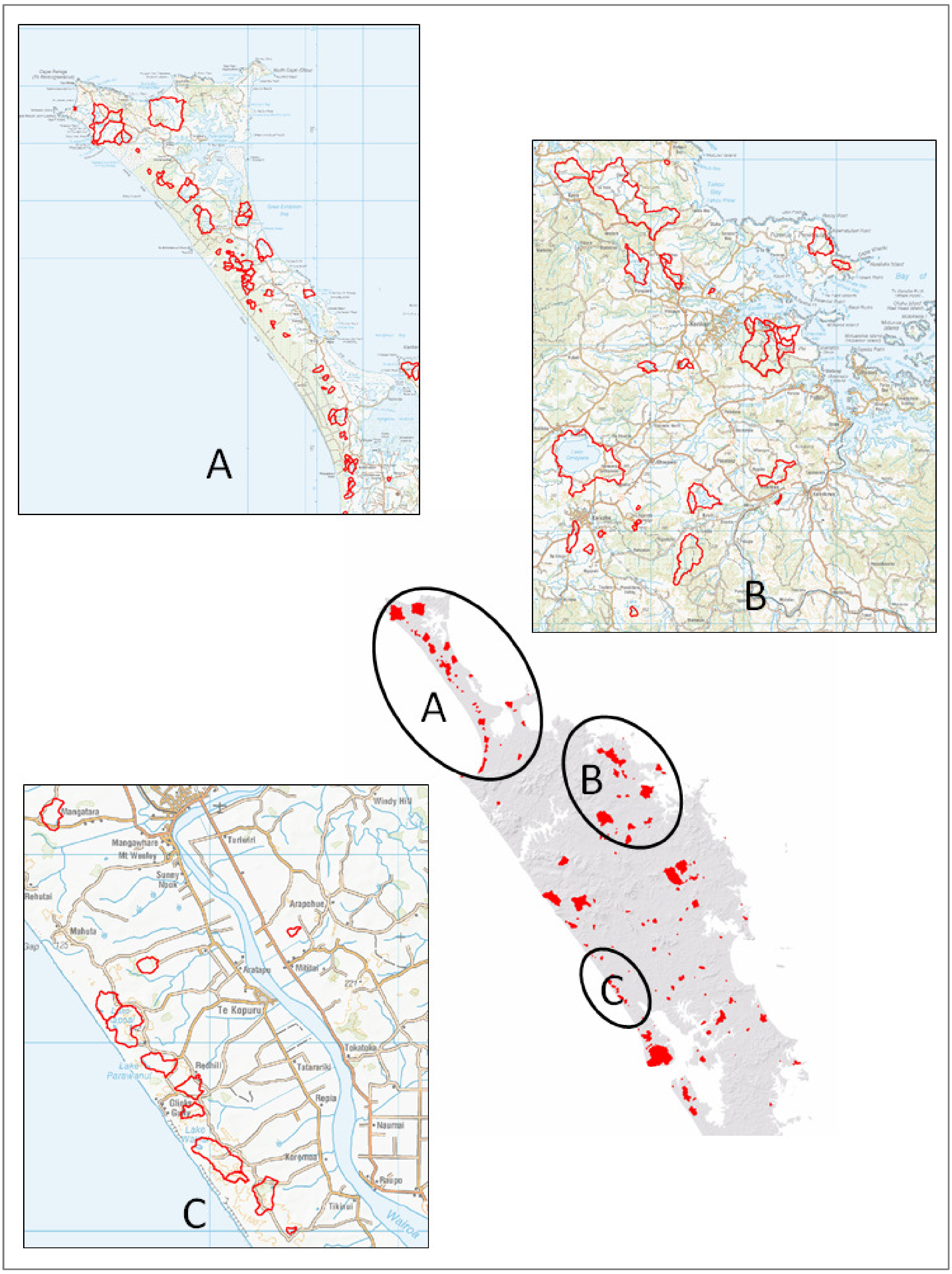

Figure 8. Illustrative examples of surface water catchments assigned to dune lakes in the Northland Region based on the FENZ lake catchment boundaries

Lakes currently classified as window lakes[10] occur in two geographic areas:

- Kai-Iwi Lakes area

[10] Derived from the listing in Part II of the Northland Lakes Strategy, updated based on results of the Jacobs (2014) assessment

- Pouto Peninsula

These areas (particularly the Pouto Peninsula) contain a number of lakes (some of which are included in the Outstanding Lake classification) that are hydraulically connected to the unconfined aquifer hosted in the surrounding Holocene sand deposits. Potential groundwater contribution to a sub-set of lakes in the Pouto Peninsula area was investigated by water balance modelling undertaken by Jacobs (2014). For other lakes, evidence for hydraulic connection to the groundwater system is anecdotal. For example, Champion (2014) noted observed temporal variations in algal blooms in Lake Karaka and Lake Mokeno as reflecting nutrient inputs from the surrounding regional aquifer system.

Jacobs (2014) identified that no specific investigations have been undertaken to characterise the hydrogeology of the Pouto Peninsula. However, from a review of available geological, geomorphological and lake water level data the following inferences were made regarding the nature of groundwater movement and hydraulic connection to lakes in the area:

- A groundwater divide occurs along the approximate centre line of the peninsula. East of the groundwater divide, groundwater flows from higher elevations toward the Kaipara Harbour while west of the divide groundwater flow occurs towards the Tasman Sea. Groundwater flow direction is inferred to predominantly occur perpendicular to the coast on either side of the peninsula;
- The underlying geology reflects the accumulation of aeolian dune deposits with units of permeable sand intercalated with discontinuous layers of podsolised soils and lignite. Perched water tables may occur in areas where cemented layers are laterally continuous;
- Lakes located at higher elevations (e.g., Lake Rototuna and Phoebe) are more likely to be perched above the regional groundwater table than the more numerous lakes at lower elevations around the outer margins of the peninsula.

In the Kai-Iwi Lakes area, Jacobs (2014) interpreted the general nature of groundwater flow from geomorphology and the limited hydrogeological data available. Groundwater flow was inferred to occur regionally from the weathered basalts in the east, westward through the Kai-Iwi Lakes area ultimately discharging along the Tasman Sea coastline. Locally groundwater flow was influenced by topography with discharge occurring to lakes and streams. In particular, Ngakiriparauri Stream runs parallel to the lakes along the contact between the sedimentary Karioitahi Group and basaltic Waipoua Group and is reported to be incised to a level lower than the elevation of Lake Taharoa thus potentially forming a hydraulic divide around the possible groundwater recharge area for the lakes.

Multiple window lakes occur in both the Kai-Iwi Lakes area and the Pouto Peninsula. In both areas the nature and extent of the hydraulic connection between the regional groundwater system and individual lakes is poorly characterised. In addition, knowledge of the hydraulic characteristics of the regional aquifer systems is insufficient to reliable delineate groundwater recharge areas for individual lakes.

It is therefore recommended an initial approach to defining recharge areas for window lakes in both areas is conservative and is adopted as follows:

- Delineation of a Pouto Peninsula window lake recharge area comprising full width of peninsula as far north as the Okaro Creek catchment to the east of the (approximate) groundwater divide shown in Jacobs (2014), and to a line perpendicular to the coast approximately 1 km north of waterbodies shown in the vicinity of Lake Wairere on the Topo50 Dargaville map sheet, to the west of the groundwater divide; and

- A preliminary Kai-Iwi Lakes recharge area extending between the coastline and the Waihaupai Stream to the north, the Ngakiriparauri Stream to the east and Kai-Iwi Stream to the south. These features are inferred to form hydraulic boundaries encompassing the groundwater system hydraulically connected to the Kai-Iwi lakes. It is noted that three of the four lakes in this area (Taharoa, Waikare and Kai-Iwi) are included in the Outstanding Lakes classification

The spatial extent of recharge areas suggested for window lakes in the Kai-Iwi Lakes and Pouto peninsula areas are shown on Figure 9 and Figure 10 below respectively.

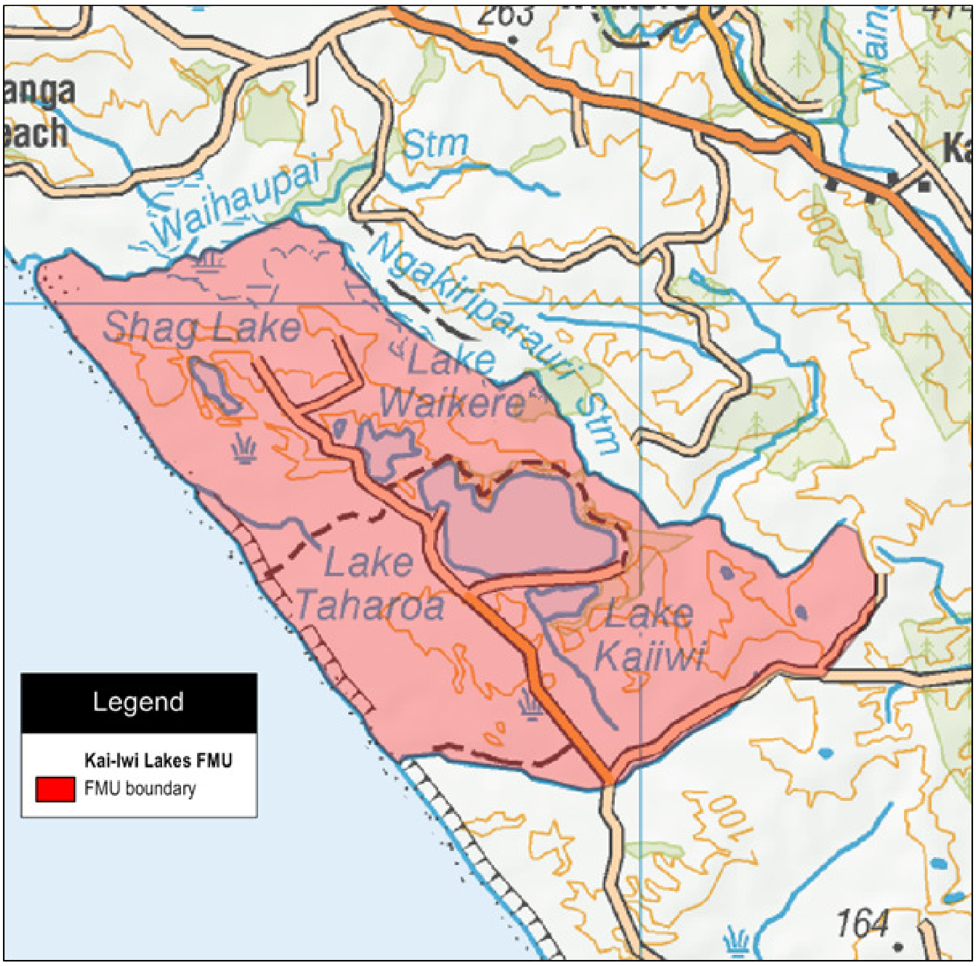

Figure 9. Proposed recharge area for window lakes in the Kai-Iwi lakes area

Figure 10. Proposed FMU for window lakes in the Pouto area

At this time no window lakes have been identified on the Aupouri Peninsula, with all lakes currently classified as perched. Further work to characterise groundwater connectivity to lakes in this area is recommended, as the potential influence of nutrient inputs from wider groundwater recharge areas is not well understood.

4.4 Discussion of how FMU's might be applied for lake water quality

The proposed management classification for lakes in Northland outlined in Section 2.3 recognises the significant influence of lake depth on water quality. In addition to lake depth, the proposed Management Classification also recognises the fundamental difference in nutrient input sources (and aerial loading) of window lakes compared to perched lakes. The rationale being that while all lakes receive nutrient inputs from their immediate surface water catchments, window lakes may also receive a significant flux of nutrients via groundwater from a wider recharge area (the capture zone). This groundwater inflow has the potential to contribute nutrients (in dissolved form) to the overall nutrient balance of the lake, as well as supply minerals that affect internal nutrient cycling rates (e.g., iron, manganese, calcium and aluminium).

4.4.1 Nutrient inputs and influence on lake water quality

In considering management objectives for the different management classes it is important to consider the sensitivity of lake trophic state to specific nutrient inputs as well as the potential mode of nutrient transport.

Gibbs et al (2014) undertook an assessment of potential nutrient limitation the group of 26 Northland lakes also analysed for water quality patterns and drivers in this report. Results of this assessment suggest a majority of lakes in the Northland Region were (at the time of sampling) phosphorus limited, in both Spring and Autumn. While it is recognised that nutrient limitation may vary temporally, the monitoring data that was analysed by the present study suggests that:

- Nutrient limitation status of shallow lakes is variable. While a majority (~60%) appear to be phosphorus limited, a significant sub-set also appear to be either nitrogen limited or have no limiting nutrient (approximately 20% in each category);
- Deeper lakes exhibit a stronger tendency to be phosphorus limited, although a significant sub-set of lakes sampled (~20%) had no limiting nutrient;
- In general, perched lakes have more varied nutrient limitation status in contrast to window lakes, which tend to be phosphorous limited.

Nutrient inputs to lakes can occur via three primary mechanisms; direct deposition, surface runoff and groundwater inflow to window lakes. While direct deposition and surface runoff have the potential to contribute nitrogen and phosphorus in both dissolved and particulate forms to the overall lake nutrient balance, nutrient inputs via groundwater inflows are primarily limited to dissolved forms of these nutrients (nitrate and dissolved reactive phosphorus (DRP)). The potential for nutrient input from groundwater inflows varies significantly depending on both land use overlying the groundwater recharge area, as well as geochemical conditions within the aquifer itself.

Geological information suggests that shallow unconfined aquifers that are hydraulically connected to window lakes comprise interlayered coastal sand and alluvial deposits that contain abundant organic carbon reflecting wetland deposits accumulated in interdune areas (Jacobs 2014). An abundance of electron donor materials (organic carbon) typically results in reducing conditions in soils and underlying aquifers which contain groundwater exhibiting mixed to anoxic redox states (e.g., McMahon and Chapelle, 2008). Anecdotal information (Susie Osbaldiston, NRC, *pers comm*) suggests that elevated iron concentrations are widespread in sand aquifers in many parts of Northland. Under such redox conditions, significant denitrification commonly occurs. This is likely to reduce the potential for groundwater inflows to window lakes to provide a major source of soluble N (nitrate) to the nutrient budget of window lakes. However, under such conditions, the solubility of phosphorus may increase, particularly where groundwater is strongly reducing and acidic, raising the possibility of appreciable phosphate contribution to window lakes (in the form of DRP) from groundwater inflows.

4.4.2 Application of management actions to recharge areas of window lakes

Ultimately, objectives and policies developed for the management of water quality in window lakes may mean that management actions applicable to their surface catchments differ from those applying to their groundwater recharge areas. For example, management actions in surface catchments may include provisions related to matters such as stock access and riparian management, while management actions applying to groundwater recharge areas may be restricted to management of the contribution these areas make to cumulative nutrient inputs.

Inclusion of recharge areas in the management zones of the window lake classes may require the application of a sub-set of management actions that only apply to their recharge areas (possibly restricted to management of diffuse nutrient sources). It is noted that it may be possible to exclude groundwater recharge areas from a sub-set of window lake FMUs on the basis of geochemistry (e.g. reducing conditions in groundwater which remove nitrate). However, exclusion of groundwater recharge areas which make a more than minor contribution to overall lake nutrient budgets is unlikely to provide an effective framework for managing lake water quality.

4.4.3 Lake water quality state objectives

The Northland Regional Policy Statement (RPS) directs the NRC to set objectives and limits that are designed to improve the overall quality of freshwater in lakes, with particular emphasis on improving the overall Trophic Level Index (TLI) status of these waterbodies. At a minimum, the NPS-FM requires that national bottom lines are met in all lakes.

As noted in Section 3, national bottom lines for TN and Chl-a (median and maximum) are not currently met in some shallow perched and shallow window lakes. Assuming the lakes for which water quality data is available are representative of the over 400 lakes identified in the Northland region by Champion and de Winton (2012), a larger number of lakes across the region may currently not meet the NPS-FM NOF bottom line for one or more NOF water quality attributes (TN, median Chl-a, maximum Chl-a).

The Northland Regional Policy Statement (RPS) directs the NRC to set objectives and limits that are designed to improve the overall quality of fresh and coastal water with a particular focus on matters including an overall reduction in the Trophic Level Index status of the region's lakes. The analysis of water quality indicates that there is appreciable variability in water quality within individual management classes. The study was unable to identify consistent predictors of water quality variation other than the depth variable and was therefore not able to recommend a more detailed management classification that could further resolve regional differences in lake water quality.

Water quality objectives for each Management Class would likely require the improvement, of the current water quality of lakes in the class. However, due to the heterogeneity of water quality in the classes, objectives that are appropriate to the class as a whole may meet the requirement to improve water quality is some or most lakes, but may allow a reduction of water quality in those lakes that currently have the best water quality in the class. This may be inconsistent with requirements of the RPS depending on whether it is interpreted as meaning that the water quality state is improved (or at least maintained) in **all** lakes or whether it is interpreted as applying generally (or "overall") to each Management Class. If the former interpretation is used, the inconsistency may be addressed by implementing policies that require maintenance of existing water quality state every lake. This would mean that where water quality currently exceeds the objectives established for a lake's class, the relevant objective would be to at least maintain the current quality. The former interpretation would reduce the certainty of plan provisions because the current state of a lake would need to be established before its objectives and policies can be defined. The former interpretation may also have implications for monitoring because progress toward objectives could not be assessed on the basis of a representative sample of lakes in each management class.

5 Discussion

5.1 Proposed Management Classification

Lake water quality is driven by both internal recycling of nutrients and external inputs of nutrients and other contaminants from their catchments. A Management Classification has been developed for Northland lakes that broadly discriminates differences in dune lake water quality and functioning based on these internal and external functional differences by using maximum depth (deep from shallow).

Deep and shallow lakes differ water quality state naturally due to differences in lake mixing and thermal stratification. If sufficiently deep, a lake can stratify into upper, more oxygenated and deeper, less oxygenated layers. Lower oxygenation in bottom-waters alters sediment redox conditions thereby also altering nutrient release from bed sediments. External nutrient loads are then superimposed on this internal-driven nutrient supply, to result in the observed in-lake nutrient concentrations.

Geomorphic categories discriminate differences in the hydraulic connection between the lake and its surface and subsurface catchment areas. Connection to regional aquifers potentially alters external nutrient loading rates by effectively increasing the spatial extent of the contributing catchment.

Analysis of quarterly water quality monitoring data indicated that maximum lake depth was a highly significant factor explaining observed differences in ten of twelve water quality variables assessed. Maximum depth is the single factor that most efficiently discriminates variation in the region's lake water quality variables, with the exception of median and maximum ammoniacal-nitrogen whose concentration varied little between lakes. The analysis also indicated that a maximum depth threshold of 10 meters for the deep and shallow lake classes most effectively discriminated observed water quality differences.

With the exception of clarity, the geomorphic categories (perched and window) did not significantly discriminate variation in other water quality indicators. Note here that one-way ANOVA based on geomorphic type discriminated differences in TLI and TN in addition to TLS and SD, but two-way ANOVA has demonstrated this affect was attributable to depth (i.e., 6 of 8 window lakes are deep). Despite this, we recommend retaining the geomorphology component of proposed management classification to ensure management of all external inputs of dissolved nutrients to lakes that are connected to a regional aquifer system.

Other physical characteristics of lake catchments (e.g., the proportion occupied by pasture or exotic forestry land cover, slope, hardness, phosphorus subsoil content, mean windspeed) and lakes themselves and lakes themselves (e.g., area, elevation, maximum depth) also explained variation in water quality between lakes. However, depth was the only factor to significantly at explain differences in all of the ten NOF and TLI attributes tested.

Further work to identify the potential role and influence of groundwater inputs to the nutrient budget of window lakes may indicate that groundwater has an insignificant role in determining water quality, in both or one depth class. This would enable simplification of the proposed Management Classification to two classes (shallow and deep).

Limited data are available to characterise water quality in several lake types lakes defined by Champion and de Winton (2012), including volcanic, alluvial and artificial lakes. We have assumed that the major drivers of water quality in these lake types will be similar to those identified for dune lakes, presuming here that internal processes of sediment disturbance in shallow lakes or nutrient regeneration in deeper lakes also operate in the other types. These waterbodies can be managed under the proposed Management Classification but targeted monitoring and investigations are required to validate this extension of the Management Classification beyond dune lakes alone.

5.2 Delineation of management zones

Management zones comprise catchment areas for individual lakes or groups of lakes which are assigned to the same class under the Management Classification. For the purposes of this report the catchment delineation of catchments for individual lakes depends on their management classification:

- For shallow and deep perched lakes, the management zones consist of the spatial extent of all surface water catchments draining to the lakes in each class;
- For shallow and deep window lakes, the management zones consist of the spatial extent of the surface water catchments draining to all lakes in the class plus the recharge area for hydraulically connected groundwater, up-gradient of the lake.

This approach means that window lakes include a larger catchment area than equivalent perched systems. It is acknowledged nutrient inputs to the wider groundwater recharge area are subject to complex attenuation processes in-transit to the lake.

Following the recommendations outlined in Section 4.3, Lakes identified as 'unclassified' should be assigned to a management zone once information is available to quantify their depth and geomorphic characteristics. A single classification is identified for window lakes given the proposed recharge areas (outlined in Section 4.3 above) include closely spaced shallow and deep lakes.

Also, as previously noted, the classification of perched and window lakes could potentially be simplified (for some or all lakes) to a simple shallow/deep classification if the Council can be satisfied that the wider groundwater recharge area only makes a minor contribution to the water and nutrient balance of lakes assigned to the window lake geomorphic classification

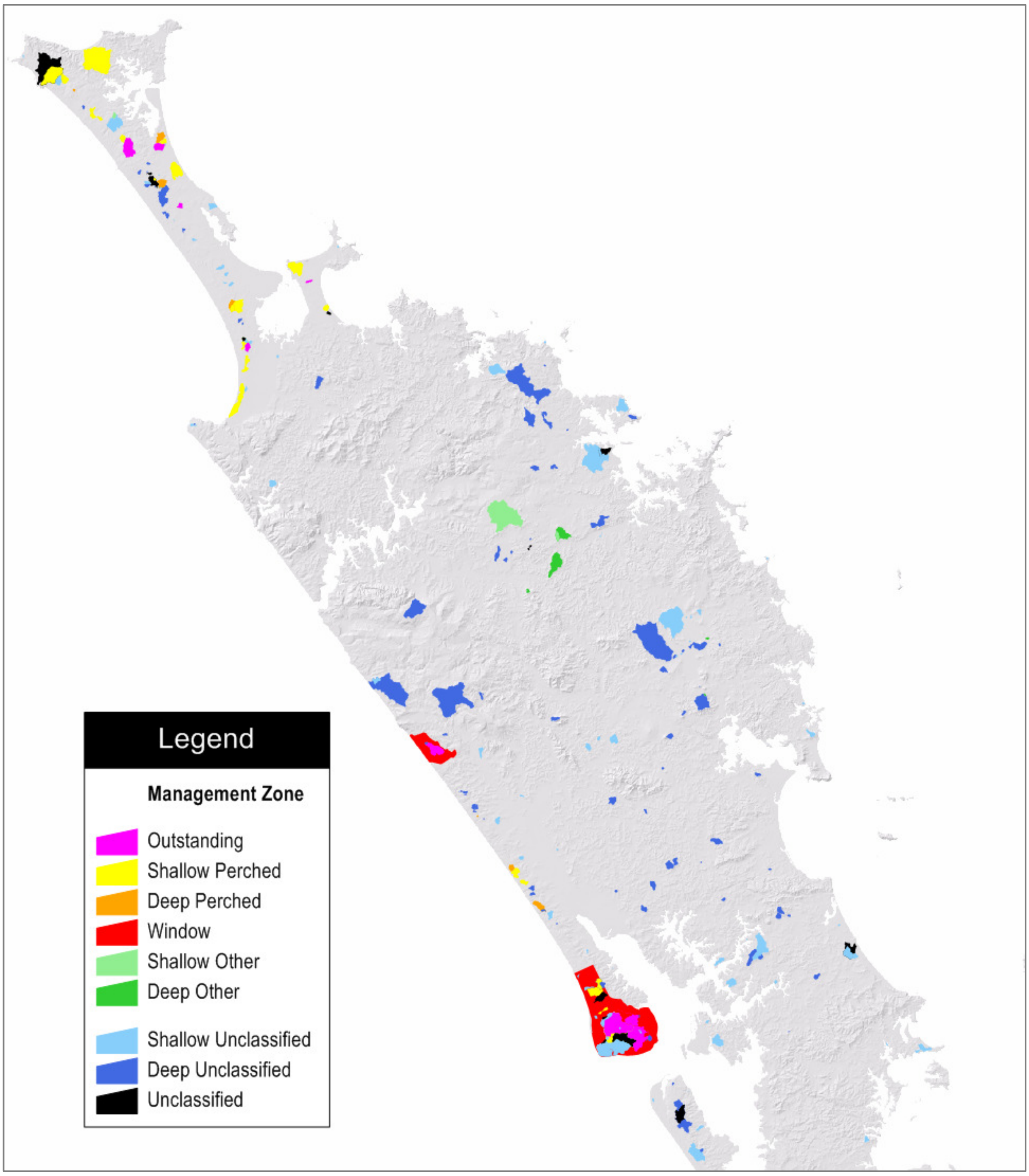

Figure 11 illustrates provisional management zones for dune lakes in Northland. The management zones illustrated comprise the following areas:

- Outstanding - surface water catchments of lakes included in the NRC list of outstanding freshwater bodies;
- Unclassified - surface water catchments of lakes for which no depth or geomorphic classification is available;
- Shallow Unclassified - surface water catchments of shallow lakes (<10 m max depth) for which no geomorphic classification has been assigned;
- Deep Unclassified - surface water catchments of deep lakes (>10 m max depth) for which no geomorphic classification has been assigned;

- Shallow Perched - surface water catchments of lakes (<10 m max depth) assigned to the perched geomorphic classification;
- Deep Perched - surface water catchments of lakes (>10 m max depth) assigned to the perched geomorphic classification;
- Window - provisional groundwater recharge areas for all window lakes (regardless of depth) in the provisional Pouto and Kai-Iwi Lakes recharge areas;
- Other Shallow - surface water catchments of shallow lakes (<10 m max depth) other than dune type;
- Other Deep - surface water catchments of deep lakes (<10 m max depth) other than dune type.

Lakes identified as ‘unclassified’ should be assigned to a management zone once information is available to quantify their depth and geomorphic characteristics. A single classification is identified for window lakes given the proposed recharge areas (outlined in Section 4.3 above) include closely spaced shallow and deep lakes.

Also, as previously noted, the classification of perched and window lakes could potentially be simplified (for some or all lakes) to a simple shallow/deep classification if the Council can be satisfied that the wider groundwater recharge area only makes a minor contribution to the water and nutrient balance of lakes assigned to the window lake geomorphic classification

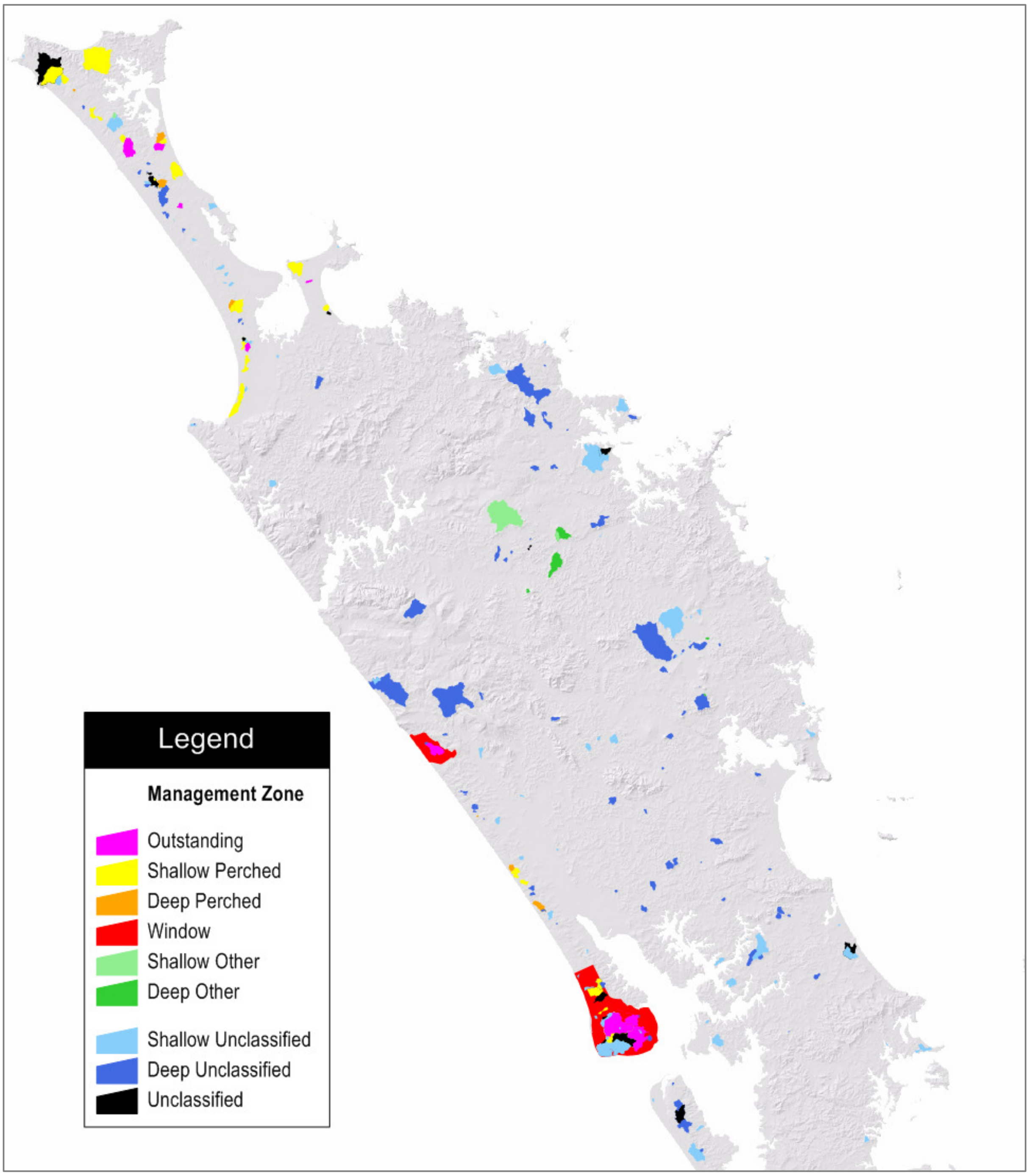

Figure 11. Provisional management zones for dune (and other) lakes in the Northland Region

We recommend that the plan has policies or other provisions that allows the provisional assignment of any particular dune lake to a FMU to be modified if better information on its hydraulic connection to groundwater becomes available. In addition, we recommend that the plan has policies or other provisions that allow management zones based on surface water catchments to be refined using improved topographic data to better delineate the spatial extent of surface water catchments.

Given the geographic distribution and nature of hydraulic connection, it is recommended that a single recharge area be defined for the multiple window lakes in the Kai-Iwi Lakes and Pouto Peninsula sub-regions. It is noted that this arrangement does not preclude the 'nesting' of catchments for individual perched lakes within more spatially extensive recharge areas defined for window lakes.

5.3 Identifying management objectives

Based on current water quality state, a sub-set of lakes in the shallow-perched and shallow-window classifications are likely to require policies that are aimed at improving water quality to at least meet the NOF bottom line. Of the 26 lakes for which monitoring data was available, 8 failed to meet one or more NOF bottom lines. All were shallow but included both perched and window classes across the Aupouri, Pouto and Central sub-regions.

Defining the appropriate management objectives for each of the four management classes is a Council decision. This study has assisted this decision making process by characterising the current water quality state of the proposed dune lake Management Classes using the available data. These analyses indicate that there is appreciable variability in water quality within individual management classes.

Council will need to consider if the approach of setting a common objective for a group of lakes with somewhat heterogeneous current state is an acceptable response to the NPS-FM requirement to maintain and improve water quality overall[11]. Because of the within class heterogeneity, a single water quality objective for each class theoretically results in improvement in some lakes in the class whose water quality below that implied by the objective, while potentially allowing some degradation of water quality in lakes whose current water quality state is better than implied by the objectives. Whether degradation could occur is dependent on the policies that are applied to the class. If policies are defined that could allow a degradation in water quality in a sub-set of lakes in a particular class, the justification for this approach would need to be that some "unders and overs" is within a FMU 9i.e. that water quality in the FMU is maintained or improved "overall").

Council will also need to consider the implications of the requirement established in the Proposed RPS to at least maintain the overall Trophic Level Index status of all lakes, regardless of their current water quality state. A stringent interpretation of this may be that management actions must not allow degradation of water quality in **any** lake. A difficulty with approach is that it may introduce uncertainty into the plan because the current state of many lakes is not currently known.

An alternative to the overall approach of defining class-wide objectives for each of the proposed FMUs would be to further subdivide the region's lakes to reduce within-class heterogeneity. Council may wish to consider establishing additional management classes or specific policies for lakes that have water quality that is significantly higher than their current management class objective. However, defining which lakes belong to these additional classes would require additional monitoring data to establish the current state of a larger number of the region's lakes than is currently available. With data describing the current state of more of the region's lakes, it may be possible to establish better relationships between water quality state and physical characteristics of lakes, in particular their catchment characteristics. This would enable identification of additional management

[11] NPS-FM Objective A2.

classes and provide justification for adoption of alternative water quality objectives and/or policies for individual lakes.

5.4 Suggested application of the proposed management classification

The following steps are recommended for applying the proposed framework for management of lake water quality in the Northland Region

1. Adopt the proposed four class Management Classification (Shallow-Perched, Deep-Perched, Shallow-Window, Deep-Window) as a conservative approach to managing regional dune lake water quality which reflects the potential influence of both in-lake processes, and external inputs of nutrients from surface and groundwater catchments on water quality state;

2. Define provisional catchments for individual lakes in the 'perched' classifications on the basis of surface water catchments defined in the FENZ database. Allow for redefinition of the provisional management zones if individual catchment boundaries are further refined by collection and analysis of additional high-resolution topographical data (e.g., Lidar imagery);

3. Define provisional recharge areas for window lakes based on the inferred maximum extent of hydraulically connected unconfined aquifers in the Kai-Iwi and Pouto sub-regions. Allow for redefinition of provisional recharge areas for individual window lakes by studies that characterise the nature and magnitude of groundwater/lake interaction and the spatial extent of contributing groundwater recharge areas. For any additional areas where window lakes are identified in the future (e.g., Aupouri Peninsula), management zones should be defined on a similar basis using available hydrogeological data to define the potential maximum spatial extent of hydraulically connected aquifers;

4. Undertake further investigations to characterise the potential groundwater contribution to lake nutrient budgets in individual window lakes. This will require investigation of the potential influence of groundwater hydrology and geochemistry on potential nutrient fluxes (e.g., aerial loading, residence time and nutrient mobilisation/attenuation). If investigations indicate lake nutrient budgets are relatively insensitive to nutrient input associated with groundwater inflows (particularly in terms of denitrification and the solubility of P), the classification system may be able to be refined to a simple shallow and deep lake classification, at least in individual sub-regions;

5. Define management zones as comprising the spatial extent of surface water catchments and groundwater recharge areas identified for lakes of each class

For lakes that are currently unclassified (including both dune lakes and other lake classes), the following steps are suggested to assist assignment of the appropriate management classification:

1. Adopt an initial classification (shallow/deep) based on the maximum depth attribute recorded on the FENZ database (or other relevant data sources such as bathymetric surveys). In the absence of information to identify the potential for groundwater contribution to the lake water balance, lakes should be assigned to the geomorphic

class (perched/window) that has more stringent management controls[12] for the respective depth classes;

2. Conduct a bathymetric survey to confirm assignment to the correct depth classification (i.e., +/-10 metres);
3. Undertake a physical survey of the lake environment to characterise the overall geomorphological setting and confirm approximate surface water catchment boundaries;
4. Undertake assessment of potential hydraulic connection to groundwater based on relative lake stage and groundwater levels. Lake stage may be assessed by physical surveying or Lidar surveys and groundwater level information determined from available static water level information in the local area. If this assessment indicates the potential for hydraulic connection, or where insufficient data is available to infer relative groundwater levels, further investigations may be required to characterise the potential groundwater contribution to the lake water balance.

[12] It is noted this may not be the class for which the highest water quality objectives are set.

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Appendix A Lake Water quality analysis

Since 2009, NRC has regularly monitored 26 shallow and deep lakes in the Northland region for water quality. This regional lake dataset is analysed here with the objectives of:

- Identifying key differences in water quality between lakes;
- Examining factors responsible for water quality differences;
- Developing a regional lake classification.

From this, a lake classification is recommended for implementation of the NPS-FM on a robust evidence basis by the NRC.

A1 Water Quality Indicators

Water quality is described across all lake classes, using a mix of physicochemical and ecological indicators for ‘ecosystem health’, a general term referring to the quality of water to support a healthy and resilient natural ecosystem appropriate to a lake class (Table A1). In this report, we use “lake water quality” to describe some or all of these 17 indicators. Each is reported from data sampled consistently at quarterly temporal resolution and using equivalent field and laboratory techniques, over a six year period from 2009-2014. The sampling approach is aligned with the National Objective Framework (NOF) (MfE, 2014).

Table A1 explicitly excludes information on submerged macrophytes. Although this indicator is offers a complementary picture of water quality for ecosystem health, plant macrophyte communities are subject to more complex processes than lake physicochemical or algal indicators; plant distribution is often influenced not simply by the physicochemical or algal lake environment at which limit-setting is directed but by introduced pest fish and plants, recreational pressures and differences in trophic structure (Drake et al., 2009). The 17 lake water quality indicators explored here do though characterise the health of submerged macrophyte communities by describing trophic state. For instance, water column nutrient availability is altered by uptake to submerged macrophytes as well as through changes in sediment release, but drives changes to algal biomass which in turn can alter macrophyte biomass [Scheffer and Jeppesen, 1998; Kelly and McDowall, 2004]).

Table A1: Lake water quality indicators included in this study.

Indicator type	Indicator	Abbreviation	Units
Physical	Total Suspended Solids	TSS	mg/m^3
	Secchi depthTemperature	SDTemp	m°C
Chemical	pH Conductivity Dissolved oxygen Total Phosphorus Total Nitrogen	pH Cond DO TP TN	N/A mS/cm^{-1} mg/L mg/m^3 mg/m^3
	Ammoniacal Nitrogen (median	NH_4-N	mg/m^3

	and maximum)		
Phytoplankton	Chlorophyll-a (median and max)	Chl-a	mg/L
Index	Trophic Level Index (and four TLx)	TLI	N/A

Secchi depth (referred to as SD) reports on water clarity and is affected by both suspended organic (algae or phytoplankton) and inorganic material (eroded sediment). SD measures the maximum depth at which a black and white Secchi disk is visible to an observer at the lake surface, a proxy for the euphotic depth or the depth to which submerged macrophytes can colonise a lake floor (Wetzel, 2001).

Temperature (Temp) regulates phytoplankton production and alters dissolved oxygen availability, potentially generating stress in aquatic organisms. Temperature is also crucial to driving a process of thermal stratification in lakes, which coupled to lake morphological characteristics (e.g., maximum depth, volume, residence time), can result in marked changes to nutrient availability. Variations in temperature report on differences to the internal functional processes affecting lake water quality (Wetzel, 2001).

pH records a critical aspect of water column physicochemical environment, which affects the solubility of toxins, availability of nutrients and responds to changes in biological production so much so that differences in lake health are often accompanied and/or driven by changes in water column pH (Wetzel, 2001).

Conductivity (Cond) varies with catchment geology and hydrogeology, climate, mixing and resource use, recording the dissolved solute concentration (Larned et al., 2015). Inspection of conductivity can highlight differences in hydrogeology that may also drive differences in nutrient availability and/or physicochemical environment for submerged macrophytes and algal biomass.

Dissolved oxygen (DO) records availability of oxygen in the upper (epilimnion) or entire water column (if mixed). Changes to DO alter habitat availability to both submerged macrophytes and aquatic faunal communities (Wetzel, 2001). Whilst bottom-water DO is more indicative of the effects mediated by internal nutrient cycling on total nutrient availability, the varying frequency of latter observations and incomplete coverage, precluded its inclusion here. Nonetheless, by examining the effects of maximum depth on lake trophic state, internal nutrient cycling processes linked to thermal stratification and capable of driving changes to benthic DO are examined by this report (see Section A1.3.3).

Chlorophyll-a concentration (Chl-a) is a measure of lake phytoplankton or algal biomass, whose abundance varies in response to both internal (in-lake) and external processes (nutrient supply from the catchment). High Chl-a may occur during periods of high internal and/or external nutrient loading, and is the primary indication of eutrophication effects in lakes (Wetzel, 2001). Phytoplankton Chl-a is reported as a measure of lake 'ecosystem health in the National Objective Framework, and used to calculate lake Trophic Level Index (TLI) score, as described below. The NOF uses relevant statistics for typical (median) and extreme (maximum) phytoplankton biomass, to characterise lake ecosystem health .

Total nutrients, both phosphorus (TP) and nitrogen (TN), record the total fraction of dissolved and particulate, organic and inorganic nutrients available to phytoplankton. TP and TN therefore offer a measure of the likelihood of algal blooms and associated risks to water quality degradation. Both TP and TN are used to calculate TLI scores, as described below, and are included in reporting on lake "ecosystem health" (Verburg, 2012). Within the NOF, TN thresholds vary between shallow (polymictic) and deep (seasonally stratifying) lakes. Note, both are reported from annual medians whilst TP thresholds are identical.

Ammoniacal nitrogen (NH_4-N) is a component of TN that is included with the NOF because it is toxic to lake fauna at elevated concentrations. The NOF bands are based on both immediate (acute) and long-term (chronic) toxicity risk, assessed using median and maximum NH_4-N concentrations, respectively. The NOF follows the USEPA (1998) and earlier ANZECC (2000) guidance to standardise NH_4-N concentration to pH 8.0, irrespective of temperature (e.g., Volume 2 of ANZECC, 2000).

The Trophic Level Index (TLI) summarises data related to trophic state and potential primary production in New Zealand lakes (Burns et al., 1999). Trophic state records the nutrient and productivity state of a lake (Burns et al., 2000). The TLI is used to classify a lake along a gradient of low (ultra-microtrophic) to very high (hypertrophic) nutrient availability and phytoplankton production; TLI scores increase with increasing eutrophication (Table A.2). Here, the four-component TLI is applied, using the modification to TLs recommended by Burns et al. (2000) (where all concentrations are mg/L and SD is m^{-1}):

$$TLc = 2.22 + 2.54 \log(Chla)$$

$$TLs = 5.10 + 2.6 \log(\frac{1}{SD} - \frac{1}{40})$$

$$TLp = 0.218 + 2.92 \log(TP)$$

$$TLn = -3.61 + 3.01 \log(TN)$$

$$TLI = \frac{1}{4}(TLc + TLs + TLp + TLn)$$

Table A.2: Definition of lake trophic status using the Trophic Level Index (TLI; Burns et al., 2000) (modified from Sorrell et al., 2006)

TLI	Trophic State	Nutrient Enrichment Description
<1	Ultra-microtrophic	Practically no availability
1-2	Microtrophic	Very low availability
2-3	Oligotrophic	Low availability
3-4	Mesotrophic	Median availability
4-5	Eutrophic	High availability
5-6	Supertrophic	Very high availability
>6	Hypertrophic	Saturated availability

A1.1 Data acquisition

Lake water quality data for 28 lakes was obtained from Northland Regional Council, in identical reporting format that included indicator name, measurement, time and date format. Data was available at quarterly resolution continuously throughout the interval 2009-2014 for only 26 lakes, grouped into four regions (Aupouri Peninsula, Central, Kai-Iwi and Pouto

Peninsula); Lakes Kapoai and Whakaneke lacked monitoring data for the 2009-2011 interval and were excluded from further analysis. Unique identifiers, including location, name and LakeID code (LID) in Freshwater Environments of New Zealand (FENZ; Leathwick et al., 2010) and regional council database, were assigned to each monitoring record.

Lake water quality records were linked by LID to the FENZ database for supplementary information on 61 catchment variables (e.g., land cover, geology, climate, topography and geometry) and 17 in-lake variables (e.g., morphology, depth). Each lake was also assigned a management class (MC) based on geomorphology (window, perched), for which two further sub-classes were developed describing deep and shallow lakes (max >10m and ≤10 m depth). The 10 m depth threshold was also employed for NOF reporting, to approximate 'seasonally stratified' and 'polymictic' lakes, respectively (e.g., for assigning TN bands which vary between both). The 10 m threshold is a modification of the 15 m recommendation by the NOF Lakes Science Panel (Verburg, 2014). Tests of the efficacy of the threshold for discriminating lake water data are provided in Section A1.3.2. Whether a lake stratifies influences aspects of its physicochemistry, including nutrient availability and phytoplankton production (e.g., Verburg et al., 2010). Notably, all lakes were conservatively assumed naturally "clear" for the purposes of NOF reporting in Section A2.1 (i.e., at greater risk and sensitivity to eutrophication).

Inspection of FENZ maximum depth estimates revealed disparities with bathymetric surveying by NIWA and maximum depths were revised accordingly (e.g., altered classification of Lake Rototuna [≤10 m maximum depth] and Rotokawau-Pouto [>10m maximum depth]).

Note: *surface water data is assumed indicative of the wider lake environment (both laterally and vertically, for the mixed upper epilimnion or whole water column).*

Note: *all 26 monitored lakes assessed here are presumed equally unlikely to experience natural limitation of phytoplankton production by staining.*

A1.2 Data Processing

Lake water quality data was processed in several steps to ensure accuracy. Internal consistency was assured from laboratory techniques remaining unchanged (2009-2014) and sampling location georeferenced (fixed at deepest location) (Macdonald, pers. comm., 2015). Note that the small sizes of most sampled lakes limits the capacity for spatially complex patterns distorting longer term monitoring records (e.g., median, max and min lake area [mean depth] of 18.7 Ha [3.0 m], 46.6 Ha [16.4 m] and 2.5 Ha [0.8 m], respectively).

All '0' entries were replaced with "NA" and the data series from "DO Lab" and "DO mg/L" merged as were the three non-overlapping series entitled "Nitrate-nitrogen". Nutrient records were censored if total nutrient sums were less than constituent nutrient species, utilising additional information on nutrient species provided by NRC but omitted from reporting here (e.g., dissolved and particulate organic and inorganic nutrient concentration – DRP, DOP, DIN, DON), replacing all such occurrences in both total and constituent observations with "NA" (i.e., where total nutrient sum < dissolved + particulate organic and inorganic fractions).

Data were then manually inspected, replacing outliers within each indicator with "NA" (e.g., 10>pH<4), and contrasting observed abundance with relevant detection limits presented in Table A.3 (i.e., some observed values for indicators are too low or high for the relevant level of precision assigned to the NIWA laboratory). This is a common characteristic of DRP, TP and NH_4-N measurements in New Zealand lake datasets (Larned et al., 2015). Any non-detectable observations were replaced with the detection limit (Table A.3). Note that subsequent status reporting accounts for censoring by assessing the proportion of observations identified as “below detection limit” or “not available” (see Section A1.3.1), as replacement of censored data can distort or bias statistical tests (e.g., Helsel, 2012).

Note: *there was no replacement of censored values.*

Table A.3: Lake water quality indicator detection limits applied to this study. – indicates no minimum threshold crossed by observed records across the 26 sampled Northland lakes.

Indicator type	Indicator	Detection limit	Units
Physical	Total Suspended Solids	0.5	mg/L
	Secchi depth	0.1	M
	Temperature	-	℃
Chemical	pH	-	N/A
	Conductivity	-	mS/cm^{-1}
	Dissolved oxygen	-	mg/L
	Total Phosphorus	0.001	mg/m^3
	Total Nitrogen	0.010	mg/m^3
	Ammoniacal Nitrogen	0.001	mg/m^3
Phytoplankton	Chlorophyll-a	0.1	mg/L
Index	Trophic Level Index	-	N/A

A1.3 Data analysis

A1.3.1 Water Quality Status

For each of the 26 lakes, water quality state was characterised using both the NOF attribute bands and TLI (Tables A.3 & A.4). NOF statistics were either median or median of annual maxima-based, whereas TLI statistics were all derived from averages. In both cases, surface water observations were utilised only as per recommendations in Verburg (2012).

Table A.4: NOF ecosystem health attribute band thresholds (MfE, 2014).

Value	*NOF attribute*	*Units*	*Water Quality Status*	
			Band	***Thresholds (annual statistics)***
Ecosystem Health	Phytoplankton Chl-a	mg/L	A	≤2 (median) ≤10 (max)
			B	≤5 (median) ≤25 (max)
			C	≤12 (median) ≤60 (max)
			D	>12 (median) >60 (max)
	Total Phosphorus	mg/L	A	≤10 (median)
			B	≤20 (median)
			C	≤50 (median)
			D	>50 (median)
	Ammoniacal-Nitrogen	mg/L	A	≤0.03 (median) ≤0.05 (max)
			B	≤0.24 (median) ≤0.40 (max)

		C	≤1.30 (median) ≤2.20 (max)	
		D	>1.30 (median) >2.20 (max)	
			Seasonally stratified	***Polymictic***
Total Nitrogen	mg/L	A	≤160 (median)	≤300 (median)
		B	≤350 (median)	≤500 (median)
		C	≤750 (median)	≤800 (median)
		D	>750 (median)	>800 (median)

Larned et al. (2015) recommend minimal reporting windows for water quality assessment of 30 observations, building on earlier recommendations in McBride (2005) for striking a balance between sufficient samples to assure confidence in the estimated statistic, versus integrating too long a time period that the envelope fails to identify current state. As monitoring observations are of quarterly resolution, status is reported here by the entire integrated statistic for the 2009-2014 period (n = 24).

Rules were also applied to increase the confidence in reported lake status statistics. State is only reported if: (1) less than 50% of values for an indicator are censored; and (2) values were distributed over at least five of the six years from 2009-2014. Failure to exceed detection limits in 50% of observations (e.g., Rule [1]) meant “A” grade was assigned for that NOF attribute, whereas censored values were used to compute the equivalent average TLI statistic.

Note: *the approach adopted here, by utilising below detection observations of TN, TP, Chl-a and SD as censored values at their detection limit, is conservative and will under-estimate the true observed TLI (i.e., will under-estimate water quality as lower scores are better).*

A1.3.2 Lake Classification

Lake water quality classes or grouping techniques have been reviewed by Snelder (2012) and only brief explanation follows. The objective of the grouping analyses in the present study is to test if the management classification discriminates observed water quality well, examining geomorphic and depth factors independently and together. Then, regression models test if other possible drivers of water quality variation are important to the present differences in state across the 26 sampled lakes.

Note: *given the uniform dune-lake geomorphic classes of lakes analysed here, the grouping analysis described here is limited to dune lakes (i.e., of the 26 lakes assessed, only Lake Omapere is not of dune origin).*

Earlier, a management classification was presented that groups the Northland dune lakes into similar classes based on their nutrient loading and internal nutrient cycling processes. Both top-down (inductive) and bottom-up (deductive) classification techniques were explored against this management scheme.

Prior to these, linear unconstrained ordinations (PCA) were performed on $\log_{10}$ transformed centred and standardised water quality indicators, using 2009-2014 series medians (NOF) and averages (TLI) as well as medians for temperature, conductivity, pH, dissolved oxygen, Secchi depth and total suspended solids. PCA (principal components analysis) determines the underlying patterns of change in the suite of NOF and TLI water quality indicators, across the full range of 26 lakes, and then spreads those lakes as widely as possible along these ‘principal gradients’ of water quality. Output is utilised to demonstrate which of the water quality indicators are most likely to vary between lakes, and shed light on how to build a robust lake classification framework. PCA was performed in R using VEGAN package (Oksanen, 2015).

Top-down, univariate classification built on expert opinion that water quality in shallow and deep dune lakes differ, due to fundamental differences in internal nutrient cycling (e.g., Drake et al., 2010; Verberg, et al., 2010). In addition, the importance of catchment extent and therefore external nutrient loading, varying between groundwater-connected (“window”) and isolated (“perched”) lakes was highlighted; perched dune lakes often possess higher organic matter and/or iron content, which can form an impermeable bed and alter nutrient availability (e.g., Timms, 1982). Table A.5 displays membership to both depth and hydrological classes.

Table A.5. Depth and geomorphic class membership for each of 26 Northland lakes utilised for top-down classification through one and two-factor ANOVA. Depth is “shallow” (≤10m max) or “deep” (>10m max). Geomorphic class is “window” (groundwater-connected) or “perched” (isolated). MC is management classification – a nominal code discriminating between the two depth and geomorphic factors, and including a fifth class to describe the only non-dune system examined (Lake Omapere).

Sub-Region	Lake	LID	Depth	Geomorphic	MC
Aupouri	Carrot	23690	Shallow	Perched	1
	Heather	23682	Shallow	Perched	1
	Morehurehu	24628	Deep	Perched	2
	Ngakapuha (North basin)	18717	Shallow	Perched	1
	Ngakapuha (South basin)	18718	Shallow	Perched	1
	Ngatu	23691	Shallow	Perched	1
	Rotokawau	18719	Shallow	Perched	1
	Rotoroa	23681	Shallow	Perched	1
	Te Kahika	24633	Deep	Perched	2
	Waihopo	24511	Shallow	Perched	1
	Waipara	19575	Deep	Perched	2
	Waiparera	13467	Shallow	Perched	1
Central	Omapere	23721	Shallow	Volcanic	5
	Waiporohita	24415	Shallow	Perched	1
Pouto	Humuhumu	50401	Deep	Window	4
	Kahuparere	50371	Shallow	Window	3
	Kanono	50373	Deep	Window	4
	Karaka	50320	Shallow	Perched	1
	Mokeno	50314	Shallow	Perched	1
	Rotokawau*	50413	Deep	Window	4
	Rototuna**	50345	Shallow	Perched	1
	Swan	50403	Shallow	Window	3
	Wainui	17761	Deep	Perched	2
Kai-iwi	Kai-iwi	21918	Deep	Window	4
	Taharoa	21917	Deep	Window	4

Waikare	21926	Deep	Window	4

*Note that following detailed bathymetric surveys, the maximum depth of Lake Rototuna (Pouto) and Lake Rotokawau (Pouto) were revised to ≤10 m and >10 m respectively, contrary to FENZ inferred depths (Snelder et al., 2006). No other changes to depth occurred when FENZ predicted maximum and NIWA observed maximum depths were compared. **Note that Lake Rototuna (Pouto) was identified as a perched lake in Jacobs (2014), which contrasts with the NIWA Lakes Strategy recommendations (Champion, 2014).

Analysis of variance (ANOVA) was employed in single and dual-factor designs on a subset of the 25 dune lakes (excluding Omapere as the sole volcanic lake) and each of the TLI and NOF attributes, to test if statistically significant (p<0.05) differences in mean water quality exist across hydrological and depth classes. Two-way ANOVA was performed with an interaction term for depth by geomorphic class. TLI parameters were approximately normally distributed as were NOF attributes (e.g., ANOVA is able to handle approximately normal distributions [Sorrell et al., 2006; Borcard, 2011]) (see Table A-6). ANOVA was performed on 2009-2014 series average (TLI) or median and maxima (NOF). Residuals were inspected for normality and equivalence of variance. Post-hoc membership Tukey boxplots were generated for each indicator. All analyses were undertaken in R using inbuilt functions (R Core Development Team, 2015).

The discrimination of water quality variation by maximum depth was assessed for differing depth thresholds. The analysis calculate the performance of classifications based on ANOVA r^2 values for eight incremental maximum depth thresholds of one metre from 5-12 m (using observed maximum lake depths, supplied by NIWA form a 2015 survey). The test was performed on each of six NOF water quality attributes and mean r^2 value used to identify the optimal depth threshold.

Bottom-up, hierarchical cluster analysis was performed on a suite of 12 NOF attributes and TLI in R (excluding TSS, temperature, pH, conductivity and DO), following standardisation, using the STATS package in R (R Core Development Team, 2015). Whereas ANOVA considers each water quality indicator separately, hierarchical classification is multivariate, attempting to discriminate groups of lakes whose members are similar within their class but dissimilar between classes, across all 12 water quality indicators simultaneously. As per the top-down exercise, attributes for the 26 lakes were derived from the 2009-2014 series averages (TLI) and annual median or maxima (NOF) (note – bottom up classification included Lake Omapere to assess whether volcanic lakes are dissimilar from dune albeit with only the one volcanic lake). These were standardised to zero unit mean deviation, to equalise their importance before computing a Euclidean distance matrix. Clustering was performed on this using six linkage functions (e.g., complete, average, Ward-linear, Ward-squared, single, median). The optimal linkage function was selected to minimise cophenetic distance and maximise cophenetic correlations (e.g., Gower, 1983). The number of meaningful clusters, or classes, was determined from inspection of fusion-level plots generated in R (e.g., Borcard, 2011).

Confusion tables were generated in R to demonstrate the degree of coherence between top-down and bottom-up classifications, highlighting whether the two approaches would result in the same classification of lakes (i.e., whether the 26 lakes differ markedly in water quality due to their fundamental differences in water quality aligned to depth and geomorphic categories alone, or whether other factors are also responsible for their differences in current state).

Note: *bottom-up hierarchical clustering is arguably more objective than top-down expert-led classification, as requires no a-priori assumptions made about the data or class boundaries and is therefore repeatable. However, it relies on subjective decisions about which water quality indicators to include, how to weight indicators, what measure of distance and linkage function to utilise, and how many meaningful clusters to retain. Different clustering linkage functions can result in markedly different classifications. We chose to use the method that best matched the arrangement of sites, to the input dissimilarity matrices (i.e., choosing the linkage function with best cophenetic correlation).*

A1.3.3 Water Quality Drivers

Modified stepwise linear regression was employed to model relate the median site water quality indicators to physical lake characteristics available in the FENZ database. The analysis used limnological theory to postulate a number of physical lake characteristics as potential drivers of variation in water quality amongst the 26 lakes. Stepwise multiple linear regression was used to select characteristics that best explained the observed water quality differences amongst the 26 Northland lakes. The purpose of this available was to consider if the lake classifications could be further improved by including variables that consistently explain variation in water quality, and from this, whether water quality could be predicted for lakes without a sampling programme.

The following steps were taken to fit the linear regression models:

1. Estimated median (average) water quality state for NOF (TLI) indicators over the period 2009-2014 were transformed, with the exception of TP and NH_4-N availability, to approximate normality (Table A-6). Between-lake variability for NH_4-N was minimal and often below the detection limit and it was excluded from subsequent modelling;

2. Catchment characteristics were collated for 61 predictors obtained from the FENZ database, before visual inspection of variation between lakes. Those of minimal to no variation and/or including multiple ‘0’ entries were eliminated (e.g., % of catchment with low intensity grass cover). 20 of the 61 predictors were retained;

3. In-lake characteristics were collated for five predictors using bathymetric data collected by NIWA in 2014/15 (max depth, mean depth, residence time, lake area and volume). With the exception of two FENZ in-lake characteristics (lake elevation and lake N-load modelled through CLUES), other internal lake predictors of water quality were overlooked due to concern about their accuracy (e.g., Snelder et al., 2006).

4. Most external (catchment) and internal (lake) water quality predictors were transformed to approximate normality using various transformations (see Table A-6), as were water quality responses (with the notable exception of TP but inclusion of TLP);

5. The full suite of 27 water quality predictors were filtered to exclude highly collinear variables, using a stepwise variance inflation function (VIF) in R (https://beckmw.wordpress.com/2013/02/05/collinearity-and-stepwise-vif-selection/; visited on 30/11/2015). The function assigns each predictor a VIF score, drops the parameter with the greatest VIF at each step, and proceeds until all remaining predictors are at worst, weakly collinear (i.e., the higher the VIF, the higher the collinearity and less reliable the linear regression [Borcard, 2011]). A VIF≤10 threshold was set from which a mix of 10 catchment and 6 in-lake predictors

were retained as potential predictors for the linear models (Table A-6). Collinear and therefore, excluded parameters included catchment area, catchment perimeter, catchment particle size, catchment annual temperature, % high producing grassland, catchment June and December solar irradiance, catchment calcium content, catchment elevation, lake volume and lake average depth (i.e., other variables included for MLR are highly correlated to these);

6. Linear models were then constructed through backward automated stepwise regressions using the MASS package in R (Venables and Ripley, 2002). In backwards stepwise regression, differences in model performance between a full linear model (with all 17 predictors) and the next smaller equivalent (15 parameters, dropping the least powerful predictor), are assessed using the relevant Akaike's Information Criterion (AIC; a measure of the model performance, penalising for the number of predictors and weighted against over-fitting to offer better explanatory power for the model outside its limited training dataset of 26 lakes). A simpler model is only accepted if it improves (decreases) the AIC. That is, the least complex model is selected that doesn't increase the AIC and overall model deviance (Borcard, 2011);
7. The significance of each coefficient included in backwards selected linear models was then inspected. Any insignificant predictors were dropped ($p>0.05$), the model rerun and residuals in estimated water quality tested for differences relative to the original backward model using ANOVA. Where insignificant ($p>0.05$), the modified backwards structure with lesser predictors was deemed more parsimonious (i.e., more likely to yield greater predictive power across the unmonitored dune lakes). Where significant differences arose, the least insignificant predictor was added back into the linear model until predicted water quality was insignificantly different from the full backwards structure.

Note: *linear regressions make several assumptions of input data, including that the population of observed responses (water quality score) are normally distributed.*

Table A-6 Summary table of 10 water quality indicators and 17 catchment and lake predictors included in the stepwise regression. External or internal predictor status refers to the predictor representing external or internal effects on trophic state.

Response	Transformation	Normality (Shapiro-Wilk *p*)
TN	$Log_{10}+1$	Normal (0.4)
TP	$Log_{10}+1$	Not normal (0.01)
Median Chl-a (Chlamed)	$Log_{10}+1$	Normal (0.38)
Maximum Chl-a (Chlamax)	1/(SQRT+0.5)	Normal (0.34)
SD	1/(SQRT+0.5)	Normal (0.09)
TLC	^2	Normal (0.34)
TLS	^2	Normal (0.13)
TLP	^2	Normal (0.69)
TLN	^2	Normal (0.30)
TLI	^2	Normal (0.10)
Predictor (External/Internal)	**Transformation**	**Normality (Shapiro-Wilk *p*)**
Catchment Phosphorus (external)	$Log_{10}+1$	Not normal (<0.01)
Catchment Elevation (external)	$Log_{10}+1$	Normal (0.42)
Catchment Hardness (external)	$Log_{10}+1$	Not normal (<0.01)
Catchment N-load (external)	SQRT+0.5	Not normal (<0.01)
% Natural Vegetation Cover (external)	SQRT+0.5	Normal (0.56)
% Pasture Cover (external)	SQRT+0.5	Normal (0.34)
Catchment slope (external)	$Log_{10}+1$	Normal (0.66)
% Natural Vegetation Cover Removed (external)	$Log_{10}+1$	Not normal (<0.01)
% Natural Forest Cover (external)	$Log_{10}+1$	Not normal (0.01)
% Exotic Forest Cover (external)	$Log_{10}+1$	Not normal (<0.01)
Clarity Proxy (internal)	$Log_{10}+1$	Normal (0.43)
Lake Mean Wind-speed	$Log_{10}+1$	Not normal (<0.01)
Lake Elevation (internal)	$Log_{10}+1$	Normal (0.23)
Lake N-load (internal)	$Log_{10}+1$	Not normal (<0.01)
Lake Area (internal)*	1/(SQRT+0.5)	Normal (0.08)
Lake Max Depth (internal)*	1/(SQRT+0.5)	Normal (0.32)
Lake Residence Time (internal)*	1/(SQRT+0.5)	Not normal (0.03)

*Derived from updated bathymetric survey data supplied by NIWA (courtesy of M. De Winton and P. Champion, 2015).

A2 Results and Interpretation

A2.1 Water Quality Status

All 11 water quality indicators had sufficient observations for reporting against NOF and TLI criteria, at all 26 lakes (see Table A-7). Incomplete quarterly surveying affected four lakes otherwise when examined at lower resolution (e.g., Omapere, Kahuparere, Rotokawau-Pouto, Swan at 3-yr intervals). Recent water quality state is summarised in Table A-7 by management class (depth, geomorphology) and sub-region (Aupouri, Pouto, Kai-Iwi and Central). Note we report on the long-term NOF banding rather than individual yearly-bands (e.g., median of annual maxima or median overall). The reason being, this long-term status is the focus of subsequent clustering and exploration of catchment or internal drivers[13].

For the six year period, five lakes failed the national bottom-line for long-term TN (all shallow, polymictic lakes – Swan, Rotoroa, Ngatu, Waiporohita, Mokeno). Five lakes failed Chl-a median long-term bottom-lines (again all shallow, polymictic lakes – Waiparera, Rototuna, Swan, Waiporohita and Karaka) whilst only one lake failed to meet the long-term Chl-a maxima bottom-line (Karaka). All 26 lakes passed the national long-term bottom-line for TP and both median and median of annual maximum bottom-lines for NH_4-N. Those five lakes which exceed a long-term polymictic median TN concentration of 800 mg/m^3 are distributed throughout three of the four lake subregions (Aupouri, Central, Pouto). Of these lakes, only two breached long-term Chl-a median (Swan) or median of annual maxima limits (Waiporohita).

Of the five lakes failing long-term median Chl-a bottom-lines, three lakes received a “C” grade for long-term maximum phytoplankton biomas (Figure A-1). For instance, in Lakes Rototuna, Swan and Waiporohita, periodic blooms do not breach the NOF maxima threshold when converted to a median of annualised maxima, but did exceed the 60 mg/m^3 Chl-a threshold if examined at annual time-steps instead (in addition to Lake Waiparere) (Figure A.1). . For instance, Waiporohita and Waiparere exceeded 60 mg/m^3 Chl-a in November 2014. Rototuna approached the limit in four of the six years, but only breached the guideline in August 2013. Whereas, Karaka and Swan experienced repeated, excessive algal blooms (i.e., >60 mg/m^3 Chl-a in two or more years). The five lakes failing long-term median phytoplankton NOF bottom-lines are distributed in the Aupouri, Central and Pouto sub-regions but are all shallow, polymictic systems (≤10 m max depth). Likewise, these five lakes include four perched and one window system (although note that this represents a fifth and quarter of each respective class given that only five lakes are connected to the regional aquifer). Each of these five lakes received a “C” grade for TP, accounting for five of the seven lakes graded “C” for TP. With the exception of Lake Karaka which received a “B” for TN, each also received a “D” or “C” for TN. However this equates to only four of the 14 lakes graded “C” or “D” for TN, also having failed phytoplankton bottom-lines. Indeed half of the lakes graded “C” or “D” for TN actually received a “B” for median phytoplankton biomass. Taken together, this implies particular sensitivity to TP availability, more so when TN availability is also relatively high, but little sensitivity to TN availability if TP concentrations are relatively low (i.e., <10 mg/L TP).

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[13] Note that the NOF does not provide guidance on how the annual maxima should be reported (i.e., from what minimum of observations, whether to weight those observations between years). Here, to ensure the Chl-a and NH4N maxima bands assigned reflect the long-term maxima, we have generated the median of annual maxima (i.e., avoid any station being graded D for maxima simply for one observation over the entire 6-year series).

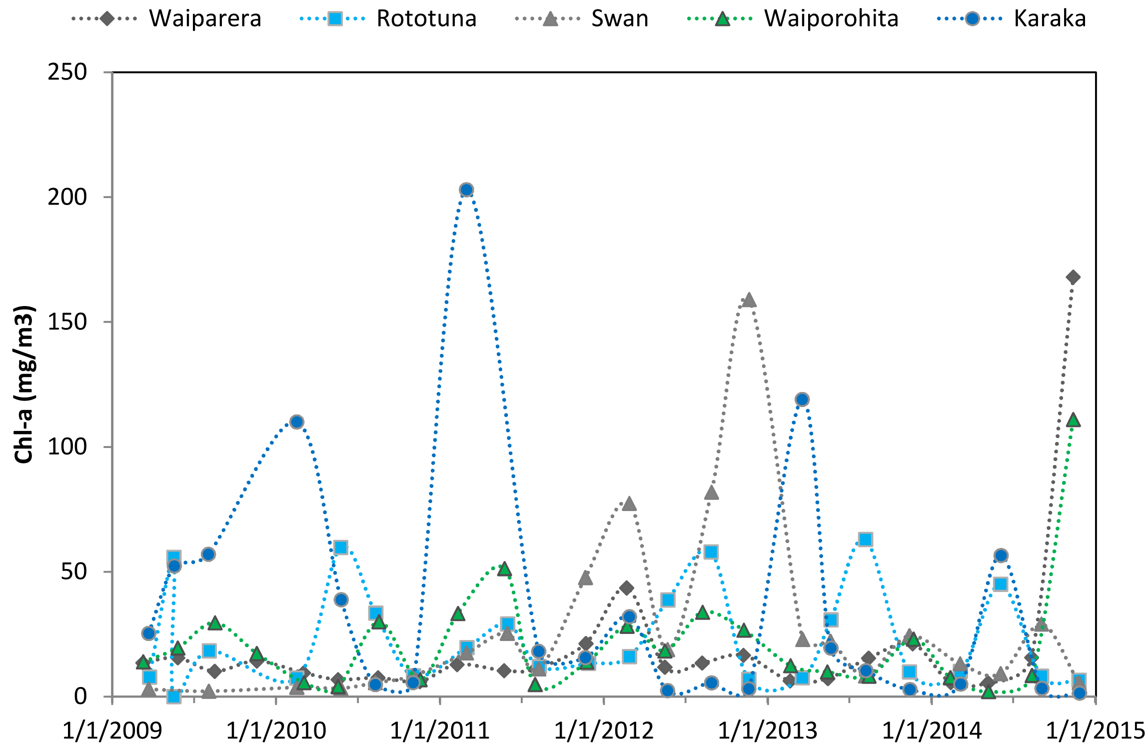

Figure A.1. Time-series of lake phytoplankton abundance from 2009-2014 in 5 Northland lakes that breached the NOF "D" band for long-term annual median and annual maxima concentration in any one year (>12 and >60 mg/m^3, respectively).

A depth related gradient in lake water quality is therefore clear in lakes of poorer health (Figure A.2). Shallower lakes recorded greatest nutrient availability (both TN and TP) and phytoplankton abundance (both peak and long-term). The same pattern is not clear by sub-region. Overall, eight of the 26 lakes failed to meet one or more NOF bottom-lines, again all being shallow, polymictic systems distributed in three of the four sub-regions. Note that examined within each NOF attribute only five lakes would breach a single bottom-line (Table A-7).

Overall, long-term NOF grades varied widely in terms of TN, TP and phytoplankton availability but are most frequently assigned to "B" status. For median NH_4-N concentration, 25 of 26 were assigned "A" status emphasising the very small chronic (≥99% community protection) toxicity risk to Northland lake fauna from ionised or unionised ammoniacal nitrogen. The number of lakes in the "A" grade for acute or short-term risk remained similar, with 23 lakes assigned "A" grade and 3 lakes assigned "B" grade (Table A.7).

For the lakes with higher water quality, fewer achieved "A" grade for TN (4%) compared to either TP (23%) or Chl-a (both median and maxima; 12%, 58%). More lakes recorded "A" grade for TP and maximum Chl-a than "D", whereas the opposite was true for TN and median Chl-a. That said, the majority of lakes were in "A" or "B" state across all four NOF attributes (all in the instance of NH_4-N median and maxima). These "A" and "B" graded lakes are distributed widely across the four sub-regions. For instance, all four regions have between a third and a half of their lakes in “A” or “B” grade for TN, whereas for TP nearly all lakes in Kai-Iwi and Aupouri are in “A” or “B” grade compared to half of Pouto lakes and neither of the two central lakes – both being “C” grade. Phytoplankton biomass shares a similar pattern to TP.

Clearer differences in lake water quality were evident when classified by depth, akin to the differences in lakes of poorer state. Deeper lakes are more likely to record an “A” or “B” status just as shallow are disproportionately more likely to record “D” status. A third of shallow lakes but two thirds of deep lakes recorded “A” or “B” for TN and median Chl-a. Two thirds of shallow and all of deep lakes recorded an “A” or “B” for maximum Chl-a. Finally, two thirds of shallow and all of deep lakes recorded an “A” or “B” for TP.

The discrimination of lake water quality state by the geomorphic classification was less distinct (Figure A.3b), with nearly equivalent proportions of window and perched lakes in “A” or “B” grade for TN, TP and peak phytoplankton biomass. Only the proportion of lakes with long-term (median) Chl-a in the “A” or “B” grade appear to differ markedly between window (80%) and perched classes (45%).

Inspection of lake trophic indicator (TLI) status presents a similar picture to individual NOF attributes. Overall, the majority (14) of the 26 lakes are classified as “eutrophic” (TLI of 4-5) with no supertrophic lakes (TLI>5) and the remainder being largely mesotrophic (9) or oligotrophic (3). Importantly, all oligotrophic lakes were deep but were either perched or window types.

Sub-regional differences are apparent in the average TLI of Kai-Iwi lakes, only (Figure A.4a). The latter are on average oligotrophic (TLI_{Ave} 2.6) whilst Aupouri, Central and Pouto lakes are eutrophic (average TLI_{Ave} ranging from 4.0 to 4.8). The same pattern is evident in each of the four TLx parameters. That said there is quite marked variation in individual lake TLx within Pouto and Aupouri lake classes, suggesting average TLx or TLI are not particularly informative of lake trophic states within these sub-regions (Figure A.4a – boxplots of TLx by sub-region). For instance, Kai-Iwi lakes vary from oligotrophic to mesotrophic (TLI_{Ind} 2.1-3.1), Pouto lakes vary from mesotrophic to eutrophic (TLI_{Ind} 3.3 to 4.9) and Aupouri lakes vary from oligotrophic to eutrophic (TLI_{Ind} 2.9 to 4.7). By contrast, both central lakes are eutrophic (TLI_{Ind} 4.8).

TLI scores were better explained by depth than other classifications. Shallow lakes were consistently, a trophic class above, or more enriched, than deep lakes; shallow TLI_{AVE} is 4.3 (eutrophic) compared to deep TLI_{AVE} of 3.3 (mesotrophic). Given the firm foundation of the TLI in earlier New Zealand lake classifications (Vant, 1993), similarity to international lake classification schemes (Carlson, 1977) and application elsewhere in New Zealand (Drake et al., 2010; Verburg et al., 2010), a full trophic state class difference in average TLx and TLI between shallow and deep lakes is evidence that lake water quality throughout Northland is driven, in part, by the effect of depth-associated processes . A caveat here is that individual lake TLI scores vary within, although with little overlap between, depth classes; deep and shallow TLI_{Ind} varying from 2.1-4.1 and 3.9-4.9, respectively.

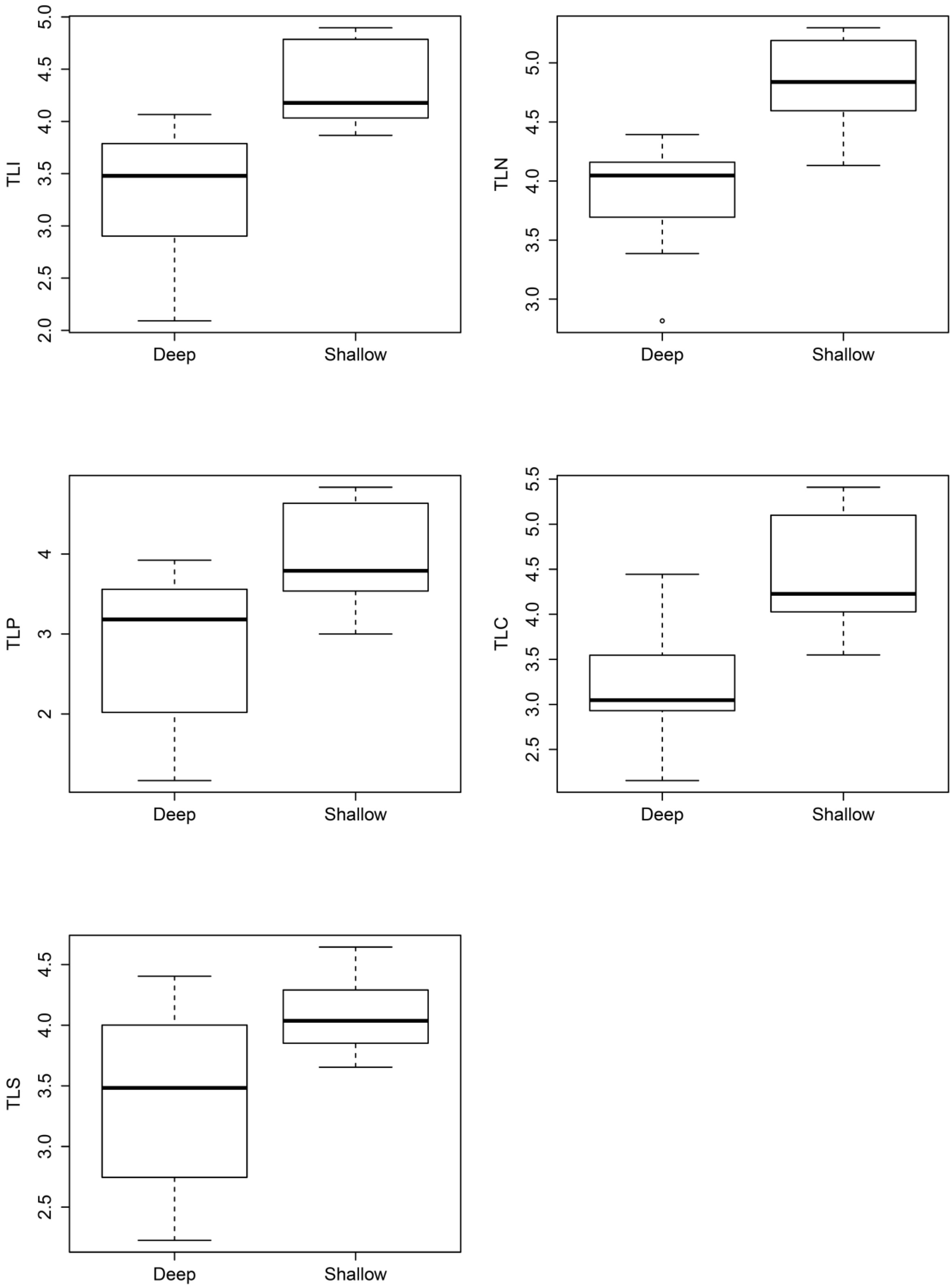

Figure A.2a Tukey boxplots of TLI variability across the 26 Northland shallow (max ≤10 m) and deep lakes (max ≥10 m).

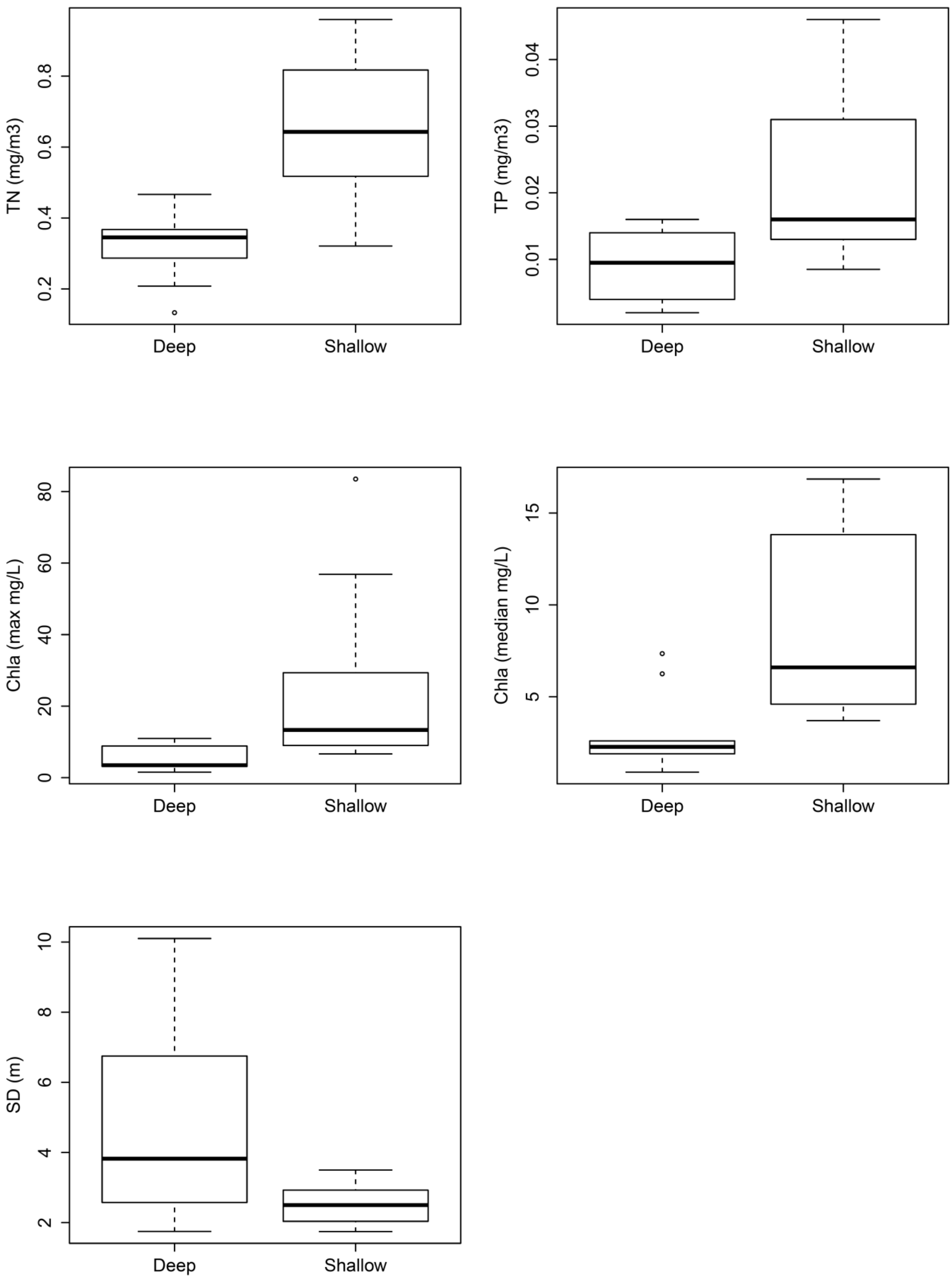

Figure A.2b Tukey boxplots of NOF variability across the 26 Northland shallow (max ≤10 m) and deep lakes (max ≥10 m).

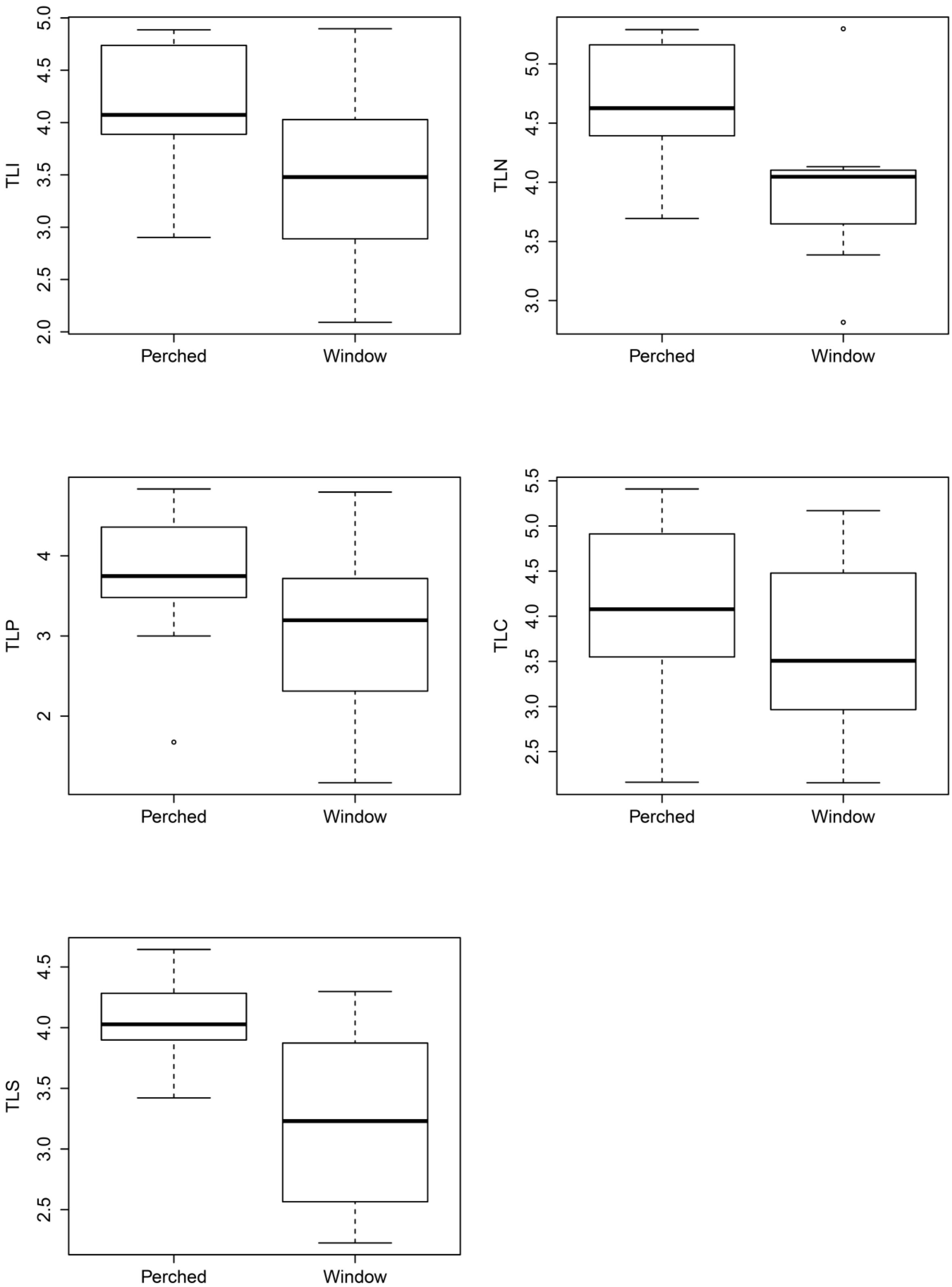

Figure A.3a Tukey boxplots of TLI variability across the 25 Northland window (groundwater connected) and perched lakes (excluding Lake Omapere as a volcanic lake).

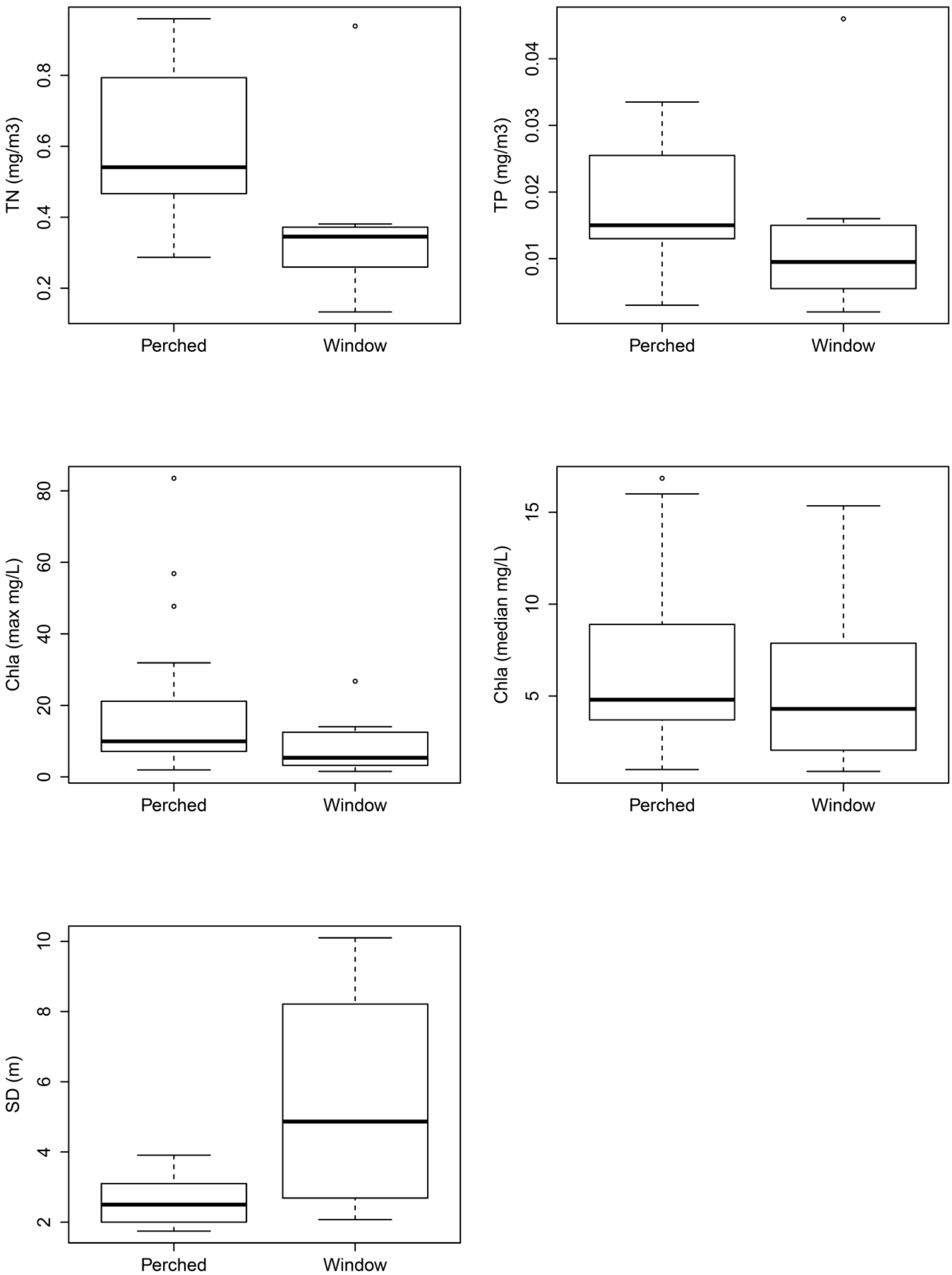

Figure A.3b Tukey boxplots of NOF variability across the 25 Northland window (groundwater connected) and perched lakes (excluding Lake Omapere as a volcanic lake).

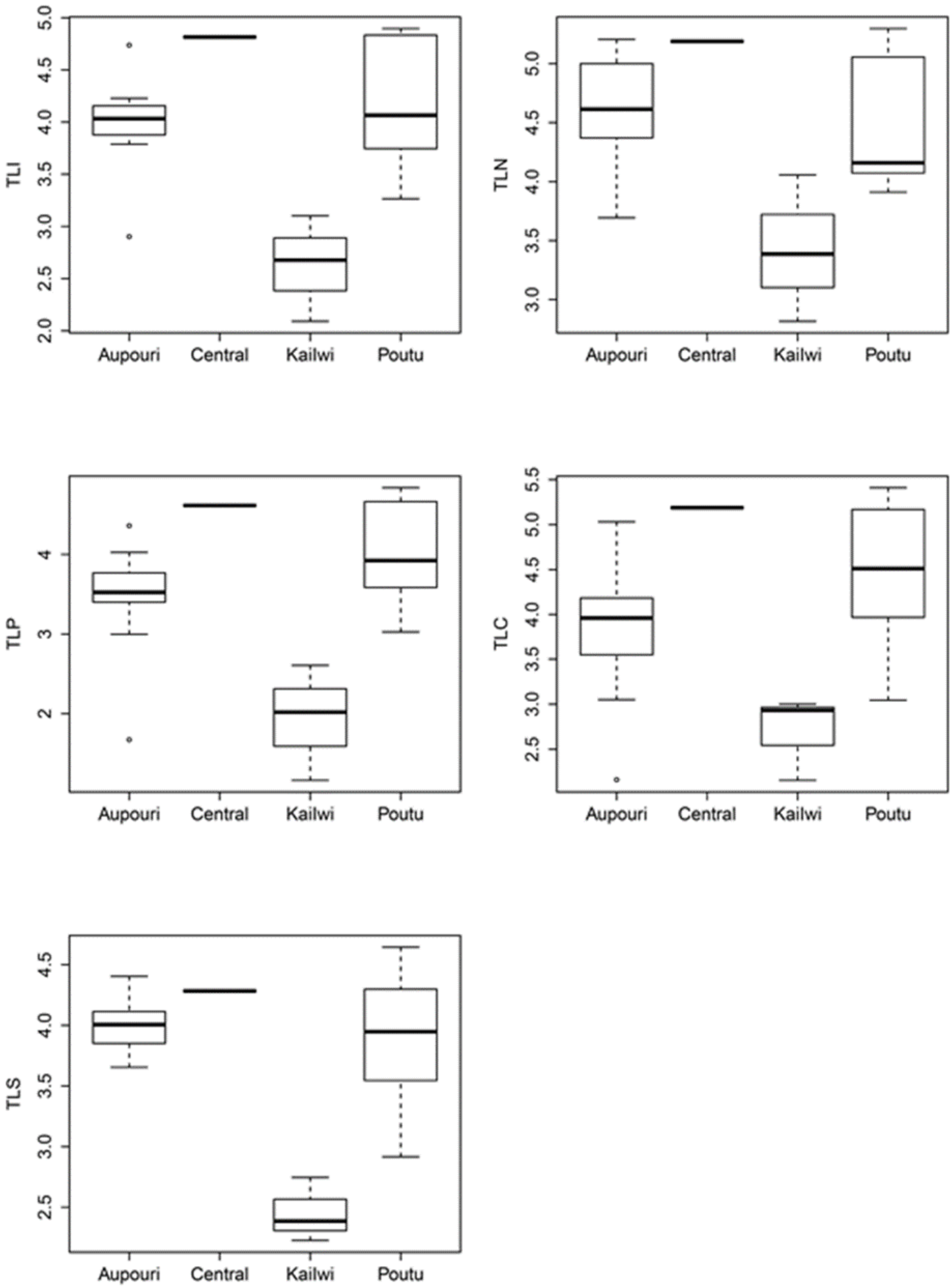

Figure A.4a Tukey boxplots of TLI variability across the 26 Northland lakes by sub-region (Aupouri, Central, Kai-Iwi, Pouto).

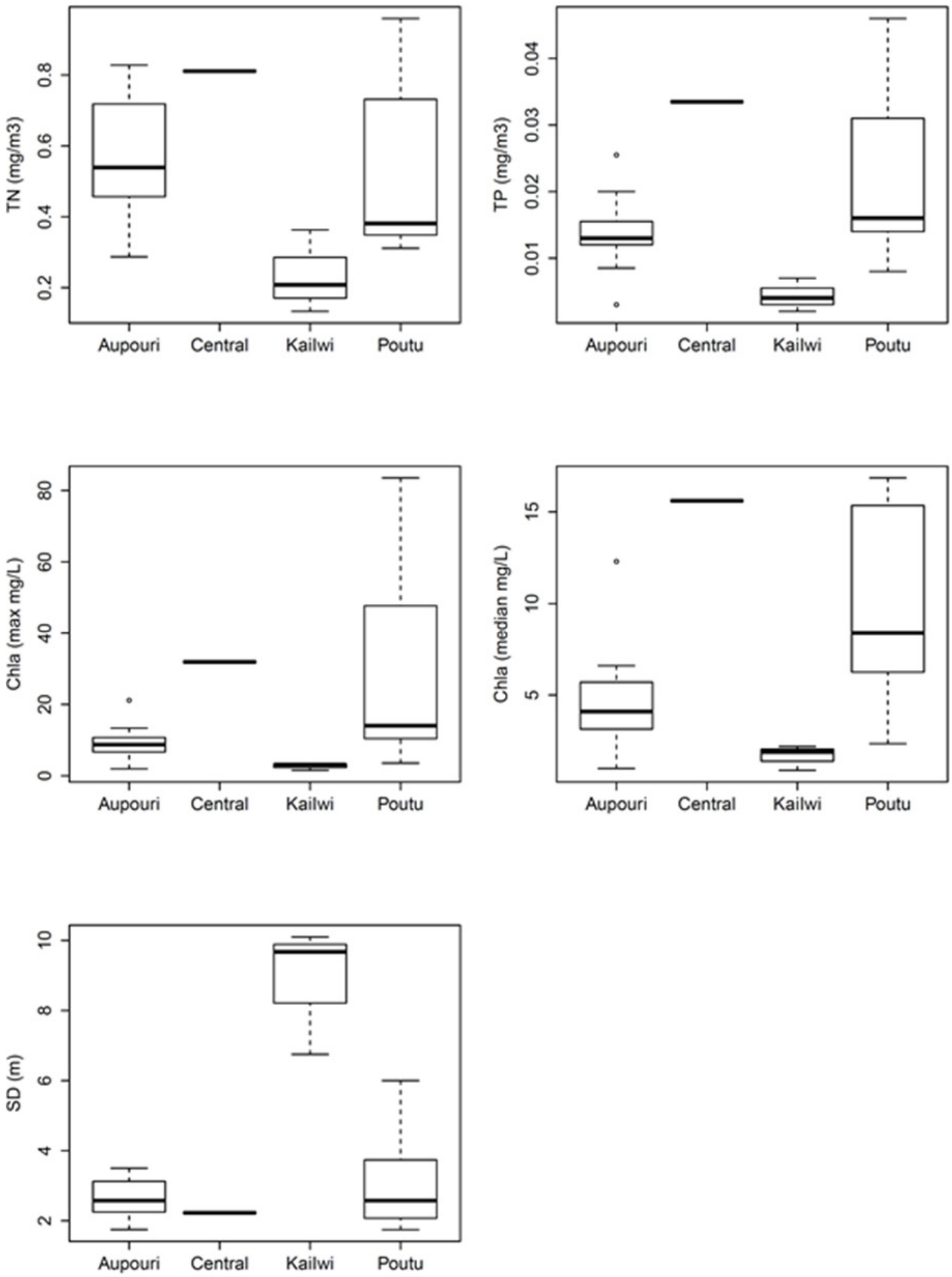

Figure A.4b Tukey boxplots of NOF variability across the 26 Northland lakes by sub-region (Aupouri, Central, Kai-Iwi, Pouto).

Table A.7 NOF (annual medians and maxima) and TLI grades for the 26 Northland lakes based on a reporting window of 2009-2014. Note NH_4-N is reported after standardisation to pH 8 (as per USEPA, 2009). TLI and TLx were generated from series-averages as per Burns et al. (2000).

Lake	LID	Sub-region	Depth	Hydra-ulics	TN	TP	Chl-a		NH_4-N		TLx				TLI
					Med	Med	Med	Max	Med	Max	TLc	TLs	TLp	TLn	
Taharoa	21917	Kai-iwi	Deep	Window	A	A	A	A	A	A	2.2	2.2	1.2	2.8	2.1
Waikare	21926	Kai-iwi	Deep	Window	B	A	A	A	A	A	2.9	2.4	2.0	3.4	2.7
Kai-Iwi	21918	Kai-iwi	Deep	Window	C	A	B	A	A	A	3.0	2.7	2.6	4.1	3.1
Omapere	23721	Central	Volcanic	Volcanic	B	C	B	A	A	A	4.0	5.4	5.4	4.7	4.8
Waiporohita	24415	Central	Shallow	Perched	D	C	D	C	A	A	5.2	4.3	4.6	5.2	4.8
Carrot	23690	Aupouri	Shallow	Perched	C	B	C	B	A	A	4.2	3.8	4.0	4.6	4.2
Heather	23682	Aupouri	Shallow	Perched	B	B	B	B	A	A	4.2	3.9	3.7	4.1	4.0
Morehurehu	24628	Aupouri	Deep	Perched	C	B	B	A	A	A	3.1	4.4	3.3	4.3	3.8
NgakapuhaN	18717	Aupouri	Shallow	Perched	B	B	C	A	A	A	4.0	3.7	3.5	4.6	3.9
NgakapuhaS	18718	Aupouri	Shallow	Perched	C	B	C	A	A	A	4.2	3.9	3.8	4.6	4.1
Ngatu	23691	Aupouri	Shallow	Perched	D	A	B	A	B	B	3.5	3.7	3.0	5.2	3.9
Rotokawau	18719	Aupouri	Shallow	Perched	C	B	B	A	A	A	3.9	4.0	3.5	4.8	4.1
Rotoroa	23681	Aupouri	Shallow	Perched	D	B	B	A	A	A	4.1	4.2	3.5	5.2	4.2
Te Kahika	24633	Aupouri	Deep	Perched	B	A	A	A	A	A	2.2	4.0	1.7	3.7	2.9
Waihopo	24511	Aupouri	Shallow	Perched	C	B	B	A	A	A	3.7	4.0	3.7	4.7	4.0
Waipara	19575	Aupouri	Deep	Perched	B	B	B	A	A	A	3.5	4.0	3.6	4.4	3.9
Waiparera	13467	Aupouri	Shallow	Perched	C	C	D	B	A	A	5.0	4.3	4.4	5.2	4.7
Humuhumu	50401	Pouto	Deep	Window	B	B	C	A	A	A	4.0	3.5	3.4	3.9	3.7
Kahuparere	50371	Pouto	Shallow	Window	B	B	C	B	A	A	4.5	3.8	3.6	4.1	4.0
Kanono	50373	Pouto	Deep	Window	B	B	C	B	A	A	4.4	3.9	3.8	4.0	4.1
Karaka	50320	Poutu	Shallow	Perched	B	C	D	D	A	B	5.2	4.4	4.8	4.6	4.8
Mokeno	50314	Pouto	Shallow	Perched	D	C	C	C	A	B	4.9	4.6	4.7	5.3	4.9
Rotokawau	50413	Pouto	Deep	Window	B	A	B	A	A	A	3.0	2.9	3.0	4.1	3.3
Rototuna	50345	Pouto	Shallow	Perched	C	C	D	C	A	A	5.4	4.2	4.7	5.1	4.8
Swan	50403	Pouto	Shallow	Window	D	C	D	C	A	A	5.2	4.3	4.8	5.3	4.9

Wainui	17761	Poutu	Deep	Perched	C	B	B	B	A	A	3.5	3.4	3.9	4.2	3.7

A2.2 Lake Classification

Principal components analysis (PCA) on the 17 $\log_{10}$ transformed, standardised indicators demonstrated the largest variation in long-term water quality between the 26 Northland lakes (the first principal component) is associated with nutrient availability, which is also strongly, positively associated with phytoplankton biomass, total suspended solids, and inversely associated with Secchi Depth (Figure A.5). Both first and second principal components explained more variance than expected by chance (i.e., the variance explained by λ_1 and λ_2 exceeded that of a corresponding broken-stick model – see Figure A.6).

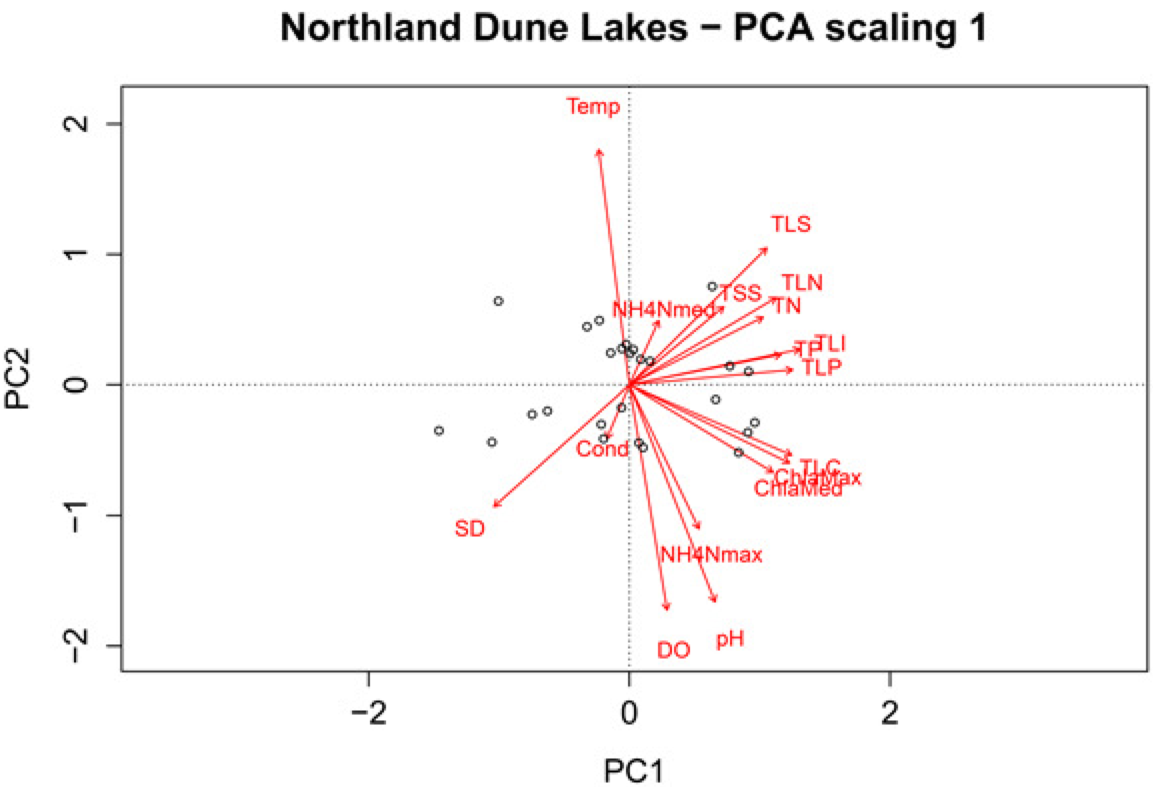

Figure A.5. PCA biplot of axes 1 and 2 for 26 Northland lakes, using standardised and $\log_{10}$-transformed, median and average water quality scores across 17 indicators. The major differences in water quality between the lakes are aligned with changes in TLI.

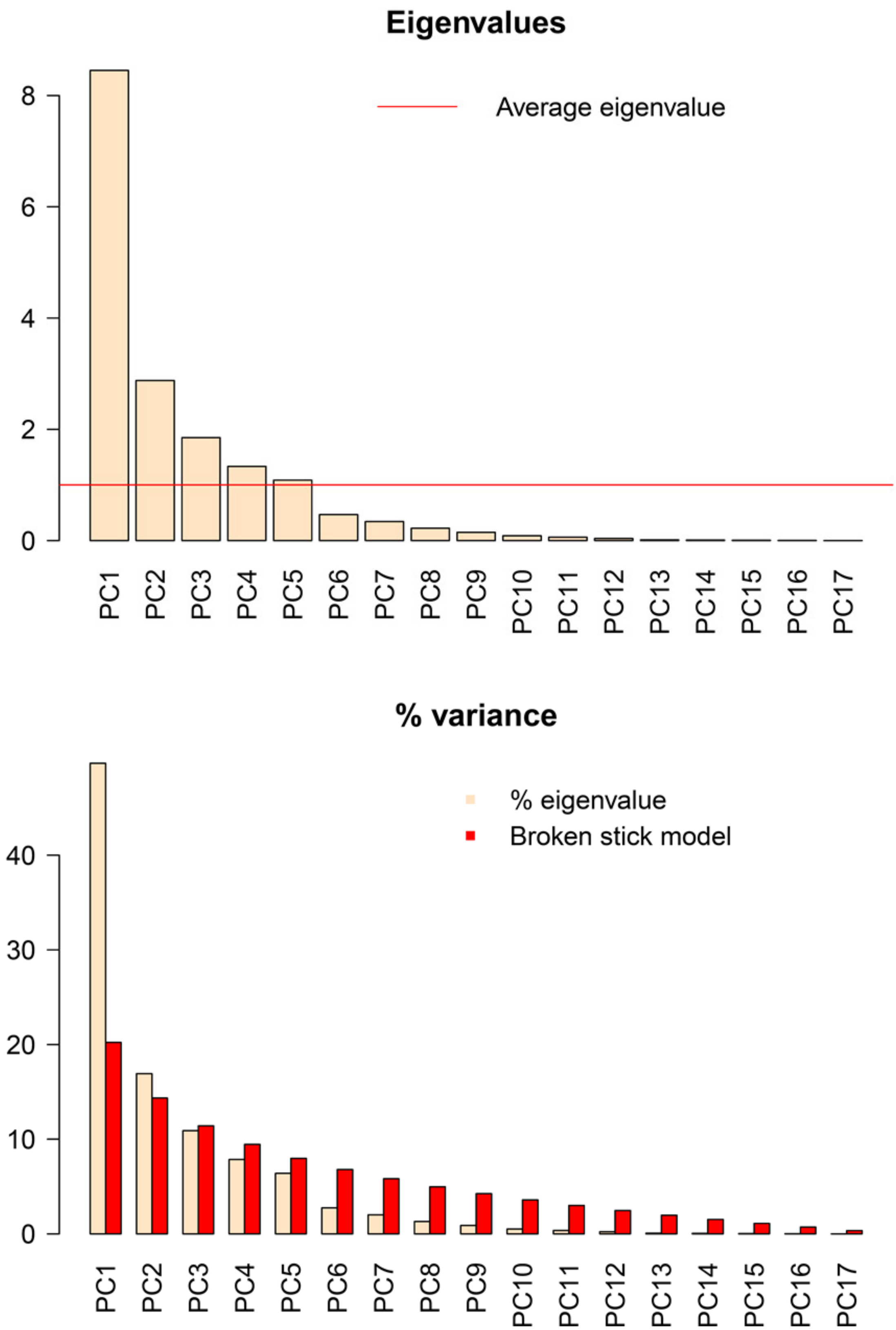

Figure A.6. PCA broken-stick model for variance explained by each principal component relative to random effect. Where the % explained by the axis Eigenvalue (beige bar) exceeds the corresponding broken stick (red bar), the axis may be considered to significantly explain a component of water quality variation.

Table A.8. PCA statistics for ordination on 17 log-10 transformed, centred and standardised water quality indicators, across 26 Northland lakes using summary information for the period 2009-2014. Only the first two PCA axes are likely to be meaningful.

PCA Axis	1	2	3	4	5	6	7	8	9	10…
Eigenvalue	8.452	2.878	1.852	1.335	1.087	0.468	0.342	0.222	0.150	0.087
Proportion explained	0.497	0.169	0.109	0.079	0.064	0.028	0.020	0.013	0.009	0.005
Cumulative proportion	0.497	0.666	0.775	0.854	0.918	0.945	0.965	0.979	0.987	0.992

The first principal component explains nearly half of all variation in water quality over the 17 indicators, across the 26 lakes (λ_1 = 49.7%; Table A.8). As the component of variation is strongly associated with TLI, a simple measure of performance for the lake classification, is therefore how effectively it discriminates differences in TLI.

The second PCA component was associated with temperature and varied inversely with dissolved oxygen (DO), maximum NH_4-N concentration and pH (i.e., warmer lakes were associated with lesser surface water oxygenation, peak concentration of NH_4-N and higher pH). The second axis explained considerably less variation than the first (λ_2 = 16.9%; Table A-8). While this means changes in surface lake temperature, pH and DO appear unrelated to changes in nutrient availability and TLI, this **does not** mean benthic (bottom-water) conditions do not affect nutrient availability or TLI (see ANOVA results below). The reason being, top and bottom-water DO and pH conditions can be markedly different during periods of thermal stratification.

One-way ANOVA, using a 10 m maximum depth threshold to define two lake classes, demonstrated that the average TLI of deep and shallow dune lakes was significantly different ($F_{1,\ 23}$ = 25.47; p<0.00001). As expected, depth was discriminated significant (p<0.05) differences in all other NOF and TLx water quality indicators with the exception of NH_4-N concentrations[14] (e.g., TLN, TLP, TLS, TLC, TN, TP, Chl-a median, Chla max– Table A.9). The MANOVA statistics confirmed this, with significant differences jointly across all four TLx indicators between deep and shallow lakes (Pillai = 0.687; $F_{1,23}$ = 10.96; p<0.001) (Table A.10).

[14] As noted above, median NH_4-N concentrations varied little across the 25 dune lakes with all bar one accorded "A" grade. Hence, any grouping system is unlikely to isolate differences in chronic NH_4-N toxicity.

Table A.9 One-way ANOVA results for differences in water quality between 25 shallow (≤10 m maximum depth) and deep dune lakes (≥10 m maximum depth). Variation in water quality indicators in bold were significantly explained by depth class.

Water Quality Indicator	**ANOVA output**					
	Factor	d.f.	SS	MS	*F*-ratio	*P*-value
TLI	Depth	1	6.457	6.457	25.47	**<0.001**
	Residual	23	5.83	0.253		
TLN	Depth	1	5.479	5.479	29.79	**<0.001**
	Residual	23	4.23	0.184		
TLP	Depth	1	8.127	8.127	14.37	**<0.001**
	Residual	23	13.013	0.57		
TLS	Depth	1	3.116	3.116	11.47	**0.003**
	Residual	23	6.247	0.2719		
TLC	Depth	1	10.224	10.224	23.58	**<0.001**
	Residual	23	9.974	0.434		
TN	Depth	1	0.6487	0.6487	22.86	**<0.001**
	Residual	23	0.6527	0.0295		
TP	Depth	1	0.000923	0.000923	11.13	**<0.001**
	Residual	23	0.001906	0.0000829		
Chl-a (median)	Depth	1	206.5	206.5	11.98	**0.002**
	Residual	23	396.6	17.24		
Chl-a (max)	Depth	1	1999	1999	6.322	**0.019**
	Residual	23	7272	316.2		
NH_4-N (median)	Depth	1	0.0001333	0.00001333	1.095	0.306
	Residual	23	0.0027999	0.0001217		
NH_4-N (max)	Depth	1	0.004515	0.004515	3.76	0.06
	Residual	23	0.027619	0.001201		
SD	Depth	1	37.6	37.6	10.2	**0.004**
	Residual	23	84.8	3.69		

Table A.10 MANOVA results for TLN, TLP, TLC and TLS, for depth (2 classes) and geomorphic (2 classes) classifications on the 25 Northland dune lakes, using summary statistics for the 2009-2014 period.

Water Quality Indicator	**MANOVA output**						
	Factor	d.f.	Pillai	Approx. F	num DF	den DF	*P*-value
TLN, TLP, TLC,	Geomorphic	1	0.52823	5.5983	4	20	0.003431
	Residual	23					

TLS	Depth	1	0.68668	10.958	4	20	0.000717
	Residual	23					

For comparison, one-way ANOVA demonstrated that the TLI of perched and window lakes was significantly different ($F_{1, 23}$ = 6.22; *p*=0.02). Geomorphic class also apparently explained significant differences in mean TLS and SD ($F_{1, 23}$ = 14.95, 13.27; *p*<0.01 respectively) and TLN and TN ($F_{1, 23}$ = 9.84, 5.53; *p*<0.05 respectively) (Table A.11).

Table A.11 One-way ANOVA results for differences in water quality between 25 window and perched dune lakes. Water quality indicators in bold exhibited significant differences by geomorphology.

Water Quality Indicator	**ANOVA output**					
	Factor	d.f.	SS	MS	*F*-ratio	*P*-value
TLI	Geomorphology Residual	1 23	2.61559.672	2.6160.421	6.22	**0.02**
TLN	Geomorphology Residual	1 23	2.9086.801	2.9080.296	9.84	**0.005**
TLP	Geomorphology Residual	1 23	2.92918.21	2.9290.792	3.70	0.07
TLS	Geomorphology Residual	1 23	3.6885.675	3.6880.247	14.95	**0.0008**
TLC	Geomorphology Residual	1 23	1.10219.096	1.1020.830	1.33	0.26
TN	Geomorphology Residual	1 23	0.2521.049	0.2520.046	5.53	**0.028**
TP	Geomorphology Residual	1 23	0.00001160. 002713	0.00001160. 000118	0.98	0.332
Chl-a (median)	Geomorphology Residual	1 23	8.6594.5	8.625.85	0.33	0.571
Chl-a (max)	Geomorphology Residual	1 23	675373.7	675373.7	1.81	0.192
NH_4-N (median)	Geomorphology Residual	1 23	0.000023880 .0026945	0.0002390.0 00117	2.04	0.167
NH_4-N (max)	Geomorphology Residual	1 23	0.0035850.0 28549	0.003590.00 124	2.89	0.103
SD	Geomorphology Residual	1 23	44.7977.6	44.793.37	13.27	**0.001**

Two-way ANOVA is highly informative, clarifying the relevance of depth as a classifying variable for lake water quality (and the irrelevance of geomorphology in all indicators tested bar TLS and SD). As before, when accounting for the interactions and direct effects between depth and geomorphology, all NOF and TLI parameters, except maximum and median NH_4-N concentrations, were significantly different between deep and shallow lakes. Whereas, only TLS and SD vary significantly between perched and window lakes when the effect of maximum depth is excluded. Two-way ANOVA also indicated that interactions between maximum depth and geomorphic class on differences in average water quality were largely unimportant (Table A-12) – the exception being in TLS where significant differences remained between deep window and deep perched dune lakes (Table A.13). The absence of significant differences in all TLx indicators bar TLS suggests that clarity is influenced by factors other than algal biomass and indirectly, nutrient availability (given their insignificant differences between geomorphic classes), with this additional driver of clarity operating only in deep lakes.

Table A.12 Two-way ANOVA results for differences in water quality between 25 shallow (≤10 m maximum depth) and deep (≥10 m maximum depth), window and perched dune lakes. Factors in **bold** drove significant differences in water quality.

Water Quality Indicator	**ANOVA output** Factor	d.f.	SS	MS	*F*-ratio	*P*-value
TLI	**Depth**	1	6.457	6.457	25.27	<0.001
	Hydrology	1	0.182	0.182	0.71	0.408
	Depth:Hydrology	1	0.282	0.282	1.10	0.305
	Residuals	21	5.366	0.256		
TLN	**Depth**	1	5.479	5.479	30.786	<0.001
	Hydrology	1	0.41	0.41	2.304	0.144
	Depth:Hydrology	1	0.083	0.083	0.466	0.502
	Residuals	21	3.373	0178		
TLP	**Depth**	1	8.127	8.127	13.704	0.001
	Hydrology	1	0.13	0.13	0.219	0.65
	Depth:Hydrology	1	0.429	0.429	0.723	0.41
	Residuals	21	12.454	0.593		
TLS	**Depth**	1	3.116	3.116	16.988	<0.001
	Hydrology	1	1.466	1.466	7.992	0.01
	Depth:Hydrology	1	0.929	0.929	5.063	0.035
	Residuals	21	3.852	0.1834		
TLC	**Depth**	1	10.224	10.224	22.419	<0.001
	Hydrology	1	0.352	0.352	0.772	0.39
	Depth:Hydrology	1	0.045	0.045	0.098	0.76
	Residuals	21	9.577	0.456		
TN	**Depth**	1	0.6487	0.6487	21.805	<0.001
	Hydrology	1	0.0152	0.0152	0.512	0.48
	Depth:Hydrology	1	0.0127	0.0127	0.426	0.52
	Residuals	21	0.6248	0.0298		
TP	**Depth**	1	0.009	0.009	11.252	0.003
	Hydrology	1	0.00002	0.00002	0.272	0.61
	Depth:Hydrology	1	0.00002	0.00002	1.978	0.17
	Residuals	21	0.0017	0.00008		
Chl-a (median)	**Depth**	1	206.5	206.5	11.732	0.003
	Hydrology	1	22.3	22.3	1.268	0.27
	Depth:Hydrology	1	4.6	4.6	0.26	0.62
	Residuals	21	369.7	17.6		
Chl-a (max)	**Depth**	1	1999	1999	5.795	0.03
	Hydrology	1	22	22	0.062	0.80
	Depth:Hydrology	1	7	7	0.019	0.89
	Residuals	21	7243	344.93		
NH_4-N (median)	Depth	1	0.00013	0.00013	1.047	0.32
	Hydrology	1	0.0013	0.0013	0.992	0.33

	Depth:Hydrology	1	0	0	0	0.99
	Residuals	21	0.0027	0.0001		
NH_4-N (max)	Depth	1	0.0045	0.0045	3.602	0.07
	Hydrology	1	0.0010	0.0010	0.762	0.39
	Depth:Hydrology	1	0.0003	0.0003	0.271	0.61
	Residuals	21	0.0263	0.0013		
SD	**Depth**	1	37.6	37.6	14.925	<0.001
	Hydrology	1	17.9	17.9	7.104	0.01
	Depth:Hydrology	1	14.0	14.0	5.56	0.28
	Residuals	21	52.9	2.52		

Table A.13 Tukey HSD results for each TLI and NOF water quality indicator, highlighting the lack of significant differences between shallow window or perched lakes, and between deep window and deep perched lakes (except for TLS). The results highlighted in bold indicate significant differences between window and perched lakes of the same depth class.

Interaction	**Tukey HSD**	**TLI**	**TLN**	**TLP**	**TLS**	**TLC**	**TN (mg/L)**	**TP (mg/L)**	**Chl-a (median) (mg/L)**	**SD (m)**
Deep, window – deep, perched	Mean Difference	-0.43	-0.44	-0.45	**-1.00**	-0.20	-0.11	-0.003	1.43	**3.65**
	Adj. p.	0.56	0.41	0.80	**<0.01**	0.97	0.20	0.95	0.95	**<0.01**
Shallow, window – shallow, perched	Mean Difference	0.10	0.15	0.20	-0.04	0.41	0.00	0.01	3.56	-0.09
	Adj. p.	0.23	0.97	0.99	0.99	0.85	0.99	0.51	0.68	0.99

One-way ANOVA tests revealed differences in average TLI between sub-regions are insignificant ($F_{1, 23} = 2.318$; $p = 0.14$). Whilst sub-regional significant differences exist in TLN ($F_{1, 23} = 5.182$; $p = 0.008$), TLP ($F_{1, 23} = 8.475$; $p < 0.001$), TLS ($F_{1, 23} = 14.2$; $p < 0.0001$) and TLC ($F_{1, 23} = 5.445$; $p = 0.006$), post-hoc tests indicated that the significant differences arose from the oligo/mesotrophic Kai-Iwi lakes being less enriched than Aupouri, Pouto and Central lakes (i.e., that the Kai-Iwi lakes are significantly less enriched than any other sub-region but that the other three sub-regions are insignificantly different). Given earlier findings on the significance of depth-driven differences across all regions and that all three Kai-Iwi lakes are deep, any sub-regional effect on water quality is more likely a depth-driven effect. These results indicate that a simple sub-regional geographically-based classification is not as justifiable as a classification approach based on depth.

Taken together one- and two-way ANOVA results indicate that the proposed lake management classification scheme based on maximum depth effectively groups lakes of differing and similar water quality. However, bottom-up hierarchical clustering of the 12 NOF and TLI indicators generated a different classification structure. This suggests that factors other than and in addition to those associated with depth are driving differences in contemporary water quality. Of the six linkage functions tested, average-linkage (UPGMA) offered lowest Gower distance (458) and greater similarity to the original Euclidean distance matrix (r_{Coph} = 0.66) and was therefore selected. From an associated fusion-level plot about 4-5 lake clusters appear meaningful. The resulting dendrogram is presented in Figure A.7. The associated confusion matrix (Table A.14) demonstrates a lack of concordance between the clusters and management classification with 58% being non-concordant.

The cluster analysis indicates that the patterns in lake water quality are complex and that the grouping implied by the management classification imperfectly explains the observed variation. However, the analysis presented above indicates that the single variable, depth, nonetheless explains a large and significant amount of this variation, and is an effective basis for classifying the region's lakes for water quality management.

Table A.14 Confusion matrix comparing the five management (top-down) and average-linkage, Euclidean distance (bottom-up) lake clusters, derived from 26 Northland lakes using the full suite of NOF and TLI indicators.

Number of lakes in each grouping system			**Bottom-up, average-linkage groups**				
			1	2	3	4	5
Top-down, functional groups	Perched	Shallow	7	1	5	0	0
		Deep	4	0	0	0	0
	Window	Shallow	1	0	1	0	0
		Deep	4	0	0	2	0
	Volcanic		0	0	0	0	1

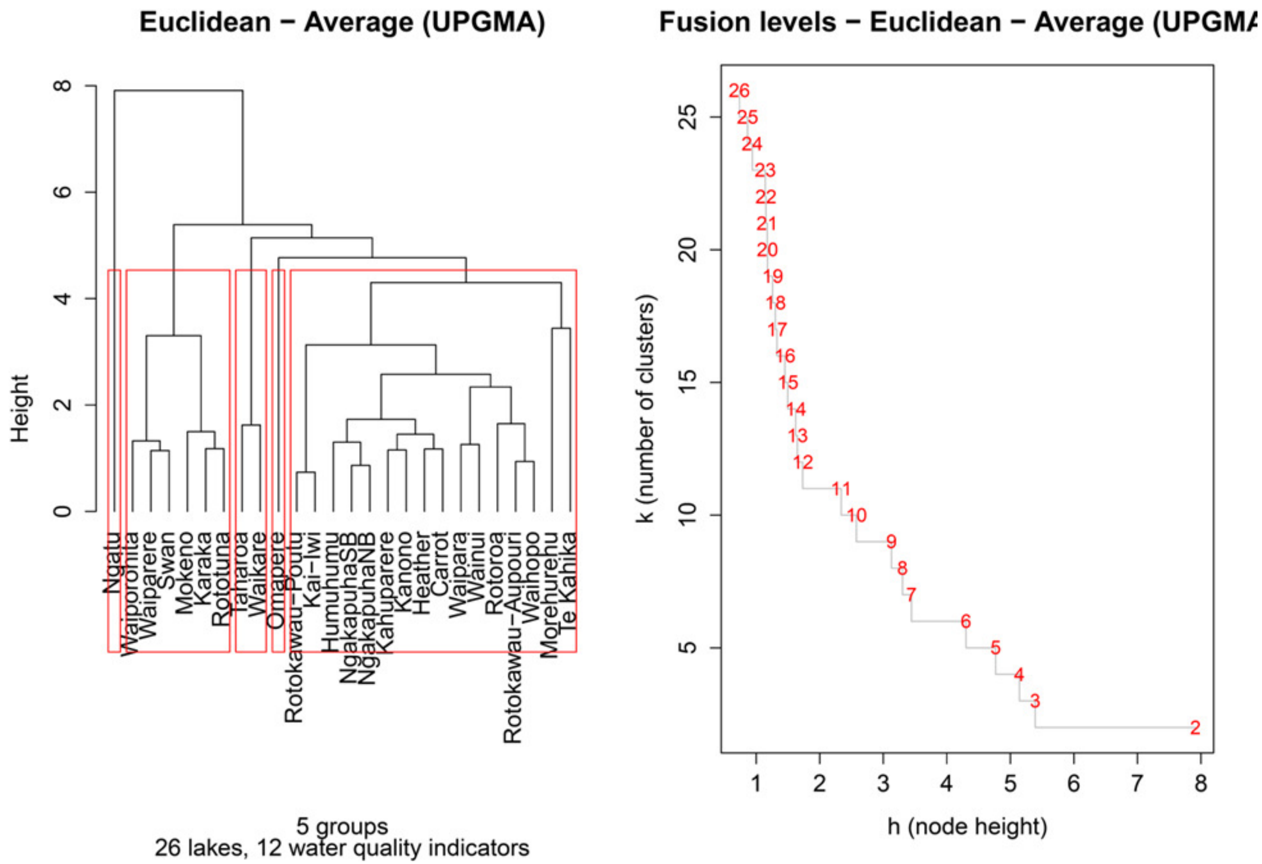

Figure A.7 Average-linkage cluster dendrogram on 12 NOF and TLI indicators, across 26 Northland lakes. The associated fusion-level plot suggests 4-5 clusters are meaningful.

A2.3 Water Quality Drivers

The regression models relating water quality to physical characteristics of lakes performed well. Linear models for all 10 NOF and TLI water quality indicators (excluding NH_4-N) were significant (p<0.05) with an adjusted R^2 ranging between 0.51 to 0.87 (Table A.15).

Linear models for water clarity (SD) and TLS both explained nearly 90% of the variation between lakes (adj.R^2 = 0.86 and 0.87, p<0.0001). The poorest performing linear model, maximum Chl-a, still explained nearly 50% of the variation between lakes (adj.R^2 = 0.51, p=0.001) and was improved upon by the model structure for median Chl-a (adj.R^2 = 0.61, p=0.0001). Moderate performance was also generated by linear models for algal biomass, both median and maximum Chl-a (adj.R^2 = 0.61 and 0.63, p=0.0001) as well as TLC (adj.R^2 = 0.61, p=0.0001). Linear models for TLN performed better than TN (adj.R^2 = 0.71 and 0.60, p=0.0001).

We caution against the 10 linear models being applied more widely despite the relatively good performance because it is not clear that the 26 training lakes are representative of those unmonitored lakes[15]. In addition, given the uncertainty surrounding the true extent of groundwater-fed window lakes meaning any estimate of percentage land cover is equally uncertain, the linear models require re-examination with refined catchment boundary information, preferably for perched lakes only.

The linear models are most useful for informing which factors may produce efficient lake classifications. Those significant predictors highlighted consistently across the 10 NOF and TLI linear models are likely to be effective at successfully classifying lake water quality.

Despite differences in their model structure four factors were consistently included as predictors of both TLS and SD: catchment phosphorus subsoil content (catPhos; p<0.0001), lake elevation (lkElev; p<0.05), a proxy for clarity (ClarityProxy; p<0.01) and maximum Depth (maxDepth; p<0.0001). Bearing in mind the different normalising transformations required of SD and TLS, both linear models suggest that greater inputs of phosphorus (greater catPhos = greater background P-loading from erosion or dissolution) coupled to lower maximum depth, result in poorer clarity (lesser SD and higher TLS). Whilst uncertain of the underlying mechanism(s) by which lake elevation affects clarity, this is likely indirect, through some association with geology, land use or climate.

TLN and TN model structures were the simplest, involving two consistent variables; lake area (lkArea; p = 0.07, 0.02) and maximum depth (p<0.0001) (note: lake area was an insignificant predictor for TLN but residuals of the simpler model were significantly larger than the linear model that included lake area only). Greater maximum depth coupled to smaller lake area is associated with lower nitrogen concentrations.

TLP and TP models involve 4 and 7 catchment and in-lake predictors, respectively. Of these, percentage exotic forestry cover (ExForest; p = 0.06-0.05), catchment phosphorus subsoil content (p = 0.09-0.003) and maximum depth (p<0.0001) were all significant variables affecting phosphorus concentrations, with percentage pasture cover approaching significance (i.e., without which predicted TP and TLP altered significantly; p = 0.09-0.08). Higher phosphorus concentrations occurred in lakes with greater relative pastoral and exotic forestry, catchment phosphorus subsoil content and lesser maximum depth.

[15] We recommend extending the linear models developed here to the wider unmonitored lake network following assessment of catchment and in-lake characteristics of those lakes, testing whether the gradients covered by the 26 training set lakes are sufficient for predictive purposes.

TLC and both median and maximum Chl-a models included between 4 and 5 predictors, of which exotic forest percentage cover (p = 0.01-0.26), pasture percentage cover (p = 0.11-0.03) and maximum depth were significant (p<0.01). Greater algal biomass occurs in lakes with greater exotic forestry cover, pastoral cover and lower depth..

Taken across all ten NOF and TLI indicators, maximum depth is the only consistent, significant predictor of water quality (p<0.002). . Maximum depth is inversely associated with nutrient availability, algal biomass, TLI and TLx. Deeper lakes have higher clarity.

The results suggest that internal lake processes associated with depth are a key determinant of water quality, altering any baseline from which subsequent external nutrient loads associated with pasture and exotic forestry cause further change. Other factors that appear to be associated with water quality include the underlying catchment geology (e.g., subsoil phosphorus content, hardness)[16].

[16] A caveat applies to this interpretation. Earlier filtering for collinear or correlated predictors, means any VIF-excluded water quality driver could if correlated to those significant predictors, be responsible for some of the effect. Fortunately, Table 5.4-16 demonstrates that maximum lake depth is not strongly correlated with any predictors excluded for collinearity (i.e., the effect assigned max depth does not suffer from shared effect of VIF-excluded catchment predictors).

Table A.15 Linear model regression structures selected from backward, modified stepwise linear regression. Steps from full suite of 17 weakly-collinear (VIF≤10) catchment and in-lake predictors. Responses are 2009-2014 average TLI and TLx or median TN, TP, SD, or median and maximum Chl-a, observed over 26 Northland lakes.

Water Quality response	**Model structure**	**Model Performance** Adj. R^2 (R^2)	**Sig. (*P*)**
TLI (average)	TLI~99.17-5.03*Nload-2.03*lkElev+2.22vegRemoval+1.4*ExForest-74.57*maxDepth	0.71 (0.76)	<0.0001
TLN (average)	TLN~-719.27-24.64*catHard+592.03*lkArea-72.64*maxDepth	0.71 (0.74)	<0.0001
TLP (average)	TLP~49.79+65.84*catPhos+1.14*pastPCT+5.20*ExForest-63.26*maxDepth	0.58 (0.65)	0.0001
TLS (average)	TLS~35.46+91.51*catPhos-6.65*lkElev+4.01*ClarityProxy+1.35*ExForest-38.04*maxDepth	0.87 (0.90)	<0.0001
TLC (average)	TLC~95.04-6.12*Nload+1.03*pastPCT+3.84*vegRemoval+6.26*ExForest-86.13*maxDepth	0.61 (0.69)	0.0001
TN (median)	TN~-13.10+10.10*lkArea-0.89*maxDepth	0.60 (0.63)	<0.0001
TP (median)	TP~0.09+0.00075*pastPCT-0.0050*lkElev-0.044*MeanWind+0.0024*vegRemoval+0.0048*ExForest-0.058*maxDepth+0.035catPhos	0.67 (0.76)	0.0001
SD (median)	SD~1.45+1.69*catPhos-0.80*catHard-0.09*lkElev+0.09*catSlope+0.15*ClarityProxy-0.84*maxDepth	0.86 (0.89)	<0.0001
Chl-a (median)	Chla~2.79+0.06*PastPCT+0.26*ClarityProxy+0.18*vegRemoval+0.29*ExForest-2.89*maxDepth	0.61 (0.69)	0.0001
Chl-a (max)	Chla~2.022-0.026*PastPCT-2.238*lkArea-0.076*ExForest-0.113catSlope+1.686*maxDepth	0.52 (0.61)	0.001

Table A.16 Kendall's tau (rank) correlation coefficient of collinear variables (VIF-excluded) by significant (p<0.05) water quality predictors in backwards stepwise linear regressions.

Water Quality Indicator	catArea	catPerim	catPsize	catAnnTemp	HighGrass	catJuneSolRad	catDecSolRad	catElev	Rtime
Nload	0.58	0.58	0.25	-0.21	0.03	-0.50	-0.30	0.11	-0.08
VegRemoval	0.10	0.09	-0.01	-0.14	0.13	-0.31	-0.35	0.10	0.11
pastPCT	-0.06	-0.04	-0.27	0.11	0.93	0.03	-0.09	-0.10	-0.06
ExForest	0.11	0.08	0.24	-0.10	-0.63	-0.04	0.13	0.08	-0.11
catSlope	0.31	0.28	0.46	-0.31	-0.35	-0.25	-0.18	0.22	-0.19
catHard	0.01	0.05	0.84	-0.33	-0.43	-0.25	-0.15	0.32	-0.13
catPhos	-0.29	-0.25	0.40	-0.03	0.04	0.15	0.01	0.17	-0.38
ClarityProxy	0.05	0.11	0.01	0.21	-0.18	-0.02	0.25	-0.31	0.19
MeanWind	-0.39	-0.39	-0.31	0.52	-0.05	0.25	0.41	-0.32	0.16
lkArea	0.47	0.41	-0.11	-0.04	0.00	-0.19	-0.19	-0.05	0.33
lkElev	0.08	0.03	0.21	-0.54	-0.02	-0.18	-0.43	0.66	-0.06
maxDepth	0.30	0.25	-0.05	-0.31	-0.04	-0.24	-0.26	0.20	0.29

Appendix B Management Classifications for Northland Lakes

Lake	FENZ LID	FENZ Max Depth	Max Measured Depth	Depth Class	Geomorphic Class	Management Classification
Waitahora Lagoon	-				Perched	
Waitahora Lake	24434	3.8		Shallow	Perched	Shallow-Perched
Te Werahi Lagoon	21450 / 21444 / 21448				Perched	
Ngakaketa North	21434	7.0		Shallow	Perched	Shallow-Perched
Ngakaketa North	21433	8.7		Shallow	Perched	Shallow-Perched
Te Paki dune	19585	0.0		Shallow	Perched	Shallow-Perched
Austria	19567	0.0		Shallow	Perched	Shallow-Perched
Ngatuwhete	19576	0.0		Shallow	Artificial	Deep Perched
Pretty	19559	0.0		Shallow	Perched	Shallow-Perched
Waipara/Dead	19575	0.0	4.43	Shallow	Perched	Shallow-Perched
Te Kahika	24633	11.0	11.06	Deep	Perched	Deep Perched
Te Kahika South	24632	3.0		Shallow	Perched	Shallow-Perched
Kihona	24621	8.3		Shallow	Perched	Shallow-Perched
Morehurehu	24628	14.0	14.91	Deep	Perched	Deep Perched
Morehurehu South 1	-				Perched	
Wahakari	24620	12.0		Deep	Perched	Deep Perched
Morehurehu South 2	-			Shallow	Perched	Shallow-Perched
Taeore	24619	3.2		Shallow	Perched	Shallow-Perched
Te Arai Ephemeral Wetland/Pond	-			Shallow	Perched	Shallow-Perched
Te Arai Lake	24594	8.7		Shallow	Perched	Shallow-Perched
Salt	24605	8.5		Shallow	Perched	Shallow-Perched
Bulrush	24596	16.1		Deep	Perched	Deep Perched
Waihopo	24511	7.0	3.74	Shallow	Perched	Shallow-Perched
Waiparera	13467	6.0	5.16	Shallow	Perched	Shallow-Perched
Katavich	13466	11.3		Deep	Perched	Deep Perched
Forest Lake/Deans Swamp	18720	0.0		Shallow	Perched	Shallow-Perched
Yelavich	13463	4.7		Shallow	Perched	Shallow-Perched
Ngakapua	18717 / 18718		8.32/5.46	Shallow	Perched	Shallow-Perched
Rotokawau	18719	0.0	3.35	Shallow	Perched	Shallow-Perched
Carrot	23690	3.0	7.94	Shallow	Perched	Shallow-Perched
Ngatuwhete	23691	6.5	6.26	Shallow	Perched	Shallow-Perched
West Coast Road	23689	8.9		Shallow	Perched	Shallow-Perched
Little Gem	-			Shallow	Perched	Shallow-Perched
Heather	23682	5.6	6.81	Shallow	Perched	Shallow-Perched
Rotoroa	23681	8.0	7.26	Shallow	Perched	Shallow-Perched
Mini/Split	23676	6.7		Shallow	Perched	Shallow-Perched
Waimimiha North	23660	6.3		Shallow	Perched	Shallow-Perched
Waimimiha South	23657	2.0		Shallow	Perched	Shallow-Perched

Rotokawau West	24422	2.5		Shallow	Perched	Shallow-Perched
Rotokawau East	24423	2.5		Shallow	Perched	Shallow-Perched
Waiporohita	24415	3.0	3.45	Shallow	Perched	Shallow-Perched
Rotopokaka	19509	0.0		Shallow	Perched	Shallow-Perched
Omapere	23721	2.6	6.53	Shallow	Volcanic	
Owhareiti	24039	49.9		Deep	Volcanic	
Jacks/Owaheiti Lagoon	24024	6.5		Shallow	Artificial	
Kaiwai	24015	24.1		Deep	Alluvial	
Tauanui	24001	24.2		Deep	Volcanic	
Horahora Dune	-			Shallow	Perched	Shallow-Perched
Waro	23994	18.0		Deep	Artificial	
Ora	23863	23.0		Deep	Volcanic	
Waingata	23314	7.3		Shallow	Perched	Shallow-Perched
Te Riu	23306	10.4		Deep	Perched	Deep Perched
Shag	21912	23.9		Deep	Window	Deep Window
Waikere	21926	30.0	29.48	Deep	Window	Deep Window
Taharoa	21917	37.0	38.81	Deep	Window	Deep Window
Kai-Iwi	21918	16.0	15.65	Deep	Window	Deep Window
Midgeley	21814	15.0		Deep	Perched	Deep Perched
McEvoy	-			Shallow	Perched	Shallow-Perched
Grevilles Lagoon	21773	11.2		Deep	Perched	Deep Perched
Kapoai	21759	12.0	9	Shallow	Perched	Shallow-Perched
Parawanui	21760	5.0		Shallow	Perched	Shallow-Perched
Wainui	17761	0.0	10.53	Deep	Perched	Deep-Perched
Rototuna	50345	5.0	4.04	Shallow	Perched	Shallow-Perched
Wairere	50336	5.0		Shallow	Perched	Shallow-Perched
Phoebe's	50326	21.6		Deep	Window	Deep Window
Karaka	50320	5.0	7.59	Shallow	Perched	Shallow-Perched
Rotopouua	50405	12.3		Deep	Window	Deep Window
Humuhumu	50401	15.0	15.22	Deep	Window	Deep Window
Roto-otauauru/Swan	50403	5.5	5.38	Shallow	Window	Shallow-Window
Mokeno	50314	5.5	6.53	Shallow	Perched	Shallow-Perched
Rotokawau	50413	11.0	12.96	Deep	Window	Deep Window
Waingata	50377	7.0		Shallow	Window	Shallow-Window
Kanono	50373	14.0	15.59	Deep	Window	Deep Window
Kuhuaparere	50371	7.5	7.61	Shallow	Window	Shallow-Window
Whakaneke	50309	3.2	3.20	Shallow	Perched	Shallow-Perched