# Technical advice for environmental monitoring and nutrient modelling in Lake Ngātu

*Prepared for MBIE Envirolink and Northland Regional Council*

*February 2024*

Prepared by:
Anika Kuczynski, James Griffiths, Aidin Jabbari

For any information regarding this report please contact:

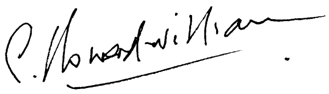
Anika Kuczynski
Water Quality Modeller
Freshwater Modelling
+64 3 343 8023
anika.kuczynski@niwa.co.nz

National Institute of Water & Atmospheric Research Ltd
PO Box 8602
Riccarton
Christchurch 8440

Phone +64 3 348 8987

NIWA CLIENT REPORT No: 2024011CH
Report date: February 2024
NIWA Project: ELF24201

| Revision | Description | Date |
|---|---|---|
| Version 1.0 | Draft sent to client | 24 January 2024 |
| Version 2.0 | Revised version sent to client | 19 February 2024 |
| Version 3.0 | Final version sent to client | 27 February 2024 |

| Quality Assurance Statement | | |
|---|---|---|
|  | Reviewed by: | Clive Howard-Williams |
|  | Formatting checked by: | Rachel Wright |
|  | Approved for release by: | Helen Rouse |

# Contents



## Tables

## Figures

# Executive summary

Northland Regional Council (NRC) contracted NIWA via an Envirolink Medium Advice Grant to provide technical advice on environmental monitoring, model input requirements, and an action plan and cost estimate for nutrient modelling for Lake Ngātu. The work plan, as agreed with NRC, and outcomes are as follows:

1. Hold project initiation meeting (video conference) to ensure that existing reports and data are noted and plans for transferring them are made, and to discuss the work items. Provide a record of items, discussion points, and actions.

   <u>Outcome</u>: An online project initiation meeting was held on 11 September 2023 with Susie Osbaldiston and Manas Chakraborty from NRC and Sandy Elliott, Jim Griffiths, Aidin Jabbari, and Anika Kuczynski from NIWA. We discussed the work plan and which reports and data were to be reviewed. NRC agreed to provide the reports and available environmental datasets.

2. Review the existing lake water balance modelling report, hydrogeology assessment report in relation to their suitability for identifying lake budgets and supporting appropriate modelling.

   <u>Outcomes</u>:

   - The Water Management Group water balance modelling report (2016) suggests that water level records should be revisited due to vandalism of the water level gauge during the monitoring and analysis period predating 2011 and that the model should be verified when additional lake water level data became available. A conversion factor should be determined for this period (2004–2010) to adjust readings, which will improve agreement between the water balance model output and observed water levels. Rainfall was the main inflow term (greater than runoff), while evaporation was the main loss term (greater than groundwater losses). We agree that the water balance should be recalculated using more recently collected water level data (from 2017 onwards).

   - The GNS report (2013) indicates that Lake Ngātu is believed to have formed from an elevated deflation hollow, becoming a sealed basin perched on an impermeable layer and isolated from regional groundwater variability. The average lake water level is 35 masl, compared to the regional groundwater level of 6–15 masl. There are seven bore holes around the lake in the Aupōuri aquifer, indicating that occasionally a groundwater dome may be produced by slow vertical seepage through the lake sediments or from areas around the lake margin when the lake is closer to its capacity. We agree that piezometers should be installed to provide more detailed information of the hydraulic gradients around the lake and with depth. A cluster of three depth-integrated piezometers (if preferred to nested piezometers), as recommended by the previous GNS study would provide information about the vertical hydraulic gradient. The advantage of placing this in the vicinity of the wetland area to the northeast of the lake is that it would provide information about wetland connectivity with deeper groundwater (which is analogous to the lake's relationship with deeper groundwater). In addition, eight shallow piezometers should be placed around the lake to characterize lateral heterogeneity of the shallow groundwater and its relationship with lake level fluctuation. We also recommend groundwater quality measurements at any installed boreholes.

3. Review existing data on inflows and lake modelling, existing monitoring programmes in relation to lake inflows and lake budget and modelling needs.

   Outcomes:

   - Existing data includes meteorological data (precipitation, relative humidity, wind speed and direction, cloud cover, solar radiation), lake water level, quarterly groundwater quality data for four bores (e.g., nutrients, metals), and monthly lake water quality data (e.g., nutrients, dissolved oxygen, and chlorophyll *a*).

   - Lake Ngātu is considered of high quality in terms of the Lake Submerged Plant Indicators (LakeSPI, 56.5%), with 20 native macrophyte species and five exotic species. Limited macrophyte biomass data are available.

   - In terms of water quality, Lake Ngātu is mesotrophic and tending toward eutrophic, indicating deterioration in terms of nutrient concentrations and potential for algal blooms.

   - No lake sediment data are available. We recommend collecting at least one sediment core (10 cm depth) to determine sediment nutrient and metal content (see **Error! Reference source not found.** for details). Alternatively, NRC could contact the Lakes380 team (Cawthron Institute), which has collected a core and may allow additional sample analysis.

   - Determining the role of groundwater and its potential contribution to lake nutrient cycling is key. We recommend monitoring for characterisation of shallow groundwater variability around the lake and connectivity to lake level (at least 8 piezometers (at 5 m and 10 m) monitored at least monthly) and a depth integrated piezometer cluster (10 m, 50 m, 90 m) to the northeast of the lake. We also recommend collecting groundwater quality data from existing and any new bores (see Table 5-1).

4. Site visit to examine potential monitoring locations.

   Outcomes:

   - During the site visit on 24 October 2023, it was raining, and the field team anecdotally noted that Lake Ngātu's water level was close to its highest recorded level. Roadside drainage ditches serve as sediment traps for runoff along the north and east sides of the lake. There were several Macrocarpa stumps, indicating removal of exotic vegetation. After rainfall, surface runoff from properties around the lake may act as small point source discharges, with the school on the east side thought to be the largest of these. In addition, if there is shallow groundwater connectivity to the lake, then septic leach field infiltration may be important. Private properties have water supply boreholes drawing from deeper groundwater (as deep as >80 m below ground level, pers. comm. Hagen Robertson).

   - It was determined that a depth-integrated piezometer cluster should be installed northeast of the lake to assess the extent of groundwater recharge from the northeast direction and shallow piezometers around the lake to assess shallower groundwater connectivity to the lake level, and response after rain events. If it is determined that there is shallow groundwater seepage into to the lake, then potential leachate from the school and other surrounding septic fields needs to be considered.

5. Produce a report providing technical advice on additional groundwater data assessment and additional monitoring to enable establishment of nutrient budgets and to support modelling of nutrient budgets. This report will clearly state what is to be monitored, when, where, and at what frequency, and for how long. If appropriate, a staged approach for future work will be provided, whereby additional monitoring is contingent on achieving milestones and review of earlier results. The advice will also be transferrable and provide input requirements for in land nutrient load modelling for other dune lakes.

   <u>Outcome</u>: In this report, we provide the following recommendations:

   - Establishment of a cluster of piezometers (10 m, 50 m, 90 m) in the wetland to the northeast of the lake to determine the vertical pressure gradient of shallow and deep groundwater. Establish eight shallow (at 5m and 10 m) piezometers around the lake to assess the potential for lateral inflow and nutrient flows to the lake.
   - Collection of additional lake water quality and groundwater quality data as specified in this report.
   - Development of a linked catchment-lake water quality model (SWAT-PCLake).

6. The report is to provide additional advice on costs for setting up and running in-lake nutrient load modelling for Lake Ngātu that is appropriate for Northland.

   <u>Outcome</u>:

   We suggest developing a catchment model (e.g., SWAT) to simulate nutrient loads from overland runoff after rainfall, linked to a lake water quality model (e.g., PCLake/PCLake+) that simulates nitrogen and phosphorus dynamics in Lake Ngātu. Model input requirements are listed, and these inform our monitoring recommendations. We suggest simulating at least two years with available data, so that one year of data can be used for model calibration and another year of data for model validation.

# 1 Introduction

The aim of this project was to provide technical advice to NRC with respect to nutrient monitoring and modelling of Lake Ngātu. We reviewed the existing relevant monitoring data and made recommendations for additional monitoring to support future in-lake nutrient modelling. A lake model of Lake Ngātu could be used to gain a better understanding of nutrient dynamics in other shallow dune lakes and in identifying important nutrient sources. Such understanding could enable implementation of mitigative measures to safeguard or improve lake water quality and could also be applied to other shallow dune lakes in the region.

## 1.1 Background

There are several shallow dune lakes in Northland, and Lake Ngātu is one of the more extensively monitored of these. Dune lakes are found in dune ecosystems close to the coast and are often closed systems with no permanent lake inlets or outlets. Lake Ngātu was selected as a focus lake for nutrient modelling to gain a better understanding of nutrient concentrations in Northland dune lakes, what affects in-lake nutrient concentrations, and what can lead to eutrophication[1]. Ultimately, a lake model would be used to 1) identify key drivers or processes that control in-lake nutrient levels, 2) determine the ecosystem response, 3) test potential measures to reduce nutrient loads, and 4) potentially develop target nutrient states in accordance with the National Policy Statement for Freshwater Management (NPS-FM) for dune lakes. A lake water quality model could also be used to determine the effect of different land uses (e.g., type or intensity of agriculture) on lake water quality state.

NRC has a robust monitoring programme for Lake Ngātu and commissioned several reviews and a water balance study in preparation for future lake modelling. This review is intended to provide technical advice based on previous work, available data, and future modelling goals.

## 1.2 Objectives

The objectives of this study were to:

1. Hold project initiation meeting (video conference) to ensure that existing reports and data are noted and plans for transferring them are made, and to discuss the work items. Provide a record of items, discussion points, and actions.

2. Review the existing lake water balance modelling report, hydrogeology assessment report in relation to their suitability for identifying lake budgets and supporting appropriate modelling.

3. Review existing data on inflows and lake modelling, existing monitoring programmes in relation to lake inflows and lake budget and modelling needs.

4. Site visit to examine potential monitoring locations.

5. Produce a report providing technical advice on additional groundwater data assessment and additional monitoring to enable establishment of nutrient budgets and to support modelling of nutrient budgets. This report will clearly state what is to be monitored, when, where, and at what frequency, and for how long. If appropriate, a staged approach for

[1] Nutrient enrichment (particularly nitrogen and phosphorus) resulting in increased primary production (algal blooms) and decreases in water clarity.

future work will be provided, whereby additional monitoring is contingent on achieving milestones and review of earlier results. The advice will also be transferrable and provide input requirements for in land nutrient load modelling for other dune lakes.

6. The report is to provide additional advice on costs for setting up and running in-lake nutrient load modelling for Lake Ngātu that is appropriate for Northland.

Objective 1 was completed in September 2023 and informed subsequent objectives.

Objectives 2 and 3 are addressed in section 2, where we review existing monitoring and management plans (Chakraborty 2022), monitoring strategy recommendations (Champion 2021), a GNS hydrogeology report (Moreau et al. 2013), and a report by the Water Management Group (2026).

Objective 4 was completed in October 2023. Notes from the site visit are included in Appendix A and this information informs our recommendations (objective 5).

Objective 5 is addressed in sections 3, 4, and 0 where we provide technical advice for monitoring (section 3), technical advice for modelling (section 4), and specific recommendations for next steps (section 0).

Objective 6 is addressed in section 0, where we provide a cost estimate for setting up and running a lake nutrient model for Lake Ngātu.

The overall purpose of reviewing previous studies, data, and making recommendations for nutrient budget modelling is based on a desire to inform optimal lake management, which will minimise nuisance and toxic algal blooms and maintain or improve ecosystem health (e.g., considering fish and macrophytes) and aesthetics (e.g., lake water clarity)

## 1.3 Scope

The monitoring advice sought by NRC is to ensure that the council collects appropriate data to improve understanding of nutrients in Northland dune lakes and model processes driving in-lake nutrient concentrations. This improved understanding will enable focussed mitigative measures to be implemented to maintain or improve lake water quality in Lake Ngātu and other dune lakes in Northland.

The scope of this advice includes review of NRC's current monitoring programme (existing data) and the four provided technical reports (Chakraborty 2022, Champion 2021, Moreau et al. 2013, Water Management Group 2016), recommendations for additional environmental monitoring and a strategy for lake nutrient modelling, and a cost estimate for model development and application.

Data analysis, extensive review of lake modelling options, and modelling *per se* are outside the scope of this work.

# 2 Review of previous studies and existing data

Lake Ngātu is a dune lake located northwest of Kaitaia in Northland. It has a maximum depth of ~6 m and is 55.54 ha in surface area in a 177.9 ha catchment (including the lake area). The northern half of the lake is shallow, and the two southern basins are deeper. There are two small islands on the east side.

Results from the recent Lakes380 programme suggest that "prior to human settlement Lake Ngātu was surrounded by native forest abundant in rimu, other tall podocarps and kauri", and post-European settlement, "native trees were replaced by grasses, and exotic trees such as pine were planted in the region. Algae have always been present in the lake, but there has been a sharp increase in levels in the last about 100 years" (Lakes380 Lake Ngātu factsheet).

Meteorological data (air temperature, precipitation, relative humidity, wind speed and direction, cloud cover, shortwave radiation) are available from a meteorological station and precipitation gauge at Kaitaia Airport and another precipitation gauge at Forest HQ (8.5 km and 1.6 km from Lake Ngātu, respectively).

NRC collects lake water quality data by profiling, continuous sampling (buoy), and grab sampling for State of the Environment (SOE) monitoring. The collected data includes Secchi disk depth (Secchi), pH, conductivity, turbidity, salinity, water temperature, concentrations of chlorophyll *a*, dissolved oxygen (DO), dissolved organic carbon (DOC), ammoniacal nitrogen ($NH_4$-N), nitrate nitrogen ($NO_3$-N), total Kjeldahl nitrogen (TKN), dissolved organic nitrogen (DON), total nitrogen (TN), dissolved reactive phosphorus (DRP), dissolved organic phosphorus (DOP), total phosphorus (TP), total suspended sediments (TSS), *Escherechia coli* (*E. coli*), and total cyanobacteria biovolume (cyano-tot) and cell count. Aupōuri Aquifer groundwater quality was measured at four bores (109993, 102039, 101820, and 106737, Table 2-1, Appendix B) with 33 to 108 m depth as part of the SOE Monitoring Network. Bore 102039 was shared with the National Groundwater Monitoring Programme (NGMP). Samples were collected annually or quarterly at the SOE bores during 1990–2013 and quarterly at bore 102039 by NGMP during 1998–2013. The nutrient concentration in the groundwater at these bores was generally low and the dissolved oxygen was less than 4 mg $L^{-1}$ (Appendix B).

**Table 2-1: Inventory of existing data for Lake Ngātu.**

| Data type | Location | Temporal resolution/ start/end | Notes |
|---|---|---|---|
| Precipitation only | Aupōuri Forest at Forest HQ (530204) | Monthly from 15 Sept 1989, daily from March 1967 to present | Manual gauges |
| | Waiharara (439201) | Daily from 1 Jun 1956 – present | |
| Meteorological data: Precipitation and air temperature, evapotranspiration, evaporation, relative humidity, wind speed and direction, cloud cover, | Kaitaia EWS (531207)<br>Kaitaia Aero EWS (530206) | 531207: 10 min resolution from 17 Dec 1998 to present<br>530206: 10 min resolution from 23 Feb 2000 to present | Electronic weather station (EWS) |
| | Kaitaia Airport AWS (530208) | 530208: Hourly from 16 Nov 2017 to present | Automatic weather station (AWS) |

| Data type | Location | Temporal resolution/ start/end | Notes |
|---|---|---|---|
| shortwave (solar) radiation | | | |
| Lake level | Western Acres staff gauge on west side of lake as indicated in Figure 2.12 of Moreau et al. (2013)<br>Easting: 16617846<br>Northing: 6123202 | ~monthly (1987–2017) and 30 min and more recently 15 min interval since 2017 to present | Lake water level - continuous with telemetered water level sensor |
| Lake water quality: nutrients, phytoplankton biomass, dissolved oxygen, suspended solids, *E. coli*, conductivity, salinity, pH | 35.0358°S 173.1985°E<br>Surface grab samples | SOE monthly monitoring: $NH_4$-N, $NH_4$-N pH adjusted $NO_3$-N, $NO_2$-N, DIN, TDN, TN, DRP, DOP, TP, DOC, CDOM, turbidity, TSS, VSS, inorganic SS, *E. coli*<br><br>$NH_4$-N, chl *a*, DO, DRP, $NO_3$-N, Secchi, TN, TP, TSS, pH: quarterly in Dec 2005 – Nov 2021, monthly in Jan 2022 – Jun 2023<br><br>Cyano-tot: Aug 2018, and monthly in Jan 2022 – Jul 2023<br><br>*E. coli*: 1 sample in 2016, quarterly in 2020 – 2021, monthly in Jan 2022 – Jul 2023<br><br>DO: daily 28/09/2022–20/03/2023 | NRC Lakes Water Quality Monitoring Plan (Chakraborty 2022) |
| | Depth profiles at the maximum depth of the SOE sampling locations (see above) | Chl *a*, dissolved oxygen, specific conductivity, total algae (phycocyanin), cyanobacteria phycocyanin, total dissolved solids, pH, temperature, turbidity measured quarterly 13/11/2018–20/06/2023 | |
| | Easting: 1618107<br>Northing: 6122973 | Continuous (15 min interval) time series of water temperature and DO: 27/09/2022–16/11/2023<br><br>DO (% saturation): 3/10/2022–11/09/2023<br><br>Conductivity at 25°C, salinity, turbidity: 27/07/2023–16/11/2023 | NRC buoy data |
| Groundwater quality | Waipapakauri (323844) | Quarterly/biannually<br>323844: 2019 – current | Both from the deep shellbeds |

| Data type | Location | Temporal resolution/ start/end | Notes |
|---|---|---|---|
| | Waimanoni (106737)<br>Paparore (102039) | 106737: 2003 – current<br>102039: 1996 – current | 323844: 3 km west<br>106737: 5 km east<br>102039: 5 km North |
| Groundwater quality (GNS report): total solids, dissolved oxygen, pH, ammonium, bicarbonate, boron, bromine, calcium, chloride, fluorine, magnesium, nitrate-nitrogen, nitrite-nitrogen, dissolved reactive phosphorus, potassium, silicon, sodium, sulphate, iron, manganese, arsenic, *E. coli* (see Appendix B) | 109993 (bore 209330)<br>102039<br>101820<br>106737 | Quarterly 2010-2013<br>Quarterly 1998-2013<br>Quarterly 2003-2006 and annually in 1990, 1991, 2000<br>Quarterly 2003–2006 | 3 km west<br>5 km north<br>3 km west<br>5 km east |
| Groundwater levels | East side of lake, as indicated in Figure 2-3 (Figure 2.12 in Moreau et al. 2013). | Monthly Jan – Jul 2000<br>Monthly at Lake Heather piezometers | Aupōuri aquifer (data via LAWA) |
| | West Coast bore and Armitage bore | West Coast 1999–2000,<br>Armitage 2007–2009 | WM Group report (2016) |
| Catchment information: DEM, soil maps, land cover and land use information | n/a | n/a | NRC provided LiDAR data (DEM, 1 m resolution), soil data from nrcgis.maps.arcgis.com, land cover (LCDB5) and land use (2008 land use fractions available in GNS report, from Land Use and Carbon Analysis System 2012) |
| Macrophytes: species present, LakeSPI, species depth ranges, average and maximum cover within any 2 $m^2$ area, average and maximum height | Five standard lake sites in the lake nearshore | 7 LakeSPI surveys since 2004, most recently surveyed in 2023 | NIWA records |

## 2.1 Meteorology and hydrology

Manual rainfall records were collected from two sites near Lake Ngātu: 1) Aupōuri Forest at Forest HQ (530204) records dating back to 1989, and 2) Waiharara (439201) records dating back to 1956. The nearest automatic weather station (AWS) is at Kaitaia Airport (530208), followed by Kaitaia Hospital (531208). The duration and resolution of the data collected at these monitoring stations are shown in Table 2-1. The most recent climate station installation is at Kaitaia Airport (2017), though climate data can be sourced back to 1998 from Kaitaia EWS. Additional information can be sourced from NIWA SIMS (https://sims.niwa.co.nz). The automated climate stations record air temperature, relative humidity, wind speed and direction, cloud cover, and daily radiance data.

## 2.2 Groundwater

Lake Ngātu is located within Pleistocene and Holocene sediments of the Kariotahi Group (Isaac, 2006), with historic dune formations ranging from uncemented to weakly cemented. Grey and brown sands predominate to approximately -50 m above sea level (masl) in nearest boreholes to Lake Ngātu, but peat beds are identified at depths of 14 and 0 masl (201420); 3 masl (201269); and 31, 0, and -24 masl (201544). The underlying shell rich basal layer, usually defined as shell bed (but occasionally as limestone or lime rock), represents the more productive layer of the Aupōuri aquifer and can be seen from 80–120 m below ground level across the region (Figure 2-1).

Lake Ngātu is believed to have formed from an elevated deflation hollow, the humic layer of which then formed a sealed basin. No cores of the lakebed are available presumably because of the risk of punching through this impermeable layer. The average water level in the lake is 35 masl compared to the regional groundwater level, which ranges between 6 and 15 masl (Moreau et al. 2013). This indicates that the lake is likely isolated from regional groundwater variability, similar to that measured in the vicinity of Lake Heather (Figure 2-2). Thus, with a maximum depth of ~6 m, Lake Ngātu's deepest point is at 29 masl, which is well above the maximum ground water level (15 masl) reported by Moreau et al. (2013) and above those measured near Lake Heather (~1 km south of Lake Ngātu, (Figure 2-3); that is, there is no deep regional groundwater connection to Lake Ngātu.

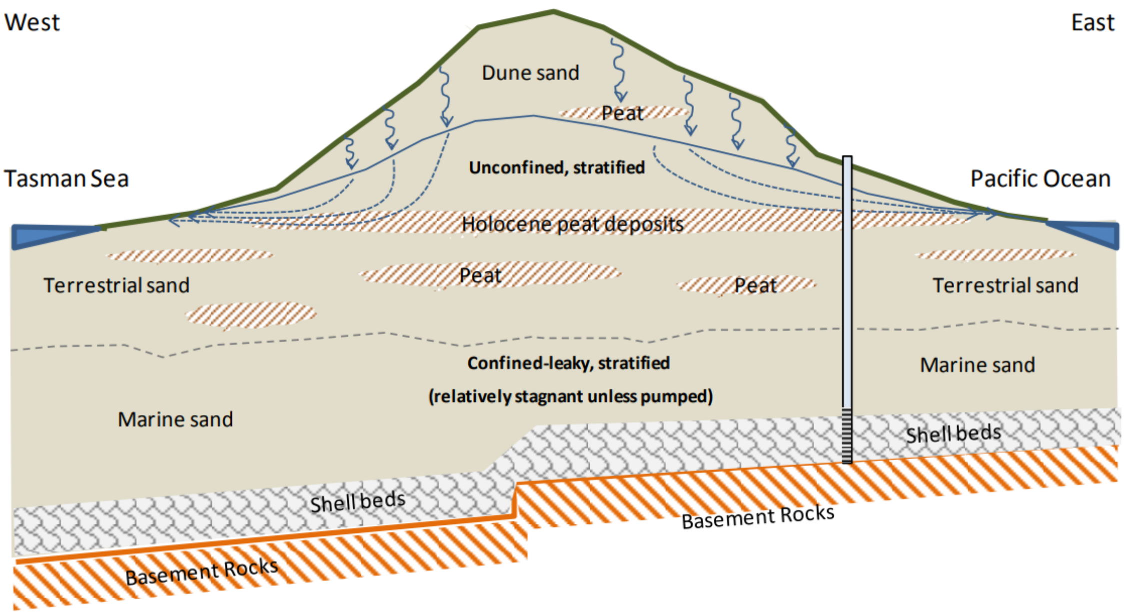



**Figure 2-1: Conceptual model of the Aupōuri Aquifer (Wilson and Shokri 2014).**

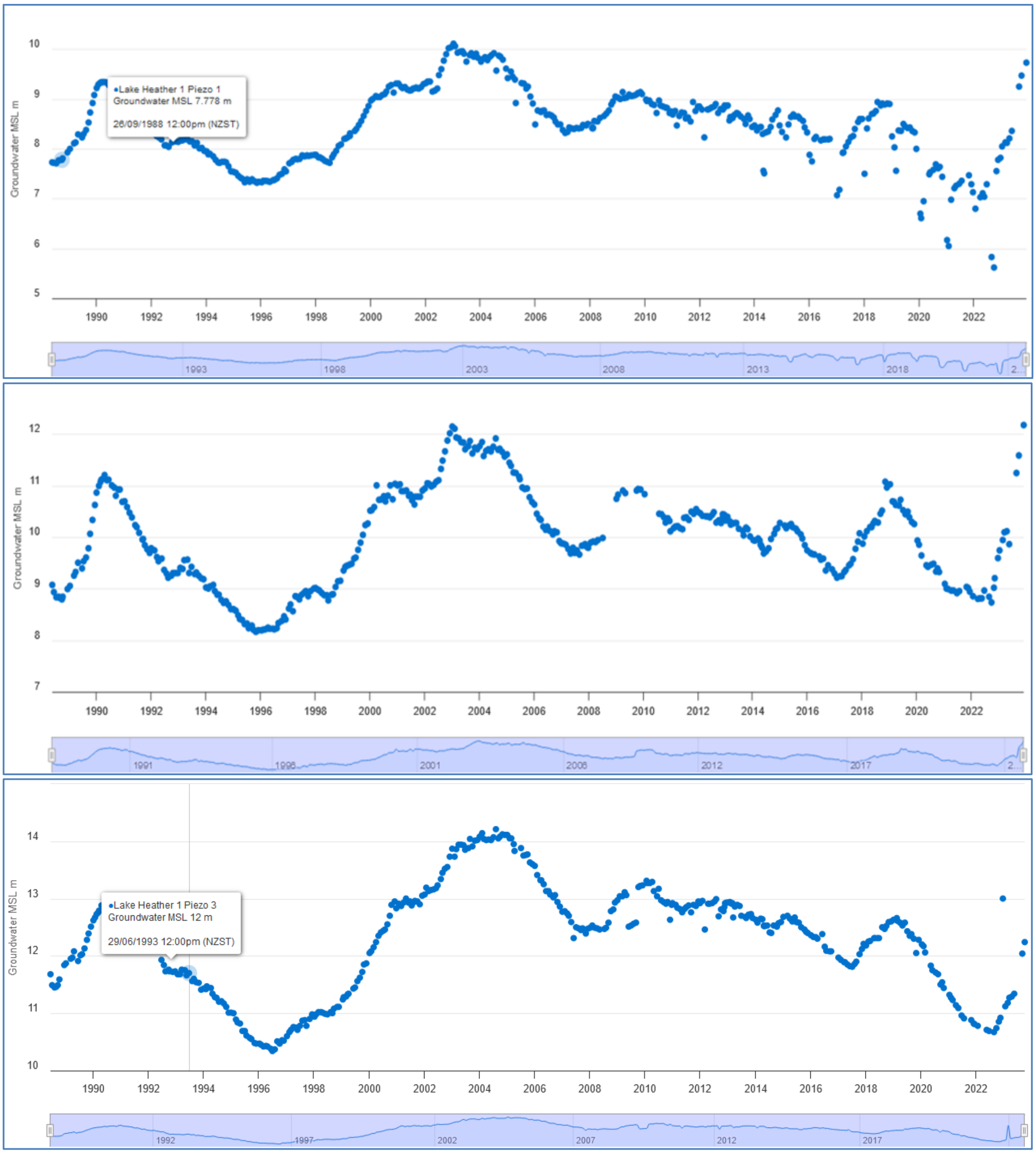



**Figure 2-2: Groundwater level (metres above sea level) at Lake Heather.** (200226; Piezo 1 at 26–29 mbgl, Piezo 2 at 58–61 mbgl; Piezo 3 at 102–105 mbgl), May 1988 to November 2023 (nrc.govt.nz).

Seven monitoring wells in the Aupōuri aquifer exist around the lake and are identified in Moreau et al. (2013, Figure 2-3). Comparison of groundwater levels in these boreholes provides an indication of groundwater gradients across the lake. A groundwater dome reported by Moreau et al. (2013) may be produced either by direct slow vertical seepage through the lake sediments and underlying layers, or from areas around the lake margin when the lake is closer to its capacity. If the latter case is true, then we would expect to see greater seepage at time of high rainfall (i.e., more spill from the lake).

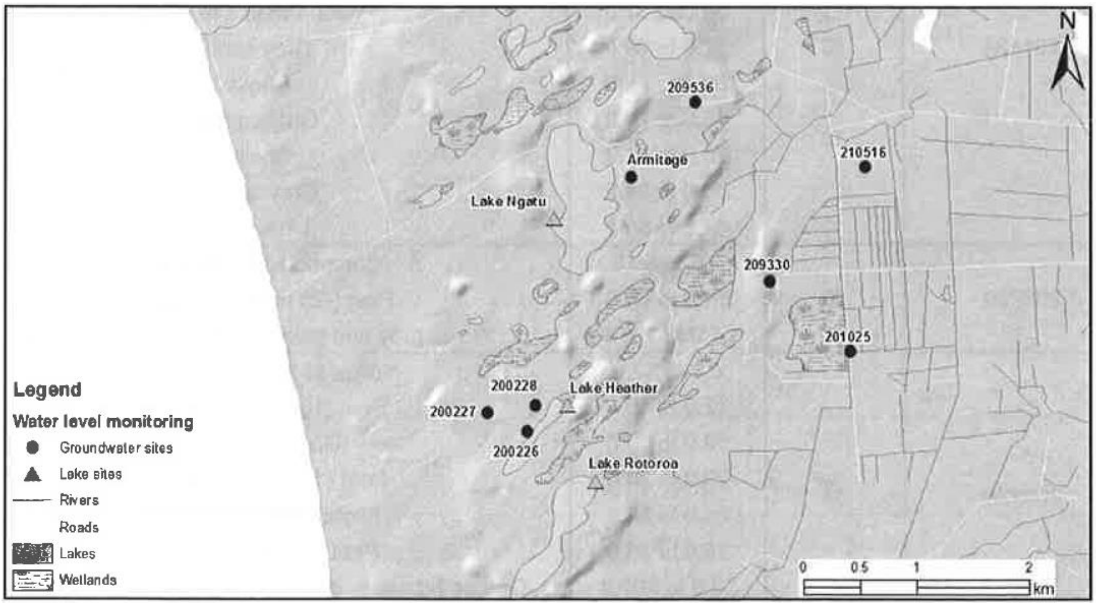



**Figure 2-3: Location of regional groundwater monitoring sites around Lake Ngātu.** (reproduced Figure 2.12 from Moreau et al. 2013).

The geology generally consists of clay-rich sandy soils, and the eastern shore of the lake is known to be dominated by organic soils of the One Tree Point (OT) series, surrounded by yellow-brown soils of the Houhora (HO) series. The OT peaty sand soils often deposit an iron pan which creates an impermeable layer, similar to that which is known to occur north of Lake Ngātu at Ngakapura Road. The western shore of the lake is dominated by Pinaki sand (PN), while the smaller lakes to the north of Lake Ngātu lie within Ruakaka peaty sand loam soils (RK). For distribution of soil types see Figure 2-4 (www.nrcgis.maps.arcgis.com).

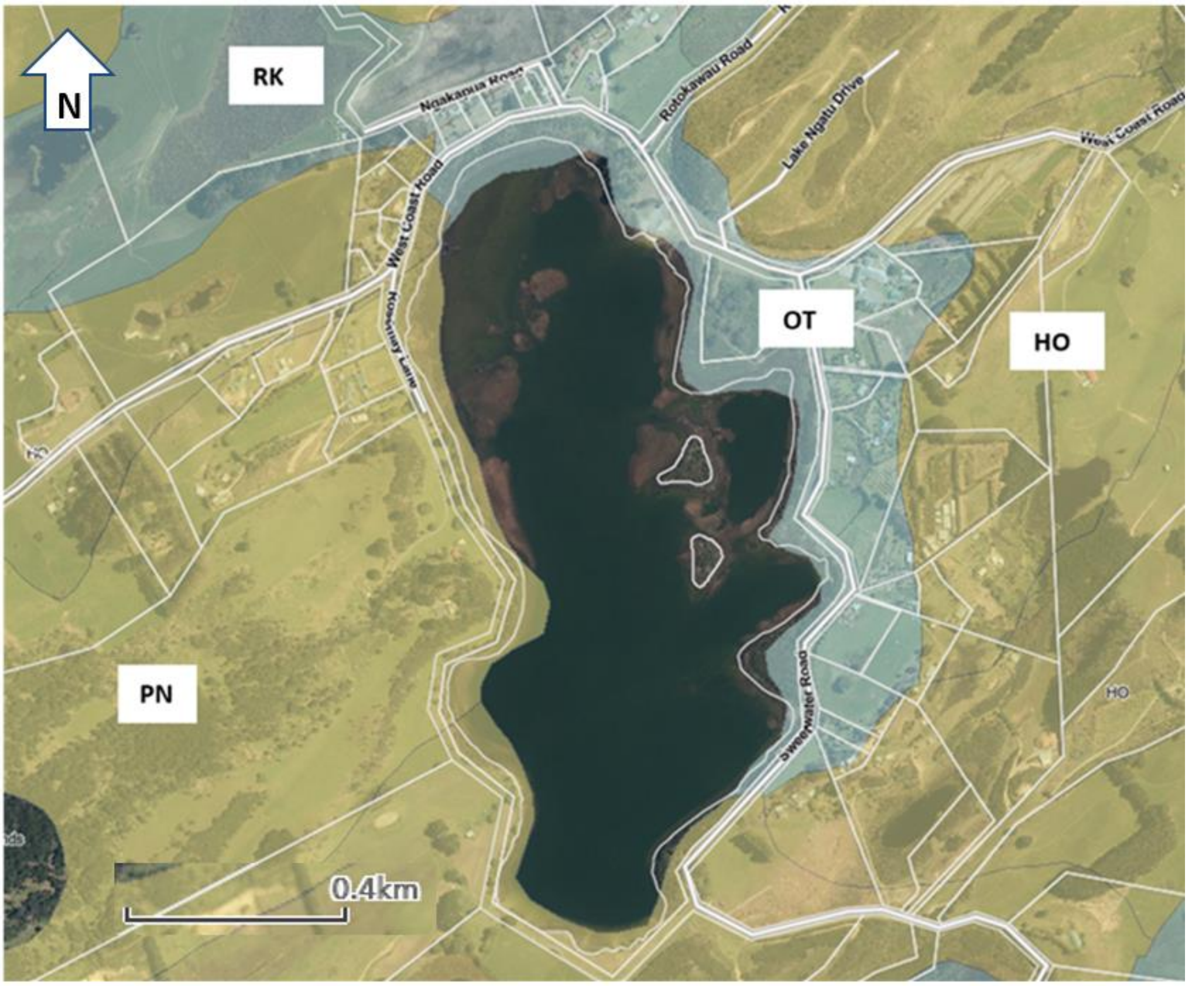



**Figure 2-4: Distribution of soil types found around Lake Ngātu.** (For colour key used in map, see source: https://nrcgis.maps.arcgis.com/apps/webappviewer/index.html?id=fd6bac88893049e1beae97c3467408a9). RK marks Ruakaka peaty sand loam soils. PN marks Pinaki sand. OT marks organic soils of the One Tree Point series. HO marks yellow-brown soils of the Houhora (HO) series.

We note that, while deep groundwater records indicate no connection to the lake, shallow groundwater is likely to intermittently feed the lake during storm events. Further work (e.g., aquifer hydraulic property testing of the shallow groundwater), is recommended because knowledge of the shallow hydrogeology is critical for management of the catchment and nutrient sources (Elliott et al. 2020).

## 2.3 Lake water quality and ecology

Lake Ngātu has no inlets in the form of permanent tributaries or river outflows, and the catchment includes some wetland patches, high and low producing exotic grassland, freshwater sedgeland/rushland, short rotation cropland and orchard, other perennial crops, and built-up settlement (Lake Ngātu Management Plan). During a field visit, some roadside ditches and sediment traps were seen along the northeast side of the lake; these are in the form of dug channels or ditches, to trap sediments from surface runoff during and following rain events.

Surrounding developments, including a nearby school, rely on often older septic systems. These as well as nearby Department of Conservation toilets are suspected to affect lake water quality during high rainfall events either via surface runoff or shallow groundwater connecting to the lake. In addition, surface runoff from sealed surfaces (roads), and the use of the lake by freedom campers and others for bathing and washing of livestock, cooking and other gear using detergents may also play a role in observed declines in lake water quality. Champion (2021) reported that Lake Ngātu was "recently fenced to prevent vehicle access".

The lake is considered well-mixed by wind, but phytoplankton blooms were observed in 2009 and 2015. Results from a recent analysis of the 5-year (2017–2022) water quality state of Lake Ngātu in terms of National Policy Statement for Freshwater Management (NPS-FM) are presented in Table 2-2. A 10-year (2012–2022) trend analysis (to be published) indicates that bottom DO is very likely decreasing (deteriorating); TP is very likely decreasing; TSS is likely decreasing; $NH_4$-N, pH, and TN are likely increasing; and Secchi disk depth is very likely increasing (water clarity is improving). There was no apparent 10-year trend in $NO_3$-N. The 5-year (2017–2022) state of the trophic level index (TLI, determined from TN, TP, and chl *a*) was 3.9 in 2022, indicating mesotrophic (almost eutrophic) conditions, consistent with Champion (2021). The mean 5-year pH was 6.22. pH and DO are important factors affecting the lake sediment's capacity to bind P. At high pH (>10) or low DO (<5 mg/L), sediments can release P to the water column, which can fuel algal blooms. According to Elliott et al. (2020), Lake Ngātu is presumably P-limited, but N may also be an important driver for primary production and increases in TP and decreases in Secchi disk depth were correlated with increases in the proportion of pasture, soil P content, and pine forest in the catchment (Hughes 2016).

**Table 2-2: Results from a recent 5-year (2017-2022) water quality state analysis.** The state is classified in terms of National Policy Statement for Freshwater Management (NPS-FM) band attributes ranging from A to E, where A is the best and E is the worst grade.

| Variable | Measurement and unit | NPS-FM band |
|---|---|---|
| Annual median surface chlorophyll *a* | 1.95 mg/m$^3$ | A |
| Annual maximum surface chlorophyll *a* | 32.0 mg/m$^3$ | C |
| Annual median total nitrogen | 1.05 mg/m$^3$ | D |
| Annual median total phosphorus | 0.0084 mg/m$^3$ | A |
| Annual median ammoniacal nitrogen (adjusted for pH) | 0.49 mg/L | C |
| Near-bottom dissolved oxygen | 6.6 mg/L | A |

Lake Ngātu is of high quality with respect to the Lake Submerged Plant Indicators (LakeSPI 56.5%, lawa.org.nz). There are 20 native macrophyte species, including the nationally critical *Utricularia australis*; there are five exotic species of which three are invasive, including *Lagarosiphon* which can colonise the entire lakebed (Lake Ngātu Management Plan) and alligator weed. Yellow flag iris and the pest plant Christmas berry have been eradicated. Champion (2021) reported a slight improvement in LakeSPI since 2012, with reduced presence of the exotic *Utricularia gibba* in September 2020 and treatment of *Lagarosiphon* with endothall in 2020 with no subsequent detection of *Lagarosiphon* in the lake. In spite of its less-than-optimal water quality, Lake Ngātu's ecological value rating was "outstanding" with an improved difference in status from 2012 to 2020 as species richness and charophytes increased since 2014 (Champion 2021). The most recent LakeSPI survey (2023) indicated that fringing emergent macrophytes reach depths of 1.7–2 m and charophytes are found at high cover (>75%) to ~4–5 m deep (pers. comm., Mary de Winton). Native fish include common bully and inanga; other fish in Lake Ngātu include *Gambusia*, goldfish, rudd, perch, and introduced trout (Lake Ngātu Management Plan). Champion (2021) recommended annual aquatic weed surveillance for Lake Ngātu, as it is one of the region's six highest risk lakes for aquatic biosecurity.

## 2.4 WM Group water balance modelling study

The Water Management (WM) Group developed a Microsoft Excel spreadsheet model for water balance assessments in Lake Ngātu (Aupōuri Lakes Water Balance Assessment, March 2016) based on a conceptual hydrogeological model that includes catchment properties, climate data, water levels, water level-volume-surface area (hypsographic) relationships, groundwater level monitoring, and hydrogeology. The water balance model calculates flows between components of the hydrological system and changes in water storage on a daily timestep. The main components of this model are catchment rainfall-runoff (SIMHYD, Podger 2004 and Tan 2005), groundwater seepage losses (based on the lake using Darcy's Law), overflows (when the lake volume is greater than the maximum volume capacity), and the daily rainfall and open water evaporation.

### 2.4.1 Conceptual hydrogeological model

The maximum depth of the lake is approximately 6.3 m, and there are no surface water streams flowing into or out of the lake (Figure 2-5). The lake surface area is approximately 555,141 $m^2$ with a catchment area of 1,254,893 $m^2$, which is mainly covered by 19anuka/19anuka scrub and grassland (Table 2-3). The NIWA Kaitaia Aero EWS station is the closest climate station and within 9 km of the lake (summary of climate data in Table 2-4). Lake water level records (1986–2017) at the staff gauge (Figure 2-6) show maximum, median and minimum values of 34.5 m RL, 33.7 m RL and 32.7 m RL m, respectively, i.e., water level fluctuations of 1.8 m have been observed (Figure 2-7). The WM Group report indicates that the staff gauge was vandalised in 2011, followed by remedial works in 2015 that likely have shifted the position of the reference level. Relationships between water level, lake volume and surface area and time series data of absolute (710,000–900,000 $m^3$) and relative volume change for the period between 1 July 2015 and 30 June 2016 were provided in the WM Group report (not reproduced here).

The lake overlies a dune sand formation, which is underlain by a peat layer above a layer of fine sand (Figure 2-8, Figure 2-9). Since the inferred groundwater table is far beneath the lake bottom (>20 m), groundwater flow from the regional groundwater system to the lake appears to be unlikely. There are limited available historical groundwater level monitoring data for inactive bores (West Coast 1999–2000 and Armitage 2007–2009, Figure 2-10). Groundwater levels at the Armitage bore were >2 m higher than groundwater levels at the West Coast bore; however, the lack of overlap between the monitoring periods for the two bores reduces confidence in estimation of groundwater flow gradients.

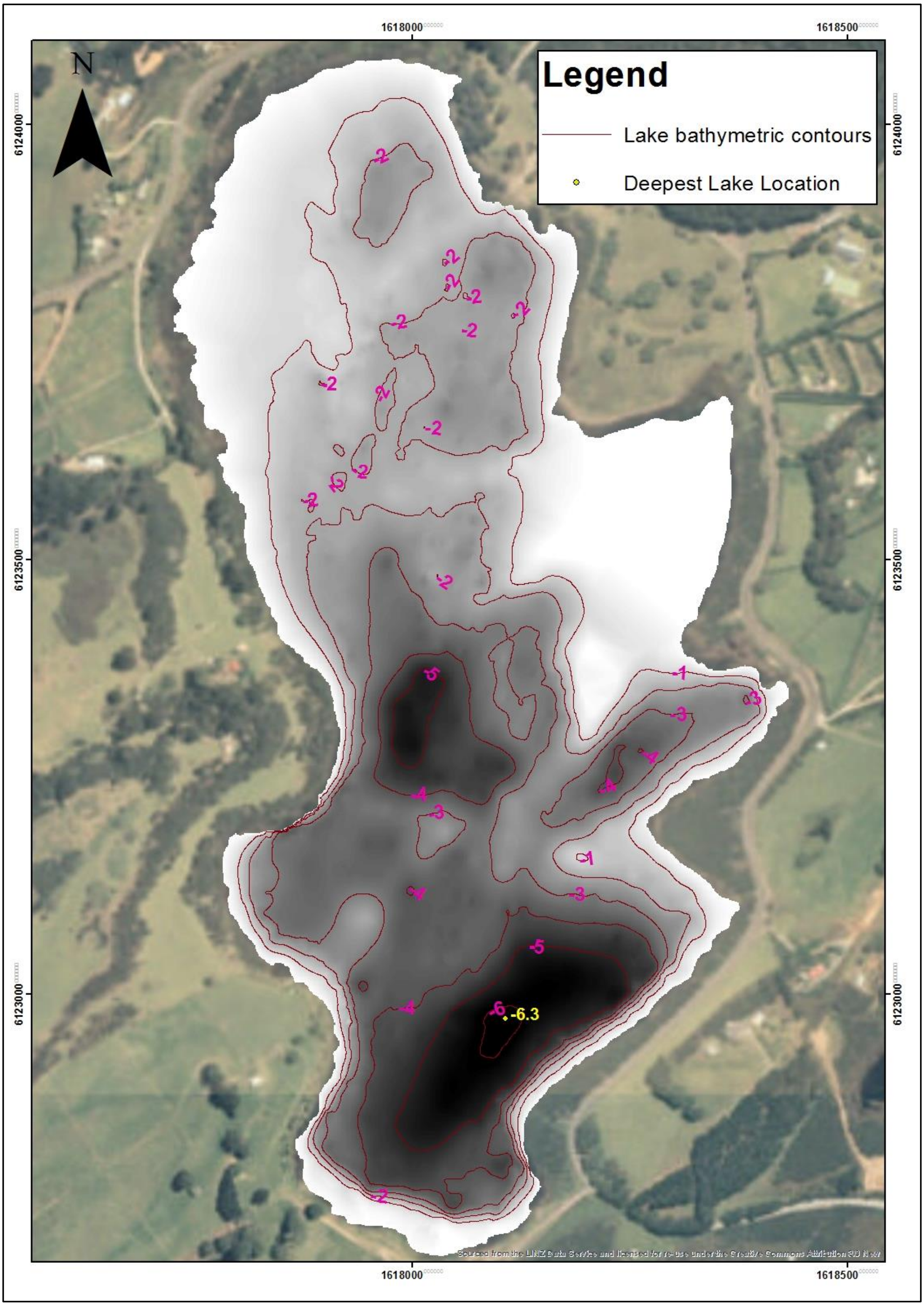



**Figure 2-5: Lake Ngātu bathymetry showing depths measured in metres from the surface.** Reproduced from the WM Group report (2016).

Table 2-3: **Land cover distribution in the Lake Ngātu catchment (as reported by WM Group).**

| Landcover | Area ($m^2$) | Percentage coverage |
|---|---|---|
| Grassland | 419,851 | 33% |
| Manuka/Kanuka scrub | 279,900 | 22% |
| Lake | 555,142 | 44% |
| **Total** | **1,254,893** | **100%** |

Table 2-4: **Climate data from Kaitaia Aero EWS weather station (as reported by WM Group).**

| Parameter | Daily Median (mm/day) | Daily Maximum (mm/day) | Mean Annual (mm/yr) |
|---|---|---|---|
| Rainfall | 0* | 158.2 | 1,282 |
| Evapotranspiration (Penman) | 2.7 | 7.9 | 1,085 |
| Open water evaporation | 2.7 | 9.5 | 1,065 |

*This likely means that there were more days with no rainfall, so the daily median was zero.

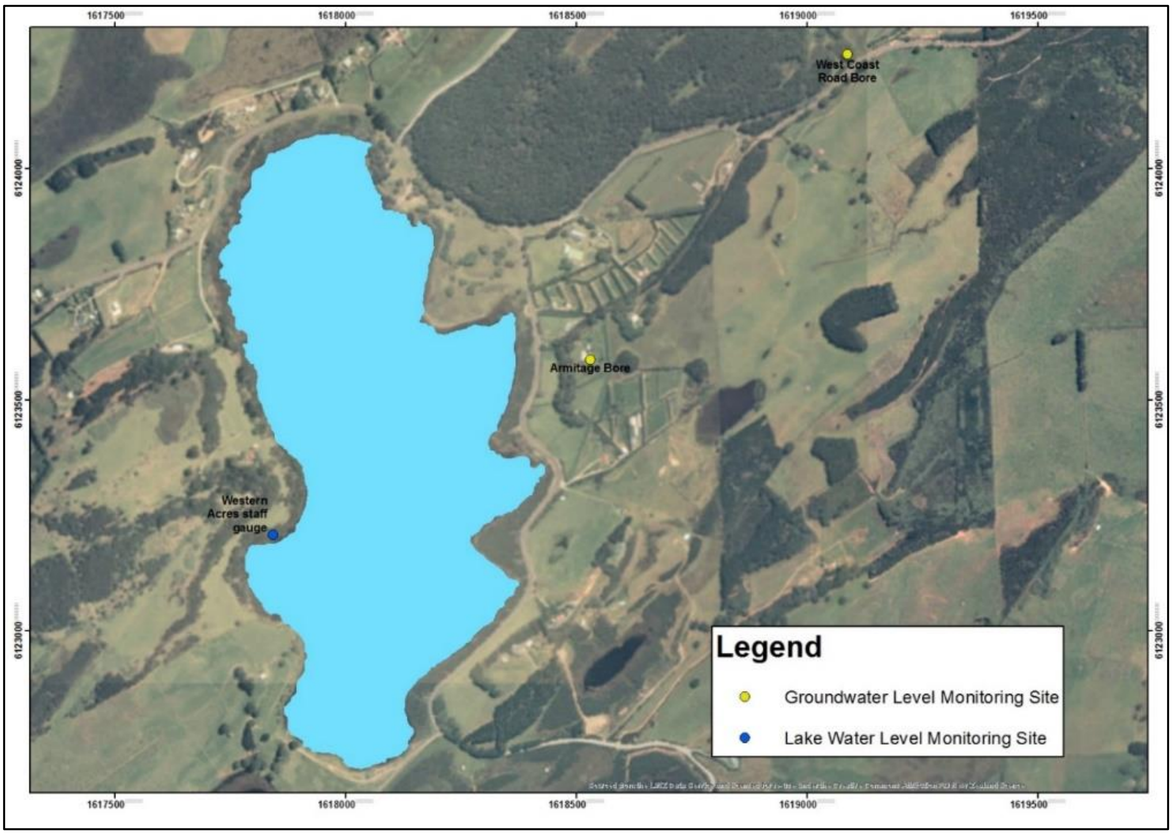



**Figure 2-6: Lake Ngātu water level monitoring sites.** Reproduced from the WM Group report (2016).

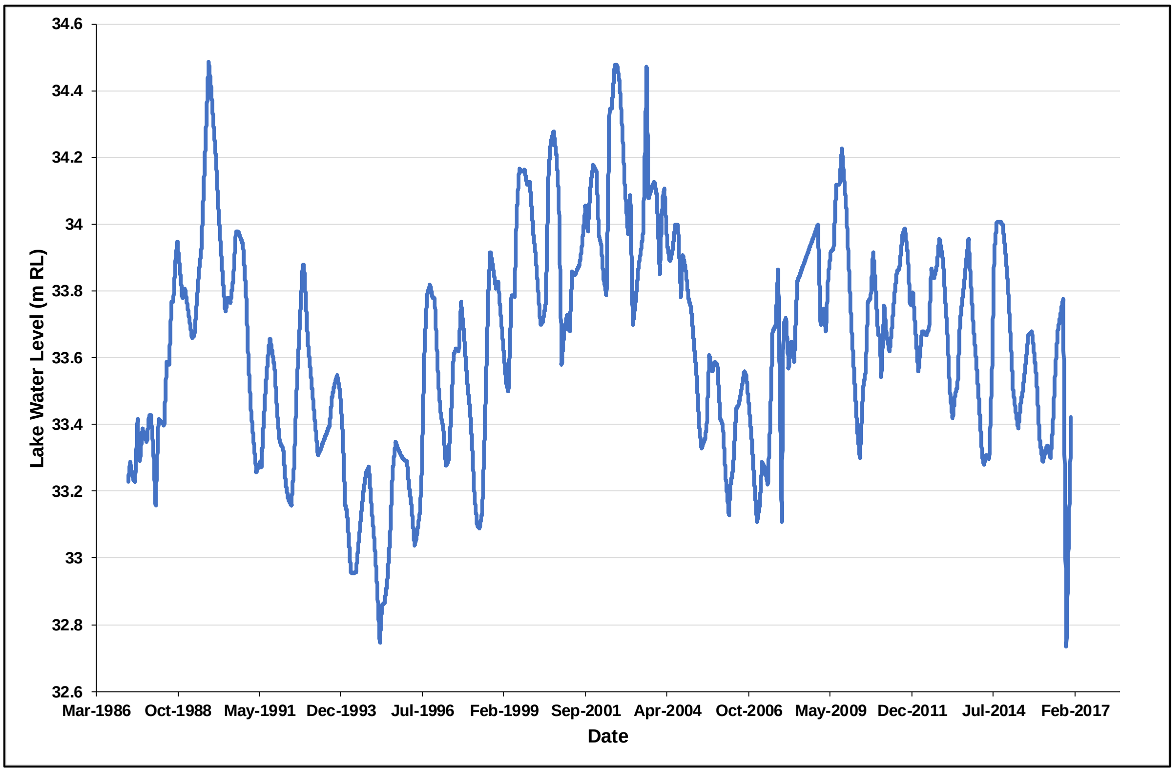



**Figure 2-7: Lake Ngātu water levels (1988–2017).** Reproduced from the WM Group report (2016) Sea level = 0 m RL.

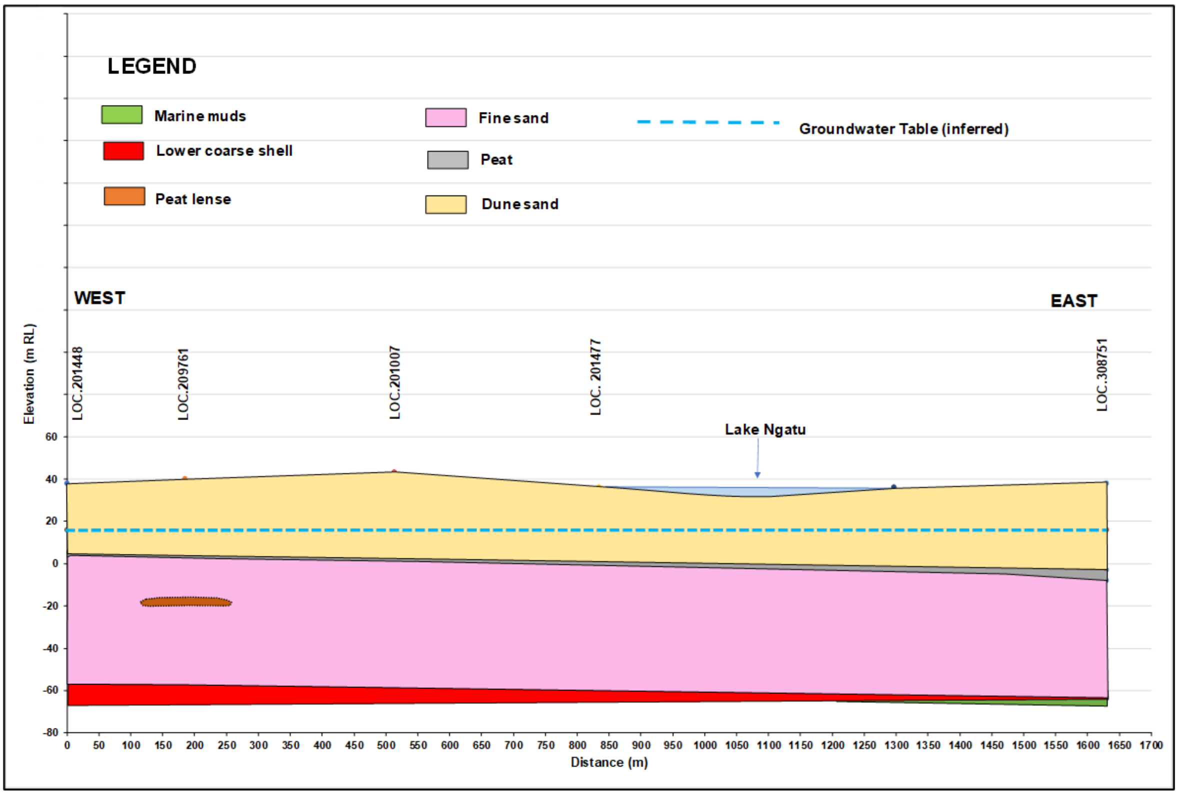



**Figure 2-8: Hydrogeological details along the cross section shown in Figure 2-9.** Reproduced from the WM Group report (2016) Sea level = 0 m RL.

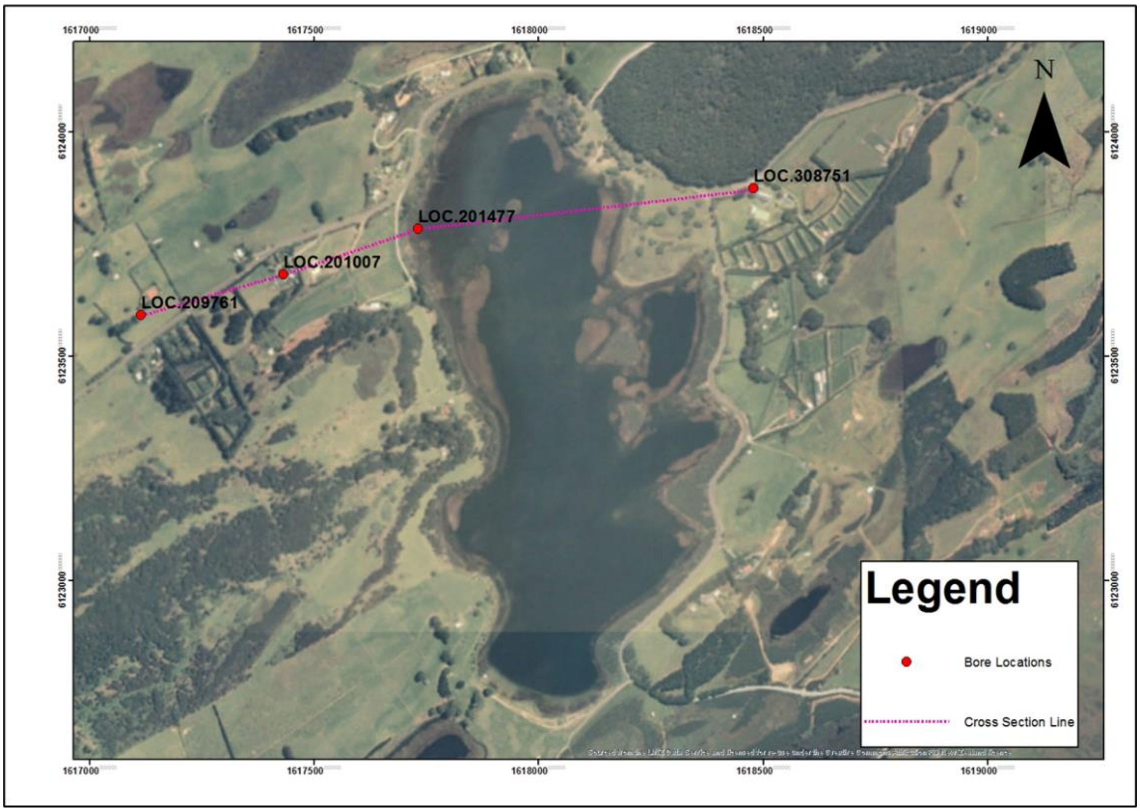



**Figure 2-9: Bore hole locations and cross-section along which hydrogeological information is provided in Figure 2-8.** Reproduced from the WM Group report (2016).

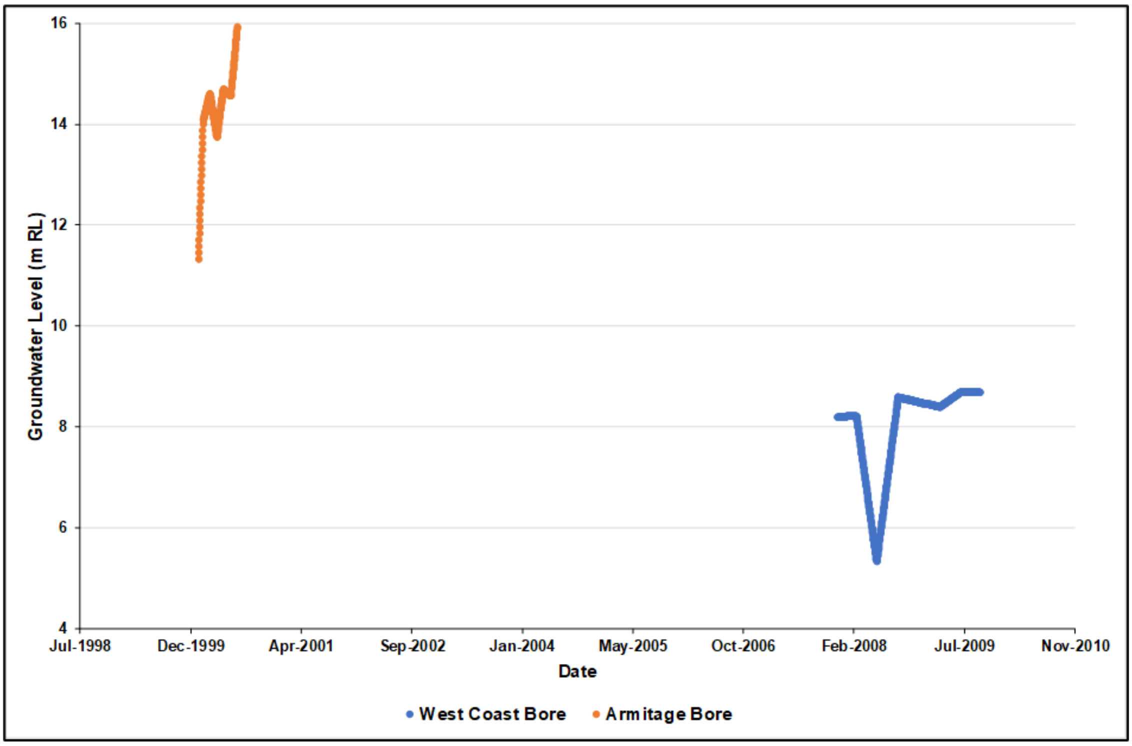



**Figure 2-10: Groundwater level at two bores: West Coast and Armitage (Figure 2-11).** Reproduced from the WM Group report (2016). Although the measured groundwater levels at the Armitage bore were higher than those at the West Coast bore, the lack overlap between the monitoring periods reduces the confidence in concluding a west to east groundwater flow gradients. Sea level = 0 m RL.

### 2.4.2 Water balance modelling results

While there was good agreement between simulated and observed lake water levels for the period before 2004 and after 2010 (the root mean squared error for the period between 2010 and 2017 was 10%, Figure 2-12), the model predictions were >0.3 mRL (masl) greater than the observations at times between 2004 and 2010 due to measurement errors. Therefore, WM Group recommended a model verification exercise of the Lake Ngātu water balance model when additional lake water level monitoring data were available. They also recommended a review of historical lake water level to assess the possibility of a correction factor to the historical data to increase the length of the model validation.

The mean water balance for the period between 2010 and 2016 showed that direct rainfall and surface runoff contribute approximately 80% and 20% of the inflows, respectively (Table 2-5). In the model, evaporation and groundwater seepage contribute approximately 67% and 33% of the outflows, respectively. The water balance assessment for the 2015–2016 hydrological year showed comparable values to those for 2010–2016 (difference <4%). The long-term mean monthly water balance for 2010–2016 (Figure 2-13) suggests that lake losses due to evaporation are greater than those from groundwater seepage throughout the year; monthly lake water seepage to groundwater were consistent throughout the year (~650 $m^3$/day), with negligible variability.

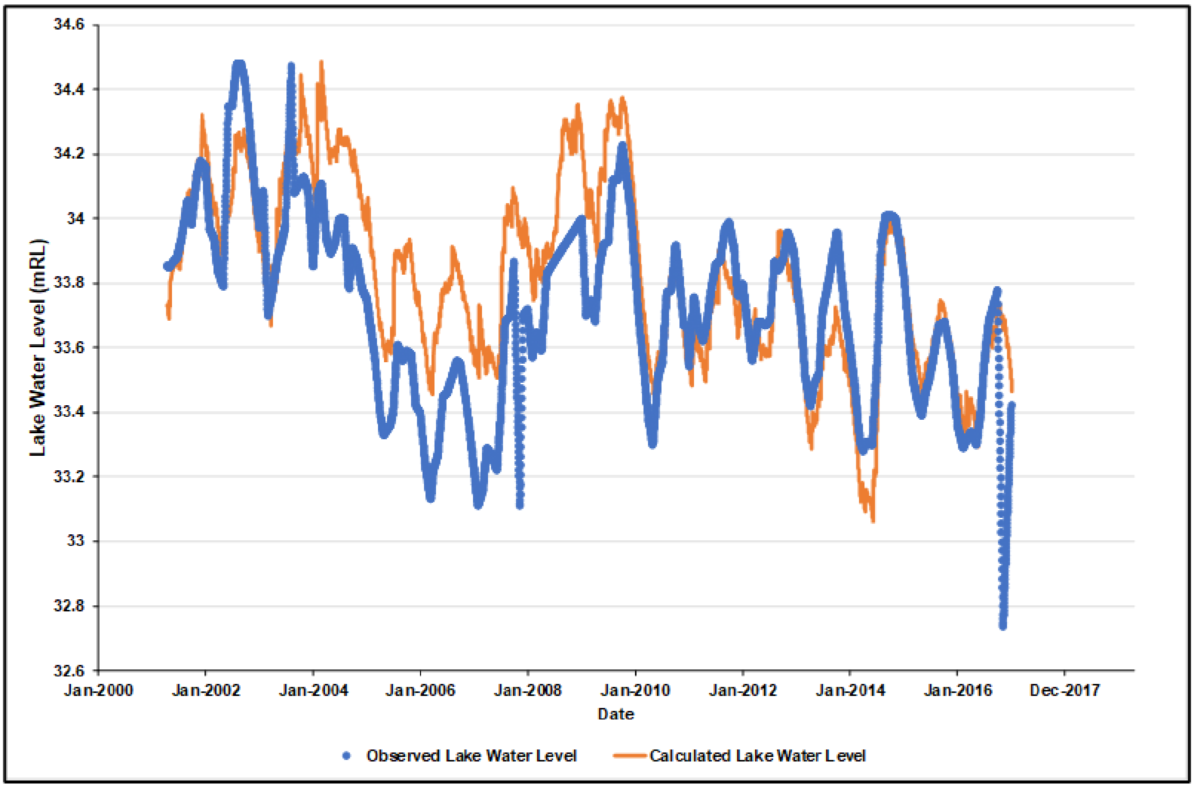



**Figure 2-12: Observed and calculated Lake Ngātu water levels (2000–2017).** Reproduced from the WM Group report (2016) (Sea level = 0 m RL).

**Table 2-5: Water balance summary for 2001–2016 (average daily flow rates).**

| **Lake inflows** | **Volumetric Flow ($m^3\ d^{-1}$)** | **%** |
|---|---|---|
| Rainfall | 1509.41 | 80 |
| Runoff | 381.12 | 20 |
| TOTAL IN | 1890.54 | 100 |
| **Lake outflows** | **Volumetric flow ($m^3\ d^{-1}$)** | **%** |
| Evaporation | 1262.63 | 67 |
| Overflow | 0.00 | 0 |
| Groundwater Seepage | 613.20 | 33 |
| TOTAL OUT | 1875.84 | 100 |
| **WA Group water balance discrepancy [(1)]** | | |
| Water Balance discrepancy | 14.70 $m^3$/day | |
| Percentage of inflows | 0.78% | |

**Notes.** [(1)] Actual model error is less than calculated because water balance discrepancy does not consider changes in lake storage.

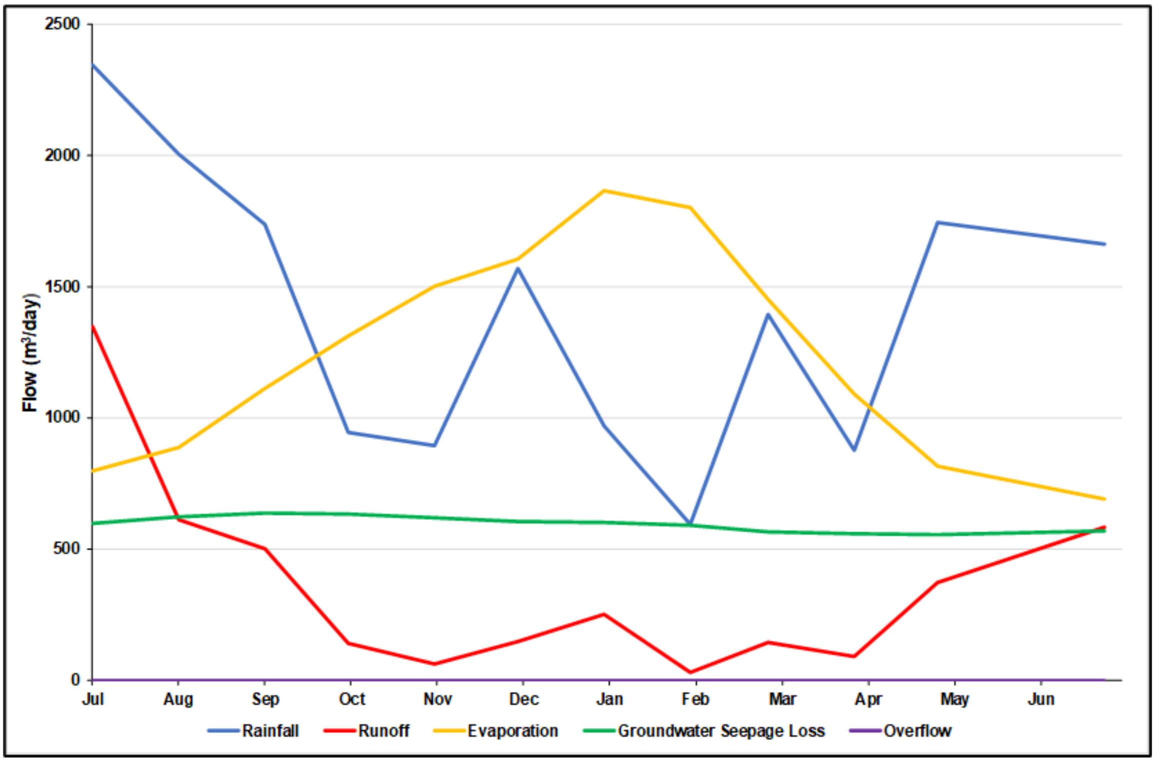



**Figure 2-13: Mean monthly water balance summary for Lake Ngātu (2010–2016).** Reproduced from the WM Group report (2016).

# 3 Technical advice for monitoring

In the following subsections, we describe recommendations and context for additional environmental monitoring to enable estimation of the Lake Ngātu nutrient budget. The approach we describe can be applied to other dune lakes.

## 3.1 Data requirements for nutrient budget estimates

Key pieces of information required to quantitatively describe a lake nutrient budget with emphasis on internal phosphorus loading include lake characteristics, stratification status, and sediment nutrient release rates (Hickey and Gibbs 2009). In addition to understanding and quantifying physical inputs and outputs as described in section 2.4, nutrient input and output concentrations to/from the lake must also be considered to make assessments about changes in nutrient concentrations in the lake water column. Nitrogen (N) and phosphorus (P) are the key nutrients affecting primary production (algal growth) and considered here. In dune lakes with no inlets or outlets (i.e., they are fed by rainfall, surface runoff, and/or groundwater), water column nutrient concentrations are likely controlled by groundwater, surface runoff, and/or lake sediment nutrient concentrations. A list of key information required for a lake nutrient budget estimate follows:

1. A **lake water balance** forms the basis for a lake nutrient budget calculation. The physical lake characteristics required for the water balance include bathymetry, lake water level, inflow, outflow, rainfall, and runoff data. Evaporation and evapotranspiration are calculated from meteorological measurements. Groundwater inflow/seepage is ideally also measured but often not possible to measure and thus calculated in a water balance.

2. **Stratification** must be assessed to determine if or for how long the lake stratifies (forms two distinct thermal layers with minimal mixing of substances across those layers). This is important because long periods of stratification (more than a few days per year) can deplete hypolimnetic and sediment oxygen concentrations. Anoxia (0 mg/L dissolved oxygen) can lead to phosphorus release from the sediments. **Dissolved oxygen** (DO) concentrations and **temperature** profiles should be collected continuously (or at least monthly) along with **near-bottom nutrient samples** to determine if the lake sediments release large amounts of P in low DO conditions (see **Error! Reference source not found.**).

3. **Nutrient concentrations** in the lake, in inflows (if present), in groundwater that enters/seeps from the lake, and in lake sediments can vary spatially and temporally, so these should be sampled at several sites and times to determine seasonal variability. Sediment nutrient concentrations should ideally be determined from sediment surface grabs (0–4 cm) and cores (0 to several metres deep), when possible. For a perched dune lake like Lake Ngātu, we recommend collection of surface sediment cores for the top 10 cm.

4. **Metal concentrations** in the lake sediments, because iron and manganese bind phosphorus (when oxygen is available and pH is not too high) and thus make it biologically unavailable.

5. **Phytoplankton and macrophyte** biomass and species composition are important because algae and rooted aquatic plants take up (consume) and release (respire) nutrients, which affect lake water column nutrient concentrations.

A simplified approach for calculating a lake nutrient budget is to assume a static system; that is, dynamic nutrient cycling processes (e.g., sedimentation, denitrification, nitrogen fixation) are not resolved, as Schallenberg and Vermeulen (2022) have done for Lake Horowhenua. The simple mass balance is the difference in the steady input and output nutrient loads, which determine the change in standing stock in-lake nutrients per year. If such a simple approach is used to calculate the change in lake water nutrients (nitrogen and phosphorus) per year, the following sources (annual loads) and sinks must be quantified: surface inflow loads (if applicable), lake outflow rate (if applicable), atmospheric deposition, groundwater, sediment nutrient release at times of low water column DO or high pH, nutrient uptake by live algae and macrophytes, and nutrient release by decaying biomass. Dissolved oxygen, pH, and iron and manganese in the sediments determine how much phosphorus can be bound (retained) in the sediments and thus biologically unavailable.

While Northland's dune lakes are likely primarily P-limited with sediments that can bind P, N cycling must also be considered as is could become limiting for some algal, cyanobacteria, or macrophyte species if P is abundant. It is important to collect at least one triplicate set of surface lake sediment samples (ideally 0–10 cm cores) to determine the sediment phosphorus content. If results indicate that sediments could be an important source of phosphorus, then additional sediment samples should be collected to determine potential seasonal variability (e.g., quarterly sampling over one year, triplicate samples from three shallow and three deep sites in Lake Ngātu).

## 3.2 Groundwater data collection

As indicated in Section 2.2 and 2.4, the dominant sub-surface hydrological processes that may impact the lake water balance are 1) lateral shallow groundwater flow, and 2) seepage (losses) through the lakebed to regional groundwater. Whilst the water balance model employed by the WM Group (described in 2.4) suggest seepage losses equivalent to 33% of inflow, from the lake, there is some uncertainty in their estimates of 'runoff' (or throughflow) into the lake. This can be quantified by monitoring the variability of shallow groundwater dynamics around the lake. Similarly, estimates of seepage from the lake to regional groundwater can be validated by installing depth integrated piezometers in the wetland area to the northeast of the lake, which is suspected to have an analogous relationship the underlying groundwater (Moreau 2013).

### 3.2.1 Shallow groundwater

Lateral movement of shallow or perched groundwater will depend on local variation of soil type and topography. For example, hard pans and peat layers are common in the areas and will influence near-surface hydraulic gradients around the lake. Evidence for the existence of shallow groundwater comes from the shallow borehole (LOC.201477) on the north-east side of the lake which is used for stock-water supply (see Figure 3-1 and Figure 2-9). This borehole has a depth of just 9 m and a static water level of -1 m (data supplied by NRC). If possible, the water table variation in this borehole should be monitored in relation to the lake level variation to indicate the hydraulic connectivity between shallow groundwater and the lake.

Additional piezometers (5 and 10 m depth) should be installed perpendicular to and on each side of the lake to determine the depth of the shallow perched groundwater and direction of hydraulic gradient around the lake. These piezometers should be sited near boreholes LOC.209861 (north), LOC.20154 (east), LOC.201558 (south), LOC.331885 (west) so that resulting shallow groundwater data can be viewed with regional groundwater data at synchronous locations. Data from the piezometers will be used with rainfall and lake level data to determine the extent and magnitude of shallow groundwater interaction with the lake. Core retrieval during borehole installations will also provide information on the existence of impermeable hardpan or peat layers around the lake. The piezometers will allow optional retrieval of sub-surface water quality samples.

The cost estimate for shallow groundwater monitoring as described above would be as follows if conducted by NIWA staff:

- 6 days for 2 NIWA staff (for installation of 8 piezometers)
- Pressure transducer and logger (~$2500 per borehole/piezometer),
- Travel and consumables (~$2500),
- 10% project management.


**Figure 3-1: Boreholes in the vicinity of Lake Ngātu, indicating borehole number (left) and depth (m).**

### 3.2.2 Interaction with deep groundwater

For assessment of possible interaction between local shallow groundwater and deeper regional groundwater (and potential leakage rate from the lake to groundwater), the GNS report recommended installation of a piezometer nest with three 50 mm diameter piezometers at depths of 30, 60 and 90 m below ground level. If shallow boreholes are installed at 5 m and 10 m depth (as described in section 3.2.1) it would be pertinent to install the piezometers at 10 m, 50 m, and 90 m to obtain the hydraulic properties of the aquifer (using a slug testing method). NRC have stated they prefer to use clustered rather than nested piezometers (i.e. each piezometer in a separate borehole).

Installation of three piezometers (15 m, 50 m, 90 m) can be arranged by NRC or can be arranged by NIWA. The following options (and approximate costs) should be considered:

- drilling contractor (estimated $25,000–30,000 depending on configuration),
- pressure transducers and loggers (~$10,000),
- NIWA project management (10%).

Networked communication to loggers would require additional costing based on reception conditions at sites. The approximate costs provided do not constitute a formal quote but illustrate an order of magnitude cost for which a detailed estimate could be provided later in a full proposal.

# 4 Technical advice for modelling

## 4.1 Catchment and lake nutrient modelling

The combination of a catchment model and a lake model would allow for an assessment of the nutrient budget for Lake Ngātu. A catchment model can simulate nutrient loads in the form of runoff to the lake, using topography and land cover/land use data. Linked with a catchment model and driven by observations of groundwater nutrient loads, a lake nutrient model would allow for investigation of the relative contribution of catchment, groundwater, internal water column, and sediment P and N sources and cycling to in-lake nutrient concentrations and primary production. This, in turn, would inform what drives the lake’s current trophic status (mesotrophic) and model scenarios could be run to determine what changes in nutrient loading to the lake might curb eutrophication and protect ecosystem health.

Elliott et al. (2020) found that previous models predicted long-term steady state conditions rather than simulating the effectiveness of catchment mitigation activities and suggested that a dynamic catchment model such as SWAT linked with a lake model such as PCLake may enable quantification of nutrient budgets in NRC dune lakes.

We note that a NIWA-developed screening tool, the Hydrological Flow Path Explorer (driven by the Hydrological Predictions for the Environment or HYPE model), could be used prior to SWAT model development to estimate the relative contribution of overland runoff and shallow nutrient loads to the lake. In addition, we note that GLM with AED may be another suitable lake model option that was considered (Appendix C), but PCLake may be better suited for simulating macrophytes, which likely play an important role in nutrient cycling in Lake Ngātu.

In the following sections, we describe the capability and data needs of the suggested models.

### 4.1.1 SWAT

We suggest development of a catchment model to simulate nutrient loads from runoff to Lake Ngātu. The Soil and Water Assessment Tool (SWAT) can be used to simulate the overland flow (surface runoff) and TN, TP, and TSS concentrations entering the lake. SWAT requires several model inputs as listed in Table 4-1.

**Table 4-1: Data requirements to set up SWAT, the catchment model.**

| Type of data | Details | Source |
|---|---|---|
| Digital Elevation Model (DEM) | DEM data covering the model area with a 500 m buffer | LiDAR data provided by NRC (1 m resolution) |
| Climate | - Rainfall<br>- Maximum and minimum temperature<br>- Humidity<br>- Solar radiation<br>- Wind speed | meteorological station (Kaitaia airport) data and perhaps other data held by NIWA (e.g., estimates from the Virtual Climate Station Network – VCSN) |

| Type of data | Details | Source |
|---|---|---|
| Soil | - Soil types<br>- Soil texture: percent of sand, silt, clay, organic carbon, phosphorus<br>- Soil characteristics: bulk density, water content | Either based on existing information from GNS and NRC or subcontract with Landcare to provide SWAT soil inputs |
| Land use and cover | - Land use<br>- Land cover<br>- Management practice information<br>For example, if the land use is grazing pasture, the following information is needed:<br>o Number of cattle and cattle types<br>o Frequency of grazing and both summer and winter stocking rates<br>o Availability of fencing<br>o Average fertilizer application on grass pasture | Land use layer to be provided by NRC (e.g., classification developed by MWLR). We assume that Agribase parameters such as stocking rate will also be available.<br><br>Land cover from the Land Cover Database (LCDB)<br><br>Information regarding farm practices, obtained by expert knowledge or general practices in similar farm types. |
| Point sources | Data for any point sources (e.g., septic wastewater facilities) that potentially directly discharge to the lake or reach the lake via shallow groundwater if the groundwater table is high | Currently not available, to be investigated (e.g., school septic system) or make assumptions/estimates for leach field losses ONLY IF groundwater connectivity is observed |

The data would be used as follows to set up SWAT:

- The DEM is required to calculate flow paths and delineate the catchment area into multiple sub-basins (if possible).
- A slope map is created from the DEM.
- The soil type, land use, and slope information are used to further divide sub-basins into modelling units (Hydrological Response Units, HRUs). This is done using standard ArcGIS-SWAT processing tools.
- Agribase data are used to categorise farms for the current land use in combination with land cover (from LCDB) to create a catchment land use map.
- Climate information (precipitation, air temperature, relative humidity, solar radiation, wind speed) will be used as model inputs.

Given the nature of the dune lake system, which does not have any tributary inflows, SWAT cannot be traditionally calibrated to observations of tributary flows and nutrient concentrations. However, a sensitivity analysis can be conducted, and several scenarios (e.g., low vs. high rainfall, different land uses) might be selected to provide inputs to a lake model. SWAT model output will consist of daily time series of runoff loads of TSS, TN, and TP. This model would be loosely coupled with a lake model, i.e., SWAT output would become input (nutrient loads) to a lake model but there is no feedback from the lake model to SWAT.

### 4.1.2 PCLake/PCLake+

PCLake (or its enhanced version PCLake+) is a complex one-dimensional ecosystem model that can simulate nutrient and food web dynamics, including macrophytes and fish. PCLake is appropriate for application to well-mixed shallow lakes, while PCLake+ can simulate stratification when the user defines two vertical layers. PCLake water quality and ecosystem components have been linked to sophisticated hydrodynamic models. In the case of Lake Ngātu, which is well mixed, we do not expect the need to simulate complex hydrodynamics.

PCLake was originally developed for shallow, non-stratifying lakes (Janse 2005), primarily distinguishing between phytoplankton and macrophyte dominated systems. The model can also be used to evaluate the effects of hydrological and morphological changes, climate change, regional management options like dredging and biomanipulation, or combinations of those. Because it simulates key ecological processes, the model provides an opportunity to investigate the impact of changes in various ecological inputs. PCLake+ can simulate stratification into two layers (Janse 2005; Janse et al. 2010; Janssen et al. 2019). PCLake has also been linked to sophisticated hydrodynamic models using FABM (Bruggeman and Bolding 2014, Hu et al. 2016).

The model can include more than 100 state variables, including phosphorus, nitrogen, and silica in the water column, sediment nutrients, detritus, cyanobacteria, diatoms, other phytoplankton, zooplankton, benthic algae, zoobenthos, dissolved oxygen, macrophytes, and several fish groups. PCLake can be used to simulate effects of birds, fishing, dredging, and mowing (Figure 4-1).

PCLake processes include transport, phytoplankton, aquatic vegetation, and food web interactions (Janse 2005; Janssen et al. 2019). Transport processes include inflow, outflow, and nutrient and organic and inorganic matter loading, and groundwater seepage. Nutrient processes include inorganic matter and detritus settling and resuspension, dissolved N and P exchange between water column and sediment pore water, mineralisation, nitrification, denitrification, adsorption of inorganic P, and P release from the sediment layer. Water column DO is simulated dynamically, depending on the biological oxygen demand (BOD) and the sediment oxygen demand (SOD), reaeration from the atmosphere, and oxygen production by photosynthesis.

Three functional phytoplankton groups (cyanobacteria, diatoms, other) can be simulated, provided information is available for their maximum specific growth rates and responses to light, temperature, and nutrient conditions. Loss processes include respiration, mortality, and settling. Settled phytoplankton may re-enter the water column by resuspension. The parameter values of the three algal groups in the model differ.

Macrophytes can be simulated as partly in the sediment (roots) and partly homogeneously distributed in the water column (shoots). Seasonality is simplified by assuming a high root fraction in the winter and a lower root fraction in the growth season (default 0.6 and 0.1 respectively). The switch is triggered by temperature.

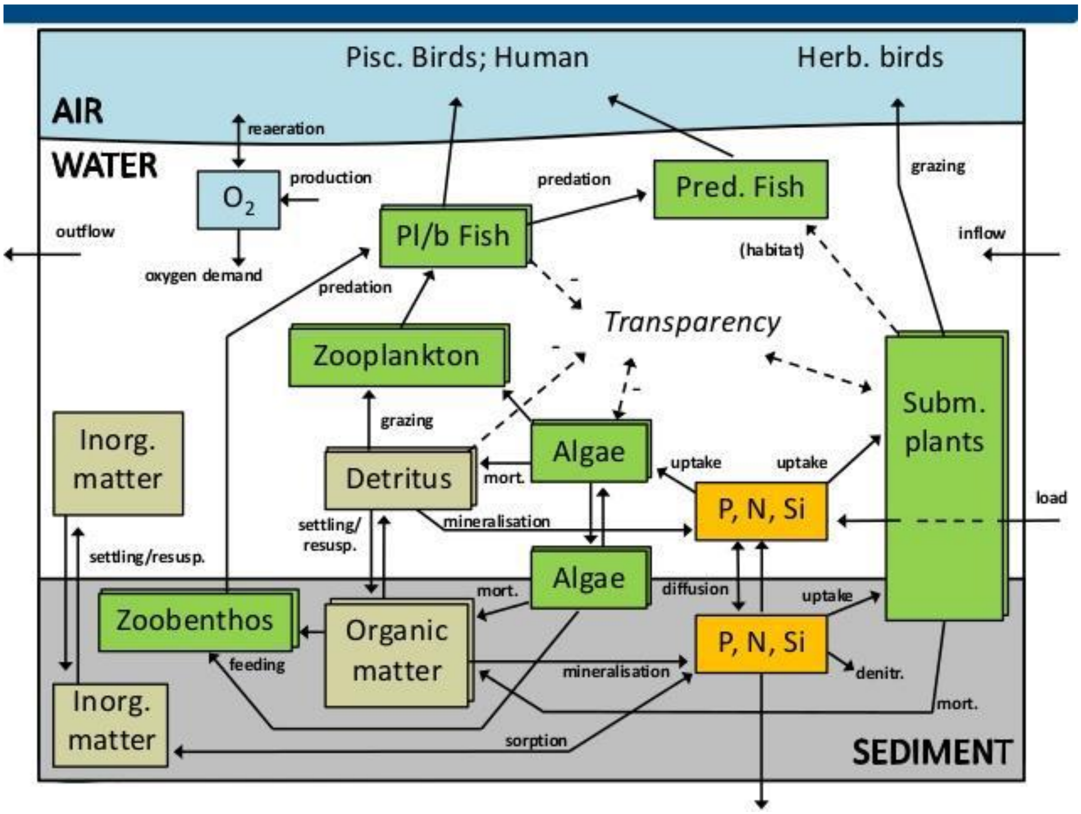



**Figure 4-1: PCLake process diagram. Solid lines indicate mass fluxes. Dashed lines indicate interactions.** Reproduced from Jeuken and Janssen (2014).

The model is open source (available on GitHub3) and in Database Approach to Modelling (DATM) (van Gerven et al. 2015, Chang et al. 2019) and runs in Excel, R, GRIND for MATLAB, Delft3D, ACSL, FORTRAN, and C++. PCLake has been applied to at least 56 lakes in the Netherlands, Belgium, Poland, Denmark, Spain, Ireland, and China.

PCLake has been used to model Lake Waahi in New Zealand to simulate the effects of koi carp and tuna on the lake nutrient budget, not only via nutrient excretion but also via sediment resuspension by carp feeding (Allan 2018). Ten scenarios were simulated to determine potential effects of climate change (air temperature), water level, fish (tuna/shortfin eel and koi carp) presence/absence, macrophyte establishment, and lake sediment dredging on lake water quality parameters (water temperature, dissolved oxygen, Secchi depth, total suspended solids, total phosphorus, phosphate, total nitrogen, nitrate, ammonia, chlorophyll *a*).

While GLM-AED may also be an appropriate model framework for Lake Ngātu, PCLake has been applied in New Zealand and NIWA has worked with an overseas expert on setting up a version of PCLake that would be suitable for simulations in the southern hemisphere.

### 4.1.3 Lake model data needs

Any process-based lake model requires environmental data for model forcing conditions (inputs), calibration, validation (confirmation), and testing. NRC has already collected a significant amount of environmental data that can be used to set up a lake model for Lake Ngātu. Ideally, there would be calibration and confirmation data for all state variables (every metric to be simulated), and there would be some data representing baseline/dry and rain event/wet conditions.

**Error! Reference source not found.** lists the data requirements to set up a process-based lake model. L ake characteristics, meteorological data, and river and groundwater inflows/outflows are required to simulate hydrodynamics (water movement and changes in temperature). Inflow, sediment, and lake water nutrient concentrations are required to simulate water quality.

**Table 4-2: Lake model data requirements.**

| Type of data | Details | Source/availability |
|---|---|---|
| Lake data | - Bathymetry<br>- Water level time series<br>- Any water take data, if water is removed for stock or domestic use<br>- Temperature and (ideally also) DO profile time series<br>- At least near-surface and near-bottom TN, TP, $NH_4$-N, $NO_3$-N, $NO_2$-N, DRP, TDP, DOC, chlorophyll *a*, DO (at least monthly) | DEM 1 m resolution, hypsographic curve (NRC), monthly discrete samples from SOE monitoring, buoy temperature and DO data at three depths (0.3–0.5 m below surface, mid-hypolimnion at 3 m, and 0.5 m above lake bottom) |
| Meteorological data | - Air temperature<br>- Wind speed and direction<br>- Relative humidity<br>- Cloud cover<br>- Rainfall<br>- Solar radiation | Kaitaia Airport meteorological station and/or VCSN |
| Inflows (groundwater) | - Bore hole data<br>- Nutrient concentrations: DO, $NO_3$-N, DRP, DOC, pH, Fe, Mn | NRC |
| Sediments | - Total N, P, C, Al, Fe, Mn content (e.g., mg TP/mg sediment dry mass)<br>- Sediment oxygen demand | A 10 cm sediment core to be collected at least once, with analysis of the top 10 mm followed by 20 mm depth intervals from the surface. Additional sampling to be considered after analysis of initial results.<br>Sediment oxygen demand can be sampled in situ using a benthic chamber (preferable) or as a laboratory bottle test. |
| Macrophytes | - Species<br>- Average cover, height, depth range<br>- Standing crop in grams dry mass per unit area | NIWA LakeSPI survey data |

| Type of data | Details | Source/availability |
|---|---|---|
| Potential additional data | - Management measures (e.g., biomanipulation, macrophyte harvesting or mowing, dredging)<br>- Fish data (species, abundance, location) | NRC |
| Model rate coefficients | Phytoplankton and macrophyte growth, respiration, mortality, settling, nutrient uptake and release rates with respect to light and temperature.<br>Sediment oxygen demand, sediment nutrient uptake and release rates.<br>Particulate settling rates. | Estimates of these values will be obtained from the literature in the first instance. Later, laboratory experiments may be recommended to define physiological rates. |

## 4.2 Potential data limitations and model uncertainty

All models are imperfect representations of reality and thus come with limitations and some level of uncertainty. The input and calibration/validation data quality (accuracy, precision, temporal, and spatial resolution) affects model performance.

The key potential limitations and uncertainty associated with the data and modelling approach recommended here are as follows:

- The accuracy of **water level records** could affect water balance calculations. Thus, records should be verified and adjusted as appropriate.
- **Meteorological data** from the Kaitaia monitoring station may not be sufficiently representative of environmental conditions in the lake catchment. E.g., **evapotranspiration** will be calculated from the best available data sets. Uncertainty will be assessed if secondary data are available (e.g., north climate stations).
- Monitoring data serving as **daily loads** (i.e., groundwater nutrient concentrations × flows) are unlikely to be available, but intermittent monitoring as recommended will provide some information regarding nutrient loads. Higher frequency sampling, interpolation, or shallow groundwater modelling may be required to better define groundwater loads to the lake.
- **Macrophyte standing crop** (gDM/$m^2$) data are currently unavailable and may not become available, but could be estimated from available vegetation maps, stand heights, and biovolume estimates.

Additional data and model limitations may be identified during the modelling process, resulting in recommendations for additional monitoring. Model refinement is iterative as knowledge is gained from monitoring data analysis, modelling, identification of knowledge gaps, additional data collection, analysis, and modelling, and so on.

# 5 Recommendations and modelling cost indication

To quantify and better understand the nutrient budget and dynamics in Lake Ngātu, we recommend investigating groundwater connectivity and development of a modelling framework including a catchment model and a hydrodynamic-lake water quality model. Initially, we suggest additional data collection followed by set-up, calibration, and validation of a catchment model (SWAT) and a lake model (PCLake) for Lake Ngātu. PCLake is appropriate for well-mixed shallow lakes. PCLake+ is more suitable for shallow lakes that stratify. If the buoy data indicate regular summer stratification, we recommend using PCLake+. Depending on modelling results of this initial effort, additional monitoring and/or experimental work may be recommended to improve model accuracy and reduce uncertainty. If desired, NIWA could provide cost estimates for the suggested monitoring as part of a proposal (Table 5-1).

**Table 5-1: Lake Ngātu monitoring recommendations in addition to ongoing monitoring by NRC (all recommended to be continued), in order of priority.**

| Variable(s) | Why | Where | When | Notes |
|---|---|---|---|---|
| **Shallow groundwater** monitoring boreholes (piezometers to 5 and 10 m bgl), optional water quality monitoring (DO, $NO_3$-N, DRP, DOC, Fe, Mn concentrations) | Determine groundwater connectivity/ seepage to the lake (e.g., during high rainfall) and associated nutrient loads.<br><br>Allow hydraulic testing of shallow aquifer. | A 5 m and 10 m piezometers placed perpendicular to the lake in the vicinity of existing deep boreholes: LOC.209861 north, LOC.20154 east, LOC.201558 south, LOC.331885 west. | Ideally continuous measurement, or else at least monthly. | Borehole logs taken during piezometer installation will be of use in determining nature of shallow aquifer properties and continuity. |
| **Deep groundwater**: water quality metrics (DO, $NO_3$-N, DRP, DOC, Fe, Mn concentrations) | To quantify hydraulic gradient within aquifer in vicinity of lake and allow hydraulic testing. | Three piezometers installed between the northeast wetland and the lake | Groundwater quality and level to be sampled monthly for two years | If there is evidence of mixing between groundwater and lake water, then impact of septic tank leaching should be investigated. |
| **Lake water level** | To hindcast water levels<br>To recalculate the water budget for a longer period, including more recently collected data (since 2017) | | | Re-examine the record to determine if a conversion factor can be identified to correct values after the level recorder was vandalised and before it was resurveyed |

| Variable(s) | Why | Where | When | Notes |
|---|---|---|---|---|
| **Sediment** nutrient, oxygen and metal content (sediment oxygen demand, and total N, P, C, Fe, Mn, and Al) in a single sediment core (0–10 cm) | To determine if there is potential nutrient release from the sediments | In a deep part of the lake | Once in spring | Use a small sediment corer to collect a ~10 cm core (e.g., Wildco hand core sampler used by a diver). Depending on results of a single core, collect more samples during different seasons. |
| **Macrophyte** vegetation map and biomass (standing crop) | PCLake simulates macrophyte biomass in grams dry mass per unit area. This can be estimated from available data but should be confirmed with this field data. | The five LakeSPI monitoring sites on the lake | Ideally monthly, or at least quarterly for two years. | A sampling protocol would need to be developed. |
| **Phytoplankton** species composition | The relative abundance of cyanobacteria, diatoms, and green algae determines the value of rate coefficients used in PCLake. | Epilimnion and (if/when the lake is stratified then also) hypolimnion | Monthly for two years | Esp. if there are concerns about harmful algal blooms (toxic cyanobacteria), phytoplankton biomass and composition should be monitored. |

We recommend development of a catchment model (SWAT) and a lake model (PCLake) for Lake Ngātu while monitoring is ongoing. SWAT would simulate nutrient loads from surface (overland) runoff and this output would be used as input to PCLake, to dynamically simulate lake nutrient concentrations and quantify relative source contributions.

Depending on the initial success in calibrating the SWAT-PCLake model for Lake Ngātu and when remaining data requirements to improve model performance have been identified, additional data collection or experimental work may be recommended.

A ballpark cost estimate for the development of a Lake Ngātu catchment-lake model framework, as outlined in this report, is presented in Table 5-2. This is a preliminary, indicative estimate provided purely to give NRC an idea of the order of magnitude of the cost of the proposed work. The actual cost would be provided in a proposal and depend on the agreed scope of work at that time.

**Table 5-2: Estimated fees and expenses summary for Lake Ngātu water quality modelling.**

| Task | Fees and expenses ($NZ) |
|---|---|
| Project management | 6,000 |
| Data compilation and analysis | 31,000 |
| SWAT model development | 50,000 |
| PCLake development | 107,000 |
| Reporting | 31,000 |
| **Total (excluding GST)** | **225,000** |

# 6 Acknowledgements

This work was funded by an Envirolink Medium Advice Grant (C01X2310). NRC staff (Susie Osbaldiston, Manas Chakraborty, Hagan Robertson, Katrina Hansen, and Peter Wiessing) provided GIS layers and information related to data availability and quality and met with NIWA staff during a site visit to Lake Ngātu on 24th October 2023. Representatives from Ngāi Takoto also attended the site visit and supplied anecdotal and historical information relating to water management around and within the lake.

# 7 References


Allan, M.G. (2018) Ecological modelling of water quality management options in Lake Waahi to support Hauanga Kai species: Technical report.

Bruce, L.C., Frassl, M.A., Arhonditsis, G.B., Gal, G., Hamilton, D.P., Hanson, P.C., Hetherington, A.L., Melack, J.M., Read, J.S., Rinke, K., Rigosi, A., Trolle, D., Winslow, L., Adrian, R., Ayala, A.I., Bocaniov, S.A., Boehrer, B., Boon, C., Brookes, J.D., Bueche, T., Busch, B.D., Copetti, D., Cortés, A., de Eyto, E., Elliott, J.A., Gallina, N., Gilboa, Y., Guyennon, N., Huang, L., Kerimoglu, O., Lenters, J.D., MacIntyre, S., Makler-Pick, V., McBride, C.G., Moreira, S., Özkundakci, D., Pilotti, M., Rueda, F.J., Rusak, J.A., Samal, N.R., Schmid, M., Shatwell, T., Snorthheim, C., Soulignac, F., Valerio, G., van der Linden, L., Vetter, M., Vinçon-Leite, B., Wang, J., Weber, M., Wickramaratne, C., Woolway, R.I., Yao, H., Hipsey, M.R. (2018) A multi-lake comparative analysis of the General Lake Model (GLM): Stress-testing across a global observatory network. *Environmental Modelling & Software*, 102: 274-291. https://doi.org/10.1016/j.envsoft.2017.11.016

Chakraborty, M. (2022) Environmental Monitoring Plan - Lakes Water Quality Monitoring Network. Northland Regional Council.

Champion, P. (2021) Review of Northland Lakes Strategy 2020 and recommendations for the future. NIWA Report No. 2021106HN, prepared for Northland Regional Council.

Champion, P., de Winton, M. (2012) Northland Lakes Strategy, NIWA Project: ELF12213, NIWA Client Report No: HAM2012-121, prepared for Northland Regional Council: 42.

Chang, M., Teurlincx, S., DeAngelis, D.L., Janse, J.H., Troost, T.A., van Wijk, D., Mooij, W.M., Janssen, A.B.G. (2019) A Generically Parameterized model of Lake eutrophication (GPLake) that links field-, lab- and model-based knowledge. *Science of The Total Environment*, 695: 133887. https://doi.org/10.1016/j.scitotenv.2019.133887

Elliott, S., Verburg, P., Champion, P. (2020) Nutrient load limits to protect high-value Northland dune lakes – Review of existing information. NIWA Report No. 2020060HN, prepared for Auckland Council: 74 p.

Hickey, C.W., Gibbs, M.M. (2009) Lake sediment phosphorus release management—decision support and risk assessment framework. *New Zealand Journal of Marine and Freshwater Research*, 43(3): 819-856.

Hipsey, M., Bruce, L., Hamilton, D. (2013) Aquatic Ecodynamics (AED) Model Library. Science Manual, October 2013, 34.

Hipsey, M.R., Bruce, L.C., Boon, C., Busch, B., Carey, C.C., Hamilton, D.P., Hanson, P.C., Read, J.S., de Sousa, E., Weber, M. (2019) A General Lake Model (GLM 3.0) for linking with high-frequency sensor data from the Global Lake Ecological Observatory Network (GLEON). *Geoscientific Model Development*, 12(1): 473-523.

Hu, F., Bolding, K., Bruggeman, J., Jeppesen, E., Flindt, M.R., van Gerven, L., Janse, J.H., Janssen, A.B.G., Kuiper, J.J., Mooij, W.M., Trolle, D. (2016) FABM-PCLake – linking aquatic ecology with hydrodynamics. *Geosci. Model Dev.*, 9(6): 2271-2278. https://doi.org/10.5194/gmd-9-2271-2016

Hughes, B. (2016) Lake FMUs for Northland – Recommendations for policy development. Land Water People client report for Northland Regional Council: 90 p.

Isaac, M.J. (2006) Geology of the Kaitaia area. 1:250,000 geological map. Geological and Nuclear Sciences Ltd, Lower Hutt.

Janse, J.H. (2005) Model studies on the eutrophication of shallow lakes and ditches. Wageningen Universiteit, Wageninge. http://edepot.wur.nl/121663

Janse, J.H., Scheffer, M., Lijklema, L., Van Liere, L., Sloot, J.S., Mooij, W.M. (2010) Estimating the critical phosphorus loading of shallow lakes with the ecosystem model PCLake: Sensitivity, calibration and uncertainty. *Ecological Modelling*, 221(4): 654-665. https://doi.org/10.1016/j.ecolmodel.2009.07.023

Janssen, A.B.G., Teurlincx, S., Beusen, A.H.W., Huijbregts, M.A.J., Rost, J., Schipper, A.M., Seelen, L.M.S., Mooij, W.M., Janse, J.H. (2019) PCLake+: A process-based ecological model to assess the trophic state of stratified and non-stratified freshwater lakes worldwide. *Ecological Modelling*, 396: 23-32. https://doi.org/10.1016/j.ecolmodel.2019.01.006

Moreau, M., White, P.A., Lovett, A., Rawlinson, Z. (2013) State of hydrogeological knowledge and identification of information gaps for water management plan, Lake Ngātu. Northland GNS Science Consultancy Report 2013/188. 62p.

National Policy Statement for Freshwater Management. (2020) Wellington, New Zealand: Ministry for the Environment.

Podger, G. (2004) Rainfall Runoff Library Use Guide. CRC for Catchment Hydrology Report.

Schallenberg, M., Vermeulen, M. (2022) Phosphorus and nitrogen budgets for Lake Horowhenua. Hydrosphere Research Ltd. client report prepared for Horizons Regional Council: 30 p.

Tan, K.S., Chiew, F.H.S., Grayson, R.B., Scanlon, P.J., Siriwardena, L. (2005) Calibration of a Daily Rainfall-Runoff Model to Estimate High Daily Flows, MODSIM, International Congress on Modelling and Simulation: advances and applications for management and decision making, pp. 2960 - 2966 (7).

Trolle, D., Hamilton, D.P., Hipsey, M.R., Bolding, K., Bruggeman, J., Mooij, W.M., Janse, J.H., Nielsen, A., Jeppesen, E., Elliott, J.A., Makler-Pick, V., Petzoldt, T., Rinke, K., Flindt, M.R., Arhonditsis, G.B., Gal, G., Bjerring, R., Tominaga, K., Hoen, J.t., Downing, A.S., Marques, D.M., Fragoso, C.R., Søndergaard, M., Hanson, P.C. (2012) A community-based framework for aquatic ecosystem models. *Hydrobiologia*, 683(1): 25-34. https://doi.org/10.1007/s10750-011-0957-0

van Gerven, L.P.A., Brederveld, R.J., de Klein, J.J.M., DeAngelis, D.L., Downing, A.S., Faber, M., Gerla, D.J., Hoen, J.t., Janse, J.H., Janssen, A.B.G., Jeuken, M., Kooi, B.W., Kuiper, J.J., Lischke, B., Liu, S., Petzoldt, T., Schep, S.A., Teurlincx, S., Thiange, C., Trolle, D., van Nes, E.H., Mooij, W.M. (2015) Advantages of concurrent use of multiple software frameworks in water quality modelling using a database approach. *Fundamental and Applied*

*Limnology / Archiv für Hydrobiologie*, 186(1-2): 5-20. https://doi.org/10.1127/fal/2015/0631

Water Management Group (2016) Aupōuri Lakes Water Balance Assessment: Lake Heather, Lake Waiparera, Lake Ngātu & Lake Rotoroa. Report No. 17001-001-R-001. For Northland Regional Council.

Wilson, S. and Shokri, A. 2015 Aupori Aquifer Review, Aupouri Aquifer Review Report 1056-1-R1, Lincoln Agritech Ltd.

# Appendix A Lake Ngātu site visit on 24 October 2023

Weather at time of visit was heavy showers. Lake was near to its highest recorded water level with some flooding of path on west side of lake. Description of three areas around the lake visited as follows:

View south across Lake Ngātu from road entrance to boat launch car park (left) and drainage ditch draining valley from east (right) (note Macrocarpa stump, one of many around lake).

Roadside ditch drainage / swale with sediment trap (middle) (West Coast Road) and culvert draining from east, valley along Rotokawau Road.

**Figure A-1: Site 1: Carpark at boat launch area, drainage from Rotokawau Road and sediment trap.**

Ngakapua Road looking north to worked land area (small hill pine forest in distance). Area is historically drained via a tunnel dug into compacted sandstone laterite layer. The area also drains west under gravity to the wetlands and smaller lakes northwest of Lake Ngātu (subsequently draining to west coast)

Typical surface water drainage from properties around lake (this one from hill section of Ngakapua road). Numerous private properties around lakes may act as small point source discharges to the lake (from septic tanks). School on the east side of lake thought to be the largest of these point sources. Many private properties will have water supply boreholes drawing from deeper groundwater (though some non-drinking water bores may draw only from the shallow GW (approx. 10 m bgl).

Planted wetland area adjacent to north bank of lake Ngātu (left). Sump / sediment trap partly draining tunnel from area north of Ngakapua Road (right).

**Figure A-2: Site 2: Ngakapua Road.**

Bankside of Lake Ngātu (south-bank looking north-west; and east).


Location of path to Gem Lake. Lake Ngātu in background (top left). Gem Lake seen from path (lower). More pristine and sheltered (harder to access than Lake Ngātu).

**Figure A-3: Site 3: SW bankside (and path to Gem Lake).**

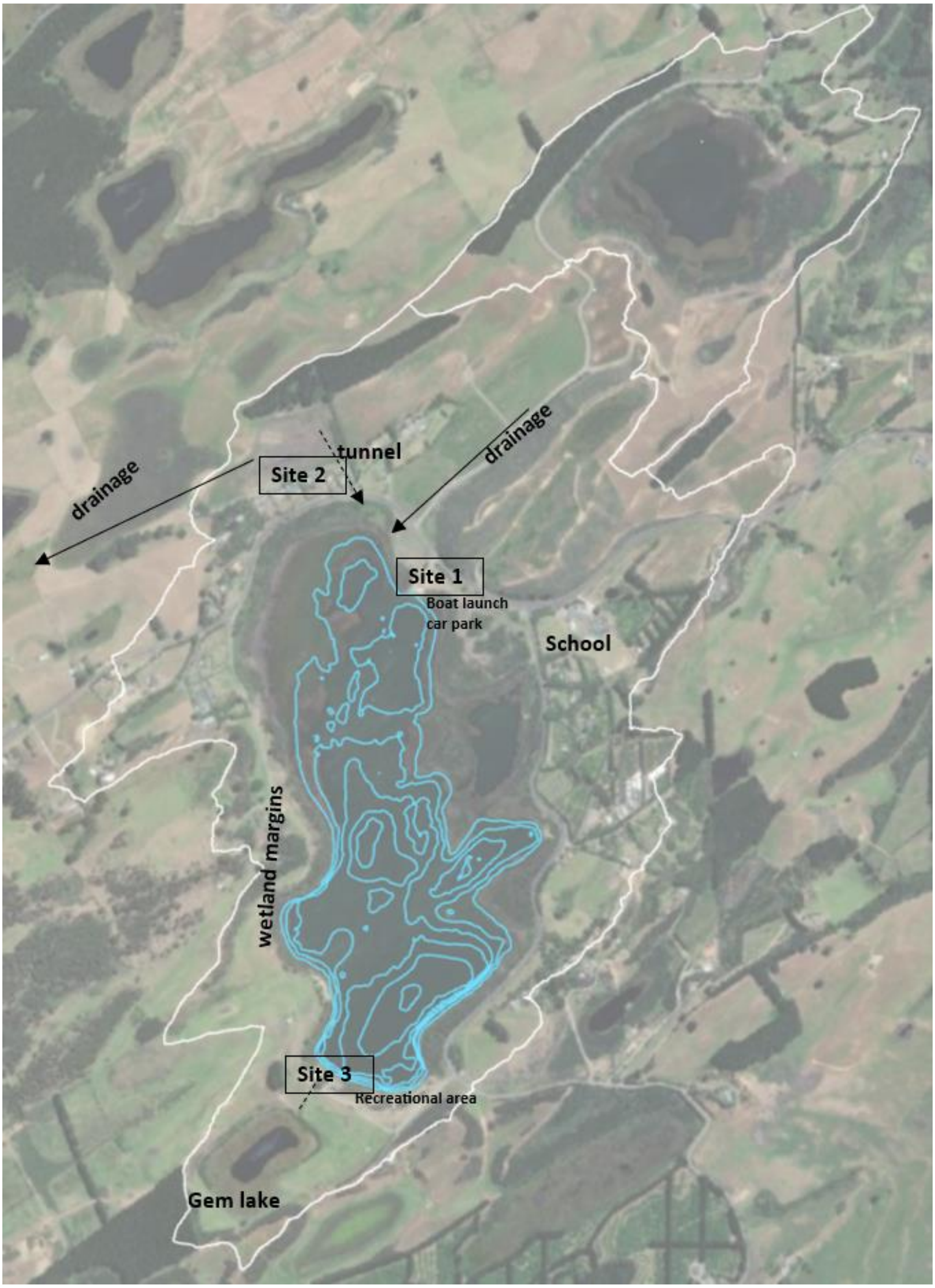



**Figure A-4: Figure illustrating locations of main stops during site visit.**

## Site visit questions and responses:

1. **What is known about wetland connectivity to lakes?**
   Some wetland areas at lake margin directly connected. Wetlands that are disconnected from the lake depend on local topography to control their connectivity. No monitoring of these processes currently undertaken.

2. **Are there any water level data for the wetlands?**
   No

3. **Is there uncertainty in the catchment boundary (GNS report 2013)? What is the DEM resolution GNS report used 20 m elevation contours)?**
   More recent catchment boundaries drawn with a 1 m resolution DEM but produced drainage maps will vary, if the resolution is re-scaled, and will not represent the influence of drainage works.

4. **Has a piezometer nest been installed (as recommended by GNS) to understand GW connectivity and hydraulic properties?**
   No

5. **Bore holes: what are there now and what could be installed in future?**
   As per map in GNS report, predominantly GW extraction for drinking water from the deeper aquifer. Some monitoring done quarterly by NRC. This data is available.

6. **Can existing bore holes be used for water level monitoring and WQ data. How deep is GW, is it perched on the impermeable peat layer?**
   Possible to monitor through existing boreholes but will depend on owners. See notes below on conceptual GW model.

7. **Has any WQ data been collected from within the lake (i.e., instruments on a lake buoy)? When is mid-hypolimnion and bottom temperature and DO data collected?**
   Lake buoy monitoring is available for the last 3 months. Historic discrete data is also available.

8. **Is the lake water level gauge automatic or is a staff gauge monitored manually?**
   There has been continuous loggers in the lake since Nov 2017, although there are some gaps in the record. There also appears to be an issue with the data since June 2023. Prior to 2017 level was recorded via monthly manual staff gauge readings

9. **What permissions would be needed to sample lake bottom sediments?**
   (remains unanswered)

10. **Any recent changes in land use?**
    Small gradual changes. Areas to north and south-west of lake probably most active. Macrocarpa removed to encourage native species.

11. **Have any pine trees been removed?**
    Some from areas around Lake Ngātu and around Gem Lake (southwest of Lake Ngātu)

12. **Is there any more recent GW nutrient data if available (apart from the median values in the 2013 GNS report and the 2 sites reported by LAWA)?**
    There is one additional site at Waipapakauri (323844) approximately 3 km to the west.

# Appendix B Lake Ngātu groundwater quality

(GNS hydrogeology report; Moreau et al. 2013)

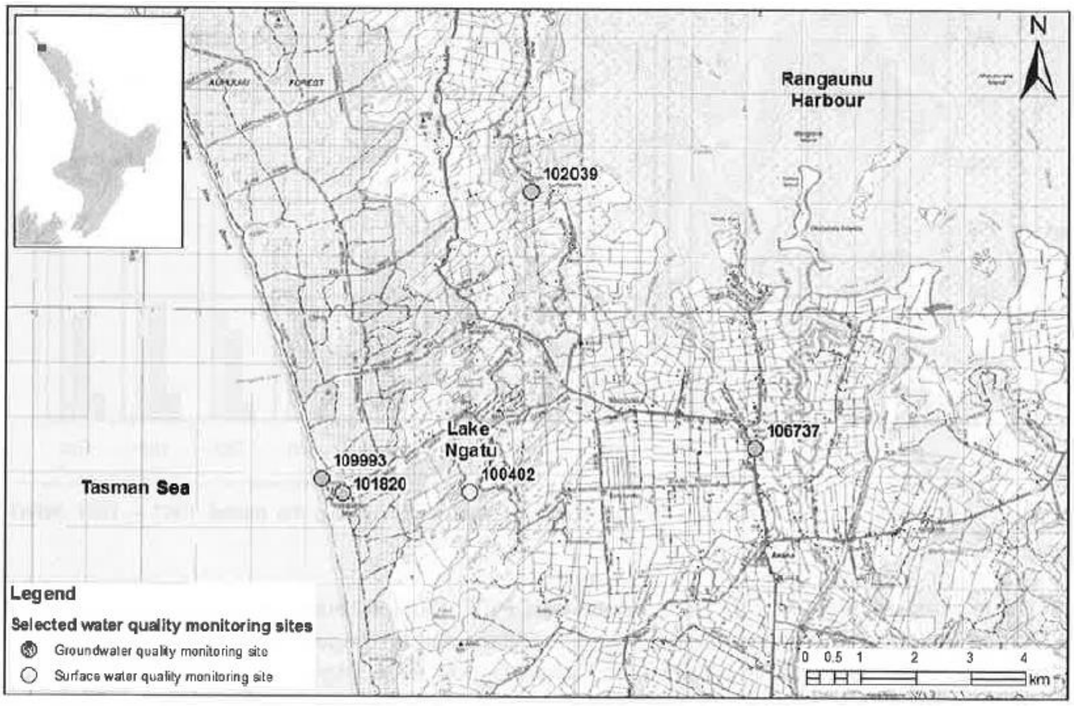



**Figure B-1: Location of the groundwater measurement sites around Lake Ngātu (GNS 2013).**

Median concentrations for water quality constituents in 4 deepwater bores (GNS, 2013). The number of samples are shown in the brackets show, and ND indicates the number of analysis samples which were below the detection level where applicable.

| Parameter and unit | Well 101820 | Well 109993 | Well 102039 | Well 106737 |
|---|---|---|---|---|
| Total solids (EC) uS/cm at 25°C | 280 | - | 410 (47) | 488 (14) |
| Oxygen mg/L ($O_2$ – dissolved) | 3.6 | - | 3.75 (8) | 2.5 (2) |
| Acidity – pH units | 8.25 (16) | 8.20 (15) | 7.93 (69) | 7.75 (14) |
| Ammonium – mg/L (as $NH_4$) | 0.06 | - | 0.06 (4) | 0.54 (7) |
| Bicarbonate – mg/L | 74 (7) | 64 (2) | 151 (87) | 159 (6) |
| Boron – mg/L | 0.05 (1) | 0.019 (1) | 0.06 (1) | - |
| Bromine – mg/L | 0.15 (4 and 3 ND) | 0.22 (8) | - | 0.21 (4 and 3ND) |
| Calcium – mg/L | 16.3 (7) | - | 34 (55) | 24.2 (7) |
| Chloride – mg/L | 42 (16) | 35 (14) | 53 (15) | 69.6 (13) |
| Fluorine – mg/L | 0.09 (5 – 2 ND) | 0.060 (6 and 2 ND) | 0.07 (12) | 0.14 (5 and 2 ND) |
| Magnesium – mg/L | 3.7 | 3.50 (8) | 5.70 (55) | 6.0 (7) |
| Nitrate-nitrogen – mg/L | 0.027 | 0.0069 (3 and 5 ND) | 0.030 (5 and 8) | 0.002 (3 and 4ND) |
| Nitrite-nitrogen – mg/L | 0.0155 | 0.0046 (1 and 7 ND) | - | - (5 ND) |
| Phosphorus – mg/L (P- Reactive) | 0.09 | 0.14 (8) | 0.083 (19 and 4ND) | 0.30 (7) |
| Potassium – mg/L (K –filterable) | 1.78 | 1.70 (8) | 2.70 (54) | 6.19 (2) |
| Silicon – mg/L ($SiO_2$ – total) | 30.8 | 44.5 (8) | 41 (14) | 34.0 (7) |
| Sodium – mg/L (Na – filterable) | 31.7 | - | 41.0 (54) | 68.4 (5) |
| Sulphate – mg/L ($SO_4$ – total) | 9.9 | 6.15 (8) | 8.90 (14) | 0.75 (6 and 1 ND) |
| Iron – mg/L | <0.02 | 0.005 (3 and 5 ND) | 0.06 (53 and 4 ND) | 0.52 (7) |
| Manganese – mg/L | 0.011 | - | 0.11 (55) | 0.044 (7) |
| Arsenic – mg/L (filterable) | 0.001 (1) | 0.0039 (1) | - | - (1ND) |
| Escherichia coli – cfu/100 ml | 8 (4 – 10 ND) | 9 (13 and 3 ND) | - | 5 (5 and 8ND) |

* 11 samples for Total coliforms at Bore 109993 were above the detection limit of 2419 cfu/100 ml

**Figure B-2: Median concentrations for water quality constituents in four deepwater bores (GNS 2013).**

# Appendix C GLM-AED

We also considered another model as an option, if PCLake is not quite the right fit for Lake Ngātu: a more complex model combining a physical lake model (GLM) with a lake ecological model (AED).

The General Lake Model (GLM, Hipsey et al. 2019,Figure C-1) is a one-dimensional hydrodynamic model that can be coupled with the Aquatic EcoDynamics model library (AED, Hipsey et al. 2013, (Figure C-2) to simulate water quality and ecosystem dynamics. GLM simulates the physical dynamics, while AED can simulate a simplified food web including macrophyte biomass, sediment geochemistry and pathogens, but not fish.

GLM and AED are open source (available on Github) models and output can be visualised in a rudimentary 2-D graphics module. GLM was tested globally on 32 lakes, including Lake Rotorua and Lake Tarawera (Bay of Plenty RC, University of Waikato, NIWA, Andy Bruere), in the Multi-Lake Comparison Project (MLCP, Bruce et al. 2018). However, ecosystem modelling using AED was not tested in this study. GLM simulates vertical mixing, and the AED library can be used to simulate dissolved oxygen, nitrogen, phosphorus, silica, organic matter, heterotrophic bacteria, phytoplankton (3 groups: dinoflagellates, greens, diatoms), zooplankton (micro- and macro-grazers), and pathogens. The model library includes process descriptions for sediment diagenesis, nutrient hydrolysis/decomposition, and mineralisation. The library offers different options for selecting species-specific light response, respiration, and nutrient uptake functions (e.g., static or dynamic).

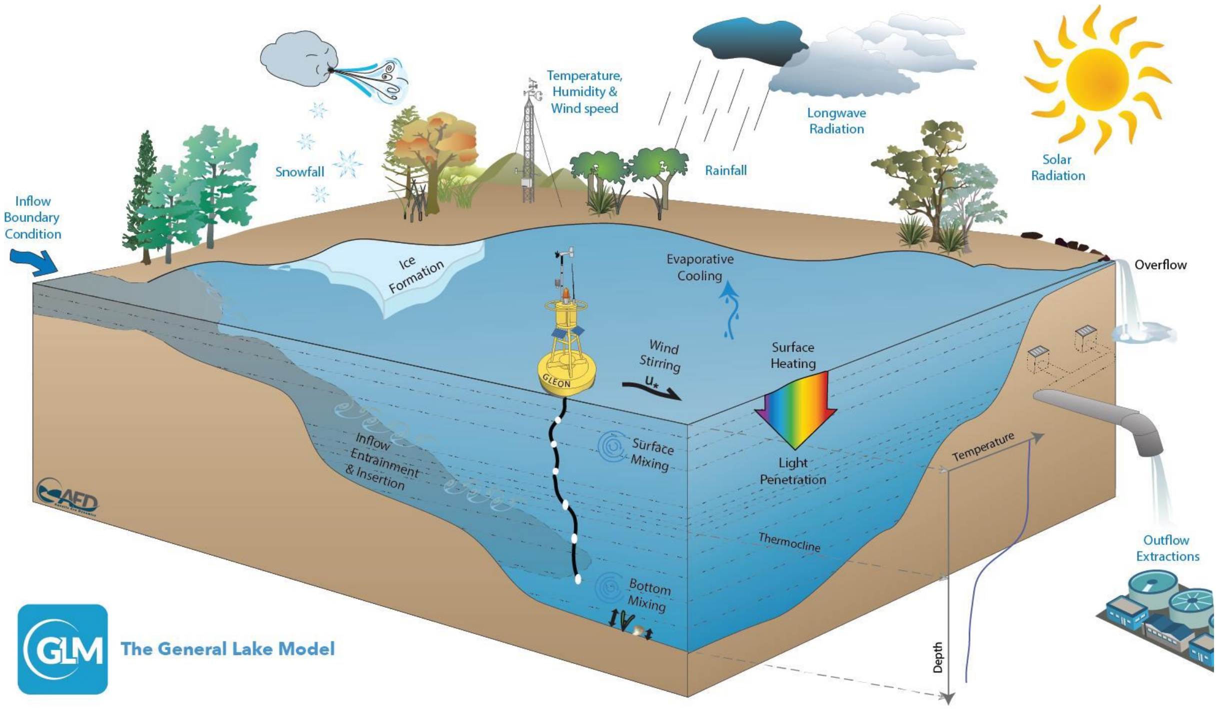



**Figure C-1: General Lake Model (GLM) components (Hipsey et al. 2019).** Blue text indicates model inputs. Black text indicates simulated processes. https://aed.see.uwa.edu.au/research/models/glm/overview.html.

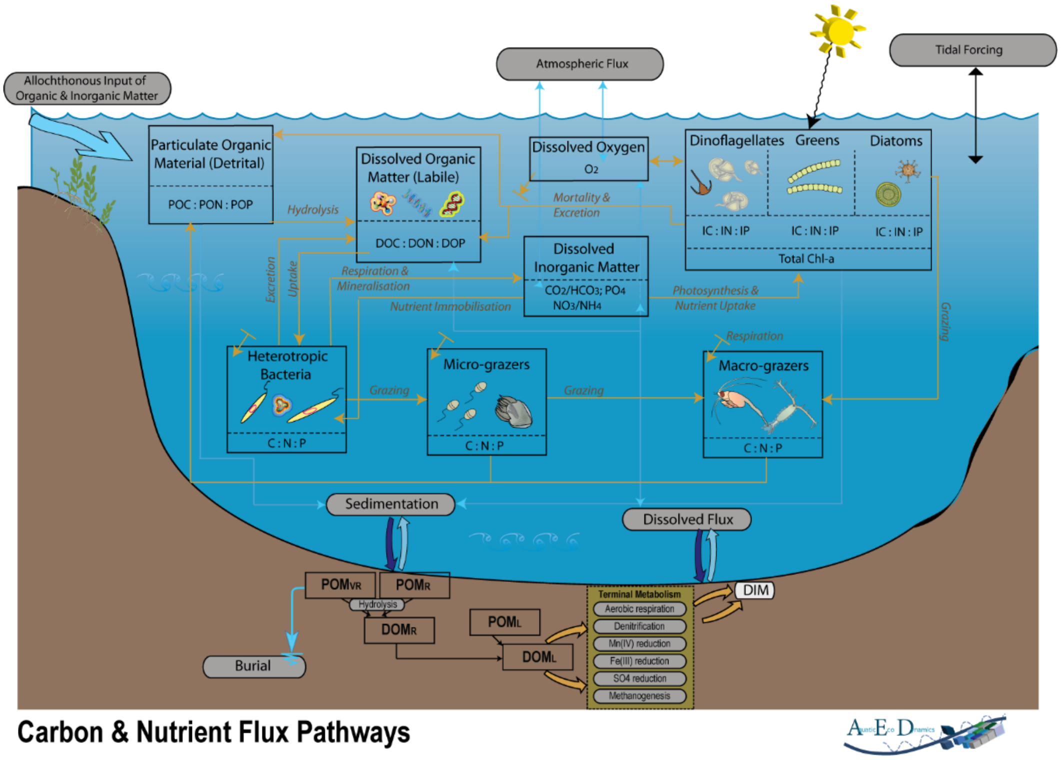



**Figure C-2: Carbon and nutrient flux pathways in the Aquatic Ecodynamics (AED) modelling library.** Black text indicates model state variables. Brown text indicates simulated processes. https://aed.see.uwa.edu.au/research/models/aed/overview.html.

In setting up AED for Lake Ngātu, one challenge would be that species-specific light response, respiration, and nutrient-uptake functions cannot be used using existing formulations because Lake Ngātu species are different. Some model coefficients could be chosen using existing information from the scientific literature. We are not aware of examples of a GLM-AED model application that includes simulation of macrophytes in New Zealand. If we were to set up this model for Northland dune lakes, we would identify knowledge or data gaps that may limit model performance and make recommendations for improvements.