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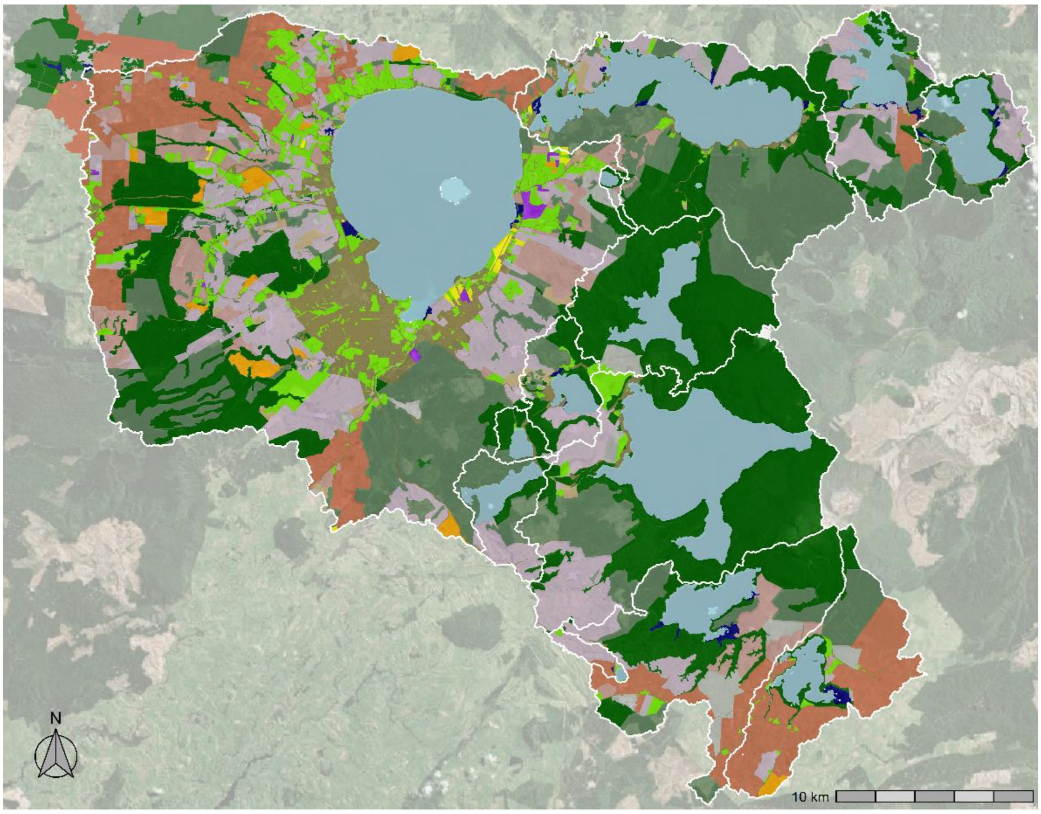
Estimated catchment loads of nitrogen and phosphorus to the Rotorua Te Arawa Lakes

Catchment, atmospheric and geothermal inputs



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Executive Summary

The Rotorua Te Arawa Lakes are central to the identity of their region, of immense historical and cultural importance, and provide ecosystem services that underpin biodiversity, conservation and socioeconomic aspirations of the community. The diversity of water quality in the lakes reflects their catchments, which are diverse in topography, hydrogeology and intensity of land use, ranging from the largely undeveloped land around lakes Tikitapu and Okataina, to highly developed forestry and pastoral land around lakes Rerewhakaaitu, Rotorua and Okaro. Lake water quality is strongly linked to nutrients received by each lake from surface flows and groundwater springs. It therefore follows that management of lake water quality requires a good understanding of nutrient loads derived from the landscape, as does the assessment or prediction of the in-lake effects of catchment-based management initiatives aimed at improving lake water quality.

An established method for estimating nutrient loads to lakes is the export coefficient modelling approach, whereby estimated nutrient loss rates from land uses within the catchment are multiplied by area in each land use, and any relevant attenuation factors are applied, to calculate total 'load-to-lake'. This method has broad precedent in the Rotorua Te Arawa Lakes, having been used to estimate catchment loads for several Lake Action Plans. An update of many of these previous estimates is required, because land use has changed over time, as has the understanding of nutrient loss rates for various land uses and attenuation processes within the catchments.

The aim of the present study is to review nitrogen (N) and phosphorus (P) loads to all major Rotorua Te Arawa Lakes. This necessitates not only the most up-to-date estimates of nutrient losses from various catchment land uses, but also consideration of additional nutrient sources and sinks, including naturally occurring geothermal inputs, hydrological connections among lakes and catchments, and the effects of constructed wetlands and natural lagoons. The nutrient loss model Overseer® (version 6.2.3) has been applied to lakes in the Bay of Plenty region to estimate losses of N and P for major land use classes in all catchments. Of specific interest to nutrient budgets is anthropogenic point sources, principally on-site effluent treatment systems (septic tanks) and, in the case of Lake Rotorua, discharge of municipal wastewater for land-based treatment. Applying consistent methodology to estimate catchment loads and atmospheric deposition at the regional scale enables comparison among catchments, and provides a benchmark against which the impacts of present and/or future catchment intervention and/or management strategies can be assessed.

We calculated land use areas for the surface and groundwater catchments of each lake, and estimated nutrient loss rates per land use by a variety of methods. For agricultural land we analysed Bay of Plenty Regional Council's Overseer® modelling outputs, and calculated average loss rates per land use per catchment. For other land uses we conducted a literature review of N and P losses from similar land uses, attempting to account for local features that might modify export rates (for example, the abundance of pest marsupials in the catchments of Lake Okataina and Tarawera leading to forest flora removal, and probably enhanced phosphorus loss). The literature review also extended to features contributing additional loads, including geothermal sources and wastewater inputs (predominantly from septic tanks) associated with resident populations and visitors. We estimated attenuation of land-based nutrient losses using available data and simple relationships with physiography. The result of this work was a comprehensive nutrient budget for each catchment arrived at using consistent methodology (Table A).

Land use among catchments varies widely, and as expected where agricultural land uses were present, these contributed a disproportionate amount of N and P loading due to relatively higher areal export rates (Figure A). Contributions from other sources were notable in some catchments. Specifically, geologically-derived P is a large contributor to overall load in Lake Rotorua, but has not been quantified well for other catchments. Geothermal sources contributed a large proportion of (estimated) overall load in some catchments and relative geothermal contributions of N and P varied greatly among the different geothermal fields. Atmospheric deposition was a large contributor to N and P loads for most lakes. Connected lakes were a large source of nutrients to Lake Tarawera but made up a relatively small component (if any) of loads to other lakes.

Comparison of present load estimates with 'reference' loads (estimated by assuming conversion of all intensive land uses to native forest nutrient export rates) showed that several catchment loads exceed reference conditions by two- or three-fold, or more. Even assuming a linear response of water quality to catchment loading, these comparisons highlight the challenge in restoring water quality to conditions that approximate a reference state, and in setting water quality targets appropriate to both community aspirations and the opportunities for land use practice changes within the basin. In practice, and on less than decadal time scales, water quality may respond to catchment loading in a non-linear fashion (for the worse with respect to water quality) due to internal feedbacks and internal loading. The estimates of catchment loading provided here can serve as a basis from which to use mass balance methods to estimate the degree of internal loading occurring in each lake, and to inform discussions about managing catchment nutrient loads as well as other lake restoration approaches.

Table A. Summary of lake catchment loads for 13 Rotorua Te Arawa Lakes.

Lake	Surface catchment (ha)	Nitrogen load (kg y^{-1})	Phosphorus load (kg y^{-1})
Okareka	1980	14912	984.7
Okaro	368	4045	633.6
Okataina	6301	22821	1385.4
Rerewhakaaitu	1559	15823	1080.8
Rotoehu	4714	45418	3370
Rotoiti	11722	109876	4087.9
Rotokakahi	1922	9847	857.4
Rotokawau	197	970	77.2
Rotoma	2813	15332	2072.6
Rotomahana	8382	95579	20705.8
Rotorua	47798	721427	56760.5
Tarawera	14547	106767	10652.6
Tikitapu	573	2187	116.5

* Much of Lake Rerewhakaaitu's surface catchment does not drain to the lake, resulting in the low observed nutrient yields.

** The load given for Rotorua is a steady-state load, which is higher than the observed load at present (see Rutherford & Palliser 2019)

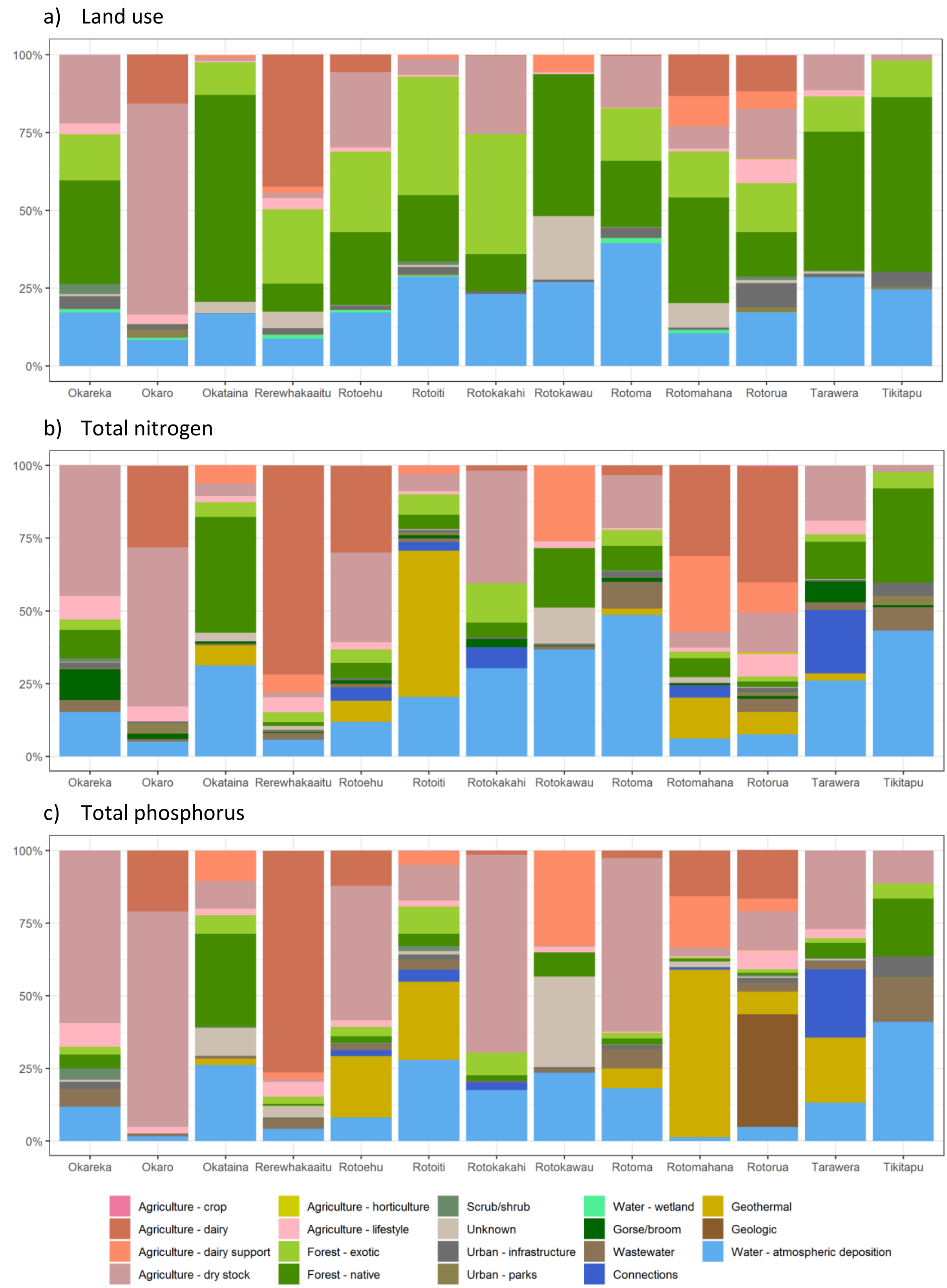

Figure A. Catchment land use and nutrient loads (expressed as percentage contribution to total) for all Rotorua Te Arawa lakes. Nutrient loads for the 'Water – atmospheric deposition encompass both wet (dissolved) and dry (particulate) inputs.

Acknowledgements

The present study was funded under Bay of Plenty Regional Council's Lakes and Freshwater Chair research program. We acknowledge the valuable work of John McIntosh and Paul Scholes for earlier nutrient budgets contained in various Lake Action Plans. Landcare Research New Zealand provided the Land Cover Database underpinning some of this work, and the Overseer® model provided data underpinning much of the nutrient budgets contained herein. David Hamilton (Griffith University, Australia) and Jonathan Abell (Ecofish Research, Canada) provided valuable reviews of an initial draft report.

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1. Introduction

The Rotorua Te Arawa Lakes are diverse in their history, topography and water quality (Table 1). They are central to the identity of the region, of immense historical and cultural importance, and provide ecosystem services that underpin biodiversity, conservation and socioeconomic aspirations of the community.

The diversity of water quality in the lakes reflects their similarly diverse catchments, in both topography and intensity of land use, ranging from the largely undeveloped land around lakes Tikitapu and Okataina, to highly developed forestry and pastoral land around Lakes Rerewhakaaitu, Rotorua and Okaro. Lake water quality is strongly linked to nutrient loads received from surface flows and groundwater springs within each catchment. This nutrient relationship between land and water was characterised by Vollenweider (1976), who showed that annual mean lake water total phosphorus levels were well-predicted by catchment phosphorus load and hydraulic retention time in a sample of predominantly deep lakes. It therefore follows that management of lake water quality requires a robust understanding of nutrient loads derived from the catchment and atmosphere, as does the assessment or prediction of the in-lake effects of catchment-based management initiatives aimed at improving lake water quality.

Estimation of nutrient loads to lakes can be accomplished by various approaches. A direct approach would include measurement of nutrient concentrations and discharge volume of surface inflows. However, calculating nutrient loads in this manner is labour intensive and may not provide a complete budget where sub-surface groundwater flows contribute substantially to the lake water balance, as is the case for some Te Arawa lakes (Morgenstern et al. 2015). Where fairly comprehensive catchment measurements are available, this approach may provide the best available estimate of total catchment loading. For example, Hoare (1980, 1987) estimated nitrogen and phosphorus loads to Lake Rotorua by detailed measurement of stream flows and nutrient concentrations. McBride et al. (2019) adopted a similar approach to estimate annual nutrient loads to Lake Rotorua for the period 1960 to 2017.

Catchment loads of nitrogen and phosphorus can also be estimated by 'reverse application' of mass balance equations along the lines of Vollenweider (1976) (as in Hoare 1980, Nurnberg 1984, and Vant 1987). However, these mass balance equations are generalised relationships derived from large datasets of lakes and reservoirs. For any given lake, observed nutrient retention rates may differ markedly from retention predicted using mass balance equations. Further, other factors such as internal loading (nutrient release from bottom sediments into the water column most prevalent during periods of bottom water anoxia) can complicate the relationship between external loading and in-lake water quality (e.g., Burger et al. 2008).

An established method for estimating nutrient loads to lakes is the export coefficient modelling approach, which uses estimation of average nutrient loss rates from land uses within the catchment, multiplied by land use area, in order to calculate total 'load-to-lake'. This method generally predicts steady-state (long-term average) nutrient loads. An advantage of this approach is that it is confounded to a lesser degree by differences in catchment hydrology (e.g. surface vs. groundwater flows). In New Zealand, the nutrient budget model Overseer® has achieved widespread use for the estimation of nutrient leaching and loss, particularly from agricultural land uses. Export coefficient modelling has broad precedent in the Rotorua Te Arawa Lakes, having been used to estimate catchment loads for several Lake Action Plans (e.g. BoPRC 2007, 2009a,b, 2011, 2013b), as well as for Lake Taupo (Regional Plan Variation 5 – Lake Taupo Catchment). An update of many of these previous estimates is required, because land use has changed over time as has the understanding of nutrient loss rates for various land uses. For example, nitrogen (N) and phosphorus (P) losses estimated using the nutrient loss model Overseer® have varied markedly across sequential updates of the model. For the Rotorua region, predicted nutrient loss rates increased due to the updated model accounting for increased loss rates from porous volcanic soils, in some cases as much as two-fold between Overseer® versions 5 and 6 for intensive land uses.

The aim of the present study is to review nitrogen and phosphorus loads to all major Rotorua Te Arawa Lakes. This necessitates not only the most up-to-date estimates of nutrient losses from various catchment land uses, but also consideration of additional nutrient sources and sinks, including naturally occurring geothermal nutrient inputs, and hydrological connections between lakes, constructed wetlands and natural wetlands or lagoons. Of specific interest to nutrient budgets are also anthropogenic point sources, principally on-site effluent treatment systems (septic tanks) and in the case of Lake Rotorua, discharge of municipal wastewater for land-based treatment. The present study explicitly excludes nutrient loads from internal recycling of nutrients from bottom sediments. This should enable subsequent estimation of internal loading based on the difference between expected total loads derived from mass balance methods using existing water quality, and catchment loads derived under the present study.

The objective of the present study is to estimate catchment loads of nitrogen and phosphorus to all Rotorua Te Arawa lakes. Other desired outcomes include assessing the relative importance of each nutrient source to each lake, as well as evaluating present day N and P loads against estimated ‘reference loads’ (i.e., pre-human loads). By applying consistent methodology to estimate catchment loads and atmospheric deposition at the regional scale we aim to enable comparison among catchments, and provide a benchmark against which the impacts of present and/or future catchment intervention and/or management strategies can be assessed.

2. Methods

2.1 Study site – Rotorua Te Arawa Lakes

The 13 major lakes of the Rotorua Lakes District occupy a total catchment of 110,000 ha (Figure 1). Most are situated in caldera basins and explosion craters of the Okataina Volcanic Complex, and several contain geothermal inputs (Healey 1962). The lakes are diverse in history and physiography. Lake Rotorua is the oldest in the region, thought to have been formed shortly after the Mamaku Ignimbrite eruption about 140,000 years ago, while the youngest, Lake Rotomahana, was formed during the 1886 eruption of Mt. Tarawera (Viner 1987). The lakes range in surface area from 0.33 to 80.5 km^2, maximum depth 8 to 125 m, and mean depth 5 to 55 m. Phytoplankton communities in these lakes are typically dominated by green algae and diatoms, although cyanobacterial dominance and surface blooms have become an increasing concern over recent decades in Lakes Rotorua, Rotoiti, Rotoehu, Okaro, and to a lesser extent in Lake Tarawera. Water quality and nutrient concentrations are highly variable, ranging from the oligotrophic Lake Rotoma (TLI = 2.2) to highly eutrophic Lake Okaro (TLI = 4.8) (Table 1).

Table 1. Lake morphology, outflow volume (based on CLUES simulations, see section 2.2), mean surface water quality measurements 2012 to 2017 (BoPRC unpubl. data), and Burns (1999) Trophic Level Index (calculated using surface water measurements only). Total P = total phosphorus, Total N = total nitrogen.

	Area (km^2)	Volume (1000 m^3)	Mean depth (m)	Residence time (y)	Outflow rate (m^3 s^{-1})	Total P (ppb)*	Total N (ppb)	Chl *a* (ppb)	Secchi depth (m)	Trophic Level Index
Okareka	3.34	63594	19	3.8	0.53	8.54	190.98	3.01	7.4	3.14
Okaro	0.33	3445	10.4	0.99	0.11	37.16	717.65	17.97	3.2	4.77
Okataina	10.73	499040	46.5	6.79	2.33	6.04	87.79	1.96	10.6	2.54
Rerewhakaaitu	5.17	36647	7.1	3.63	0.32	9.27	325.24	3.42	6.6	3.41
Rotoehu	7.9	61001	7.7	0.98	1.98	27.04	322.13	8.92	3	4.23
Rotoiti	33.69	1042300	30.9	6.84	4.83	19.75	161.09	4.67	7	3.49
Rotokakahi	4.33	76832	17.7	4.87	0.5	39.38	212.46	2.48	4.4	3.75
Rotokawau	0.53	5732	10.8	1.82	0.1	NA	120	1.5	10	NA
Rotoma	10.03	455803	45.4	11.37	1.27	3.43	102.74	1.14	13.2	2.19
Rotomahana	9.02	479050	53.1	7.16	2.12	23.09	185.66	4.1	5.2	3.63
Rotorua	80.48	801690	10	1.63	15.57	17.1	324.25	10.88	3	4.14
Tarawera	41.15	2273700	55.3	12.15	5.93	8.9	93.99	1.61	8.3	2.71
Tikitapu	1.44	26320	18.3	6.42	0.13	5.42	173.88	1.96	7.5	2.84

* Phosphorus data are means for the period 2012-2017 that have been adjusted by a coefficient derived from comparison of analytical methods for silica sensitivity conducted by BoPRC in 2019-2020 (see section 3.3.2).

Figure 1: Map of Te Arawa lake catchments. Grey lines within catchments of Lakes Rotorua, Rerewhakaaitu and Rotoiti define subcatchments used in the present study.

2.2 Preliminary estimates of loading and outflow

Catchment nutrient loads, as well as average lake outflow were initially estimated using the Catchment Land Use for Environmental Sustainability (CLUES) modelling platform. CLUES is a modelling system for assessing the effects of land use on water quality and socio-economic factors. NIWA developed CLUES for the Ministry of Agriculture and Forestry (MAF) in association with the Ministry for the Environment (MfE), in collaboration with Lincoln Ventures, Harris Consulting, AgResearch, HortResearch, Crop and Food Research, and Landcare Research. CLUES couples a number of existing models within a GIS-platform and is provided to users as a front-end interface for ArcGIS which queries a geo-spatial database. Further details on the CLUES modelling framework can be found in Woods et al. (2006) and Elliott et al. (2016).

CLUES returns annual average discharge and nutrient (as well as sediment) loads for each REC river reach in the country. Within CLUES, lakes are conceptualised as river reaches, but with additional attenuation (retention) factors applied for nutrients. Lake outlets are identified as such within the REC geo-database, whereas inlet reaches are not identified. In the present study, CLUES estimates of discharge at the outflow of each lake were multiplied by observed mean lake concentrations of N and P to estimate outgoing nutrient loads which connect to 'downstream' lakes (for example, the outlet of Lake Rotokakahi flows directly to Lake Tarawera). To estimate catchment loading to each lake using CLUES outputs, we back-calculated the total load in the lake inflows from the loads in outflows using the following method:

1. CLUES (V10.3, REC V2) was run with default land use settings for all river reaches in Bay of Plenty. The results for all reaches were exported to MS EXCEL along with REC data (e.g., annual rainfall) needed for calculations.
2. Outlet reaches were identified, including for those lakes where the actual outlet reach differed from that assigned as the lake outlet by CLUES (e.g., because of the Ohau Channel diversion wall in Lake Rotoiti).
3. Where the outlet reach was identified within the REC as a lake outflow, the load from the reaches immediately *upstream* was summed (in order to bypass CLUES' internal lake nutrient retention algorithm, which is applied at the outlet reach).
4. Nutrient load for the outflow reach was added to the upstream reach loads, by:

   Load = yield * area * *p*

   Where yield is the CLUES 'generated nutrient yield for that reach' in kg ha^{-1}, area is the catchment area in ha, and *p* is the proportion of the outlet subcatchment which lies within the topographical boundary of the lake catchment (estimated manually by overlaying 'Waters of National Importance' GIS layer of lake catchments on River Environment Classification reaches.

CLUES nutrient loading estimates were used for comparison with loads arrived at by the nutrient budget method, whereas estimates of average outflow rates were used to calculate loads to connected lakes downstream.

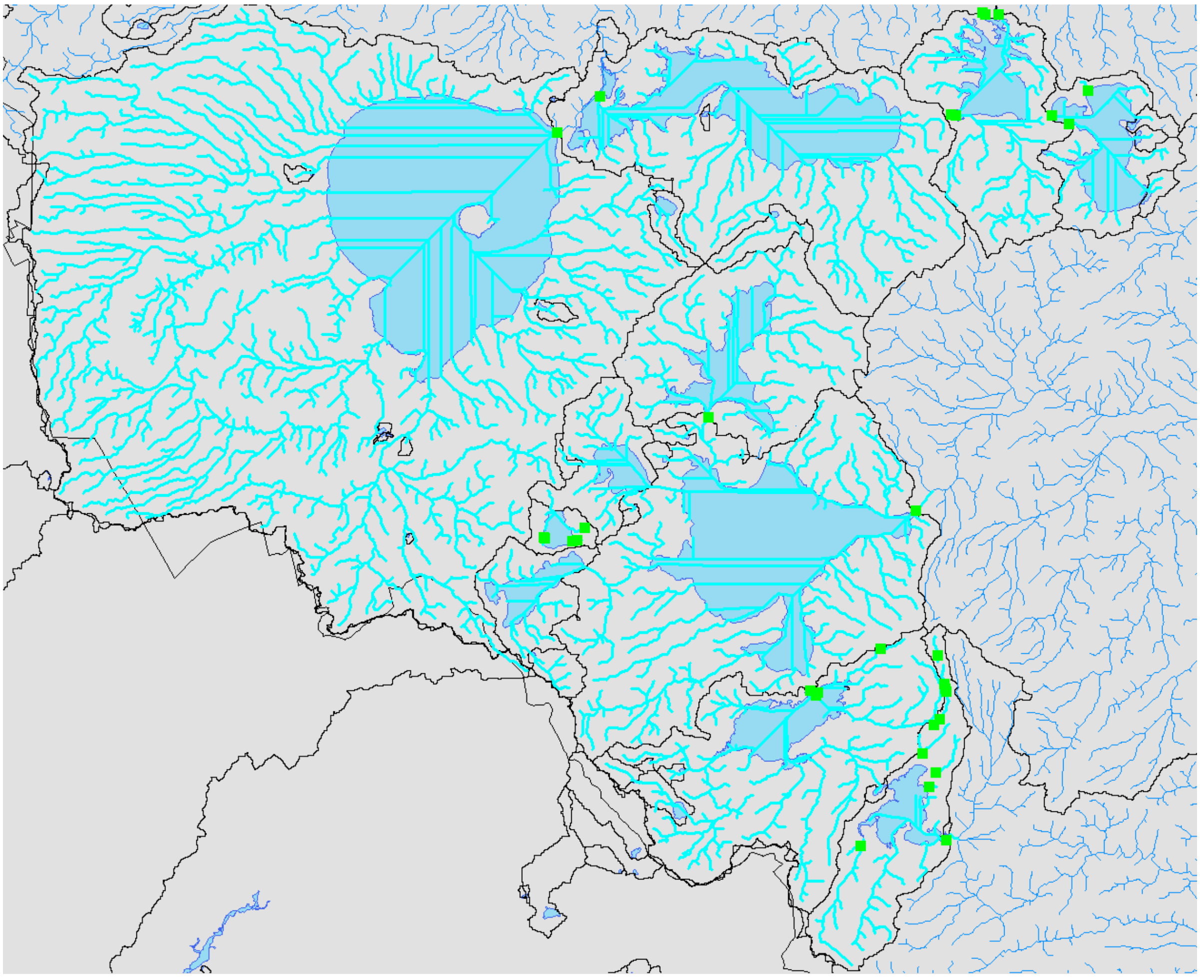

Figure 2: CLUES reaches simulated for all Rotorua Te Arawa lakes. Green squares denote terminal reaches or lake outlet reaches that were summed to estimate the total load to the lake.

2.3 Nutrient budget modelling

2.3.1 Overview

A nutrient budget model for 13 Te Arawa lakes was constructed using the R statistics platform. The budget model accounts for contributions of nutrients from a range of sources and transport pathways. Transport pathways accounted for in the model include surface (overland and stream) flow and groundwater transport. Nutrient sources considered include loads derived from land use, direct inputs from atmospheric deposition, geothermal inputs, wastewater inputs, and connections to 'upstream' lakes. Loads from land use were adjusted for nutrient attenuation between the landscape and lake edge, whereas loads from other sources were estimated at the point of discharge to the lake.

2.3.2 Catchment boundaries

For each of the 13 study lakes, catchment boundaries were defined as the surface topographic catchment determined by Light Detection And Ranging (LIDAR) (data: BoPRC). In addition to the exterior lake catchment boundaries, for some lakes it was important to distinguish subcatchment boundaries.

For Lake Rotorua, the catchment boundary of White (2015) was adopted (Figure 1), which defines an area of c. 600 ha beyond the northwestern surface topographical catchment boundary that is thought to contribute groundwater to Lake Rotorua aquifers. A separate nutrient budget was completed and groundwater loads for this area were combined with the nutrient loads for the surface topographical catchment. A similar approach was taken for Lake Rotokawau, which lies entirely within the topographical catchment of Lake Rotorua.

At Lake Rotoiti, the Ohau Channel diversion prevents almost all water from Lake Rotorua from entering into the main basin of Rotoiti. The wall also effectively prevents water from one end of the topographical catchment from draining into the lake's main basin. Therefore, we defined a separate subcatchment for the 'Okere/behind wall' area, which was assumed to always drain directly to the Kaituna River and was thus inputs originating from west of the wall were excluded from the nutrient budget for Rotoiti (Figure 1).

2.3.2.a Tarawera catchment complex

Multiple lake catchments are connected hydrologically to Lake Tarawera, either by direct surface flows (e.g., Rotokakahi), subsurface connection (e.g., Okataina) or indirectly via other lakes (e.g., Okaro). For several of these Okataina Caldera lakes, the effective groundwater catchment is likely to differ from the surface water catchment, i.e., groundwater within the surface topographical catchment may in fact drain towards a different lake catchment. White et al. (2020) provides possible groundwater boundaries for the Tarawera lakes complex. These groundwater boundaries were not adopted for the present analysis, because surface topographical boundaries are subject to less uncertainty with respect to managing catchment nutrient loads. However, the boundaries estimated by White et al. (2020) are shown in Appendix 3, and these or future iterations could potentially be incorporated in future load estimates.

Lake Rerewhakaaitu is hydrologically 'perched', meaning that much of the surface catchment drains to deep groundwater, bypassing the lake. Cho et al. (2020) undertook a detailed water budget for Rerewhakaaitu as part of an ecosystem modelling study, and in the process defined an 'effective hydrological catchment' of about 5.1 km^2, which we have adopted for the present study in order to more accurately represent the 'load-to-lake' for the catchment nutrient budget.

2.3.3 Land use catchment composition

Land use within each lake catchment was delineated by Bay of Plenty Regional Council, using aerial images from 2016. Land use information was provided by BoPRC as a GIS layer and processed into aggregate area for each land use class and catchment/subcatchment.

2.3.4 Nutrient losses from land use classes

Areal loss rates of nitrogen (N) and phosphorus (P) were estimated for each land use, using the best available data on a case-by-case basis, as described in detail below.

2.3.4a Overseer®

Over recent years, the on-farm fertiliser and nutrient budgeting model Overseer® (Wheeler et al. 2009, developed by Ministry for Primary Industries, the Fertiliser Association and AgResearch) has had widespread use for the estimation of nutrient loss from agricultural and other land uses. Overseer® represents the state-of-the-art for these estimations in New Zealand, as it considers factors including (but not limited to) soil type, fertiliser application rates and timing, stock density, and on-farm mitigation. The CLUES model (see Section 2.2) uses Overseer® in conjunction with other nutrient and transport models (e.g., SPASMO, SPARROW), although it uses a substantially older version of Overseer® then does more recent nutrient loss 'benchmarking' estimates undertaken by BoPRC.

The Bay of Plenty Regional Water and Land Plan (BoPRC 2008) includes a series of regulations, collectively termed 'Rule 11', with the objective of protecting water quality in five degraded lakes (i.e., those showing declining TLI for three consecutive years) by capping losses of nitrogen and phosphorus within the lake catchments. Rule 11 requires landowners to provide specific property information for the period July 2001 to June 2004, from which a 'nutrient benchmark' equivalent to the property's average annual nitrogen and phosphorus loss is calculated using the Overseer® model, assuming best management practice. Current and future land uses that stay within the nutrient benchmark are permitted, whilst a discretionary resource consent is needed to exceed the benchmark (Park and MacCormick 2011). Therefore, the present study considers that benchmarked land use areas for 2001 to 2004 should be representative of present land use under best management practice. Nevertheless, discretionary resource consenting and/or non-notified changes to land use practices are acknowledged sources of uncertainty to the present study.

For this study, Overseer®-derived loss rates for N and P were restricted to output from version 6.2.3 for pastoral and cropping land uses only, for consistency among catchments. Within Overseer®, areas used for fodder production are transient and have no spatial allocation, therefore nutrient losses for 'Fodder' were aggregated with their parent land use ('Dairy', 'Dairy Support', or 'Dry Stock'). Areas of 'Effluent' were associated with Dairy land, and minor pastoral land uses (e.g. Cut and Carry, etc.) were combined with Dry Stock land. In most cases benchmarked areas did not cover the entire catchment area for all of these land uses. Thus the average areal nutrient loss modelled by Overseer® for benchmarked areas in each individual catchment was extrapolated to all areas with the same land use. For Lake Rerewhakaaitu, Overseer® estimates were not included in the BoPRC benchmarking dataset, however, aggregated average losses were available from a separate project (S. Park, pers. comm.) and these were adopted for the present study.

Overseer® estimates losses of nutrients from the soil zone for each block of land (Wheeler 2009), and generally does not consider attenuation across the landscape (e.g. between a farm and receiving waterways). Therefore, attenuation was applied as a percentage (same for all land uses) of land use loading to estimate loads-to-lake (see Section 3.2.5).

For land uses not assessed using Overseer®, loss rates were estimated based on available literature, preferably within local context, i.e. peer reviewed field studies from within the Rotorua Te Arawa

Lakes District, and/or Lake Action Plans. Where reliable literature estimates were not available, loss rates were estimated by consideration of, and comparison with, the most similar land uses. Attenuation was applied to these land uses in a similar manner to those land uses assessed using Overseer®.

2.3.4b Nitrogen fixing shrubs

Gorse is an efficient fixer of atmospheric nitrogen and has been shown in New Zealand to increase nitrogen losses from land (Mageson et al. 2008, 2012, Hamill 2012). Land cover by gorse and other nitrogen fixing shrubs was not specifically delineated within the available land use classifications, but nevertheless may make a substantial contribution to nitrogen loading in certain lakes. Hamill et al. (2012) describes enhanced nitrogen loss from land occupied by gorse and other nitrogen fixing shrubs (e.g., broom, silver wattle). Hamill et al. (2012) identified 869 ha of gorse in the Lake Rotorua catchment. Further examination of the 2003 aerial imagery and comparison with high definition imagery collected in 2011, 2014 and 2016 refined this area to 882 ha (BoPRC unpublished). However, percentage cover within these areas has been estimated to average 41%, giving equivalent total gorse coverage of 362 ha for the Rotorua catchment. At Lake Okareka, Hamill et al. (2012) identified 70 ha of dense gorse cover. For all other lakes the extent of gorse coverage has not been examined in detail, although some gorse coverage is likely. In order to approximate the contribution of gorse to nitrogen loading in other catchments we applied the ratio of the area of gorse to pastoral plus exotic forest land from Lake Rotorua scaled appropriately for the area of pastoral and exotic forest land in each catchment. We assumed that dairy land, which is generally highly developed, would have little to no gorse coverage.

2.3.4c Attenuation of land use nutrient losses between land block and lake edge

Nutrient losses modelled using Overseer® consider only loss from the farm edge and root zone (~60 cm soil depth). It is likely that some portion of these nutrient losses is 'attenuated' (i.e., reduced) while in transit between the block edge and lake edge, either during overland flow and/or groundwater transport. Attenuation may occur by direct loss of nutrient (denitrification in the case of N) and/or by retention on the landscape (e.g., adsorption of P by soils or uptake of N and P by plants). The nutrient budget constructed here allows for partitioning of nutrient losses between surface and groundwater transport, and individual attenuation rates can be prescribed for each lake, transport pathway and nutrient species (i.e., N or P).

Ideally, estimates of attenuation would be informed by comparison of estimated land-use losses with observed loading calculated using comprehensive measurements of catchment discharge and nutrient concentrations, as well as detailed understanding and/or modelling of catchment hydrology. The only lake that satisfies these criteria is Lake Rotorua, for which catchment budgets based on stream observations are available (e.g., Hoare 1987, McBride et al. 2019) as well as detailed catchment modelling (Rutherford et al., 2011, Palliser et al. 2019, Rutherford et al. 2019). However, Lake Rotorua is complicated by long groundwater time lags (Morgenstern et al. 2015), meaning that the observed load is lower than the 'steady-state' (long-term) loading which would reflect the steady-state nutrient losses of current land-use practice.

In practice, a lack of detailed information for various catchments meant that we assumed identical attenuation and an even split of loads transported between surface and groundwater pathways.

Further, a lack of information necessitated broad assumptions with respect to the degree of attenuation applied.

2.3.5 Geothermal inflows

Geothermal waters are known to influence several Rotorua Te Arawa Lakes. The volumes of many of these inflows are in most cases poorly quantified, particularly at Lake Rotomahana and to a lesser extent Tarawera. Some sampling of geothermal springs and streams was undertaken by Environment Bay of Plenty in the mid-1990s and mid-2000s. Nairn (1981) considered geothermal hydraulic load using ion concentrations in the lakes, particularly chloride, and Hoare (1985) used similar methods to estimate geothermal flow (but not nutrient loads) to Lake Rotorua. Donovan & Donovan (2003) reviewed available data and studies to estimate geothermal loads for all the Rotorua lakes. Here we adopted a mixed approach of available literature values and recent sampling and analyses to estimate the geothermal load to each lake.

2.3.6 Inflows from inter-lake connections

Several Rotorua Te Arawa lakes are connected hydrologically to one another, by surface and/or subsurface flow. Annual outflow N and P loads from each lake were estimated by multiplying lake outflow volume (as modelled using CLUES) and average observed surface water concentrations of TN and TP for the period 2012 to 2017 (BoPRC unpubl. data). Only a very small proportion of water entering Lake Rotoiti from Lake Rotorua was included to account for backflow around the Ohau diversion wall (which was completed in 2008). Where lake outflows discharge only partially to another lake (i.e., where a lake has multiple outflows, for example, Lake Rotoma in Figure 10), loads were allocated proportionately based on previously published estimates of connectedness.

2.3.7 Wastewater

Wastewater nutrient sources in all catchments other than Lake Rotoura are derived from septic tank leachate. Estimated household numbers and occupancy rates for each lake were obtained from BoPRC and/or Rotorua Lakes Council (RLC), and expressed as full-time resident equivalents. These estimates account for number of households, average occupancy, frequency of visitors to private residences and public facilities, and communal facilities such as campgrounds and schools. Wastewater nutrient loads were omitted from areal (Overseer®-based) loss estimates and instead calculated as additional loads without their own allocation. Values were determined by multiplying estimated full-time resident equivalents by the loss rates recommended for the Bay of Plenty in a review of nutrient loads from septic tanks by McIntosh (2013). Attenuation was not applied to wastewater loads in this study because houses that remain unreticulated tend to be located close to lake shores and the estimates of McIntosh (2013) include some degree of attenuation.

For Lake Rotorua, wastewater nutrient loads arise from spray irrigation of treated wastewater to the Whakarewarewa Land Treatment System (LTS). Annual average load-to-lake for N and P from the Waipa Stream wastewater sources was obtained from BoPRC monitoring data (source: Rotorua Lakes Council), downstream of the LTS.

3. Results

3.1 Land use in all 12 lake surface topographical catchments.

The Rotorua lakes are characterised by diverse catchment land uses, from predominantly indigenous vegetation (e.g., Tikitapu, Okataina) to heavily altered (e.g., Rerewhakaaitu, Okaro, Rotorua) (Figure 3). Area for each land use is shown in Figure 3 and Table 2. Land use for individual lake catchments is shown in Appendix 1.

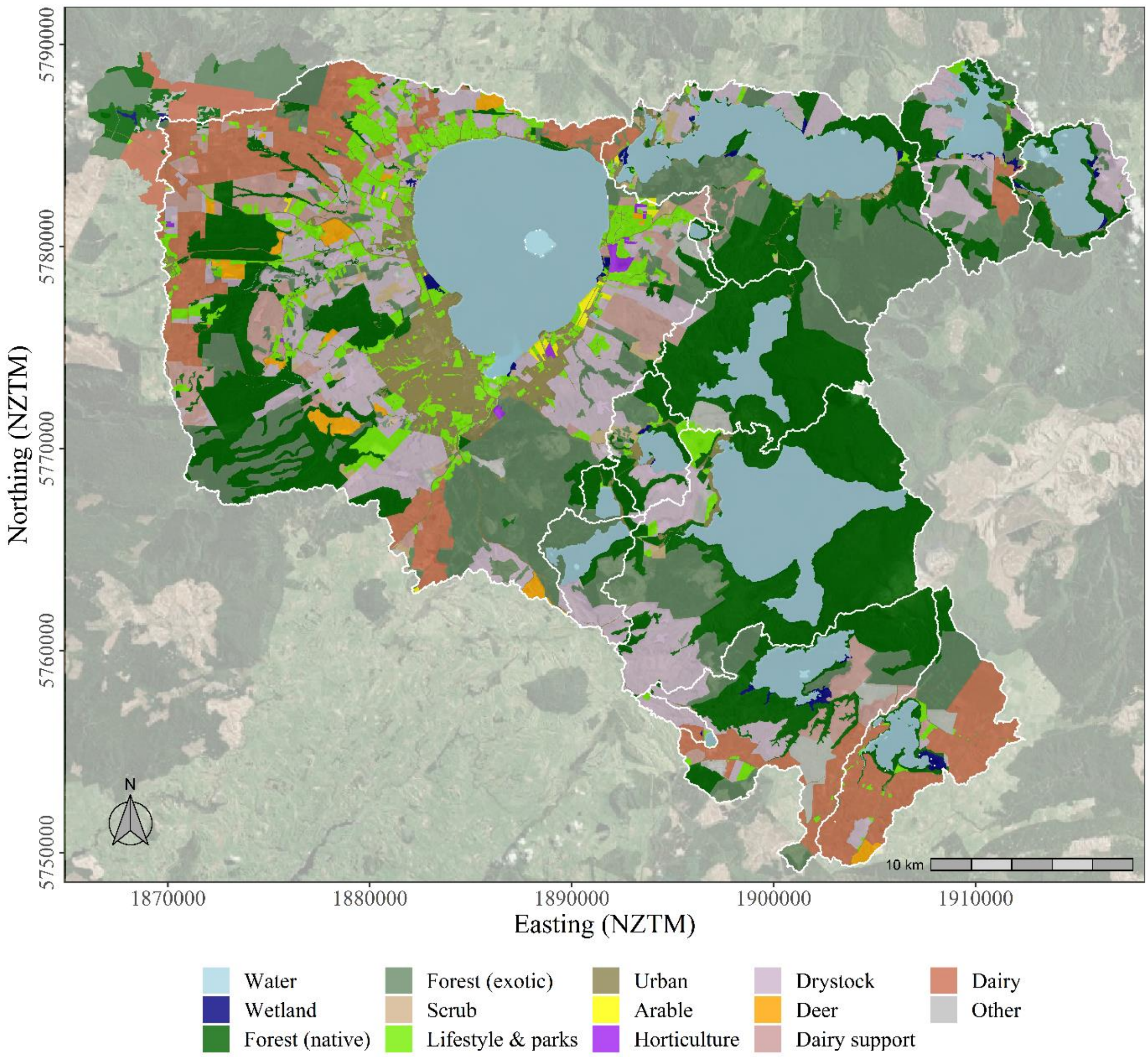

Figure 3. Land use for the entire Rotorua Te Arawa lakes region (data: Bay of Plenty Regional Council, layer created based on 2016 land use).

Table 2. Catchment land use by category. Source, BoPRC, values given in hectares.

	Okareka	Okaro	Okataina	Rerewhakaaitu	Rotoehu	Rotoiti				Rotokakahi	Rotorua				Rotoma	Rotomahana	Tarawera	Tikitapu
Land use						**Okawa**	**Okere**	**Other**	**Total**		**Surface**	**Rotokawau**	**GW only**	**Total**				
Native forest	659.2	0.2	4184.4	437.8	1097.4	3.5	8.8	2495.0	2507.3	437.8	6834.5	89.9	615.0	7539.5	599.9	2842.4	6481.7	321.7
Exotic forest	294.4		660.7	743.5	1215.6	17.3	49.6	4439.8	4506.8	743.5	7838.9	0.0	1466.7	9305.6	475.9	1237.4	1647.2	67.7
Scrub	63.0		6.8		8.2	20.6	45.4	105.1	171.0		560.6		0.5	561.1			43.2	
Dairy		57.7		2897.8	267.5		138.0		138.0	2897.8	5405.6		1157.8	6563.4	11.0	1113.1		
Dairy support			65.1	64.8				133.6	133.6	64.8	3393.5	11.0	6.8	3411.3		822.3		
Sheep and beef	437.0	249.7	57.1	121.6	1141.7		47.4	624.6	672.1	121.6	7392.6	0.2	0.0	7392.8	466.7	599.8	1669.4	10.7
Deer				92.2						92.2	803.4			803.4				
Lifestyle or mixed use	67.2	11.8	26.9	91.5	64.7		15.5	70.2	85.7	91.5	3982.7	1.3	7.2	3991.1	6.4	76.0	288.7	
Orchard or horticulture											191.9			191.9				
Arable							7.2	7.4	14.6		199.6		0.0	199.6				
Urban/road/rail	80.1	5.4	8.5	79.1	62.4	20.3	97.7	224.5	342.6	79.1	3875.7	1.5	11.6	3888.7	91.5	60.7	159.0	27.8
Parks and reserves	3.0	10.1		19.9	3.6	5.7	7.4	63.5	76.6	19.9	800.2		0.0	800.2	1.8	0.6	1.9	4.6
Wetland	21.9	2.5		71.2	37.5	2.9	21.3	42.8	67.0	71.2	95.3		28.2	123.5	44.7	89.1		
Water surface	341.2	31.0	1066.1	552.6	809.0	1.3	84.4	3359.4	3445.1	552.6	8169.1	53.3	0.0	8222.4	1111.8	880.7	4159.5	141.0
Other	13.4		225.7	130.4	6.0		12.2	85.1	97.2	130.4	532.3	40.0	222.8	795.0	3.1	660.0	96.0	
Total	**1980**	**368**	**6301**	**5302**	**4714**	**72**	**535**	**11651**	**12258**	**5302**	**50076**	**197**	**3517**	**53790**	**2813**	**8382**	**14547**	**574**

3.2 Loss rates of nitrogen and phosphorus by land use

3.2.1 Native forest

Average catchment nutrient loss rates modelled by Overseer® (v6.2.3) ranged from 2.01 to 3.05 kg N ha^{-1} y^{-1} and 0.06 to 0.13 kg P ha^{-1} y^{-1} for the Te Arawa lakes, although Overseer® estimates were not adopted for this land class in the present study.

A review of nutrient loss rates by land use in New Zealand (McDowell & Wilcock 2008) described loss rates from native forest ranging from 0.01 to 7 kg N ha^{-1} y^{-1}, and 0.01 to 0.6 kg P ha^{-1} y^{-1}. In the Bay of Plenty, Cooper and Thomsen (1988) measured N and P concentrations in streams draining an area of podocarp/mixed hardwood on the central volcanic plateau between Rotorua and Taupo. Average loss rates were determined to be 3.67 kg N ha^{-1} y^{-1} and 0.12 kg P ha^{-1} y^{-1}. Here, we adopted the values of Cooper and Thomsen as default nutrient loss rates for native forest cover.

3.2.2 Exotic forest

Average catchment loss rates modelled by Overseer (v6.2.3) for exotic forest in Te Arawa lakes ranged from 2.35 to 2.60 kg N ha^{-1} y^{-1} and 0.00 to 0.12 kg P ha^{-1} y^{-1}, however, Overseer® estimates were not adopted for this land class in the present study. Cooper and Thomsen (1988) measured N and P concentrations in streams draining an area of plantation (pine) forestry on the central volcanic plateau and found average loss rates of 1.31 kg N ha^{-1} y^{-1} and 0.095 kg P ha^{-1} y^{-1}. It should be noted that loss rates before, during and after harvesting can vary substantially (Davis 2014). Several studies have shown that loss rates of N and P increase following harvest, returning to equilibrium rates as trees mature and the canopy closes. For example, Quinn & Ritter (2003) described losses following harvest of greater than 20 kg N ha^{-1} y^{-1} and 1.0 kg P ha^{-1} y^{-1}. (see Figure 4). When taking into account the post-harvest period, long-term losses from forestry land may be higher than estimated by Overseer® or by Cooper and Thomsen (Hamilton 2005). However, some studies have found that loss rates *decrease* following harvest, and that loss rates from plantation forestry may be as high as 12 kg N ha^{-1} y^{-1} (Parfitt et al. 2001). Loss rates may also vary substantially depending on land use history (e.g., native forest vs. improved pasture), and duration of the harvesting cycle can vary based on land management needs and/or market reasons. For these reasons, it can be difficult to assign a 'one-size-fits-all', steady-state loss rate to forestry. For pragmatic reasons, and in the absence of more detailed supporting information, for the present study we adopted steady state loss rate estimates of 3.0 kg N ha^{-1} y^{-1} and 0.15 kg P ha^{-1} y^{-1}. Use of this estimate may imply plantation forestry occupies sites with little history of nitrogen accumulation under agriculture (Davis 2014).

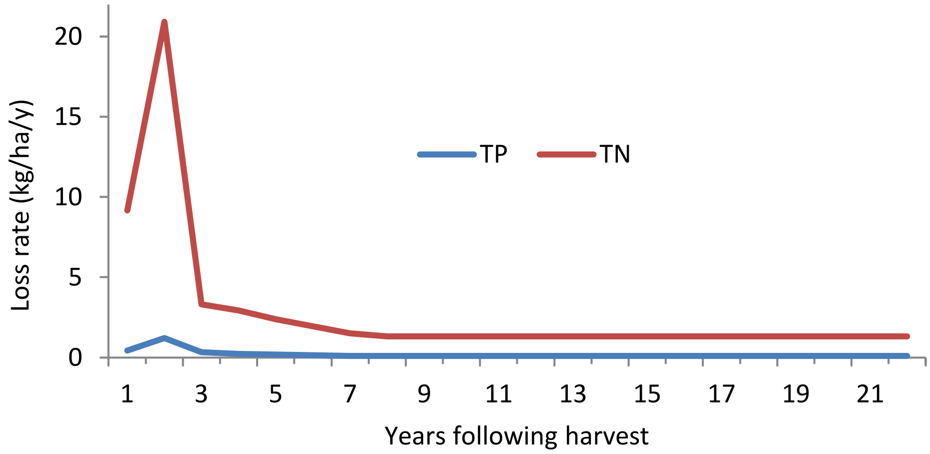

Figure 4. Estimated loss rates of N and P from plantation forestry, over a 22-year harvest cycle. Inferred from combining Cooper & Thomsen (1988) and Quinn & Ritter (2003).

3.2.3 Pastoral land

Agricultural areas are highly variable in their characteristics, farming intensity, and management. They are, therefore, also highly variable in loss rates of nitrogen and phosphorus. A review of available New Zealand studies by McDowell and Wilcock (2008) found published loss rates for dairy land ranging from 7 to 54 kg N ha^{-1} y^{-1}, and 0.1 to 10 kg P ha^{-1} y^{-1}, whereas for dry stock land loss rates ranged from 0.8 to 19 kg N ha^{-1} y^{-1}, and 0.1 to 2.1 kg P ha^{-1} y^{-1}. The only Bay of Plenty study included in this review was mixed pasture described in Cooper and Thomsen (1988), where land use intensity was likely far lower than present dairying operations in the region. Reported loss rates for the mixed pasture were 12 kg N ha^{-1} y^{-1} and 1.7 kg P ha^{-1} y^{-1}.

For the present study we adopted loss estimates modelled by Overseer® (v6.2.3) as described in section 2.3.4a. A summary of average nutrient loss rates for agricultural land is shown by catchment and land class in Figure 5.

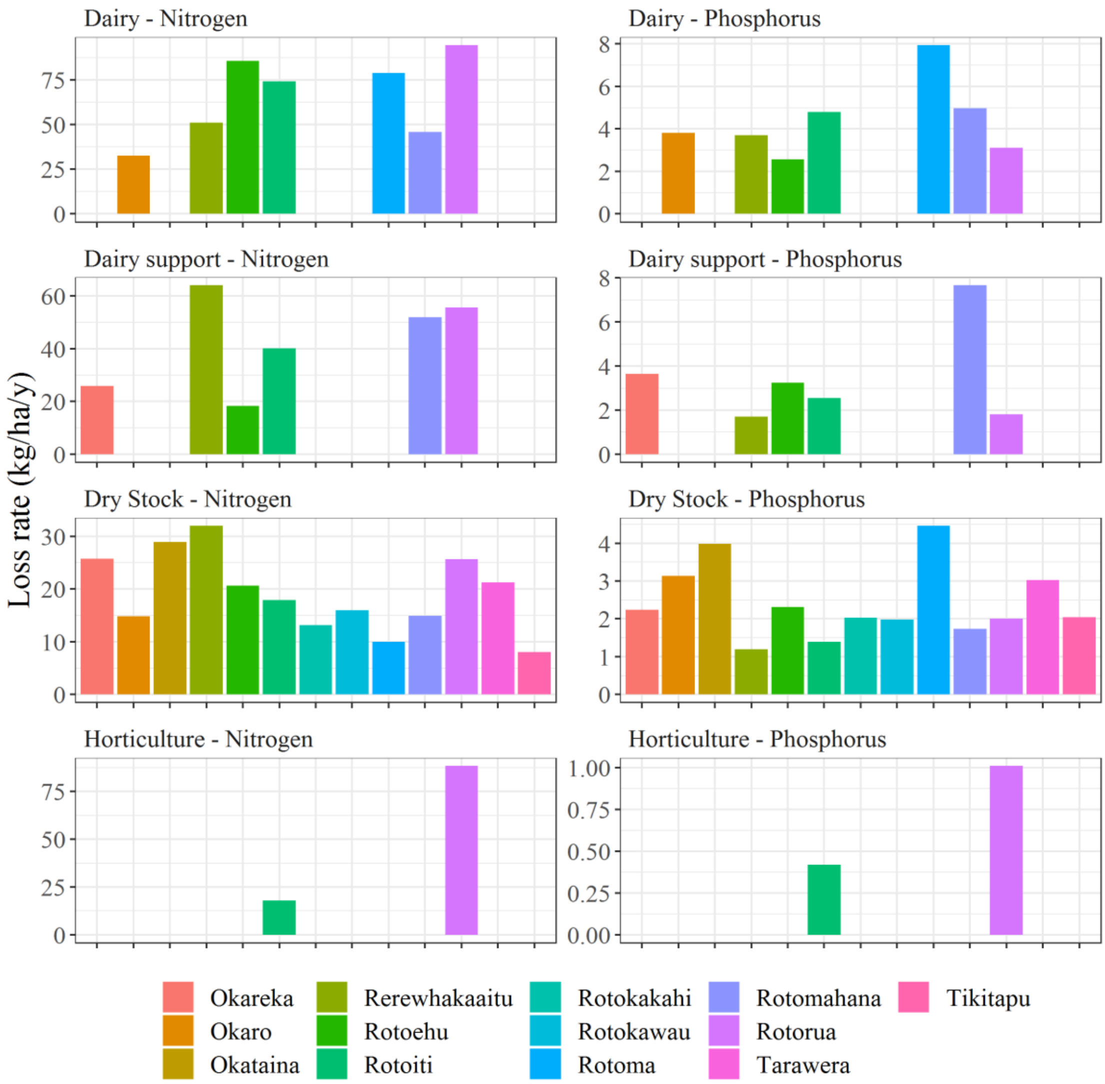

Figure 5. Comparison of average Overseer®-derived nitrogen (left side plots) and phosphorus (right side plots) loss rate estimates for each agricultural land use (one land use per row of plots) for all Rotorua Te Arawa lakes.

Figure 6 presents the proportion of land classes modelled using Overseer® for each catchment, in comparison to land use areas defined under LCDB4 and BoPRC's own land cover database. For some catchments Overseer estimates were not made for all land, however, coverage of agricultural land use was generally good. Differences among catchments are likely to be driven primarily by differences in stock density and local geology/topography.

Figure 6. Comparison of land use areas assessed using Overseer® with total within-catchment area for each class assessed under Land Cover Database version 4 and BoPRC's land cover database. Note that Overseer estimates for Rerewhakaaitu are not shown here because these were derived from a separate source. Also, not all land classes were assessed using Overseer for all catchments (e.g., forest in Tikitapu).

3.2.4 Urban areas

Loss rates for urban areas were derived from Rotorua city stormwater sampling (as referenced in McIntosh 2010). Values used were 5.9 kg N ha^{-1} y^{-1} and 0.5 kg P ha^{-1} y^{-1}. The Rotorua Lakes District Council landfill is situated in the upper Puarenga sub-catchment of Lake Rotorua. Although its leachate has high nutrient concentrations, most flow is diverted to the WWTP. Parks and reserves for all catchments were set equal to the values assessed by Overseer® for the Lake Rotorua catchment (25.5 kg N ha^{-1} y^{-1} and 0.14 kg P ha^{-1} y^{-1}). Limited areas of housing had been assessed using Overseer®, however in most catchments coverage was incomplete. Therefore, housing areas were included under the Urban and infrastructure category, and nutrients derived from septic tanks were added to the nutrient budgets independently of land use (see Section 3.3.3).

3.2.5 Attenuation

Nutrient loads were assumed to be delivered equally by surface and groundwater transport, and attenuation was assumed to be likewise identical. However, the nutrient budget model allows for more sophisticated parameterisation of transport and attenuation if/when adequate supporting information becomes available. Attenuation for Lake Rotorua was set such that the final 'load-to-lake' was consistent with estimates using the ROTAN model (Rutherford 2016) of c. 700 t TN y^{-1} (excluding atmospheric deposition) and the estimates of McBride et al. (2019) of c. 55 t TP y^{-1}. We lesser attenuation in smaller catchments with shallower aquifers and shorter transit times, therefore, as a coarse method we estimated attenuation relative to catchment surface area, as shown in Figure 7. In practice, actual attenuation is unlikely to vary against such a simple single metric, and may also be influenced by factors including elevation, soil geology, slope, as well as the extent of riparian planting and presence or absence of substantial wetland intercepting inflows. Figure 8 shows catchment maps of factors that may influence the degree of attenuation and variability of attenuation among different catchments.Figure 8 More detailed estimation of attenuation was beyond the scope of the present study but would be a useful area of future investigation.

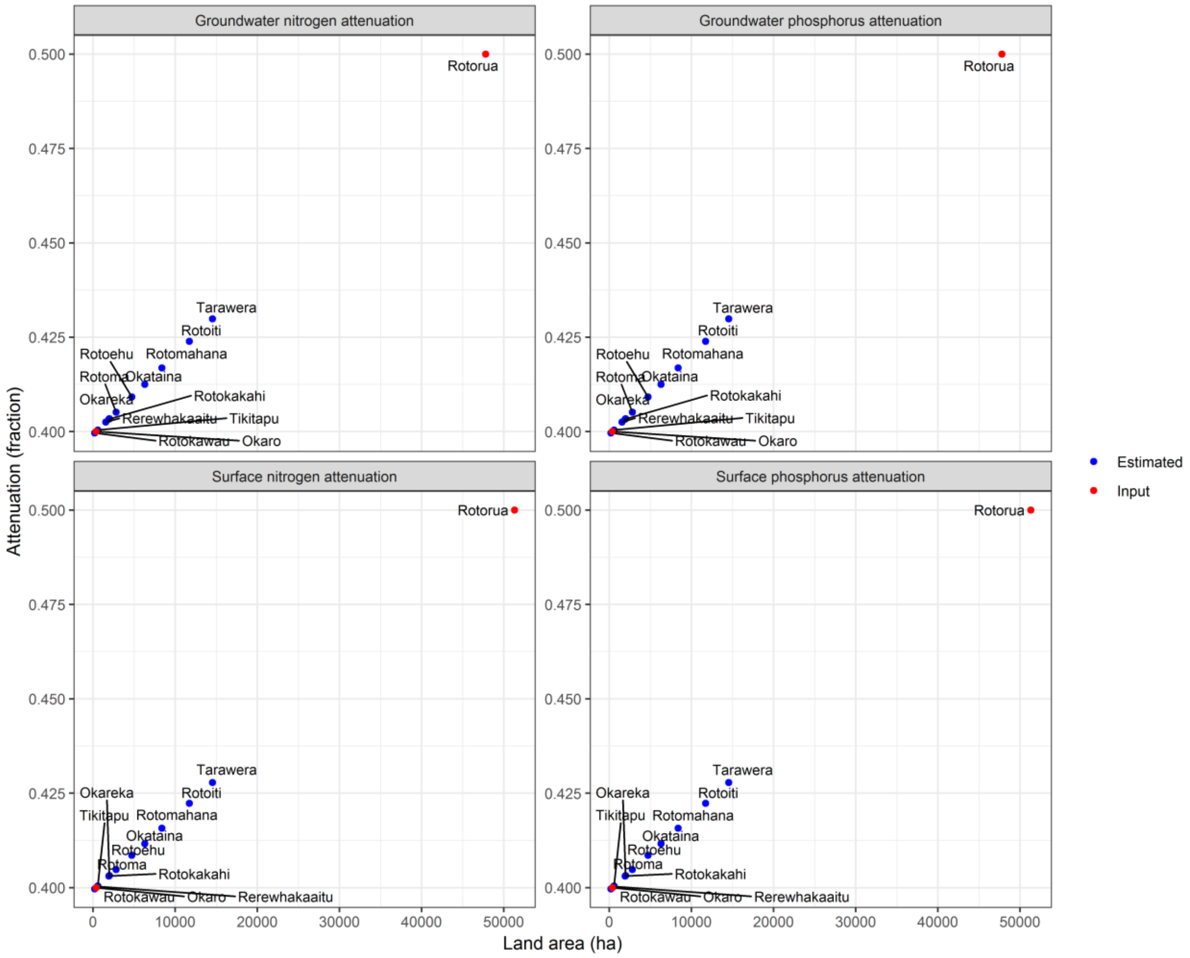

Figure 7. Estimated attenuation for surface and groundwater transport of N and P in the Rotorua Te Arawa lakes catchments. Lake Rotorua was assumed to have attenuation of 50% and Lake Okaro was assumed 40%, with attenuation for the remaining lakes estimated by linear regression against catchment area.

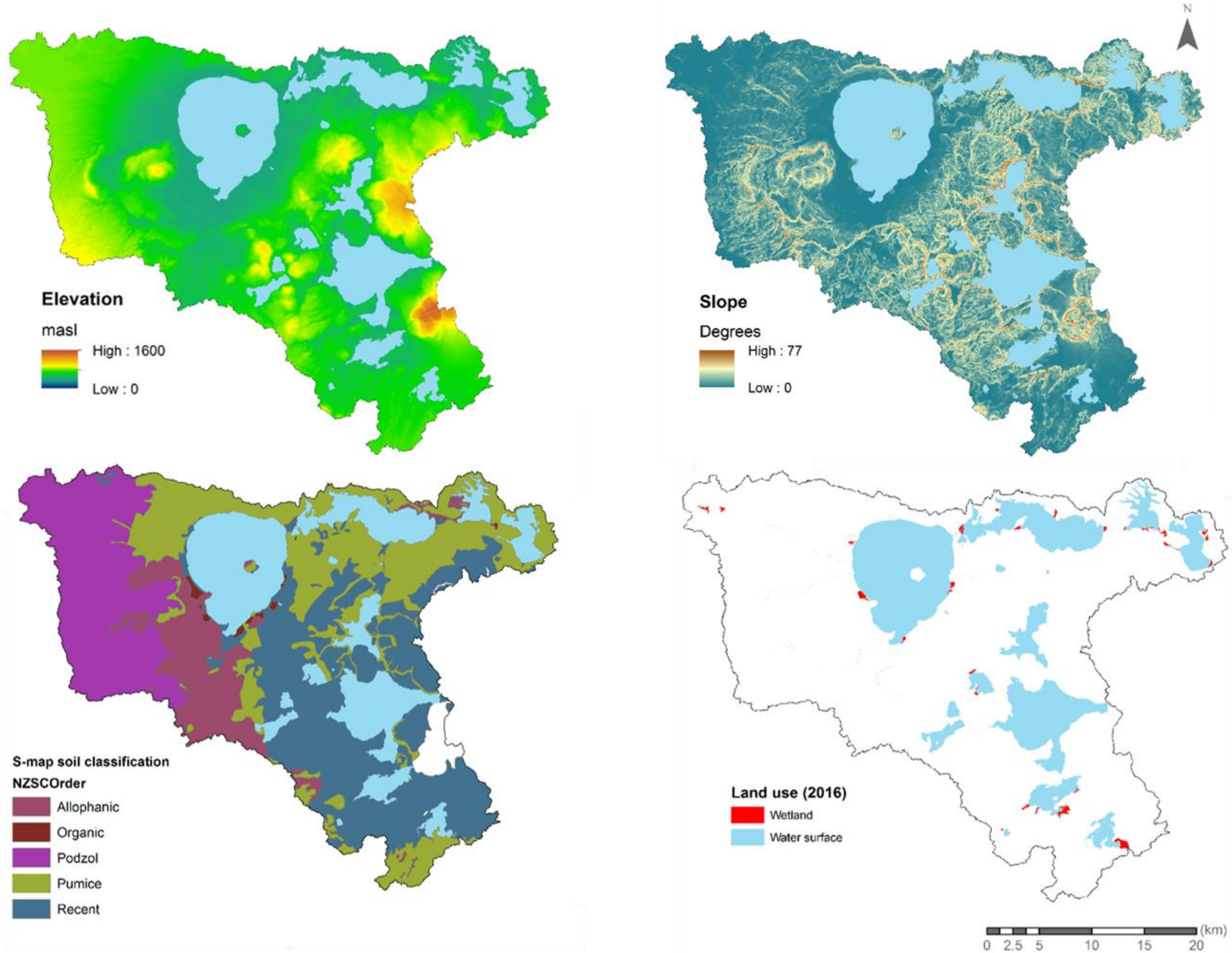

Figure 8. Factors potentially affecting nutrient and sediment attenuation in Rotorua Te Arawa lake catchments, showing A) elevation, B) slope, C) soil type and D) wetlands.

3.3 Other sources of nutrients

3.3.1 Atmospheric deposition to water surface

Lake surfaces receive nutrient loads via aerial deposition, both wet (dissolved nutrients in rainfall), and dry (particulates). In previous studies of the Rotorua lakes, atmospheric deposition has often been assigned an areal rate in the order of 3.7 kg N ha^{-1} y^{-1}, a value representative of the mean of measurements within the Lake Taupo catchment in the late 1970s, 1980s and in 1997 (White and Downes 1977; Schouten 1983; Timperley and Vigor-Brown 1986; Dyck et al. 1987; Nichol et al. 1997), and 0.17 kg P ha^{-1} yr^{-1} (Schouten, 1983); both values are very close to those previously assigned to Lake Rotorua by Hoare (1987). However, these studies did not always include both wet and dry deposition, and/or both organic and inorganic deposition. In a review of North Island studies which accounted for all forms of deposition of N and P, Verburg et al. (2018) found that average deposition rates were 6.37 kg N ha^{-1} y^{-1} (standard deviation 2.38 kg N ha^{-1} y^{-1}), and 0.34 kg P ha^{-1} y^{-1} (standard deviation 0.17 kg N ha^{-1} y^{-1}). Here we adopted the estimated rates of Verburg et al. (2018) and made no adjustment for annual rainfall variations though interplay between rainfall volume, N and P concentrations, cloud and dry deposition has been noted (Parfitt et al., 2006). For calculations presented here, deposition only directly enters N and P budgets when occurring directly to the surface of lakes. Additional measurements of N and P concentrations in precipitation and dry deposition within the Te Arawa lakes complex could help refine these estimates.

3.3.2 Nitrogen fixing shrubs (gorse, broom, silver wattle)

A review of gorse (*Ulex europaeus*) management options by OPUS International Consultants recommended a root zone leaching coefficient of 38 kg N ha^{-1} y^{-1} for mature, dense gorse cover (Hamill et al, 2012), although this may be an overestimate due to not accounting for throughfall (D. Hamilton, pers. comm.). Using these yields, gorse accounted for ~1% of nitrogen loading in Lake Rotorua and >11% in Okareka. In all other catchments gorse coverage was unknown, so similar percentage cover was assumed as for Rotorua. We assumed that broom (*Cytisus scoparius*) contributed similarly to N fixation as gorse.

The Lake Tarawera Restoration Plan (BoPRC 2015) describes an estimated coverage of silver wattle (*Acacia dealbata*) of 230 ha throughout the southern part of the Tarawera catchment, with an estimated nitrogen loss of 1,150 kg N per year. Silver wattle coverage in other catchments, if any, has not been quantified.

3.3.3 Geothermal inputs

Nairn (1981) summarised the work of McColl (1975) and Taylor et al. (1977), grouping lakes by chloride concentration as an indicator of geothermal influence. Strongly geothermal lakes (Cl > 100 mg L^{-1}) included Rotoehu, Tarawera and Rotomahana, and moderately influenced lakes (Cl 20 - 35 mg L^{-1}) were Rotoiti, Rotoma and Rotorua. Non-geothermal lakes (Cl < 6 mg L^{-1}) were Rerewhakaaitu, Rotokakahi, Tikitapu, Okareka, and Okaro, while Lake Okataina was considered slightly influenced (Cl 11 mg L^{-1}).

Figure 9 shows the six major geothermal fields of the Rotorua Te Arawa Lakes region, as well as known point sources of geothermal discharge.

3.3.3a Description and water chemistry of geothermal fields

The Te Arawa lakes region intersects a number of geothermal fields (Figure 9). The Rotoma/Tikorangi field straddles the catchments of Lakes Rotoehu and Rotoma. Lake Rotoehu receives water from a geothermal spring-fed inflow at the south-eastern end of the lake (Waitangi Soda Spring), and another geothermal spring flows to the Rakaumakere Stream and into the lake immediately west of Waitangi Spring. Nairn (1981) inferred from lake chloride concentrations and mixing models that there are likely to be additional subsurface geothermal sources. Monitoring of Waitangi Springs shows moderate concentrations of nitrogen and fairly elevated concentrations of phosphorus (Table 3). An early study of nutrient loads to Lake Rotoma (Donovan & Donovan 1991) noted that the Otei Hot Spring flows to the lake, and described geothermal flows ranging from 11 to 53 L s^{-1}. Nairn (1981) described chloride concentrations in the lake water of > 35 mg Cl L^{-1}, indicating a moderate geothermal influence and subsurface geothermal flows in addition to the Otei Hot Spring. However, Donovan & Donovan (2003) concluded that geothermal nutrient load to the lake was negligible.

Lake Rotoiti has high heat flow and hot sediments within the main basin of the lake. Nairn (1981) estimated subsurface flow from the bottom of the main basin of c. 0.3 m^3 s^{-1}. Additionally, several springs in the western catchment (Tikitere field) discharge geothermal water to the lake. Monitoring of geothermal flows within the Tikitere field has shown that waters here are very high in N (average c. 13 g N m^{-3}, mostly as ammonium) and very low in P (c. 0.1 g P m^{-3}). Reflecting this high N:P ratio, Donovan & Donovan (2003) estimated geothermal loads of 41.6 t N y^{-1} and 0.13 t P y^{-1}. However, at observed concentrations from the Tikitere field, and a combined estimated flow of 0.4 m^3 s^{-1}, (0.3 m^3 s^{-1} at the crater site plus as much as 0.1 m^3 s^{-1} from the western springs) geothermal N load could be as high as 164 t y^{-1} (i.e., nearly three-fold higher than N from all other sources). For the present study, we adopted relatively conservative concentrations (because the N and P concentrations of geothermal fluid from the crater site are unknown) and geothermal flow (estimated here as 0.35 m^3 s^{-1} total flow), resulting in loads of 1.1 t P y^{-1} and 55.3 t N y^{-1}. It should be noted that the actual geothermal load is highly uncertain and may be much higher.

Much of the geothermal load to Lake Rotorua derives from the Tikitere field, and to a lesser extent from the Rotorua field near the city as well as Sulphur Point. Much of the Tikitere load is captured in monthly monitoring of the Waiohewa Stream and as such is sometimes not separately accounted for in load estimates derived from stream measurements (e.g., McBride et al. 2019). However, for the present study estimates of geothermal load account are for <u>all</u> geothermal sources because the geothermal portion of Waiohewa loads is not characterised by land use nutrient exports for that subcatchment.

In contrast to measurements at Tikitere, monitoring of Lake Tarawera inflows by Terry Beckett and UoW from 2007 to 2020 found lower concentrations of N but very high concentrations of P in water derived from the Rotomahana geothermal field. Average concentrations in the Hot Water Beach geothermal inflow were 0.38 g P m^{-3} and 0.42 g N m^{-3}. Although measured volumes of these inputs are small, Shepard (1986) used chloride as a tracer to estimate a geothermal flux to Lake Tarawera of 1270 L s^{-1}, suggesting that substantial additional, ungauged inputs are likely to be present.

In Lake Rotomahana, large upwellings of hot water in the lake suggest major submerged hot springs 10 to 20 m offshore (Tivey et al. 2016). Total heat flow has not been estimated, although relatively warmer winter water temperatures and visual comparison with other measured areas show that Rotomahana has the largest geothermal inputs of any Te Arawa lakes (Timperly & Vigor-Brown 1986).

The volume of hot water inflows to geothermally influenced lakes is often difficult to measure, and as such overall geothermal nutrient loads are generally not well understood for most lakes. A range of approaches was used to estimate geothermal loads of N and P, and these are summarised in Table 3.

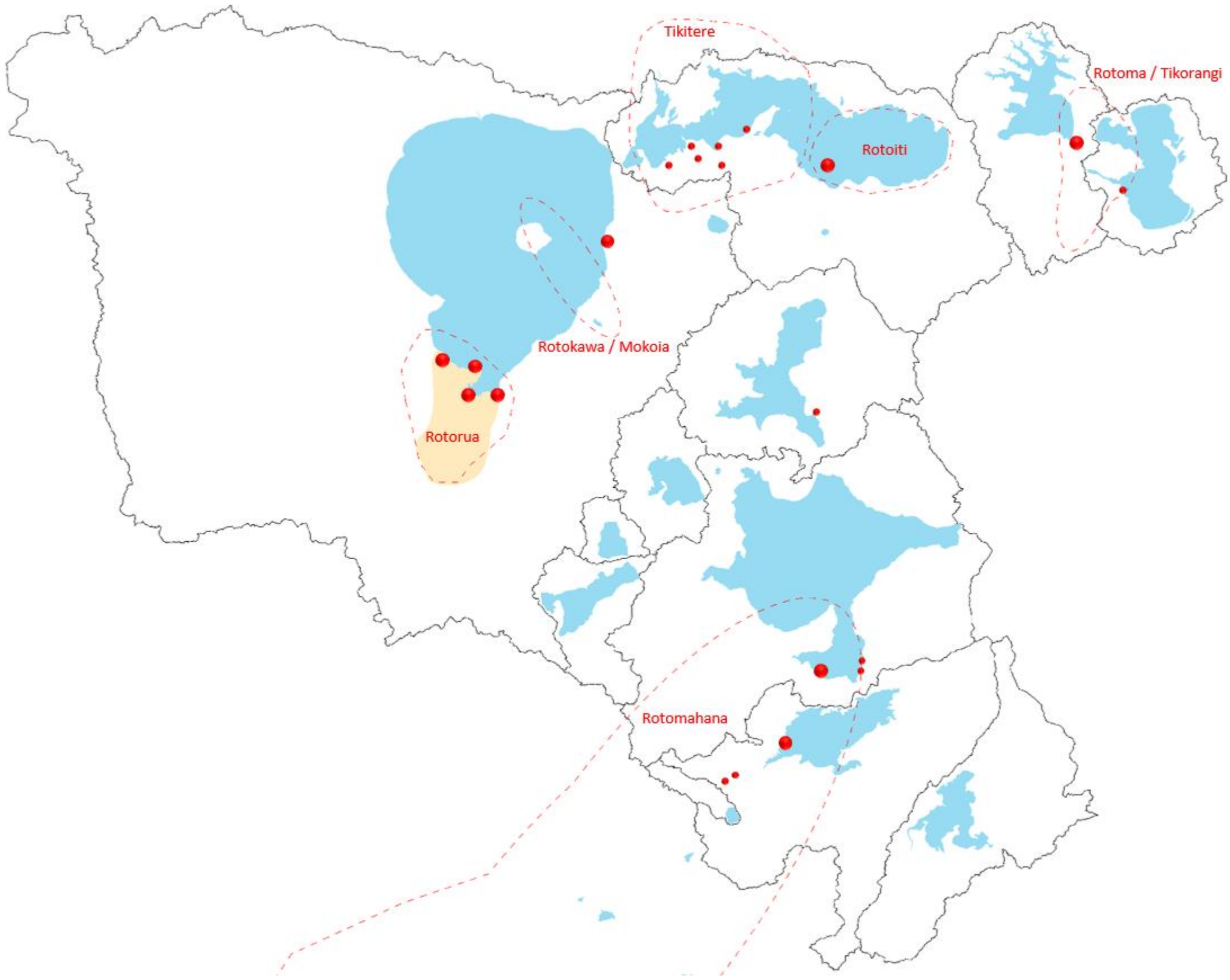

Figure 9. Geothermal point sources in the Rotorua Te Arawa lakes. Sources: catchment shapes: BoPRC; geothermal fields: LINZ; point source locations: Donovan and Donovan (2003). Large dots represent major springs and small dots represent minor springs.

Table 3. Summary of available literature for geothermal inputs to the Rotorua Te Arawa lakes, and resulting estimates of flow and load used for the present study.

Lake	Reference(s)	Field	Location(s)	Volume ($m^3 s^{-1}$)	TP ($mg\ m^{-3}$)	TN ($mg\ m^{-3}$)	TP ($t\ y^{-1}$)	TN ($t\ y^{-1}$)	Comments
Okareka	Nairn (1981)			0.00			0.00	0.00	Not geothermally influenced
Okaro	Nairn (1981)			0.00			0.00	0.00	Substantial inputs unlikely
Okataina	Nairn (1981)	*Undefined*	*Okataina Springs*						Small hydrothermal flow
Okataina	*(best estimate)*	*(best estimate)*		0.01	100	5000	0.03	1.58	
Rerewhakaaitu	Nairn (1981)			0.00			0.00	0.00	Not geothermally influenced
Rotoehu	Nairn (1981)	*Rotoma/Tikorangi*	*Waitangi spring*	0.05					
Rotoehu	Nairn (1981)	*Rotoma/Tikorangi*	*Shore seepage*	?					Anecdotal, not quantified
Rotoehu	Donovan & Donovan (1991)	*Rotoma/Tikorangi*	*Waitangi spring*				0.80	4.70	
Rotoehu	BoPRC unpubl. data	*Rotoma/Tikorangi*	*Waitangi spring*	0.20	150	350	0.95	2.21	Temperature = 40 °C, maybe mixed with cold sources?
Rotoehu	*(best estimate)*			0.30	150	350	1.42	3.31	Assumed additional stream & diffuse inputs to shores etc
Rotoiti	Nairn (1981)	*Rotoiti*	*Crater*	0.30					Chemistry not known
Rotoiti	Nairn (1981)	*Tikitere*	*Catchment springs*	0.02					
Rotoiti	Vincent et al. (1986)		*All sources*	0.10			0.13	41.60	25% of total N load
Rotoiti	Donovan & Donovan (2003)	*Tikitere*	*Wharetata Bay*	0.10	(95)		0.30		Based on BoP samples
Rotoiti	Donovan & Donovan (2003)	*Tikitere*	*Parengarenga Springs*	0.10	(292)	(21174)	0.92	66.82	Based on BoP samples
Rotoiti	BoPRC (2009 - 2010)	*Tikitere*	*Streams and springs*	~0.05	90	12900	(0.14)	(20.35)	
Rotoiti	*(best estimate)*		*All sources*	0.35	100	5000	1.10	55.23	Conservative; TN could be higher
Rotokakahi	Nairn (1981)			0.00			0.00	0.00	Not geothermally influenced
Rotokawau	Nairn (1981)			0.00			0.00	0.00	Low/negligible geothermal influence
Rotoma	Mongillo & Clelland (1984)	*Rotoma/Tikorangi*	*Otei Hot Spring*	0.011 - 0.053					
Rotoma	Nairn (1981)	*Rotoma/Tikorangi*							Subsurface inputs likely based on Cl^- concentrations
Rotoma	*(best estimate)*		*All sources*	0.03	150	350	0.14	0.33	Assumed similar chemistry to Rotoehu inputs
Rotomahana	Mongillo & Clelland (1984)	*Tikorangi*	*Frying Pan/Crater Lakes*	0.12					Likely largest geothermal inputs of any BoP lake
Rotomahana	*(best estimate)*		*All sources*	1.00	378	426	11.93	13.44	Highly uncertain; assumed similar chem. to Tarawera inputs
Rotorua	Hoare (1985)	*Rotorua (springs)*		0.10					
Rotorua	Hoare (1985)	*All*		0.60					
Rotorua	Donovan & Donovan (2003)	*All*	*All sources*				5.60	67.30	Includes Waiohewa Stream
Rotorua	BoPRC (2001-2009)	*Rotorua (springs)*		0.05	280	900	0.44	1.42	
Rotorua	BoPRC (2019)	*Tikitere*	*Tikitere*				(0.17)	25.00	P estimate based on Rotoiti (Tikitere) N:P ratio
Rotorua	*(best estimate)*		*All sources*	0.50	280	3500	4.42	55.23	Includes gothermal to Waiohewa
Tarawera	Sheppard (1986)	*Rotomahana*	*All sources*	1.27		680			NH_4 only
Tarawera	White (1991)	*Rotomahana*	*All sources*	1.27	100 - 500	4 - 20	13.00	27.30	Coarse estimates based on Cl^-
Tarawera	Howard-Williams & Gibbs (1987)	*Rotomahana*	*All sources*				<0.20		
Tarawera	Donovan & Donovan (2003)	*Rotomahana*	*Beach, Te Puha, Tarawera*	0.10	(146)	(130)	0.46	0.41	BoP samples
Tarawera	Donovan & Donovan (2003)	*Rotomahana*	*Peak & Camp Stream*	0.10	(292)	(263)	0.92	0.83	BoP samples
Tarawera	Gillon 2009	*Rotomahana*	*All sources*	1.02					Water budget only
Tarawera	Beckett/UoW (2017 - 2019)	*Rotomahana*	*Springs*	0.008	378	426			Hotwater beach, total flow from multiple sites
Tarawera	*(best estimate)*		*All sources*	0.200	378	426	2.39	2.69	Allowing for additional ungauged inputs
Tikitapu	Nairn (1981)			0.00			0.00	0.00	Not geothermally influenced

3.3.2 Connected lakes

Hydrological connections between lake outflows and Te Arawa lakes downstream are detailed in the catchment nutrient budgets of section 3.4. Transfer of surface and groundwater among catchments of the Tarawera complex has been modelled previously and is presented in White et al. (2016). A diagrammatic summary of these connections is shown in Figure 10. A portion of the nutrient load from a lake/catchment may be attenuated in transit between lakes/catchments, particularly where subsurface transport is concerned. Because nutrient transport and attenuation along these connection pathways is relatively unknown, assumptions were required as to the transfer of nutrient loads among lakes. The assumed 'connectedness' of lake catchment nutrient loads adopted here are summarised in Table 4.

Where all lake outflow stays within the greater lakes complex, we assumed complete transfer of water to the downstream catchment. If the connection between lake catchments was surface only (e.g., Okareka to Tarawera) or very short (e.g., Tikitapu to Rotokakahi) we also assumed complete transfer of N and P loads. Where transport pathways between lake catchments are longer and involve sub-surface transport, we assumed 90% transfer of outflowing N and P loads to the downstream lake catchment (i.e., allowing for a small amount of interception/loss/retention in transit). These assumptions could be refined by additional empirical investigations and/or modelling. Transfer of 2% N and P loads from Rotorua to Rotoiti was to allow for a small amount of backflow around the wall as per Hamilton et al. (2009).

The chemistry of water received by a lake from connected lakes was represented by central lake monitoring data provided by BoPRC for the period 2012-2017. For Lake Rotokakahi, measurements were taken from Te Wairoa Stream (Rotokakahi outflow). For phosphorus, data were adjusted by a coefficient derived from comparison of analytical methods to assess sensitivity to silica, conducted by BoPRC for duplicate analyses for the period 2019-2020. Among all lakes, inputs from connected lakes comprised from 0% to 20% of all sources of N and 0 to 39% of P. Further, Lakes Rotoma and Rerewhakaaitu discharge to 'downstream' lakes but also to outside of the entire lakes complex (Figure 10).

Table 4. Connections between lakes, showing the fraction of N and P loads assumed to transfer from one lake (rows) to another (columns).

		RECEIVING						
		Rotoehu	Rotoiti	Rotokakahi	Rotoma	Rotomahana	Rotorua	Tarawera
DISCHARGING	Okareka							1
	Okaro					0.9		
	Okataina							0.9
	Rerewhakaaitu					0.5		
	Rotokakahi							0.9
	Rotokawau						0.9	
	Rotoma	0.5						
	Rotomahana							0.9
	Rotorua		0.02					
	Tikitapu			1				

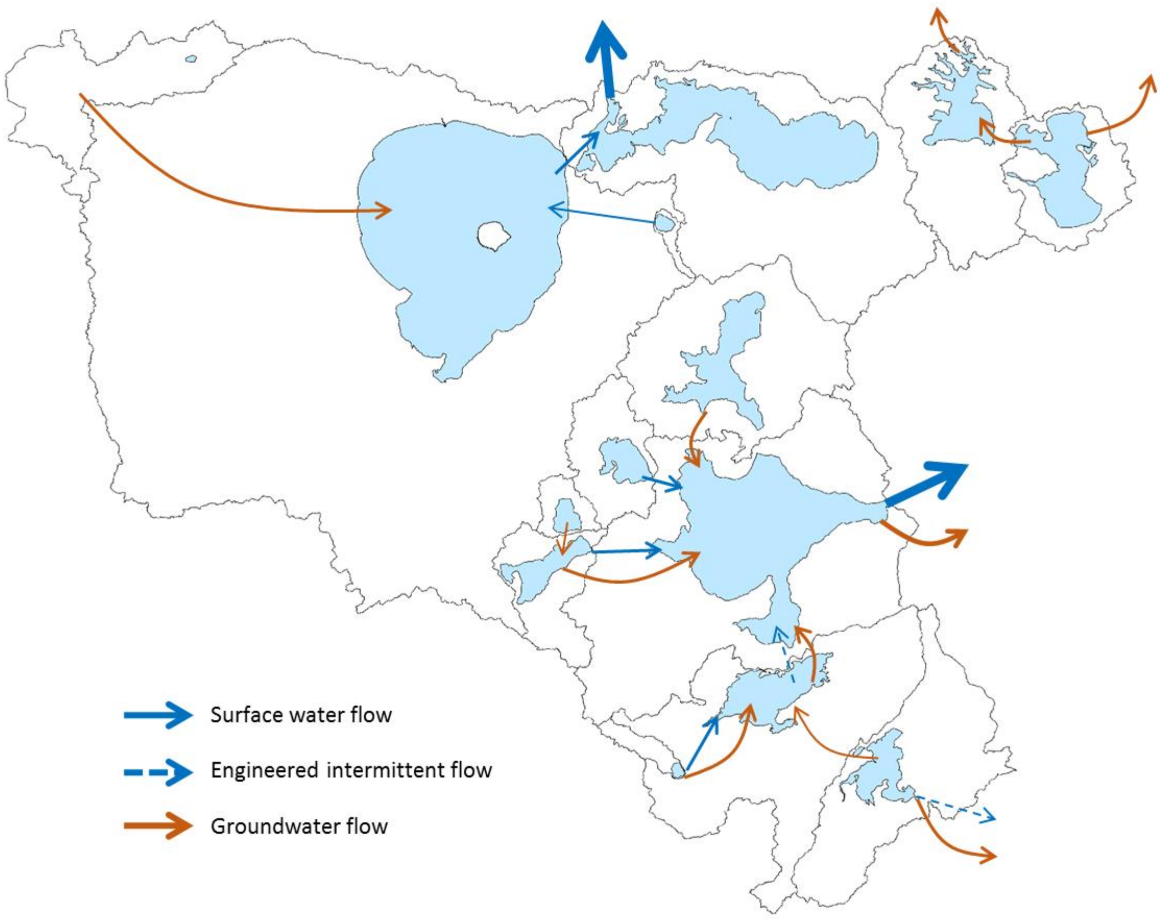

Figure 10. Schematic diagram of hydrological connections between Rotorua Te Arawa lakes. Exit points of water from the lakes complex are also shown. Adapted and expanded from White et al. (2015). The area of groundwater transfer at the northwest of Rotorua lies outside Rotorua's surface catchment but is thought to contribute groundwater to Lake Rotorua predominantly via Hamurana Spring.

3.3.3 Wastewater

A literature review by McIntosh (2013) estimated wastewater N losses in Bay of Plenty lake catchments of 3.65 kg N per resident per year. The ratio of N:P in groundwater nearby septic tank drainage fields was highly variable. A rule-of-thumb N:P ratio of 10:1 was recommended (0.365 kg P per resident per year). Annual loads from wastewater were estimated by multiplying these loss rates by the number of equivalent full-time residents in each catchment (Table 5). For Lake Rotorua, the catchment is reticulated and treated at the Rotorua wastewater treatment plant with subsequent discharge to the Puarenga subcatchment Land Treatment System (LTS). Monitoring data from the Waipa Stream (within the Puarenga subcatchment) 2010 to 2015 gave an average estimated, post-treatment load to the lake of c. 32 t N y^{-1} and 1.6 t P y^{-1} (McBride et al. 2019). For Lakes Rotoiti and Okareka, wastewater loads were multiplied by 0.5 and 0.25, respectively, to reflect recent reticulation works within these catchments.

Table 5. Estimates of built areas (residential and recreational facilities), and resident numbers for each catchment. Also given is a 'best estimate' for both built area and resident numbers used in the present study to calculate nutrient loading from urban areas and unreticulated wastewater (septic tanks).

Lake	LCDBv4.1 built area (ha)	Action Plan houses (n)	Action Plan built area (ha)	Action Plan residents (n)	Benchmarked 'House' (ha)	Estimated built area (ha)	Residents septic systems (n)
Okareka*	43.7	288		662	5	**43.7**	**662**
Okaro	0.0				2.6	**2.6**	**10**
Okataina	0.0		2.8	30		**2.8**	**30**
Rerewhakaaitu	3.7		7			**7**	**100**
Rotoehu	10.8	91	16.8	161	2.7	**16.8**	**161**
Rotoiti*	175.1	840		840	10.2	**175.1**	**753**
Rotokakahi	0.0					**0**	**0**
Rotoma	30.0	280	48	703		**48**	**386**
Rotomahana	0.0				1.2	**1.2**	**20**
Rotorua	3242.9				91.2	**2548**	**100**
Tarawera	98.8	391	93.5	775	0.2	**93.5**	**775**
Tikitapu*	3.0					**3**	**0**

* Denotes lakes with recent reticulation works within the catchment.

3.4 Catchment nutrient budgets

Average catchment-wide nutrient export rates per area ranged from 0.20 (Tikitapu) to 1.8 kg P ha^{-1} (Rotomahana), and 4.0 (Okataina) to 15.1 kg N ha^{-1} (Rotorua) (

Table 6). In most lakes, catchment load N:P ratio was dissimilar to lake water N:P, most likely as a result of proportional differences in denitrification and sediment burial rates. In some lake catchments N:P was higher, and in some it was lower than lake N:P (± 20 % or more for 10 lakes). Lakes Rerewhakaaitu and Tikitapu had very high catchment N:P relative to lake waters, which could be due to iron (Rerewhakaaitu) or pumice (Tikitapu) sediments in these lakes, inaccuracies in the load estimations, or the different characteristics of N retention by lakes compared with P retention (Harrison et al. 2009). In most other cases estimated catchment N:P was greater than lake N:P, suggesting that loss of N by denitrification and burial is greater than the loss of P by burial in most of these lakes.

Table 6. Summary of lake catchment loads for 13 Rotorua Te Arawa Lakes.

Lake	Surface catchment (ha)	Nitrogen load (kg y^{-1})	Phosphorus load (kg y^{-1})
Okareka	1980.4	14912	984.7
Okaro	368.4	4045	633.6
Okataina	6301.3	22821	1385.4
Rerewhakaaitu	1558.7	15823	1080.8
Rotoehu	4713.6	45418	3370
Rotoiti	11722.4	109876	4087.9
Rotokakahi	1922	9847	857.4
Rotokawau	197.2	970	77.2
Rotoma	2812.8	15332	2072.6
Rotomahana	8382.1	95579	20705.8
Rotorua	47797.8	721427	56760.5
Tarawera	14546.6	106767	10652.6
Tikitapu	573.5	2187	116.5

* Note that much of Lake Rerewhakaaitu’s surface catchment does not drain to the lake, resulting in the low observed nutrient yields.

** Note that the load given is a steady-state load, which is higher than the observed load at present (see Rutherford 2016)

Relative contributions of all catchment sources to areal nitrogen load and phosphorus load are summarised for all lakes in Figure 11 and Table 6. For a detailed breakdown and budget for individual catchments refer to Appendix 1. Broadly, where agricultural land uses are present, these contributed disproportionately to N and P loads, as expected, due to relatively high export rates. Contributions from additional sources were notable in some catchments. Specifically, geologically-derived P is a large contributor to overall load in Lake Rotorua (see Tempero et al. 2015), but has not been quantified well for other catchments (except as accounted for in Overseer® soil inputs). For the purposes of the present study, ‘geologic’ P refers to dissolved phosphorus from dissolution of P into old-age groundwater over very long transit times (Morgenstern et al. 2015), and therefore, geologic P is likely to be a much less substantial source of P in catchments other than Rotorua, where groundwater is generally from smaller, younger aquifers. Geothermal sources contributed a large proportion of (estimated) overall load in some catchments and relative geothermal contributions of N and P varied greatly among the different geothermal fields. Atmospheric deposition was a large contributor to load for most lakes. Connected lakes were a large source of nutrients to Tarawera but made up a relatively small component (if any) among all other lakes.

3.4.1 Comparison of estimated present-day loads with 'reference' loads

Nutrient budgets were estimated for hypothetical 'reference conditions' by converting all intensive land uses (i.e., agricultural, forestry and urban) to native forest cover (Figure 12). Resultant N and P loads for reference scenarios were then compared with present day loads (Figure 14). Incoming loads from hydrologically connected lakes were considered constant under the reference scenarios (i.e., conversion of the interior catchment only was simulated). This is because estimating reference loads from connected lakes would require modelling water quality in upstream lakes under reference catchment conditions, which was beyond the scope of the present study. Comparison of present load estimates with 'reference' estimates shows that several catchment loads exceed reference conditions by three-fold, or more.

3.4.2 Effects of varying attenuation assumptions

Table 7 summarises the dependence of estimated nutrient loads on assumptions relating to the degree of attenuation between the land and lake. We adopted three scenarios representing a range of assumed attenuation for the various catchments. For the 'low' scenario, Lake Rotorua was assumed to have 40% attenuation and Lake Okaro 20%, with the remaining catchments estimated by linear regression against catchment area (see Figure 7). The 'best guess' scenario represents the assumed attenuation values that generated the final load estimates used throughout the remainder of this study – namely, Lake Rotorua was assumed to have 50% attenuation and Lake Okaro 40%, with the remaining catchments estimated by linear regression against catchment area. For the 'high' scenario, attenuation of 70% was assumed for all catchments, representative of an upper bound of the range of possible attenuation factors.

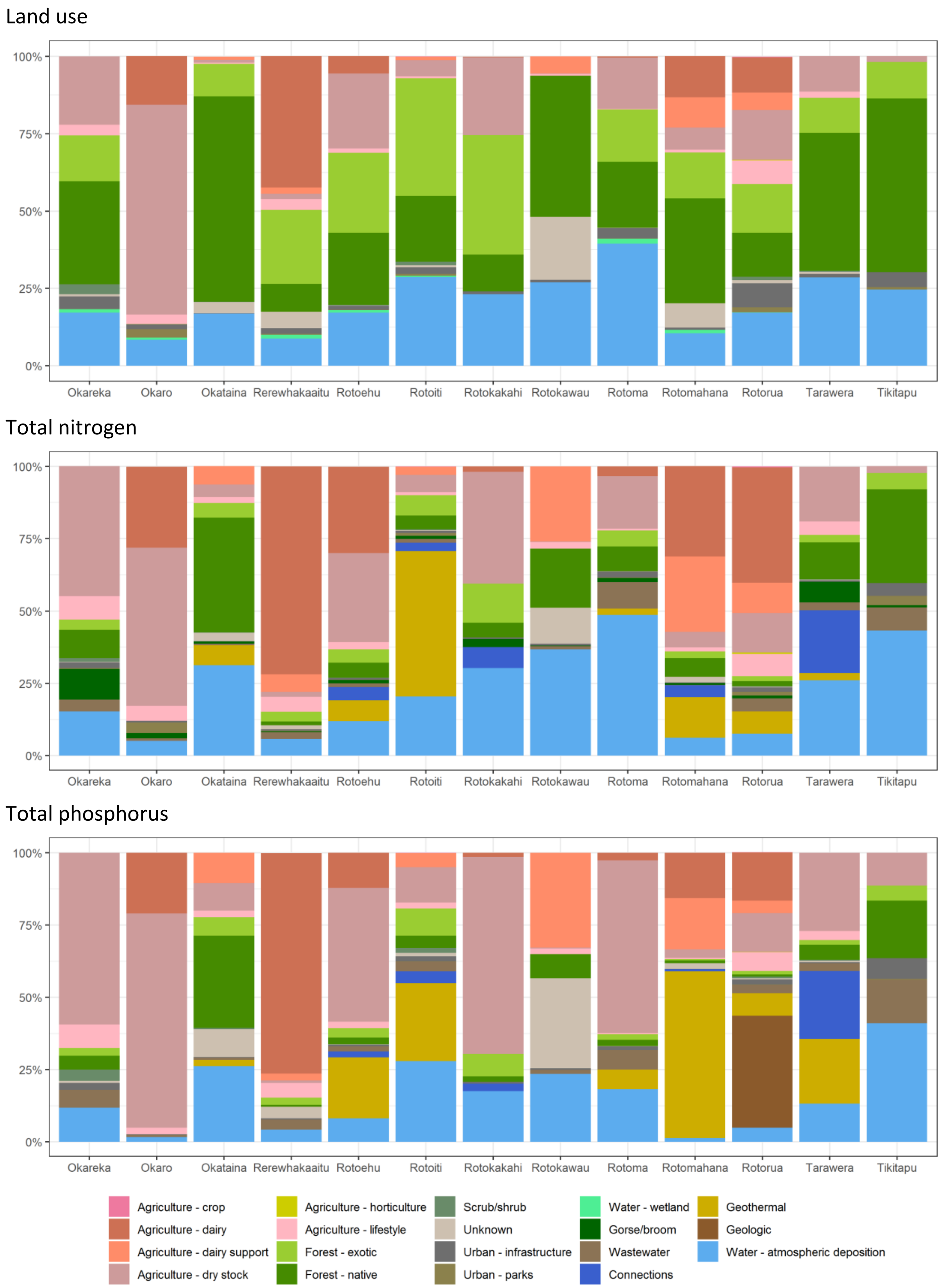

Figure 11. Catchment land use and nutrient loads (expressed as percentage contribution to total) for all Rotorua Te Arawa lakes. Nutrient loads for the 'Water – atmospheric deposition encompass both wet (dissolved) and dry (particulate) inputs.

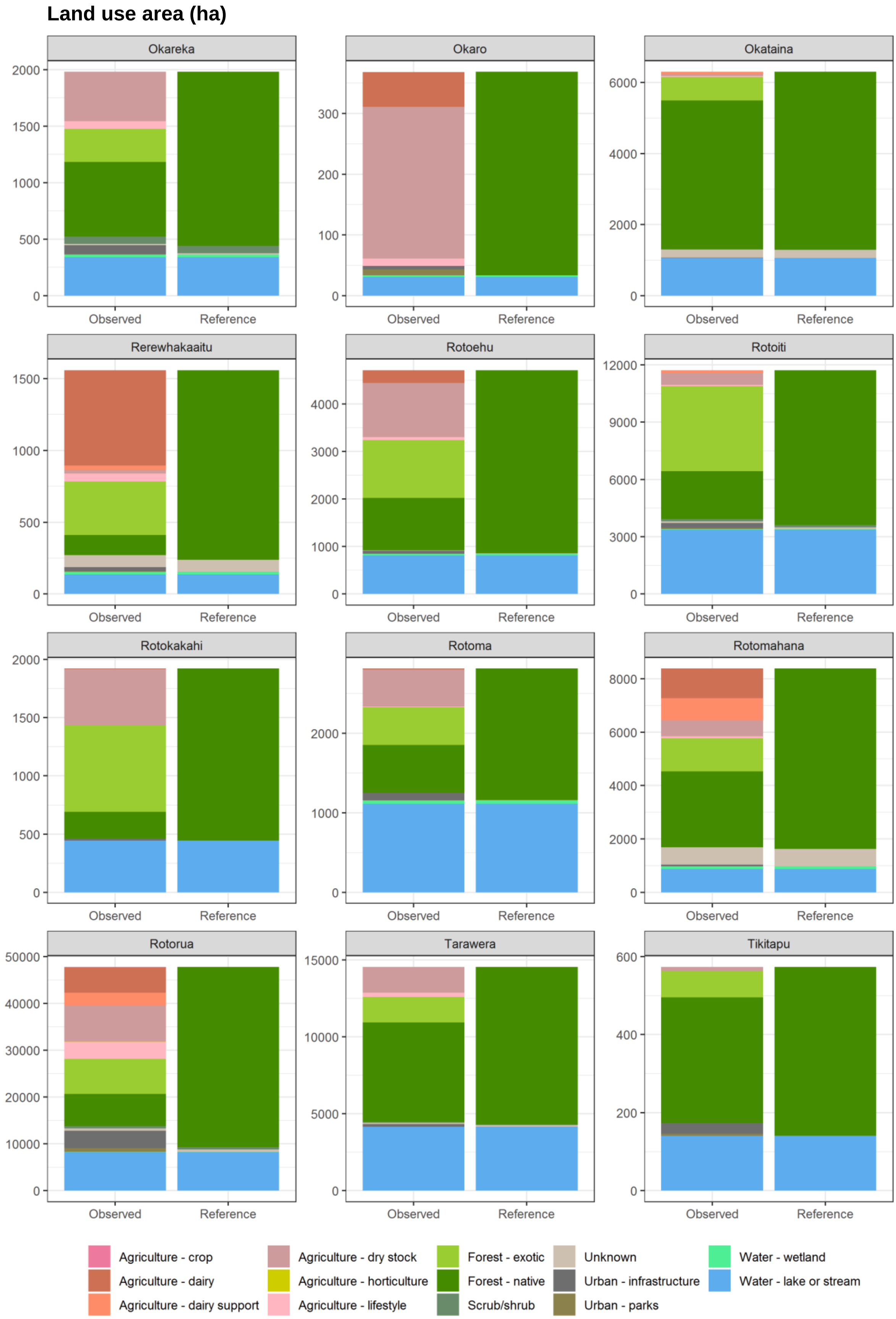

Figure 12. Catchment land use under present ('Observed') and hypothetical reference conditions ('Reference') where all intensive land use is converted to native forest.

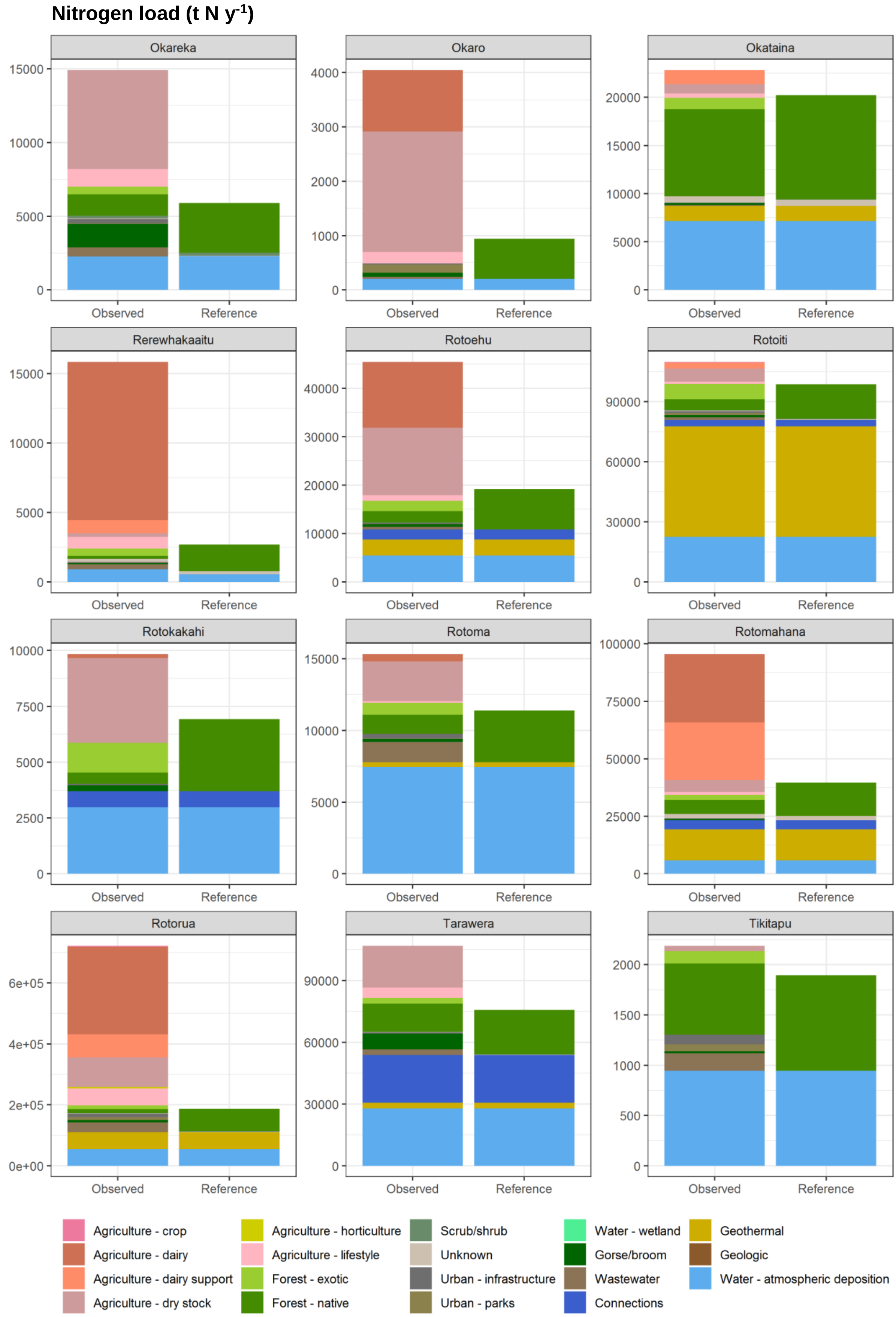

Figure 13. Nitrogen loading from all sources under present ('Observed') and hypothetical reference conditions ('Reference') where all intensive land use is converted to native forest.

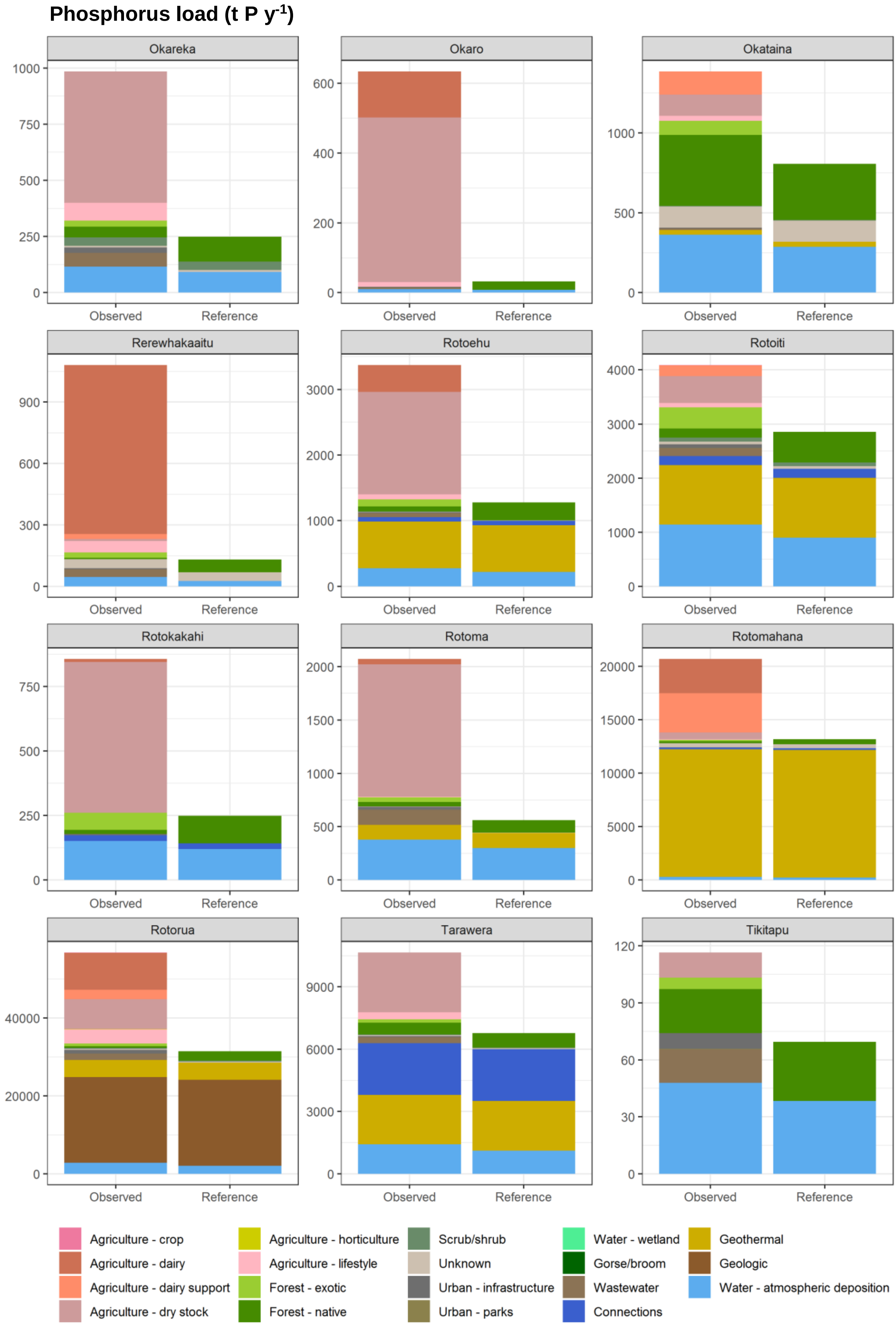

Figure 14. Phosphorus loading from all sources under present ('Observed') and hypothetical reference conditions ('Reference') whereby all intensive land use is converted to native forest.

Table 7. Sensitivity of estimated nutrient loads to varying degrees of assumed attenuation of nutrients between the root zone/block boundary and lake edge.

	ATTENUATION						LOADS					
	Nitrogen			Phosphorus			Nitrogen (t y^{-1})			Phosphorus (t y^{-1})		
	Low	Best guess	High	Low	Best guess	High	Low	Best guess	High	Low	Best guess	High
Okareka	0.207	0.403	0.7	0.207	0.403	0.7	18.9	14.9	8.9	1.25	0.98	0.58
Okaro	0.200	0.400	0.7	0.200	0.400	0.7	5.3	4.0	2.1	0.84	0.63	0.32
Okataina	0.225	0.413	0.7	0.225	0.413	0.7	27.3	22.8	16.0	1.70	1.39	0.90
Rerewhakaaitu	0.205	0.403	0.7	0.205	0.403	0.7	20.6	15.8	8.6	1.41	1.08	0.58
Rotoehu	0.218	0.409	0.7	0.218	0.409	0.7	56.4	45.4	28.7	4.10	3.37	2.26
Rotoiti	0.248	0.424	0.7	0.248	0.424	0.7	118.3	109.9	96.6	4.56	4.09	3.35
Rotokakahi	0.207	0.403	0.7	0.207	0.403	0.7	11.9	9.8	6.8	1.08	0.86	0.52
Rotokawau	0.199	0.400	0.7	0.199	0.400	0.7	1.2	1.0	0.7	0.10	0.08	0.05
Rotoma	0.210	0.405	0.7	0.210	0.405	0.7	17.3	15.3	12.3	2.54	2.07	1.37
Rotomahana	0.234	0.417	0.7	0.234	0.417	0.7	118.3	95.6	60.4	23.32	20.71	16.67
Rotorua	0.400	0.500	0.7	0.400	0.500	0.7	837.2	721.4	490.0	61.95	56.76	46.38
Tarawera	0.260	0.430	0.7	0.260	0.430	0.7	121.5	106.8	83.5	11.87	10.65	8.72
Tikitapu	0.201	0.400	0.7	0.201	0.400	0.7	2.5	2.2	1.7	0.13	0.12	0.09

4. Discussion

In the present study we aimed to provide transparent and reproducible estimates of nutrient loads to each of the Rotorua Te Arawa lakes. This region is fortunate to have been the site of an abundance of historical and recent catchment and lake research, relative to New Zealand as a whole. We considered all possible catchment nutrient sources and used consistent methodology across all catchments, to produce comprehensive budgets for each lake based on areal nutrient export rates, with careful consideration of attenuation as well as additional catchment features such as wastewater and geothermal inputs that might contribute loads over and above basic land use nutrient export. We included a broad sensitivity analysis using a range of attenuation rates, as well as literature review of previous loading estimates, to place the present estimates in a context of previous work and likely ranges of loading. This synthesis can thus be used to inform management going forward.

4.1 Study limitations

The Rotorua Te Arawa lakes and their catchments are highly heterogeneous, with a range of rainfall and/or geothermal zones, hydrology (e.g., perched catchments such as Rerewhakaaitu), surface or groundwater dominance, and nitrogen to phosphorus ratios in lake water and catchment inputs. Thus there are many challenges when applying consistent methodology at the regional scale to derive nutrient budget estimates.

We found a wealth of information and prior studies relating to geothermal loads to the lakes, nevertheless, a great deal of uncertainty remains at many lakes. For lakes where geothermal loads are potentially a large proportion of the total nutrient load (Rotoehu, Rotomahana, Tarawera, Rotoiti), more detailed investigation is justified.

Attenuation (i.e., the loss of nutrients to the atmosphere or retention on the landscape between the land and lake edge) is moderately well characterised for Rotorua, but lacks quantification for many other catchments. A lack of information necessitated broad assumptions with respect to the degree of attenuation applied. A relationship between attenuation and catchment area seems a reasonable assumption (with respect to increased travel distance and opportunity for interception in larger catchments), although may be unrealistic if other factors such as soil geology are more important. For some catchments (e.g., Rotorua and Tarawera), substantial monitoring and additional work (modelling) mean it is possible to compare the estimates in this study with estimates derived using more sophisticated approaches (albeit that there are still numerous uncertainties). Indeed, our estimate of likely attenuation factors in these catchments was guided by previously published modelling (e.g., Rutherford & Paliser 2019) and empirically-based loading estimates (Hamilton et al. 2006, McBride et al. 2019).

The Rotorua Te Arawa lakes region has a complex geology and in many catchments the contribution to groundwater is significant (e.g., Morgenstern et al. 2015, White et al. 2016). Groundwater lags mean that steady-state models of nutrient flux may not reflect present-day loads (particularly for Lake Rotorua), and the interconnectedness of surface and ground waters brings additional uncertainties. This presents a major challenge to applying export coefficient modelling approaches, although in some respects the method has an advantage, because budgets based upon measurements of stream discharge and nutrient concentrations (and hence surface loads) may represent only a fraction of the total input to the lake (e.g., Rotokakahi, Tarawera). In these cases, catchment groundwater modelling has an important role to play in reducing uncertainty of loading estimates.

The nutrient budget model constructed for the present study allows for separate transport pathways for groundwater and surface water, each with unique attenuation factors. In practice, a lack of detailed information for multiple catchments means that we assumed identical attenuation for groundwater and surface water, meaning that the split between surface and groundwater volumes was largely irrelevant to the total estimated loads. Nevertheless, if and when additional information is generated with respect to attenuation in surface vs groundwater, individual attenuation factors could be used. These values could be incorporated with, for example, a review of the groundwater volume estimates of White et al. (2016) to further refine the loading estimates presented here. Better information on attenuation, particularly with respect to the transfer of loads to downstream lakes, could also improve the usefulness of the loading sensitivity analysis presented here. Local analyses of atmospheric deposition could also help refine the likely range of loading.

Many of the nutrient export rates presented here are based on outputs from the Overseer® model, and as such are subject to the assumptions, limitations and uncertainties therein. For example, Overseer® outputs have varied dramatically between major revisions of the model, particularly so for the Bay of Plenty Region. Additionally, many regions within the Rotorua Te Arawa lakes complex have rainfall greater than that for which presently available versions of Overseer® have been calibrated. Trials are nearly complete to improve this situation in upcoming Overseer® versions. Further, some inputs to the Overseer® analyses used here are based on land use from the early 2000s and as such may have changed in the intervening years. Overseer® assumes best farming practice when generating export coefficients, and this may not always be the case for every block of land in each catchment. Additionally, in some catchments, not all agricultural land was assessed using Overseer®, therefore, an underestimate of loads may occur if N and P losses in un-benchmarked areas exceed those in benchmarked areas.

4.2 Recommendations

Additional nutrient budgets

1. Additional nutrient budgets based on empirical measurements of stream discharge and concentration. These estimates would need to account for climate (e.g., wet and dry years), as well as storm flow loading, and groundwater discharge where appropriate. If multiple catchments were measured in this way, then regional-scale attenuation (and variability among lake catchments) could be more accurately assessed.
2. Improved estimation of geothermal water chemistry and discharge to improve confidence in geothermal nutrient budgets. Complete 'budgets' of geothermal loading to some lakes is difficult, as these tend to be diffuse and difficult to measure. Nevertheless, in some cases, even a limited number of samples analysed for N and P of geothermal fluid could help greatly narrow the possible range of geothermal loading. For example, no information was uncovered relating to the water chemistry of the 0.3 m s^{-1} of geothermal fluid estimated to discharge to the bottom of Lake Rotoiti at the Crater site. A more widely applicable and effective approach may be the use of geochemical tracers (isotopes or trace elements) to characterise sources and quantify accumulation lakes or stratified layers (hypolimnia).

3. Completion of Overseer® assessments for all agricultural land in all catchments could help reduce uncertainty due to unassessed areas of some catchments.
4. Local and up-to-date measurements of wet and dry deposition of N and P to refine atmospheric deposition loads.
5. Regular revision of the budgets presented here, accounting for new information, or Overseer® versions with improvements to calibrations for volcanic soils and/or high rainfall areas.

4.3 Conclusions

Comparison of present load estimates with 'reference' loads (estimated by assuming conversion of all intensive land uses to native forest nutrient export rates) showed that several catchments have loads that exceed those of reference conditions by two- or three-fold, and sometimes much more. For context, Snelder (2018) found that anthropogenic increases in loads of TN and TP exported from the New Zealand land mass to the ocean were 74%, and 48%, respectively, whereas for the Bay of Plenty, increases were 40% and 12%, respectively. Because we assumed that atmospheric deposition and loads from connected lakes were unchanged under the reference scenario, reference (pre-human) loads are likely to be *overestimates*, particularly for Lake Tarawera. Even if a linear response of water quality to catchment loading is assumed, these comparisons highlight the challenge in restoring water quality to an approximate reference state, and in setting water quality targets appropriate to both community aspirations and practicable land use modifications within the basin.

In practice, water quality may respond to catchment loading in a non-linear fashion (i.e., accelerating degradation in water quality as catchment loading increases) due to internal feedback mechanisms in lakes such as sediment nutrient release during periods of bottom water anoxia (i.e., internal loading). The estimates of catchment loading provided here can serve as a basis from which to use mass balance methods to estimate the degree of internal loading occurring in each lake, further informing restoration approaches.

This study provides a repository of present knowledge relating to nutrient loading to the Rotorua Te Arawa Lakes. Numerous opportunities exist to further refine these estimates, in order to better support programmes of lake and catchment management but this study has provided information to support and target catchment management programmes that can help to address wide gaps between current and reference nutrient loads that will help to address water quality problems in the lakes.

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Appendix 1. Individual catchment nutrient budgets

Lake Okareka

Okareka is a moderately deep lake (maximum depth c. 34 m). Its water quality is classed as mesotrophic, with average surface water concentrations of 191 mg TN m^{-3}, 10.6 mg TP m^{-3}, and 3.0 mg chl *a* m^{-3} for the period 2012 – 2017 (Table 1). Okareka's TN:TP ratio of approximately 18:1 is relatively high, meaning phytoplankton productivity is likely to be P-limited or co-limited depending on seasonal variation.

Catchment description

Lake Okareka has a surface topographical catchment area of 19.6 km^2, including the lake area of 3.4 km^2 (LCDB4). The catchment is approximately half forested, of which nearly three quarters is indigenous. The remaining land is largely pastoral or invasive vegetation (Figure 15). Okareka's lakeside community wastewater was reticulated in 2011.

Previous load estimates

The Lake Okareka Catchment Management Action Plan estimated nutrient loads to Lake Okareka of 10.98 t N y^{-1} and 0.41 t P y^{-1} (EBoP 2004), whereas Hamilton et al. (2006) estimated 10.5 t N y^{-1} and 1.54 t P y^{-1}.

CLUES load estimates (present study)

Nutrient loads estimated using CLUES were 7.28 t N y^{-1} and 1.16 t P y^{-1}.

Land use classes

Results from OVERSEER version 6.2.3 were available for estimating nutrient losses from 78% of Okareka's catchment, including all pastoral land.

Geothermal inputs of nitrogen and phosphorus

Lake Okareka is not geothermally influenced (Nairn 1981).

Connected lakes

Lake Okareka does not receive surface water from the outflow of any other lakes.

Wastewater

The population estimate used for the purpose of calculating nutrient loads from septic tanks comprised a daily equivalent of 662 permanent residents (288 household equivalents at average occupancy of 2.3 persons) (EBoP 2004). Because the community's wastewater was reticulated in 2011, the estimated wastewater load was multiplied by 0.25, with the resultant loads accounting for approximately 2% of N and P loads to the lake. It is expected that wastewater loads will reduce towards zero as nutrient-rich effluent from previous septic tanks is depleted from soil water over time.

Summary

Total estimated loads to Lake Okareka were 14.9 t N y^{-1} and 0.99 t P y^{-1} (Table 8). For both N and P, more than half of estimated total load was derived from pastoral land (~25 % of land area). These loads are higher than earlier estimates by EBoP (2004), and from the land use model CLUES.

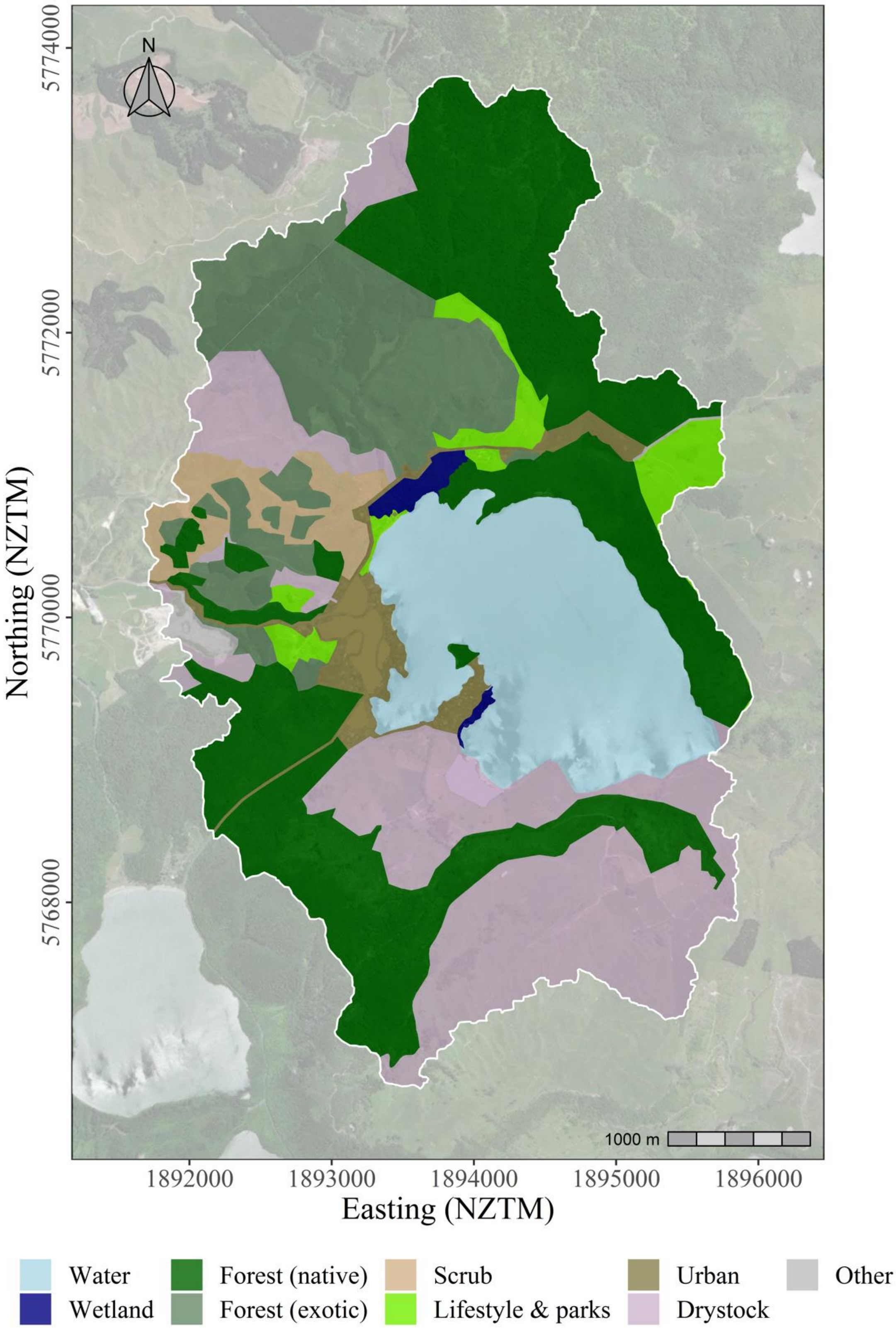


Figure 15. Map of land use (data: BoPRC) in the Okareka catchment.

Key assumptions and opportunities for improving knowledge

- Extent of legacy effects of previously unreticulated wastewater.
- Prevalence of gorse/broom.

Table 8. Sources of nitrogen and phosphorus to Lake Okareka from its catchment.

Land use	Surface catchment (ha)	Groundwater catchment (ha)	TN yield (kg ha^{-1} y^{-1})	TP yield (kg ha^{-1} y^{-1})	Yield method	Nitrogen attenuation	Phosphorus attenuation	TN load (kg y^{-1})	TP load (kg y^{-1})	Landuse (%)	TN load (%)	TP load (%)
Agriculture - dry stock	437.0	437.0	25.7	2.24	Overseer	0.40	0.40	6704	584.5	22.1	45.0	59.4
Agriculture - lifestyle	67.2	67.2	30.0	2.00	Estimated	0.40	0.40	1203	80.2	3.4	8.1	8.1
Forest - exotic	294.4	294.4	3.0	0.15	Estimated	0.40	0.40	527	26.4	14.9	3.5	2.7
Forest - native	659.2	659.2	3.7	0.12	Estimated	0.40	0.40	1444	47.2	33.3	9.7	4.8
Scrub/shrub	63.0	63.0	5.0	1.00	Estimated	0.40	0.40	188	37.6	3.2	1.3	3.8
Unknown	13.4	13.4	5.0	1.00	Estimated	0.40	0.40	40	8.0	0.7	0.3	0.8
Urban - infrastructure	80.1	80.1	5.9	0.50	Estimated	0.40	0.40	282	23.9	4.0	1.9	2.4
Urban - parks	3.0	3.0	25.0	0.14	Estimated	0.40	0.40	44	0.2	0.1	0.3	0.0
Water - lake or stream	341.2	341.2	6.7	0.34	Verburg (2015)			2286	116.0	17.2	15.3	11.8
Water - wetland	21.9	21.9	0.0	0.00	Estimated	0.40	0.40	0	0.0	1.1	0.0	0.0
Gorse/broom			38.0	0.00	BoPRC	0.40	0.40	1587	0.0		10.6	0.0
Wastewater					BoPRC			607	60.7		4.1	6.2
All sources								**14912**	**985**			

Lake Okaro

Okaro is a small lake (area c. 0.3 km^2) in a eutrophic state. It is subject to frequent and severe blooms of cyanobacteria during spring-summer, and has had an extensive program of water quality management, including land-based interventions (e.g., constructed wetland, agricultural detention bunds) and in-lake remediation (e.g. flocculation and sediment capping). Its water quality is classed as supertrophic, with average surface water concentrations of 718 mg m^{-3} TN, 41.0 mg m^{-3} TP, and 18.0 mg m^{-3} chl *a* for the period 2012 – 2017 (Table 1). At present Lake Okaro is classed asass eutrophic based on its TLI of 4.8, however, relatively recently it has been classed as supertrophic, with TLI continuously > 5.Lake Okaro's TN:TP ratio of approximately 17.5:1 means phytoplankton productivity is likely P-limited or co-limited depending on seasonal variation. However, periods of N-limitation may lead to a competitive advantage for N-fixing cyanobacteria (White et al. 1989).).

Catchment description

Lake Okaro has a surface topographical catchment area of 3.9 km^2, including the lake area of 0.31 km^2 (LCDB4). The catchment is almost entirely pastoral, and there are few residential homes within the catchment. There is a surface inflow draining most of the catchment to the lake, and a smaller inflow that drains a small portion of the catchment to the south. Both inflows and drainage from a cowshed race are intercepted by a constructed wetland on either side of the main road, which was completed in 2007 with the intention of filtering particulate phosphorus, and taking up dissolved inorganic nutrients, as well as performing denitrification. More recently, a detainment bund was completed in 2014, located upstream of the wetland, in order to balance peak flows and settle out particulate matter, particularly P.

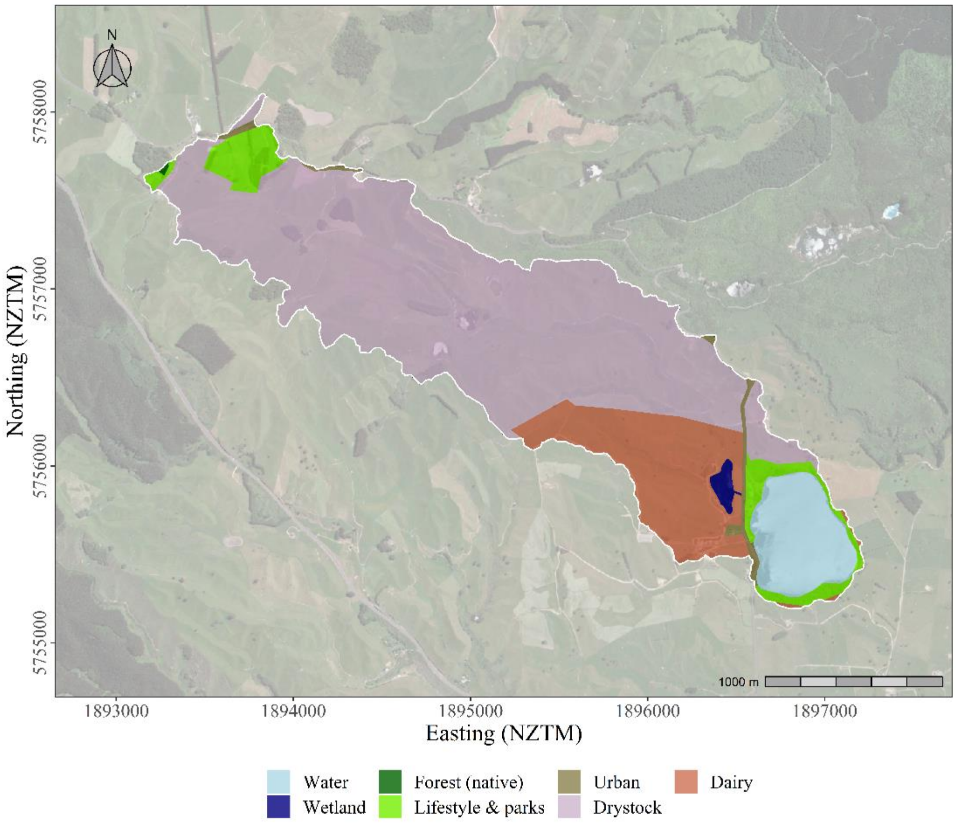


Figure 16. Map of land use (data: BoPRC) in the Okaro catchment.

Previous load estimates

The Lake Okaro Action Plan estimated nutrient loads to Lake Okaro of 5.0 t N y^{-1} and 0.78 t P y^{-1} (EBoP 2006), whereas Hamilton et al. (2006) estimated 2.7 t N y^{-1} and 0.41 t P y^{-1}.

CLUES load estimates (present study)

Nutrient loads estimated using CLUES were 4.9 t N y^{-1} and 0.39 t P y^{-1}. These loads do not account for geothermal inputs, which are likely to be very small relative to other inputs.

Land use classes

Results from OVERSEER version 6.2.3 were available for estimating nutrient losses from 82% of Okaro's catchment, including most pastoral land (Figure 7).

Geothermal inputs of nitrogen and phosphorus

Warm water has been observed deep Okaro catchment groundwater (> 20 m depth; McIntosh, pers. comm.), however, substantial geothermal inputs to Lake Okaro are unlikely. Nairn (1981) described chloride concentrations in the lake water of < 6 mg Cl L^{-1}, indicative of a very low geothermal contribution to lake water.

Connected lakes

Lake Okaro is not known to receive water from the outflow of any other lakes aside from the constructed wetland and detention bunds (note: one of these is a small natural lake).

Wastewater

The population estimate used for the purpose of calculating nutrient loads from septic tanks comprised a daily equivalent of 10 permanent residents. The contribution of wastewater to overall load-to-lake is estimated to be less than 1 % for both N and P.

Constructed wetlands

Two wetlands were constructed in 2007 to intercept the inflows of Lake Okaro and reduce nutrient load to the lake by filtration and settling of particulates, as well as by uptake of dissolved nutrients. Annual load reductions of 150 kg N y^{-1} and 40 kg P y^{-1} were estimated from data presented in Hudson and Nagels (2011).

Summary

Total estimated loads to Lake Okaro were 3.9 t N y^{-1} and 0.59 t P y^{-1} (
Table 13). Almost all N and P load is derived from agricultural land, as the catchment land use is overwhelmingly pastoral. The N and P loads estimated here were both somewhat lower than previously published estimates. It should be noted that BoPRC monitoring data show the northern inflow of Lake Okaro has the highest phosphorus concentration of all inflows to any Rotorua lake. Rotomahana mud deposited across the Okaro catchment is very high in P, and as such the P load presented here may be an underestimate. Contributions of phosphorus from Rotomahana mud could be included in the 'Geologic' category, following more detailed investigation.

Key assumptions and opportunities for improving knowledge

- Extent of changes to the efficacy of the constructed wetland over time.
- Effect of 'Rotomahana mud' geology on P loss from landscape.
- Prevalence of gorse/broom.

Table 9. Sources of nitrogen and phosphorus to Lake Okaro from its catchment.

Land use	Surface catchment (ha)	Groundwater catchment (ha)	TN yield (kg ha^{-1} y^{-1})	TP yield (kg ha^{-1} y^{-1})	Yield method	Nitrogen attenuation	Phosphorus attenuation	TN load (kg y^{-1})	TP load (kg y^{-1})	Landuse (%)	TN load (%)	TP load (%)
Agriculture - dairy	57.7	57.7	32.7	3.82	Overseer	0.40	0.40	1132	132.4	15.7	28.0	20.9
Agriculture - dry stock	249.7	249.7	14.8	3.14	Overseer	0.40	0.40	2214	470.5	67.8	54.7	74.2
Agriculture - lifestyle	11.8	11.8	30.0	2.00	Estimated	0.40	0.40	212	14.1	3.2	5.2	2.2
Forest - native	0.2	0.2	3.7	0.12	Estimated	0.40	0.40	0	0.0	0.1	0.0	0.0
Urban - infrastructure	5.4	5.4	5.9	0.50	Estimated	0.40	0.40	19	1.6	1.5	0.5	0.3
Urban - parks	10.1	10.1	25.0	0.14	Estimated	0.40	0.40	151	0.8	2.7	3.7	0.1
Water - lake or stream	31.0	31.0	6.7	0.34	Verburg (2015)			207	10.5	8.4	5.1	1.7
Water - wetland	2.5	2.5	0.0	0.00	Estimated	0.40	0.40	-150*	-40.0*	0.7	0.0	0.0
Gorse/broom			38.0	0.00	BoPRC	0.40	0.40	73	0.0		1.8	0.0
Wastewater					BoPRC			37	3.7		0.9	0.6
All sources								**3895**	**594**			

* Nutrient removal by the Okaro constructed wetland was investigated by Hudson and Nagels (2009).

Lake Okataina

Okataina is a deep lake (maximum depth c. 78 m), of low productivity. Its water quality is classed as oligotrophic, with average surface water concentrations of 88 mg m^{-3} TN, 12.0 mg m^{-3} TP, and 2.0 mg m^{-3}chl *a* for the period 2012 – 2017 (Table 1). Okataina's very low TN:TP ratio of approximately 7.5:1 strongly suggests co-limitation or periods of N-limitation. The lake has no surface outlet, and as such water level varies considerably over annual to decadal time-scales.

Catchment description

Lake Okataina has a surface topographical catchment area of 6.0 km^2, including the lake area of 10.8 km^2 (LCDB4). Based on land use, the catchment may be perceived to be relatively pristine, with the majority of land remaining in indigenous vegetation, and only small proportions of exotic forestry and dry stock land (Figure 17). However, recent attention has focussed on the abundance and effects of pest species, particularly wallabies, which have stripped much of the understory in the forested catchment (Figure 18). Kpodonu et al. (2019) describes the history and paleolimnology of Lake Okataina and its catchment.

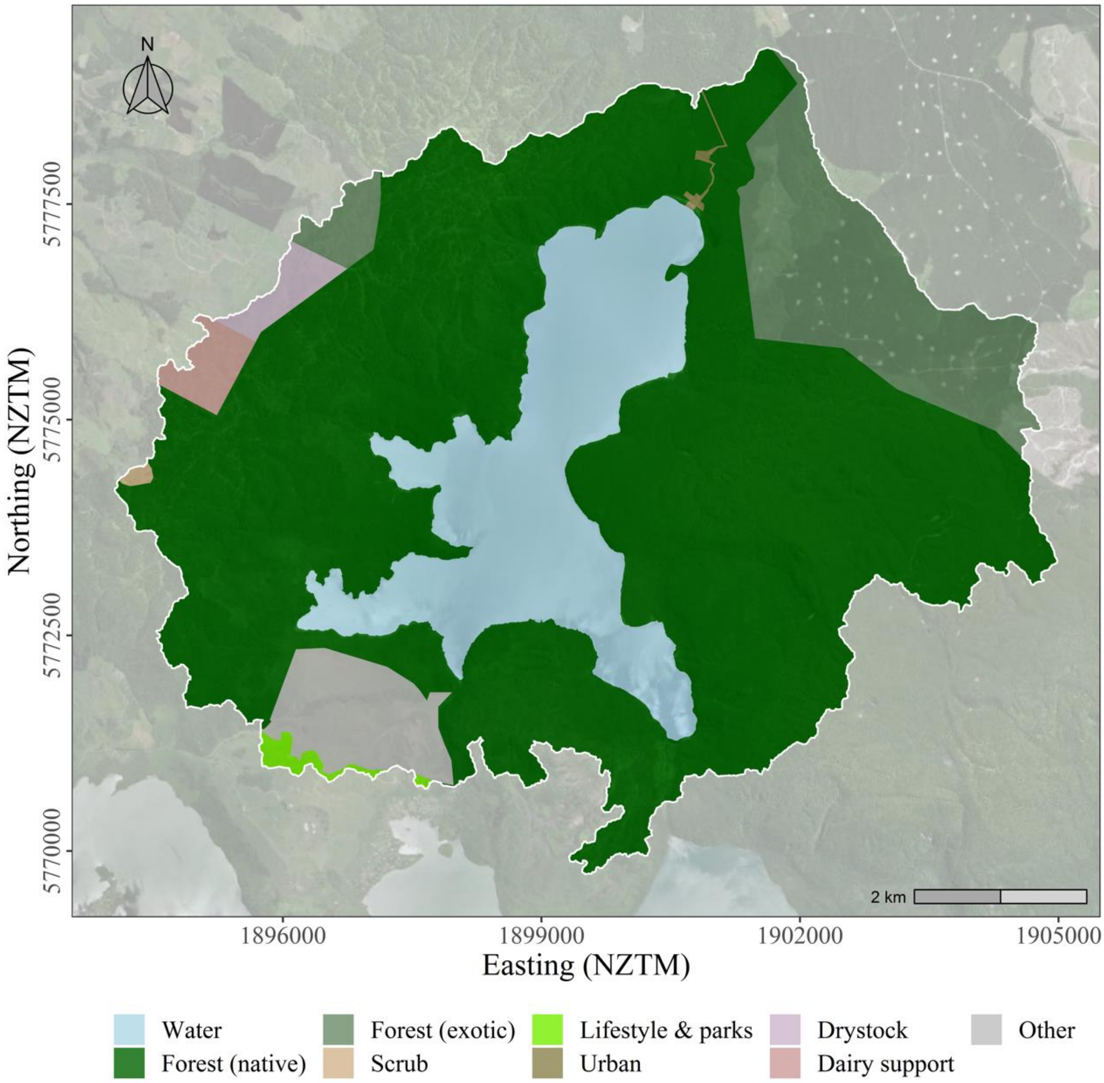


Figure 17. Map of land use (data: BoPRC) in the Okataina catchment.

Previous load estimates

The loads estimated by the Lake Okataina Action Plan (BoPRC 2013) were 27.1 t N y^{-1} and 2.1 t P y^{-1}, whereas Hamilton et al. (2006) estimated 22.3 t N y^{-1} and 2.93 t P y^{-1}.

CLUES load estimates (present study)

Nutrient loads estimated using CLUES were 19.7 t N y^{-1} and 3.2 t P y^{-1}. These loads do not account for geothermal inputs.

Figure 18. Indigenous forest in the Lake Okataina catchment, showing the contrast between an area with pest exclusion (right) and without (left). Image by D. Hamilton.

Land use classes

Results from OVERSEER version 6.2.3 were available for estimating nutrient losses from 37% of Okataina's catchment, including two-thirds of pastoral land. For exotic and indigenous cover, P loss rates from forest were multiplied by 1.5 to account for the effect of reduced understory cover due to pest animals.

Geothermal inputs of nitrogen and phosphorus

Nairn (1981) described slightly elevated chloride concentrations in the water of Lake Okataina (11 mg Cl L^{-1}) due to a known small hydrothermal inflow.

Connected lakes

Lake Okataina does not receive water from the outflow of any other lakes.

Wastewater

The population estimate used for the purpose of calculating nutrient loads from septic tanks comprised a daily equivalent of 30 permanent residents (BoPRC 2013). The contribution of wastewater to overall load-to-lake is estimated to be <1 % for both N and P.

Summary

Total estimated loads to Lake Okataina were 22.8 t N y^{-1} and 1.39 t P y^{-1} (Table 10). Dry stock land represents a substantial source of N and particularly P, although total loads to the lake are relatively low due to the undeveloped catchment.

Key assumptions and opportunities for improving knowledge

- Magnitude and chemistry of geothermal inputs.
- Magnitude of the effect of wallabies on nutrient losses from forested areas.

Table 10. Sources of nitrogen and phosphorus to Lake Okataina from its catchment.

Land use	Surface catchment (ha)	Groundwater catchment (ha)	TN yield (kg ha^{-1} y^{-1})	TP yield (kg ha^{-1} y^{-1})	Yield method	Nitrogen attenuation	Phosphorus attenuation	TN load (kg y^{-1})	TP load (kg y^{-1})	Landuse (%)	TN load (%)	TP load (%)
Agriculture - dairy support	65.1	65.1	38.0	3.80	Estimated	0.41	0.41	1455	145.5	1.0	6.4	10.5
Agriculture - dry stock	57.1	57.1	28.9	3.98	Overseer	0.41	0.41	971	133.4	0.9	4.3	9.6
Agriculture - lifestyle	26.9	26.9	30.0	2.00	Estimated	0.41	0.41	474	31.6	0.4	2.1	2.3
Forest - exotic	660.7	660.7	3.0	0.22	Estimated	0.41	0.41	1165	87.4	10.5	5.1	6.3
Forest - native	4184.4	4184.4	3.7	0.18	Estimated	0.41	0.41	9028	442.8	66.4	39.6	32.0
Scrub/shrub	6.8	6.8	5.0	1.50	Estimated	0.41	0.41	20	6.0	0.1	0.1	0.4
Unknown	225.7	225.7	5.0	1.00	Estimated	0.41	0.41	663	132.7	3.6	2.9	9.6
Urban - infrastructure	8.5	8.5	5.9	0.50	Estimated	0.41	0.41	29	2.5	0.1	0.1	0.2
Water - lake or stream	1066.1	1066.1	6.7	0.34	Verburg et al. (2018)			7143	362.5	16.9	31.3	26.2
Gorse/broom			38.0	0.00	BoPRC	0.41	0.41	183	0.0		0.8	0.0
Wastewater					BoPRC			110	11.0		0.5	0.8
Geothermal					Estimated			1580	30.0		6.9	2.2
All sources								**22821**	**1385**			

Lake Rerewhakaaitu

Rerewhakaaitu is a shallow (maximum depth c. 15 m), polymictic lake of moderate productivity. Its water quality is classed as mesotrophic, with average surface water concentrations of 325 mg m^{-3} TN, 9.1 mg m^{-3} TP, and 3.4 mg m^{-3} chl *a* for the period 2012 – 2017 (Table 1). Rerewhakaaitu's TN:TP ratio of approximately 36:1 is the highest of all the Rotorua Te Arawa Lakes. The lake is known to have sediments very rich in iron, which may bind P in the water column, maintaining the very high N:P ratio and thus limiting phytoplankton production. Monitoring of bottom water dissolved oxygen concentration is considered important for Rerewhakaaitu, due to the potential for anoxia to result in the desorption (release) of dissolved phosphorus into the water column, resulting in increased phytoplankton production (Gibbs, pers. comm.). A water column profiling buoy was deployed in the lake in 2015 for the purpose of recording variations in bottom water oxygen.

Catchment description

Lake Rerewhakaaitu has a surface topographical catchment area of 37.02 km^2, including the lake area of 5.5 km^2 (LCDB4). The catchment is predominantly pastoral (c. 65 %) and exotic forestry (c. 10%), with emergent vegetation in shallow areas around the lake shores, and a small amount of exotic and indigenous forest/scrub (Figure 19). Importantly, the lake itself lies within a perched sub-catchment, and likely only receives a small part of the total rainfall to the catchment (White et al. 2003; Cho et al., 2020).

Previous load estimates

McIntosh (2012) estimated loads to Lake Rerewhakaaitu of 106.6 t N y^{-1} and 4.3 t P y^{-1}. The catchment soils and lake sediments of Rerewhakaaitu are very high in iron (Fe). These soil characteristics are beneficial to dairy farming but could have implications for loads to the lake if these soils do reach saturation (which will be very high). Additionally, P bound to iron-rich lake sediments may be released into the water column during periods of bottom water anoxia.

CLUES load estimates (present study)

Nutrient loads estimated using CLUES were 58.51 t N y^{-1} and 2.82 t P y^{-1}. These loads are likely large overestimates, because much of the surface topographic catchment of Rerewhakaaitu is not connected to the lake (White et al. 2016).

Land use classes

Further, agricultural land, according to LCDB (2392 ha), was less than given in McIntosh (2012a). OVERSEER benchmarking of agricultural land was not available for each block in the catchment, however, summaries with average N and P losses for dairy, dairy support, and dry stock land within the catchment were able to be cited (S. Park, pers. comm.).

Geothermal inputs of nitrogen and phosphorus

Lake Rerewhakaaitu is not geothermally influenced. Nairn (1981) described chloride concentrations in the lake water of < 6 mg L^{-1}.

Connected lakes

Lake Rerewhakaaitu does not receive surface water from the outflow of any other lakes.

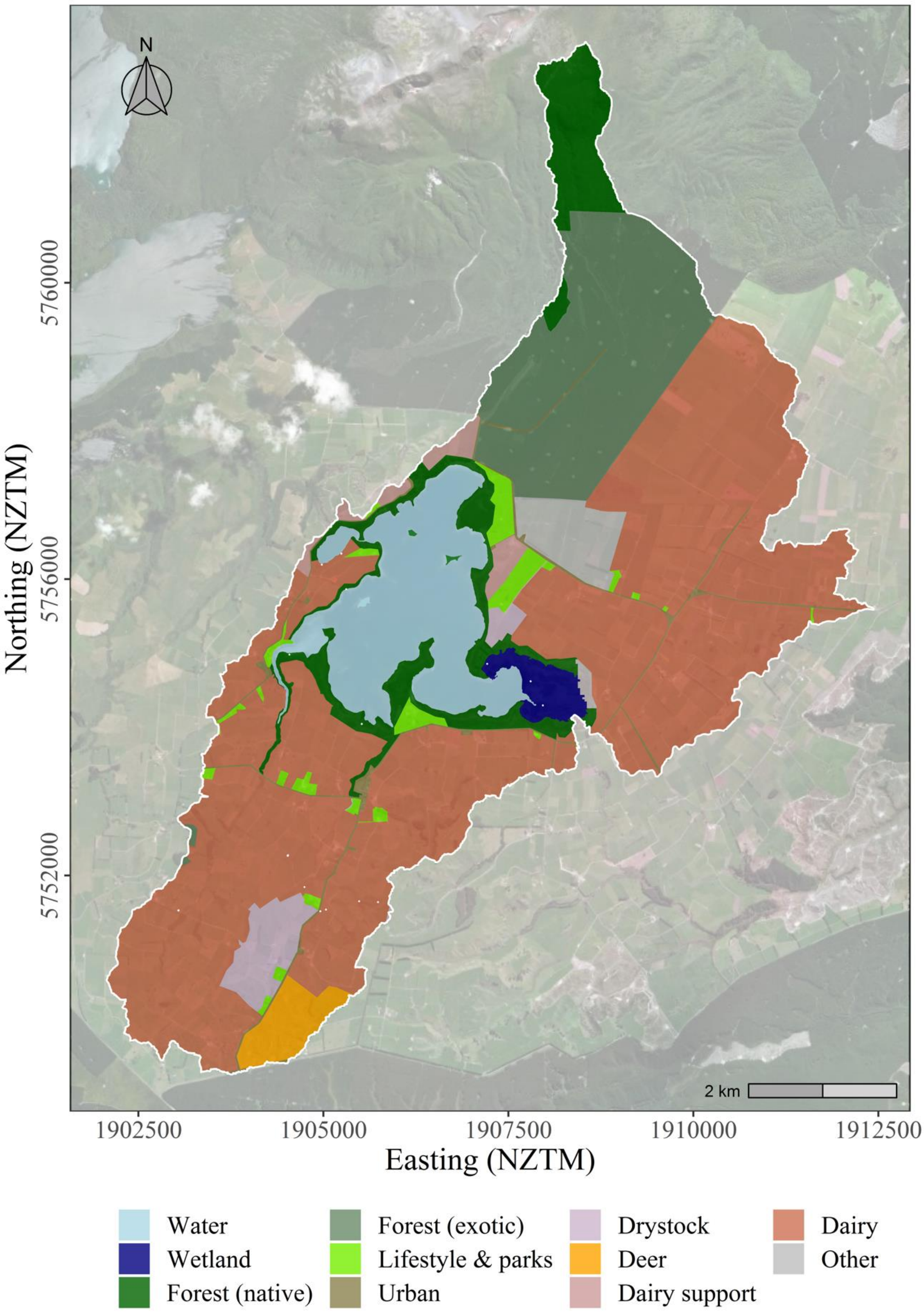


Figure 19. Map of land use (data: BoPRC) in the Rerewhakaaitu catchment.

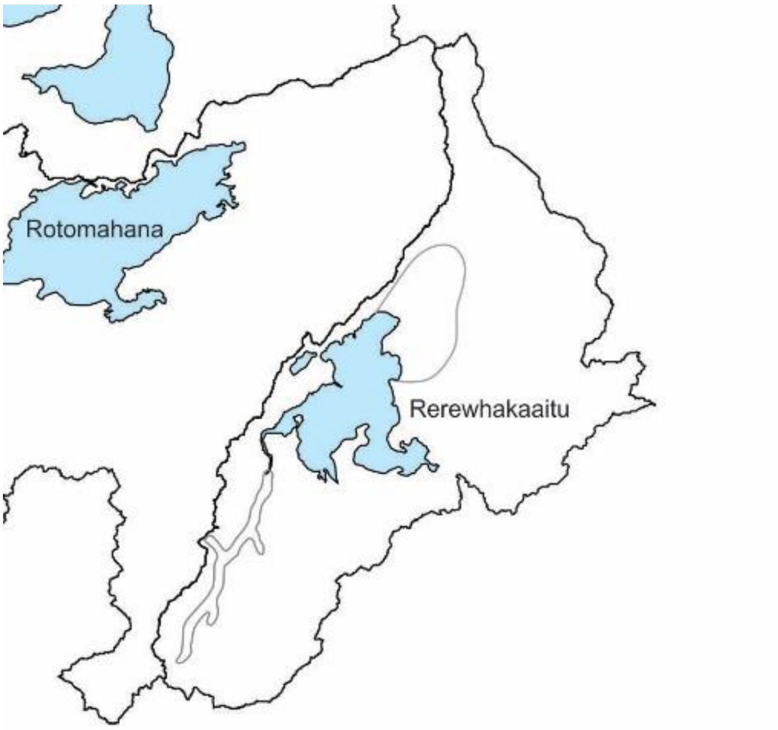


Figure 20. Map of the Rerewhakaaitu catchment. The topographic catchment is shown by the black outline, whereas the estimated groundwater catchment (Cho et al. 2020) is shown by the grey outline. Here we also assumed that 80% of surface-transport nutrient loads outside the grey borders did not reach the waterbody.

Wastewater

The population estimate used for the purpose of calculating nutrient loads from septic tanks comprised a daily equivalent of 100 permanent residents (McIntosh 2012). The contribution of wastewater to overall load-to-lake is estimated to be <1% for both N and P.

Summary

Total estimated loads from the total Lake Rerewhakaaitu catchment were 15.8 t N y^{-1} and 1.08 t P y^{-1} (Table 11). The estimated nitrogen load was substantially lower (approximately 50%) than the estimate of BoPRC (2012a). Nutrient inputs from non-agricultural land were a relatively insignificant proportion of overall load. It is important to note that because the lake is part of a perched sub-catchment, there still exists substantial uncertainty regarding catchment hydrology and hence nutrient loading.

Key assumptions and opportunities for improving knowledge

- Groundwater boundaries and water movement among catchments.
- Prevalence of gorse/broom.

Table 11. Sources of nitrogen and phosphorus to Lake Rerewhakaaitu from its catchment.

Land use	Topographic catchment (ha)	Estimated surface catchment (ha)	Groundwater catchment (ha)	TN yield (kg ha^{-1} y^{-1})	TP yield (kg ha^{-1} y^{-1})	Yield method	N atten.	P atten.	TN load (kg y^{-1})	TP load (kg y^{-1})	Landuse (%)	TN load (%)	TP load (%)
Agriculture - dairy	2897.8	662.7	83.2	51.0	3.70	Overseer	0.40	0.40	11369	824.8	42.5	71.9	76.3
Ag - dairy support	64.8	31.3	18.4	64.0	1.70	Overseer	0.40	0.40	952	25.3	2.0	6.0	2.3
Agriculture - dry stock	213.8	26.1	1.7	32.0	1.20	Overseer	0.40	0.40	266	10.0	1.7	1.7	0.9
Agriculture - lifestyle	91.5	55.2	36.9	30.0	2.00	Estimated	0.40	0.40	826	55.1	3.5	5.2	5.1
Forest - exotic	743.5	372.2	223.5	3.0	0.15	Estimated	0.40	0.40	535	26.7	23.9	3.4	2.5
Forest - native	437.8	140.5	52.9	3.7	0.12	Estimated	0.40	0.40	212	6.9	9.0	1.3	0.6
Unknown	126.6	84.1	58.8	5.0	1.00	Estimated	0.40	0.40	214	42.8	5.4	1.4	4.0
Urban - infrastructure	79.1	27.6	11.8	5.9	0.50	Estimated	0.40	0.40	70	5.9	1.8	0.4	0.5
Urban - parks	19.9	4.2	0.3	25.0	0.14	Estimated	0.40	0.40	33	0.2	0.3	0.2	0.0
Water – lake/stream	136.5	136.5	26.0	6.7	0.34	Verburg			915	46.4	8.8	5.8	4.3
Water - wetland	71.2	18.3	4.1	0.0	0.00	Estimated	0.40	0.40	0	0.0	1.2	0.0	0.0
Gorse/broom				38.0	0.00	BoPRC	0.40	0.40	64	0.0		0.4	0.0
Wastewater						BoPRC			367	36.7		2.3	3.4
All sources									**15823**	**1081**			

Lake Rotoehu

Rotoehu is a shallow lake (maximum depth c. 14 m), of high productivity, that showed substantial water quality improvements from 2010 to 2014 but with declining water quality more recently. The lake experiences severe blooms of cyanobacteria during summer and is frequently closed for recreational use. Its water quality is classed as eutrophic, with average surface water concentrations of 322 mg m^{-3} TN, 31.2 mg m^{-3} TP, and 8.9 mg m^{-3}chl *a* for the period 2012 – 2017 (Table 1). Rotoehu's TN:TP ratio of approximately 10:1 means that phytoplankton production is likely co-limited. The lake has been subject to multiple interventions and management strategies, including conversion of pastoral land to forestry, alum dosing of the soda springs geothermal inflow, and in-lake aeration during summer (2011 – 2014). Substantial amounts of aquatic weeds have been harvested from the southern end of the lake in certain years (accounted for in some previous nutrient budgets but not counted here due to a lack of any harvesting over recent years), and a small floating wetland has been deployed near the southern shore.

Catchment description

Lake Rotoehu has a surface topographical catchment area of 36.7 km^2, including the lake area of 7.9 km^2 (LCDB4). The lake surface is a substantial proportion of the overall catchment, and land use is relatively evenly split among indigenous forest, exotic forest, and pasture (Figure 21). There is a lakeside community which is not yet connected to a reticulated wastewater system. The geothermal Waitaingi spring flows to the lake at its south-eastern end. Substantial areas of exotic forest within the catchment have been harvested over recent years.

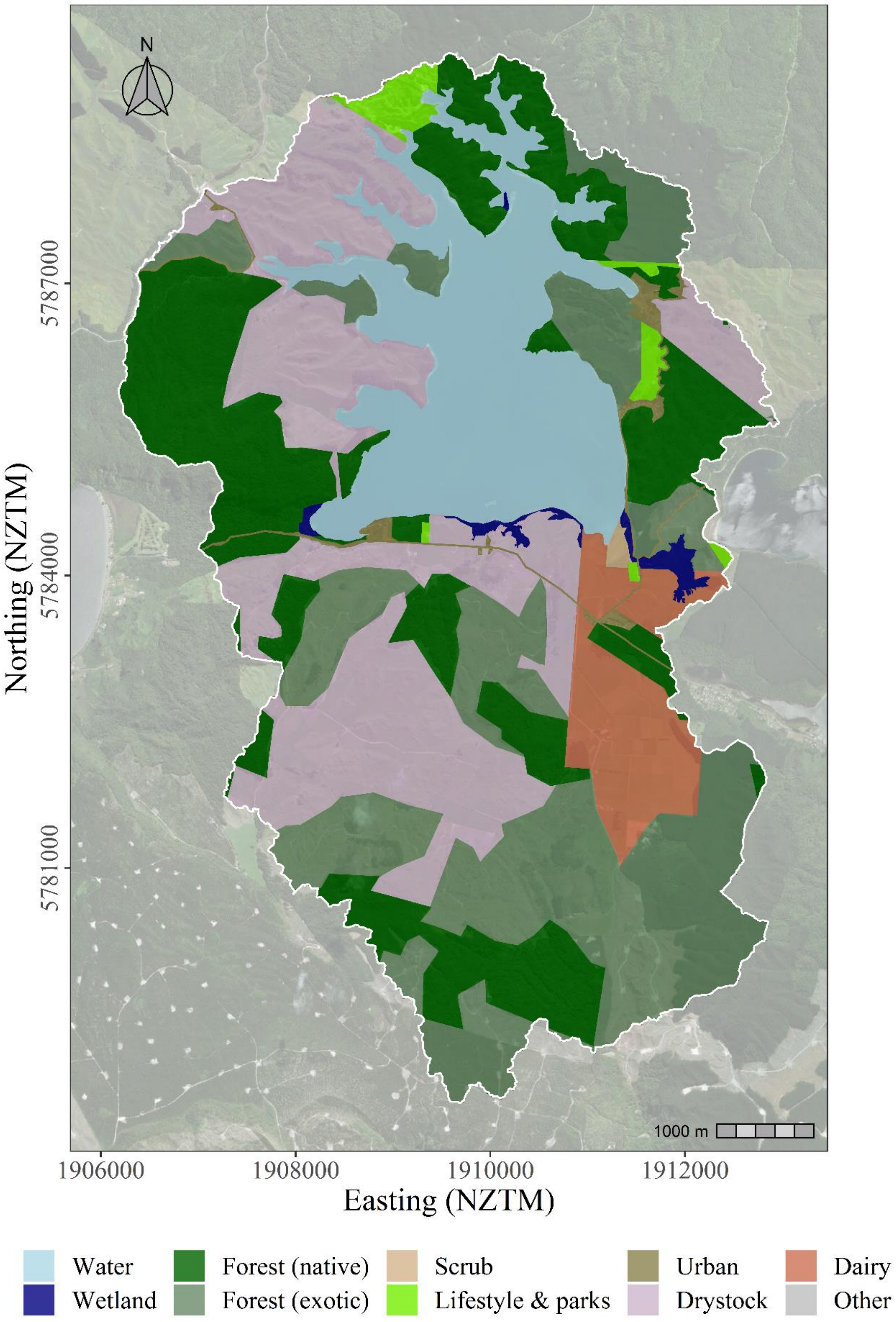


Figure 21. Map of land use (data: BoPRC) in the Rotoehu catchment.

Previous load estimates

The Lake Rotoehu Action Plan (BoPRC 2007) gave load estimates to Lake Rotoehu of 53.1 t N y^{-1} and 2.45 t P y^{-1}.

Land use classes

Results from OVERSEER version 6.2.3 were available for estimating nutrient losses from agricultural land.

Geothermal inputs of nitrogen and phosphorus

Lake Rotoehu is geothermally influenced, and Nairn (1981) described chloride concentrations in the lake water of > 100 mg Cl L^{-1}. The lake receives water from a geothermal spring-fed inflow at the south-eastern end of the lake (Waitangi Soda Spring), and another geothermal spring flows to the Rakaumakere Stream and into the lake immediately west of Waitangi Spring. Allan et al. (2011) used a three-dimensional hydrodynamic model to simulate the intrusion of geothermal water into the lake. Nairn (1981) also inferred from lake chloride concentrations and mixing models that there are likely to be additional subsurface geothermal sources. Donovan and Donovan (2003) estimated the geothermal loads of N and P from this spring to be 4.7 t N y^{-1} and 0.8 t P y^{-1}. Over recent years BoPRC has dosed the Waitangi inflow with alum, therefore, the present study has assumed a 50% reduction of the geothermal P load estimated by Donovan & Donovan, and no reduction in N load (Table 3).

Connected lakes

Two freshwater springs that flow from Lake Rotoma into the Mire to the east of Waitangi Springs and together with another geothermal upflow, pass under Manawahe Rd and join the Waitangi Stream as it flows to Rotoehu. Pittams (1968) gauged these flows, finding an average of 0.5 $m^3 s^{-1}$. The combined inflow (0.5 $m^3 s^{-1}$) has been alum dosed upstream in the Waitangi Stream, with residual alum likely to also affect the additional inflows that occur en route to Rotoehu.

Wastewater

The population estimate used for the purpose of calculating nutrient loads from septic tanks comprised a daily equivalent of 161 permanent residents (BoPRC 2007). The contribution of wastewater to overall load-to-lake was estimated to be 1.2 and 2.1 % for N and P respectively.

Summary

Total estimated loads to Lake Rotoehu were 45.4 t N y^{-1} and 3.37 t P y^{-1} (Table 12). These estimates are very similar to those given in BoPRC (2007). Pastoral land accounted for roughly half of N and P loads, and geothermal sources were a substantial contributor. It should be noted that there is considerable uncertainty in the geothermal load estimate.

Key assumptions and opportunities for improving knowledge

- Total magnitude of geothermal fluxes.
- Prevalence of gorse/broom.
- Effects of slips/landslides in the early 2010s.
- Effects of recent and substantial forestry harvesting.

Table 12. Sources of nitrogen and phosphorus to Lake Rotoehu from its catchment.

Land use	Surface catchment (ha)	Groundwater catchment (ha)	TN yield (kg ha^{-1} y^{-1})	TP yield (kg ha^{-1} y^{-1})	Yield method	Nitrogen attenuation	Phosphorus attenuation	TN load (kg y^{-1})	TP load (kg y^{-1})	Landuse (%)	TN load (%)	TP load (%)
Agriculture - dairy	267.5	267.5	85.8	2.57	Overseer	0.41	0.41	13568	406.7	5.7	29.9	12.1
Agriculture - dry stock	1141.7	1141.7	20.6	2.31	Overseer	0.41	0.41	13926	1561.2	24.2	30.7	46.3
Agriculture - lifestyle	64.7	64.7	30.0	2.00	Estimated	0.41	0.41	1147	76.5	1.4	2.5	2.3
Forest - exotic	1215.6	1215.6	3.0	0.15	Estimated	0.41	0.41	2156	107.8	25.8	4.7	3.2
Forest - native	1097.4	1097.4	3.7	0.12	Estimated	0.41	0.41	2381	77.8	23.3	5.2	2.3
Scrub/shrub	8.2	8.2	5.0	1.00	Estimated	0.41	0.41	24	4.8	0.2	0.1	0.1
Unknown	6.0	6.0	5.0	1.00	Estimated	0.41	0.41	18	3.6	0.1	0.0	0.1
Urban - infrastructure	62.4	62.4	5.9	0.50	Estimated	0.41	0.41	218	18.4	1.3	0.5	0.5
Urban - parks	3.6	3.6	25.0	0.14	Estimated	0.41	0.41	54	0.3	0.1	0.1	0.0
Water - lake or stream	809.0	809.0	6.7	0.34	Verburg (2015)			5420	275.1	17.2	11.9	8.2
Water - wetland	37.5	37.5	0.0	0.00	Estimated	0.41	0.41	0	0.0	0.8	0.0	0.0
Gorse/broom			38.0	0.00	BoPRC	0.41	0.41	546	0.0		1.2	0.0
Wastewater					BoPRC			591	59.1		1.3	1.8
Connections					Observed			2059	68.7		4.5	2.0
Geothermal					Estimated			3310	710.0		7.3	21.1
All sources								**45418**	**3370**			

Lake Rotoiti

Rotoiti is a deep lake (maximum c. 120 m), where water quality has varied dramatically over the past two decades. Severe blooms of the invasive cyanobacteria *Anabaena planktonica* in the early 2000s resulted in the implementation of multiple management strategies, the principal measure being the construction of a diversion wall to prevent the intrusion of water from Lake Rotorua into the lake. The wall reduced the nutrient load to the lake by c. 150 t N y^{-1} and 20 t P y^{-1}, and substantially increased its residence time. The model of Woods (2006) estimates an outflow from Rotoiti of 21.6 $m^3 s^{-1}$. By subtracting the mean observed Ohau Channel flow (16.57 $m^3 s^{-1}$) from the Rotoiti outflow, estimated residence time of the lake increases from c. 1.5 y to c. 6.8 y. Water quality since completion of the diversion wall has improved dramatically, and the lake is now classed as mesotrophic, with average surface water concentrations of 161 mg TN m^{-3}, 19.8 mg TP m^{-3}, and 4.7 mg chl *a* m^{-3} for the period 2012 – 2017 (Table 1).

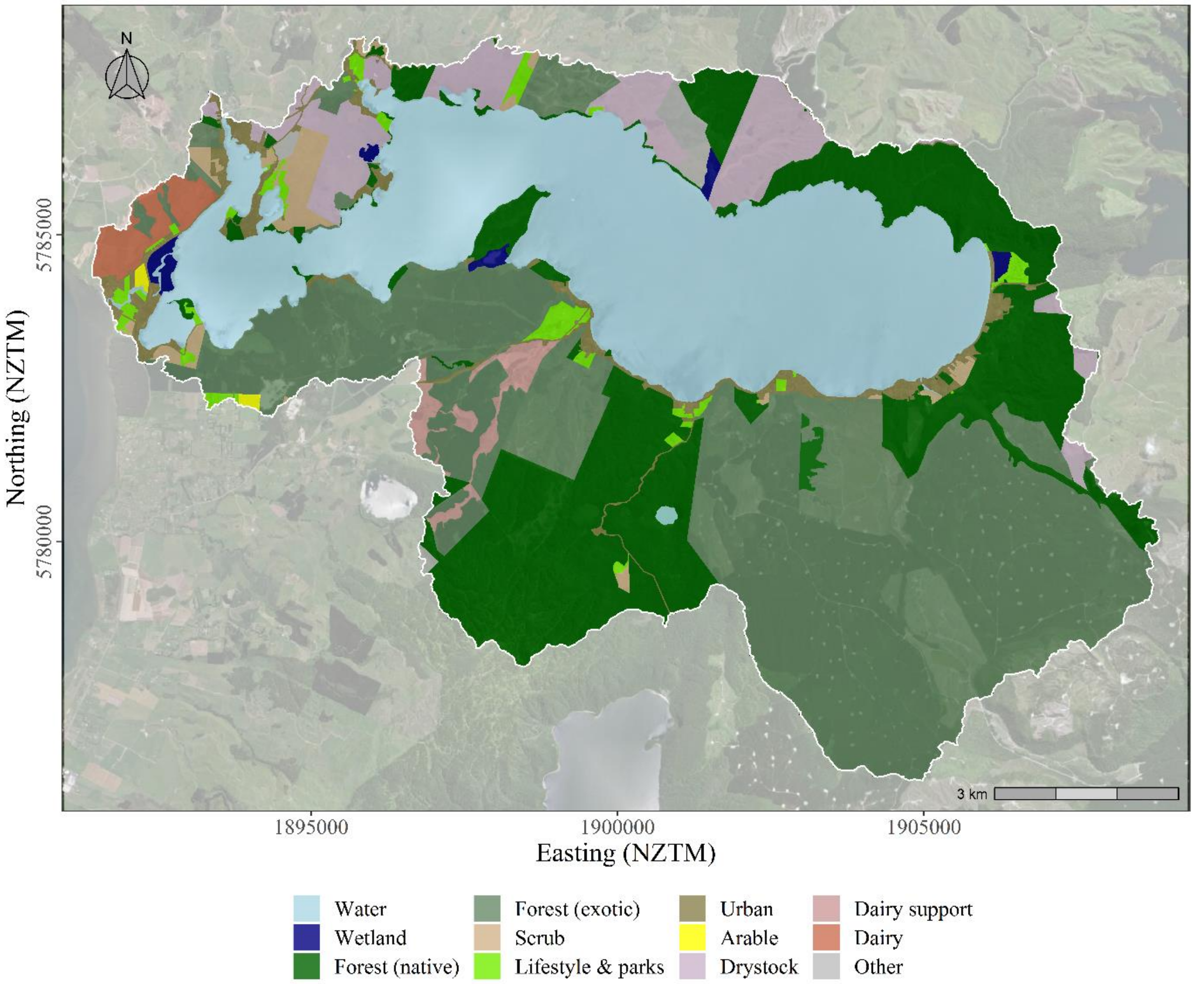


Figure 22. Map of land use (data: BoPRC) in the Rotoiti catchment.

Catchment description

Lake Rotoiti has a surface topographic catchment area of 124.8 km^2, including the lake area of 34.0 km^2 (LCDB4). The catchment is predominantly forested, with a relatively small proportion of pastoral land being fairly evenly split between dairy and dry stock (Figure 22). Communities are scattered around the lake, with the community at Okawa Bay having already been reticulated (2006), and many of the remaining households scheduled for reticulation in the coming years.

Previous load estimates

BoPRC (2009a) estimated loads to Lake Rotoiti of 364 t N y^{-1} and 29 t P y^{-1}, however, these estimates included loads form the Ohau Channel (i.e. pre-completion of the diversion wall) and as such are not comparable with the loads presented here.

Land use classes

For agricultural land, OVERSEER benchmarking in 6.2.3 was available. Land use loss rates used for non-agricultural land-use are described in section 3.2, and no adjustments to these rates were made for the catchment of Lake Rotoiti.

Geothermal inputs of nitrogen and phosphorus

Lake Rotoiti has several known geothermal inflows as well as high heat flow and hot sediments within the main basin of the lake. Nairn (1981) described a small flow from the Tikitere field of c. 20 L s^{-1} and subsurface flow from the bottom of the main basin of c. 0.3 m^3 s^{-1}. Monitoring of geothermal flows within this catchment has shown that geothermal waters here are very high in dissolved N (average c. 13 g N m^{-3}, mostly as ammonium) and relatively low in P (c. 0.1 g P m^{-3}). Reflecting this high N:P ratio, Donovan & Donovan (2003) estimated geothermal loads of 41.6 t N y^{-1} and 0.13 t P y^{-1}. At observed concentrations and estimated flow of 0.4 m^3 s^{-1}, geothermal N load could be as high as 164 t y^{-1} (c. nearly three-fold higher than N from all other sources). For the present study, we adopted relatively conservative estimates of geothermal flows and concentrations (Table 3). Nevertheless, geothermal loads were estimated to account for c. 50 % and 25 % of N and P respectively. It should be noted that the actual geothermal load is highly uncertain and may be much higher.

Table 13. Flows from geothermal springs and streams entering Lake Rotoiti (BoPRC). Gauging was relatively infrequent (n < 10 per site).

Source	NIWA 1973 - 1974 Mean (L s^{-1})	McIntosh 1993 - 1994 Mean (L s^{-1})	Bruesewitz 2009 - 2010 Mean (L s^{-1})	**Combined** Mean (L s^{-1})
Manupirua Spring	6			6
Parengarenga Stream		9	4	7
Tumoana/Ruahine		16	20	18
Otuatura		2		2
Tumoana/Ruahine		16	20	18
Wairau Bay Stream			5	5
Wharetata Bay Springs			1.5	2
Wharetata West stream			4.5	5
Total				**62**

Connected lakes

With the Ohau Channel diversion wall in place, the main basin of Lake Rotoiti no longer receives the outflow of Lake Rotorua, rather the water from Rotorua is routed directly to Rotoiti's outflow at Okere falls. However, Hamilton et al. (2009) found that a small portion (<5%) may intrude to the lake via backflow around the diversion wall's end point.

Wastewater

The population estimate used for the purpose of calculating nutrient loads from septic tanks comprised a daily equivalent of 753 permanent residents (435 households at an average occupancy of 1.73; BoPRC). The contribution of wastewater to overall load-to-lake was estimated to be 2.9% and 4.4% for N and P, respectively.

Summary

Total estimated loads to Lake Rotoiti were 109.9 t N y^{-1} and 4.09 t P y^{-1} (Table 14). Geothermal nitrogen appears to be a very important source, contributing as much as half or more of annual load. Wastewater (excluding Okawa Bay) contributes a small yet significant portion of annual load, particularly for P. It is important to note that loads to Lake Rotoiti are highly dependent on the presence or absence of the Ohau Channel diversion wall, and figures presented here exclude any input of water from Lake Rotorua. Geothermal loads appear to be highly important, but are also highly uncertain.

Key assumptions and opportunities for improving knowledge

- Quantification of total geothermal water inputs, and chemistry of geothermal water at the Crater site.
- Prevalence of gorse/broom.

Table 14. Sources of nitrogen and phosphorus to Lake Rotoiti from its catchment.

Land use	Surface catchment (ha)	Groundwater catchment (ha)	TN yield (kg ha^{-1} y^{-1})	TP yield (kg ha^{-1} y^{-1})	Yield method	Nitrogen attenuation	Phosphorus attenuation	TN load (kg y^{-1})	TP load (kg y^{-1})	Landuse (%)	TN load (%)	TP load (%)
Agriculture - crop	7.4	7.4	50.0	1.00	Estimated	0.42	0.42	215	4.3	0.1	0.2	0.1
Agriculture - dairy support	133.6	133.6	40.1	2.55	Overseer	0.42	0.42	3092	196.3	1.1	2.8	4.8
Agriculture - dry stock	624.6	624.6	17.9	1.39	Overseer	0.42	0.42	6440	501.0	5.3	5.9	12.3
Agriculture - lifestyle	70.2	70.2	30.0	2.00	Estimated	0.42	0.42	1214	81.0	0.6	1.1	2.0
Forest - exotic	4457.1	4457.1	3.0	0.15	Estimated	0.42	0.42	7714	385.7	38.0	7.0	9.4
Forest - native	2498.4	2498.4	3.7	0.12	Estimated	0.42	0.42	5290	173.0	21.3	4.8	4.2
Scrub/shrub	125.6	125.6	5.0	1.00	Estimated	0.42	0.42	362	72.5	1.1	0.3	1.8
Unknown	85.1	85.1	5.0	1.00	Estimated	0.42	0.42	245	49.1	0.7	0.2	1.2
Urban - infrastructure	244.8	244.8	5.9	0.50	Estimated	0.42	0.42	833	70.6	2.1	0.8	1.7
Urban - parks	69.2	69.2	25.0	0.14	Estimated	0.42	0.42	998	5.6	0.6	0.9	0.1
Water - lake or stream	3360.7	3360.7	6.7	0.34	Verburg (2015)			22517	1142.6	28.7	20.5	28.0
Water - wetland	45.7	45.7	0.0	0.00	Estimated	0.42	0.42	0	0.0	0.4	0.0	0.0
Gorse/broom			38.0	0.00	BoPRC	0.42	0.42	1188	0.0		1.1	0.0
Wastewater					BoPRC			1382	138.2		1.3	3.4
Connections					Observed			3186	168.0		2.9	4.1
Geothermal					Estimated			55200	1100.0		50.2	26.9
All sources								**109876**	**4088**			

Lake Rotokakahi

Rotokakahi is a privately owned lake of moderate size and depth (c. 4.4 km^2 and 32 m deep), of moderate productivity. Its water quality is classed as mesotrophic, with average surface water concentrations of 212 mg m^{-3} TN and 48.5 mg m^{-3} TP and 4.7 mg m^{-3}chl *a* for the period 2012 – 2017 (Table 1). Water quality has been highly variable in this lake, with steep increases in water column total nutrients coincident with logging activity in plantation forest adjacent to the lake shore. Rotokakahi's TN:TP ratio of approximately 4.4:1 is the lowest of all the Rotorua Te Arawa Lakes, meaning it is likely N-limited, which may favour the proliferation of cyanobacteria at certain times.

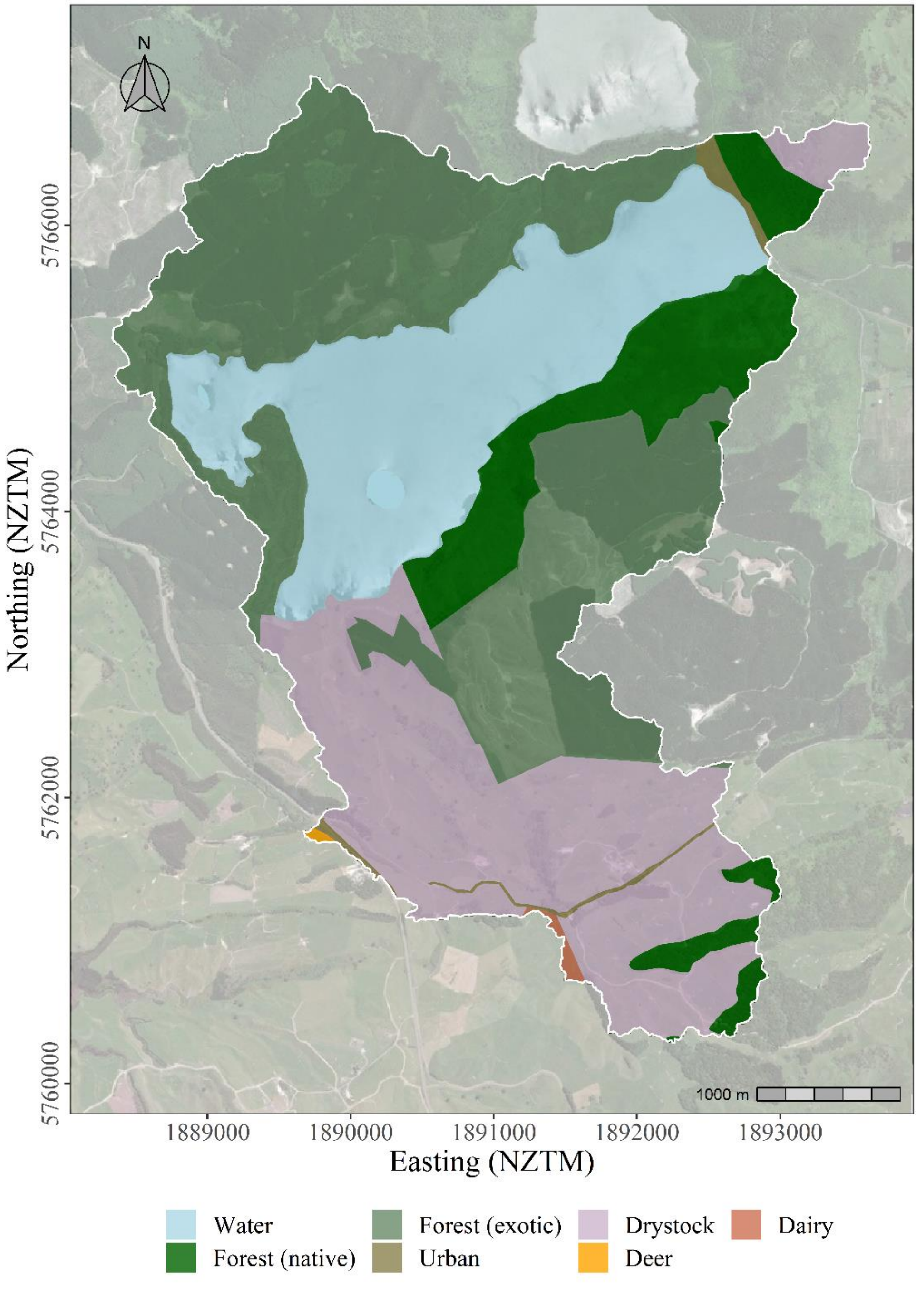


Figure 23. Map of land use (data: BoPRC) in the Rotokakahi catchment.

Catchment description

Lake Rotokakahi has a surface topographical catchment area of 19.7 km^2, including the lake area of 4.4 km^2 (LCDB4). Land use in the catchment is a simple mix of indigenous forest, exotic forestry and pastoral land (Figure 22). There are no built-up areas and all pastoral land is dry stock.

Previous load estimates

Hamilton et al. (2006) estimated loads to Lake Rotokakahi of 7.39 t N y^{-1} and 1.12 t P y^{-1} using the export coefficient method. Jones et al. (2014) calculated loads of N and P as part of a modelling study of Lake Rotokakahi, estimating 9.11 t N y^{-1} and 1.18 t P y^{-1}.

Land use classes

OVERSEER benchmarking of agricultural land use was available in version 6.2.3 for only a very small portion of the agricultural (Dry Stock) land in the Rotokakahi catchment – as such export coefficients here should be considered to have a wider margin of uncertainty than for other catchments. For non-agricultural land uses, loss rates used are described in section 3.2 and no adjustments were made for the catchment of Lake Rotokakahi.

Geothermal inputs of nitrogen and phosphorus

Although inflow to Lake Rotokakahi is dominated by subsurface groundwater inputs, the lake is not geothermally influenced (Nairn 1981).

Connected lakes

White et al. (2016) shows that Rotokakahi receives the outflow of Lake Tikitapu by subsurface flow.

Wastewater

There are no residential or other wastewater systems in the Rotokakahi catchment.

Summary

Total estimated loads to Lake Rotokakahi were 9.8 t N y^{-1} and 0.86 t P y^{-1} (Table 15). Pastoral sources represented the majority of the P load, however, the proximity of harvested forest to the lake shores over the period 2009 – 2014 may have resulted in higher P loads from forestry than have been estimated here.

Key assumptions and opportunities for improving knowledge

- Limited on-lake monitoring.
- Prevalence of gorse/broom.

Table 15. Sources of nitrogen and phosphorus to Lake Rotokakahi from its catchment.

Land use	Surface catchment (ha)	Groundwater catchment (ha)	TN yield (kg ha^{-1} y^{-1})	TP yield (kg ha^{-1} y^{-1})	Yield method	Nitrogen attenuation	Phosphorus attenuation	TN load (kg y^{-1})	TP load (kg y^{-1})	Landuse (%)	TN load (%)	TP load (%)
Agriculture - dairy	4.4	4.4	70.0	4.50	Estimated	0.40	0.40	184	11.8	0.2	1.9	1.4
Agriculture - dry stock	483.0	483.0	13.2	2.03	Overseer	0.40	0.40	3797	584.1	25.1	38.6	68.1
Forest - exotic	743.9	743.9	3.0	0.15	Estimated	0.40	0.40	1332	66.6	38.7	13.5	7.8
Forest - native	229.0	229.0	3.7	0.12	Estimated	0.40	0.40	502	16.4	11.9	5.1	1.9
Urban - infrastructure	17.0	17.0	5.9	0.50	Estimated	0.40	0.40	60	5.1	0.9	0.6	0.6
Water - lake or stream	444.7	444.7	6.7	0.34	Verburg (2015)			2980	151.2	23.1	30.3	17.6
Gorse/broom			38.0	0.00	BoPRC	0.40	0.40	279	0.0		2.8	0.0
Connections					Observed			713	22.2		7.2	2.6
All sources								**9847**	**857**			

Lake Rotoma

Rotoma is a deep monomictic lake (maximum depth c. 83 m). It has the highest water quality of all the Rotorua Te Arawa Lakes, with average surface water concentrations of 102.7 mg TN m^{-3}, 6.43 mg TP m^{-3}, and 1.14 mg chl *a* m^{-3} for the period 2012 – 2017 (Table 1). Rotoma's TN:TP ratio of approximately 16:1 is high among the Rotorua Te Arawa Lakes, and the lake is likely P-limited at times.

Catchment description

Lake Rotoma has a surface topographical catchment area of 27.9 km^2, including the lake area of 11.2 km^2 (LCDB4). The ratio of land to lake surface area is very low, and land use is predominantly forest (mostly indigenous), although there is a substantial area of low intensity dry stock land in the eastern catchment (Figure 24). Small lagoons near the eastern shore of the lake likely intercept some proportion of nutrient loads from the (predominantly dry stock) land on the eastern side of the catchment. Further, the exact catchment boundaries to the northeast are uncertain. There are two springs that drain to the north and arise outside the catchment boundary, and there is a 100 ha basin within the Rotoma catchment that has no surface outlet (McIntosh pers. comm.). The lakeside community was not connected to a reticulated wastewater system as at 2014, although reticulation is proposed for the near future.

Previous load estimates

BoPRC (2009b) estimated loads to Lake Rotoma of 18.1 t N y^{-1} and 0.74 t P y^{-1}.

Land use classes

Results from OVERSEER version 6.2.3 were available for estimating nutrient losses from agricultural land. For other land uses, loss rates are described in section 3.2, and no adjustments to these rates were made for the catchment of Lake Rotoma.

Geothermal inputs of nitrogen and phosphorus

An early study of nutrient loads to Lake Rotoma (Donovan and Donovan 1991) noted that the Otei Hot Spring flows to the lake, and described geothermal flows ranging from 11 to 53 L s^{-1}. Nairn (1981) described chloride concentrations in the lake water of > 35 mg Cl L^{-1}, indicating a moderate geothermal influence and subsurface geothermal flows in addition to the Otei Hot Spring. However, Donovan & Donovan (2003) concluded that geothermal nutrient load to the lake was negligible. Nevertheless, here we assigned a small geothermal contribution for Lake Rotoma (Table 3).

Connected lakes

Lake Rotoma does not receive water outflowing from any other lakes.

Wastewater

The population estimate used for the purpose of calculating nutrient loads from septic tanks comprised a daily equivalent of 386 permanent residents (336 households at an annual average occupancy of 1.15 persons; RLC). The contribution of wastewater to overall load-to-lake is estimated to be 9 and 12 % for N and P respectively – the highest percentage contribution for any of the Rotorua Lakes.

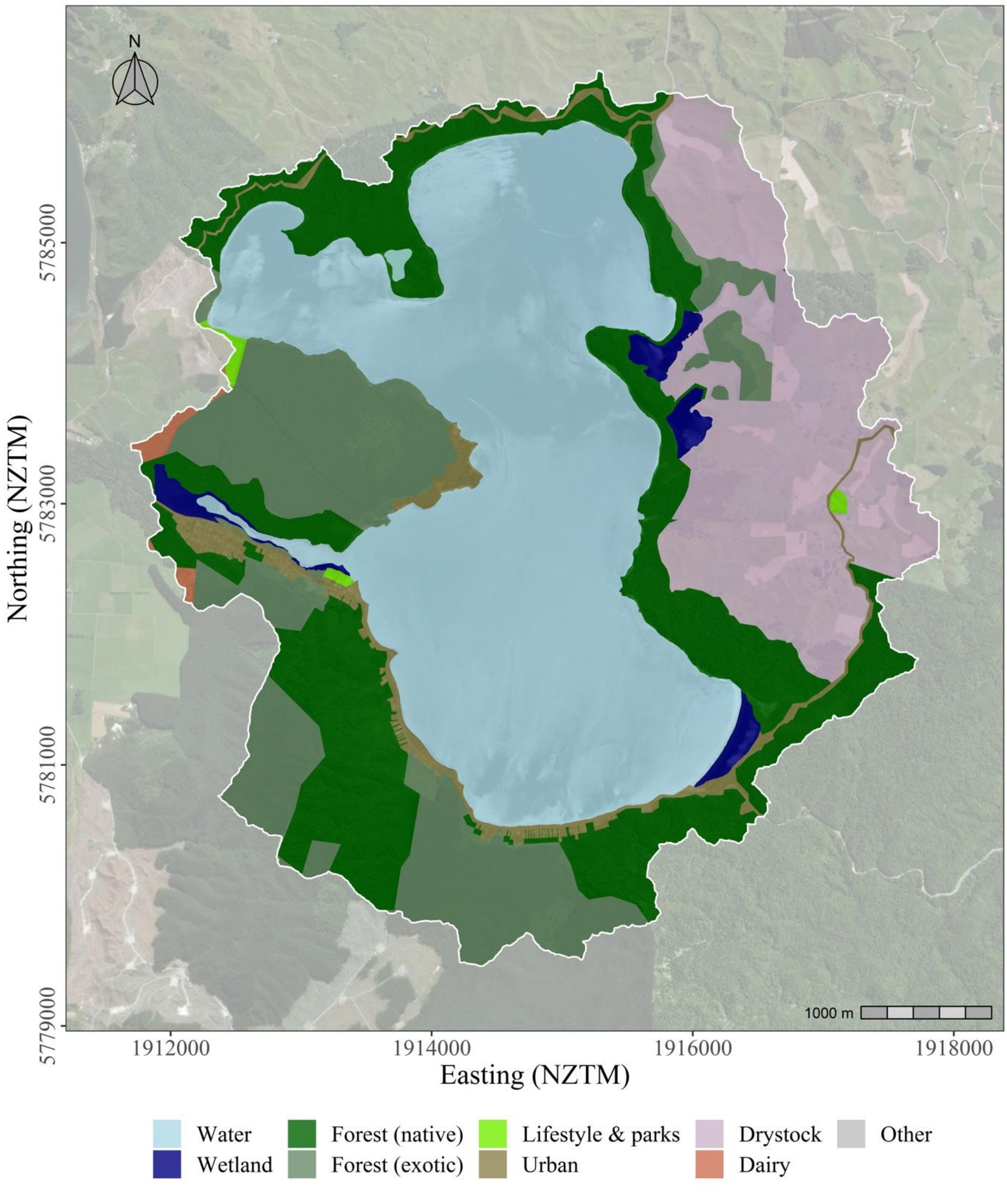


Figure 24. Map of land use (data: BoPRC) in the Rotoma catchment.

Summary

Total estimated loads to Lake Rotoma are 15.3 t N y^{-1} and 2.07 t P y^{-1} (Key assumptions ***and opportunities for improving knowledge***

- Possible attenuation at lakeside lagoons.
- Little is known about submerged flow paths and rates.
- More accurate quantification of geothermal inputs.

Table 16), slightly lower for N and much higher for P compared with previous estimates. The combination of a low ratio of land to water volume, likely results in the very high water quality at Rotoma. Wastewater appears a potentially strong contributor to overall load, and the proposed reticulation should go some way towards protecting water quality of the lake into the future. The pastoral land is estimated to contribute substantially to N, and particularly P loads, however, uncertainty over groundwater flows and catchment boundaries, and the interception of surface flows by the lake shore lagoons, may mean that the loads presented here are a slight overestimate.

Key assumptions and opportunities for improving knowledge

- Possible attenuation at lakeside lagoons.
- Little is known about submerged flow paths and rates.
- More accurate quantification of geothermal inputs.

Table 16. Sources of nitrogen and phosphorus to Lake Rotoma from its catchment.

Land use	Surface catchment (ha)	Groundwater catchment (ha)	TN yield (kg ha^{-1} y^{-1})	TP yield (kg ha^{-1} y^{-1})	Yield method	Nitrogen attenuation	Phosphorus attenuation	TN load (kg y^{-1})	TP load (kg y^{-1})	Landuse (%)	TN load (%)	TP load (%)
Agriculture - dairy	11.0	11.0	78.8	7.94	Overseer	0.41	0.41	514	51.8	0.4	3.4	2.5
Agriculture - dry stock	466.7	466.7	10.0	4.46	Overseer	0.41	0.41	2777	1238.9	16.6	18.1	59.8
Agriculture - lifestyle	6.4	6.4	30.0	2.00	Estimated	0.41	0.41	114	7.6	0.2	0.7	0.4
Forest - exotic	475.9	475.9	3.0	0.15	Estimated	0.41	0.41	849	42.5	16.9	5.5	2.0
Forest - native	599.9	599.9	3.7	0.12	Estimated	0.41	0.41	1310	42.8	21.3	8.5	2.1
Unknown	3.1	3.1	5.0	1.00	Estimated	0.41	0.41	9	1.9	0.1	0.1	0.1
Urban - infrastructure	91.5	91.5	5.9	0.50	Estimated	0.41	0.41	321	27.2	3.3	2.1	1.3
Urban - parks	1.8	1.8	25.0	0.14	Estimated	0.41	0.41	27	0.2	0.1	0.2	0.0
Water - lake or stream	1111.8	1111.8	6.7	0.34	Verburg (2015)			7449	378.0	39.5	48.6	18.2
Water - wetland	44.7	44.7	0.0	0.00	Estimated	0.41	0.41	0	0.0	1.6	0.0	0.0
Gorse/broom			38.0	0.00	BoPRC	0.41	0.41	215	0.0		1.4	0.0
Wastewater					BoPRC			1417	141.7		9.2	6.8
Geothermal					Estimated			330	140.0		2.2	6.8
All sources								**15332**	**2073**			

Lake Rotomahana

Rotomahana is a deep lake (maximum depth c. 112 m) of mesotrophic water quality, with average surface water concentrations of 192 mg TN m^{-3}, 44 mg TP m^{-3}, and 4.5 mg chl *a* m^{-3} for the period 2009 – 2014 (Table 1). Rotomahana's TN:TP ratio of approximately 4.4:1 is very low among the Rotorua Te Arawa Lakes. The lake is strongly geothermally influenced, as evidenced by annual minimum water temperatures which are several degrees warmer than all other lakes considered in this study. Geothermal waters in this area have been found to be very high in P, which may contribute to the low observed TN:TP ratio.

Catchment description

Lake Rotomahana has a surface topographical catchment area of 83.0 km^2, including the lake area of 9.1 km^2 (LCDB4). Lake Rotomahana's catchment is predominantly forested with substantial areas of manuka/kanuka and exotic forestry. There are also large areas of dry stock pastoral land (Figure 25). The outflow drains to Lake Tarawera at the north.

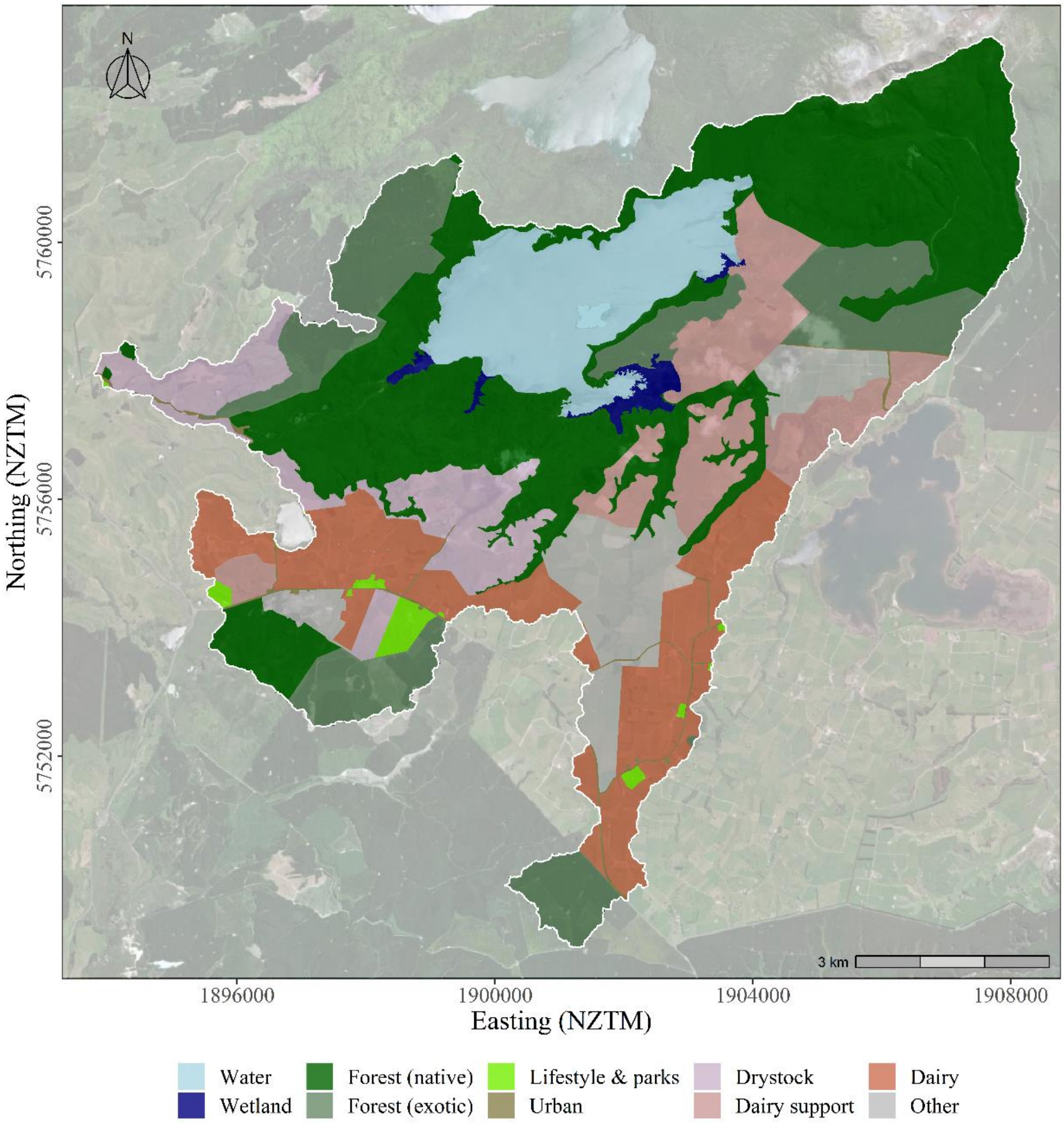


Figure 25. Map of land use (data: BoPRC) in the Rotomahana catchment.

Previous load estimates

As part of a nutrient budget for Lake Tarawera, Hamilton et al. (2006) estimated loads to Lake Rotomahana of 38.9 t N y^{-1} and 5.4 t P y^{-1}. This estimate did not consider geothermal sources of N and P to the lake.

Land use classes

Results from OVERSEER version 6.2.3 were available for estimating nutrient losses from agricultural land. For other land uses, loss rates are described in section 3.2, and no adjustments to these rates were made for the catchment of Lake Rotomahana.

Geothermal inputs of nitrogen and phosphorus

Lake Rotomahana is substantially geothermally influenced, with chloride concentrations > 250 mg Cl L^{-1} reported by McColl (1975). Geothermal influence at Lake Rotomahana is highly visible, and Nairn (1981) described large surface hydrothermal inflows from the Waimangu Valley and western lake shore. Upwellings of hot water in the lake suggest major submerged hot springs 10 to 20 m offshore (Gillon 2009). Total heat flow has not been estimated, although relatively warmer winter water temperatures and visual comparison with other measured areas show that Rotomahana has the largest geothermal inputs of any Te Arawa lakes (Timperly & Vigor-Brown 1986). The actual volume of geothermal water has not been estimated and as such there is high uncertainty in the geothermal load. Nevertheless it is likely to be an important component of the overall load-to-lake. For the present study we assumed a similar chemistry but higher load to neighbouring Lake Tarawera. It should be noted that these loads are highly uncertain.

Connected lakes

Lake Rotomahana receives outflow water from Lake Okaro. Part of Lake Rerewhakaaitu's catchment lies within the greater Tarawera catchment, therefore we assumed that 50% of surface and sub-surface outflow reaches Lake Rotomahana, as in Hamilton et al. (2006).

Wastewater

An approximate population estimate of 20 permanent residents equivalents was used for the purpose of calculating nutrient loads from septic tanks. The contribution of wastewater to overall load-to-lake is estimated to be negligible for both N and P.

Other features

Recent work at Rotomahana has focussed on the retiring and replanting of lake margins. Any effects on nutrient loads to the lake have not been quantified and as such are not considered for the present nutrient budget.

Summary

Total estimated loads to Lake Rotomahana were 95.6 t N y^{-1} and 20.7 t P y^{-1} (Key assumptions ***and opportunities for improving knowledge***

- Quantification/estimation of total geothermal inputs.
- Effect of 'Rotomahana mud' geology on P loss from landscape.
- Prevalence of gorse/broom.

Table 17). These loads are substantially higher than the estimates of Hamilton et al. (2006), due in part to the inclusion of (highly uncertain) geothermal loads to the lake. The high concentration of P in geothermal waters in this area means that quantification of geothermal loads to Lake Rotomahana is potentially very important to the management of its water quality.

Key assumptions and opportunities for improving knowledge

- Quantification/estimation of total geothermal inputs.
- Effect of 'Rotomahana mud' geology on P loss from landscape.
- Prevalence of gorse/broom.

Table 17. Sources of nitrogen and phosphorus to Lake Rotomahana from its catchment.

Land use	Surface catchment (ha)	Groundwater catchment (ha)	TN yield (kg ha^{-1} y^{-1})	TP yield (kg ha^{-1} y^{-1})	Yield method	Nitrogen attenuation	Phosphorus attenuation	TN load (kg y^{-1})	TP load (kg y^{-1})	Landuse (%)	TN load (%)	TP load (%)
Agriculture - dairy	1113.1	1113.1	45.8	4.96	Overseer	0.42	0.42	29784	3223.9	13.3	31.2	15.6
Agriculture - dairy support	822.3	822.3	52.0	7.66	Overseer	0.42	0.42	24951	3677.1	9.8	26.1	17.8
Agriculture - dry stock	599.8	599.8	14.9	1.73	Overseer	0.42	0.42	5208	606.1	7.2	5.4	2.9
Agriculture - lifestyle	76.0	76.0	30.0	2.00	Estimated	0.42	0.42	1331	88.7	0.9	1.4	0.4
Forest - exotic	1237.4	1237.4	3.0	0.15	Estimated	0.42	0.42	2167	108.3	14.8	2.3	0.5
Forest - native	2842.4	2842.4	3.7	0.12	Estimated	0.42	0.42	6089	199.1	33.9	6.4	1.0
Unknown	660.0	660.0	5.0	1.00	Estimated	0.42	0.42	1926	385.2	7.9	2.0	1.9
Urban - infrastructure	60.7	60.7	5.9	0.50	Estimated	0.42	0.42	209	17.7	0.7	0.2	0.1
Urban - parks	0.6	0.6	25.0	0.14	Estimated	0.42	0.42	8	0.0	0.0	0.0	0.0
Water - lake or stream	880.7	880.7	6.7	0.34	Verburg (2015)			5900	299.4	10.5	6.2	1.4
Water - wetland	89.1	89.1	0.0	0.00	Estimated	0.42	0.42	1	0.1	1.1	0.0	0.0
Gorse/broom			38.0	0.00	BoPRC	0.42	0.42	608	0.0		0.6	0.0
Wastewater					BoPRC			73	7.3		0.1	0.0
Connections					Observed			3884	162.9		4.1	0.8
Geothermal					Estimated			13440	11930.0		14.1	57.6
All sources								**95579**	**20706**			

Lake Rotorua

Rotorua is a relatively shallow polymictic lake (mean depth c. 10 m), of high productivity, but where water quality has improved dramatically over the last few decades. As at Rotoiti, the lake experienced severe blooms of the invasive cyanobacteria *Anabaena planktonica*, as well as *Microcystis* sp., in the early 2000s. Its water quality is classed as eutrophic, with average surface water concentrations of 324 mg TN m^{-3}, 19.0 mg TP m^{-3}, and 10.9 mg chl *a* m^{-3} for the period 2012 – 2017 (Table 1). Rotorua's TN:TP ratio of approximately 17:1 is relatively high, possibly a result of alum dosing of two of its inflows (Ozkundakci et al. 2014, Hamilton et al. 2015). Although there is evidence the lake is presently strongly P-limited, co-limitation has also been described in the lake (e.g. Abell et al. 2010, Smith et al. 2016).

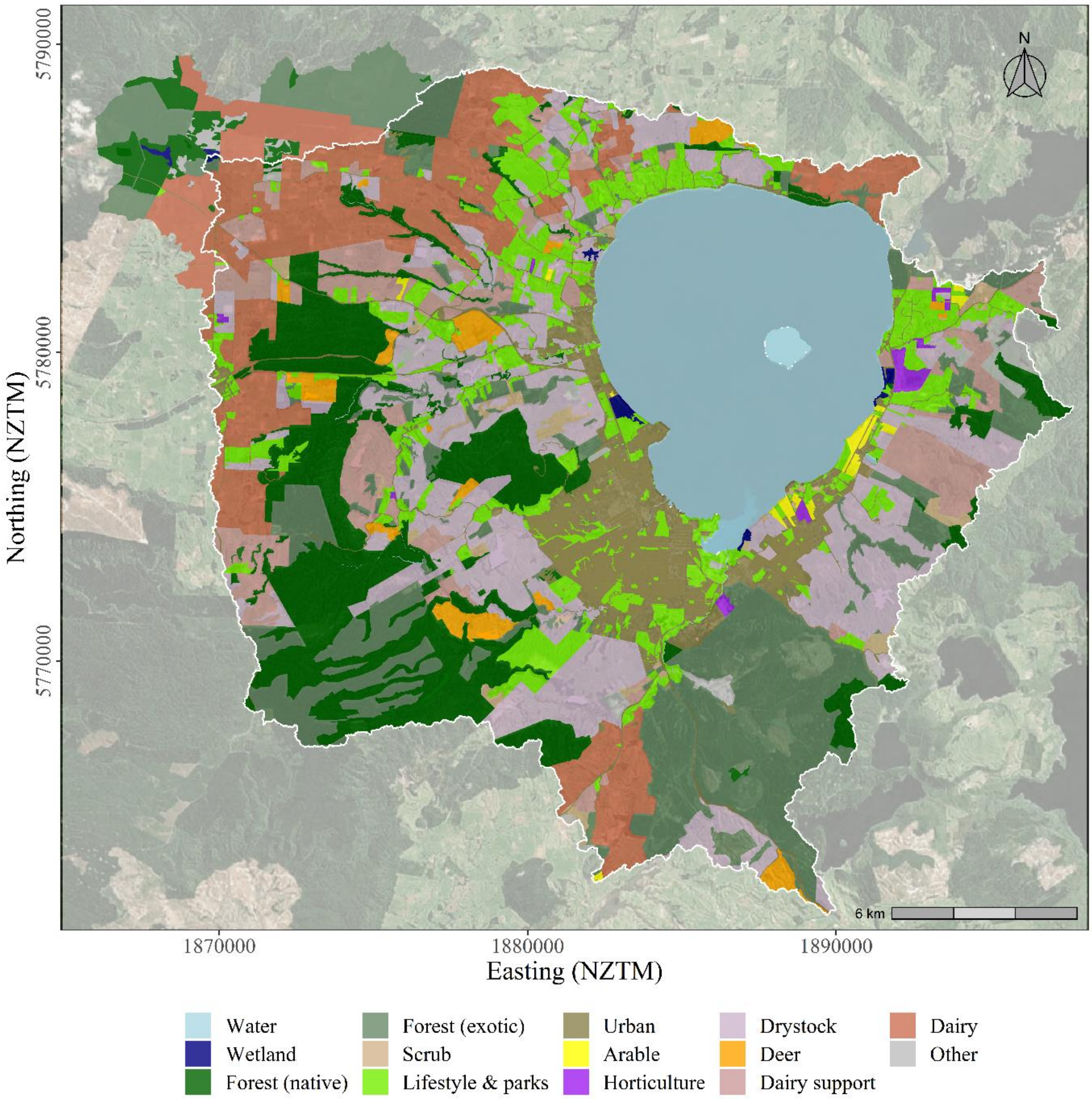


Figure 26. Map of land use (data: BoPRC) in the Rotorua surface catchment.

Catchment description

Lake Rotorua has a surface topographical catchment area of 538.2 km^2, including the lake area of 80.8 km^2 (LCDB4). Much of the catchment is forested (roughly evenly split between indigenous and exotic), and a similar amount is pastoral, including substantial dairy and dairy support (Figure A1g). The city of Rotorua lies entirely within the lake catchment, home to some 65,000 residents. Wastewater from the resident population is treated at the Rotorua Wastewater Treatment Plant and has been disposed of by spray-irrigation to the Whakarewarewa forest in the Puarenga catchment since 1991. The catchment boundary defined here includes an area outside of the surface topographical catchment that is presumed to contribute groundwater to Lake Rotorua (White, pers. comm.).

Previous load estimates

Water quality of Lake Rotorua has been the focus of a substantial body of research, and many estimates of catchment loads to the lake have been made by a variety of methods, summarised in Table 18. Rutherford et al. (1989) presented a summary of catchment nutrient budgets that used in stream measurements and estimates of sewage loads and atmospheric deposition. Rutherford (2011) described nutrient budgets for various time periods, used as *input* to the ROTAN model and based on pastoral loss rates from Overseer® v5.4. Burger et al. (2007) and Hamilton et al. (2015) estimated total load to the lake in the process of establishing lake models. For Burger et al. (2007) both N and P loads were derived from linear interpolation of monthly instream measurements. Nitrogen load estimates presented in Hamilton (2015) were derived from ROTAN model *output*. McBride et al. (2019) provides a detailed summary of previous estimates of loading to Lake Rotoura, as well as long-term annual load estimates.

Table 18. Previous estimates of catchment total nutrient loads to Lake Rotorua. Internal loading has been excluded from total loads presented in the final two columns. Estimates of Fish (1975) are not shown because only dissolved nutrients were measured. Table shows whether each study accounted for atmospheric deposition (Yes (Y) or No (N))

Study	Source	Period	Atmospheric deposition (Y/N)	Geothermal (Y/N)	Wastewater nitrogen (t N y^{-1})	Wastewater phosphorus (t P y^{-1})	Total N load (t N y^{-1})	Total P load (t P y^{-1})
Estimated from Hoare 1987	Rutherford et al. (1989)	1965	Y	Streams only	70	5	475	39
Hoare (1987)	Rutherford et al. (1989)	1976-77	Y	Streams only	146	7.8	558	42
Estimated from Hoare 1987	Rutherford et al. (1989)	1981-82	Y	Streams only	149	20.6	554	55
Estimated from Hoare 1987	Rutherford et al. (1989)	1984-85	Y	Streams only	160	33.8	565	68
Burger et al. (2008)		2001-04	N	Y	ns	ns	502	33
BoPRC (2009)		2009	ns	ns	ns	ns	556	39
Rutherford (2003)		2002	Y	Y	32	1	692	35
Rutherford et al. (2011)		2000-10	N	Y	ns	ns	520-750*	ns
Hamilton et al. (2015)		2001-12	Y	Y	30	<2	661*	33
Abell et al. (2015)		2005-15	Y	Y	30	1.4	629	46
McBride et al. (2019)		2010-15	Y	Y	32	1.6	640	54.5

*Nitrogen load estimate from ROTAN for Rutherford et al. (2011) and Hamilton et al. (2015). ns = not specified.

Land use classes

Results from OVERSEER version 6.2.3 were available for estimating nutrient losses from agricultural land. For other land uses, loss rates are described in section 3.2, and no adjustments to these rates were made for the catchment of Lake Rotorua.

Attenuation

Attenuation has been characterised for nitrogen at Rotorua through catchment modelling with ROTAN (Rutherford 2016). Estimation of attenuation by comparison of root zone nutrient loads and observed loads at the lake is confounded by long time-lags in transit of nutrients form the landscape to the lake via large deep groundwater aquifers. As such, here we set attenuation parameters for nitrogen to approximate the 'steady-state' (c. year 2100) nitrogen loads simulated using the ROTAN model (c. 700 t N y^{-1} excluding atmospheric deposition. Presently observed loads (see Table 18) could be matched by altering the attenuation coefficients. Attenuation factors for P were guided by information presented in Tempero et al. (2015) and McBride et al. (2019).

Geothermal inputs of nitrogen and phosphorus

Lake Rotorua is considered moderately geothermally influenced, with McColl (1975) observing chloride concentrations of c. 25 mg Cl L^{-1}. The Whakarewarewa Field has upflow regions in the Sulphur Bay and Polynesian Pools area, Kuirau Park and Ohinemutu. Ngapuna may be a separate field with upflow near the mouth of the Puarenga Stream. The Tikitere field discharges via the Waiohewa Stream inflow to the lake. Donovan & Donovan (2003) estimated geothermal loads of 67.3 t N y^{-1} and 5.6 t P y^{-1}. However, these loads were largely derived from Waiohewa Stream, and recent monitoring data suggest that Waiohewa loads are lower. Available flow and nutrient concentration data from BoPRC (unpubl.) were used to estimate geothermal loads for the present study (Table 3).

Connected lakes

Lake Rotokawau lies entirely within the Waiohewa subcatchment of Rotorua, and as such its entire outflow was assumed to flow to Rotorua. Unfortunately the water quality of Rotokawau is not well characterised, so only coarse estimates could be made of outgoing N and P loads.

Wastewater

Post-treatment wastewater loads are measured intensively and well quantified by the Rotorua Wastewater Treatment Plant (WWTP). Annual average load-to-lake for N and P was obtained from Rotorua WWTP monitoring data from the Waipa Stream, downstream of the Whakarewarewa land treatment system (LTS). Annual average baseflow-corrected loads for 2010 to 2015 were 32.0 t N y^{-1} and 1.6 t P y^{-1}. An additional load from septic tanks on unreticulated properties equivalent to 50 full time residents was also included.

Summary

Total estimated loads to Lake Rotorua were 721.5 t N y^{-1} and 56.76 t P y^{-1} (Key assumptions ***and opportunities for improving knowledge***

- Change over time to nutrient losses from the Land Treatment System.
- Attenuation processes in the relatively large catchment.

Table 19), within the range of previous estimates (Table 18). The estimate for phosphorus was higher than some previous estimates, which may be explained by high loads during stormflows (Abell 2013) not being captured by relatively infrequent stream sampling. According to the present study, pastoral land accounts for c. 65% of N load and more than 30 % of P load. Lake Rotorua has been set a catchment nitrogen load target of 435 t N y^{-1}, roughly commensurate with catchment loads prior to the earliest measurements summarised in Rutherford et al. (1989), i.e., prior to substantial degradation of water quality in the lake. Estimates presented in Key assumptions ***and opportunities for improving knowledge***

- Change over time to nutrient losses from the Land Treatment System.
- Attenuation processes in the relatively large catchment.

Table 19 could be used to test various combinations of land use change and/or mitigation in order to create scenarios which might meet the nitrogen target. It should be noted, that the loads estimated here, are the equilibrium (long-term, steady-state) loads, and are not representative of present-day loads, which are lower due to very long residence times in some groundwater aquifers–see Morgenstern et al. (2015), Rutherford & Palliser (2019) and McBride et al. (2019) for further details.

Key assumptions and opportunities for improving knowledge

- Change over time to nutrient losses from the Land Treatment System.
- Attenuation processes in the relatively large catchment.

Table 19. Sources of nitrogen and phosphorus to Lake Rotorua from its catchment.

Land use	Surface catchment (ha)	Groundwater catchment (ha)	TN yield (kg ha^{-1} y^{-1})	TP yield (kg ha^{-1} y^{-1})	Yield method	Nitrogen attenuation	Phosphorus attenuation	TN load (kg y^{-1})	TP load (kg y^{-1})	Landuse (%)	TN load (%)	TP load (%)
Agriculture - crop	104.6	104.6	50.0	1.00	Estimated	0.50	0.50	2614	52.3	0.2	0.4	0.1
Agriculture - dairy	5445.3	6696.9	94.6	3.12	Overseer	0.50	0.50	287069	9457.5	11.4	39.8	16.7
Agriculture - dairy support	2709.4	2716.2	55.7	1.81	Overseer	0.50	0.50	75532	2460.5	5.7	10.5	4.3
Agriculture - dry stock	7645.8	7645.8	25.7	2.01	Overseer	0.50	0.50	98241	7686.5	16.0	13.6	13.5
Agriculture - horticulture	98.9	98.9	88.4	1.01	Overseer	0.50	0.50	4370	50.0	0.2	0.6	0.1
Agriculture - lifestyle	3660.8	3668.2	30.0	2.00	Estimated	0.50	0.50	54967	3664.5	7.7	7.6	6.5
Forest - exotic	7496.8	8963.8	3.0	0.15	Estimated	0.50	0.50	12345	617.3	15.7	1.7	1.1
Forest - native	6811.0	7426.0	3.7	0.12	Estimated	0.50	0.50	13062	427.1	14.2	1.8	0.8
Scrub/shrub	516.3	516.8	5.0	1.00	Estimated	0.50	0.50	1291	258.3	1.1	0.2	0.5
Unknown	501.4	628.2	5.0	1.00	Estimated	0.50	0.50	1412	282.4	1.0	0.2	0.5
Urban - infrastructure	3750.8	3764.2	5.9	0.50	Estimated	0.50	0.50	11085	939.4	7.8	1.5	1.7
Urban - parks	774.2	774.2	25.0	0.14	Estimated	0.50	0.50	9677	54.2	1.6	1.3	0.1
Water - lake or stream	8211.6	8211.6	6.7	0.34	Verburg (2015)			55018	2791.9	17.2	7.6	4.9
Water - wetland	70.9	99.1	0.0	0.00	Estimated	0.50	0.50	0	0.0	0.1	0.0	0.0
Gorse/broom			38.0	0.00	BoPRC	0.50	0.50	7019	0.2		1.0	0.0
Wastewater					BoPRC			32184	1618.4		4.5	2.9
Connections					Observed			341			0.0	
Geothermal					Estimated			55200	4400.0		7.7	7.8
Geologic					Tempero et al (2015)			0	22000.0		0.0	38.8
All sources								**721427**	**56761**			

Lake Tarawera

Tarawera is a deep lake (maximum depth c. 87 m) of fairly low productivity, however, proliferations of cyanobacteria sometimes occur during summer. Nevertheless, its water quality is classed as oligotrophic, with average surface water concentrations of 94.0 mg TN m^{-3}, 8.9 mg TP m^{-3} (data: NIWA, NRWQN) and 1.9 mg chl *a* m^{-3} (data: BoPRC) for the period 2012 – 2017 (Table 1). Tarawera's TN:TP ratio of approximately 10.5:1 is moderate among the Rotorua Te Arawa Lakes.

Catchment description

Lake Tarawera has a surface topographical catchment area of 143.4 km^2, including the lake area of 41.5 km^2 (LCDB4). Much of the catchment is relatively unaltered, with indigenous hardwoods, forest, and manuka/kanuka accounting for over half of all land use (Figure 27). Approximately 1800 ha of pastoral land lies within the western catchment, and geothermal waters (both surface inflows and sub-surface springs) influence the lake from the south. Tarawera's lakeside community is not yet connected to a reticulated wastewater system.

Lake Tarawera receives outflowing water from several other Rotorua Te Arawa Lakes, thus it has an 'inner' catchment (described above), and 'greater' catchment which includes the catchments of seven additional lakes (Figure 10). Lakes Rotokakahi and Okareka flow to Tarawera via Te Wairoa and Waitangi Streams, respectively. Lakes Tikitapu, Okataina and Rotomahana are connected to Tarawera by sub-surface flows (although a surface 'siphon' operates intermittently between Rotomahana and Tarawera). Tarawera receives water indirectly from the catchments of Lakes Okaro and Rerewhakaaitu, which both flow to Lake Rotomahana.

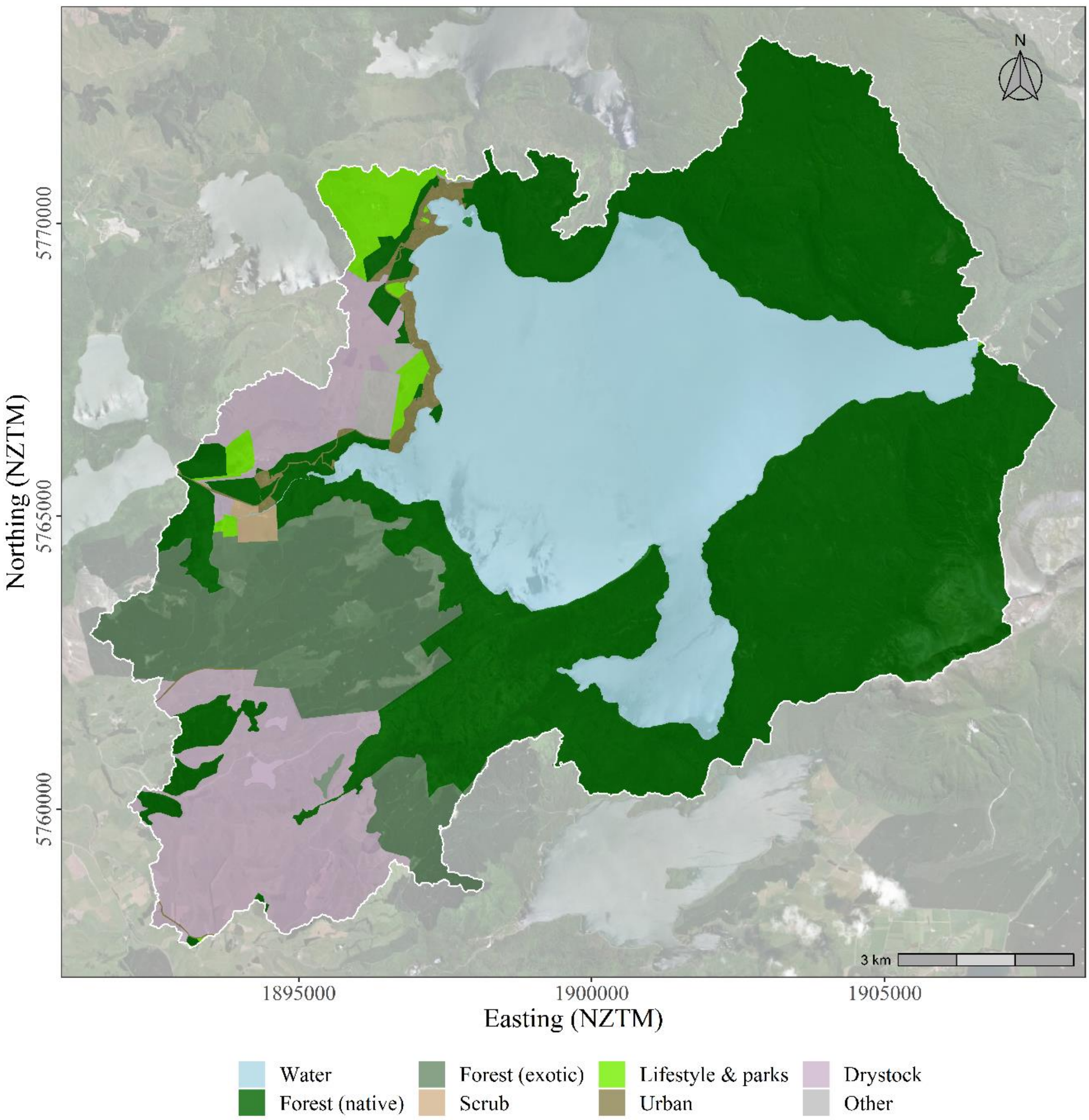


Figure 27. Map of land use (data: BoPRC) in the Tarawera catchment.

Previous load estimates

The Lake Tarawera Action Plan (BoPRC 2015) estimated annual loads for the greater Tarawera catchment of 94.85 t N y^{-1} and 11.39 t P y^{-1}. Hamilton et al. (2006) estimated annual loads from the greater Tarawera catchment of 84.6 t N y^{-1} and 10.41 t P y^{-1} based on export coefficients (excluding geothermal sources), and 96.2 t N y^{-1} and 12.7 t P y^{-1} based on stream sampling (excluding lake-bed geothermal inputs). McIntosh (2012b) estimated loads for land use in the inner catchment only, of 67.7 t N y^{-1} and 5.6 t P y^{-1}. Donovan and Donovan (2003) estimated loads of 91.4 t N y^{-1} and 17.53 t P y^{-1}, including geothermal P load of 12 t P y^{-1}. But these estimates must be reconciled at a lower end with the mean TP concentration (8.9 mg m^{-3}) and observed outflow of 6.7 m^3 s^{-1} which implies an output of P from the lake of as little as 1.9 t P y^{-1}.

Land use classes

Results from OVERSEER version 6.2.3 were available for estimating nutrient losses from agricultural land. For other land uses, loss rates are described in section 3.2, and no adjustments to these rates were made for the catchment of Lake Tarawera.

Geothermal inputs of nitrogen and phosphorus

White and Cooper (1991) estimated in a desktop study that the contribution of geothermal sources of N and P to Lake Tarawera as 27.3 t N y^{-1} and between 4.0 and 20.1 t P y^{-1}. A study by the Department of Chemistry at the University of Waikato in 2004 using sodium concentrations to infer the contribution of water sources concluded that 5 to 10% of the hydraulic load was derived from geothermal sources. Donovan & Donovan (2003) estimated a geothermal load to Tarawera of 12 t P y^{-1} and gave a possible range of geothermal P load of between 4 and 20 t P y^{-1}, however only specifically identified four inflow sources with a combined estimated flow of 0.4 m^3 s^{-1} with stated loads of 0.92 t P y^{-1} and 0.83 t N y^{-1}. Monitoring of Tarawera inflows by Terry Beckett and UoW 2007 to 2014 (n = 17 samples) found very high concentrations of P in these geothermal waters, with average concentrations in the hotwater beach geothermal inflow of c. 0.4 g m^{-3} for both N and P.

Connected lakes

Nutrient loads from lakes within the greater Tarawera catchment were estimated by multiplying the outflow of these lakes, as calculated by the model of Woods (2006), with the average observed surface water (<10 m) concentrations of TN and TP for the period 2012 to 2017 (BoPRC unpubl. data). Loads from Lakes Rerewhakaaitu and Okaro were not included because they are connected to Tarawera via Lake Rotomahana. The total contribution from the five directly connected lakes was estimated to be 23.2 t N y^{-1} and 4.78 t P y^{-1} (Key assumptions ***and opportunities for improving knowledge***

- More accurate quantification of total geothermal inputs.
- Water movement among connected catchments (see White et al. 2016).
- Magnitude of effects of wallabies on nutrient loss from forest within the catchment.

Table 20). No attenuation between lakes was assumed.

Wastewater

The population estimate used for the purpose of calculating nutrient loads from septic tanks comprised daily equivalents of 291 permanent residents, 184 household visitors, and 300 casual visitors per day, for a total of 775 full-time resident equivalents (source: BoPRC).

Other features

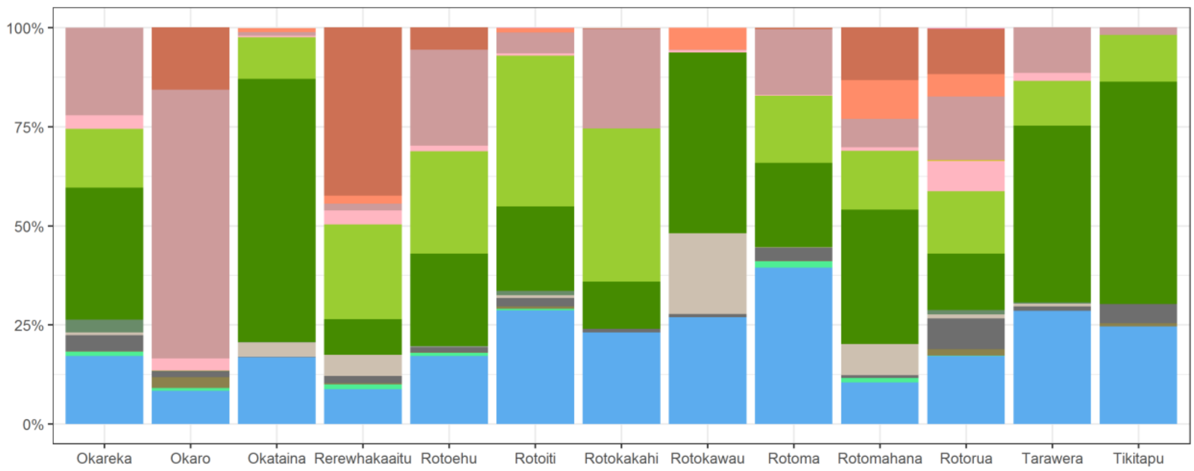
Mean measured flow at the Lake Tarawera outflow is approximately 6.7 $m^3 s^{-1}$. Combined outflow from the hydrologically connected lakes; Okareka, Okataina, Rotomahana, Rotokakahi, was 5.5 $m^3 s^{-1}$ (Table 1). Lake Tarawera outflow would be expected to be much higher than the combined flows from the smaller lakes due to hydraulic load from its 'inner' catchment. This suggests additional subsurface outflows from the lake, and/or partial connectedness of the 'tributary' lakes. This introduces further uncertainty to the nutrient loads assumed here for inputs of N and P from connected lakes to Tarawera. It has been suggested that up to an additional c. 4 $m^3 s^{-1}$ discharges from the lake, also to the Tarawera River but downstream of the lake outlet (White et al. 2016), which may account for hydraulic load from all sources.

Summary

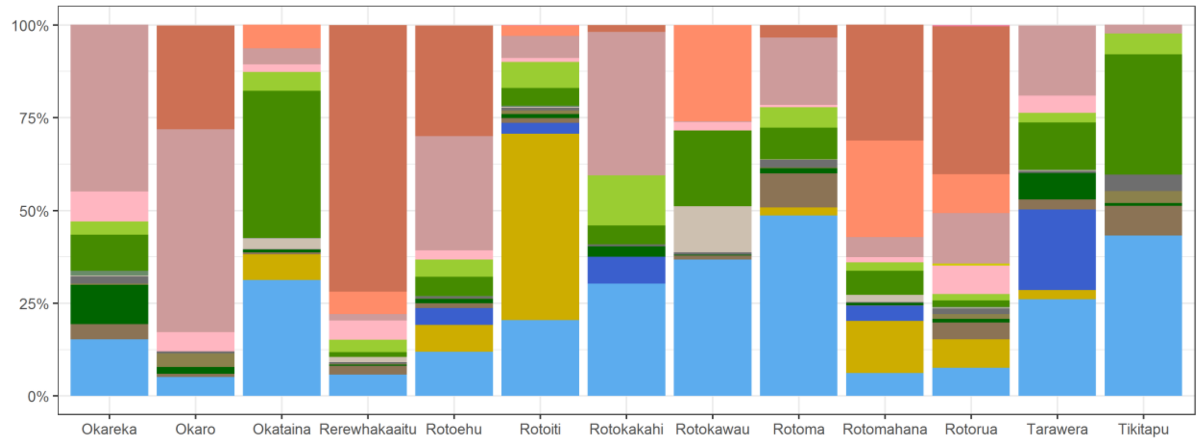
Total estimated loads to Lake Tarawera were 106.7 t N y^{-1} and 10.65 t P y^{-1} (Key assumptions ***and opportunities for improving knowledge***

- More accurate quantification of total geothermal inputs.
- Water movement among connected catchments (see White et al. 2016).
- Magnitude of effects of wallabies on nutrient loss from forest within the catchment.

Table 20). Estimates of the contribution from geothermal sources and connected smaller lakes are highly uncertain due largely to difficulties in quantifying sub-surface flows. Nevertheless, it seems plausible that Lake Tarawera is regionally unique in that the majority of its P load and a substantial portion of its N load appear to be derived from a combination of 'tributary' lakes and geothermal sources (Land use



Total nitrogen



Total phosphorus

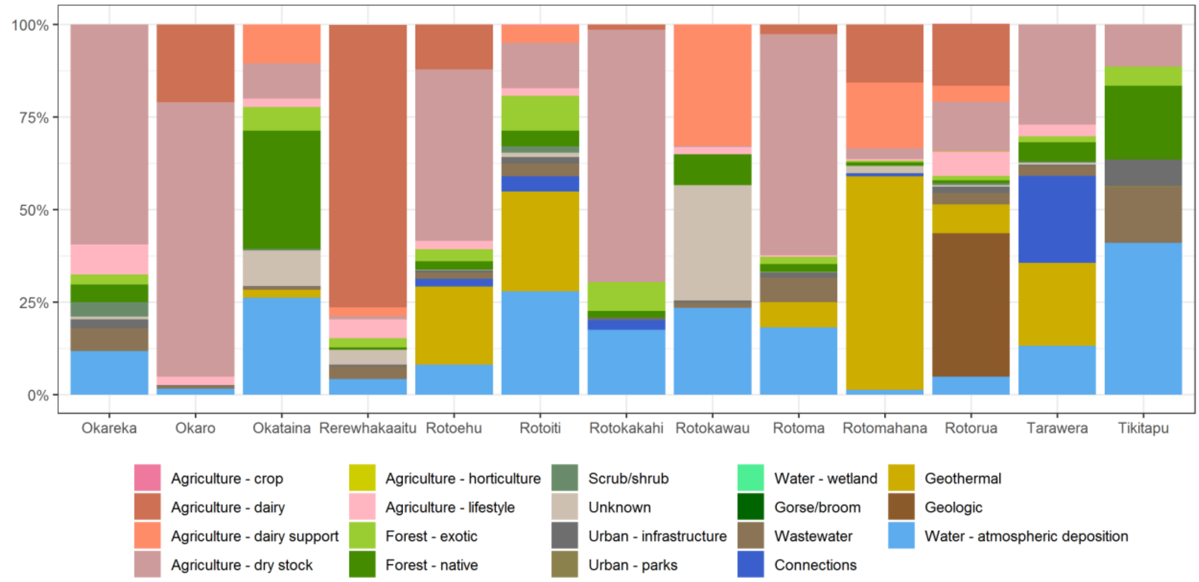


Figure 11).

Key assumptions and opportunities for improving knowledge

- More accurate quantification of total geothermal inputs.
- Water movement among connected catchments (see White et al. 2016).
- Magnitude of effects of wallabies on nutrient loss from forest within the catchment.

Table 20. Sources of nitrogen and phosphorus to Lake Tarawera from the greater Tarawera catchment.

Land use	Surface catchment (ha)	Groundwater catchment (ha)	TN yield (kg ha^{-1} y^{-1})	TP yield (kg ha^{-1} y^{-1})	Yield method	Nitrogen attenuation	Phosphorus attenuation	TN load (kg y^{-1})	TP load (kg y^{-1})	Landuse (%)	TN load (%)	TP load (%)
Agriculture - dry stock	1669.4	1669.4	21.3	3.02	Overseer	0.43	0.43	20266	2879.1	11.5	19.0	27.0
Agriculture - lifestyle	288.7	288.7	30.0	2.00	Estimated	0.43	0.43	4946	329.7	2.0	4.6	3.1
Forest - exotic	1647.2	1647.2	3.0	0.19	Estimated	0.43	0.43	2822	176.4	11.3	2.6	1.7
Forest - native	6481.7	6481.7	3.7	0.15	Estimated	0.43	0.43	13586	555.3	44.6	12.7	5.2
Scrub/shrub	43.2	43.2	5.0	1.25	Estimated	0.43	0.43	123	30.8	0.3	0.1	0.3
Unknown	96.0	96.0	5.0	1.00	Estimated	0.43	0.43	274	54.8	0.7	0.3	0.5
Urban - infrastructure	159.0	159.0	5.9	0.50	Estimated	0.43	0.43	536	45.4	1.1	0.5	0.4
Urban - parks	1.9	1.9	25.0	0.14	Estimated	0.43	0.43	28	0.2	0.0	0.0	0.0
Water - lake or stream	4159.5	4159.5	6.7	0.34	Verburg (2015)			27869	1414.2	28.6	26.1	13.3
Gorse/broom			38.0	0.00	BoPRC	0.43	0.43	7583	0.2		7.1	0.0
Wastewater					BoPRC			2844	284.4		2.7	2.7
Connections					Observed			23200	2492.1		21.7	23.4
Geothermal					Estimated			2690	2390.0		2.5	22.4
All sources								**106767**	**10653**			

Lake Tikitapu

Tikitapu is a small monomictic lake of low productivity, hence its commonly used name, Blue Lake. Its water quality is classed as oligotrophic, with average surface water concentrations of 174 mg TN m^{-3}, 4.3 mg TP m^{-3}, and 1.96 mg chl *a* m^{-3} for the period 2012 – 2017 (Table 1). Tikitapu's TN:TP ratio of approximately 35:1 is very high, likely indicating strong P-limitation.

Catchment description

Lake Tikitapu has a surface topographical catchment area of 6.2 km^2, including the lake area of 1.5 km^2 (LCDB4). Tikitapu's catchment is almost entirely forested and predominantly indigenous. There is a small amount of grassland near the campground and at the eastern tip of the catchment (Figure 28). There is a lakeside campground and public amenities which were reticulated in October 2010.

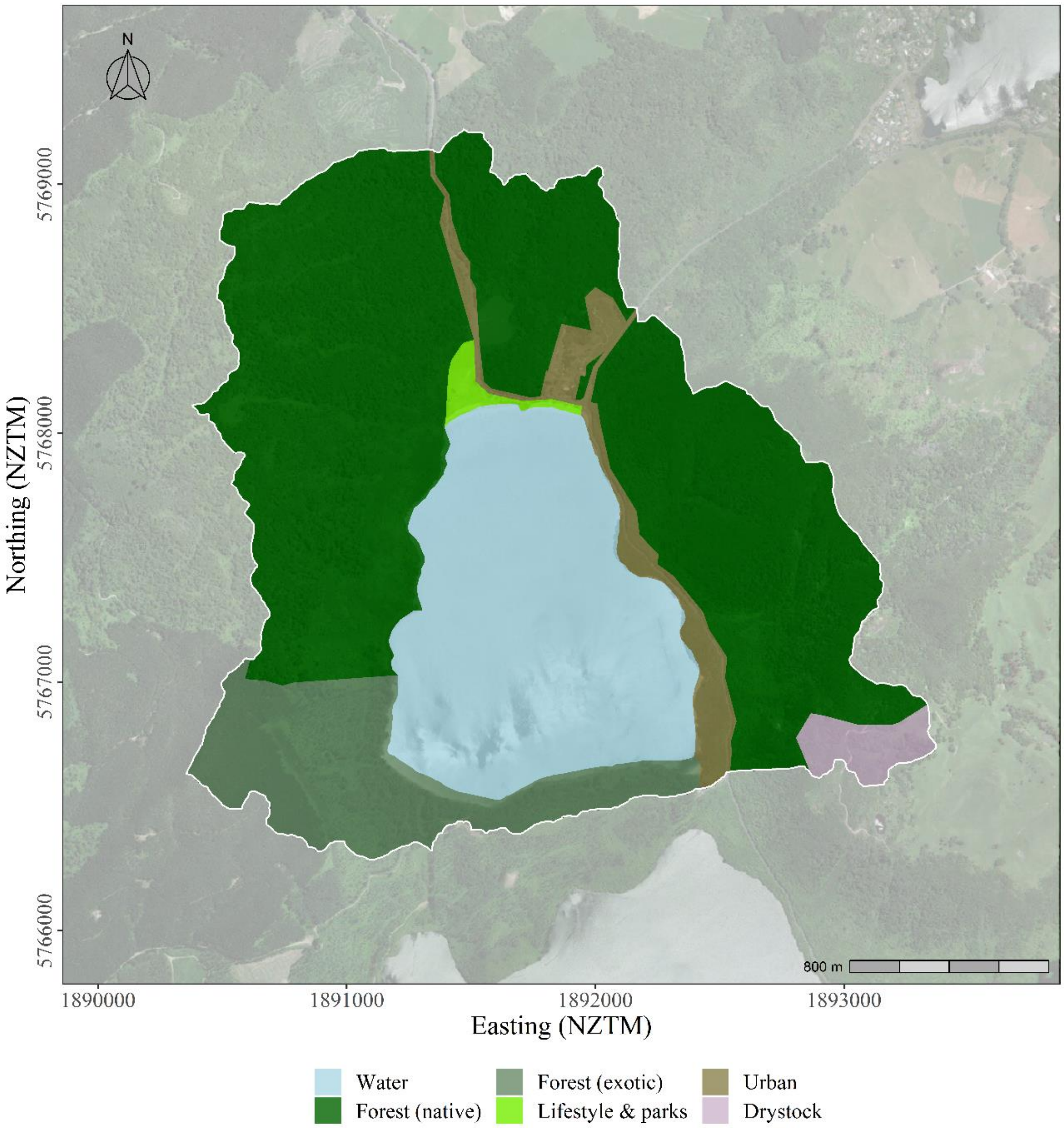


Figure 28. Map of land use (data: BoPRC) in the Tikitapu catchment.

Previous load estimates

Hamilton et al. (2006) estimated annual loads from the greater Tarawera catchment of 2.4 t N y^{-1} and 0.30 t P y^{-1} based on export coefficients. BoPRC (2009b) estimated loads to Lake Tikitapu of 2.5 t N y^{-1} and 0.13 t P y^{-1}. It should be noted that these estimates were prior to the reticulation of wastewater in the catchment.

Land use classes

Results from OVERSEER version 6.2.3 were available for estimating nutrient losses from agricultural land. For other land uses, loss rates are described in section 3.2, and no adjustments to these rates were made for the catchment of Lake Tikitapu.

Geothermal inputs of nitrogen and phosphorus

Lake Tikitapu is not geothermally influenced. Nairn (1981) described chloride concentrations in the lake water of < 6 mg Cl L^{-1}.

Connected lakes

Lake Tikitapu is not known to receive outflow water from any other lakes.

Wastewater

Nitrogen load from the adjacent campground and public amenities at the lake has been previously estimated as approximately 0.7 t y^{-1} (BoPRC 2009b). Although wastewater in the catchment has recently been reticulated, for the purpose of this study we have assumed a load of one quarter of this previously estimated value, to account for legacy enrichment of groundwater sources to the lake. The contribution of wastewater to overall load-to-lake is therefore estimated to be c. 8 and 15 % for N and P, respectively, although these values are highly uncertain and wastewater loads are likely to further reduce with time.

Summary

Total estimated loads to Lake Tikitapu were 2.19 t N y^{-1} and 0.12 t P y^{-1} (

Table 21). Loads to Tikitapu are low due to the small catchment and predominance of forest. It should, however, be noted that the lake has exotic forest to the lake shore at the south, and any harvesting of these trees may temporarily increase the load to the lake substantially (see 3.2.2).

Table 21. Sources of nitrogen and phosphorus to Lake Tikitapu from its catchment.

Land use	Surface catchment (ha)	Groundwater catchment (ha)	TN yield (kg ha^{-1} y^{-1})	TP yield (kg ha^{-1} y^{-1})	Yield method	Nitrogen attenuation	Phosphorus attenuation	TN load (kg y^{-1})	TP load (kg y^{-1})	Landuse (%)	TN load (%)	TP load (%)
Agriculture - dry stock	10.7	10.7	8.1	2.04	Overseer	0.40	0.40	52	13.2	1.9	2.4	11.3
Forest - exotic	67.7	67.7	3.0	0.15	Estimated	0.40	0.40	122	6.1	11.8	5.6	5.2
Forest - native	321.7	321.7	3.7	0.12	Estimated	0.40	0.40	708	23.1	56.1	32.4	19.9
Urban - infrastructure	27.8	27.8	5.9	0.50	Estimated	0.40	0.40	98	8.3	4.9	4.5	7.2
Urban - parks	4.6	4.6	25.0	0.14	Estimated	0.40	0.40	69	0.4	0.8	3.2	0.3
Water - lake or stream	141.0	141.0	6.7	0.34	Verburg (2018)			945	47.9	24.6	43.2	41.1
Gorse/broom			38.0	0.00	BoPRC	0.40	0.40	18	0.0		0.8	0.0
Wastewater					BoPRC			175	17.5		8.0	15.0
All sources								**2187**	**117**			

Appendix 2. Comparison of land use data

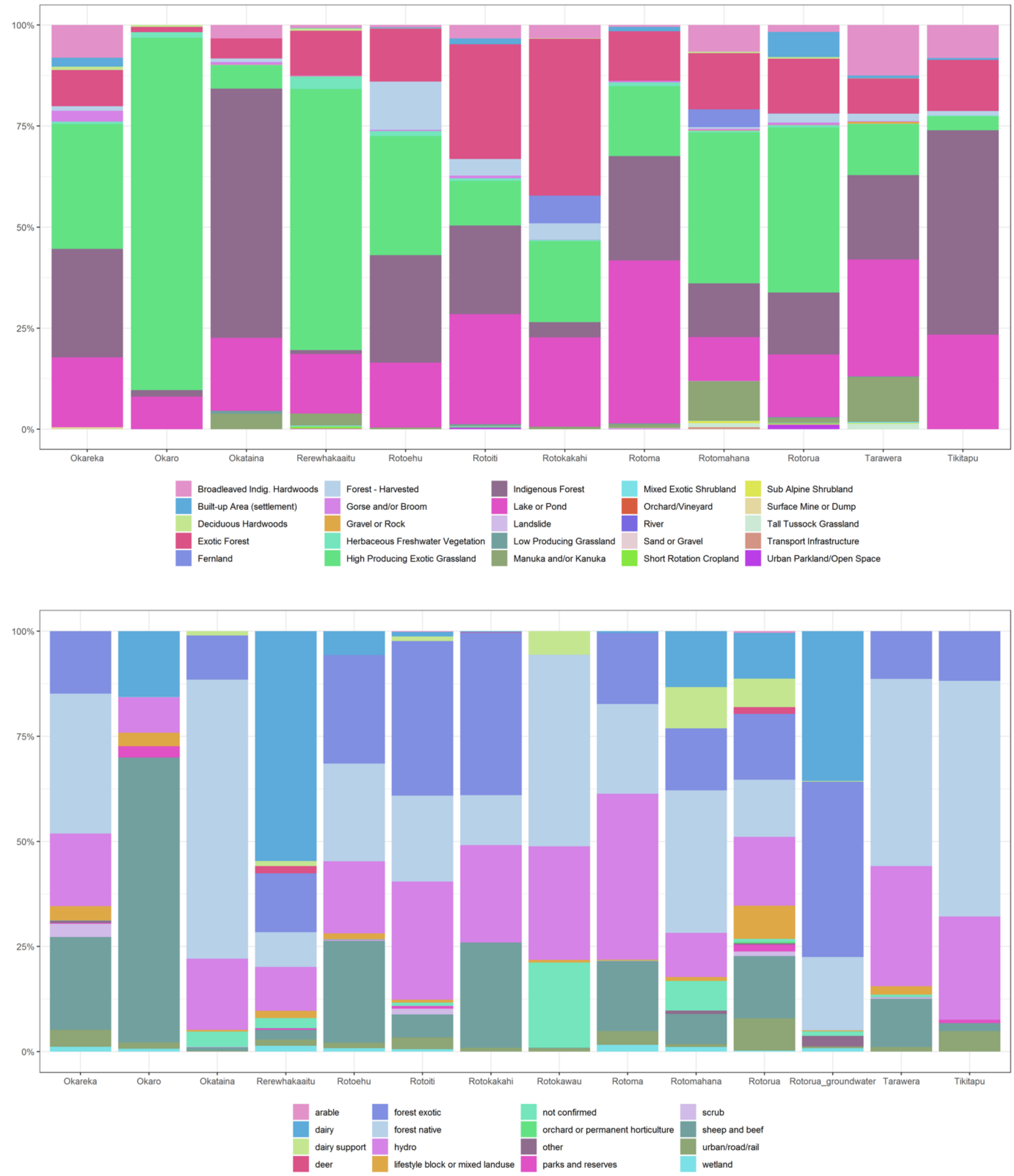


Figure 29. Breakdown of landuse contribution from two separate sources, A) Land Cover Database version 4, and B) Bay of Plenty Regional Council’s land use database.

Appendix 3. Alternative groundwater boundaries for Tarawera lakes.

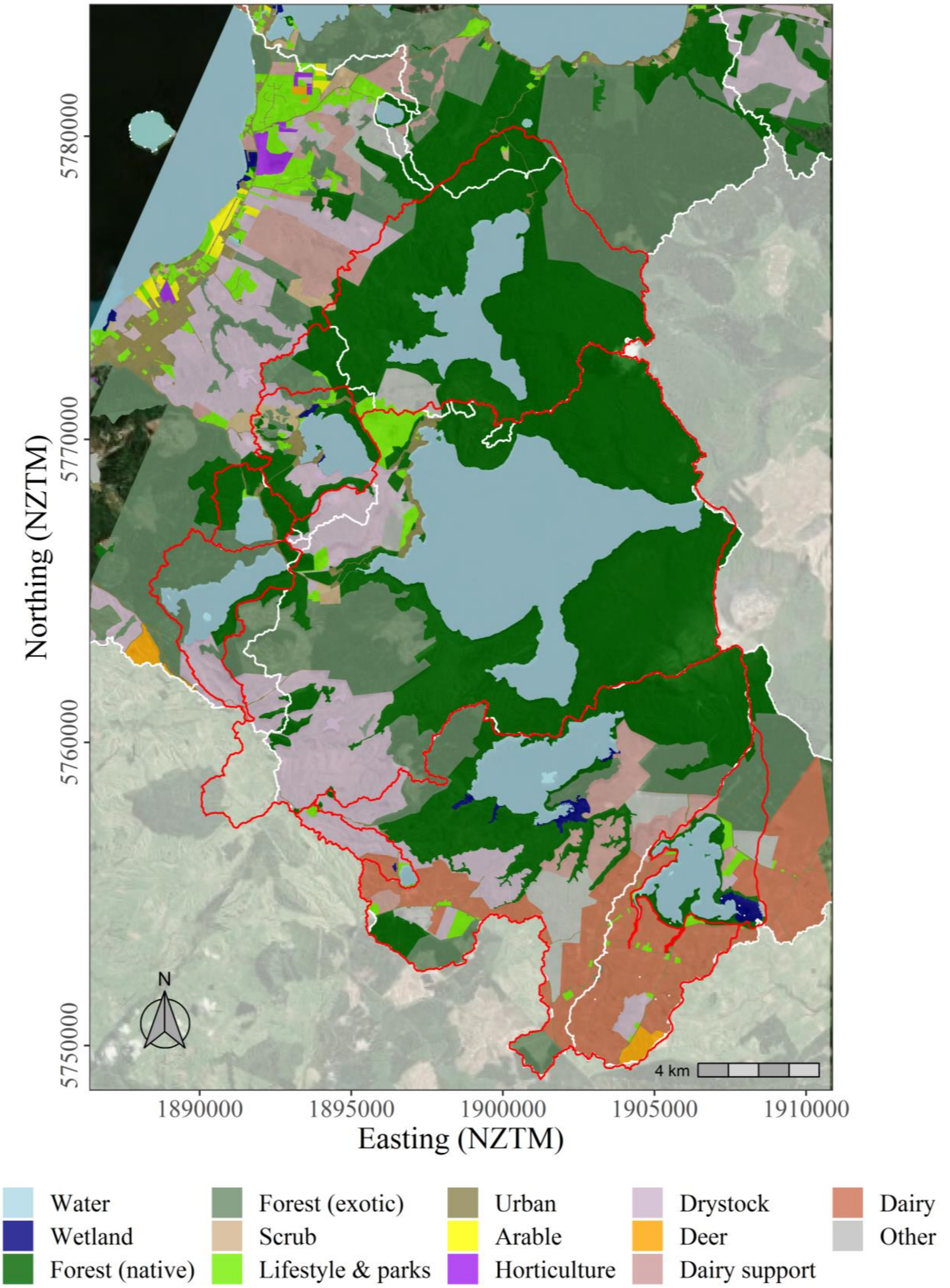


Figure 30. Effective groundwater boundaries for the lakes of the Tarawera lakes complex (in red), as described in White et al (2020). These boundaries were not adopted for the present study, but could be used in future iterations. Surface topographical boundaries used in the present study are shown in white.