Estimates of nitrogen and phosphorus loads to twelve Bay of Plenty Lakes.

Part 1: Land use and atmospheric deposition

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ERI report: XXX

Prepared for Bay of Plenty Regional Council

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OVERSEER

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1. Introduction

The twelve major lakes of the Rotorua Lakes District 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 the extent of development and anthropogenic impacts on the landscape. Bay of Plenty lake catchments range from the largely undeveloped land around Lakes Tikitapu and Okataina, to the highly developed forest and pastoral land around Lakes Rotorua and Okaro. Lake water quality is inextricably linked to water and nutrients received from surface flows and groundwater springs within the catchment. This relationship between land and water was characterised by Vollenweider (1976), who showed that lake water total phosphorus levels were well predicted by catchment phosphorus load and hydraulic retention time. It therefore follows that management of lake water quality requires a robust understanding of nutrient loads derived from the landscape, as does the assessment or prediction of the in-lake effects of changes within catchments aimed at reducing nutrient loads in order to improve lake water quality.

Estimation of nutrient loads to lakes can be accomplished by various approaches. Measurement of nutrient concentrations and discharge volume of surface inflows to a lake can enable estimation of annual loads. For example, Hoare (1980) estimated nitrogen and phosphorus loads to Lake Rotorua by measurement of stream flows and nutrient concentrations. However, this method may not be appropriate where sub-surface groundwater flows contribute substantially to the lake water balance.

Alternatively, catchment loads of nitrogen and phosphorus can be estimated by applying mass balance equations along the lines of Vollenweider (1976) (as with Hoare (1980) and/or Nernberg (1984) as in Vant (1987). However, these mass balance equations are generalised relationships derived from large datasets of lakes and reservoirs. Predicted nutrient retention rates may differ markedly from observed retention where exceptional circumstances are present, for example, nutrient desorption from bottom sediments during anoxia ('internal loading').

Comment [CM1]: Check this

An established method for estimating nutrient loads to lakes is the estimation of nutrient loss rates from land uses within the catchment, multiplied with land use area in order to calculate total 'loads-to-lake'. This method considers steady-state (long-term average) nutrient loads. An advantage of this approach is that it is not adversely affected by catchment hydrology (e.g. surface vs. groundwater flows). This method has broad precedent in the Bay of Plenty Lakes, having been used to estimate catchment loads for several lake Action Plans (e.g. BoPRC 2007, BoPRC et al. 2009a). Nevertheless, land use has changed over time, as has the understanding of nutrient loss rates for various land uses. For example, the nutrient loss model OVERSEER has recently been applied to various land uses within six 'priority catchments' in the Bay of Plenty.

The aim of the present study is to review nitrogen and phosphorus loads to all twelve major Bay of Plenty 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, hydrological connections between lake outflows and inflows of 'downstream lakes', constructed wetlands and natural lagoons. Of specific interest are also anthropogenic point sources, principally on-site effluent treatment systems (septic tanks) and in the case of Lake Rotorua, discharges of treated municipal wastewater. The present study explicitly excludes considering nutrient loads from internal sources, i.e. recycling of nutrients from bottom sediments. This should enable later estimation of these internal loads by mass balance methods examining the difference between 'expected' and 'observed' catchment loads (see Verburg et al. 2015, in prep.).

Applying consistent methodology to estimate catchment loads and atmospheric deposition at the regional scale should enable comparison between catchments, and provide a benchmark against which the impacts of present and/or future catchment intervention and/or management strategies can be assessed.

Table 1. Lake area, annual average outflow (from the model of Woods (2006)), Burns (1999) Trophic Level Index (as presented in BoPRC et al. (2013)), surface water N and P concentrations 2009 to 2014 (BoPRC unpubl. data), and estimated outflow load.

Lake	Area	Outflow	TLI	TLI	TLI	TP_{lake}	TN_{lake}	TP_{out}	TN_{out}
	km^2	$m^3\ s^{-1}$	target	observed (2009 – 2011)	observed - target	mg m^{-3}	mg m^{-3}	t y^{-1}	t y^{-1}
Okareka	3.39	0.49	3.0	3.3	0.3	9.29	187.8	0.14	2.93
Okaro	0.31	0.12	5.0	5.1	0.1	75.96	954.9	0.28	3.47
Okataina	10.83	2.58	2.6	2.8	0.2	10.54	91.2	0.86	7.42
Rerewhakaaitu	5.45	1.06	3.6	3.8	0.2	10.60	366.8	0.35	12.26
Rotoehu	7.91	2.03	3.9	4.4	0.5	33.20	268.3	2.13	17.20
Rotoiti	33.96	5.08	3.5	3.9	0.4	19.16	163.8	3.07	29.15
Rotokakahi	4.37	0.50	3.1	4.2	1.1	55.30	235.0	0.88	3.72
Rotoma	10.03	1.24	2.3	2.3	0.0	5.32	102.4	0.21	4.01
Rotomahana	9.07	2.62	3.9	4.0	0.1	43.98	191.6	3.64	15.87
Rotorua	80.97	16.57	4.2	4.6	0.4	19.99	320.6	10.45	167.60
Tarawera	41.46	*6.70	2.6	2.8	0.2	17.10	88.1	3.62	18.62
Tikitapu	1.46	0.08	2.7	3.0	0.3	4.68	161.3	0.01	0.42

2. Methods

2.1 Study site –Rotorua Lakes

The 12 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 0.3 to 80.8 km^2, maximum depth 8 to 125 m, and mean depth 4 to 60 m. Water quality and nutrient concentrations are also highly variable, ranging from the oligotrophic Lake Rotoma (Trophic Level Index (TLI; Burns 1999) = 2.3 to supertrophic Lake Okaro (TLI > 5) (BoPRC et al. 2013). Phytoplankton communities 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 Tarawera.

Figure 1: Aerial image of 13 Rotorua Lakes with catchment borders.

2.2 Land use classes and areas

Land use areas for each lake and catchment were calculated by BoPRC using Land Cover Database version 4 (LCDB4; Landcare Research (2012)). LCDB groups together similar land classes as identified in digitised satellite images.

2.3 Nitrogen and phosphorus export rates

Areal loss rates of nitrogen (N) and phosphorus (P) were estimated for each land use by a variety of methods.

For agricultural land uses, nutrient exports rates were estimated by BoPRC using the OVERSEER model (Ministry for Primary Industries, the Fertiliser Association and AgResearch). OVERSEER output was available for the catchments of Lakes Okareka, Okaro, Rotoehu, Rotoiti, Rotoma, and Rotorua. For each catchment, average loss rates for all sub-classes of pastoral land use were calculated. OVERSEER version 6.1.2a or later was used, except at Okaro where only version 5.4.3 was available. OVERSEER estimates losses of nutrients from each block of land, and generally does not consider attenuation across the landscape (e.g. between a farm and receiving waterways). Therefore, attenuation factors were applied to estimate the final 'loads-to-lake' (see section 3).

Where OVERSEER results were not available for all agricultural land within a catchment (i.e. OVERSEER area was less than grassland specified by LCDB4), the remaining land was assumed to be in dry stock, and the appropriate, catchment-specific, rates of N and P loss were assumed. Where OVERSEER results were given for a greater area than specified as 'High Producing Grassland' by LCDB4, OVERSEER loss rates were applied proportionally to the LCDB4.0 area.

For catchments where OVERSEER results were not available, pastoral land use was generally for dry stock. In these cases, average nutrient loss rates and attenuation factors for dry stock across all the OVERSEER catchments were applied.

For all non-pastoral land uses, loss rates were estimated based on available literature, preferably within local context, i.e. peer reviewed field studies from within the Bay of Plenty 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.

2.4 Other sources of N and P

2.4.1 Geothermal inflows

Geothermal waters are known to influence several Bay of Plenty lakes. Volumes of many of these inflows are relatively poorly quantified, particularly at Lake Rotomahana. Geothermal spring and stream sampling was undertaking by Environment Bay of Plenty in the mid-1990s and mid-2000s. 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 data to estimate the geothermal load to each lake.

2.4.2 Inflows from lakes outside the surface topographical catchment

Annual N and P loads from each lake were estimated by multiplying lake outflow volume, as modelled by Woods (2006), and the average observed surface water (<10 m) concentrations of TN and TP for the period 2009 to 2014 (BoPRC unpubl. data). This study concerns the period 2009 – 2014, therefore water entering Lake Rotoiti from Lake Rotorua was not considered (the Ohau Channel diversion wall was completed in 2008).

2.4.3 Wastewater

Estimated households and occupancy for each lake were obtained from BoPRC and/or Rotorua District Council (RDC), and expressed as full-time resident equivalents. These estimates considered 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 calculated by multiplying the estimated full-time resident equivalents by the loss rates recommended for the BoP lakes in a review of nutrient loads from septic tanks by McIntosh (2013). Specific details of the calulations for each catchment are given in section 3.4.

In the case of Lake Rotorua, annual average load-to-lake for N and P was obtained from BoPRC monitoring data from the Waipa Stream, downstream of the Whakarewarewa land treatment system (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 the predominantly unaltered (e.g. Tikitapu) to the predominantly pastoral (Rerewhakaaitu, Okaro). Area for each land use in each ctable 1atchment is shown in Table 2.

Table 2. Catchment land use by category from Land Cover Database (version 4). Lake areas are highlighted in blue. Source: BoPRC.

Land use (ha)	**Okareka**	**Okaro**	**Okataina**	**Rere whakaaitu**	**Rotoehu**	**Rotoiti**	**Roto kakahi**	**Rotoma**	**Roto mahana**	**Rotorua**	**Tarawera**	**Tikitapu**
Alpine Grass/Herbfield											0	
Broadleaved Indig. Hardwoods	159	0	198	27	30	418	65	14	552	905	1792	51
Built-up Area (settlement)	44			4	11	175		30		3243	99	3
Deciduous Hardwoods	16	2		22	2	1	2		30	221	4	
Exotic Forest	175	5	297	412	647	3540	768	342	1156	7068	1249	79
Fernland							135		368	26		
Forest - Harvested	23		54		588	519	80		38	1168	267	7
Gorse and/or Broom	53		41	5	15	80	1	10	31	310	23	
Gravel or Rock			1	3		0			9	20	70	
Herbaceous Freshwater Vegetation	12	5	10	114	59	84	6	26	34	282	21	1
High Producing Exotic Grassland	605	340	342	2392	1453	1374	396	482	3110	21344	1803	22
Indigenous Forest	527	6	3695	35	1307	2742	74	721	1110	8012	2990	315
Landslide									5			
Lake or Pond	**339**	**31**	**1083**	**545**	**791**	**3396**	**437**	**1124**	**907**	**8097**	**4146**	**146**
Low Producing Grassland			42			36		6	2	125	27	
Manuka and/or Kanuka			229	111	21	31	11	25	813	597	1590	
Mixed Exotic Shrubland				9		22			5	66	41	
Orchard, Vineyard…										44		
River						5				4		
Sand or Gravel								5				
Short-rotation Cropland				17		11				90		
Sub Alpine Shrubland									47		24	
Surface Mine or Dump	10					1				55		
Tall Tussock Grassland									83		191	
Transport Infrastructure				4					41	20		
Urban Parkland/Open Space				3		47		4	0	569		
TOTAL	**1961**	**390**	**5992**	**3702**	**4925**	**12484**	**1974**	**2788**	**8340**	**52268**	**14337**	**623**

Comment [CM2]: Should probably serperate non-lake areas e.g. rotorua has rotokawau in catchment and Rotoma has lagoons etc

3.2 Loss rates of nitrogen and phosphorus by LCDB land use

3.2.1 Indigenous vegetation

3.2.1a Broadleaved indigenous hardwoods

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}. Locally, 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}. The loss rates of Cooper and Thomsen (1988) were adopted for the present study.

3.2.1b Fernland

Fernland was a substantial land cover only in the catchment of Lake Rotokakahi (6.8%). No detailed studies of loss rates from fernland were available. Therefore, loss rates were assumed to be similar to those for indigenous forest.

3.2.1c Indigenous forest

Loss rates used for indigenous forest were those described by Cooper and Thomsen (see 3.1.1).

3.2.1d Manuka and/or kanuka

No detailed studies of loss rates from Manuka and/or kanuka were available. Therefore, loss rates were assumed to be similar to those for indigenous forest.

3.2.2 Exotic vegetation

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 these loss rates were from mature, closed-canopy forestry, whereas loss rates during and after harvesting are likely substantially higher, returning to equilibrium loss rates as trees mature and the canopy closes. Quinn & Ritter (2003?) DETAIL OF THIS REF. These two studies were combined to estimate loss rates for a typical 22 year harvest cycle (Figure X), yielding long-term average loss rates for plantation forestry of 2.8 kg N ha^{-1} y^{-1} and 0.18 kg P ha^{-1} y^{-1}.

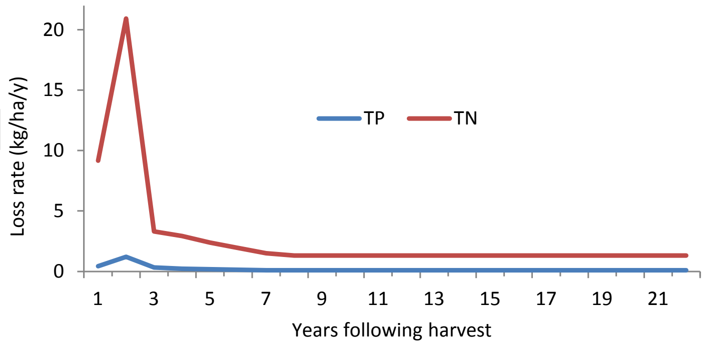

Figure 2. Estimated loss rates of N and P from plantation forestry, over a 22-year harvest cycle. Inferred from Cooper & Thomsen (1988) and Quinn & Ritter (2003).

3.2.2a Exotic forest

Exotic forest was presumed to be mature with a closed canopy, therefore the loss rates of Cooper and Thomsen (1988) were used, yielding 1.31 kg N ha^{-1} y^{-1} and 0.10 kg P ha^{-1} y^{-1}.

3.2.2b Deciduous hardwoods

Deciduous hardwoods were assumed to have similar loss rates to those of mature (non-harvested) plantation forestry as described by Cooper and Thomsen (1988; see 3.1.4 below), 1.31 kg N ha^{-1} y^{-1} and 0.010 kg P ha^{-1} y^{-1}.

3.2.2c Forest - harvested

Areas of harvested forest as specified by LCDB 4 were considered to be representative of the proportion of catchment in bare or open-canopy forestry land within the catchment between 2009 and 2014. As such, loss rates were assumed to be the average of the first five years following harvest as presented in Figure 2. This yielded loss rates of 7.74 kg N ha^{-1} y^{-1} and 0.47 kg P ha^{-1} y^{-1}.

3.2.2d Mixed exotic shrubland

Mixed exotic shrubland accounted for a very small portion of total land use in all catchments (maximum 0.3 %). Loss rates of 3.0 kg N ha^{-1} y^{-1} and 0.2 kg P ha^{-1} y^{-1} were assumed.

3.2.7 Gorse and/or broom

Gorse and broom accounted for a small portion of total land use in each catchment (maximum 2.7 %). Because gorse can fix nitrogen, a relatively high loss rate of 15.0 kg N ha^{-1} y^{-1} was used. P loss was set at 0.2 kg P ha^{-1} y^{-1} , roughly equivalent to that used for exotic forest.

3.2.3 Pastoral land

Pastoral land cover is substantial in many of the Rotorua Lakes. Agricultural land uses are highly variable in their use, and correspondingly variable in the loss of nitroegen and phosphorus from the farm. A review of available New Zealand studies by McDowell and Wilcock (2008) found 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 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) which had loss rates of 12 kg N ha^{-1} y^{-1} and 1.7 kg P ha^{-1} y^{-1}.

Over recent years, the farm fertiliser application and nutrient loss model OVERSEER (Wheeler et al. 2009) has gained widespread use for the estimation of nutrient loss from farm blocks. OVERSEER represents the state-of-the-art for these estimations, as it considers factors including (but not limited to) soil type, fertiliser application rates and timing, stock density, and on-farm mitigation.

Bay of Plenty Regional Council has identified five 'Rule 11' catchments – Lakes Okareka, Okaro, Rotoehu, Rotoiti, and Rotorua (see http://www.boprc.govt.nz/knowledge-centre/plans/regional-water-and-land-plan/#). For these catchments agricultural land has been 'benchmarked' for nutrient loss using the OVERSEER model. In this study, where overseer results were available, they were used to estimate loads derived from agricultural sources. For other catchments, the mean of loss rates from all benchmarked catchments was used.

3.2.3a High producing exotic grassland

In priority catchments, OVERSEER results were aggregated by land use category. Average N and P loss rates for all sub-classes of agricultural land in the catchments of Lakes Okareka, Okaro, Rotoehu, Rotoiti, Rotoma, and Rotorua are detailed in Section 3.4.

Because OVERSEER version 6.1.3 does not account for attenuation between the land block and the receiving waters, a nitrogen attenuation rate of 26 % N was estimated by comparison of OVERSEER output from versions 6.1.3 and 5.4.3 from individual BoP lakes. An attenuation rate of 60 % P was estimated by comparison of OVERSEER output with literature estimates of pastoral P loss summarised by McDowell & Wilcock (2008) and various BoPRC Lake Action Plans.

Average loss rates and attenuation factors for dry stock across all the OVERSEER catchments were 10.18 kg N ha^{-1} y^{-1} and 1.02 kg P ha^{-1} y^{-1}. These estimates compared well with rates previously adopted by several Lake Action Plans (e.g. BoPRC 2007, McIntosh 2012a), and similar to the review of McDowell & Wilcock (2008) which found mean loss rates across New Zealand for mixed dry stock of 11 kg N ha^{-1} y^{-1} and 1.3 kg P ha^{-1} y^{-1}. Therefore, these rates were applied to dry stock land in catchments where OVERSEER results were unavailable.

3.2.3b Low producing grassland

Low producing grassland accounted for a very small portion of total land use in all catchments (maximum 0.7 %). Loss rates of 5.0 kg N ha^{-1} y^{-1} and 0.5 kg P ha^{-1} y^{-1} were assumed.

3.2.3c Short-rotation cropland

Short-rotation cropland accounted for a very small portion of total land use in all catchments (maximum 0.2 %). Loss rates of 5.0 kg N ha^{-1} y^{-1} and 0.2 kg P ha^{-1} y^{-1} were assumed.

Comment [CM3]: John Mc: Some of this will be maize and your loss rates probably apply. There has been winter grazing of root crops which has a very high nutrient loss. In this section it would be worth including the nutrient loss for such a landuse even if you dont have the speciifc information to apply it. It is worth it as a reference. BOPRC had a site on upper Otuaroa Rd which monitored such a landuse.

3.2.4 Urban areas

3.2.4a Built-up area (settlement)

Loss rates for urban areas were derived from Rotorua city stormwater sampling (as referenced in McIntosh 2010). Values used were 3.0 kg N ha^{-1} y^{-1} and 0.7 kg P ha^{-1} y^{-1}.

3.2.4b Surface mine or dump

Surface mines or dumps were located only in the catchments of Lakes Okareka, Rotoiti and Rotorua, and accounted for a very small portion of total land use in all catchments (maximum 0.5 %). These were assumed to be quarries rather than dumps, and so relatively low loss rates of 5.0 kg N ha^{-1} y^{-1} and 2.0 kg P ha^{-1} y^{-1} were assumed.

3.2.4c Transport infrastructure

Transport infrastructure accounted for a very small portion of total land use in all catchments (maximum 0.5 %). Loss rates were assumed to be similar to urban areas (5.0 kg N ha^{-1} y^{-1} and 1.0 kg P ha^{-1} y^{-1}).

3.2.4d Urban parkland/open space

Urban parkland and open spaces accounted for a relatively small portion of total land use in all catchments (maximum 1.1 %). Loss rates were assumed to be similar to urban areas (5.0 kg N ha^{-1} y^{-1} and 1.0 kg P ha^{-1} y^{-1}).

3.2.5 Atmospheric deposition

3.2.5a Lake or pond

Lake surfaces receive nutrient loads via aerial deposition, both wet (dissolved nutrients in rainfall), and dry (particulates). A review of studies of North Island deposition rates by Verburg (unpublished data), found average total deposition (wet and dry) of 6.37 (standard deviation 2.38) kg N ha^{-1} y^{-1}, and 0.34 (standard deviation 0.17) kg P ha^{-1} y^{-1}. For the present study, deposition loads were not adjusted for annual rainfall because of complex interplay between rainfall volume, N and P concentrations, and dry deposition.

3.3 Other sources of nutrients

3.3.1 Geothermal

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

Sampling by Bay of Plenty Regional Council found geothermal flows around Lake Rotoiti were very high in nitrogen (average c. 13 g N m^{-3}, mostly ammonium) but relatively low in phosphorus (c. 0.1 g P m^{-3}) (BoPRC unpubl. data). In contrast, monitoring of Lake Tarawera inflows by Terry Beckett and UoW 2007 to 2014 found relatively lower concentrations of N but very high concentrations of P. Average concentrations in the Hot Water Beach geothermal inflow were 0.4 g P m^{-3} and 0.5 g N m^{-3} (n = 17 samples).

The volume of hot water inflows to the geothermally influenced lakes is difficult to measure, and as such is generally not well understood. A range of approaches were used to estimate geothermal loads of N and P, and these are detailed in sections 3.4.1 to 3.4.12.

3.3.2 Connected lakes

Estimated annual loads of N and P from surface and/or sub-surface outflow(s) for each lake are presented in Table 1. Hydrological connections between these outflows and other lakes are detailed in the catchment nutrient budgets of section 3.4.

3.3.3 Wastewater

A literature review by McIntosh (2013), recommended wastewater N losses in BoP 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.

The exception was Lake Rotorua, where monitoring data from the Waipa Stream 2009 to 2014 observed an average, post-treatment load of 30 t N y^{-1} and 1.7 t P y^{-1}.

3.4 Individual catchment nutrient budgets

3.4.1 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 188 mg TN m^{-3}, 9.3 mg TP m^{-3}, and 3.8 mg chl *a* m^{-3} for the period 2009 – 2014 (Table 1). Okareka's TN:TP ratio of approximately 20:1 is relatively high, meaning the lake is likely to be P-limited or co-limited depending on seasonal variation.

3.4.1a 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 3). Okareka's lakeside community wastewater was reticulated in 2011.

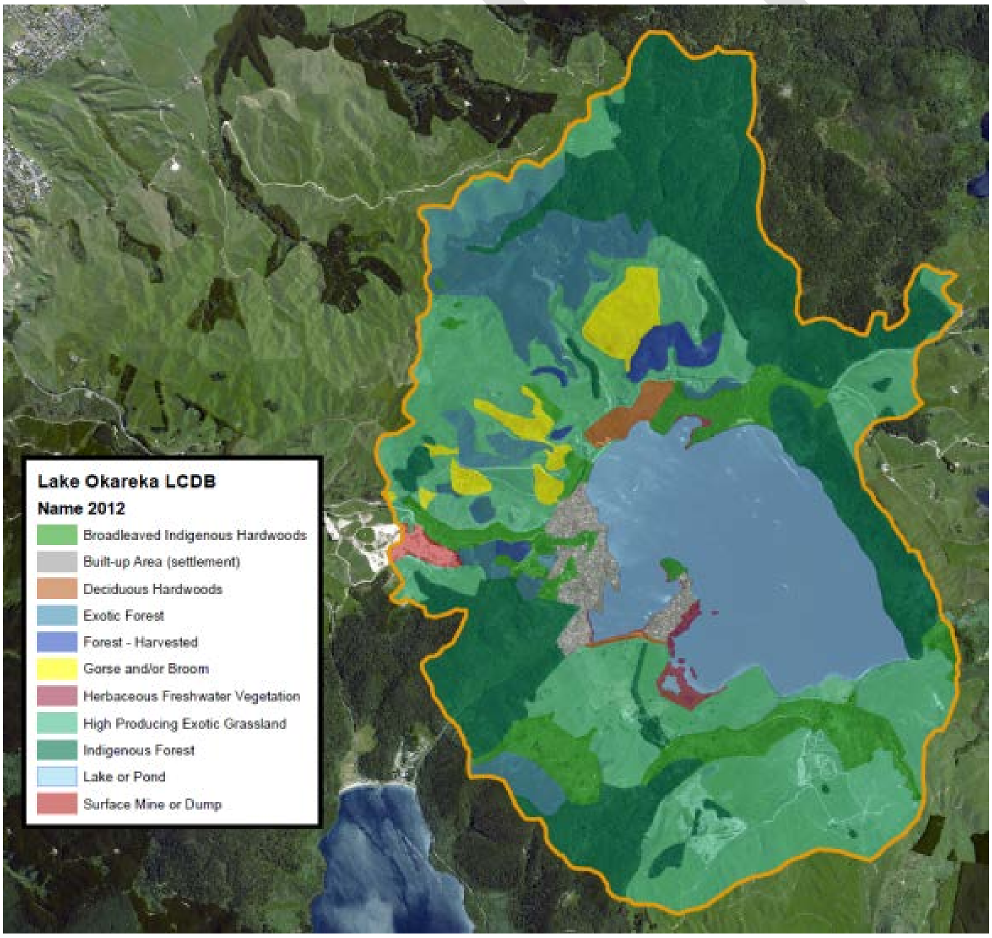

Figure 3. Map of land use (LCDB4) in the Okareka catchment.

3.4.1b 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).

3.4.1c Land use classes

Results from OVERSEER version 6.1.3 were available for estimating nutrient losses from agricultural land (Table 3). 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 Okareka.

3.4.1d Geothermal inputs of nitrogen and phosphorus

Lake Okareka is not geothermally influenced (Nairn 1981).

3.4.1e Connected lakes

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

3.4.1f 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). Because the community wastewater was reticulated in 2011 the estimated wastewater load was divided by two, with the resultant loads accounting for approximately 7 % of N and 13 % of P load 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.

3.4.1g Summary

Total estimated loads to Lake Okareka were 15.7 t N y^{-1} and 0.86 t P y^{-1} (Table 3). For both N and P, approximately half of total load was derived from pastoral land (Figure 4). These loads are high compared to earlier estimates in EBoP (2004).

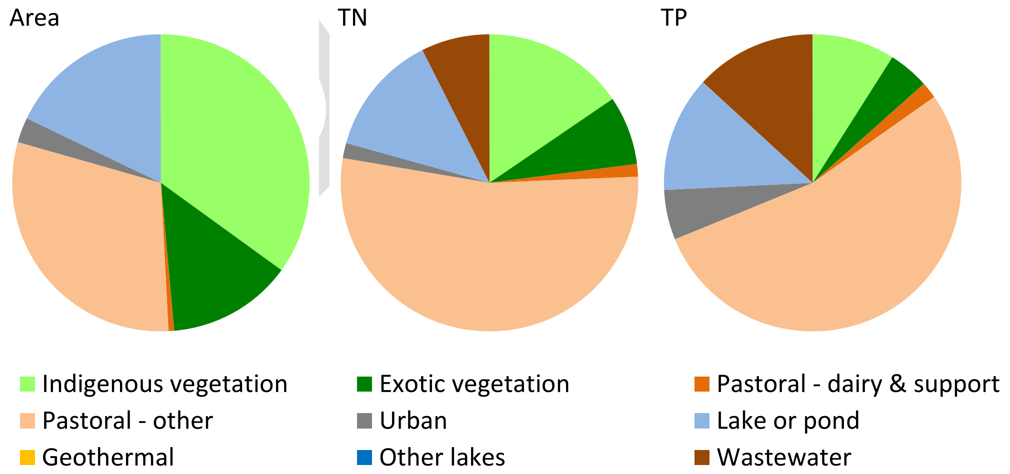

Figure 4. Proportional contribution of all sources within the Lake Okareka catchment to area, total nitrogen load, and total phosphorus load.

Table 3. Sources of nitrogen and phosphorus to Lake Okareka from its catchment.

Land use (LCDB 4)	Area (ha)	Rule 11 (ha)	Area (%)	OVERSEER (version)	N yield (kg N ha y^{-1})	N attenuation (%)	N load (kg N y^{-1})	N load (%)	P yield (kg P ha y^{-1})	P attenuation (%)	P load (kg P y^{-1})	P load (%)
Broadleaved Indigenous Hardwoods	158.9		8.1		3.67		**583**	3.6	0.12		**19**	2.1
Indigenous Forest	527.2		26.9		3.67		**1935**	11.9	0.12		**63**	6.9
Deciduous Hardwoods	15.8		0.8		1.31		**21**	0.1	0.10		**2**	0.2
Exotic Forest	175.1		8.9		1.31		**229**	1.4	0.10		**18**	1.9
Forest - Harvested	23.1		1.2		7.74		**179**	1.1	0.47		**11**	1.2
Gorse and/or Broom	52.8		2.7		15		**791**	4.9	0.20		**11**	1.2
High Producing Exotic Grassland	604.8											
Dairy Support		*11.8*	0.6	6.1.3	25.48	26	**223**	1.4	3.44	60	**16**	1.8
Dry Stock		*263.3*	13.4	6.1.3	19.77	26	**3852**	23.7	2.07	60	**218**	23.8
Not benchmarked		*329.7*	16.8	n/a	19.77	26	**4823**	29.6	2.07	60	**273**	29.8
Built-up Area (settlement)	43.7		2.2		5		**219**	1.3	0.70		**31**	3.3
Surface Mine or Dump	9.5		0.5		5.00		**48**	0.3	2.00		**19**	2.1
Herbaceous Freshwater Vegetation	11.7		0.6		0		**0**	0.0	0.00		**0**	0.0
Lake or Pond	338.7		17.3		6.37		**2158**	13.3	0.34		**115**	12.6
Wastewater (662 pp)							**1208**	7.4			**121**	13.2
Total	1961.4						**16269**				**916**	

3.4.2 Lake Okaro

Okaro is a small lake (area c. 0.3 km^2), of very high productivity. It is subject to frequent and severe blooms of cyanobacteria during summer, and has had an extensive program of water quality management, including land-based interventions (e.g. 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 955 mg TN m^{-3}, 76 mg TP m^{-3}, and 21.3 mg chl *a* m^{-3} for the period 2009 – 2014 (Table 1). Okaro's TN:TP ratio of approximately 13:1 means it is likely co-limited. However, periods of N-limitation may lead to a competitive advantage for N-fixing cyanobacteria (White et al. 1989).

3.4.2a 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, uptake of dissolved inorganic nutrients and denitrication. 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.

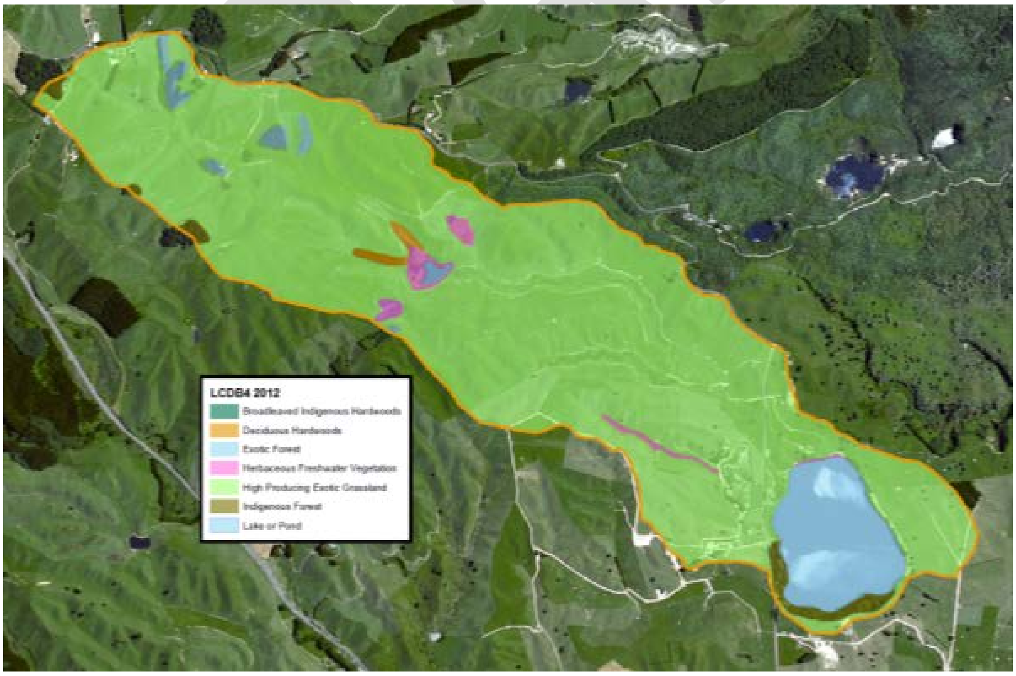

Figure 5. Map of land use (LCDB4) in the Okaro catchment.

3.4.2b 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).

3.4.2c Land use classes

Results from OVERSEER version 5.4.3 were available for estimating nutrient losses from agricultural land (Table 4). No nitrogen attenuation between land and lake was applied, because comparison of OVERSEER version 5.4.3 with version 6.1.3 for other Rotorua lakes showed that version 5.4.3 gave low nutrient yields relative to versions >6.

For non-agricultural land uses, loss rates are described in section 3.2 and no adjustments to these rates were made for the catchment of Lake Okaro.

3.4.2d Geothermal inputs of nitrogen and phosphorus

Warm water has been observed in deep in 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}.

3.4.2e Connected lakes

Lake Okaro is not known to receive water from the outflow of any other lakes.

3.4.2f 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 approximately 1 % for both N and P.

3.4.2g 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 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).

3.4.2g Summary

Total estimated loads to Lake Okaro were 4.4 t N y^{-1} and 0.45 t P y^{-1} (Table 4). Almost all N and P load is derived from agricultural land, as the catchment is overwhelmingly pastoral in land use (Figure 6). The N load was similar to previously published estimates, whereas the P load was substantially lower. 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.

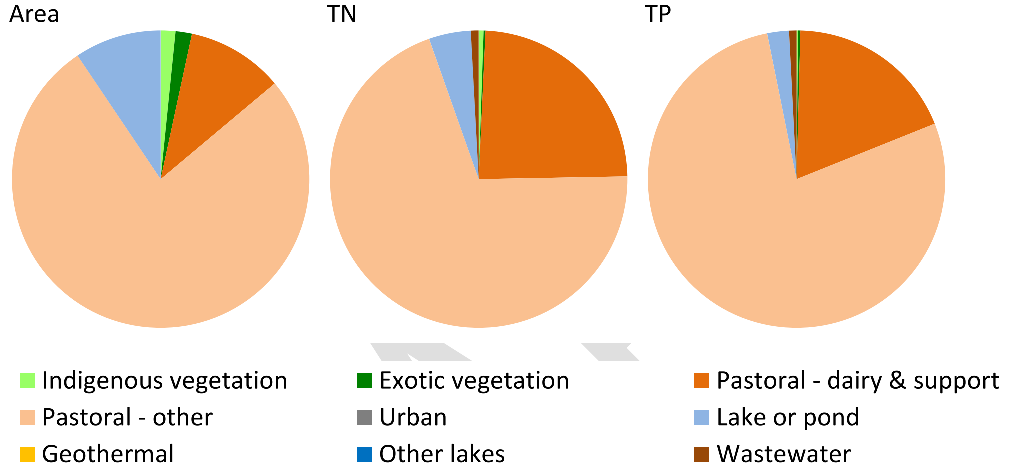

Figure 6. Proportional contribution of all sources within the Lake Okaro catchment to area, total nitrogen load, and total phosphorus load. Proportions for loads do not include reductions from the constructed wetland.

Table 4. Sources of nitrogen and phosphorus to Lake Okaro from its catchment. Estimated removal of N and P by the constructed wetland is highlighted in yellow.

Land use	**Area**	**Rule 11**	**Area**	**OVERSEER**	**N yield**	**N attenuation**	**N load**	**N load**	**P yield**	**P attenuation**	**P load**	**P load**
(LCDB 4)	(ha)	(ha)	(%)	(version)	(kg N ha y^{-1})	(%)	(kg N y^{-1})	(%)	(kg P ha y^{-1})	(%)	(kg P y^{-1})	(%)
Broadleaved Indigenous Hardwoods	0.0		0.0		3.67		**0**	0.0	0.12		**0**	0.0
Indigenous Forest	6.3		1.6		3.67		**23**	0.5	0.12		**1**	0.2
Deciduous Hardwoods	1.9		0.5		1.31		**3**	0.1	0.10		**0**	0.0
Exotic Forest	5.0		1.3		1.31		**7**	0.2	0.18		**1**	0.2
High Producing Exotic Grassland	340.0											
Dairy		*41.0*	10.5	5.4.3	25.50	0	**1044**	24.8	5.10	60	**84**	20.3
Dry Stock		*245.7*	63.0	5.4.3	10.01	0	**2459**	58.4	2.91	60	**286**	69.5
Effluent		*1.9*	0.5	5.4.3	38.16	0	**71**	1.7	7.55	60	**6**	1.4
Not benchmarked		*51.5*	13.2	n/a	10.01	0	**515**	12.2	2.91	60	**60**	14.6
Herbaceous Freshwater Vegetation	5.4		1.4		0.00		**-150**		0.00		**-40**	
Lake or Pond	31.3		8.0		6.37		**200**	4.7	0.34		**11**	2.6
Wastewater (10 pp)							**37**	0.9			**4**	0.9
Total	389.9						**4208**				**411**	

3.4.3 Lake Okataina

Okataina is a deep lake (maximum depth c. 78 m), of fairly low productivity. Its water quality is classed as oligotrophic, with average surface water concentrations of 91 mg TN m^{-3}, 10 mg TP m^{-3}, and 2.1 mg chl *a* m^{-3} for the period 2009 – 2014 (Table 1). Okataina's TN:TP ratio of approximately 9:1 means it is likely co-limited or sometimes P-limited. The lake has no surface outlet, and as such water level varies dramatically over decadal time-scales.

3.4.3a 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). The catchment is at first glance pristine, with the majority of land remaining in indigenous vegetation, and only small proportions of exotic forestry and dry stock land (Figure 7). However, the 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 (e.g. Figure 8).

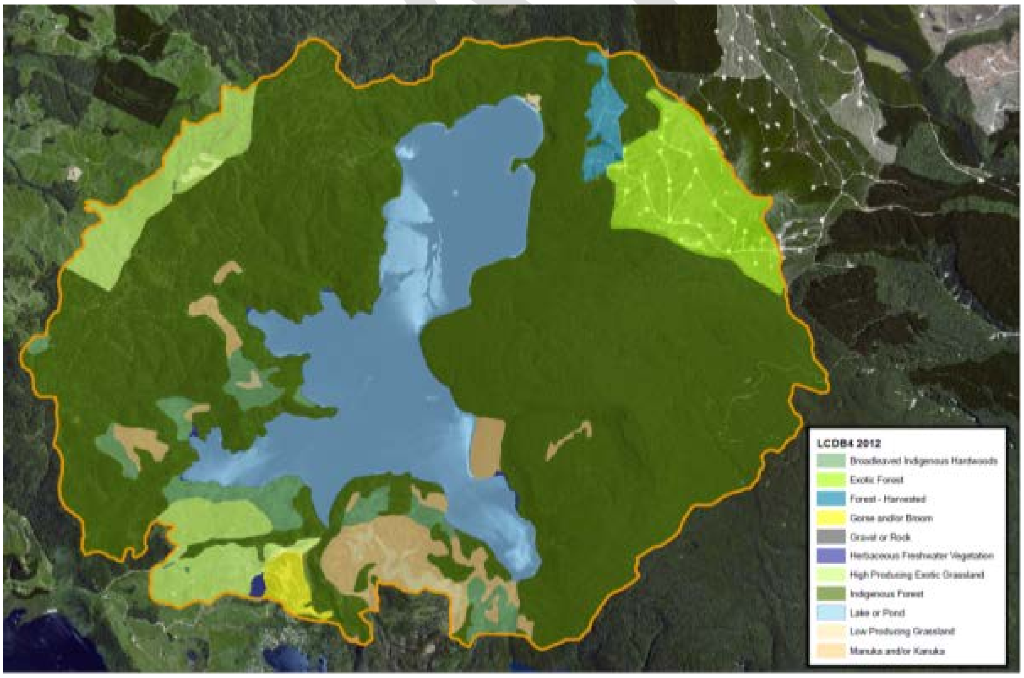

Figure 7. Map of land use (LCDB4) in the Okataina catchment.

3.4.3b Previous load estimates

The Lake Okataina Action Plan (BoPRC 2013) estimated loads to Lake Okataina of 27.1 t N y^{-1} and 2.1 t P y^{-1}.

3.4.3c Land use classes

OVERSEER benchmarking of agricultural land use within the Okataina catchment was not available. Therefore, for dry stock land, average loss rates of 10.18 kg N ha^{-1} y^{-1} and 1.02 kg P ha^{-1} y^{-1} were applied (see 3.3.2a).

For other land uses, loss rates used are described in section 3.2. For Okataina, P loss rates from forest were multiplied by 1.5 to account for the effect of reduced understory cover due to pest animals.

3.4.3d 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.

Comment [CM4]: What would nutrient composition likely be and can we estimate volume?

3.4.4e Connected lakes

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

3.4.4f 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.

Figure 8. Indigenous forest in the Lake Okataina catchment, showing the contrast between an area with pest exclusion (right) and without (left). Image by D. Hamilton.

3.4.4g Summary

Total estimated loads to Lake Okataina were 27.3 t N y^{-1} and 1.6 t P y^{-1} (Figure 9). 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.

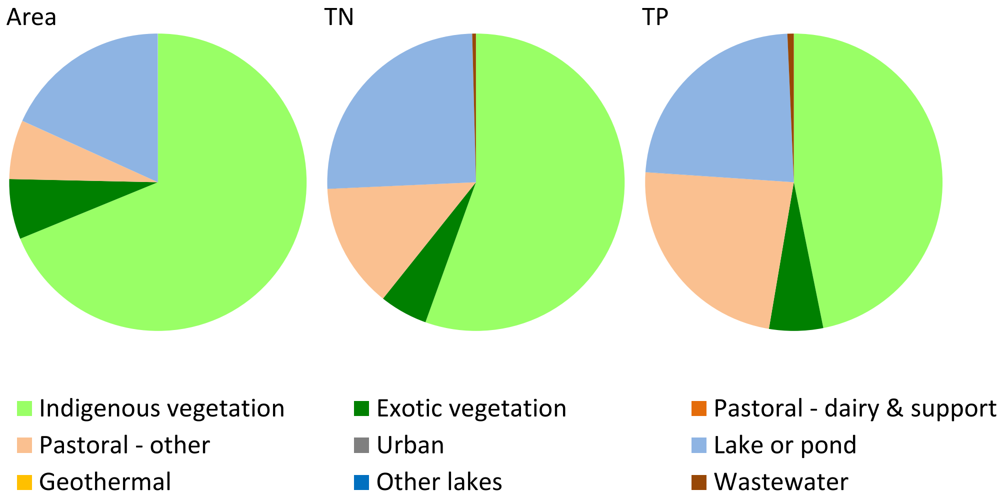

Figure 9. Proportional contribution of all sources within the Lake Okataina catchment to area, total nitrogen load, and total phosphorus load.

Table 5. Sources of nitrogen and phosphorus to Lake Okataina from its catchment. Loss rates that have been increased due to understorey clearing by pest animals are highlighted in yellow.

Land use (LCDB 4)	Area (ha)	Area (%)	N yield (kg N ha y^{-1})	N load (kg N y^{-1})	N load (%)	P yield (kg P ha y^{-1})	P load (kg P y^{-1})	P load (%)
Broadleaved Indigenous Hardwoods	198.2	3.3	3.67	**727**	2.7	0.18	**36**	2.3
Indigenous Forest	3695.1	61.7	3.67	**13561**	49.8	0.18	**665**	42.0
Manuka and/or Kanuka	228.9	3.8	3.67	**840**	3.1	0.18	**41**	2.6
Exotic Forest	297.1	5.0	1.31	**389**	1.4	0.20	**59**	3.7
Forest - Harvested	54.1	0.9	7.74	**419**	1.5	0.47	**25**	1.6
Gorse and/or Broom	40.8	0.7	15.00	**613**	2.2	0.20	**8**	0.5
High Producing Exotic Grassland								
Dry Stock	342.4	5.7	10.18	**3485**	12.8	1.02	**349**	22.0
Low Producing Grassland	42.2	0.7	5.00	**211**	0.8	0.50	**21**	1.3
Gravel or Rock	0.5	0.0	5.00	**3**	0.0	0.50	**0**	0.0
Herbaceous Freshwater Vegetation	9.8	0.2	0.00	**0**	0.0	0.00	**0**	0.0
Lake or Pond	1082.8	18.1	6.37	**6897**	25.3	0.34	**368**	23.2
Wastewater (30 pp)				**110**	0.4		**11**	0.7
Total	5991.9			**27255**			**1585**	

3.4.4 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 367 mg TN m^{-3}, 10 mg TP m^{-3}, and 4.1 mg chl *a* m^{-3} for the period 2009 – 2014 (Table 1). Rerewhakaaitu's TN:TP ratio of approximately 35:1 is the highest of all the Bay of Plenty 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 on the desorption (release) of dissolved phosphorus into the water column, resulting in increased phytoplankton production (Gibbs, pers. comm.).

3.4.4a 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 10). Importantly, the lake itself lies within a perched sub-catchment, and may only receive part of the total catchment out flow (anyone got a reference for this?).

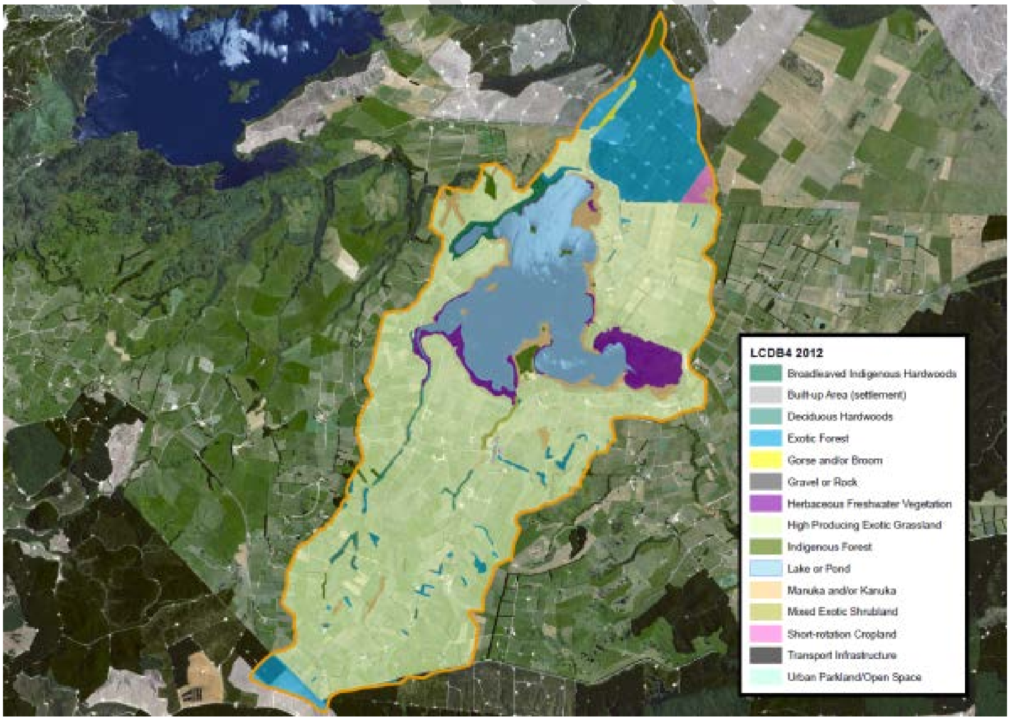

Figure 10. Map of land use (LCDB4) in the Rerewhakaaitu catchment.

3.4.4b Previous load estimates

BoPRC (2012a) estimated loads to Lake Rerewhakaaitu of 106.6 t N y^{-1} and 4.3 t P y^{-1}.

3.4.4c Land use classes

OVERSEER benchmarking of agricultural land use within the Rerewhakaaitu catchment was not available. Further, agricultural land according to LCDB (2392 ha) was less than given in McIntosh 2012a. Therefore, the high producing grassland area from LCDB was multiplied by the fraction of dairy and dry stock land presented in McIntosh 2012a, and dairy land was split evenly between dairy and dairy support. Loss rates applied to dairy land were taken from OVERSEER (v5.4.3) output for the nearest neighbouring lake, Okaro. Losses from dairy support were assumed to be half those of dairy land. Dry stock loss rates were unmodified from average loss rates described in 3.3.2a.

Land use loss rates used for non-agricultural land are described in section 3.2, and were not modified for the Lake Rerewhakaaitu catchment.

3.4.4d Geothermal inputs of nitrogen and phosphorus

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

3.4.4e Connected lakes

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

3.4.4f Wastewater

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

3.4.4g Summary

Total estimated loads from the total Lake Rerewhakaaitu catchment were 49.3 t N y^{-1} and 3.9 t P y^{-1} (Table 6). The estimated nitrogen load was substantially lower (approximately half) than the estimate of BoPRC (2012a). Nutrient inputs from non-agricultural land are a relatively insignificant proportion of overall load (Figure 11). It is important to note that because the lake sits in a perched sub-catchment, the total hydraulic (and therefore nutrient) load may not reach the lake (anyone got a reference for this?).

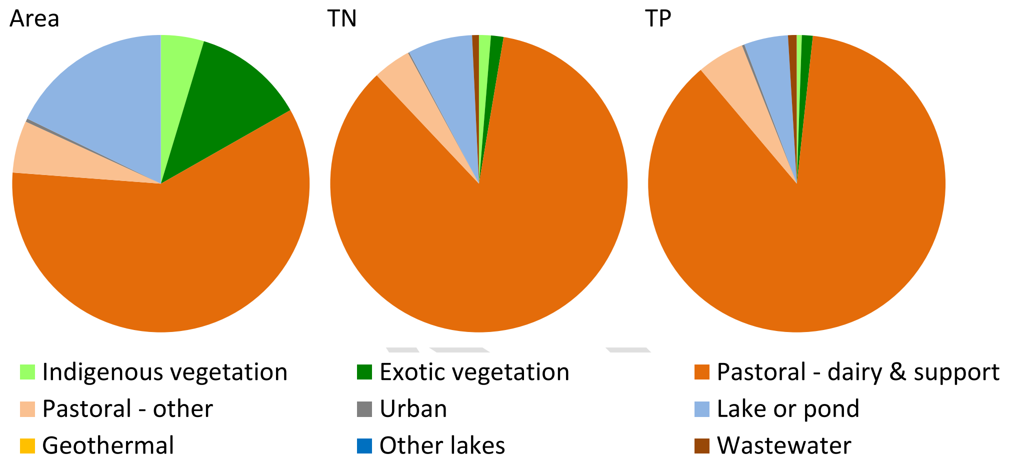

Figure 11. Proportional contribution of all sources within the Lake Rerewhakaaitu catchment to area, total nitrogen load, and total phosphorus load.

Table 6. Sources of nitrogen and phosphorus to Lake Rerewhakaaitu from its catchment.

Land use	Area	Area	N yield	N load	N load	P yield	P load	P load
(LCDB 4)	(ha)	(%)	(kg N ha y^{-1})	(kg N y^{-1})	(%)	(kg P ha y^{-1})	(kg P y^{-1})	(%)
Broadleaved Indigenous Hardwoods	27.0	0.7	3.67	**99**	0.2	0.12	**3**	0.1
Indigenous Forest	35.1	0.9	3.67	**129**	0.3	0.12	**4**	0.1
Manuka and/or Kanuka	111.2	3.0	3.67	**408**	0.8	0.12	**13**	0.3
Deciduous Hardwoods	21.8	0.6	1.31	**29**	0.1	0.10	**2**	0.1
Exotic Forest	411.7	11.1	1.31	**539**	1.1	0.10	**41**	1.1
Gorse and/or Broom	5.3	0.1	15.00	**80**	0.2	0.20	**1**	0.0
Mixed Exotic Shrubland	9.1	0.2	3.00	**27**	0.1	0.20	**2**	0.0
High Producing Exotic Grassland	(2391.75)							
Dairy	1100.0	29.7	25.50	**28050**	56.9	2.04	**2244**	58.1
Dairy Support	1100.0	29.7	12.75	**14025**	28.4	1.02	**1122**	29.0
Dry Stock	191.8	5.2	10.18	**1952**	4.0	1.02	**196**	5.1
Short-rotation Cropland	17.1	0.5	5.00	**86**	0.2	0.20	**3**	0.1
Built-up Area (settlement)	3.7	0.1	5.00	**19**	0.0	0.70	**3**	0.1
Gravel or Rock	3.3	0.1	5.00	**17**	0.0	0.50	**2**	0.0
Transport Infrastructure	3.7	0.1	5.00	**18**	0.0	1.00	**4**	0.1
Urban Parkland/Open Space	2.6	0.1	5.00	**13**	0.0	1.00	**3**	0.1
Herbaceous Freshwater Vegetation	113.9	3.1	0.00	**0**	0.0	0.00	**0**	0.0
Lake or Pond	544.7	14.7	6.37	**3470**	7.0	0.34	**185**	4.8
Wastewater (100 pp)				**365**	0.7		**37**	0.9
Total	**3702.1**			**49325**			**3864**	

Comment [CM5]: I would really like to tidy up the dairy/dairy support estimates here if possible

3.4.5 Lake Rotoehu

Rotoehu is a shallow lake (maximum depth c. 14 m), of high productivity, that has shown improvements in water quality over recent years. Nevertheless the lake still experiences blooms of cyanobacteria during summer. Its water quality is classed as eutrophic, with average surface water concentrations of 268 mg TN m^{-3}, 33 mg TP m^{-3}, and 6.6 mg chl *a* m^{-3} for the period 2009 – 2014 (Table 1). Rotoehu's TN:TP ratio of approximately 8:1 means it 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 – present). Substantial amounts of aquatic weeds are regularly harvested from the southern end of the lake, and a small floating wetland has been deployed at the southern shores.

Comment [CM6]: Include in nutrient budget?

3.4.5a 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 between indigenous forest, exotic forest, and pasture (Figure 12). 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.

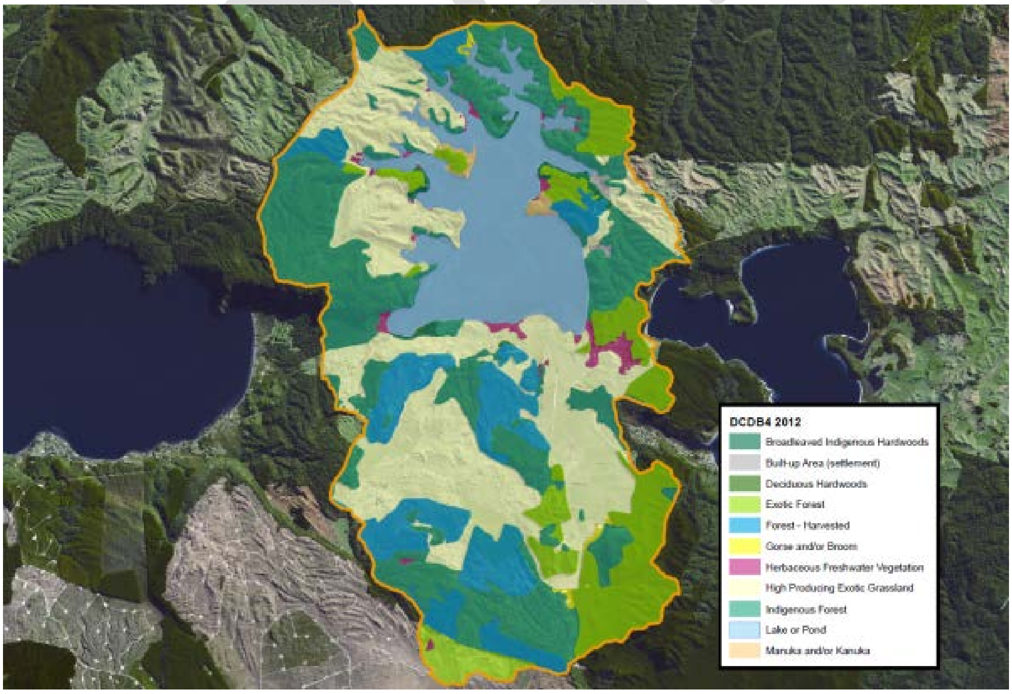

Figure 12. Map of land use (LCDB4) in the Rotoehu catchment.

3.4.5b Previous load estimates

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

3.4.5c Land use classes

Results from OVERSEER version 6.1.3 were available for estimating nutrient losses from agricultural land. The total area of benchmarked land was c. 1800 ha, whereas LCDB4 specified pastoral land cover of c. 1450 ha. For consistency with the approach in other catchments, the LCDB area was considered to be the total available pastoral land, and the OVERSEER loss rates were applied proportionally (Table 7).

Land use loss rates used for non-agricultural land in the catchment of Lake Rotoehu are described in section 3.2, and no adjustments to these rates were made.

3.4.5d 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 Wiatangi Spring. 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 7).

3.4.5e 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}. This total flow has been alum dosed although the Waitangi Stream receives the dose first.

3.4.5f Wastewater

The population estimate used for the purpose of calculating nutrient loads from septic tanks comprised a daily equivalent of 161 permanent (BoPRC 2007). The contribution of wastewater to overall load-to-lake was estimated to be 1.4 and 2.2 % for N and P respectively.

3.4.5g Summary

Total estimated loads to Lake Rotoehu were 41.4t N y^{-1} and 2.6 t P y^{-1} (Table 7). These loads were 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, and the figures from Donovan and Donovan (2003) adopted here may be an overestimate.

Comment [CM7]: Try and refine this

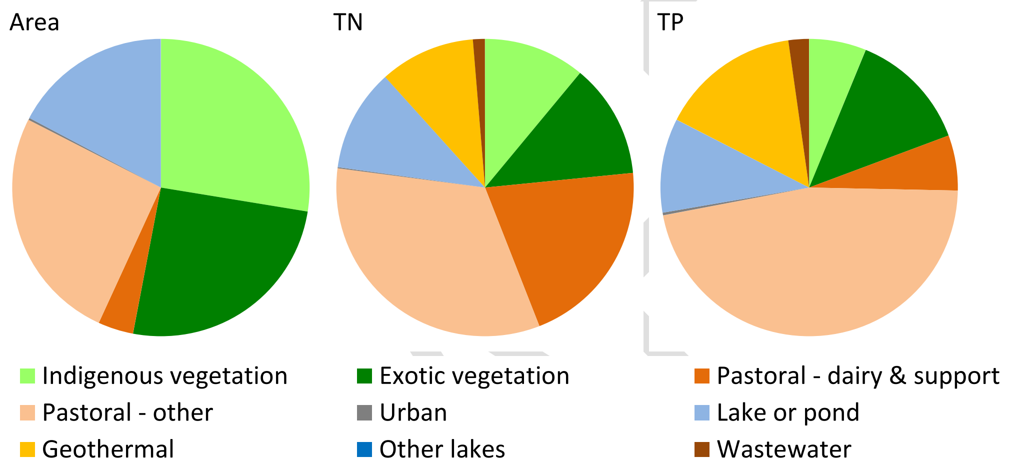

Figure 13. Proportional contribution of all sources within the Lake Rotoehu catchment to area, total nitrogen load, and total phosphorus load.

Table 7. Sources of nitrogen and phosphorus to Lake Rotoehu from its catchment. Areas highlighted in yellow denote adjusted OVERSEER area (see 3.4.5c) and in orange denotes geothermal load adjustment due to alum dosing (see 3.4.5d).

Land use	Area	Rule 11	Area	OVERSEER	N yield	N attenuation	N load	N load	P yield	P attenuation	P load	P load
(LCDB 4)	(ha)	(ha)	(%)	(version)	(kg N ha y^{-1})	(%)	(kg N y^{-1})	(%)	(kg P ha y^{-1})	(%)	(kg P y^{-1})	(%)
Broadleaved Indigenous Hardwoods	30.1		0.6		3.67		**110**	0.2	0.12		**4**	0.1
Indigenous Forest	1307.3		26.5		3.67		**4798**	10.2	0.12		**157**	5.9
Manuka and/or Kanuka	21.2		0.4		3.67		**78**	0.2	0.12		**3**	0.1
Deciduous Hardwoods	1.8		0.0		1.31		**2**	0.0	0.10		**0**	0.0
Exotic Forest	647.3		13.1		1.31		**848**	1.8	0.1		**65**	2.4
Forest - Harvested	588.2		11.9		7.74		**4552**	9.7	0.47		**276**	10.4
Gorse and/or Broom	14.8		0.3		15.00		**222**	0.5	0.2		**3**	0.1
High Producing Exotic Grassland	1453.4											
Dairy Support		14.5	0.3	6.1.3	12.33	26	**133**	0.3	2.88	60	**17**	0.6
Dairy		174.4	3.5	6.1.2a	71.26	26	**9197**	19.6	2.02	60	**141**	5.3
Dry Stock		1235.4	25.1	6.1.3	14.13	26	**12918**	27.6	2.44	60	**1206**	45.2
Effluent		29.1	0.6	6.1.2a	94.63	26	**2036**	4.3	1.73	60	**20**	0.8
Built-up Area (settlement)	10.8		0.2		5.00		**54**	0.1	0.70		**8**	0.3
Herbaceous Freshwater Vegetation	59.0		1.2		0.00		**0**	0.0	0		**0**	0.0
Lake or Pond	790.7		16.1		6.37		**5037**	10.7	0.34		**269**	10.1
Geothermal							**4700**	10.0			**400**	15.0
Other lakes (Rotoma)							**1616**				**42**	1.6
Wastewater (161 pp)							**588**	1.3			**59**	2.2
Total	4924.6						**46888**				**2668**	

3.4.6 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 2000's 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. This 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. 6.5 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 164 mg TN m^{-3}, 19 mg TP m^{-3}, and 5.0 mg chl *a* m^{-3} for the period 2009 – 2014 (Table 1).

3.4.6a Catchment description

Lake Rotoiti has a surface topographical 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 14). Lakeside communities are scattered around the lake, with the community at Okawa Bay having already been reticulated (2006), and much of the remaining households scheduled for reticulation in the coming years.

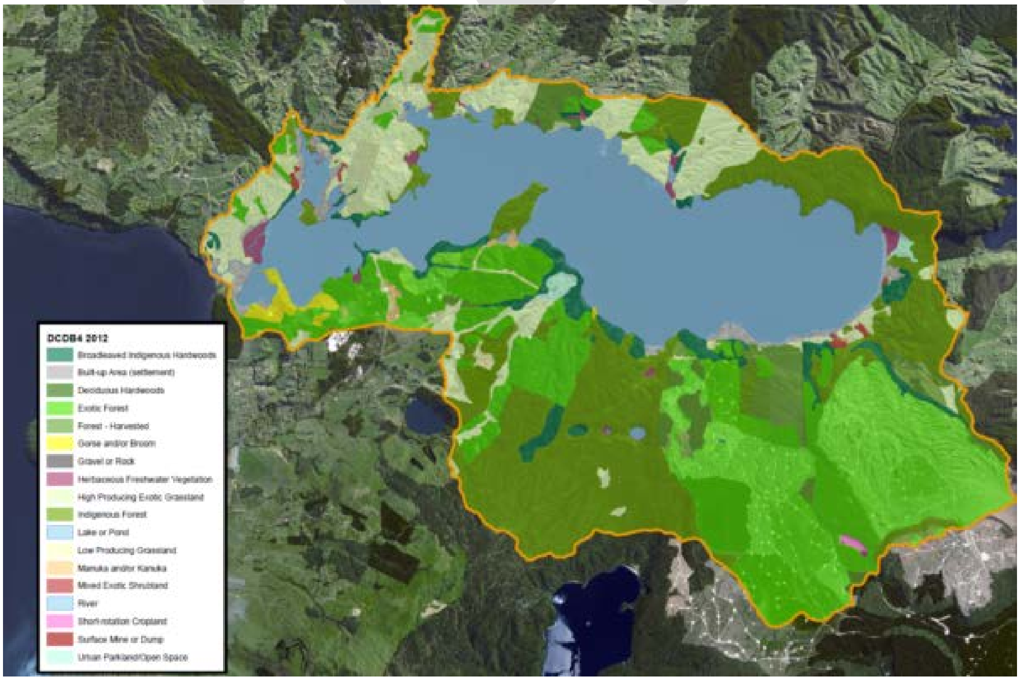

Figure 14. Map of land use (LCDB4) in the Rotokakahi catchment.

3.4.6b 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 o fhte diversion wall) and as such are not comparable with the loads presented here.

3.4.6c Land use classes

For agricultural land, OVERSEER benchmarking was available. A range of OVERSEER versions were available for various land classes. Attenuation factors were estimated as well as possible, for consistency between land uses within the Rotoiti catchment as well as for comparability of loss rates between catchments (Table 9).

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.

3.4.6d 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 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}. 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 a relatively conservative geothermal flow of 0.1 m^3 s^{-1}. Nevertheless, geothermal loads were estimated to account for c. 40 % and 8 % of N and P respectively. It should be noted that the actual geothermal load is highly uncertain and may be much higher.

Table 8. Flows from geothermal springs and streams entering Lake Rotoiti (BoPRC). Gauging was relatively infrequent (n < 10 per site).

Source	McIntosh 1993 - 1994 Mean (L s^{-1})	Bruesewitz 2009 - 2010 Mean (L s^{-1})	**Combined** Mean (L s^{-1})
Manupirua Spring			?
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			**56**

Comment [CM8]: John Mc to provide Manupirua data

3.4.6e Connected lakes

With the Ohau Channel diversion wall in place, Lake Rotoiti does not receive outflowing water from any other lakes.

3.4.6f 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 3.0 % and 6.4 % for N and P, respectively.

3.4.6g Summary

Total estimated loads to Lake Rotoiti were 87.9 t N y^{-1} and 4.0 t P y^{-1} (Table 9). Geothermal nitrogen appears to be a very important, contributing about one quarter of annual load. Wastewater (excluding Okawa Bay) contributes a small but significant portion of annual load, particularly for P. It is important to note 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. Further, the present analysis includes the entire surface catchment, whereas some of the surface catchment may drain to the area behind the diversion wall, and as such the values given here may be slight overestimates. Geothermal loads appear to be highly important, but are also highly uncertain.

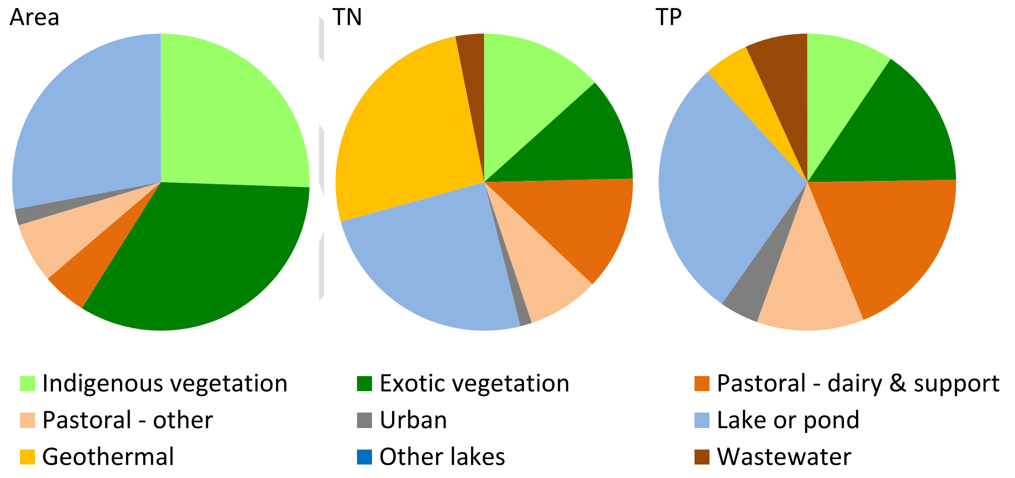

Figure 15. Proportional contribution of all sources within the Lake Rotoiti catchment to area, total nitrogen load, and total phosphorus load.

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

Land use	Area	Rule 11	Area	OVERSEER	N yield	N attenuation	N load	N load	P yield	P attenuation	P load	P load
(LCDB 4)	(ha)	(ha)	(%)	(version)	(kg N ha y^{-1})	(%)	(kg N y^{-1})	(%)	(kg P ha y^{-1})	(%)	(kg P y^{-1})	(%)
Broadleaved Indigenous Hardwoods	417.8		3.3		3.67		**1533**	1.4	0.12		**50**	1.2
Indigenous Forest	2741.8		22.0		3.67		**10062**	9.5	0.12		**329**	7.9
Manuka and/or Kanuka	31.0		0.2		3.67		**114**	0.1	0.12		**4**	0.1
Deciduous Hardwoods	1.4		0.0		1.31		**2**	0.0	0.10		**0**	0.0
Exotic Forest	3540.3		28.4		1.31		**4638**	4.4	0.10		**354**	8.5
Forest - Harvested	519.5		4.2		7.74		**4021**	3.8	0.47		**244**	5.9
Gorse and/or Broom	80.3		0.6		15.00		**1204**	1.1	0.20		**16**	0.4
Mixed Exotic Shrubland	22.4		0.2		3.00		**67**	0.1	0.20		**4**	0.1
High Producing Exotic Grassland	1374.2											
Cut and Carry		22.4	0.2	6.1.3	18.97	26	**315**	0.3	0.35	60	**3**	0.1
Dairy Support		478.2	3.8	6.1.2	19.16	26	**6806**	6.4	2.81	60	**538**	12.9
Dairy		125.0	1.0	5.4.11	33.09	0	**4136**	3.9	4.73	60	**237**	5.7
Dry Stock		463.2	3.7	6.1.3	11.30	26	**3888**	3.7	1.50	60	**278**	6.7
Non-productive		1.8	0.0	6.1.3	0.00	26	**0**	0.0	0.00	60	**0**	0.0
Not benchmarked		283.6	2.3	n/a	11.30	26	**2380**	2.2	1.50	60	**170**	4.1
Low Producing Grassland	36.5		0.3		5.00		**182**	0.2	0.50		**18**	0.4
Short-rotation Cropland	10.6		0.1		5.00		**53**	0.1	0.20		**2**	0.1
Built-up Area (settlement)	175.1		1.4		5.00		**875**	0.8	0.70		**123**	2.9
Gravel or Rock	0.3		0.0		5.00		**2**	0.0	0.50		**0**	0.0
Surface Mine or Dump	1.1		0.0		5.00		**5**	0.0	2.00		**2**	0.1
Urban Parkland/Open Space	46.7		0.4		5.00		**233**	0.2	1.00		**47**	1.1
Herbaceous Freshwater Vegetation	83.6		0.7		0.00		**0**	0.0	0.00		**0**	0.0
Lake or Pond	3396.2		27.2		6.37		**21634**	20.4	0.34		**1155**	27.7
River	5.1		0.0		0.00		**0**	0.0	0.00		**0**	0.0
Geothermal							**41025**	38.7			**316**	7.6
Wastewater (753 pp)							**2748**	2.6			**275**	6.6
Total	12483.5						**105925**				**4164**	

3.4.7 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 235 mg TN m^{-3} and 55 mg TP m^{-3} for the period 2009 – 2014 (UoW, unpubl. data). Water quality has been highly variable in this lake, with steep increases in water column total nutrients coincident with partial logging of forestry adjacent to the lake shore. Rotokakahi's TN:TP ratio of approximately 4.3:1 is the lowest of all the Bay of Plenty lakes, meaning it is likely N-limited, and the management of catchment sources of P is important for protection of water quality in the lake.

3.4.7a 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 14). There are no built-up areas and all pastoral land is dry stock.

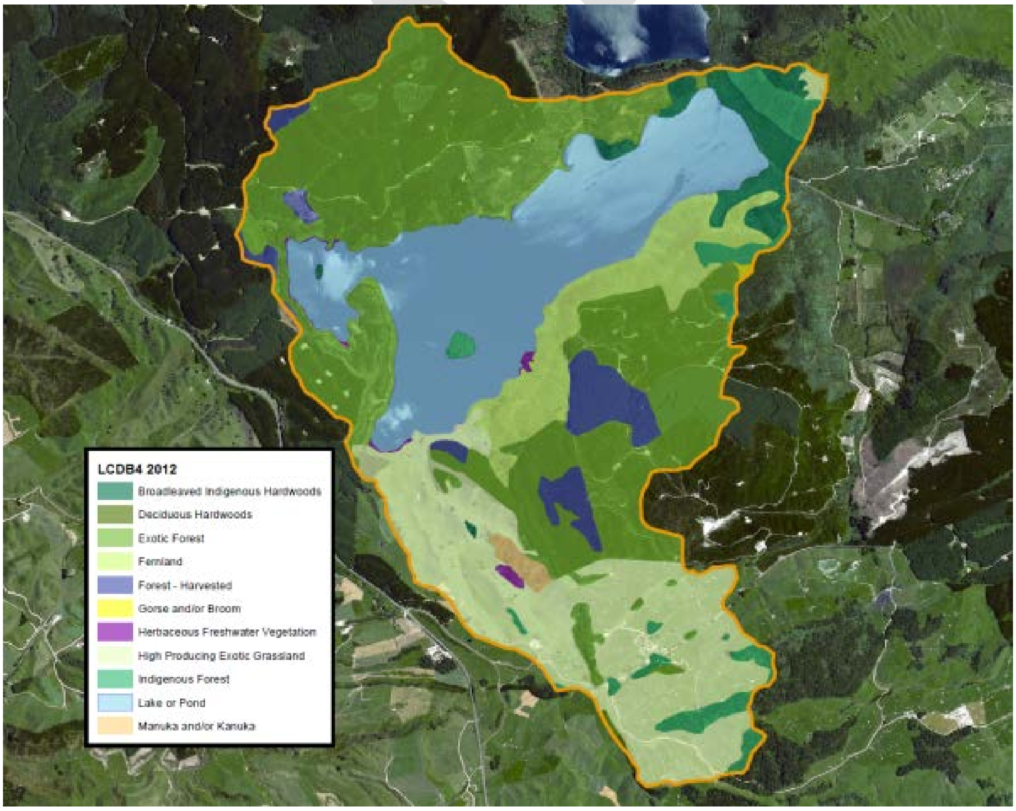

Figure 16. Map of land use (LCDB4) in the Rotokakahi catchment.

3.4.7b Previous load estimates

No previous estimates of loads to Lake Rotokakahi are available.

3.4.7c Land use classes

OVERSEER benchmarking of agricultural land use within the Rotokakahi catchment was not available. Therefore, for dry stock land, average loss rates of 10.18 kg N ha^{-1} y^{-1} and 1.02 kg P ha^{-1} y^{-1} were applied (see 3.3.2a).

For other land uses, loss rates used are described in section 3.2 and no adjustments were made for the catchment of Lake Rotokakahi.

3.4.7d Geothermal inputs of nitrogen and phosphorus

Lake Rerewhakaaitu is not geothermally influenced (Nairn 1981).

3.4.7e Connected lakes

Lake Rotokakahi may receive part of the subsurface outflow from Lake Tikitapu, although the nature of this flow is unknown (McIntosh, pers. comm.).

3.4.7f Wastewater

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

3.4.7g Summary

Total estimated loads to Lake Rotokakahi were 34.3 t N y^{-1} and 0.76 t P y^{-1} (Table 10). 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.

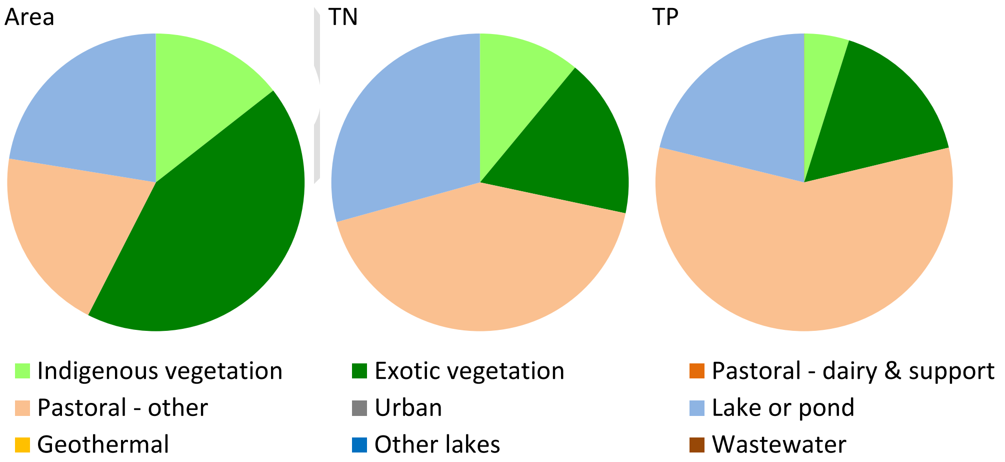

Figure 17. Proportional contribution of all sources within the Lake Rotokakahi catchment to area, total nitrogen load, and total phosphorus load.

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

Land use (LCDB 4)	Area (ha)	Area (%)	N yield (kg N ha y^{-1})	N load (kg N y^{-1})	N load (%)	P yield (kg P ha y^{-1})	P load (kg P y^{-1})	P load (%)
Broadleaved Indigenous Hardwoods	64.6	3.3	3.67	**237**	2.5	0.12	**8**	1.1
Fernland	134.6	6.8	3.67	**494**	5.2	0.12	**16**	2.3
Indigenous Forest	74.4	3.8	3.67	**273**	2.9	0.12	**9**	1.3
Manuka and/or Kanuka	11.4	0.6	3.67	**42**	0.4	0.12	**1**	0.2
Deciduous hardwoods	1.8	0.1	1.31	**2**	0.0	0.10	**0**	0.0
Exotic Forest	767.6	38.9	1.31	**1006**	10.6	0.10	**77**	11.0
Forest - Harvested	80.0	4.1	7.74	**619**	6.5	0.47	**38**	5.4
Gorse and/or Broom	1.3	0.1	15.00	**20**	0.2	0.20	**0**	0.0
High Producing Exotic Grassland								
Dry Stock	395.6	20.0	10.18	**4027**	42.4	1.02	**403**	57.6
Herbaceous Freshwater Vegetation	6.2	0.3	0.00	**0**	0.0	0.00	**0**	0.0
Lake or Pond	436.9	22.1	6.37	**2783**	29.3	0.34	**149**	21.2
Wastewater (0 pp)				**0**	0.0		**0**	0.0
Total	1974.4			**9503**			**701**	

3.4.8 Lake Rotoma

Rotoma is a deep monomictic lake (maximum depth c. 83 m). It has the highest water quality of all the Bay of Plenty lakes, with average surface water concentrations of 102 mg TN m^{-3}, 5.3 mg TP m^{-3}, and 1.1 mg chl *a* m^{-3} for the period 2009 – 2014 (Table 1). Rotoma's TN:TP ratio of approximately 19:1 is high among the Bay of Plenty lakes, and the lake is likely P-limited.

3.4.8a 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 18). 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 100ha 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.

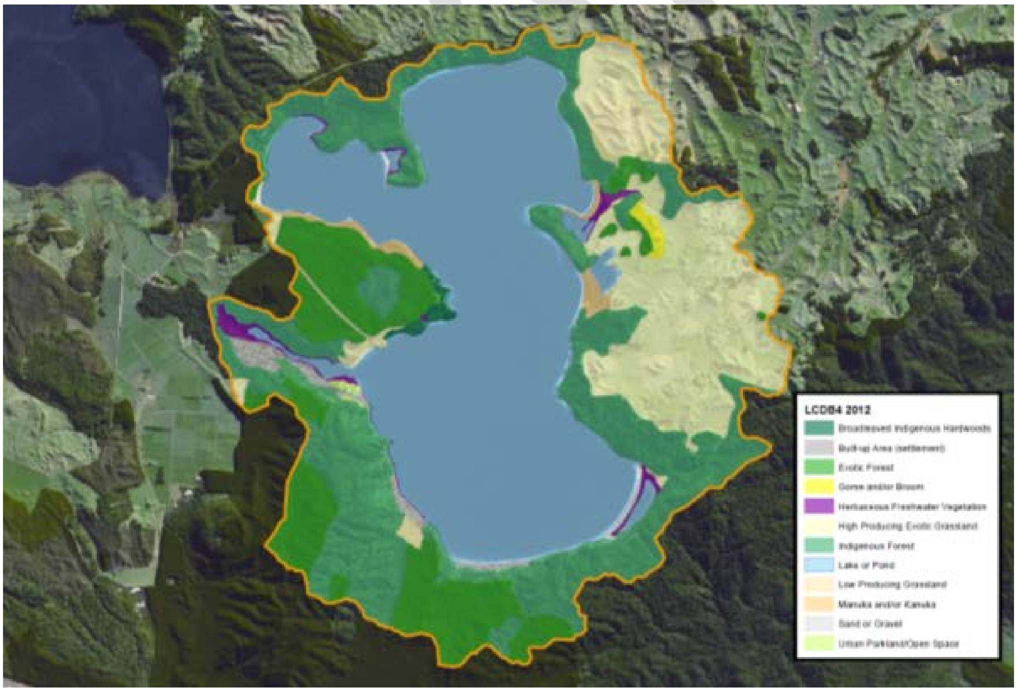

Figure 18. Map of land use (LCDB4) in the Rotoma catchment.

3.4.8b Previous load estimates

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

3.4.8c Land use classes

Results from OVERSEER version 6.1.3 were available for estimating nutrient losses from agricultural land (Table 11). 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.

3.4.8d Geothermal inputs of nitrogen and phosphorus

An early study of nutrient loads to Lake Rotoma (Bioresearches 1991) noted that the Otei Hot Spring flows to the lake, and described geothermal flows ranging from 11 to 53 L s^{-1}. Lake Rerewhakaaitu is not geothermally influenced. 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. Because of the relatively low observed volumes and uncertain nutrient concentrations, the present study therefore assumes a geothermal load of zero.

Comment [CM9]: Is this reasonable?

3.4.8e Connected lakes

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

3.4.8f 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; RDC). 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.

3.4.8g Summary

Total estimated loads to Lake Rotoma were 14.9 t N y^{-1} and 1.1 t P y^{-1} (Table 11), relatively lower for N and higher for P when 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 (see 3.4.8a), and the interception of surface flows by the lake shore lagoons, may mean that the loads presented here are a slight overestimate.

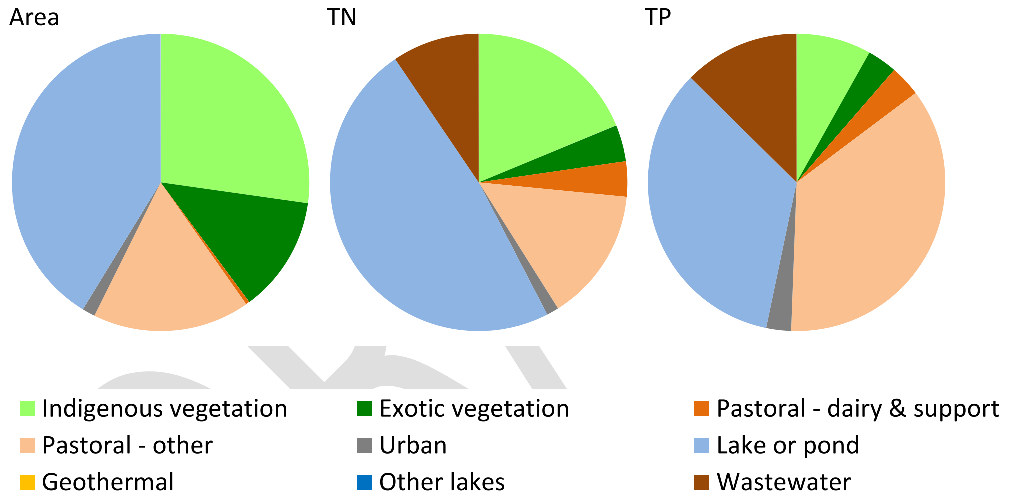

Figure 19. Proportional contribution of all sources within the Lake Rotoma catchment to area, total nitrogen load, and total phosphorus load.

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

Land use	**Area**	**Rule 11**	**Area**	**OVERSEER**	**N yield**	**N attenuation**	**N load**	**N load**	**P yield**	**P attenuation**	**P load**	**P load**
(LCDB 4)	(ha)	(ha)	(%)	(version)	(kg N ha y^{-1})	(%)	(kg N y^{-1})	(%)	(kg P ha y^{-1})	(%)	(kg P y^{-1})	(%)
Broadleaved Indigenous Hardwoods	13.7		0.5		3.67		**50**	0.3	0.12		**2**	0.1
Indigenous Forest	721.1		25.9		3.67		**2646**	17.8	0.12		**87**	7.7
Manuka and/or Kanuka	24.6		0.9		3.67		**90**	0.6	0.12		**3**	0.3
Exotic Forest	342.0		12.3		1.31		**448**	3.0	0.10		**34**	3.1
Gorse and/or Broom	9.6		0.3		15.00		**144**	1.0	0.20		**2**	0.2
High Producing Exotic Grassland	482.1											
Dairy		11.3	0.4	6.1.2a	68.01	26	**569**	3.8	8.37	60	**38**	3.4
Dry Stock		0.1	0.0	6.1.3	6.09	26	**1**	0.0	4.23	80	**0**	0.0
Not benchmarked		470.7	16.9	n/a	6.09	26	**2129**	14.3	4.23	80	**398**	35.6
Low Producing Grassland	5.7		0.2		5.00		**28**	0.2	0.50		**3**	0.3
Built-up Area (settlement)	30.0		1.1		5.00		**150**	1.0	0.70		**21**	1.9
Sand or Gravel	5.1		0.2		5.00		**25**	0.2	1.00		**5**	0.5
Urban Parkland/Open Space	4.0		0.1		5.00		**20**	0.1	1.00		**4**	0.4
Herbaceous Freshwater Vegetation	26.0		0.9		0.00		**0**	0.0	0.00		**0**	0.0
Lake or Pond	1123.9		40.3		6.37		**7159**	48.1	0.34		**382**	34.1
Wastewater (386 pp)							**1409**	9.5			**141**	12.6
Total	2787.8						**14870**				**1119**	

3.4.9 Lake Rotomahana

Rotomahana is a deep lake (maximum depth c. 112 m) of mestrophic 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 Bay of Plenty 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.

3.4.9a 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 20). The outflow drains to Lake Tarawera at the north.

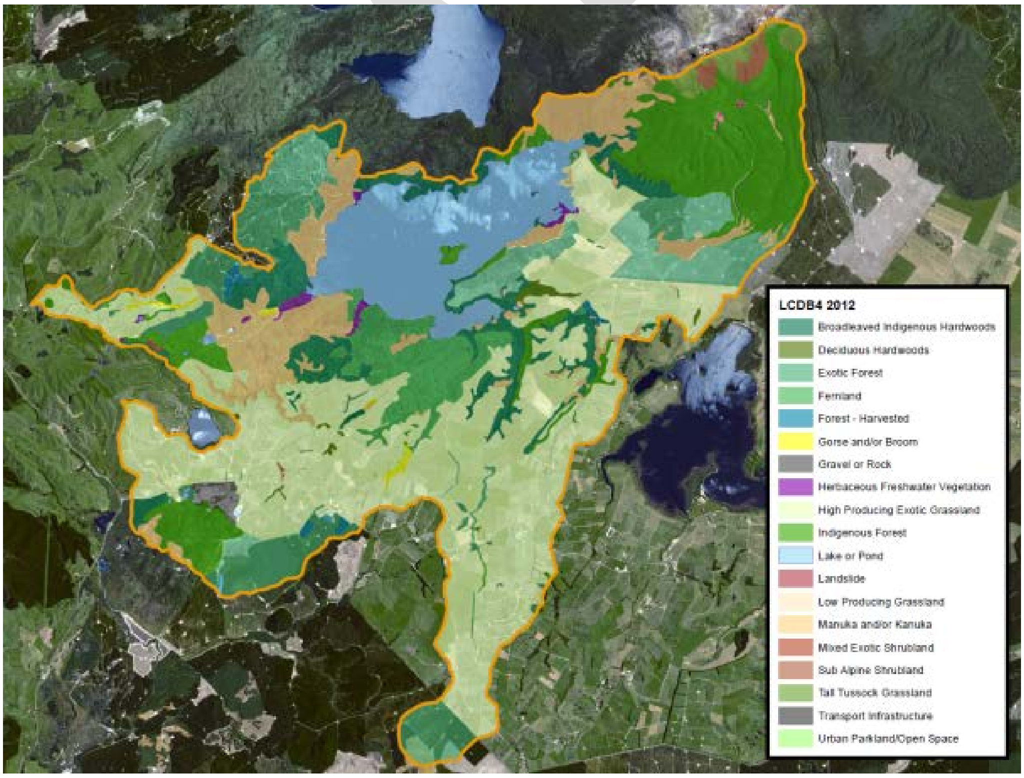

Figure 20. Map of land use (LCDB4) in the Rotomahana catchment.

3.4.9b 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.

3.4.9c Land use classes

OVERSEER benchmarking of agricultural land use within the Rotokakahi catchment was not available. Therefore, for dry stock land, average loss rates of 10.18 kg N ha^{-1} y^{-1} and 1.02 kg P ha^{-1} y^{-1} were applied (see 3.3.2a).

For other land uses, loss rates used are described in section 3.2 and no adjustments were made for the catchment of Lake Rotokakahi.

3.4.9d 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. Although the 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, as is the case with the neighbouring Lake Tarawera. For the present study we assumed a similar geothermal load to neighbouring Lake Tarawera. It should be noted that these loads are highly uncertain.

3.4.9e 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 Tarawera, as in Hamilton et al. (2006).

3.4.9f 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.

Comment [CM10]: Can anyone improve this estimate?

3.4.9g 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.

3.4.9g Summary

Total estimated loads to Lake Rotomahana were 68.0 t N y^{-1} and 9.6 t P y^{-1} (Table 12). 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.

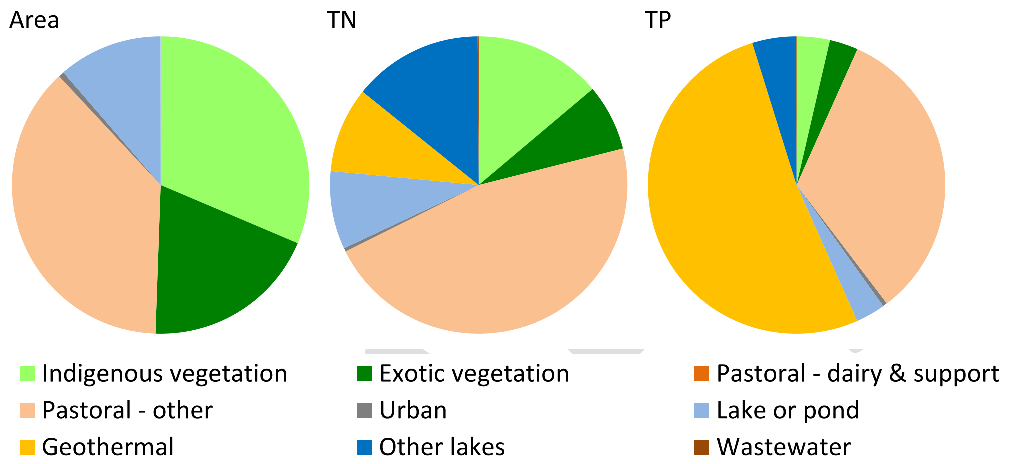

Figure 21. Proportional contribution of all sources within the Lake Rotomahana catchment to area, total nitrogen load, and total phosphorus load.

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

Land use (LCDB 4)	**Area** (ha)	**Area** (%)	**N yield** (kg N ha y^{-1})	**N load** (kg N y^{-1})	**N load** (%)	**P yield** (kg P ha y^{-1})	**P load** (kg P y^{-1})	**P load** (%)
Broadleaved Indigenous Hardwoods	551.6	6.6	3.67	**2024**	3.0	0.12	**66**	0.7
Indigenous Forest	1109.8	13.4	3.67	**4073**	6.0	0.12	**133**	1.4
Manuka and/or Kanuka	812.6	9.8	3.67	**2982**	4.4	0.12	**98**	1.0
Sub Alpine Shrubland	47.0	0.6	2.00	**94**	0.1	0.20	**9**	0.1
Tall Tussock Grassland	83.3	1.0	3.00	**250**	0.4	0.50	**42**	0.4
Deciduous Hardwoods	30.4	0.4	1.31	**40**	0.1	0.10	**3**	0.0
Exotic Forest	1155.8	13.9	1.31	**1514**	2.2	0.10	**116**	1.2
Forest - Harvested	368.2	4.4	7.74	**2850**	4.2	0.47	**173**	1.8
Gorse and/or Broom	31.5	0.4	15.00	**472**	0.7	0.20	**6**	0.1
Mixed Exotic Shrubland	4.7	0.1	3.00	**14**	0.0	0.20	**1**	0.0
High Producing Exotic Grassland								
Dry Stock	3109.7	37.5	10.18	**31657**	46.6	1.02	**3172**	32.9
Low Producing Grassland	1.6	0.0	5.00	**8**	0.0	0.50	**1**	0.0
Gravel or Rock	9.5	0.1	5.00	**47**	0.1	0.50	**5**	0.0
Transport Infrastructure	40.9	0.5	5.00	**204**	0.3	1.00	**41**	0.4
Urban Parkland/Open Space	0.0	0.0	5.00	**0**	0.0	1.00	**0**	0.0
Herbaceous Freshwater Vegetation	34.4	0.4	0.00	**0**	0.0	0.00	**0**	0.0
Lake or Pond	906.7	10.9	6.37	**5776**	8.5	0.34	**308**	3.2
Geothermal				**6300**	9.3		**5000**	51.9
Other Lakes								
Okaro				**3470**	5.1		**280**	2.9
Rerewhakaaitu (50 % of)				**6130**	9.0		**175**	1.8
Wastewater (20 pp)				**73**	0.1		**7**	0.1
Total	8297.6			**67979**			**9636**	

3.4.10 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* in the early 2000's. Its water quality is classed as eutrophic, with average surface water concentrations of 321 mg TN m^{-3}, 20 mg TP m^{-3}, and 12.2 mg chl *a* m^{-3} for the period 2009 – 2014 (Table 1). Rotorua's TN:TP ratio of approximately 16:1 is relatively high, possibly a result of alum dosing of two of its inflows (Ozkundakci et al. 2014, Hamilton et al. 2014). 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).

3.4.10a Catchment description

Lake Rotorua has a surface topographical catchment area of 597.4 km^2, including the lake area of 80.97 km^2 (LCDB4). Much of the catchment is forested (roughly evenly split between indigenous and exotic), and an equal amount is pastoral including dairy and dairy support (Figure 22). 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.

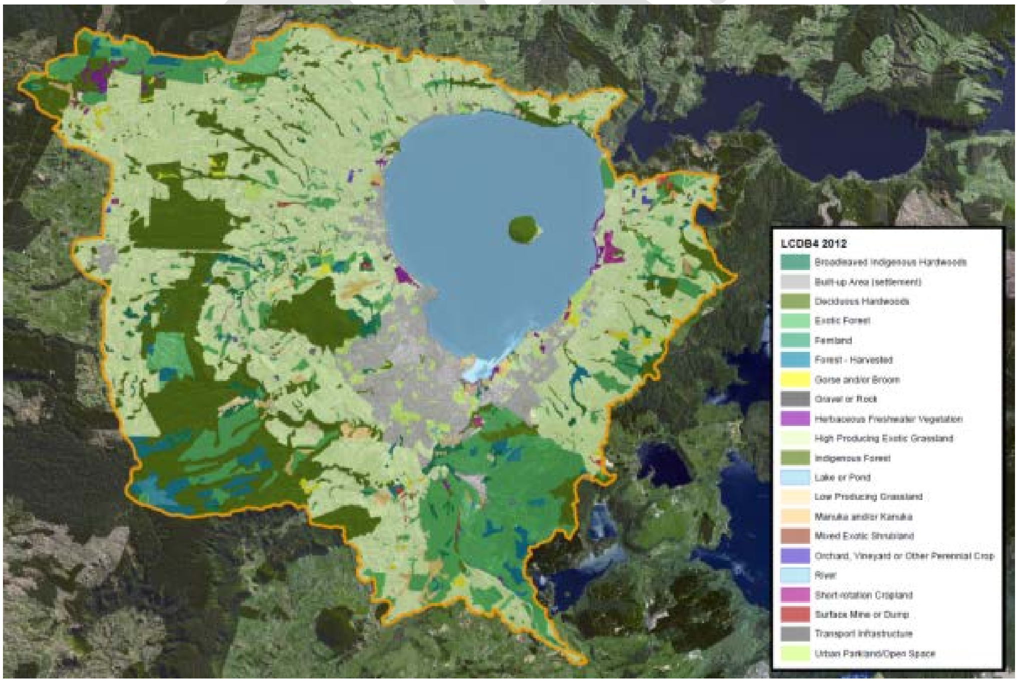

Figure 22. Map of land use (LCDB4) in the Rotorua catchment.

3.4.10b Previous load estimates

Water quality of Lake Rotorua has been the focus of a substantial body of reseach, and many estimations of catchment loads to the lake have been made by a variety of methods, summarised in Table 13. Rutherford et al. presented a summary of catchment nutrient budgets which used in stream measurements and estimates of sewage loads and atmospheric deposition. Burger et al. (2007) and Hamilton et al. (2015) estimated total load to the lake as part 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 (Rutherford et al. 2011).

Table 13. Previous estimates of catchment loads to Lake Rotorua

Study	Source	Years	Incl. atmos. Dep.?	Includes geoth. sources?	Wstwtrr N load ($t\ N\ y^{-1}$)	Wstwtr P load ($t\ P\ y^{-1}$)	Total N load ($t\ N\ y^{-1}$)	Total P load ($t\ P\ y^{-1}$)
?	Rutherford et al. (1989)	1965	Yes	streams only	70	5	**475**	**39**
Hoare (1980)	Rutherford et al. (1989)	1976 - 1977	Yes	streams only	146	7.8	**558**	**42**
?	Rutherford et al. (1989)	1981 - 1982	Yes	streams only	149	20.6	**554**	**55**
?	Rutherford et al. (1989)	1984 - 1985	Yes	streams only	160	33.8	**565**	**68**
Burger et al. (2007)		2001 - 2004	**No**	Yes	ns	ns	**501.5**	**33.1**
BoPRC (2009)		2009	**ns**	ns	ns	ns	**556**	**39.1**
Hamilton et al. (2014)		2001 - 2012	Yes	Yes	30	<2	**661***	**33.1**

*Nitrogen load estimate from ROTAN model

3.4.10c Land use classes

Results from OVERSEER version 6.1.3 were available for estimating nutrient losses from agricultural land (Table 14). 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.

3.4.10d Geothermal inputs of nitrogen and phosphorus

Lake Rotorua is moderately geothermally influenced and McColl (1975) found 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 mostly derived from the Waiohewa Stream, and recent monitoring data suggest the Waiohewa loads are much lower.

Available flow and nutrient concentration data from BoPRC (unpubl.) were used to estimate for the present study loads of 33.5 t N y^{-1} and 2.0 t P y^{-1}. These loads are subject to a substantial degree of uncertainty.

Comment [CM11]: May be possible/important to improve these estimates with more info?

3.4.10e Connected lakes

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

3.4.10e Wastewater

Post-treatment wastewater loads are intensively measured 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 2009 to 2014 were 30.0 t N y^{-1} and 1.7 t P y^{-1}.

3.4.10g Summary

Total estimated loads to Lake Rotorua were 589.3 t N y^{-1} and 31.6 t P y^{-1} (Table 14). These are within the range of previous estimates (Table 13). According to the present estimates, pastoral land accounts for more than two thirds of N load and more than 60 % of P load Figure 23. 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) and as such prior to the degradation of water quality in the lake. As an example, according to these estimates converting half of all pastoral land to indigenous forest would result in a load of 430.5 t N y^{-1}.

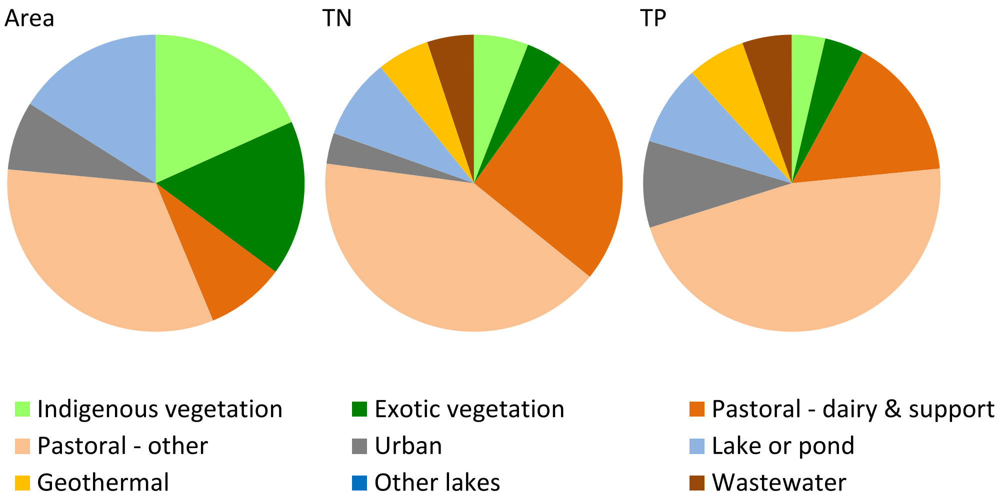

Figure 23. Proportional contribution of all sources within the Lake Rotorua catchment to area, total nitrogen load, and total phosphorus load.

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

Land use	Area	Rule 11	Area	OVERSEER	N yield	N attenuation	N load	N load	P yield	P attenuation	P load	P load
(LCDB 4)	(ha)	(ha)	(%)	(version)	(kg N ha y^{-1})	(%)	(kg N y^{-1})	(%)	(kg P ha y^{-1})	(%)	(kg P y^{-1})	(%)
Broadleaved Indigenous Hardwoods	905.5		1.7		3.67		3323	0.6	0.12		109	0.3
Fernland	26.1		0.0		3.67		96	0.0	0.12		3	0.0
Indigenous Forest	8012.1		15.3		3.67		29404	5.0	0.12		961	3.0
Manuka and/or Kanuka	597.2		1.1		3.50		2090	0.4	0.12		72	0.2
Deciduous Hardwoods	221.0		0.4		1.31		290	0.0	0.10		22	0.1
Exotic Forest	7067.8		13.5		1.31		9259	1.6	0.10		707	2.2
Forest - Harvested	1167.7		2.2		7.74		9038	1.5	0.47		549	1.7
Gorse and/or Broom	309.8		0.6		15.00		4647	0.8	0.20		62	0.2
Mixed Exotic Shrubland	66.2		0.1		3.00		199	0.0	0.20		13	0.0
High Producing Exotic Grassland	21343.7											
Cut and Carry		212.5	0.4	6.1.3	15.07	26	2379	0.4	0.31	60	26	0.1
Dairy Support		2208.6	4.2	6.1.3	28.37	26	46541	7.9	1.83	60	1617	5.1
Dairy		2273.9	4.4	6.1.3	62.86	26	106175	18.0	3.62	60	3293	10.4
Dry Stock		8914.8	17.1	6.1.3	17.70	26	117208	19.9	2.19	60	7809	24.7
Effluent		337.8	0.6	6.1.3	99.70	26	25017	4.2	2.69	60	363	1.1
Not benchmarked		7396.1	14.2	n/a	17.70	26	97241	16.5	2.19	60	6479	20.5
Low Producing Grassland	124.8		0.2		5.00		624	0.1	0.50		62	0.2
Orchard, Vineyard or Other Perennial Crop	44.3		0.1		10.00		443	0.1	0.50		22	0.1
Short-rotation Cropland	89.9		0.2		5.00		449	0.1	0.20		18	0.1
Built-up Area (settlement)	3242.9		6.2		5.00		16214	2.8	0.70		2270	7.2
Gravel or Rock	20.3		0.0		5.00		102	0.0	0.50		10	0.0
Surface Mine or Dump	55.5		0.1		10.00		555	0.1	2.00		111	0.4
Transport Infrastructure	19.7		0.0		5.00		98	0.0	1.00		20	0.1
Urban Parkland/Open Space	569.2		1.1		5.00		2846	0.5	1.00		569	1.8
Herbaceous Freshwater Vegetation	282.5		0.5		0.00		0	0.0	0.00		0	0.0
Lake or Pond	8096.9		15.5		6.37		51577	8.8	0.34		2753	8.7
River	4.4		0.0		0.00		0	0.0	0.00		0	0.0
Geothermal							33500	5.7			2000	6.3
Wastewater (LTS load-to-lake)							30000	5.1			1700	5.4
Total	52267.5		100.0				589316				31621	

3.4.11 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 88 mg TN m^{-3}, 17 mg TP m^{-3}, and 1.9 mg chl *a* m^{-3} for the period 2009 – 2014 (Table 1). Tarawera's TN:TP ratio of approximately 5:1 is low among the Bay of Plenty lakes..

3.4.11a 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 24). Approximately 1800 ha of pastoral land is 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 other Bay of Plenty lakes, thus it has an 'inner' catchment (described above), and 'greater' catchment which includes the catchments of seven additional lakes. 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. Tarawera receives water indirectly from the catchments of Lakes Okaro and Rerewhakaaitu, which both flow to Lake Rotomahana.

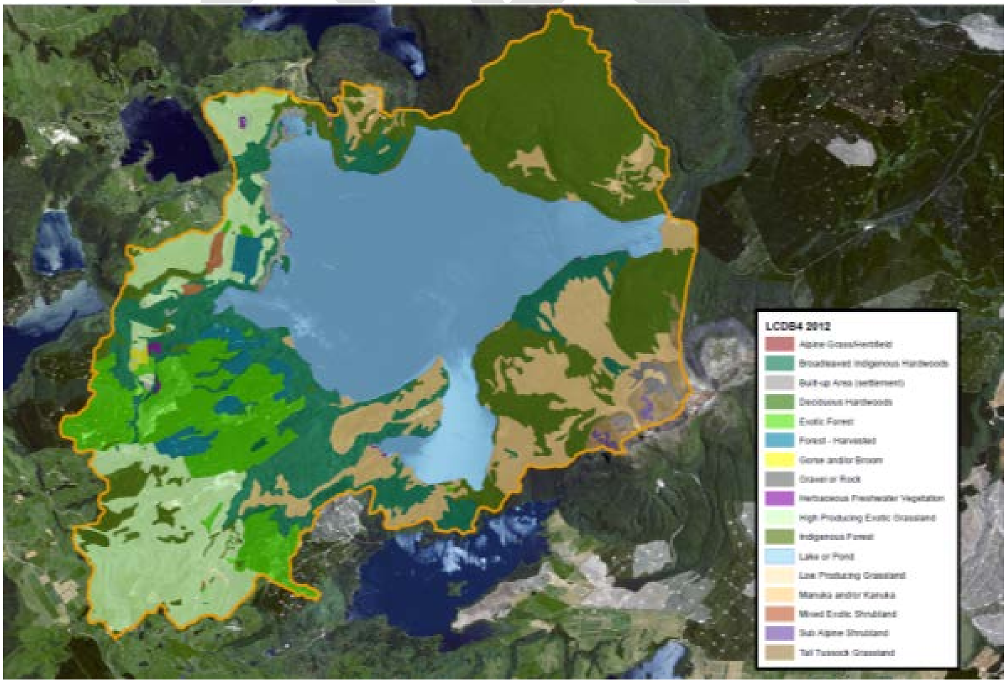

Figure 24. Map of land use (LCDB4) in the Tarawera catchment.

3.4.11b Previous load estimates

Hamilton et al. (2006) estimated annual loads from the greater Tarawera catchment of 84.6 t N y^{-1} and 10.4 t P y^{-1}. These estimates did not account for geothermal inputs to the lake. 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}.

3.4.11c Land use classes

OVERSEER benchmarking of agricultural land use within the Tarawera catchment was not available. Therefore, all pastoral land was assumed to be dry stock, average loss rates of 10.18 kg N ha^{-1} y^{-1} and 1.02 kg P ha^{-1} y^{-1} were applied (see 3.3.2a).

For other land uses, loss rates used are described in section 3.2 and no adjustments were made for the catchment of Lake Tarawera. Alpine grassland was assumed to have similar loss rates to indigenous forest.

3.4.11d 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}, 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 0.4 g P m^{-3} and 0.5 g N m^{-3}. For this study, geothermal loads were estimated by multiplying observed concentrations with estimated flow (0.4 m^3 s^{-1}; or 6% of the lake outflow), yielding estimated loads of 5 t P y^{-1} and 6.3 t N y^{-1}.

3.4.11e 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 2009 to 2014 (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 30.3 t N y^{-1} and 5.5 t P y^{-1} (Table 15). No attenuation between lakes was assumed.

3.4.11f 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).

3.4.11g Other features

Mean measrured 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 also 6 6.7 $m^3\ s^{-1}$ (Woods 2006). Lake Tarawera outflow would be expected to be much higher than the combined flows form 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 an additional c. 4 $m^3\ s^{-1}$ discharges from the lake, also to the Tarawera River but downstream of the lake outlet (P. White, pers. comm.), which may account for hydraulic load from all sources.

3.4.11h Summary

Total estimated loads to Lake Tarawera were 113 t N y^{-1} and 15.3 t P y^{-1} (Table 15). 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 (Figure 4). This may help explain the relatively high P concentrations and low TN:TP ratio in the lake.

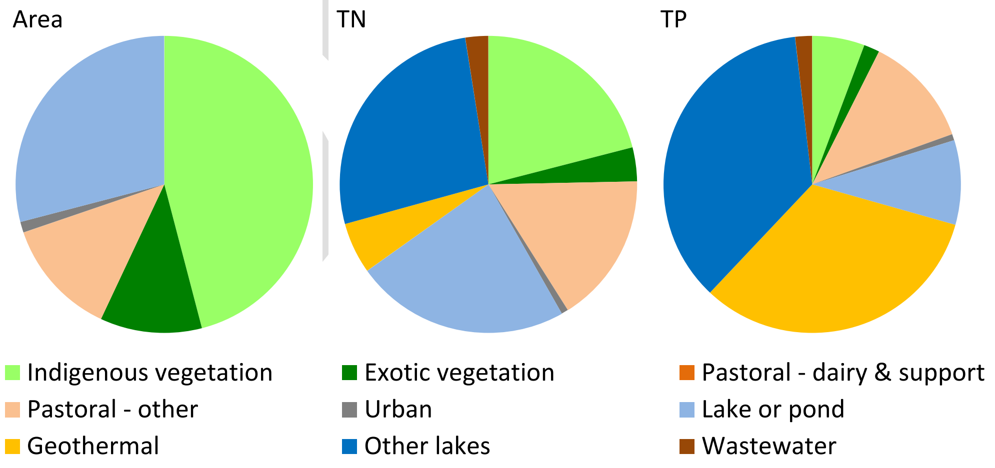

Figure 25. Proportional contribution of all nutrient sources within the greater Lake Tarawera catchment to area, total nitrogen load, and total phosphorus load.

Table 15. Sources of nitrogen and phosphorus to Lake Tarawera from the greater Tarawera catchment.

Land use (LCDB 4)	Area (ha)	Area (%)	N yield (kg N ha y^{-1})	N load (kg N y^{-1})	N load (%)	P yield (kg P ha y^{-1})	P load (kg P y^{-1})	P load (%)
Broadleaved Indigenous Hardwoods	1792.0	12.5	3.67	**6577**	5.8	0.12	**215**	1.4
Indigenous Forest	2989.5	20.9	3.67	**10972**	9.7	0.12	**359**	2.3
Manuka and/or Kanuka	1589.5	11.1	3.50	**5563**	4.9	0.12	**191**	1.2
Sub Alpine Shrubland	24.3	0.2	2.00	**49**	0.0	0.50	**12**	0.1
Tall Tussock Grassland	190.6	1.3	3.00	**572**	0.5	0.50	**95**	0.6
Deciduous Hardwoods	4.2	0.0	1.31	**5**	0.0	0.10	**0**	0.0
Exotic Forest	1249.2	8.7	1.31	**1636**	1.4	0.10	**125**	0.8
Forest - Harvested	266.7	1.9	7.74	**2064**	1.8	0.47	**125**	0.8
Gorse and/or Broom	23.1	0.2	15.00	**346**	0.3	0.20	**5**	0.0
Mixed Exotic Shrubland	41.4	0.3	3.00	**124**	0.1	0.20	**8**	0.1
High Producing Exotic Grassland								
Dry Stock	1803.5	12.6	10.18	**18359**	16.2	1.02	**1840**	12.0
Low Producing Grassland	27.5	0.2	5.00	**137**	0.1	0.50	**14**	0.1
Built-up Area (settlement)	98.8	0.7	5.00	**494**	0.4	0.70	**69**	0.5
Gravel or Rock	69.9	0.5	5.00	**350**	0.3	0.50	**35**	0.2
Herbaceous Freshwater Vegetation	20.7	0.1	0.00	**0**	0.0	0.00	**0**	0.0
Lake or Pond	4146.1	28.9	6.37	**26411**	23.4	0.34	**1410**	9.2
Geothermal				**6300**	5.6		**5000**	32.6
Other Lakes								
Okareka				**2930**	2.6		**144**	0.9
Rotokakahi				**3720**	3.3		**876**	5.7
Tikitapu				**420**	0.4		**12**	0.1
Rotomahana				**15800**	14.0		**3642**	23.8
Okataina				**7420**	6.6		**858**	5.6
Wastewater (775 pp)				**2829**	2.5		**283**	1.8
Total	14337.0			**113078**			**15318**	

3.4.12 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 161 mg TN m^{-3}, 4.7 mg TP m^{-3}, and 1.9 mg chl *a* m^{-3} for the period 2009 – 2014 (Table 1). Tikitapu's TN:TP ratio of approximately 35:1 is very high, likely indicating strong P-limitation.

3.4.12a 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 26). There is a lakeside campground and public amenities which were reticulated in October 2010.

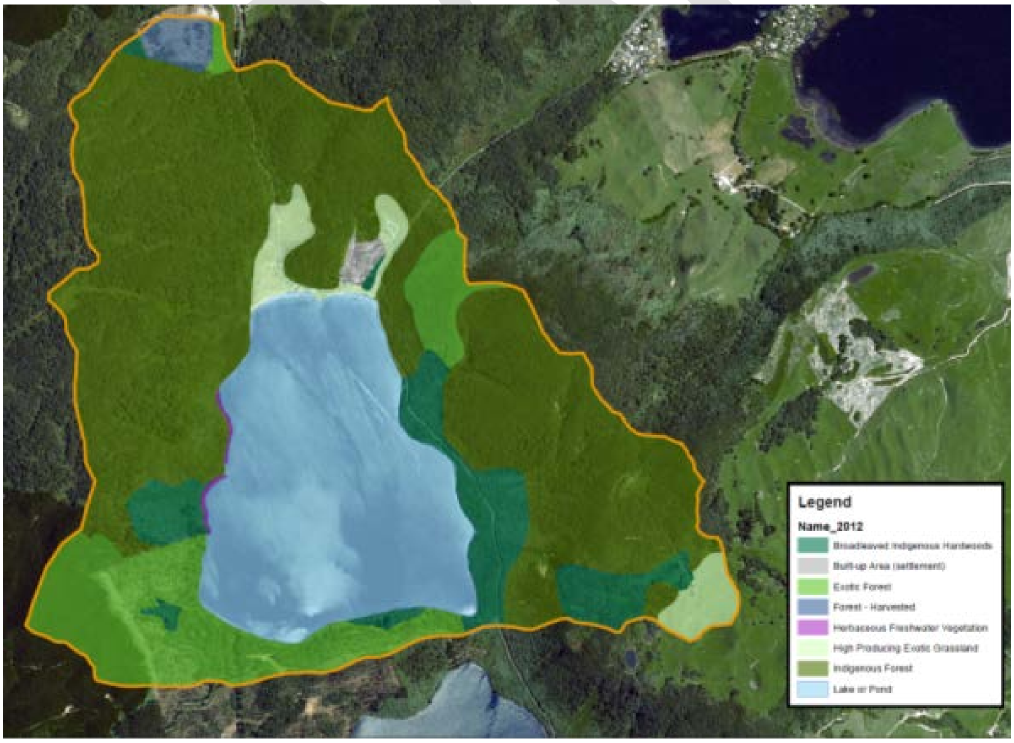

Figure 26. Map of land use (LCDB4) in the Tikitapu catchment.

3.4.12b Previous load estimates

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.

3.4.12c Land use classes

OVERSEER benchmarking of agricultural land use within the Tikitapu catchment was not available. Therefore, average loss rates of 10.18 kg N ha^{-1} y^{-1} and 1.02 kg P ha^{-1} y^{-1} were applied to grassland (see 3.3.2a).

Comment [CM12]: Is the land by the campground actually stocked, or is it just recreation?

For other land uses, loss rates used are described in section 3.2 and no adjustments were made for the catchment of Lake Tikitapu.

3.4.12d 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}.

3.4.12e Connected lakes

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

3.4.12f 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 Tikitapu action plan). Although wastewater in the catchment has recently been reticulated, for the purpose of this study we have assumed a load of half 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. 2 and 12 % for N and P, respectively, although these values are highly uncertain and wastewater loads are likely to further reduce with time.

Comment [CM13]: ?????????????

3.4.12g Summary

Total estimated loads to Lake Tikitapu were 17.0 t N y^{-1} and 0.15 t P y^{-1} (Table 16). Loads to Tikitapu are low due to the small catchment and predominance of forest. It should, however, be noted that the lake has eotic 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).

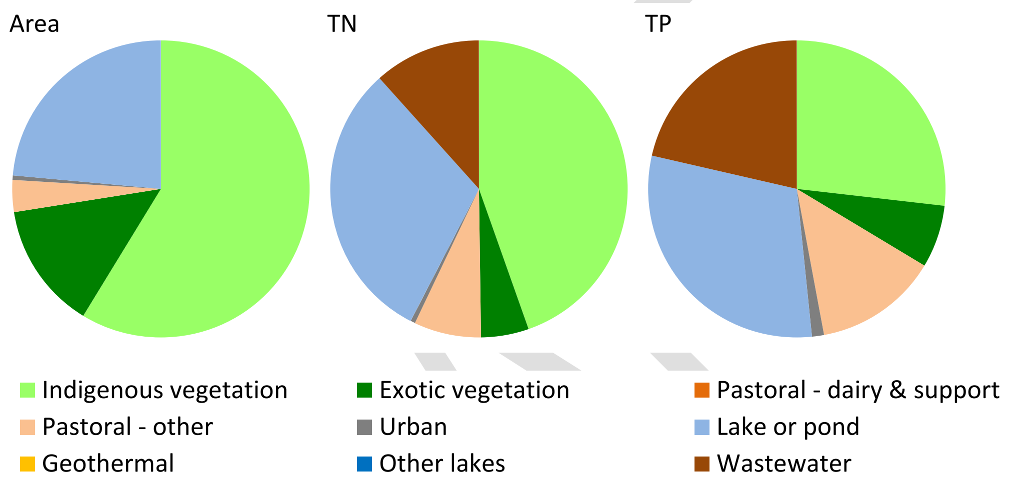

Figure 27. Proportional contribution of all sources within the Lake Tikitapu catchment to area, total nitrogen load, and total phosphorus load.

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

Land use (LCDB 4)	Area (ha)	Area (%)	N yield (kg N ha y^{-1})	N load (kg N y^{-1})	N load (%)	P yield (kg P ha y^{-1})	P load (kg P y^{-1})	P load (%)
Broadleaved Indigenous Hardwoods	50.8	8.1	3.67	**186**	6.0	0.12	**6**	3.6
Built-up Area (settlement)	3.0	0.5	5.00	**15**	0.5	0.70	**2**	1.3
Exotic Forest	79.0	12.7	2.81	**222**	7.1	0.18	**14**	8.4
Forest - Harvested	6.9	1.1	5.62	**39**	1.2	0.36	**2**	1.5
Herbaceous Freshwater Vegetation	1.1	0.2	0.00	**0**	0.0	0.00	**0**	0.0
High Producing Exotic Grassland								
Dry Stock	21.6	3.5	10.18	**220**	7.1	1.02	**22**	13.0
Indigenous Forest	315.3	50.6	3.67	**1157**	37.1	0.12	**38**	22.3
Lake or Pond	145.7	23.4	6.37	**928**	29.8	0.34	**50**	29.2
Wastewater (50 % of 192 pp)				**350**	11.2		**35**	20.7
Total	623.3			**3117**			**169**	

3.5 Regional summary

Average catchment wide nutrient loads per area ranged from 0.26 (Tiktapu) to 1.16 kg P ha^{-1} (Rotomahana), and 4.8 (TIkitapu and Rotokakahi) to 13.3 kg N ha^{-1} (Rerewhakaaitu) (Table 17).

Table 17. Summary of lake nutrient concentrations and catchment loads for 12 Bay of plenty Lakes.

Lake	Lake area	Catchment	TP load	Areal P load	TP_{lake}	TN load	Areal N load	TN_{lake}
	km^2	km^2	kg y^{-1}	kg P ha^{-1}	mg m^{-3}	kg y^{-1}	kg N ha^{-1}	mg m^{-3}
Okareka	3.39	19.6	915.7	0.47	9.29	16269	8.3	187.8
Okaro	0.31	3.9	411.2	1.05	75.96	4208	10.8	954.9
Okataina	10.83	59.9	1584.7	0.26	10.54	27255	4.5	91.2
Rerewhakaaitu	5.45	37.0	3864.4	1.04	10.60	49325	13.3	366.8
Rotoehu	7.91	49.2	2626.0	0.53	33.20	45272	9.2	268.3
Rotoiti	33.96	124.8	4163.9	0.33	19.16	105925	8.5	163.8
Rotokakahi	4.37	19.7	701.0	0.36	55.30	9503	4.8	235.0
Rotoma	10.03	27.9	1119.3	0.40	5.32	14870	5.3	102.4
Rotomahana	9.07	83.4	9635.8	1.16	43.98	67979	8.2	191.6
Rotorua	80.97	522.7	31620.9	0.60	19.99	589038	11.3	320.6
Tarawera	41.46	143.4	15317.5	1.07	17.10	113078	7.9	88.1
Tikitapu	1.46	6.2	163.8	0.26	4.68	3014	4.8	161.3

In most lakes, catchment load N:P ratio was dissimilar to lake water N:P (> ± 20 % for 10 lakes). In some lakes catchment N:P was higher, and in some it was lower than lake N:P (Figure 28). Rerewhakaaitu and Tikitapu had very high catchment N:P relative to lake waters, which could be due to iron-rich sediments in these lakes (REFS), inaccuracies in the load estimations, or complex hydrology (particularly in the case of Rerewhakaaitu), 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.

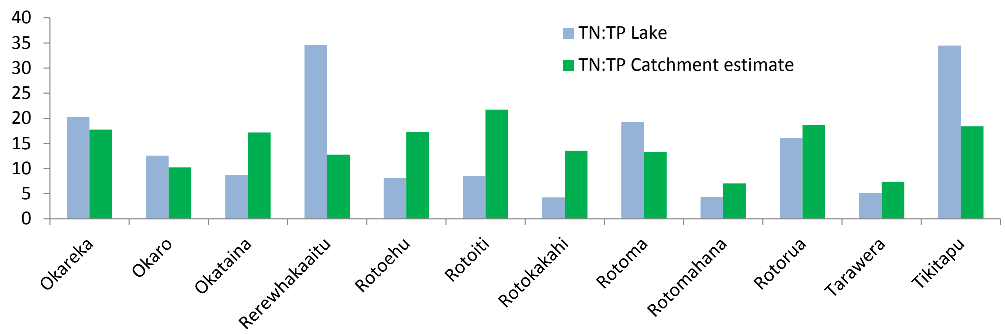

Figure 28. Comparison of nitrogen to phosphorus ratio estimated in catchment nutrient budgets with observed ratio from lake waters.

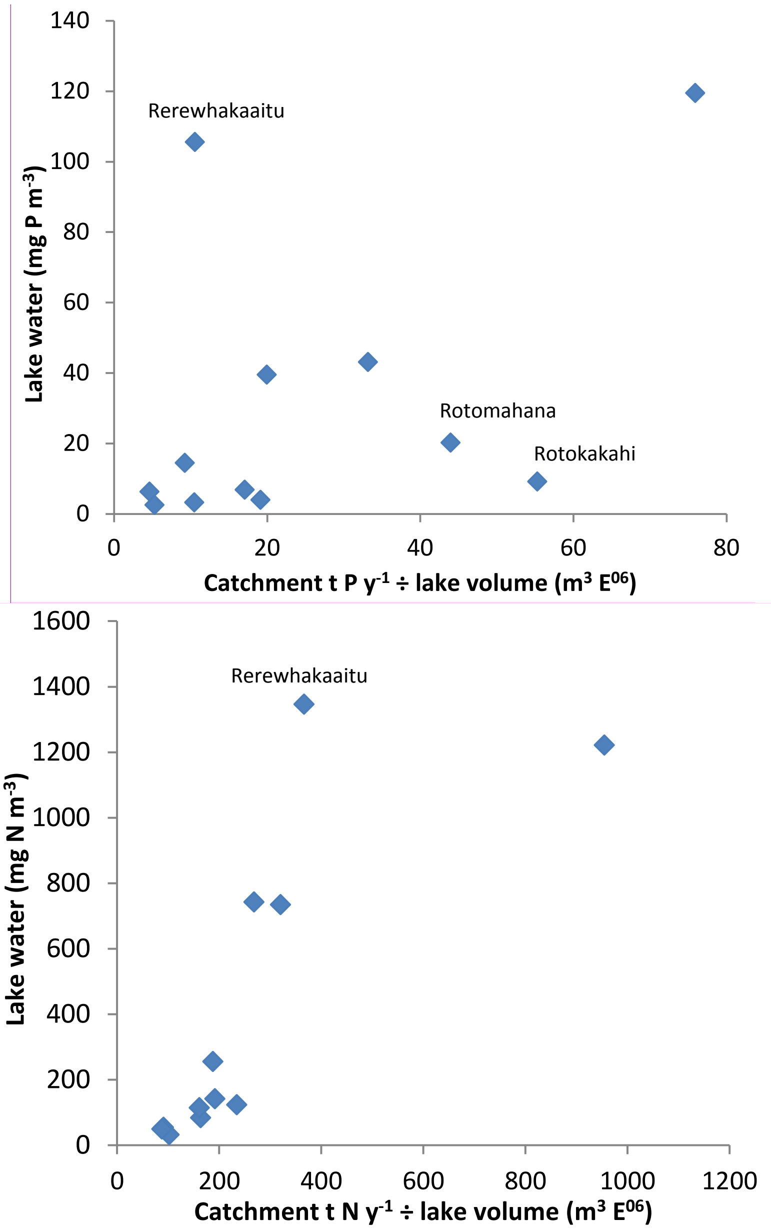

Figure 29. Observed lake water concentration vs. the ratio of catchment load to lake voluyme for a) phosphorus and b) Nitrogen.

Comment [CM14]: Probably won't keep these figs but included for interest at this stage.

4. Discussion

Text to come following TAG feedback.

6. References

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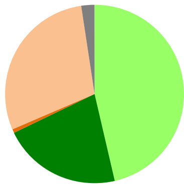
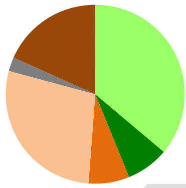
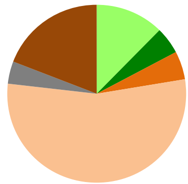
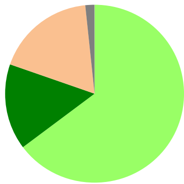
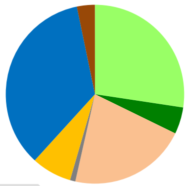
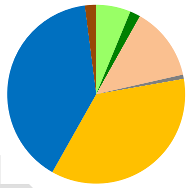
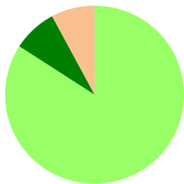
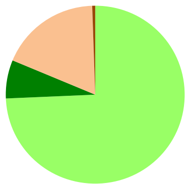
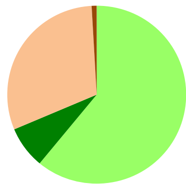
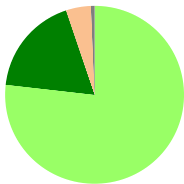
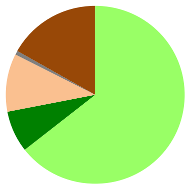
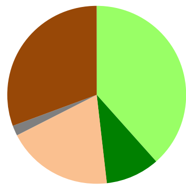
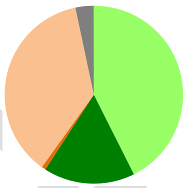
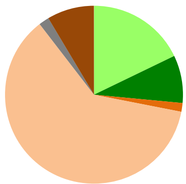
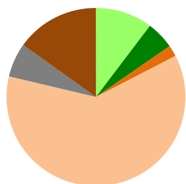
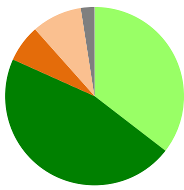
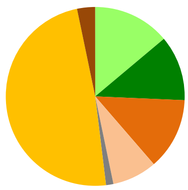
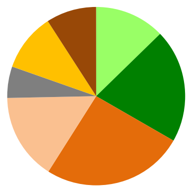
Appendix 1.

Land use and nutrient loads regional summary

Lake	Area	TN load	TP load
Rotoma TLI = 2.3			
Tarawera TLI = 2.8			
Okataina TLI = 2.8			
Tikitapu TLI = 3.0			
Okareka TLI = 3.3			
Rotoiti TLI = 3.5			

Indigenous vegetation
Exotic vegetation
Pastoral - dairy & support
Pastoral - dry stock & other
Urban
Geothermal
Other lakes
Wastewater

(Continued overleaf)

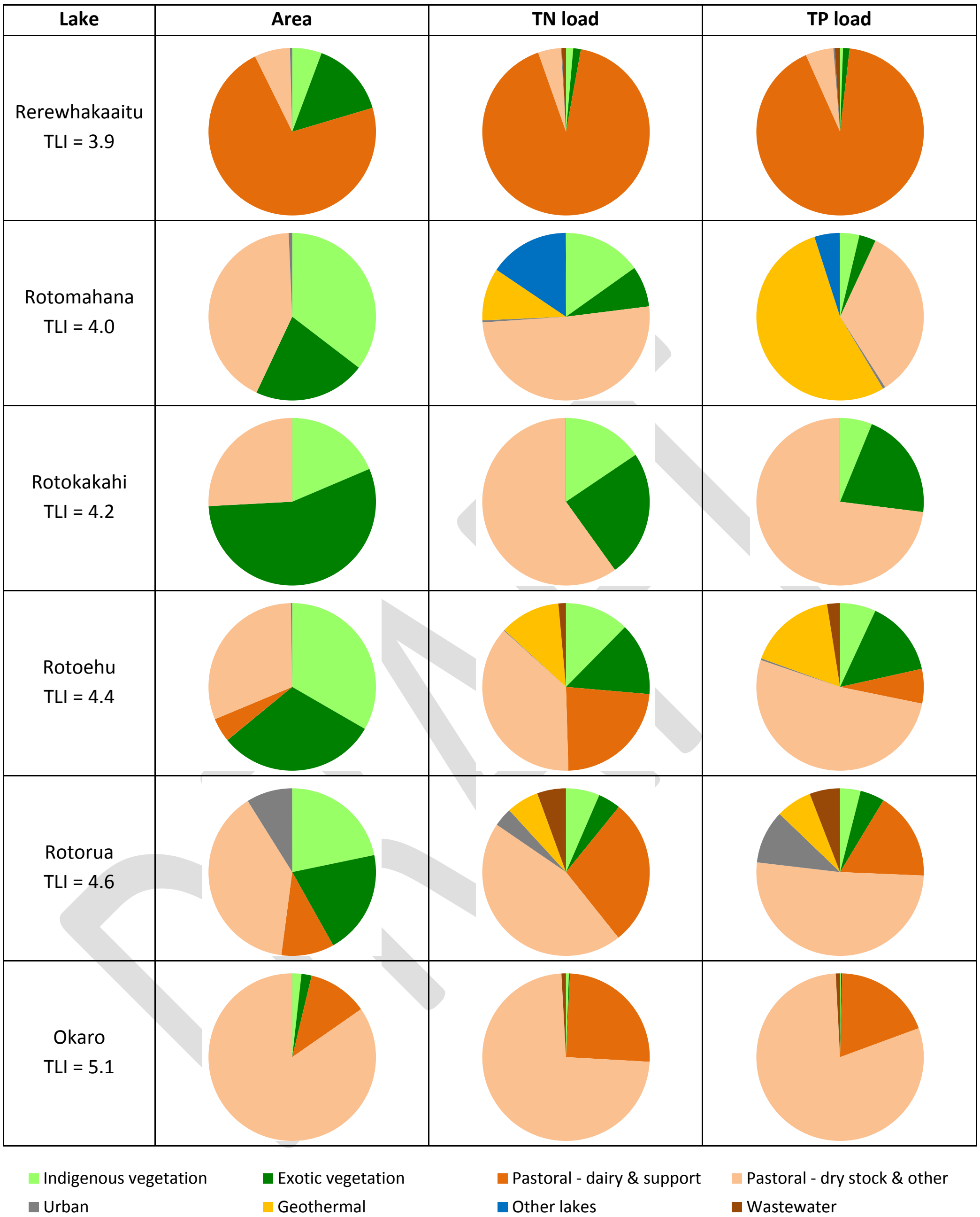


Figure 30. Percentage area, N load and P load by land use, *excluding* atmospheric deposition, for all 12 Rotorua Lakes.