RIVER LAKE

Anthropogenic Phosphorus Load to Rotorua Review and Revision

Prepared for:

Bay of Plenty Regional Council

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Contents

Executive Summary ... **1**

1 Introduction ... **2**
- 1.1 Background ... 2
- 1.2 Scope of this report ... 3
- 1.3 Lake Rotorua ... 3
- 1.4 Estimates of N and P load to Lake Rotorua ... 6

2 Method ... **7**
- 2.1 Overall approach ... 7
- 2.2 Approach by Tempero et al. 2015 ... 7
- 2.3 Delineating the surface and groundwater catchment ... 9
- 2.4 Total hydraulic load ... 11
- 2.5 Hydraulic load from ungauged sub-catchments ... 14
- 2.6 Baseline P and anthropogenic P ... 15
- 2.7 Geothermal inputs ... 15

3 Results ... **17**
- 3.1 Hydraulic load ... 17
- 3.2 Phosphorus load ... 21
- 3.3 Area specific anthropogenic phosphorus load ... 24

4 Discussion ... **27**
- 4.1 Long term estimates ... 27
- 4.2 Uncertainties in analysis ... 27
- 4.3 Bioavailable P ... 28
- 4.4 Further work ... 28

5 Conclusions ... **29**

References ... **30**

Executive Summary

This report contributes to the Science Review required by Plan Change 10 of the Bay of Plenty Regional Water and Land Plan (RWLP). It reviews estimates of anthropogenic phosphorus loads to Lake Rotorua. A previous report by Tempero et al. (2015) calculated a total external phosphorus load to Lake Rotorua and differentiated this into the load due to anthropogenic sources and load due to natural baseline sources. The approach accounted for particulate P entering the lake during stormflow events – resulting in higher loads than many past estimates. This current report builds upon the work of Tempero et al. (2015) and updates it to account for groundwater catchment areas, geothermal inputs and long-term average loads.

For the period 2007-2014, the total phosphorus load to Lake Rotorua was estimated to be 46.0 t/yr after accounting for storm flows and geothermal inputs. The TP load attributed to anthropogenic sources was 18.1 t/yr to 20.7 t/yr (39% - 45% of the total load). Most (71% to 79%) of the anthropogenic TP load was in the particulate form – which points to managing erosion as an effective way of reducing anthropogenic P loads to the lake. Most came from the following catchments: 'ungauged' (30%), Puarenga (23%), Utuhina (18%) and Ngongotaha (11%) – reflecting their relative size.

The 2007-2014 period had higher outflows and inflows compared to previous years. The long-term average TP load to Lake Rotorua was estimated to be 42.2 t/yr, and the long-term average TP load attributed to anthropogenic sources was 16.6 t/yr to 19.0 t/yr. Overall the analysis results are consistent with previous estimates of the catchment phosphorus load to Lake Rotorua (i.e. about 39-49 t/yr).

The calculation of anthropogenic P load was particularly sensitive to the drainage factor used (i.e. the proportion of net rainfall that enters lakes and stream via groundwater) and the calculation of net rainfall (i.e rain less evapotranspiration) for the lake.

There was an indication that there might be additional groundwater contributions (from outside the defined catchment) to the south of the lake via geothermal inputs. This is speculative and was based on more water being assigned to ungauged catchments than could be explained by the available rainfall data, and higher estimates of geothermal inflows from the south of the lake than could be explained by rainfall in catchments. If there was additional groundwater entering via geothermal inputs then the calculations for anthropogenic loads from 'ungauged catchments' would be over-estimated.

The anthropogenic P load is predominantly (71-79%) in the form of particulate phosphorus, so understanding the proportion of particulate P that may become bioavailable is very important. Recommendations are made for further work to fill information gaps relating to the P load to Lake Rotorua and its bioavailability.

1 Introduction

1.1 Background

1.1.1 Plan Change 10 Science Review

Bay of Plenty Regional Council (BOPRC) is in the process of approving Plan Change 10 to the Regional Water and Land Plan (RWLP). Plan Change 10 sets rules for Lake Rotorua nutrient management; it includes specific provisions to review the science supporting decisions associated with Lake Rotorua (i.e. LR M2 of the proposed plan change).

The Science Review terms of reference (TOR) includes tasks to:

- Identify the key places where phosphorus mitigation should be focussed in general terms and whether this is measurable, and
- Identify priority catchments for application of focussed phosphorus (P) control. This will include a high-level estimate of potential achievements with respect to reducing P inputs to the lake.

This report contributes to the Science Review by reviewing estimates of anthropogenic phosphorus loads to Lake Rotorua. The aim is to refine the estimates of the load of P to Lake Rotorua from anthropogenic sources, i.e. the load that can be potentially managed. In particular this report improves the spatial resolution and confidence in the magnitude of the P load to Lake Rotorua.

1.1.2 Anthropogenic Phosphorus Loads

The report titled "*Anthropogenic Phosphorus Loads to Lake Rotorua*" was prepared by University of Waikato in 2015 (Tempero et al. 2015). It identified that the natural baseline and anthropogenic P load to Lake Rotorua from nine sub-catchments and the residual ungauged catchments. The report built upon previous P load estimates by including TP and DRP loads from stormflow events in the Puarenga, Ngongotaha and Utuhina Streams.

The report estimated a TP load to Lake Rotorua of 48.7 t/yr (23.4 t/yr anthropogenic) and a DRP load of 27.7 t/yr (6.1 t/yr anthropogenic). This was higher than most other most previous load estimates, in part because stormflow events were included.

Most of the anthropogenic P came from the Puarenga River, Utuhina River, Ngongotaha River but the highest anthropogenic P load came from "ungauged" catchments with 32% of the total anthropogenic P load. "Ungauged" catchments were defined as minor streams[1], part of the urban area, and inflows below gauging sites including springs and groundwater inputs direct to the lake bed.

Ungauged catchments also had the highest area-specific anthropogenic P loads (1.2 kg TP /ha/yr), followed by Waiohewa Stream (0.65 kg TP /ha/yr), Utuhina (0.59 kg TP /ha/yr) and Puarenga (0.53 kg TP /ha/yr). This suggested that efforts to reduce P loads to Lake Rotorua might be most effective if they focused on the ungauged catchments which collectively had the highest P load and the highest P load per hectare.

[1] Some of these have occasional flow measurements (see Beyá et al. 2005)

1.2 Scope of this report

This report builds on the analysis of Tempero et al. (2015) to differentiate between the ungauged catchments based on surface and groundwater catchment size. In the process this report reviews the key assumptions in the analysis and test the sensitive to these assumptions. In particular this relates to:

- Determining the total hydraulic load to the lake and comparing with a long term average load;
- Partitioning the hydraulic load between all inflows based on monitoring data, surface water catchment size and groundwater catchment size;
- Determining the ratio of TP as DRP for groundwater and surface water;
- Accounting for geothermal inputs as part of the natural baseline of DRP and TP.

The analysis in this report informs recommendations regarding requirements for additional monitoring and investigations to fill information gaps relating to estimating and managing P loads to Lake Rotorua.

1.3 Lake Rotorua

1.3.1 Lake

Lake Rotorua is a large (81 km^2) but relatively shallow polymictic lake with an average depth of 10 metres. Lake Rotorua is eutrophic but the water quality has considerably improved since 2002 with reductions in nutrient concentrations, fewer algae blooms and increased water clarity. The Trophic Level Index (TLI) is now tracking close to the target set in the regional plan (e.g. TLI of 4.4 in 2016 compared to a target of 4.2) (Stephens et al. 2018).

The Lakes Rotorua and Rotoiti Action Plan (2009) identified 2009 inputs to Lake Rotorua from land as about 556 t N/yr and **39.1 t P/yr**. Internal loads recycled within the lake were estimated to be 360 tonne N/yr and 36 tonnes P/yr. Nutrient exports are calculated differently than inputs and were estimated to be 783 t N/yr and **39.8 t P/yr**. Natural inputs from geothermal, rain, springs and indigenous forest was estimated to contribute about 115 t N/yr and 17.8 t P/yr.

To reach the TLI target of 4.2 the catchment inputs to Lake Rotorua need to reduce to 435 tonnes N/yr and 37 tonnes P/yr. This is roughly commensurate with catchment loads prior to substantial degradation of water quality in the lake (early measurements are summarised in Rutherford et al. 1989). The nutrient reduction target for Lake Rotorua catchment by 2029 is 250 t N/yr and 10 t P/yr.

Management interventions to improve the water quality of Lake Rotorua include: land disposal of the city's wastewater since 1991 (into the Puarenga Stream catchment), sewage reticulation of smaller communities around the lake[2], trial of nitrogen removal from Tikitere geothermal inflows to Waiohewa Stream (2011), alum dosing to lock phosphorus from Utuhina Stream (2006) and Puarenga Stream (2010), and regional rules to cap land-based nutrient inputs (Rule 11).

[2] Since 2007 the following communities in the Lake Rotorua catchment has had sewage reticulation: Hamuranga/Awhoa, Brunswick/Rotokawa, Hinemoa point (Waitawa area), Tarawera Road, and Paradise Valley.

The alum dosing appears to have been particularly effective at improving water quality. Strong reductions in phosphorus concentrations have been recorded since the initiation of alum dosing of Utuhina Stream and Puarenga Stream in 2006 and 2010 respectively (Hamill and Scholes 2015). However, relying on alum dosing in the long term may have risks (e.g. Tempero 2015) and it is not preferred from a cultural perspective. Targets for reducing both nitrogen (N) and phosphorus (P) have been set to improve lake water quality over the long term.

1.3.2 Catchment

There are nine major streams that enter Lake Rotorua that contribute about two thirds (64%) of the inflow to the lake. These major inflows are regularly gauged and monitored. The remainder of the lake inflows comes from small streams, spring, groundwater upwelling to the lake bed, and rainfall direct to the lake surface. The Lake discharges to Lake Rotoiti via the Ohau channel.

Lake Rotorua has a topographical surface water catchment of 502.1 km^2 and a total groundwater catchment of 537.9 km^2. Groundwater contribution from outside the surface water catchment mostly comes from the Mamaku plateau west of the lake and contributes to a substantial baseflow in the Hamurana Stream and, to a less extent, Awahou Stream (White et al. 2014). A large proportion of the catchment is forested with an even mix of exotic and indigenous vegetation, and there is a similar amount of pastoral land used for dairy. Rotorua city lies within the catchment (Figure 1.1).

The nutrient losses from the various sources in the Lake Rotorua catchment were estimated based on land use coefficients (Bay of Plenty Regional Council, Rotorua District Council and Te Arawa Lakes Trust 2007). The catchment land uses estimated to contribute most to nitrogen load were: Pasture (72%), urban (6.4%), geothermal (5.4%) and native forest (5.4%). The catchment land uses estimated to contribute most to phosphorus load were: Pasture (42%), urban (9.6%), geothermal (3.5%) and native forest (3.3%). Geothermal inputs primarily enter via springs or direct within the lake near Rotorua township, Puarenga Stream and Waiohewa Stream.

Figure 1.2 shows relative nutrient concentrations in the main stream in each sub-catchment to Lake Rotorua. This was made to illustrate the potential for wetlands to remove N and P from stream entering Lake Rotorua (Hamill et al. 2010). '*High potential for phosphorus removal*' refers to streams with higher concentrations (>0.02 mg/l) of particulate phosphorus, and '*high potential for nitrogen removal*' refers to streams with higher concentrations (> 1 mg/l) of dissolved inorganic nitrogen (DIN). This analysis found that based solely on the concentration of particulate P[3], the catchments with most potential for P removal were Waingaehe, Waiohewa, Utuhina, Ngongotaha and Puarenga.

[3] Nutrient data from Rutherford and Timpany 2008.

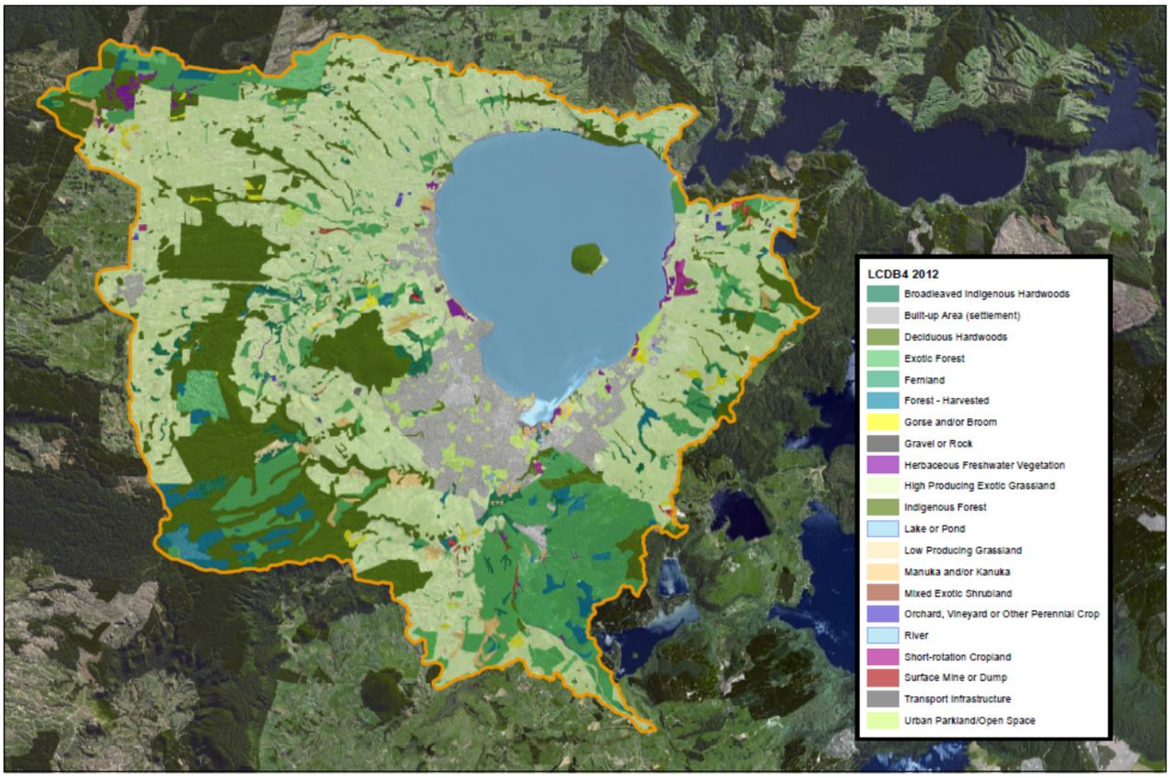

Figure 1.1: Lake Rotorua surface water catchment land-use (based on LCDB 2012).

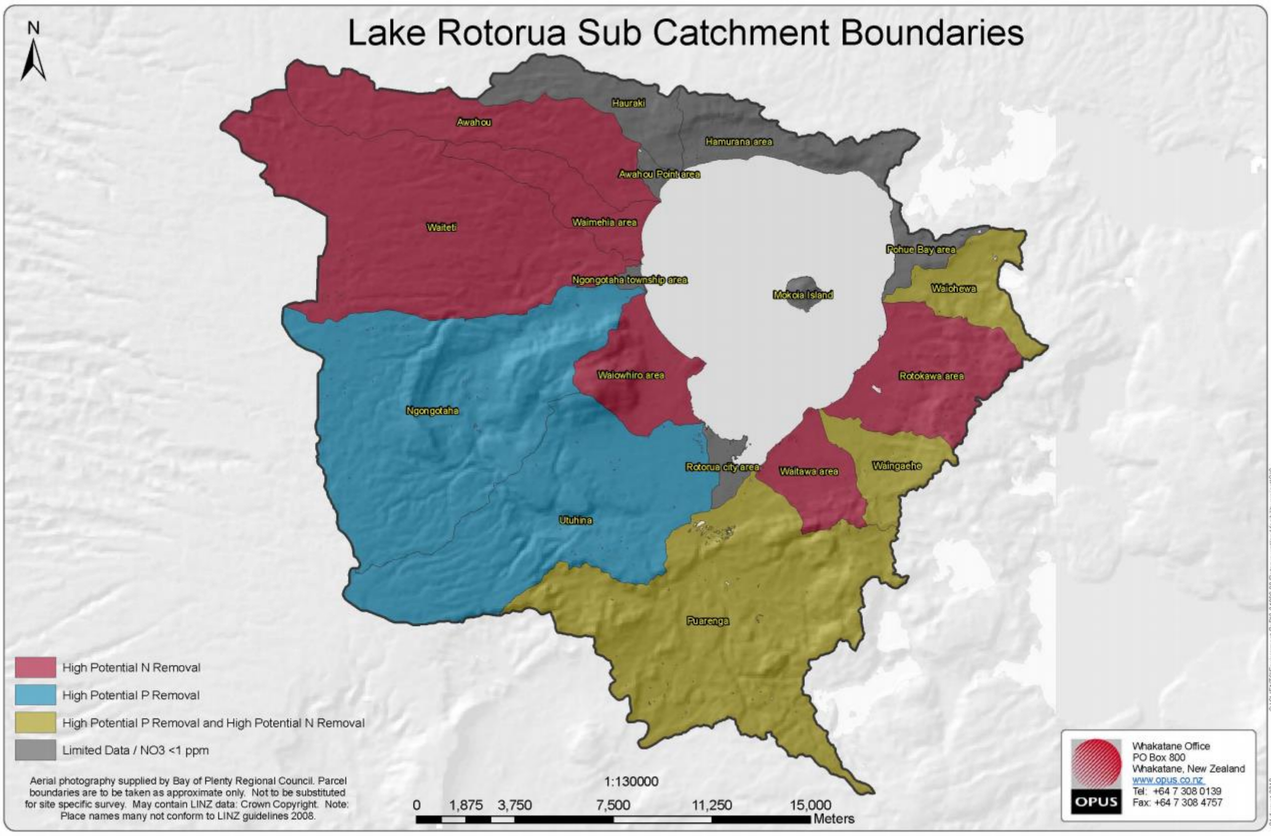

Figure 1.2: Lake Rotorua surface water sub-catchment areas. The colours indicate potential for P removal and N removal based on concentrations of particulate P and dissolved N in the surface water (source: Hamill 2010). Note that for some catchments the surface water and groundwater catchments differ (particularly for Hamurana, Hauraki, Awahou, Waimehia and Waiohewa).

1.4 Estimates of N and P load to Lake Rotorua

BOPRC (2007) report the total nitrogen and phosphorus loads to Lake Rotorua is about 783.1 tonnes/yr and 39.8 tonnes/yr respectively. BOPRC (2007) also estimated additional P release form the lake bed of about 360 tonnes N and 36 tonnes P that can be recycled into the water column from the lake bed up to 10 times per year.

The total load of P from the catchment has been estimated by different researchers over different time periods; these estimates typically fall in the range 34 t P/yr to 42 t P/yr when excluding particulate P from flood flows (Rutherford 2008)[4] (Table 1.1). The TP estimates by Tempero et al. (2015) are at the upper end of the estimates but include particulate P carried to the lake by flood flows. Part of the reason for the higher load estimate is also due to a higher estimate of hydraulic load from ungauged catchments including groundwater. Tempero et al. (2015) estimated the ungauged catchments to contribute 4.11 m^3/s while earlier water balance studies estimated the ungauged catchment load to be smaller, e.g. 2.1 m^3/s (Hoare 1980)

[4] There is one low outlier' estimate of 21 t P/yr for 1900 that was made from typical specific yields for native and pine forest but this does not account for the high DRP in old groundwater in the volcanic plateau (MacIntosh 2007)

A phosphorus target of 37 t/yr was derived by Rutherford (2008) from a catchment load of 34 t/yr plus an additional allowance for sewage of 3 t/yr. These catchment loads did not include particulate P from flood events because, at the time, this fraction was considered to be predominantly not bioavailable.

Table 1.1. Previous estimates of catchment phosphorus loads to Lake Rotorua (modified from Rutherford 2008). TP = total P, DRP = dissolved reactive P, PP = particulate P.

Source	year	DRP (t/yr)	TP (t/yr)	Note
Hoare 1978	1976-77	25-26	34-35	Excluding sewage and flood flow PP
Hoare 1980a	1976-1977		35.6 - 37.4	Excluding sewage and flood flows, but include spetic tanks
Hoare 1980a	1976-1978		42.6 - 44.9	Excluding sewage but incl. septic tanks, including flood flow PP
Rutherford et al 1978	1967-77		33-44	Excluding sewage and flood flow PP
Rutherford et al 1989	1976-77		34	Excluding sewage and flood flow PP
Morgensten	2005		39.1	Including sewage
BOPRC 2009			39.8	
Hamilton et al. 2015	2001 - 2012		33	
Tempero et al. 2015	2007-2014	27.7	48.7	Includes sewage and flood flow PP

2 Method

2.1 Overall approach

The load estimates in this report build upon the work by Tempero et al. (2015) and provide adjustments where appropriate or necessary to account of more detailed differentiation of sub-catchments and groundwater. This section reviews key inputs used by Tempero et al. (2015), and describes where a different approach was taken.

2.2 Approach by Tempero et al. 2015

Tempero et al. (2015) used monitoring data to estimate annual P loads to Lake Rotorua for a 7-year period, 2007-2014. The mean annual discharge of water to the lake was calculated for each of the nine major streams. Four of these streams had near continuous flow recording, accounting for about half of total mean discharge to the lake. A time series for the other streams was created by using either linear interpolation or by adjusting the flows of a nearby catchment with a near continuous flow record.

The discharge from ungauged[5] catchments was calculated as the residual of a water balance constructed for the lake i.e. outflows minus inflows. The formula was:

$$Ungauged = 1.18\ .\ (Q_{ohau} + E + \Delta S) - (Q_{inflow} + rainfall)$$

Where: Q_{ohau} was the daily mean discharge of the only lake surface outflow, E was daily mean evaporation rate, ΔS was daily mean rate of change in lake storage, due to water level change, Q_{inflow}

[5] Including minor streams, springs and groundwater entering the lake directly.

was daily mean stream discharge and rainfall was a 15–day mean value. The constant value (1.18) was determined iteratively to minimise error between modelled and measured water levels.

Groundwater flow was calculated as the difference between estimated surface water flow and total observed mean annual stream discharge. The surface water was calculated by multiplying the surface water catchment area by the estimated surface runoff of 47% of rainfall after evapotranspiration.

Daily TP and DRP loads were calculated for each inflow for the period 2007–2014 using the daily discharge estimates, these were summed to calculate annual loads. TP and DRP was based on measured data. Higher TP concentrations during stormflows were applied to three streams (Ngongotaha, Puarenga and Utuhina Stream) based on stormflow monitoring data (Abell et al. 2013). These rivers carry most of the water entering during flood flows (73% of the nine measured streams). TP and DRP concentrations for 'ungauged' streams was estimated as the discharge-weighted values for major streams.

Anthropogenic loads were calculated as the residual after removing baseline ('natural') loads. These baseline loads were estimated from 'reference conditions' derived from McDowell et al. (2013) and were adjusted to also account for natural inputs of 'old' ground water enriched in P from geological sources. The natural groundwater loads were derived from the relationship between DRP concentration and groundwater mean residence time (MRT) estimated for each sub-catchment in Morgenstern et al. (2015).

Table 2.1 shows the key input hydrological inputs used in Tempero et al. (2015).

Table 2.1: Summary of hydrological inputs used in Tempero et al. (2015). Catchments are ordered counter clockwise around the lake. AET = annual evapotranspiration. MRT = groundwater mean residence time.

Catchment	Abr.	catchment area (km^2)	Obs. dicharge (m^3/s)	rainfall (mm/yr)	AET (mm/yr)	calc. surface water (m^3/s)	calc. % GW	MRT
Hamurana	HAM	16.07	2.57	1950	856	0.26	89.8	125
Awahou	AWA	19.92	1.69	2000	838	0.34	79.6	75
Waiteti	WTT	61.88	1.23	2000	859	1.05	14.5	45
Ngongotaha	NGO	77.41	1.84	1950	895	1.22	33.9	30
Waiowhiro	WWH	13.63	0.31	1700	930	0.16	49.6	40
Utuhina	UTU	61.04	1.81	1900	942	0.87	51.9	60
Puarenga	PUA	82.32	1.95	1800	946	1.05	46.3	40
Waingaehe	WNG	11.06	0.27	1450	895	0.09	66.1	145
Waiohewa	WHE	11.69	0.38	1750	881	0.15	60.2	40
Ungauged		67.23	4.11	1600	900			30
Rainfall to lake		80.6	2.46	1600	637	3.96		
TOTAL		502.9						

Note: Groundwater was estimated as the residual of observed less calculated surface water flow.

AET was recorded for the lake was 0 but in fact would have needed to be about 50 mm/yr to derived a flow of 3.96 m3/s from a rainfall of 1600 mm/yr.

2.3 Delineating the surface and groundwater catchment

The catchment boundary layers used in this report come from BOPRC 2014 reversion. The surface catchment was defined using LIDAR digital terrain measurements (1m intervals). The groundwater catchment was defined separately. The total groundwater catchment generally coincides with the surface catchment, except there is an additional 35 km^2 of groundwater catchment from the Mamaku Plateau that contributes to the Hamurana Stream and, to a less extent, Awahou Stream. The groundwater boundary was defined using multiple datasets including topographic contours and water budgets (White et al. 2014).

Estimates of groundwater sub-catchment boundaries were developed for the ROTAN model (Rutherford et.al. 2009) using a scale of 1:10,000. They generally coincide with surface water catchments on the eastern side of the lake but differ for many of the western catchments, this is particularly the case for Hamurana (groundwater catchment extends over part of Hauraki and Awahou), Hauraki (groundwater catchment very small compared to surface catchment), Awahou (groundwater catchment extends over part of Waimehia and Waiteti), Waimehia (groundwater catchment small compared to surface catchment) and Waiteti (groundwater catchment small compared to surface catchment). Also, Waiowhiro groundwater catchment extends over part of Ngongotaha and Utuhina.

White et al. (2014) made a best-estimate of the Lake Rotorua's surface water and groundwater catchment size of 502.1 km^2 and 537.1 km^2 respectively – a difference of about 35 km^2. The surface catchment included about 1.97 km^2 from Lake Rotokawau that drains via groundwater to the Waiohewa. The catchment layer used for this report has a total groundwater catchment area of 537.9 km^2 but the difference is negligible. Tempero et al. (2015) used a surface water catchment area of 502.9 km^2 but again the difference is negligible.[6]

The area of a catchment to the lake edge is larger than the area at the point of stream gauging and flow estimates. This report uses catchment areas at the point of flow gauging and the area downstream of this point was assigned to 'ungauged' catchments.

Tempero et al. (2015) used catchment size to calculate surface water runoff for each of the major sub-catchments and this was used to estimate the percentage of discharge as groundwater. There appear to be several errors in the areas used for sub-catchments that affect subsequent calculations, these are:

- For some sub-catchments the areas applied reflected a general area rather than actual stream surface water catchment i.e. Hamurana area and Waiowhiro area (see Figure 1.2).
- No account was made for the groundwater catchment being c. 35 km^2 larger than the surface water catchment (this particularly effects Hamurana and Awahou).
- No account was made for the surface water catchment area being different than the groundwater catchment area in many of the western catchments.
- The Waiohewa catchment was under sized because it did not include Lake Rotokawau catchment (1.97 km^2) discharging via groundwater to Waiohewa.
- The catchment area applied to the calculations was for the bottom of the catchment where it enters Lake Rotorua rather than for the catchment area upstream of the gauging station. This meant that the area applied to 'ungauged' catchments was under-estimated, particularly for Ngongotaha, Utuhina and Puarenga.

The area assigned to sub-catchments has implications for estimates of:

- Hydraulic loads;
- Baseline loads and, as a consequence:
- Anthropogenic loads; and
- Area specific yields.

The groundwater and surface water catchment area used in this report are shown in Figure 2.1.

[6] 0.8 km^2 difference in catchment area would account for about 0.0083 m^3/s in total discharge.

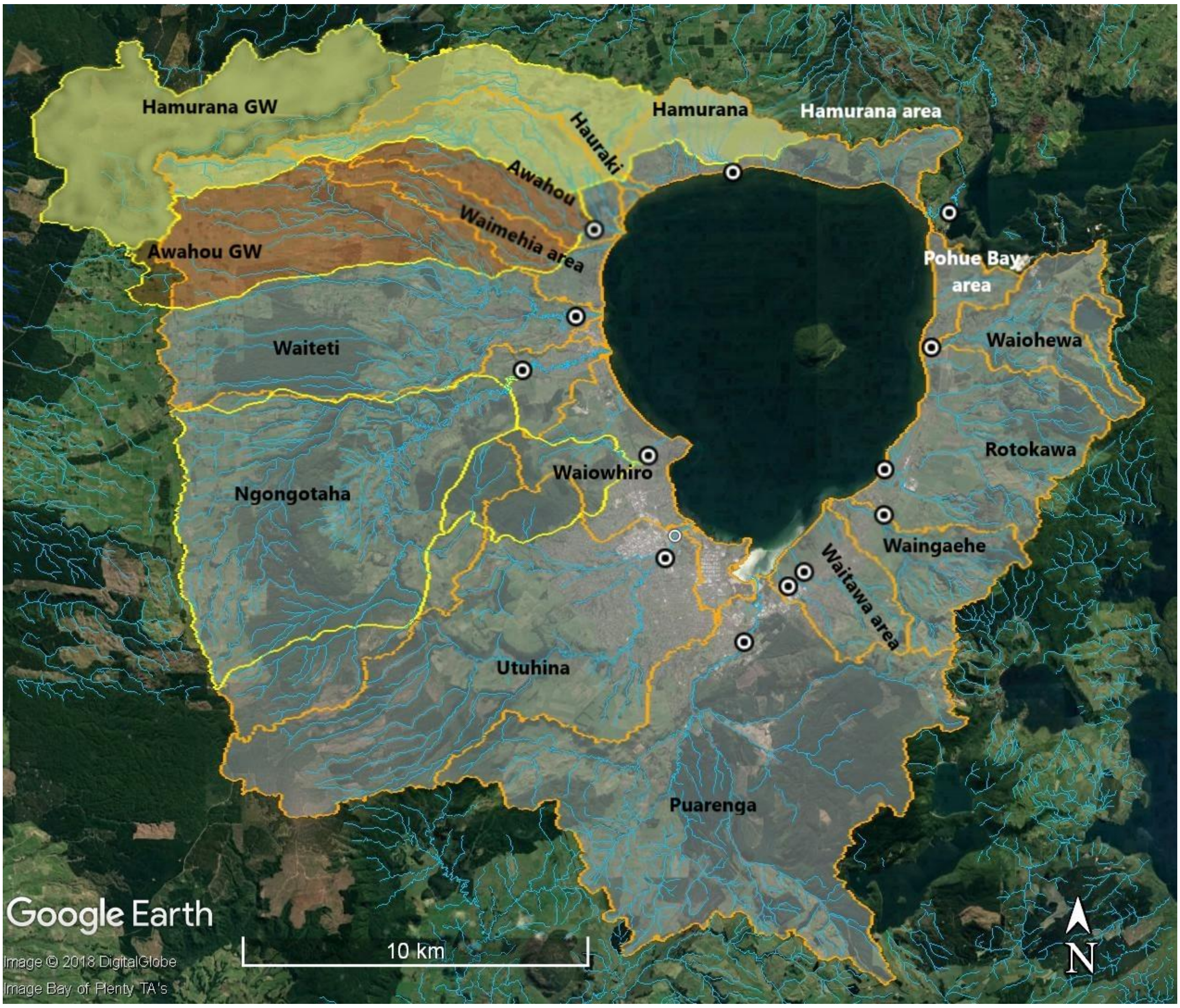

Figure 2.1: Lake Rotorua surface water catchment, groundwater catchment and the location of stream hydrology monitoring sites at the bottom of the catchments. Hamurana groundwater catchment extends over part of Hauraki and Awahou; Awahou groundwater catchment extends over part of Waimehia and Waiteti; Waiowhiro groundwater catchment extends over part of Ngongotaha and Utuhina.

2.4 Total hydraulic load

2.4.1 Water balance

This report uses a water balance approach was used to determine the hydraulic load to Lake Rotorua for the time period 2007 to 2014 (inclusive). The hydraulic load from 'ungauged' catchments was calculated as the residual after subtracting inflows (gauged streams (Q_{inflow})+ net rainfall to lake (rainfall - evapotranspiration) from outflows (Ohau channel (Q_{Ohau}), with an adjustment for any lake water storage/loss over the period, i.e. *Ungauged = (Q_{ohau} + E + ΔS) – (Q_{inflow} + rainfall)*. The approach differs from Tempero et al. (2015) by using 8-year average data and by avoiding the need to apply an adjustment factor to match a model.

2.4.2 Inflows from gauged catchments

In this report we have used the same inflows for gauged catchments as used in Tempero et al. (2015), i.e. the average of daily mean flow for an 8-year period from 2007-2014. Near continuous gauging occurs on five streams, (NGA, UTU, PUA and WNG) - providing accurate data for about half the total hydraulic load to the lake. However, the other streams (HAM, AWA, WTT, WWH, WHE) are gauged approximately monthly so there is more uncertainty associated with these values.

Rutherford and Palliser (2014a) calculated the error for estimates of inflows to be in the range of 8 – 17%. The error around the estimate of outflows to be in the range of 2 -7% (i.e. 16.5 +/- 0.3 – 1.2)[7].

2.4.3 Outflow down Ohau channel

Tempero et al. (2015) used an 8-year time period from 2007-2014 during this period the average outflow down the Ohau channel was 17.87 m^3/s (mean daily flow, BOPRC). This is higher than the long-term outflow down the Ohau channel (i.e. 16.5 m^3/s over a 37 period from 1975-2010) (Rutherford and Palliser 2014). Over multiple years outflows are proportional to inflows, so using a period with higher than average outflows will provide a higher estimate of inflows compared to the long-term average. In this case, the 2007-2014 period over-estimates inflow loads by about 8.3% compared to the long-term average.

The proportion of flow from 'ungauged' catchments appears to be consistent between years when using an 8-year rolling average. An analysis of the inflow / outflow data from 2005 to 2016 found that for an 8-year rolling average the residual of outflows (Ohau + E + ΔS) less continuously gauged inflows (rainfall, NGO, UTU, PUA, WNG) is very consistent at 51% of the outflow (+/- 0.007).

The water level in Lake Rotorua was 18mm lower on 31 December 2014 compared to 1 January 2007, this equates to an average flow over the eight-year period of 0.0035 m^3/s. This amount was subtracted from the outflow, but the impact of the water level change was very small.

2.4.4 Rainfall

Net rainfall is the difference between total rainfall and evapotranspiration. Net rainfall to the lake is used as part of the mass balance calculations and in this report net rainfall is also used as a way to examine the hydrology of sub-catchments and differentiate flow between the 'ungauged' sub-catchments.

There is a large rain gradient across the catchment and across the lake. The north-western side of the catchment is wetter (annual rainfall up to about 2300mm/yr in the Mamaku range) while the south-eastern side of the catchment is dryer (1500mm/yr near the airport). The rain gradient across the lake itself varies from about 1500mm/yr to 2000mm/yr (Figure 2.2).

Rainfall contour maps have been developed for the Rotorua catchment by Hoare (1980) and by Tait (reported in Rutherford et al. (2008), Rutherford and Palliser (2014a) and Rutherford 2016). Rutherford (2016) presents a rainfall contour map of long term average rainfall across the catchment based on a rainfall scaling factor (RF) derived from Hoare (1980) and long-term monitoring data from the airport and Dalbeth Road (averaged to provide a 'reference rainfall'). This was then used to estimate rainfall

[7] 95% confidence intervals.

for each surface water sub-catchment.[8] The long-term reference rainfall was 1615mm/yr and the estimated rainfall for the lake was 1630mm/yr.[9] The estimated long-term rainfall for ungauged catchments was 1728mm/yr.

Rainfall at the airport for the period 2007-2014 was slightly less (99%) than the long-term average. This is surprising given that the Ohau channel outflow over this period was higher than the long-term average. The difference is probably within the margins of error, but it is possible that the rainfall pattern has changed over time since the work done to derive the rain contours, and more rain is falling on the lake or western catchments than is indicated by the airport site.

This report compares observed stream flows from gauged catchments with estimates based on net rainfall and catchment area. The rainfall was split between surface water and ground water catchments using the drainage factor (D) estimated by Rutherford (2016) (Table 3.2). Note that for most streams this drainage factor is higher than some previous estimates of about 53% rainfall reaching groundwater (see Morgenstern et al. 2015 and discussion below). The value of the drainage factor makes most difference when there is a difference between the size of the surface water and groundwater catchment areas; in catchments where this difference was largest (HAM, AWA, WTT), the higher drainage factor resulted in a much better match between calculated flows with the observed flows. However, it does raise the question of why these catchments require a high drainage factor to match observed and calculated flows and whether we need to revisit estimates of catchment size or rainfall.

The total rainfall applied was based on estimates in Tempero et al. (2015), however the rainfall for HAM, AWA was increased and the rainfall in WTT and NGO was decreased to reflect the recently revised groundwater catchment boundaries and the rainfall contour map in Rutherford (2016) (Figure 2.2).

2.4.5 Evaporation

In this report I have adopted the annual evapotranspiration (AET) values applied by Tempero et al. (2015). However, Tempero et al. (2015) appeared to have not accounted for AET from the lake surface. They assumed a rainfall of 1600mm/yr to the lake, AET of 0 and surface runoff of 3.96 m^3/s (suggesting an implied AET of only 50mm/yr). The effect of this would be to underestimate the outflow. This may explain the need to apply a constant multiplier of 1.18 when calculating the flow from the ungauged catchments to minimise error between modelled water level and measured water level.

Average penman open water evaporation at the airport for the 8-year period 2007-2014 was 794mm/yr (equivalent to 2.03 m^3/s). Rutherford and Palliser (2014) used a lower estimate of evaporation (i.e. 637mm/yr = 1.63 m^3/s). The reason for these differing estimates probably reflects the higher rainfall on the lake than at the relatively dry airport site. It is unlikely to be due to the different time periods because interannual variability because a rolling eight-year average (2003-2018) shows little variation in open water evaporation between years (range 781 to 794mm).

These differences in AET estimates from the lake surface would cause the estimate of flow from 'ungauged' catchments to differ by about 0.4 m^3/s (about 10% of 4.11 m^3/s). In this report I have used

[8] The extrapolation uncertainty for a given sub-catchment is about 5-10% (Rutherford et al. 2008).

[9] Hoare 1980) estimated the average rainfall to the lake was 1.19 times the rainfall at the airport, which would equate to a long-term average of 1650mm/yr. For the purpose of understanding the sensitivity of rainfall on the lake, 100mm/yr of rain corresponds to 0.26 m^3/s.

AET from the lake surface of 637 mm/yr as a best estimate (reflecting the higher rainfall on the lake) but also included a scenario assuming 794mm/yr.

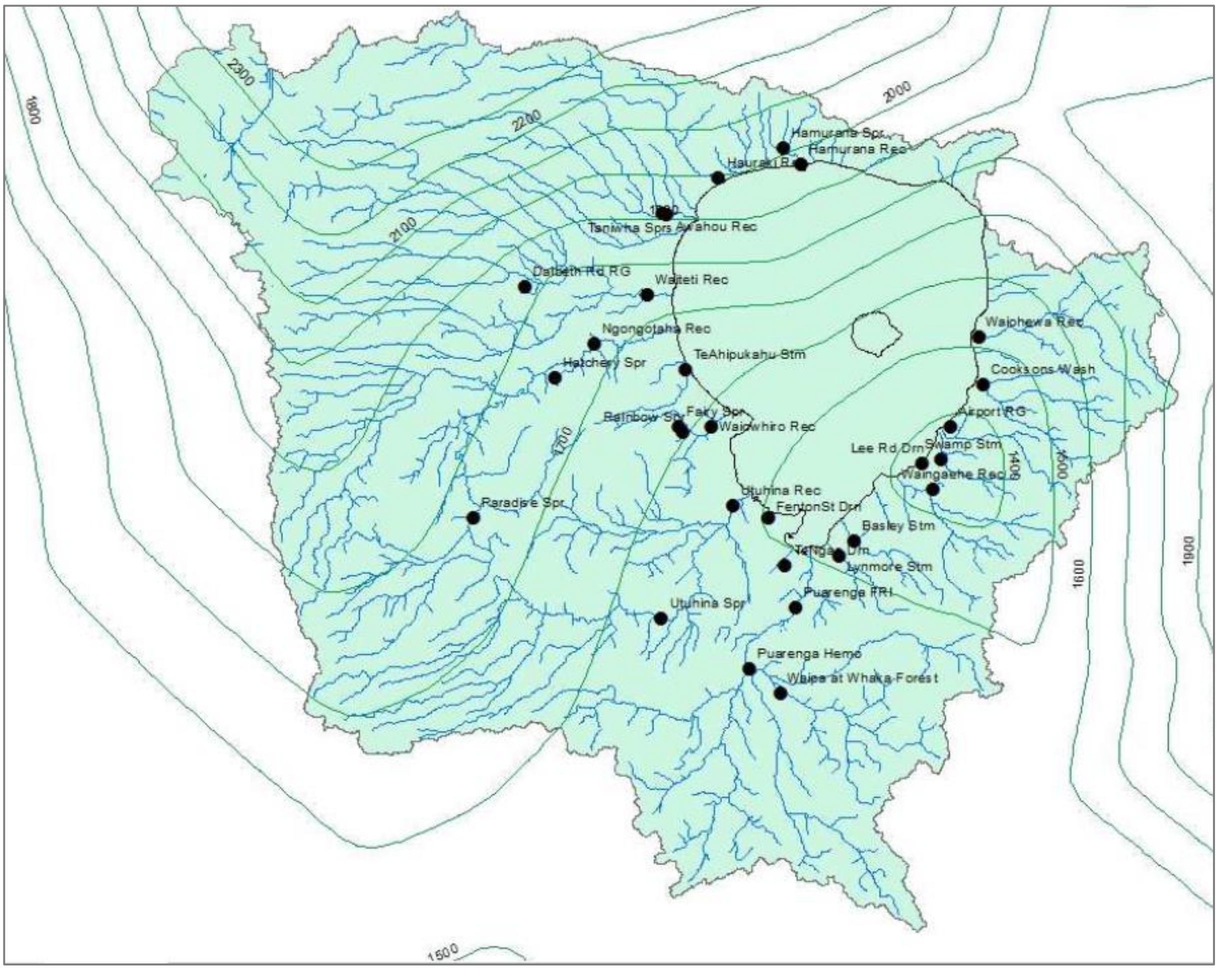

Figure 2.2: Rainfall contours (30-year average 1981-2010), streams and monitoring sites (from Rutherford 2016).

2.5 Hydraulic load from ungauged sub-catchments

The hydraulic load from 'ungauged' catchments was calculated as the residual after subtracting inflows (gauged streams + net rainfall to lake) from outflows (Ohau channel). The total for ungauged catchments was apportioned to the ungauged sub-catchments in the same proportion as the flows for these sub-catchments as calculated from net rainfall and catchment area. The net rainfall was split between surface water and ground water catchments by the drainage factor (D) estimated for each catchment by Rutherford (2016) and a default drainage factor of 0.65 to 0.8 for the ungauged catchments. The drainage factor of 0.8 was used for ungauged parts of Hamurana (HAM), Hauraki, Awahou (AWA), Waimehia and Waiteti (WTT) – reflecting high drainage factor required for the gauged catchments of HAM, AWA, and WTT (see above). This approach calculated a baseflow for Hauraki Stream of 7 L/s) which is similar to measured baseflow of Hauraki Stream (i.e. 5.1 L/s in Beyá et al. (2005) and 8 L/s from a spot measurement on 28 March 2018.

This method produced two estimates of flow from the ungauged catchments, one estimate based on net rainfall apportioned according to catchment size, and one adjusted to match the residual assigned to 'ungauged' from the water balance calculation (residual method). The discharge calculated by the residual method was 1.61 times higher (1.24 m^3/s higher) than the discharge estimated by the net rainfall method (discussed in section 3.1).

The rainfall assigned to each of the 'ungauged' sub-catchments was estimated from the rainfall contour map of Hoare (1980).

2.6 Baseline P and anthropogenic P

The anthropogenic P load was estimated as the difference between 'observed' P load and baseline P load. The baseline P load was strongly influenced by proportion of flow assigned to groundwater – particularly for DRP where the baseline contribution groundwater is higher than for surface water. We applied revised estimates of percent groundwater to calculate baseline P and anthropogenic P.

The 'observed P load' was adopted from Tempero et al. (2015), with an adjustment factor of 0.8 made to the 'ungauged' catchment to reflect the lower hydraulic load of our 'best estimate'[10]. An additional adjustment was done to account for geothermal inputs as discussed below. The modelled P concentrations applied to groundwater and surface water were adopted from Tempero et al. (2015).

The analysis in this report uses estimates of percent groundwater contribution as determined by Rutherford (2016). This is termed 'slow flow' or 'drainage fraction' that is routed to streams via groundwater. Rutherford (2016) estimated 'slow flow' by baseflow separation of daily average flows measured in the major streams, it was calculated as the average of the minimum stream flows in each four-month period. The 'slow flow' calculated in this way reflects what is measured at the bottom of the catchment - it will under-estimate what actually drains to groundwater if the groundwater emerges downstream of the gauging site.

The terms 'slow flow' and 'drainage factor' are often used interchangeably, but in this report the term drainage factor' (D) refers to an area-specific drainage, while 'slow flow' accounts of differences in the size of the groundwater and surface water catchments and can be calculated from stream flow measurements.

In this report, two estimates of D are applied in order to split the ratio of surface water to groundwater used to calculate the baseload. The first estimate, 'D1', uses the 'slow flow' estimated by Rutherford 2016) for gauged catchments (see Table 3.2). For ungauged catchments, the D values applied were 0.45 for urban catchments, 0.8 for north-western catchments and 0.65 for all other catchments. This resulted in an area-weighted D for ungauged catchments of 0.62.

The second estimate, 'D2', assumed a specific drainage factor (D) for each catchment of 0.5 (0.45 for urban areas) which was then weighted by the relative groundwater catchment area.[11] This resulted in an area-weighted D for ungauged catchments of 0.42.

2.7 Geothermal inputs

Geothermal inflows enter Lake Rotorua from the southern and eastern side of the lake. Geothermal water enters direct to the lake via springs (e.g. Polynesian Pools area, Kuirau Park and Ohinemutu) and

[10] The best estimate ungauged load (3.28 m^3/s) divided by the estimate by Tempero et al. (2015) of ungauged load (4.11 m^3/s). e.g. 'Obs. TP load' for ungauged catchments adjusted from 13.44 t/yr to 10.73 t/yr.
[11] See Morgenstern et al. 2015.

upwelling (e.g. Sulphur Bay, Te Ruapeka Bay), and via the Puarenga Stream (Whakarewarewa field) and the Waiohewa River (Tikitere field).

Most N in geothermal fluid is in the form of total ammonia. The Rotorua geothermal field (Rotorua inputs and Puarenga Stream) has relatively low in total ammonia (about 0.89 mg N/L). In contrast, the Tikitere field (Waiohewa Stream) mostly has high in total ammonia (ca. 50 mg N/L). The TN concentration of geothermal fluid to the Puarenga River appears to be only a little higher than the river upstream (White et al. 2004).

Geothermal fluid contains dissolved P in similar concentrations to the surrounding groundwater and this precipitates to insoluble minerals such as apatite when released to surface waters (White et al. 2004). Geothermal fluid can contain substantial aluminium that can also bind P (Martin et al. 2000) and this may be occurring in Sulphur Bay. Tikitere field has a TP concentration at source of about 0.1 mg/L. A similar concentration is likely in the Whakarewarewa field, but there is a paucity of data (Dine 2004 in White et al. 2004).

This report assigns geothermal loads based on the estimates in White et al. (2004) (see Table 2.2). White et al. (2004) reviewed and updated previous estimates of geothermal inflows to Lake Rotorua (e.g. Donovan and Donovan 2003, Dine 2004, Burns 1999, Glover 1992) and used additional monitoring data to provide a best estimate of geothermal inputs to the lake.[12]

Over half (58%) of the geothermal inflows to the lake are estimated to enter directly via the lake bed (estimated by Glover (1992) as the residual from the lake's chloride flux). The total fraction of geothermal fluid in the Puarenga River at FRI is likely to be about 7% of the mean flow, i.e. about 125 L/s.

In this report, I have used the flux of geothermal fluid to better apportion the natural P load between dissolved and particulate fractions. All P from geothermal inputs was assumed to be in the particulate form after entering surface water, so the estimated geothermal load from the Puarenga (0.4 t/yr), and Waiohewa (0.09 t/yr) was subtracted from the DRP calculations. No change was made to the total P load in these catchments because the P in geothermal fluids was assumed to be sourced from the surrounding groundwater.

For estimates of DRP from ungauged catchments, the 'observed DRP load' and 'baseline DRP load' were both reduced by about 29% (multiplied by 0.71). This is the fraction of the 'ungauged' hydraulic load that was estimated to come from geothermal sources (i.e. 0.95 m^3/s / 3.28 m^3/s = 0.29). As discussed above, it was assumed that all P from geothermal inputs would rapidly convert to a particulate form after entering surface water (White et al. 2004).

Geothermal inputs are estimated to provide about 2.5 t/yr P from ungauged streams near Rotorua city (about 792 L/s). This amount was added to the baseline load for ungauged catchments. No change was made to the TP 'observed' load because this estimate for the ungauged catchments already included any additional volume that geothermal inputs might contribute and the mean TP concentration used in the calculations (0.104 g/m^3) was similar to that found in geothermal fluid. The non-geothermal component of ungauged catchments was adjusted accordingly by subtracting the estimated volume of

[12] The estimate of geothermal inflows by White et al. (2004) is considerably less than some previous estimates (e.g. 67.3 t/y TN and 5.6 t/yr TP estimated by Donovan and Donovan 2003). This is because of errors in some of the previous estimates.

geothermal inputs (0.792 m^3/s) from the best-estimate of discharge (i.e. 3.28 m^3/s - 0.792 m^3/s = 2.49 m^3/s).

Table 2.2: Total nitrogen and phosphorus inputs to Lake Rotorua (adapted from White et al. 2004). Flows are back calculated from load assuming a TP concentration of 0.1 mg/L.

Location	sub-catchment	TP Flux (t/year)	TN Flux (t/year)	Flow (L/s)
Waiohewa (Tikitere)	Waiohewa	0.09	27	29
Rotokawa	n.a	unknown	unknown	
Puarenga u/s FRI	Puarenga gauged	0.4	3.4	127
Puarenga d/s FRI	Puarenga ungauged	0.38	3.2	120
Rotorua thermal streams	Rotorua urban "ungauged"	0.42	1.39	133
Rotorua "unmeasured"	Direct to lake "ungauged"	1.7	11	539

Flow back calculated from load assuming a mean TP concentration of 0.1 mg/L.

Note: It is possible that the Waingaeha Stream has a geothermal component as it is located closed to the Rotokawa geothermal area and has elevated concentrations of chloride and sulphate. However, it has not been quantified or confirmed.

3 Results

3.1 Hydraulic load

The largest inflows to Lake Rotorua come from rainfall, ungauged' catchments (which includes direct groundwater inputs) and Hamurana spring (Figure 3.1). The water balance developed for Lake Rotorua assigns the residual of inflows and outflows to 'ungauged' catchments which includes direct groundwater inputs (Table 3.1). The best-estimate is 3.28 m^3/s of flow from ungauged catchments. The estimate for ungauged catchments is sensitive to the amount of net rainfall estimated to fall on the lake (i.e. total rainfall less evapotranspiration from the lake), so the scenario with a higher evapotranspiration from the lake estimated more water being assigned to 'ungauged' catchments (i.e. 3.68 m^3/s).

Table 3.2 compares the observed discharge from gauged streams with and estimated flow based on rainfall and catchment area, using a drainage factor (D) to assign net rainfall to the surface water and groundwater catchments. Overall the estimated flow from gauged catchments was very close to the observed (i.e. within 2%). The estimates based on rainfall underestimated observed flow from the Awahou and Waingaehe catchments (86% and 66% of observed respectively). This may be due to under-estimates of rainfall or additional groundwater inputs to these streams, or error associated with the way flow was extrapolated from monthly gauging.

Flow estimates for ungauged catchments based on net rainfall were considerably less than the flow estimated from the water balance approach, i.e. 2.04 m^3/s compared to 3.28 m^3/s (Table 3.2 and Table

3.3).[13] This contrasts with the close match for gauged catchments and suggest either the water balance over-estimates residual flow, net rainfall is under-estimated from the ungauged catchments, or that there are additional groundwater contributions that cannot be explained by net rainfall to the Rotorua catchment.

Geothermal inputs from the Rotorua area from thermal springs or direct to the lake were estimated to be about 0.79 m^3/s – much of the difference between a water balance estimated and net rainfall estimate. [14] Only 0.3 m^3/s of this geothermal input from the Rotorua town area can be explained by rainfall on the ungauged catchments near Rotorua or by loss of groundwater from the Utuhina or Puarenga catchments.[15] If estimates of geothermal inputs are correct then this suggests that some of the water in geothermal inputs (about 0.49m^3/s) to the lake may be sourced from outside the catchment or from higher rainfall parts of the catchment.

There is considerable uncertainty around apportioning slow flow and quick flow in the ungauged catchments. Rain recharge of groundwater around Rotorua area can account for only one third of the estimated geothermal input from Rotorua area, so the proportion of flow attributed to slow flow may in fact be about 0.49m^3/s higher and the proportion attributed to quick flow may be 0.49m^3/s lower.

The sub-catchments that contribute most to 'ungauged' is Rotokawa area, Hamurana area, Waitawa area, Waimehia area and Hauraki Stream. These sub catchments represent about 65% of the 'ungauged' catchments by virtue of their size.

Rutherford and Palliser (2014) noted that runoff coefficients based on surface water catchments were high in the HAM, AWA and WWH streams because they receive groundwater from outside their catchment. Conversely, Rutherford and Palliser (2014a) found that the NGO and WTT catchments had surprisingly low runoff when expressed as a fraction of rainfall, they suggested that the catchments had net groundwater losses or that the rainfall was over-estimated in these catchments. This is consistent with our analysis that found calculated flows in these two catchments approximately matching observed flows when we account for the smaller size of the groundwater catchment compared to the surface water catchment (i.e. groundwater losses).

[13] When a drainage factor of 0.5 was applied to all ungauged catchments then the discharge calculated by the rainfall method was 2.29 with 41% was slow flow (i.e. average area-weighted D of 0.41).
[14] See Table 2.2.
[15] Net rainfall assigned to groundwater for ungauged portions of Rotorua, Utuhina and Puarenga is 0.145 m^3/s (Table 3.3). Estimates for flows to Utuhina and Puarenga Streams based on net rainfall are 0.15 m^3/s higher than the combined observed flow (Table 3.2)

Table 3.1: Water balance calculation to estimate flow from 'ungauged' catchments for period 2007-2014. The scenarios of 'Low E' and 'high E' are for evapotranspiration from the lake of 637 mm/yr and 794 mm/yr respectively. Rainfall to lake of 1630 mm/yr. Gauged inflows from Tempero et al. (2015).

	Catchment	**Discharge (m^3/s) Low E scenario**	**Discharge (m^3/s) High E scenario**
Gauged in-flows	Hamurana	2.57	2.57
	Awahou	1.69	1.69
	Waiteti	1.23	1.23
	Ngongotaha	1.84	1.84
	Waiowhiro	0.31	0.31
	Utuhina	1.81	1.81
	Puarenga	1.95	1.95
	Waingaehe	0.27	0.27
	Waiohewa	0.38	0.38
	Rainfall to lake	4.166	4.166
	Ungauged	**3.28**	**3.68**
out-flows	Evaporation E from lake	1.63	2.03
	ΔS	-0.004	-0.004
	Ohau discharge	17.87	17.87

Table 3.2: Water inflows to Lake Rotorua. D = Drainage Factor used for calculations (% slow flow from Rutherford (2016)). Observed (Obs.) discharge is for period the 2007-2014 (Tempero et al. 2015). The 'flow best estimate' uses a flow for 'ungauged' derived from a water balance calculation.

Catchment	**Obs. discharge (m^3/s)**	**SW area (km^2)**	**GW area (km^2)**	**SW area u/s gauging (km^2)**	**GW area u/s gauging (km^2)**	**rainfall mm/yr**	**AET mm/yr**	**D**	**Calc. Quick flow (m^3/s)**	**Calc. Slow flow (m^3/s)**	**Calc. Total flow (m^3/s)**	**Flow Best Est. (m^3/s)**
Hamurana	2.57	2.8	66.6	2.8	66.6	2200	856	0.92	0.010	2.61	2.62	
Awahou	1.69	19.5	38.6	16.6	38.6	2100	838	0.88	0.08	1.36	1.44	
Waiteti	1.23	61.9	34.0	60.4	34.0	1900	859	0.79	0.42	0.89	1.31	
Ngongotaha	1.84	76.9	61.3	73.4	57.8	1800	895	0.68	0.67	1.13	1.80	
Waiowhiro	0.31	13.6	20.6	7.5	14.5	1715	930	0.62	0.07	0.22	0.29	
Utuhina	1.81	61.0	70.0	57.6	66.5	1900	942	0.67	0.58	1.35	1.93	
Puarenga	1.95	82.1	76.1	77.0	70.9	1800	946	0.63	0.77	1.21	1.98	
Waingaehe	0.27	11.1	11.8	9.7	10.4	1450	895	0.84	0.03	0.15	0.18	
Waiohewa	0.38	13.7	13.7	13.7	13.7	1750	881	0.62	0.14	0.23	0.38	
Total gauged	12.05	342.7	392.6	318.7	373.0				2.77	9.16	11.93	12.05
Total ungauged				103.3	84.1	1670	888	0.62	0.77	1.27	2.04	3.28
Net rainfall to lake		80.8		80.8	80.8	1631	637				2.54	2.54
TOTAL				502.8	537.9						16.51	**17.87**

RIVER LAKE

Table 3.3: Water inflows to Lake Rotorua estimated for 'ungauged' sub-catchments. D = Drainage Factor used for calculations. The 'flow best estimate' applies a multiplier of *ca*.1.61 so that the total 'ungauged' flow matches the residual of 3.28 m^3/s that was derived from the water balance calculation.

Ungauged catchments	SW area ungauged (km^2)	GW area ungauged (km^2)	rainfall mm/yr	AET mm/yr	D	Calc. Quick flow (m^3/s)	Calc. Slow flow (m^3/s)	Calc. Total flow (m^3/s)	Flow Best Est. (m^3/s)
Hamurana	13.24	9.08	1950	855	0.80	0.092	0.252	0.344	0.555
Hauraki	12.63	0.26	2000	838	0.80	0.093	0.008	0.101	0.324
Awahou Point	0.37	0.37	1940	838	0.80	0.003	0.010	0.013	0.019
Awahou	2.95	1.75	1900	838	0.80	0.020	0.047	0.067	0.113
Waimehia	9.43	2.63	1960	855	0.80	0.066	0.074	0.140	0.296
Waiteti	1.50	1.50	1750	855	0.80	0.009	0.034	0.043	0.062
Ngongotaha	3.54	3.54	1700	895	0.65	0.032	0.059	0.090	0.131
Ngongotaha town	0.47	0.47	1700	895	0.45	0.007	0.005	0.012	0.017
Waiowhiro	6.11	6.11	1600	930	0.45	0.071	0.058	0.130	0.188
Utuhina	3.45	3.45	1600	942	0.65	0.025	0.047	0.072	0.104
Rotorua city	2.67	2.67	1600	920	0.45	0.032	0.026	0.058	0.083
Puarenga	5.14	5.14	1600	946	0.65	0.037	0.069	0.107	0.155
Waitawa Lynmore Stm	3.35	3.35	1450	900	0.65	0.020	0.038	0.058	0.085
Waitawa Baisley Stm	3.91	3.91	1450	900	0.65	0.024	0.044	0.068	0.099
Waitawa	2.76	8.82	1450	900	0.65	0.017	0.100	0.117	0.151
Waingaehe	1.36	1.36	1420	895	0.65	0.008	0.015	0.023	0.033
Rotokawa	24.75	24.05	1490	890	0.65	0.165	0.297	0.462	0.672
Waiohewa	0.00	0.00	1600	880	0.65	0.000	0.000	0.000	0.000
Pohue Bay	4.28	4.28	1650	890	0.65	0.036	0.067	0.103	0.150
Island	1.35	1.35	1580	890	0.65	0.010	0.019	0.029	0.043
Total for 'ungauged'	**103.3**	**84.1**	**1670**	**887.6**		**0.77**	**1.27**	**2.04**	**3.28**

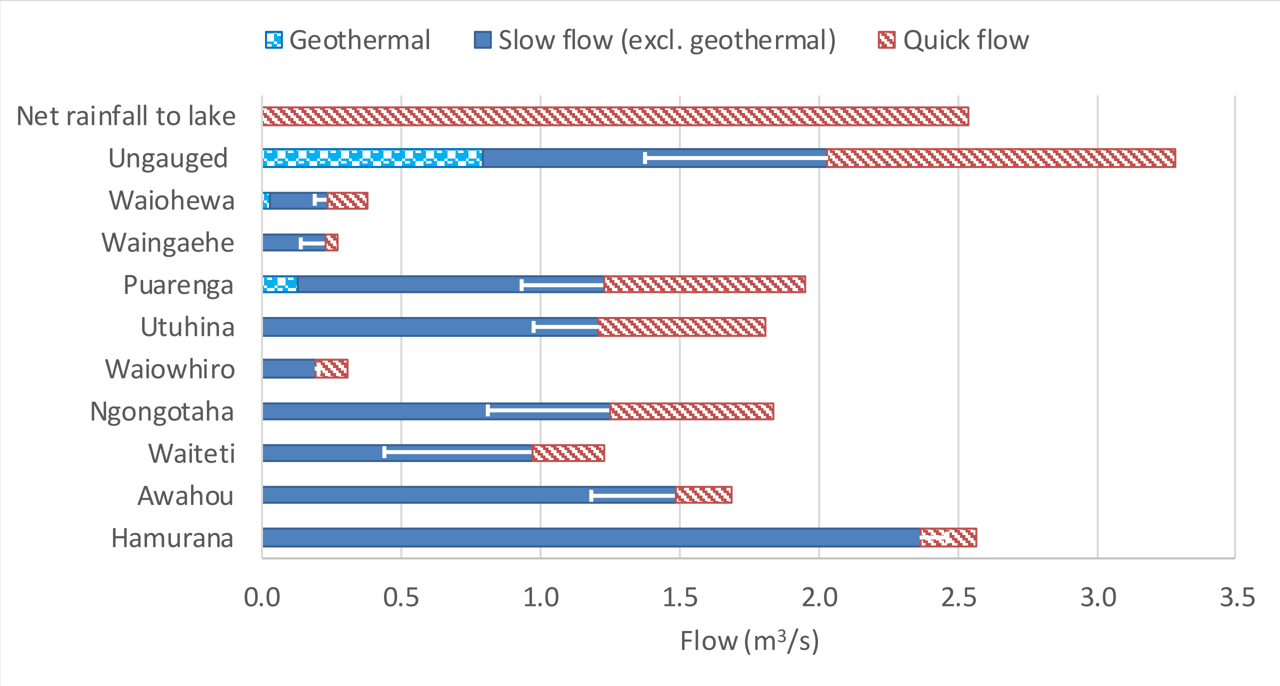

Figure 3.1: Inflow to Lake Rotorua from sub-catchments (2007-2014) indicating component of the total flow as quick flow, slow flow and any geothermal component of slow flow. Negative error bars assume a drainage factor of 0.5 weighted by relative groundwater catchment area (see D2 in Table 3.4). The range highlights the uncertainty around apportioning slow flow and quick flow in the ungauged catchments.

3.2 Phosphorus load

The estimated P load to Lake Rotorua was 46.0 t/yr as TP and 24.7 t/yr as DRP (Table 3.4). This is slightly less than the total TP load estimated by Tempero et al. (2015) (48.7 t/yr) because of differences in estimates of hydraulic load from 'ungauged' streams. If the higher flow estimate for ungauged was applied (2.68 m^3/s based on the high estimate of evapotranspiration from the lake) than the total P load to the lake would be 47.9 t/yr. The phosphorus from sub-catchments strongly mirrors the water inflows and the split between slow flow and fast flow (groundwater and surface water) (Figure 3.2).

The load of anthropogenic P was estimated to be 18.1 to 20.7 t/yr (39% - 45%) and 3.8 to 6 t/yr (19% - 24%) for TP and DRP respectively[16]. The anthropogenic TP load was dominated by 'ungauged' catchments (5.9 t/yr), Puarenga (4.36 t/yr), Utuhina (3.56 t/yr) and Ngongotaha (2.4 t/yr) (Table 3.4, Figure 3.3 and Figure 3.4).

There is a high degree of uncertainty estimating the anthropogenic load from ungauged catchments. For example, if we apply a higher average drainage factor to ungauged catchments (0.62 instead of 0.42), this would reduce the estimate of anthropogenic load of TP from 5.9 t/yr to 5.5 t/yr as indicated by the error bars in Figure 3.3.

[16] Range of estimates from D1 and D2 and excluding negative values.

Adjusting DRP to account for geothermal inputs required subtracting the DRP load attributable to geothermal inflows to account for dissolved P converting to particulate P after entering surface waters. This resulted in a higher and more realistic estimate of the anthropogenic DRP load for Puarenga and Waiohewa catchments. Nevertheless, the anthropogenic DRP load estimated for the Waiohewa Stream was still zero. This may be due to excess aluminium from geothermal inputs to this stream binding a portion of the non-geothermal DRP. Alternatively, it may be caused by an underestimate of the geothermal contribution. This is likely because the estimate of geothermal inflows to Waiohewa vary widely (White et al. 2004), and recent monitoring has found the geothermal inflow in highly variable with rainfall but has minimal dilution with rainfall (Andy Woolhouse pers. comm. 2018). Thus, flow estimates based on baseflow conditions will likely be under-estimates.

For TP, only the 'ungauged' catchments required adjusting to account for geothermal inputs. This required adding the estimated geothermal load from 'ungauged' (i.e. 2.5 t/yr) to the baseline load. There was a corresponding decrease in the estimated anthropogenic load.

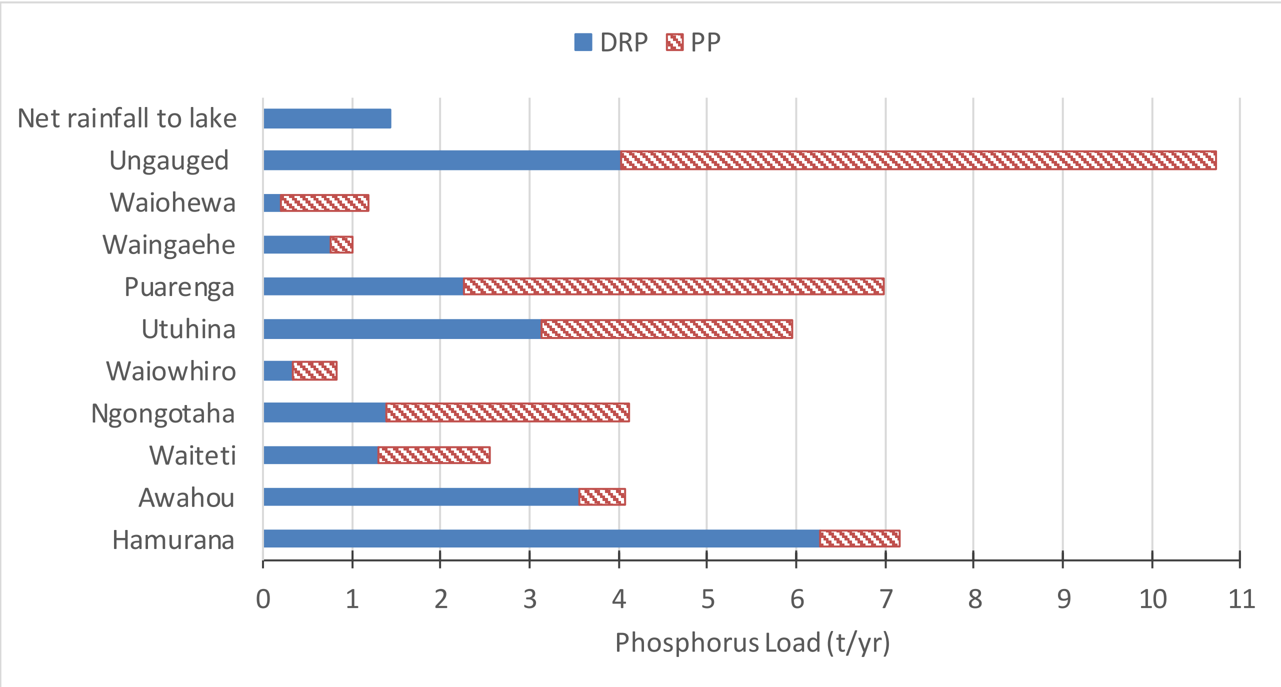

Figure 3.2: Phosphorus load to Lake Rotorua from sub-catchments (2007-2014), scenario D2. DRP = dissolved reactive phosphorus, PP = particulate phosphorus. Ungauged refers to minor streams, ungauged streams and groundwater inflows.

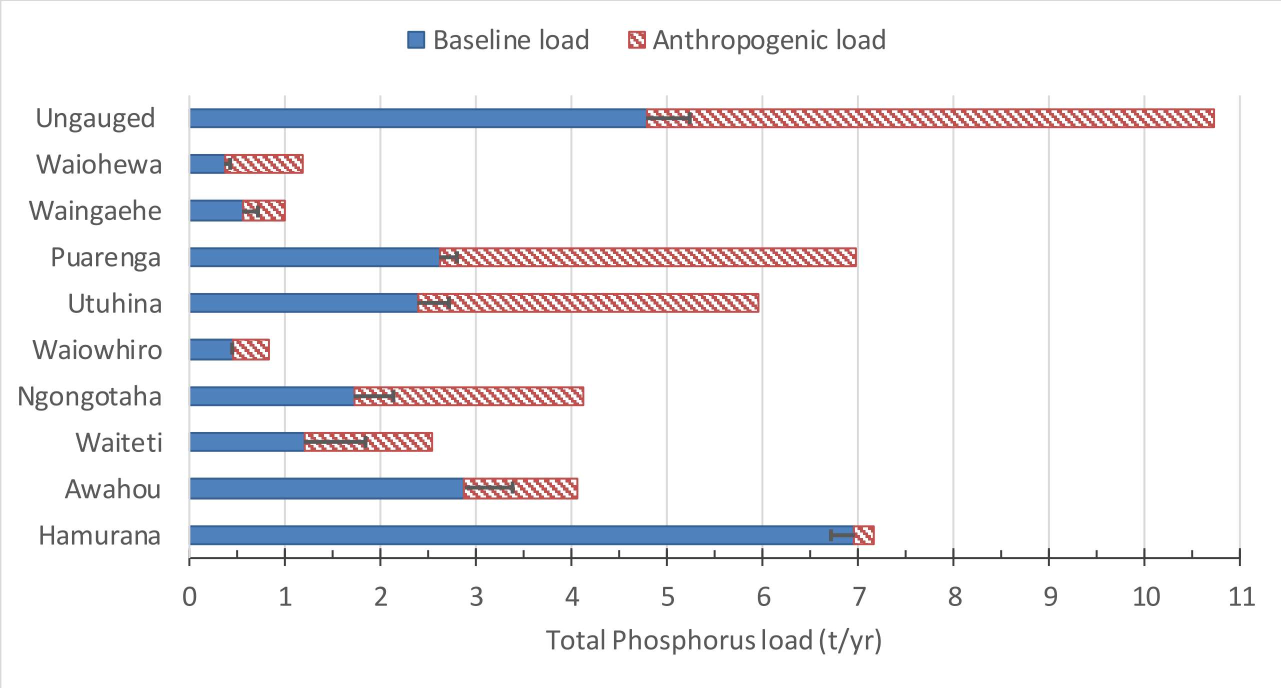

Figure 3.3: Total phosphorus load to Lake Rotorua (2007-2014) with the baseline and anthropogenic contributions indicated for drainage factor D2 and accounting for geothermal inputs. Error bars show scenario D1.

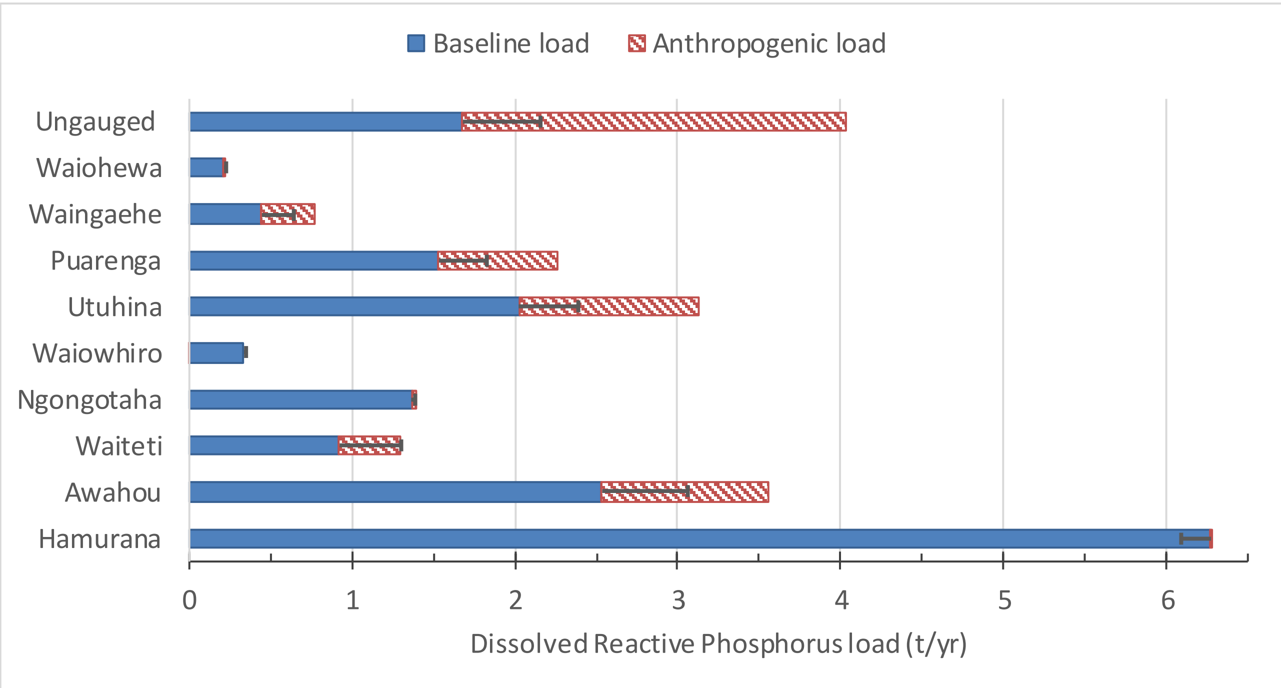

Figure 3.4: Dissolved reactive phosphorus load to Lake Rotorua (2007-2014) with the baseline and anthropogenic contributions indicated for drainage factor D2 and accounting for geothermal inputs. Error bars show scenario D1.

3.3 Area specific anthropogenic phosphorus load

The area specific anthropogenic phosphorus load from each sub-catchment is presented in Figure 3.5. The catchments with the highest area specific anthropogenic TP loads are Puarenga (0.56 to 0.59 kg/ha/yr), Waiohewa (0.55 to 0.59 kg/ha/yr), Utuhina (0.52 to 0.57 kg/ha/yr) and ungauged (0.59 to 0.63 kg/ha/yr). The relatively high area-specific load from the Puarenga Stream may be partially explained by breakthrough of P from land disposal of sewage effluent in the Waipa Stream catchment (Hamill 2013).

Catchments with a higher area-specific anthropogenic P load could be considered as having higher priority for implementing P reduction strategies because the results indicate more P runoff per area of land. However, caution is needed in interpreting the results, particularly for ungauged catchments, because they are sensitive to assumptions about groundwater contribution (slow flow) and assumptions about groundwater age. In particular, little weight can be put on the area-specific anthropogenic P load for ‘ungauged’ catchments because it is largely determined by the assumptions used to set the ‘observed load’, i.e. that DRP and TP concentrations are equal to the flow weighted mean concentrations of the major streams.

Furthermore, the area-specific loads were calculated by using the average area of the groundwater and surface water catchments. This method of calculation is likely to result in a higher area-specific load for catchments with a larger surface water compare to groundwater area, because in Rotorua catchment anthropogenic P tends to be more commonly transported via surface water. This may upwardly bias area-specific loads for ungauged catchments, Puarenga, Ngongotaha and Waiteti.

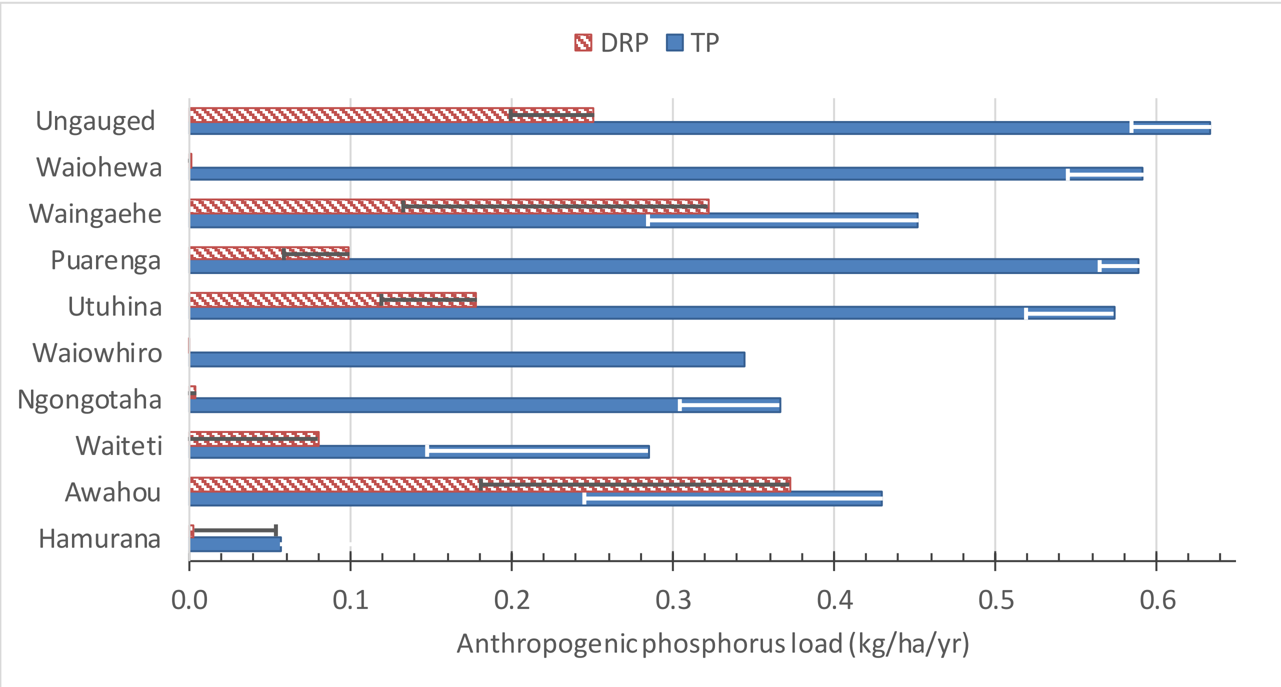

Figure 3.5: Area-specific anthropogenic phosphorus load to Lake Rotorua (2007-2014) assuming drainage factor D2 and accounting for geothermal inputs. Error bars show scenario D1.

Table 3.4: Dissolved phosphorus load to Lake Rotorua (2007-2014). D1 = drainage factor from Rutherford (2016), D2 = drainage factor of 0.5 and weighted by relative groundwater catchment area (D of 0.4 used for Waiowhiro due to part urban). See Table 3.2 for flows and catchment areas. The observed (obs.) load and modelled P concentrations adopted from Tempero et al. (2015). Adjustments were made for 'ungauged' and geothermal inputs (Geo.)

Sub-catchment	Obs. discharge (m^3/s)	Obs DRP load (t/yr)	Mod. GW DRP (g/m^3)	Mod. SW DRP (g/m^3)	D1	D1 Baseline GW load DRP (t/yr)	D1 Baseline SW load DRP (t/yr)	D1 Baseline load DRP (t/yr)	D1 Anthro DRP load (t/yr)	D1 Anthro DRP spec. load (kg/ha/yr)	D1 Anthro load (% of total)	D2	D2 Baseline GW load DRP (t/yr)	D2 Baseline SW load DRP (t/yr)	D2 Baseline load DRP (t/yr)	D2 Anthro DRP load (t/yr)	D2 Anthro DRP spec. load (kg/ha/yr)	D2 Anthro load (% of total)
Hamurana	2.57	6.28	0.081	0.008	0.92	6.04	0.052	6.09	0.19	0.05	3%	0.95	6.24	0.032	6.27	0.01	0.00	0%
Awahou	1.69	3.56	0.064	0.009	0.88	3.00	0.058	3.06	0.50	0.18	14%	0.70	2.39	0.144	2.53	1.03	0.37	29%
Waiteti	1.23	1.3	0.05	0.009	0.79	1.53	0.073	1.61	-0.31	-0.06	-23%	0.36	0.70	0.223	0.92	0.38	0.08	29%
Ngongotaha	1.84	1.39	0.042	0.009	0.68	1.66	0.167	1.82	-0.43	-0.07	-31%	0.44	1.07	0.292	1.36	0.03	0.00	2%
Waiowhiro	0.31	0.33	0.048	0.016	0.62	0.29	0.059	0.35	-0.02	-0.02	-6%	0.56	0.26	0.069	0.33	-0.00	0.00	0%
Utuhina	1.81	3.13	0.058	0.009	0.67	2.22	0.170	2.39	0.74	0.12	24%	0.54	1.79	0.236	2.02	1.11	0.18	35%
Puarenga	*1.95*	*2.26*	*0.048*	*0.016*	*0.63*	*1.86*	*0.364*	*2.22*	*0.04*	*0.00*	*2%*	*0.48*	*1.42*	*0.512*	*1.93*	*0.33*	*0.04*	*15%*
Puarenga - Geo.	1.95	2.26	0.048	0.016	0.63	1.46	0.364	1.82	0.44	0.06	19%	0.48	1.02	0.512	1.53	0.73	0.10	32%
Waingaehe	0.27	0.77	0.086	0.016	0.84	0.62	0.022	0.64	0.13	0.13	17%	0.52	0.38	0.065	0.45	0.32	0.32	42%
Waiohewa	*0.38*	*0.21*	*0.048*	*0.002*	*0.62*	*0.36*	*0.009*	*0.37*	*-0.16*	*-0.11*	*-74%*	*0.50*	*0.29*	*0.012*	*0.30*	*-0.09*	*-0.07*	*-43%*
Waiohewa - Geo.	0.38	0.21	0.048	0.002	0.62	0.27	0.009	0.28	-0.07	-0.05	-31%	0.50	0.20	0.012	0.21	0.00	0.00	0%
Ungauged	*3.28*	***5.67***	*0.042*	*0.009*	*0.62*	*2.69*	*0.354*	*3.05*	*2.63*	*0.28*	*46%*	*0.42*	*1.82*	*0.540*	*2.36*	*3.31*	*0.35*	*58%*
Ungauged - Geo.	2.33	**4.03**	0.042	0.009	0.62	1.91	0.251	2.16	1.87	0.20	46%	0.42	1.30	0.383	1.68	2.35	0.25	58%
Rainfall to lake	4.17	**1.443**	0.011	0.011		0.00	1.447	1.45						1.447	1.45			
TOTAL		**24.7**						**21.7**	**3.87**	**0.07**	**16%**				**18.8**	**6.0**	**0.13**	**24%**

Assumed all P in geothermal as TP (e.g. bound to Al). Thus, subtracted geothermal input to Puarenga (0.4 t/yr) and Waiohewa (0.09 t/yr), and reduced 'ungauged' DRP estimates by 29%, i.e. reduced discharge from ungauged catchments from 3.28 m^3/s to 2.33 m^3/s.

Table 3.5: Total phosphorus load to Lake Rotorua (2007-2014). D1 = drainage factor from Rutherford (2016), D2 = drainage factor of 0.5 and weighted by relative groundwater catchment area (D of 0.4 used for Waiowhiro due to part urban). See Table 3.2 for flows and catchment areas. The observed (obs.) load and modelled P concentrations adopted from Tempero et al. (2015). Adjustments were made for 'ungauged' and geothermal inputs (Geo.)

Sub-catchment	Obs. discharge (m^3/s)	Obs TP load (t/yr)	Mod. GW TP (g/m^3)	Mod. SW TP (g/m^3)	D1	D1 Baseline GW load TP (t/yr)	D1 Baseline SW load TP (t/yr)	D1 Baseline load TP (t/yr)	D1 Anthro TP load (t/yr)	D1 Anthro TP spec. load (kg/ha/yr)	D1 Anthro load (% of total)	D2	D2 Baseline GW load TP (t/yr)	D2 Baseline SW load TP (t/yr)	D2 Baseline load TP (t/yr)	D2 Anthro TP load (t/yr)	D2 Anthro TP spec. load (kg/ha/yr)	D2 Anthro load (% of total)
Hamurana	2.57	7.16	0.089	0.012	0.92	6.64	0.078	6.71	0.45	0.13	6%	0.95	6.85	0.05	6.90	0.26	0.07	4%
Awahou	1.69	4.07	0.07	0.017	0.88	3.28	0.109	3.39	0.68	0.25	17%	0.70	2.61	0.27	2.88	1.19	0.43	29%
Waiteti	1.23	2.55	0.056	0.017	0.79	1.72	0.138	1.85	0.70	0.15	27%	0.36	0.78	0.42	1.20	1.35	0.29	53%
Ngongotaha	1.84	4.13	0.046	0.017	0.68	1.82	0.316	2.13	2.00	0.30	48%	0.44	1.17	0.55	1.73	2.40	0.37	58%
Waiowhiro	0.31	0.83	0.053	0.033	0.62	0.32	0.123	0.44	0.39	0.35	47%	0.66	0.34	0.11	0.45	0.38	0.34	46%
Utuhina	1.81	5.95	0.063	0.017	0.67	2.41	0.320	2.73	3.22	0.52	54%	0.54	1.94	0.45	2.39	3.56	0.57	60%
Puarenga	1.95	6.98	0.053	0.033	0.63	2.05	0.751	2.80	4.18	0.56	60%	0.48	1.56	1.06	2.62	4.36	0.59	62%
Waingaehe	0.27	1.01	0.095	0.033	0.84	0.68	0.045	0.72	0.29	0.28	28%	0.52	0.42	0.13	0.56	0.45	0.45	45%
Waiohewa	0.38	1.18	0.053	0.009	0.62	0.39	0.041	0.43	0.75	0.55	63%	0.50	0.32	0.05	0.37	0.81	0.59	69%
Ungauged non-geo	*2.488*		*0.046*	*0.017*	*0.62*	*2.24*	*0.51*	*2.74*				*0.42*	*1.52*	*0.77*	*2.29*			
Ungauged Geo.	*0.792*					*2.50*	*0.00*	*2.50*					*2.50*	*0.00*	*2.50*			
Ungauged total	3.28	**10.73**	0.046	0.017		4.74	0.51	5.24	5.48	0.59	51%		4.02	0.77	4.79	5.94	0.63	55%
Rainfall to lake	4.17	**1.44**	0.011	0.011		0.00	1.447	1.45						1.45	1.45			
TOTAL		**46.0**						**27.9**	**18.1**	**0.37**	**39%**				**25.3**	**20.7**	**0.43**	**45%**

For 'ungauged' catchments, a geothermal input of 2.5 t/yr was added to the baseline TP load; and the non-gothermal discharge was reduced by 0.792 m^3/s (via geothermal).

4 Discussion

4.1 Long term estimates

Overall the analysis results are consistent with previous estimates of the catchment phosphorus load to Lake Rotorua (i.e. about 39-49 t/yr). The total P load to Lake Rotorua was estimated to be 46.0 t/yr as TP. This is less than the total TP load estimated by Tempero et al. (2015) (48.7 t/yr), but more than the TP load estimated by Hoare (1980a) (42.6 to 44.9 t/yr) – both of which accounted for stormflows. During our analysis period (2007-2014) the Ohau channel outflow was about 8.3% higher than the long-term average, so our estimates are likely to be about 8.3% higher. After applying this adjustment, the long-term average inflows of TP to Lake Rotorua are likely to be about 42.2 t/yr.

The TP load attributed to anthropogenic sources was about 18.1 t/yr to 20.7 t/yr (39% - 45% of the total load). This would convert to a long-term average load attributable to anthropogenic sources of 16.6 t/yr to 19.0 t/yr. Most of this anthropogenic TP load comes from 'ungauged' catchments (30%), Puarenga (23%), Utuhina (18%) and Ngongotaha (11%). Most of the estimated anthropogenic P was in form of particulate P (71% to 79%) – which points to managing erosion as an effective way of reducing anthropogenic P loads to the lake.

The catchments with the highest area-specific anthropogenic TP loads are Puarenga (0.56 to 0.59 kg/ha/yr), Waiohewa (0.55 to 0.59 kg/ha/yr), Utuhina (0.52 to 0.57 kg/ha/yr) and ungauged (0.59 to 0.63 kg/ha/yr). It may be worthwhile putting more attention on these catchments when implementing P reduction strategies, and to understand why their specific yield is high. However, it should be kept in mind that the results are indicative and sensitive to many assumptions. For some sub-catchments, using more accurate catchment areas made a large difference to estimates of area-specific anthropogenic TP loads compared to estimate by Tempero et al. (2015). This is particularly relevant to the area-specific load from 'ungauged' catchments which are now similar to other sub-catchments - as would be expected.

4.2 Uncertainties in analysis

The calculation of total load was sensitive to estimates of net rainfall to Lake Rotorua. If a high evapotranspiration value is applied (i.e. lower net rain) then the estimated long-term average inflows of TP to Lake Rotorua may be closer to 43.9 t/yr. This corresponds to a flow difference of about 0.4 m^3/s from ungauged catchments. Reviewing the net rainfall estimates to the lake would be useful if a more accurate estimate of nutrient loads to the lake is desired.

For the gauged catchments, the flow estimated using net rainfall was very similar to the flow estimated from the water balance approach, but for ungauged catchments the flow estimated using the rainfall approach was much lower i.e. 2.04 m^3/s to 2.29 m^3/s compared to 3.28 m^3/s. [17] This difference is considerably more than the error thought to be associated with rainfall contours (about 10%), and one possible explanation for this is that there are additional groundwater contributions to the south of the

[17] Rutherford and Palliser (2014) used the net rainfall approach to estimate that ungauged catchments contribute 2.67 m^3/s; using a similar net rainfall for a 13-year period (rainfall 1656mm, runoff 861mm/yr), but a larger catchment area 98 km^2. Hoare (1980) estimated the 'ungauged' inflows were 2.1 m^3/s.

lake via geothermal inputs. Geothermal inputs from the Rotorua area about 0.79 m^3/s (2.5 t P/yr), but only 0.3 m^3/s of this geothermal input from the Rotorua town area can be explained by rainfall on the ungauged catchments near Rotorua or by loss of groundwater from the Utuhina or Puarenga catchments. Consideration should be given to whether any additional water contribution is derived from outside the catchment or from long term time lags associated with the recovery of the geothermal fields over the last 30 years. If there was additional groundwater entering via geothermal inputs then the calculations for anthropogenic loads from 'ungauged catchments' would be over-estimated.

When estimating flow using net rainfall, the analysis assumed high drainage factors for the Hamurana, Awahou and Waiteti catchments. The high drainage factors resulted in a much better match between calculated flows with the observed flows and was in addition to accounting for the different sizes of the groundwater and surface water catchments. It is not clear why the drainage factor in these north-western catchments is so high and it may be an area for further work. If there is reason to think that the drainage factors are too high, then we may need to revisit estimates of catchment size or rainfall.

Much of the information on geothermal inputs is based on studies from early 1990's soon after the bore closure programme. In the light of this White et al. (2004) recommended additional monitoring to better characterise the hydrology and nutrient conditions of the geothermal fields and to understand if the quantity and proportion of geothermal fluids entering the lake has changed over recent decades. This should include measuring chloride (as a proxy for geothermal fluid) from stream inflows and from the Ohau channel outflow.

4.3 Bioavailable P

The reason for controlling the loss of P to Lake Rotorua is to help control algae growth. Dissolved phosphate (e.g. DRP) is considered readily available for uptake by biota, whereas only some fraction of particulate P may be transformed into a bioavailable form suitable for phytoplankton uptake (Reynolds and Davies 2001). Some P in particulate form will become bioavailable by biochemical processes (e.g. desorption, released by redox changes, released by pH changes), while some will remain unavailable for biological use because it is tightly bound to particles or is immobilised by physical processes such as burial. Beyá (2005) estimated that only 25% of the P load that entered Lake Rotorua actually left the lake via the Ohau Channel – indicating a considerable P retention in the lake's sediment pool or biomass.

The anthropogenic P load is predominantly (71-79%) in the form of particulate phosphorus, so understanding the proportion of particulate P that may become bioavailable is important. Phosphorus release from lake sediments has been estimated to be about 36 t/yr (BOPRC 2007), this is about 80% of the catchment load and double the anthropogenic catchment load. The substantial role of internal P release indicates the importance of better understanding this process and its coupling to landuse practices.

4.4 Further work

Future monitoring and investigation that will help fill information gaps relating to the load of P (and bioavailable P) entering Lake Rotorua include:

- Investigations to improve our understanding of sediment sources and phosphorus concentrations in particulate phosphorus from gauged and ungauged catchments. E.g. sampling of settleable sediment to differentiate areas with relatively higher P concentrations associated with the sediment.
- A major fraction of the anthropogenic P load is in the particulate form, much of which is transported during storm events. Additional storm event monitoring would be helpful to better quantify total P loads to the lake.
- The estimates of anthropogenic P load from ungauged catchments would be more accurate if the estimate of groundwater mean residence time (MRT) was refined.
- Improving our estimates of geothermal inflows to Lake Rotorua. One part of this is to incorporate chloride as part of the analysis suite for the Lake, Ohau channel outflow and inflowing streams.
- Past estimates of geothermal contribution to Waiohewa Stream has wide variability. This report has adopted the lower estimates, and this may explain the correspondingly high estimates of area-specific anthropogenic P for Waiohewa Stream. To resolve discrepancies in geothermal inputs to Waiohewa it is recommended that future monitoring of Waiohewa Stream include gauging and water quality samples (including phosphorus) at locations to differentiate the geothermal inputs.
- Better quantification of the extent to which particulate P derived from the human activity in the catchment is bioavailable and its contribution to internal P release from lake sediments.

This report gives an indication of sub-catchments that contribute most P load to Lake Rotorua using total loads and area-specific loads, however these estimates contain a high degree of uncertainty. A complementary approach to understanding the location of P loss within parts of the Rotorua catchment could be used to develop a risk map of P loss from the catchment based on landform, land use and catchment processes.

5 Conclusions

For the period 2007-2014, the total phosphorus load to Lake Rotorua was estimated to be 46.0 t/yr after accounting for storm flows and geothermal inputs. The TP load attributed to anthropogenic sources was 18.1 t/yr to 20.7 t/yr (39% - 45% of the total load). Most (71% to 79%) of the anthropogenic TP load was in the particulate form, and most came from the following catchments: ‘ungauged’ (30%), Puarenga (23%), Utuhina (18%) and Ngongotaha (11%).

The 2007-2014 period had higher outflows and inflows compared to previous years. The long-term average TP load to Lake Rotorua was estimated to be 42.2 t/yr, and the long-term average TP load attributed to anthropogenic sources was 16.6 t/yr to 19.0 t/yr. Overall the analysis results are consistent with previous estimates of the catchment phosphorus load to Lake Rotorua.

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