Anthropogenic Phosphorus Loads to Lake Rotorua

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Client report prepared for Bay of Plenty Regional Council

By Grant Tempero[1], Chris McBride[1], Jonathan Abell[2] & David Hamilton[1]

[1]Environmental Research Institute
Faculty of Science and Engineering
University of Waikato, Private Bag 3105
Hamilton 3240, New Zealand

[2]Ecofish Research Ltd
Victoria, BC V8W2E1
Canada

Environmental Research Institute
Te Pūtahi Rangahau Taiao
THE UNIVERSITY OF WAIKATO

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Reviewed by:

Moritz Lehmann

Research Fellow

Environmental Research Institute

University of Waikato

Approved for release by:

John Tyrrell

Research Developer

Environmental Research Institute

University of Waikato

EXECUTIVE SUMMARY

Past wastewater disposal practices and ongoing catchment land-use intensification have resulted in the eutrophication of Lake Rotorua. These changes have been associated with elevated nutrient loads to the lake from point and diffuse sources. Phosphorus and nitrogen are important macronutrients limiting phytoplankton growth. Bioassay studies in Lake Rotorua have shown temporal and spatial variability of phytoplankton growth limitation by either or both of these nutrients, hence the importance of controlling both phosphorus and nitrogen loads to the lake. This report was commissioned by the Bay of Plenty Regional Council to quantify sources of anthropogenic (i.e., associated with human activity) phosphorus in the catchment, so that these sources can be managed with the aim of reducing phytoplankton biomass in Lake Rotorua. This will form part of an integrated framework of catchment management which also aims to reduce the nitrogen load to the lake.

Determination of anthropogenic and natural (baseline) sources of phosphorus is essential for managing lake eutrophication. Natural concentrations (indicative of baseline or reference levels) of dissolved reactive phosphorus (DRP) and total phosphorus (TP) can be modelled from observed concentrations in undisturbed catchments. This model can then be used to estimate anthropogenic phosphorus in other catchments as the difference between natural and observed concentrations.

Mean annual discharge (MAD) was estimated individually for nine major stream sub–catchments of Lake Rotorua, and a combined MAD was estimated for other minor and ungauged stream sub–catchments. Natural stream phosphorus concentrations were derived from published values based on the River Environment Classification (REC) land classes within the lake catchment. Natural groundwater phosphorus concentrations were derived from published relationships between groundwater age and phosphorus concentrations in the Rotorua sub–catchments. Total phosphorus and DRP loads were calculated for each inflow for the period 2007–2014 (‘contemporary loads’) using the daily discharge estimates and time series of estimated daily mean concentrations of each nutrient species (TP, DRP) for each inflow. Daily loads were then summed to calculate annual loads. Natural loads for each inflow were subtracted from contemporary loads to estimate anthropogenic loads.

Anthropogenic phosphorus loads to Lake Rotorua were estimated to be 22% (expressed as a catchment areal rate of 0.12 kg DRP ha^{-1} y^{-1}) of the total DRP load and 48% (0.47 kg P ha^{-1} y^{-1}) of the TP load. Relative to other New Zealand catchments, anthropogenic phosphorus was a relatively low proportion of the total load, given that the Rotorua catchment is highly developed. This can be attributed to the large volume of groundwater discharge to the lake, which is DRP-enriched due to gradual dissolution of phosphorus in the rhyolitic pumice bedrock. In sub-catchments where groundwater discharge to the lake was volumetrically dominant, e.g., Hamurana (89.3%) and Awahou (79.6%), the natural contribution to DRP loads was high, despite extensive agricultural land-use. By contrast, sub-catchments dominated by surface water discharges, e.g., Ngongotaha (34% groundwater) and Waiteti (14.5% groundwater), had comparatively high anthropogenic TP loads and elevated concentrations of particulate phosphorus. The minor and ungauged catchments, representing drains, small streams, overland flow, groundwater discharge to the bed of the lake, discharge below gauged stream sites and a residual term, were estimated to contribute the largest percentage (33%) of anthropogenic particulate phosphorus loads to Lake Rotorua despite being groundwater dominated.

Previous modelling of scenarios to examine the effects of nutrient reductions on lake water quality indicates that a reduction of total nitrogen loads from 641.5 to 435 t y^{-1} and TP loads from 34.5 to 23.4

t y^{-1} (DRP reduction from 23 to 15.6 t y^{-1}) would be needed to achieve a Trophic Lake Index (TLI) target of 4.2 (equivalent to TLI3 of ~4.3; Hamilton et al. 2015). However, these scenarios utilised inflow phosphorus concentrations from monthly sampling of inflows and as such may underestimate TP and DRP loading from stormflow events. This report includes stormflow TP and DRP loadings from the Puarenga, Ngongotaha and Utuhina Streams, resulting in a lake TP load estimate of 48.7 t y^{-1} (23.4 t y^{-1} anthropogenic) and a DRP loading of 27.7 t y^{-1} (6.1 t y^{-1} anthropogenic) (Table 1). To achieve a TLI target of 4.2 would require an estimated reduction in TP of 10–15 t y^{-1}, i.e., anthropogenic TP loading would need to be reduced from c. 23 t y^{-1} to 8–13 t y^{-1}. More precise estimates cannot be provided due to interactions between nutrients (e.g., nitrogen species) and algal species composition. Alum dosing of the Utuhina and Puarenga Streams has achieved DRP load reductions of >80% in these streams (1.21 t P y^{-1}). However, without contemplating additional alum dosing of streams where natural phosphorus is the dominant source, the scope for further alum dosing to be similarly effective may be limited because anthropogenic phosphorus is predominantly particulate. Improvements in agricultural land management practices and urban storm water management are likely to be the most effective measures for reducing particulate phosphorus loading.

Table 1. Summary of annual phosphorus loading to Lake Rotorua, including estimated percentage range of anthropogenic total phosphorus reduction needed to achieve a TLI target of 4.2 (in parentheses).

	Annual loading t P y^{-1}		
	Total	Anthropogenic	Baseline
Dissolved reactive phosphorus	27.7	6.1	21.6
Particulate phosphorus	21.0	17.3	3.7
Total phosphorus	48.7	23.4 (43-64%)	25.3

ACKNOWLEDGEMENTS

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INTRODUCTION

Land use in the Lake Rotorua catchment has intensified significantly over the past 60 years. Current land use by area is forest (39%), low-intensity pasture (27%) and high-intensity dairy (9%) (Burger et al. 2011; Rutherford et al., 2009). The population of Rotorua City has increased from less than 10,000 prior to 1950, to more than 53,000 in 2013 (Statistics New Zealand 2015). Both land use intensification and population increases have contributed to eutrophication of Lake Rotorua by way of increased phosphorus and nitrogen inputs (Rutherford 1984; Rutherford et al. 1989). These inputs constitute both point- and diffuse-sources of anthropogenic origin (i.e., resulting from human activities). Control of nutrient inputs to Lake Rotorua is of increasing importance if the ecological health and aesthetic values of this ecosystem are to be maintained. Lake restoration measures such as application of alum to two of the Lake Rotorua inflows have reduced phosphorus levels in the lake, resulting in improved water quality (Rotorua Te Arawa Lakes Programme 2015). However, the amount of alum that can be applied is limited by potential toxicological effects (Tempero 2015), thus alum dosing is not considered a sustainable solution to address phosphorus loading to Lake Rotorua. A more sustainable approach is to identify anthropogenic sources of phosphorus in the catchment and implement mitigation measures to reduce losses from land or attenuate phosphorus before it reaches the lake. While this report focuses on phosphorus, it is intended to support an integrated framework of catchment management including control of loads for both phosphorus and nitrogen.

Anthropogenic loads to Lake Rotorua have previously been estimated to exceed loads from non–anthropogenic sources, hereafter termed 'natural loads' (BoPRC 2009). Nonetheless, in a national context, natural phosphorus concentrations in both surface and groundwater in the Lake Rotorua catchment are relatively high. This reflects the naturally high phosphorus concentrations associated with the rhyolitic pumice that dominates the geology of the wider Taupo Volcanic Zone which, when coupled with low calcium concentrations, this results in high dissolved reactive phosphorus (DRP) concentrations in groundwater (Timperley 1983). Dissolution of phosphorus-bearing minerals over time results in increasing DRP concentrations with increasing groundwater age, and groundwater in some aquifers within the catchment has been estimated to have a mean residence time of up to 150 years (Morgenstern et al. 2015). Particulate phosphorus concentrations are generally very low in groundwater systems (Morgenstern et al. 2015). In contrast, surface water discharges tend to have higher levels of particulate phosphorus and are strongly influenced by anthropogenic activities associated with the use of fertilizers, livestock excreta, forest harvesting and soil erosion (McDowell 2010). A smaller phosphorus load originates from urban sources, which includes septic tanks, urban storm water and treated municipal wastewater discharged to the Land Treatment System within the Puarenga sub-catchment. Urban sources have been estimated to account for approximately one-fifth of the load that originates from agricultural sources (BoPRC 2009).

Annual nutrient loads to Lake Rotorua were recently calculated from in-stream observations for individual surface sub-catchments for the period 2007–2014 (Abell et al. in preparation). Natural nutrient concentrations for a range of stream types across New Zealand have been estimated by McDowell et al. (2013), and Morgenstern et al. (2015) recently presented a detailed study of groundwater age and hydrochemistry. Drawing on these sources of information provides an opportunity to estimate 'natural' (baseline) phosphorus loads for individual lake sub-catchments, and to compare these with recent data for contemporary phosphorus loads to the lake.

In light of the importance of quantifying anthropogenic sources of phosphorus to inform management and restoration of water quality in Lake Rotorua, the aim of this report is to:

- present methods and results of an exercise to estimate natural phosphorus loads to Lake Rotorua for individual sub-catchments; and to
- compare baseline and contemporary loads to estimate anthropogenic phosphorus loads.

METHODS

Lake Rotorua catchment

Lake Rotorua has a surface area of 80.6 km^2 and a mean depth of 10.8 m (Burger et al. 2011), with a total water volume of 0.85 km^3. The basin was formed around 220-230 ka ago as a result of a rhyolitic eruption (Wood 1992). The eruption created an extensive plateau, the Mamaku ignimbrite, which contains a substantial portion of the deep aquifer storage within the catchment. Above this layer are large deposits of lake sediments derived from various eruptions from the Okataina Volcanic Centres as well as volcanic ash and alluvial deposits of pumice gravels (Nairn 2002), these layers are associated with the shallower groundwater component.

Groundwater seepage rates vary considerably in the Lake Rotorua catchment and fractures in the rhyolite and ignimbrite play a role in this variability. Morgenstern et al. (2015) indicated that approximately 50% of rainfall in the Lake Rotorua catchment infiltrates into the groundwater. Most estimates of the relative contribution of groundwater to the total discharge to Lake Rotorua have been derived from northern and eastern areas of the lake catchment where faulting in the Mamaku ignimbrite creates large springs that can be almost entirely groundwater-sourced (e.g. Hamurana) or at least have a substantial component of groundwater (e.g. Ngongotaha). Groundwater constitutes approximately 90% of stream baseflow and direct seepage through the lake bed (Hoare 1987; Morgenstern et al. 2015). However, there is a notable incongruence between surface and groundwater catchment areas. White et al. (2014) indicated that the area most responsible for the incongruence (33.2 km^2) occurs in the Hamurana sub-catchment, with the additional groundwater area extending to part of the Mamaku ignimbrite plateau to the northwest of the surface sub-catchment (Figure 1). The total groundwater catchment area for Lake Rotorua is estimated to be 537.1 km^2 but the surface water catchment area is only 502 km^2 (including lake area), a difference of approximately 35 km^2 (White et al. 2014).

There are nine major streams and several minor streams that flow into the lake (Figure 1). Details of sub-catchment area, discharge, groundwater mean residence time (MRT), groundwater contribution to discharge, annual evapotranspiration (AET) and proportion of land use in agriculture associated with these stream sub-catchments are presented in Table 2. It should be noted that in some cases there are additional discharges to gauged streams that occur between the gauging site and the lake. These are accounted for in the ungauged inflow category.

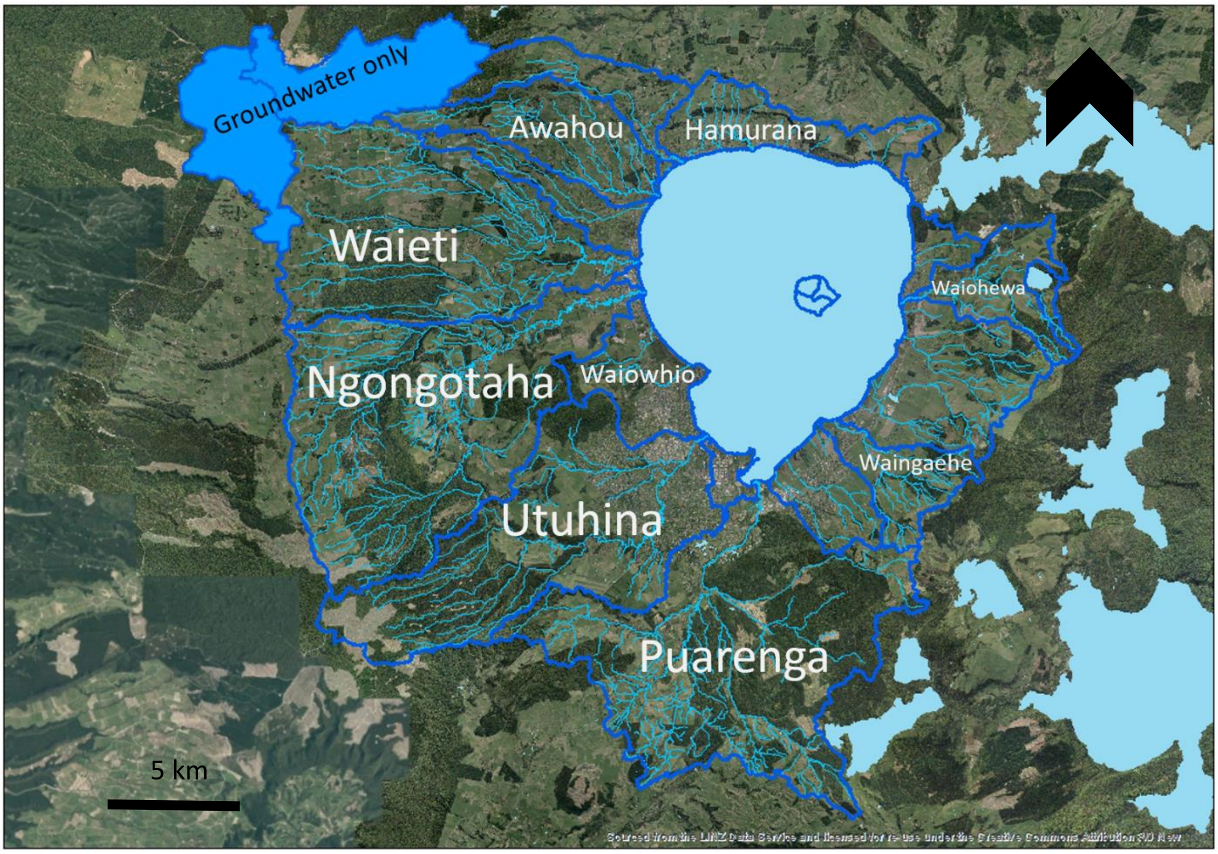


Figure 1. Major surface topographical sub-catchments of Lake Rotorua including groundwater only areas outside the surface-water catchment (shaded blue). A more detailed representation of the surface and groundwater sub-catchments is presented in Appendix 1.

Land use data for each sub-catchment was provided by the Bay of Plenty Regional Council (Figure 2). Sub-catchments dominated by agriculture include Awahou (81% by area), Hamurana (72%) and Waiteti (71%), with Awahou having the largest percentage of dairy farm land use (38% of total area). Sub-catchments with relatively large urban land-use include Waiowhiro (40%) and Utuhina (22%), while the Puarenga and Ngongotaha sub-catchments have large areas of forest and undeveloped scrub (66% and 44% respectively).

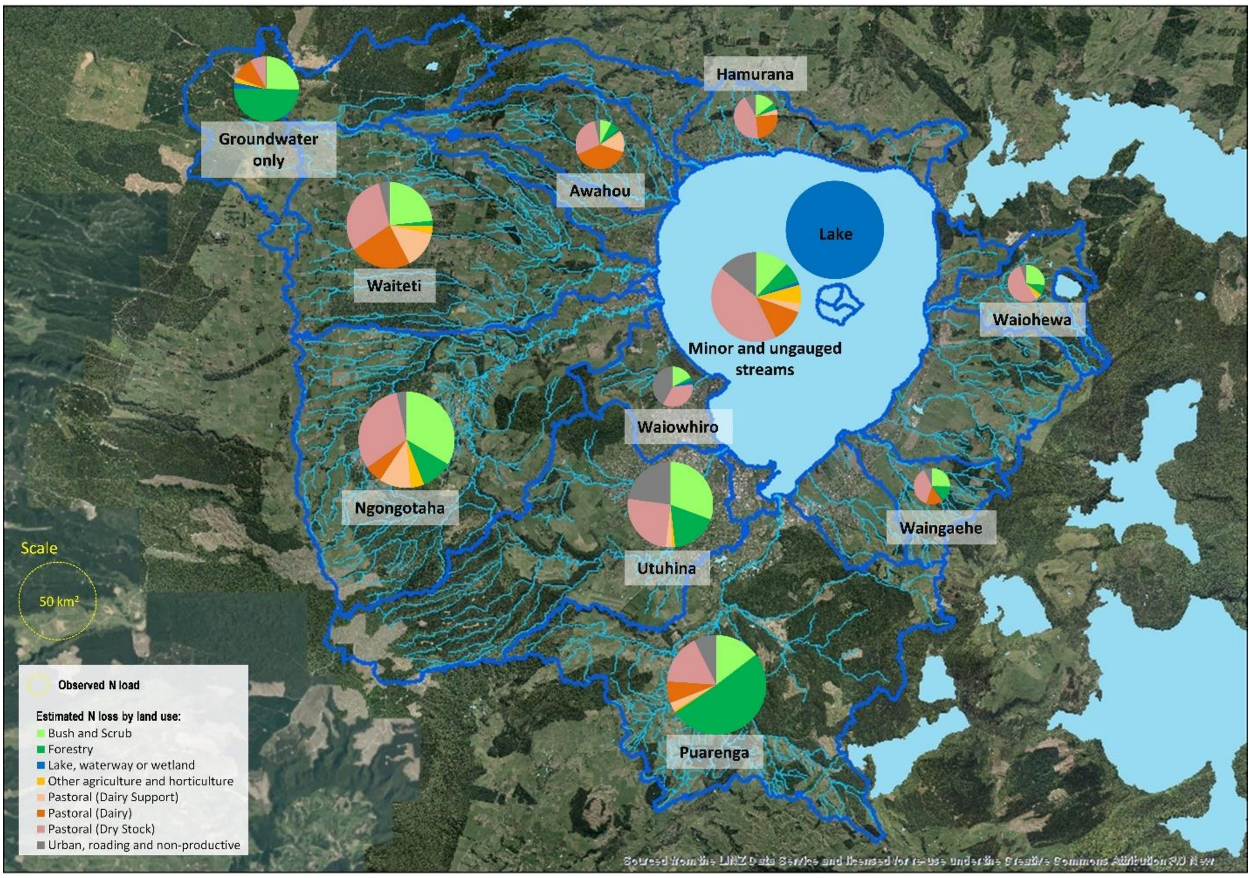


Figure 2. Land use within the Lake Rotorua sub-catchments. The size of the pie charts is scaled to the area of the corresponding catchment (see scale circle above the legend).

Table 2. Summary of estimated mean annual discharge ($m^3\ s^{-1}$), groundwater mean residence time (MRT), groundwater contribution to discharge, annual evapotranspiration (AET) and proportion of land use in agriculture is presented for Lake Rotorua sub-catchments for the calendar period 2007–2014. Runoff fraction is taken from Rutherford et al. (2011) and rainfall is estimated from Hoare (1980). * MRT value is estimated.

Sub-catchment	Total area (km^2)	Agriculture index (ratio)	Obs. discharge ($m^3\ s^{-1}$)	MRT (y)	Rainfall ($mm\ y^{-1}$)	AET ($mm\ y^{-1}$)	Runoff (fraction)	Surface water ($m^3\ s^{-1}$)	Ground-water ($m^3\ s^{-1}$)	Surface water (%)	Ground-water (%)
Awahou	19.92	0.81	1.69	75	2000	838	0.47	0.34	1.35	20.4	79.6
Hamurana	16.07	0.72	2.57	125	1950	856	0.47	0.26	2.31	10.2	89.8
Ngongotaha	77.41	0.53	1.84	30	1950	895	0.47	1.22	0.62	66.1	33.9
Puarenga	82.32	0.27	1.95	40	1800	946	0.47	1.05	0.90	53.7	46.3
Utuhina	61.04	0.29	1.81	60	1900	942	0.47	0.87	0.94	48.1	51.9
Waingaehe	11.06	0.53	0.27	145	1450	895	0.47	0.09	0.18	33.9	66.1
Waiohewa	11.69	0.60	0.38	40	1750	881	0.47	0.15	0.23	39.8	60.2
Waiowhiro	13.63	0.35	0.31	40	1700	930	0.47	0.16	0.15	50.4	49.6
Waiteti	61.88	0.71	1.23	45	2000	859	0.47	1.05	0.18	85.5	14.5
Minor & ungauged	67.23	0.65	4.11	30*	1600	900	0.47	0.70	3.41	17.1	82.9
Rainfall to lake	80.60	0	3.96	0	1600	0	0.47	3.96	0.00	100.0	0.0
TOTAL	502.9										

Hydrology

Mean annual discharge (MAD) was estimated individually for the nine major stream sub-catchments, and a combined MAD was estimated for minor and ungauged stream sub-catchments representing all remaining surface and sub-surface inflows to the lake, i.e., overland run-off and groundwater inflow to the lake bed. Details of estimation methods are presented in Table 3.

Mean annual discharge for major sub-catchments was estimated from hydrological data provided by BoPRC and NIWA. Discharge data for four of the nine major sub-catchments were derived from near–continuous measurements collected at hydrologic gauges sited in the lower reaches of the streams. These gauged streams account for 47% of the total estimated mean discharge in streams to Lake Rotorua. Estimates of MAD for the remaining major streams were derived from daily time series of discharge that were derived for each stream based on regular (typically monthly) spot measurements of discharge collected by BoPRC. Time series were developed by either linearly interpolating spot measurements (Hamurana Stream only) or using near-continuous discharge records for a comparable stream that were adjusted to match mean discharge for the stream of interest, based on spot measurements.

Estimates of MAD for ungauged inflows were estimated as the residual term in a water balance constructed for the lake:

$$Ungauged \ = 1.18 \cdot (Q_{\bar{O}hau} + E + \Delta S) - \left(Q_{inflow} + rainfall\right)$$

where *Ungauged* is daily mean ungauged inflow ($m^3\ s^{-1}$), $Q_{\bar{O}hau}$ is daily mean discharge of the only lake surface outflow ($m^3\ s^{-1}$), E is daily mean evaporation rate, ΔS is daily mean rate of change in lake storage ($m^3\ s^{-1}$) due to water level change (provided by NIWA, measured at the Mission Bay monitoring station), Q_{inflow} is daily mean stream discharge ($m^3\ s^{-1}$) and *rainfall* is a 15–day mean value ($m^3\ s^{-1}$) based on measurements at Rotorua Airport applied across the lake. The constant value (1.18) in the equation above was determined iteratively by minimising the error between measured lake water levels and those modelled using a one–dimensional water quality model (DYRESM–CAEDYM).

In order to estimate the contribution of groundwater to natural phosphorus loads, it was necessary to estimate groundwater discharge for each sub-catchment. Groundwater flow was therefore calculated as the difference between estimated surface water flow and total observed mean annual stream discharge.

Rainfall to each sub-catchment was estimated from isopleths presented in Hoare (1980) (Figure 3, Table 2). Evapotranspiration (AET) was estimated dependent on the proportion of agriculture in the catchment, using assumed values of 1000 mm for forest and 800 mm for pasture. Surface runoff was estimated as 47% of rainfall after AET, from Rutherford et al. (2011), and total surface water was calculated for the surface topographic area of each sub-catchment multiplied by runoff. Whole catchment surface water discharge estimated using this method was equal to 49% of observed whole-catchment mean annual discharge, indicating good agreement between rainfall values adopted and observed stream flows. Groundwater flow in each sub-catchment was subsequently calculated by subtracting the estimated surface water flow from the observed mean annual discharge for each stream.

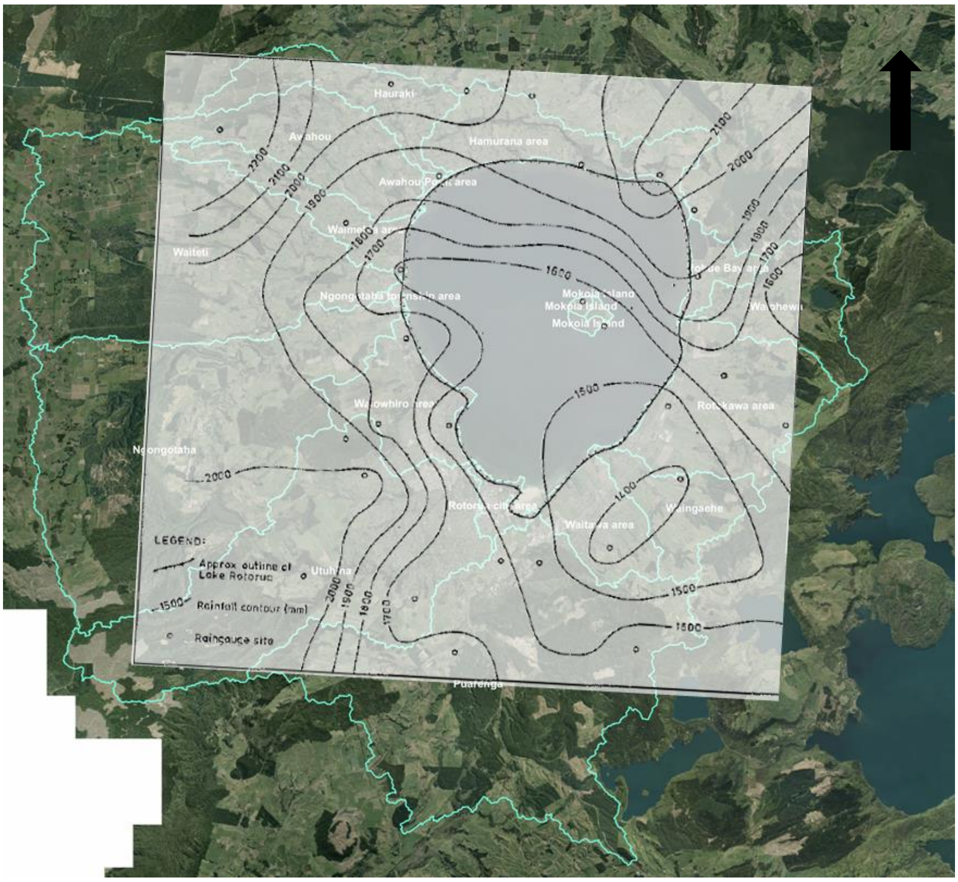


Figure 3. Rainfall isopleths from Hoare (1980) overlaid to surface water sub-catchment boundaries for Lake Rotorua.

Table 3. Methods to estimate discharge in-stream inflows to Lake Rotorua.

Inflow type	Inflow	Details	Source
Major streams	Awahou Stream	The mean discharge was set to the mean of monthly instantaneous gaugings during 2005 through 2012 (*n* = 86). Temporal fluctuations were then imposed based on fluctuations measured in the Ngongotahā Stream.	BoPRC
	Hamurana Stream	This is a groundwater spring-dominated stream. Monthly (approximate) instantaneous gaugings were interpolated for the period 2007 through 2012 (*n* = 51). Discharge set to the mean of gaugings (2.558 $m^3 s^{-1}$) during 2012 through 2014.	BoPRC
	Ngongotahā Stream	Based on measured data (99.9% of record) at SH 30 gauge. One gap of 89 h was filled with mean value of preceding and subsequent days.	NIWA
	Puarenga Stream	Based on measured data (97.2% of record) at FRI gauge (2007 to 2010) and SH30 gauge (2010 to 2014). Gaps were replaced with modelled data (2.8% of record) based on linear relationship (r^2 = 0.75) with measurements for Utuhina Stream.	BoPRC
	Utuhina Stream	Based on measured data (92.8% of record) at Depot Street gauge. Gaps were replaced with modelled data (7.2% of record) based on linear relationship (r^2 = 0.67) with measurements for Puarenga Stream.	BoPRC
	Waingaehe Stream	Based on measured data (99.5% of record) at SH30 gauge. Gaps were replaced with mean values of adjoining measurements (0.5% of record).	BoPRC
	Waiohewa Stream	As for the Awahou Stream. Mean discharge was estimated based on a sample of 70 measurements.	BoPRC
	Waiowhiro Stream	As for the Awahou Stream. Mean discharge was estimated based on a sample of 78 measurements.	BoPRC
	Waiteti Stream	As for the Awahou Stream. Mean discharge was estimated based on a sample of 76 measurements.	BoPRC
Minor and ungauged streams	Lynmore Stream	The long-term mean discharge was set to the mean of monthly instantaneous gaugings during 2005 through 2012 (*n* = 71). Temporal fluctuations were then imposed based on fluctuations measured in the Waingaehe Stream.	BoPRC
	Motutara (geothermal seep)	A representative constant discharge was assigned (0.04 $m^3 s^{-1}$)	
	Rotokawa 1 (geothermal seep)	A representative constant discharge was assigned (0.02 $m^3 s^{-1}$)	
	Rotokawa 2 (geothermal seep)	A representative constant discharge was assigned (0.04 $m^3 s^{-1}$)	
	Hauraki Stream	The long-term mean discharge was set to the mean discharge reported in Rutherford *et al* . (2008). Temporal fluctuations were then imposed based on fluctuations measured in the Waingaehe Stream.	
	Waitawa 1 Waitawa 2 Waimehia Drain Waiowhiro 2/ Waikuta	The long-term mean discharge in these four streams was calculated from the mean discharge reported in Rutherford *et al* . (2008) for 'minor' catchments (0.4 $m^3 s^{-1}$), minus the mean discharge for the other five minor streams. Temporal fluctuations were then imposed based on fluctuations measured in the Waingaehe Stream.	
	Ungauged	Based on the residual quantity in a lake water balance (mean = 3.49 $m^3 s^{-1}$), plus 18% to maximise goodness of fit between measured lake water levels and those modelled using a one-dimensional model.	

Natural phosphorus loads

Natural total phosphorus (TP) and dissolved reactive phosphorus (DRP) concentrations used for surface runoff in this study were taken from McDowell et al. (2013), with raw data provided by Prof. R. McDowell (pers. comm. 2013). McDowell et al. (2013) calculated natural stream nutrient concentrations for individual stream classifications included in the New Zealand River Environment Classification (REC) system (Snelder and Biggs 2002). Baseline concentrations were derived using data collected from >1000 stream sites across New Zealand. The data were used to develop non–linear regression models for different REC classes to quantify relationships between nutrient concentrations and the proportion of intensively-farmed pastoral land in a catchment. Based on these relationships, the authors then calculated natural (baseline) concentrations that corresponded to concentrations under a scenario with no intensively-farmed land (e.g., Ballantine and Davies–Colley 2014).

McDowell et al. (2013) used four geological classes, grouped at the second level of the REC (climate by topography) to estimate baseline stream nutrient concentrations. Streams in the Lake Rotorua catchment were assigned to REC classes after McDowell (2015). Natural stream phosphorus concentrations that correspond to this category are presented in Table 4.

Table 4. Baseline phosphorus concentrations derived by McDowell et al. (2015) for the River Environment Classification classes corresponding to inflows to Lake Rotorua. SE is standard error.

Sub-catchment	REC class	Median - SE ($g\ DRP\ m^{-3}$)	Median ($g\ DRP\ m^{-3}$)	Median + SE ($g\ DRP\ m^{-3}$)	Median - SE ($g\ TP\ m^{-3}$)	Median ($g\ TP\ m^{-3}$)	Median + SE ($g\ TP\ m^{-3}$)
Awahou	CW/H/VA	0.008	0.009	0.011	0.015	0.017	0.019
Hamurana	WW/H/VA	0.005	0.008	0.011	0.009	0.012	0.018
Ngongotaha	CW/H/VA	0.008	0.009	0.011	0.015	0.017	0.019
Puarenga	CW/L/VA	0.012	0.016	0.020	0.024	0.033	0.045
Utuhina	CW/H/VA	0.008	0.009	0.011	0.015	0.017	0.019
Waingaehe	CW/L/VA	0.012	0.016	0.020	0.024	0.033	0.045
Waiohewa	CW/Lk/VA	0.001	0.002	0.003	0.007	0.009	0.011
Waiowhiro	CW/L/VA	0.012	0.016	0.020	0.024	0.033	0.045
Waiteti	CW/H/VA	0.008	0.009	0.011	0.015	0.017	0.019
Ungauged	CW/H/VA	0.008	0.009	0.011	0.015	0.017	0.019

Median natural phosphorus concentrations (Table 4) were assumed for surface water in all stream inflows. Groundwater natural phosphorus concentrations are known to increase with age in the Rotorua catchment due to long-term dissolution from volcanic material (Morgenstern et al. 2015). Therefore, groundwater DRP concentrations specific to each sub-catchment were estimated from the non-linear relationship between MRT and DRP reported by Morgenstern et al. (2015) and reproduced in Appendix 2. Total natural phosphorus loads were calculated as the sum of estimated surface and groundwater concentrations multiplied by their respective estimated discharges.

Contemporary phosphorus loads

Daily TP and DRP loads were calculated for each inflow for the period 2007–2014 using the daily discharge estimates described in the section above, and time series of estimated mean daily concentrations for each inflow. Daily loads were summed to calculate annual loads.

Total phosphorus and DRP concentrations were assigned to inflows based on measured data. Data were primarily collected by the Bay of Plenty Regional Council (BoPRC) during routine monthly baseflow sampling. Additional stormflow data from two major stream inflows (2010–2012) (Abell et al. 2013) were used to assign stormflow concentrations for three major streams.

Daily mean DRP and TP concentrations for individual streams were typically assigned by linearly interpolating monthly measurements. Exceptions were TP concentrations in the Ngongotaha, Puarenga and Utuhina streams during periods when daily mean discharge exceeded 3.0 $m^3\ s^{-1}$. In these cases, TP concentrations were modelled using empirical relationships with discharge to reflect the relative increases in particulate phosphorus concentrations that typically occur during storm flow periods. These three streams have the greatest proportion of annual phosphorus loads transported in storm flow (Rutherford 2008). Such relationships were not used to estimate TP concentrations in other streams because there were insufficient data to robustly define relationships between concentration and discharge for these streams. Total phosphorus loads during storm flow periods may therefore be underestimated in these streams, although it should be noted that the majority of these streams receive a large component of sub-surface flow, i.e., they are less flashy. Methods used to assign daily mean nutrient concentrations to inflows are summarised in Table 5. Note that load reduction targets for the lake (BoPRC 2009) are currently based on calculations that exclude storm flow (Rutherford 2003); therefore, TP loads presented here are expected to be higher and not directly comparable with loads that are calculated by BoPRC for monitoring progress towards achieving previous targets.

Aluminium sulphate (alum) is currently dosed to the Utuhina and Puarenga streams, substantially reducing DRP. Concentrations for these streams were therefore estimated as though no dosing were taking place. Water quality monitoring in the Puarenga Stream occurs upstream of the alum dosing station and therefore measured DRP and TP concentrations were not influenced by alum dosing. Conversely, water quality monitoring in the Utuhina Stream occurs downstream of the alum dosing station and, therefore, measured DRP concentrations were increased in proportion to daily alum dose rates. Further details regarding these calculations are presented in Appendix 3.

Concentrations for minor streams were a combined discharge-weighted value. Concentrations for the ungauged inflow were estimated as equivalent to discharge-weighted values for major streams. The dissolved (i.e., filterable) organic phosphorus fraction was assumed negligible in all inflows and not included in calculations (Abell and Hamilton 2013). Natural loads for each inflow were subtracted from contemporary loads to isolate the anthropogenic components.

Table 5. Methods used to assign daily mean dissolved reactive phosphorus (DRP), particulate phosphorus (PP) and total phosphorus (TP) concentrations in lake inflows.

Inflow type	Analyte	Inflow	Estimation method	Notes
Major streams (loads calculated for individual stream catchments)	DRP	All major streams	Linear interpolation of monthly measurements collected by BoPRC.	Missing/anomalous measurements replaced with the mean of concentrations measured in adjoining months.
	PP	Puarenga	Q < 3 $m^3 s^{-1}$: Linear interpolation of monthly measurements collected by BoPRC. Q > 3 $m^3 s^{-1}$: Derived from a linear relationship between log_{10}Q and log_{10}[PP] for the Puarenga Stream with correction for transformation bias (Ferguson 1986).	Relationship was based on data presented in Abell *et al*. (2013), collected from the Puarenga Stream when dischage was 3.0 to 15.6 $m^3 s^{-1}$ (maximum [PP] = 0.44 mg L^{-1}; *n* = 174; r^2 = 0.19). Maximum modelled mean daily [PP] was 0.38 mg L^{-1}.
		Ngongotaha and Utuhina	Q < 3 $m^3 s^{-1}$: Linear interpolation of monthly measurements collected by BoPRC. Q > 3 $m^3 s^{-1}$: Derived from a linear relationship between log_{10}Q and log_{10}[PP] for the Ngongotaha Stream with correction for transformation bias (Ferguson 1986).	Relationship was based on data presented in Abell *et al*. (2013), collected when dischage was 3 to 22 $m^3 s^{-1}$ (maximum [PP] = 0.44 mg L^{-1}; *n* = 44; r^2=0.77). Maximum modelled mean daily [PP] was 0.53 mg L^{-1} and 0.44 mg L^{-1}.
		Awahou, Waiteti, Waingaehe, Waiowhiro, Waiohewa, Hamurana	Linear interpolation of monthly measurements collected by BoPRC.	Measured PP was calculated as TP minus PO_4-P.
	TP	All	By calculation.	PO_4-P + PP
Minor streams (single discharge-weighted load calculated for nine minor streams)	DRP	Minor rural surface streams (Waitawa 1, Waitawa 2, Hauraki, Waimehia Drain, Waiowhiro)	Linear interpolation of monthly measurements collected by BoPRC from Waingaehe Stream (smallest of the major stream inflows, drains a predominantly pastoral catchment).	Missing/anomalous measurements replaced with the mean of concentrations measured in adjoining months.
		Lynmore Stream (minor urban surface stream)	Linear interpolation of monthly measurements collected by BoPRC from Lynmore Stream.	
		Groundwater seeps at the lake edge	Set to volumetric mean concentration of samples collected by BoPRC from eight lake–edge springs during 1992 and 1993 (0.176 mg L^{-1}; n = 134).	
	PP	Minor rural surface streams	Linear interpolation of monthly measurements collected by BoPRC from Waingaehe Stream.	
		Lynmore Stream	Linear interpolation of monthly measurements collected by BoPRC from Lynmore Stream.	
		Groundwater seeps at the lake edge	Set to volumetric mean concentration of samples collected by BoPRC from eight lake–edge springs during 1992 and 1993 (0.074 mg L^{-1}; n = 134).	
	TP	All	By calculation.	PO_4-P + PP
Ungauged	DRP, TP	Ungauged	Set equal to discharge-weighted concentrations of concentrations for major streams.	

RESULTS

Loads

Dissolved reactive phosphorus and TP loads for sub-catchments over the period 2007-2014 are presented in Tables 6 and 7, respectively. Anthropogenic annual mean DRP loads, calculated as areal rates for each sub-catchment, ranged from 0.01 – 0.38 kg DRP ha^{-1} y^{-1} (mean 0.17 kg ha^{-1} y^{-1}) and the percentage anthropogenic DRP loads ranged from c. 5 – 55% (Table 6). The observed Waiohewa Stream DRP concentrations were low compared with other inflows, resulting in a negative estimated anthropogenic load (i.e., observed concentrations were lower than the estimated natural values). Anthropogenic mean annual TP loads ranged 0.27 to 1.21 kg P ha^{-1} y^{-1} (mean 0.51 kg ha^{-1} y^{-1}) and percentage anthropogenic TP loads ranged from c. 8 – 66% (Table 7).

The annual anthropogenic TP load to the lake was estimated to be 23.4 t P y^{-1}. The mean annual observed TP load was 48.7 t P y^{-1} (sub-catchment range 0.83 to 13.44 t P y^{-1}), indicating that the anthropogenic load comprised 48% of the annual TP load to the lake.

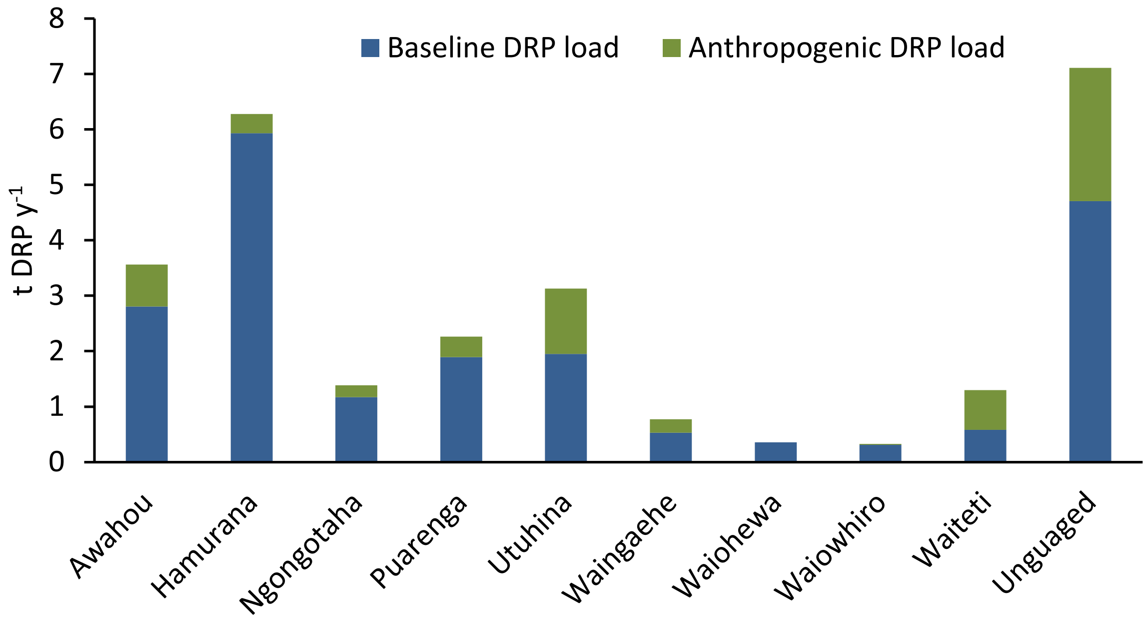
Table 6. Anthropogenic annual mean (2007–2014) dissolved reactive phosphorus (DRP) loads from Lake Rotorua sub-catchments based on the difference between baseline and observed (Obs.) concentrations from surface water (SW) and groundwater (GW). *Natural groundwater concentrations have been modified (Mod.) to account for increasing DRP concentrations with increasing mean residence time according to Morgenstern et al. (2015). ¥ Baseline surface water DRP concentrations are from McDowell et al. (2013). Negative loading values for Waiohewa are due to low DRP concentrations in the observed data.

Sub-catchment	Mean obs. DRP ($g\ m^{-3}$)	Obs. DRP load ($t\ DRP\ y^{-1}$)	Mod. GW DRP* ($g\ DRP\ m^{-3}$)	Mod. baseline SW DRP¥ ($g\ DRP\ m^{-3}$)	Baseline SW load ($t\ DRP\ y^{-1}$)	Baseline GW load ($t\ DRP\ y^{-1}$)	Baseline conc. ($g\ DRP\ m^{-3}$)	Baseline load ($t\ DRP\ y^{-1}$)	Anthro. DRP Load ($t\ DRP\ y^{-1}$)	Anthro. Load ($kg\ DRP\ ha^{-1}\ y^{-1}$)	Anthro. Load (% of total)
Awahou	0.066	3.56	0.064	0.009	0.10	2.71	0.053	2.80	0.76	0.38	21.3
Hamurana	0.079	6.28	0.081	0.008	0.07	5.87	0.073	5.93	0.35	0.21	5.5
Ngongotaha	0.029	1.39	0.042	0.009	0.35	0.82	0.020	1.17	0.22	0.03	15.5
Puarenga	0.035	2.26	0.048	0.016	0.53	1.36	0.031	1.89	0.37	0.04	16.3
Utuhina	0.055	3.13	0.058	0.009	0.25	1.71	0.034	1.95	1.17	0.19	37.5
Waingaehe	0.094	0.77	0.086	0.016	0.05	0.49	0.062	0.53	0.24	0.22	31.3
Waiohewa	0.017	0.21	0.048	0.002	0.01	0.35	0.030	0.35	-0.15	-0.13	-71.7
Waiowhiro	0.035	0.33	0.048	0.016	0.08	0.23	0.032	0.31	0.01	0.01	4.5
Waiteti	0.033	1.30	0.050	0.009	0.30	0.28	0.015	0.58	0.72	0.12	55.1
Ungauged	-	7.11	0.042	0.009	0.20	4.51	0.036	4.71	2.41	0.36	33.8
Rainfall to lake	0.011	1.40	0.011	0.011	1.40	-	0.011	1.40	-	-	-
TOTAL		27.7						21.6	**6.1**	0.12	**22.0**

Table 7. Anthropogenic mean annual (2007–2014) total phosphorus (TP) loads from Lake Rotorua sub-catchments based on the difference between baseline and observed (Obs.) concentrations from surface water (SW) and groundwater (GW).

Sub-catchment	Mean obs. TP ($g\ m^{-3}$)	Obs. TP load ($t\ P\ y^{-1}$)	Mod. GW TP ($g\ P\ m^{-3}$)	Mod. baseline SW TP ($g\ P\ m^{-3}$)	Baseline SW load ($t\ P\ y^{-1}$)	Baseline GW load ($t\ P\ y^{-1}$)	Baseline conc. ($g\ P\ m^{-3}$)	Baseline load ($t\ P\ y^{-1}$)	Anthro. Load ($t\ P\ y^{-1}$)	Anthro. Load ($kg\ P\ ha^{-1}\ y^{-1}$)	Anthro. Load (% of total)
Awahou		4.07	0.070	0.017	0.18	2.98	0.059	3.16	0.90	0.45	22.2
Hamurana		7.16	0.089	0.012	0.10	6.46	0.081	6.55	0.61	0.38	8.5
Ngongotaha		4.13	0.046	0.017	0.65	0.91	0.027	1.56	2.57	0.33	62.2
Puarenga		6.98	0.053	0.033	1.09	1.50	0.042	2.59	4.39	0.53	62.9
Utuhina		5.95	0.063	0.017	0.47	1.88	0.041	2.34	3.61	0.59	60.6
Waingaehe		1.01	0.095	0.033	0.10	0.53	0.074	0.63	0.38	0.35	37.9
Waiohewa		1.18	0.053	0.009	0.04	0.38	0.035	0.42	0.76	0.65	64.2
Waiowhiro		0.83	0.053	0.033	0.16	0.25	0.043	0.42	0.41	0.30	49.6
Waiteti		2.55	0.056	0.017	0.56	0.31	0.023	0.88	1.68	0.27	65.7
Ungauged	-	13.44	0.046	0.017	0.38	4.96	0.041	5.34	8.11	1.21	60.3
Rainfall to lake	0.011	1.40	0.011	0.011	1.40	-	0.011	1.40	-	-	-
TOTAL		48.7						25.3	**23.4**	0.47	**48.1**

Comparative natural and anthropogenic contributions to sub-catchment mean annual DRP and TP loads are presented in Figure 4. Minor and ungauged streams contributed the largest proportion of the observed TP (28%) and DRP loads (26%). The next most important contributor, Hamurana, contributed 23% of the observed DRP load to Lake Rotorua, but only 15% of the observed TP load.



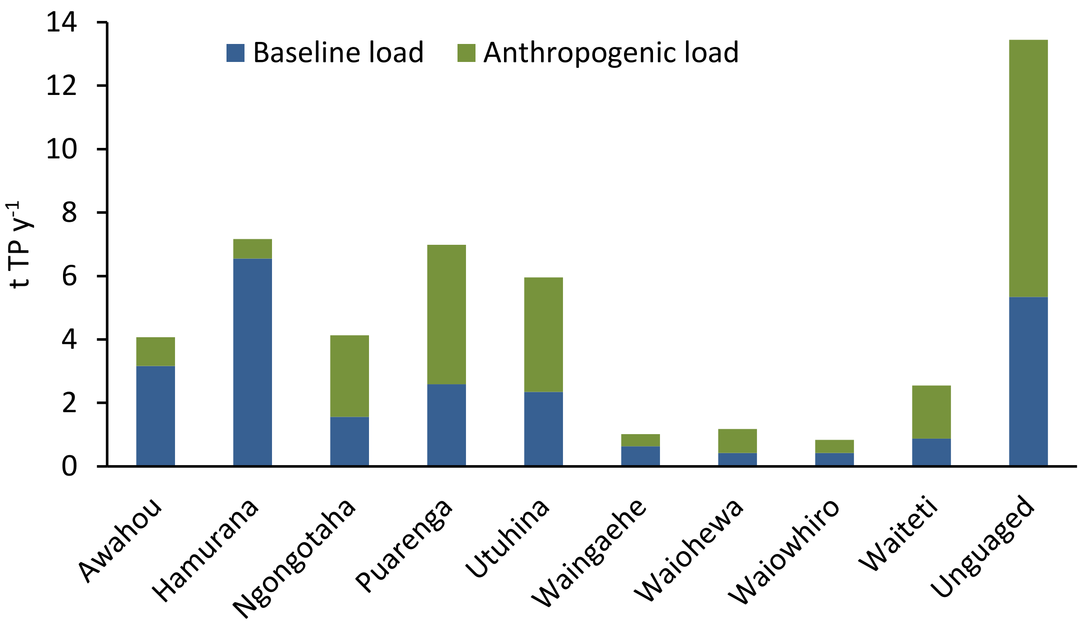


Figure 4. Sub-catchment total dissolved reactive phosphorus (DRP, top) and total phosphorus (TP, bottom) loads to Lake Rotorua with baseline and anthropogenic contributions indicated. Ungauged refers to minor and ungauged streams within the Rotorua sub-catchment.

Sub-catchment anthropogenic particulate phosphorus loads are presented in Figure 5. The mean estimated anthropogenic particulate phosphorus load, averaged over all sub-catchments, was 0.36 kg P ha^{-1} y^{-1}; in comparison, the average sub-catchment natural particulate phosphorus load was 0.11 kg P ha^{-1} y^{-1}. The Waiohewa and minor and ungauged sub-catchments were estimated to produce the largest areal particulate phosphorus loads (0.65 and 0.85 kg P ha^{-1} y^{-1} respectively). However, the Waiohewa sub-catchment is comparatively small (1169 ha) and the discharge is correspondingly small relative to other sub-catchments, resulting in the Waiohewa Stream only contributing an estimated 5% of the total anthropogenic phosphorus load. By contrast, minor and ungauged sub-catchments contributed 32% of the total anthropogenic phosphorus load.

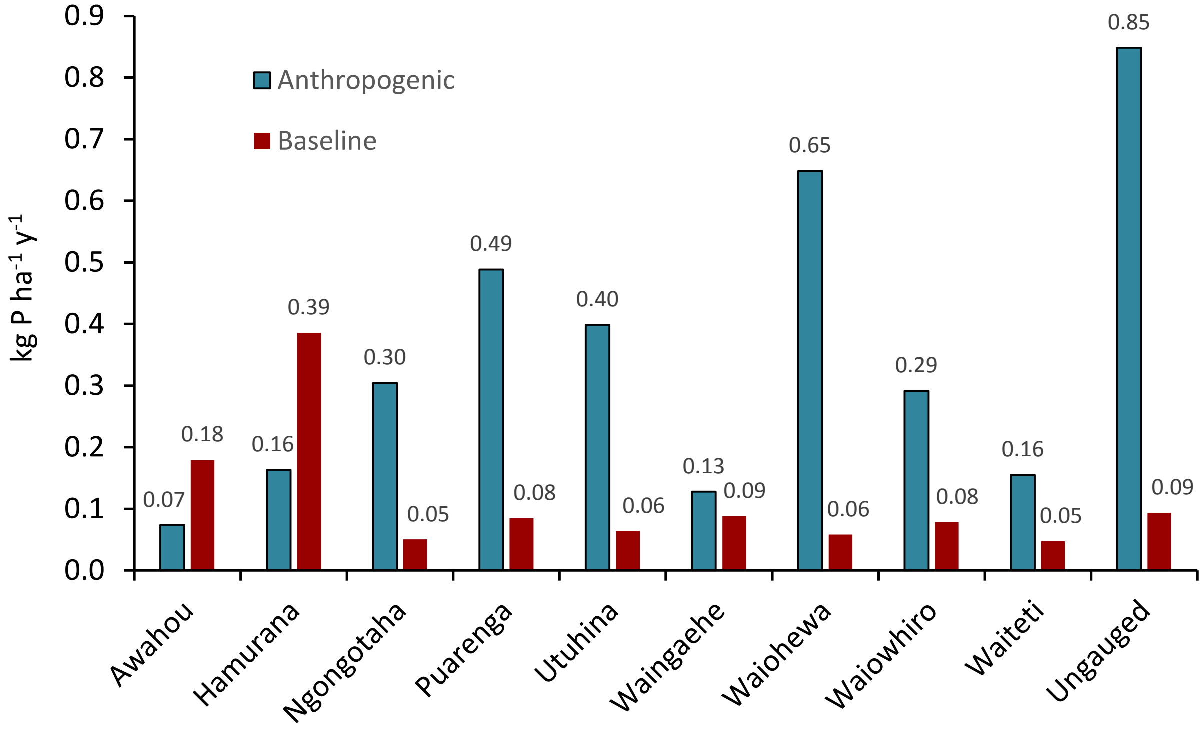


Figure 5. Sub-catchment area-specific anthropogenic and baseline particulate phosphorus loads to Lake Rotorua. Ungauged refers to minor and ungauged streams within the Rotorua sub-catchment.

DISCUSSION

Monitoring data were used to estimate annual phosphorus loads from the Lake Rotorua catchment for a 7–year period, 2007–2014. These estimates were compared with baseline ('natural') loads that represent background phosphorus loads to the lake. Baseline phosphorus concentrations in lake inflows were estimated from 'reference concentrations' derived in a national–scale study (McDowell et al. 2013), and were amended to reflect natural loads associated with localised inputs of 'old-age' groundwater enriched in phosphorus from geological sources. These natural groundwater loads were determined using the relationship between DRP concentrations and groundwater mean residence time reported by Morgenstern et al. (2015).

Approximately 48% of the TP load and 22% of the DRP load to Lake Rotorua was calculated to be of anthropogenic origin. However, there is significant variation between sub-catchments in terms of the relative contribution of groundwater versus surface water, and therefore in the proportion of TP comprised of DRP. For example, groundwater dominated catchments such as Hamurana and Awahou (Table 2) have large DRP loads (5.93 and 2.80 t y^{-1}, respectively) that cannot be attributed to anthropogenic sources. Although the Hamurana and Awahou sub-catchments are dominated by agricultural land-use (72% and 82%, respectively), discharge from these sub-catchments is dominated by groundwater (Hamurana 90% and Awahou 80%). In addition, the mean groundwater residence time (MRT) for the Hamurana and Awahou sub-catchments is approximately 125 and 75 years, respectively (Morgenstern et al. 2015). Morgenstern et al. (2015) demonstrated that within the Rotorua catchment, increasing groundwater MRT results in increasing DRP concentrations. This increase is attributable to dissolution of phosphorus rich minerals in the volcanic strata and it results in naturally high DRP loading to Lake Rotorua, particularly from the Hamurana and Awahou sub-catchments. The relative contribution of particulate phosphorus to the TP load is considerably lower in these sub-catchments compared with others in the Lake Rotorua catchment because particulate phosphorus is primarily associated with eroded soil in surface flows (McDowell 2010) and direct surface water inputs make only a small contribution to the total discharge from Hamurana and Awahou Streams. Therefore both the baseline and anthropogenic components of the particulate phosphorus load in these streams are considerably smaller than the DRP load.

Compared with the Hamurana and Awahou sub-catchments, the Ngongotaha, Utuhina and Puarenga sub-catchments have reduced groundwater contributions (34%, 46% and 52%, respectively) and less agricultural land (53%, 29% and 27% by area, respectively). The lower contribution to discharge by old-age groundwater results in less DRP loading from natural geologic sources in these sub-catchments. However, the increased proportion of anthropogenic TP loading is likely due to the higher surface water contributions that discharge more particulate phosphorus from developed land (including various proportions of agriculture and urban land) (McDowell 2010).

The Waiohewa sub-catchment has unusually low observed DRP concentrations compared with other sub-catchments, despite a moderate groundwater MRT of 40 years. As a result there was a negative anthropogenic loading value calculated following adjustments of DRP concentrations for groundwater residence time. The Waiohewa catchment is strongly geothermally influenced, and the geothermal waters in this area are often very high in ammonium but low in phosphorus. The geothermal waters of the Waiohewa sub-catchment do not fit well within the MRT model used for this study and further monitoring would be required to increase the accuracy of phosphorus load estimations from this catchment.

Morgenstern et al. (2015) found little evidence for elevated phosphate levels in groundwater despite increasing fertiliser applications in the Rotorua catchment, and suggested that phosphorus from agricultural fertiliser use has generally not been transported to groundwater or may be masked by the naturally high groundwater DRP concentrations. However, groundwater in aquifers <20 years old may be enriched with DRP from past anthropogenic activities associated with septic tank discharges or fertiliser applications (Hoare 1987). Currently, there are limited data for such cases and there is greater uncertainty in accurately determining the age of groundwater <20 years old and defining its contribution to phosphorus loads (Morgenstern et al. 2015). In this report, minor and ungauged catchments were prescribed to be groundwater dominated (83%), and an estimated MRT of 30 years was utilised in determining loads. This resulted in an estimated anthropogenic DRP load of 2.4 t y^{-1}. Given the uncertainty of the groundwater MRT and potential anthropogenic influences on aquifers with a MRT <20 years, this figure should be treated with caution.

The presence of elevated DRP in old groundwater indicates that its source is primarily due to phosphate leaching from the rhyolite ignimbrite and lava formations, because these waters were recharged before land use intensification (Morgenstern et al. 2015). With most groundwater discharging into Lake Rotorua being very old (MRT >50 years), the water has naturally high DRP concentrations and high baseline TP loads (Morgenstern et al. 2015). Baseline TP loads from the Rotorua sub-catchments ranged from 0.14 to 4.1 kg P ha^{-1} y^{-1} with a mean of 0.87 kg P ha^{-1} y^{-1}, in contrast the average baseline load for European catchments of around 0.1 kg P ha^{-1} y^{-1} (Bøgestrand et al. 2005).

The Lake Rotorua Action Plan has a stated TLI target of 4.2 as a measure of acceptable lake health (BoPRC 2009). The high natural DRP loads to Lake Rotorua provide a challenge in maintaining nutrient co-limitation for phytoplankton growth. Lake trophic state modelling involving nutrient reduction scenarios has indicated that total nitrogen loads would need to be reduced from 641.5 t y^{-1} to 435 t N y^{-1} and TP loads from 34.5 t y^{-1} to 23.4 t P y^{-1} (DRP 23 t y^{-1} to 15.6 t y^{-1}) to achieve a TLI3[*] target of 4.32, equivalent to a TLI4 value of 4.2 (Hamilton et al. 2015). However, these scenarios utilised inflow phosphorus concentrations from monthly baseflow sampling of inflows and as such are likely underestimate TP and DRP loading from stormflow events. This report includes stormflow TP and DRP loadings from the Puarenga, Ngongotaha and Utuhina Streams, resulting in a lake TP loading estimate of 48.7 t y^{-1} (23.4 t y^{-1} anthropogenic) and a DRP loading of 27.7 t y^{-1} (6.1 t y^{-1} anthropogenic). To achieve a TLI target of 4.2 would require an estimated reduction in TP of 10–15 t y^{-1}, i.e., anthropogenic TP loading would need to be reduced from 24 t y^{-1} to 8–13 t y^{-1}, based on previous modelling by Hamilton et al. (2015). More precise estimates cannot be provided without further modelling due to interactions between nutrient concentrations, species and ratios (N:P), as well as algal species composition.

Alum dosing in the Puarenga and Utuhina streams has achieved a >80% reduction in DRP loading to Lake Rotorua from these streams (Hamilton et al. 2015). Assuming that the aluminium bound fraction is no longer biologically available, this equates to a 20.1% reduction in total phosphorus loading from these streams, or 1.21 t P y^{-1} (i.e., 57.6% of the action plan target). Hamilton et al. (2015) also suggest that alum dosing may also produce beneficial in-lake effects such as flocculation of particulate phosphorus and a reduction in lake sediment phosphorus release. However, while alum dosing is effective in reducing dissolved phosphorus, aluminium can be highly toxic to aquatic organisms under certain conditions and

[*] TLI is typically calculated from four components TN, TP, chlorophyll *a* and Secchi depth. However, the Secchi depth component was ignored as the model used does not explicitly simulate Secchi depth, reducing the TLI to three components for this analysis.

concentrations. Tempero (2015) suggests that increasing alum dosing to Lake Rotorua is not a viable medium- to long-term strategy, and current levels of dosing require a precautionary approach. Lake Rotorua has a very low buffering capacity and the hydrolysis reaction of alum causes acidification in poorly buffered waters, causing aluminium to become toxic to aquatic organisms (Tempero 2015). Direct toxicity has not currently been observed, likely due to low to moderate levels of alum dosing to date.

Management of anthropogenic particulate phosphorus loads should also be a high priority for reduction as they will be most amenable to management. Sub-catchment particulate phosphorus loads are most appropriately addressed by land-use best practice (McDowell 2010), improved stormwater detention (Nix et al. 1988) and erosion control (Stutter et al. 2008). Identifying catchments where these practices will provide the greatest benefit should be a priority. Index models to evaluate where and when to direct management efforts could also be extremely useful and allow prioritisation of expenditure for catchment management in a GIS framework (Drewry et al. 2011). Figure 5 demonstrates that the minor and ungauged sub-catchments contribute 33% of the total anthropogenic particulate phosphorus load. However, this estimate should be treated with caution as it includes discharge estimates from other sub-catchments which are ungauged and it does not include corrections for storm flows. Further investigation to identify discharges with significant loads and potential critical source areas (that account for the majority of phosphorus loss on an areal basis) in these catchments is needed. Increasing the spatial extent of hydrometric gauges would also greatly improve the precision of load estimates from major streams (e.g., Awahou, Waiteti, Waiohewa).

Study limitations

The phosphorus load estimates calculated for this report have been based on the best available data, however, a number of assumptions were unavoidable and data limitations need to be specifically acknowledged. Notably, phosphorus loading from stormflows were only estimated for three inflows (Utuhina, Puarenga and Ngongotaha), as stormflow monitoring data or stream gauging data were unavailable for other sub-catchments. Estimates of anthropogenic phosphorus loads were derived from the difference between the observed total phosphorus load and the estimated natural load. The estimated natural phosphorus load was derived from the median phosphorus concentration multiplied by the annual flow, hence the natural load excludes stormflows for the Utuhina, Puarenga and Ngongotaha sub-catchments (assuming TP concentrations increase in storm flow from native forest). In addition, natural phosphorus concentration data sourced from McDowell et al. (2013) were based on the stated median concentrations rather than mean concentrations for each site. The use of median values is likely to have resulted in a bias towards lower phosphorus concentrations due to the predominance of baseflow samples as opposed to stormflow samples. This limitation may have resulted in an over-estimation of the anthropogenic load from all catchments, which may be exacerbated by inclusion of stormflow corrections for the Utuhina, Puarenga and Ngongotaha sub-catchments. This effect may be somewhat moderated under natural conditions (i.e., undisturbed evergreen forest with limited erosion) as stormflow TP concentrations would be lower than in developed catchments, however, data to quantify this effect on North Island volcanic catchments is not available.

Another assumption made when estimating the phosphorus loads was related to the groundwater mean residence time for minor and ungauged catchments. Collectively, these 'minor' catchments make a significant contribution to the external phosphorus load to Lake Rotorua. Estimates of groundwater contribution and MRT were derived from a limited set of data. A MRT of 30 years was used for estimation of the groundwater phosphorus concentrations in the minor and ungauged catchments. However, if the MRT is lower this will result in a reduction in phosphorus concentrations and the associated P load to Lake Rotorua. For example, reducing the MRT from 30 to 15 years would reduce the baseline (natural) DRP load by 1.2 t y^{-1} (i.e., a 5.5% reduction in total baseline DRP).

CONCLUSION

Estimates of DRP and TP loads indicate that approximately 22% of the DRP load and 48% of the TP load to Lake Rotorua result from anthropogenic activity. Phosphorus loads from groundwater-dominated catchments on the western side of the lake are mostly derived from DRP in old-age groundwater. Dissolved reactive phosphorus concentrations in this area are the result of natural rather than anthropogenic processes, despite land-use in these sub-catchments being mainly pastoral. The large groundwater component of the discharge means that there is also comparatively little anthropogenic TP loading during baseflow conditions. In contrast, catchments to the south and east of the lake have less agricultural land-use, but are more strongly dominated by surface water contributions. Therefore, there is a greater proportion of anthropogenic TP loading, primarily in the form of particulate phosphorus. Discharge from minor and ungauged catchments has been identified as contributing the greatest proportion of anthropogenic phosphorus, both in terms of total loading and on an areal basis, despite being heavily groundwater influenced.

Alum dosing of the Puarenga and Utuhina streams has been highly effective in reducing DRP loads to Lake Rotorua. However, particulate material is not as readily sequestered by aluminium. Particulate material is often derived from erosion, cattle excreta, fertilizer run-off and storm water run-off, all of which can be mitigated by following best practices in land management or storm water engineering. Given significant phosphorus loading is occurring by way of particulate material, it is recommended that mitigation efforts focus on improving land management practices to reduce phosphorus loads to Lake Rotorua. Every effort should be made to reduce total phosphorus loads from anthropogenic sources to levels that are commensurate with the lake target TLI of 4.2. This would entail targeting the 23.4 t y^{-1} of anthropogenic TP to align with the required 8–13 t y^{-1} (lake load 10–15 t y^{-1}) reduction necessary to meet the TLI of 4.2.

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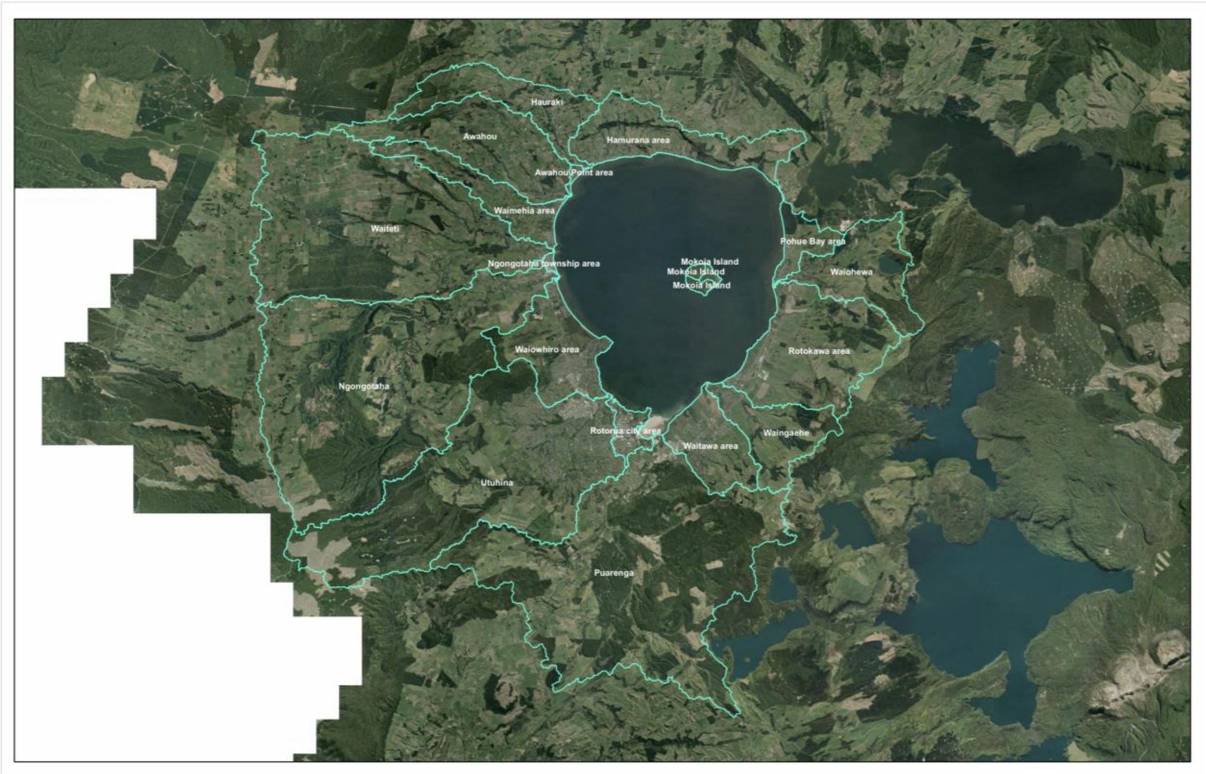
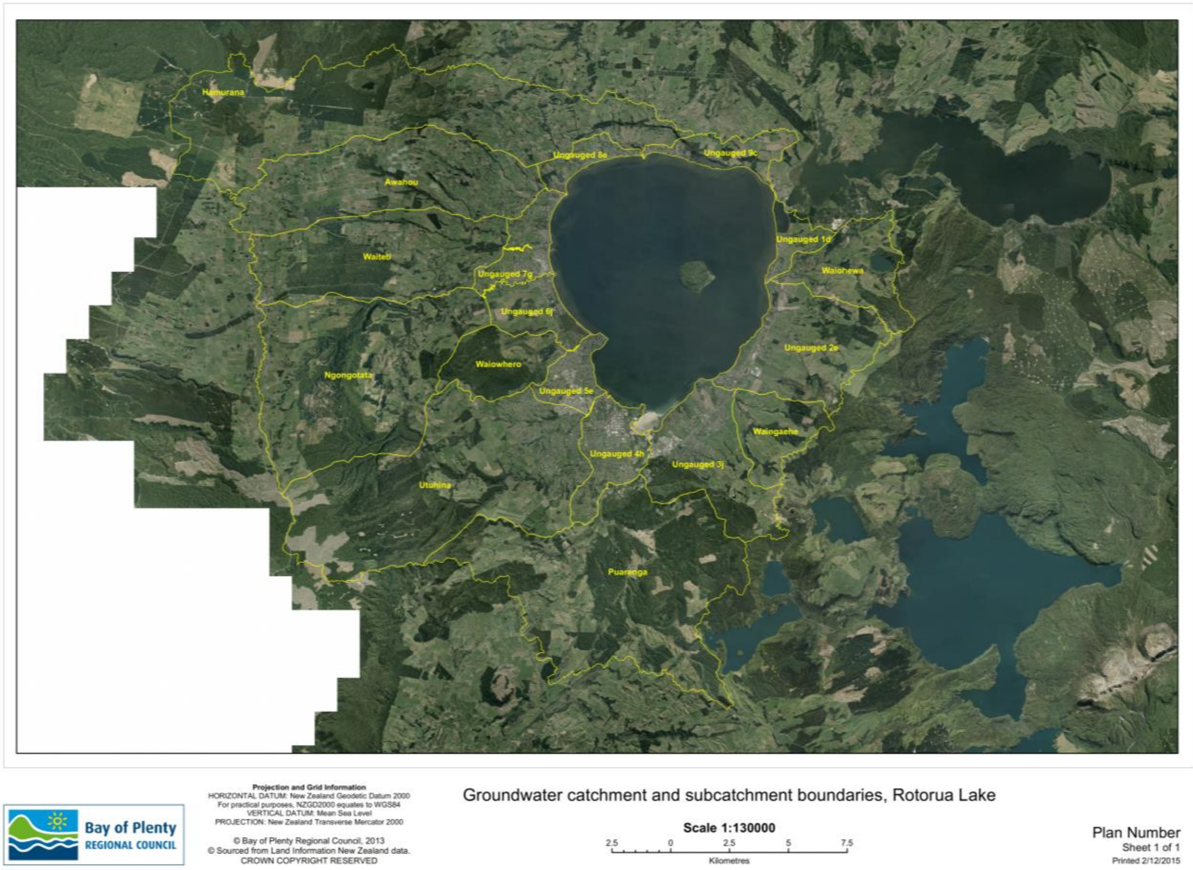
Personal Communication

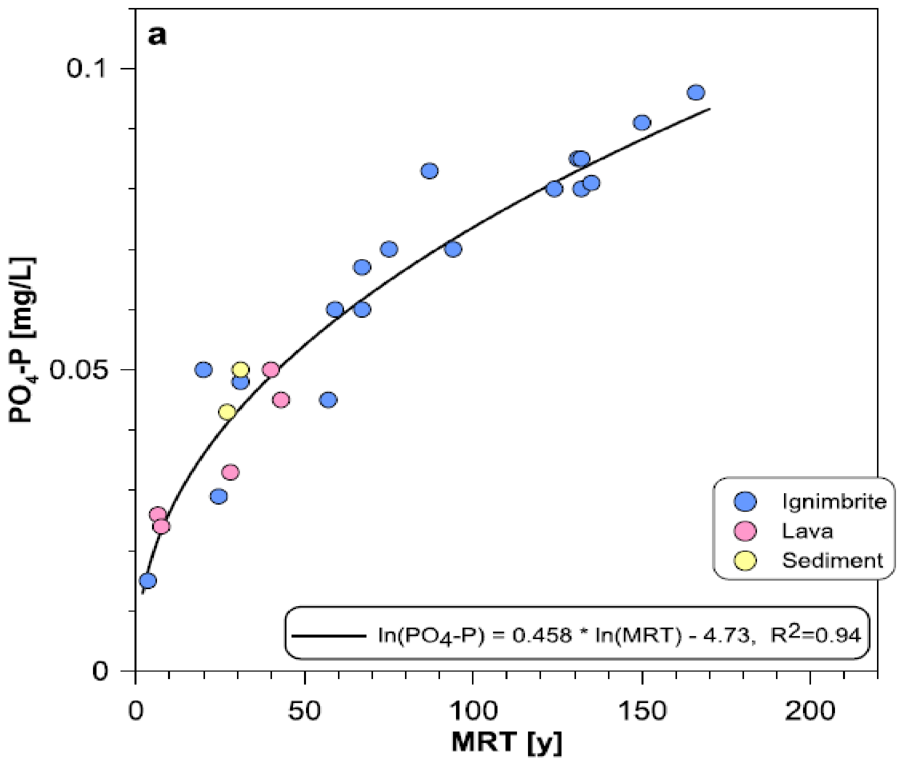
R. M. McDowell. Senior Research Scientist, Agresearch, Mosgiel. E–mail correspondence with J. Abell, 2013.

APPENDICES



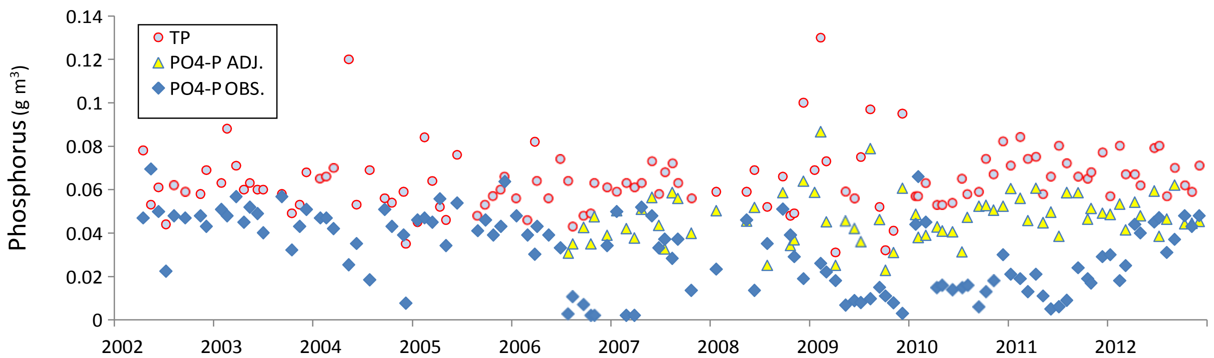


Appendix 1. Detailed catchment and sub-catchment boundaries for Lake Rotorua including surface water (top) and groundwater (bottom).



Appendix 2. Relationship between DRP (PO4-P) and groundwater mean residence time (MRT) reported by Morgenstern et al. (2015). This relationship was used to calculate sub-catchment specific groundwater DRP concentrations.

In order to simulate hypothetical scenarios with no alum dosing of either inflows, it was necessary to approximate dissolved P concentrations with the effects of alum absent. Therefore mean DRP:TP ratios were calculated for each month of the year using data between 2001 and 2006 (i.e., 'pre-alum'). This ratio was then applied to each measurement of TP 2006 – 2012, in order to estimate the DRP concentration (Appendix 3, triangles).



Appendix 3. Time-series of inflow measurements in the Utuhina inflow for TP (red dots), DRP (blue diamonds). Green triangles represent estimated DRP if alum dosing had not been undertaken 2006 – 2012. This was estimated using an average of DRP:TP for each month of the period before alum dosing commenced (Hamilton et al. 2015).