Modelling the impact of sewage reticulation on water quality of Lake Tarawera

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Client report prepared for the Lake Tarawera Ratepayers Association

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Cover image: View across Lake Tarawera (Terry Beckett).

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Executive Summary

In order to inform efforts being considered for the management of catchment sources of nutrient pollution into Lake Tarawera, a study was commissioned by the Lake Tarawera Ratepayers Association. This study, conducted by the University of Waikato, was specifically to assess the potential impacts of sewage reticulation on lake water quality.

Analyses of available data indicate that Lake Tarawera is regionally unique in that the majority of its phosphorus (P) load and a substantial portion of its nitrogen (N) load appear to be derived from a combination of 'tributary' lakes and geothermal sources. This may help explain the relatively high P concentrations and low N: P ratio in the lake. Waste water from septic systems contribute 3.3% (2.9 t N y^{-1}) of the total N load and 2.7% (0.29 t P y^{-1}) of the total P load to Lake Tarawera This source of nutrients represents approximately 15% of the 'manageable' load from land use in the surface catchment. Mass balance models are often used to estimate catchment external load corresponding to desired in-lake nutrient concentrations or trophic state (assuming internal loading is negligible). In this study we adopted a reverse approach, using mass balance models to estimate the response of in-lake concentrations to changes in external load (namely, with and without sewage reticulation). Retention of phosphorus was estimated using the method of Vollenweider (1976) and retention of nitrogen was estimated after Harrison et al. (2009), with external load retention coefficients[1] of 0.73 and 0.72 for P and N, respectively.

Improperly treated domestic sewage from lakeside properties may contain pathogens including bacteria, viruses, protozoa and helminths (intestinal worms and worm-like parasites). Historical measurements of *E.coli* concentrations from tap water samples collected from a number of sites around the lake between 1991 and 2015 were thus analysed, as many residential properties draw water directly from the lake and/or from closely linked groundwater. Given that microbiological non-compliance of drinking water samples was prevalent at most (6 out of 10) of the sampling locations considered in this analysis, authorities may need to look into more frequent testing and to reduce potential sources of faecal contamination within the catchment, including failed septic tanks, to improve public safety. In light of the current study, wastewater reticulation could make a significant contribution to mitigating public health risks associated with poorly performing on-site treatment systems.

From a public health perspective, this study also highlights the need for efforts aimed at investigating and curbing potential sources of faecal contamination of drinking water sources within the catchment. This could include the commissioning of a microbial source tracking study that uses appropriate genetic markers to discriminate among the possible sources of faecal pollution within tap water used for domestic purposes in the Lake Tarawera catchment. These efforts ideally would be put in place before and after the execution of any sewage management intervention to initially establish the extent of human faecal contamination from faulty septic tanks and ultimately, to confirm that the sewage management efforts put in place are effective.

As part of Lake Tarawera water quality management plan, a wastewater reticulation system will reduce nutrient loading by 3 to 5%. Modelling of the reticulation of wastewater nutrient loads revealed that the impact on lake water nutrient concentrations is minor, as wastewater represents a small component of overall N and P loads to Lake Tarawera. Nevertheless, much of the load to the lake is from sources that are difficult to mitigate (e.g. geothermal, other lakes). Further, time lags in response of the nutrient loads to the lake may be lower due to the proximity of current wastewater

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[1] Retention coefficient is the proportion of external load retained within the lake

inputs to the lake shore (as opposed to diffuse inputs from land use on the upper reaches of the catchment). Therefore, implementation of a reticulated sewage system as part of an overall plan to reduce loading of P and N into Lake Tarawera may be a desirable management initiative as it could make a contribution to improving manageable sources of nutrients from the lake catchment. In addition, a reticulated sewage system will reduce public health risks associated with poorly performing on-site treatment systems. From a public health perspective, efforts such as further intensive sampling for faecal coliforms in drinking water, as well as the commissioning of microbial source tracking studies to identify faulty septic tanks is recommended. These investigations will also provide information on the performance of sewage management efforts (and optimisation) to reduce the discharge of pathogenic contaminants into the lake. This report has not made recommendations on the costs or value for money that sewage reticulation would entail. These considerations will be essential to complement our environmental investigation and underpin considerations of a reticulated sewage system for Lake Tarawera.

Acknowledgements

We acknowledge the assistance of Bay of Plenty Regional Council for provision of data. The preparation of this report was assisted through support for the Bay of Plenty Regional Council Chair in Lake Restoration and the Ministry of Business, Innovation and Employment project UOWX1503 (Enhancing the health and resilience of New Zealand lakes). Thanks to Neil O'Hara for collecting and arranging analysis of tap water samples for faecal coliforms from 1991 to 2005. Faecal coliform analysis (2015-2016) of tap water samples was done by Terry Beckett (Lake Tarawera Ratepayers Association).

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1.0 Introduction

Lake Tarawera is a renowned rainbow trout fishery due to the size and condition of the trout, as well as the lakes accessibility and aesthetic qualities. Phosphorus concentrations in the lake are fairly high and cyanobacteria, including colonial and filamentous species, can be abundant during warmer months (Reid, 1991; Frye & Abroad, 2008). Nitrogen and phosphorus loads to the lake come from a wide range of catchment sources, including wastewater from built-up areas (septic tank leachate), bare ground, exotic and native forest, wetlands, and agricultural land (Figure 1). The surface topographical catchment of Tarawera does not contain any dairy farms, and average areal nutrient losses are relatively low in comparison with other lakes in the region (Verburg & Semadeni-Davies, 2013).

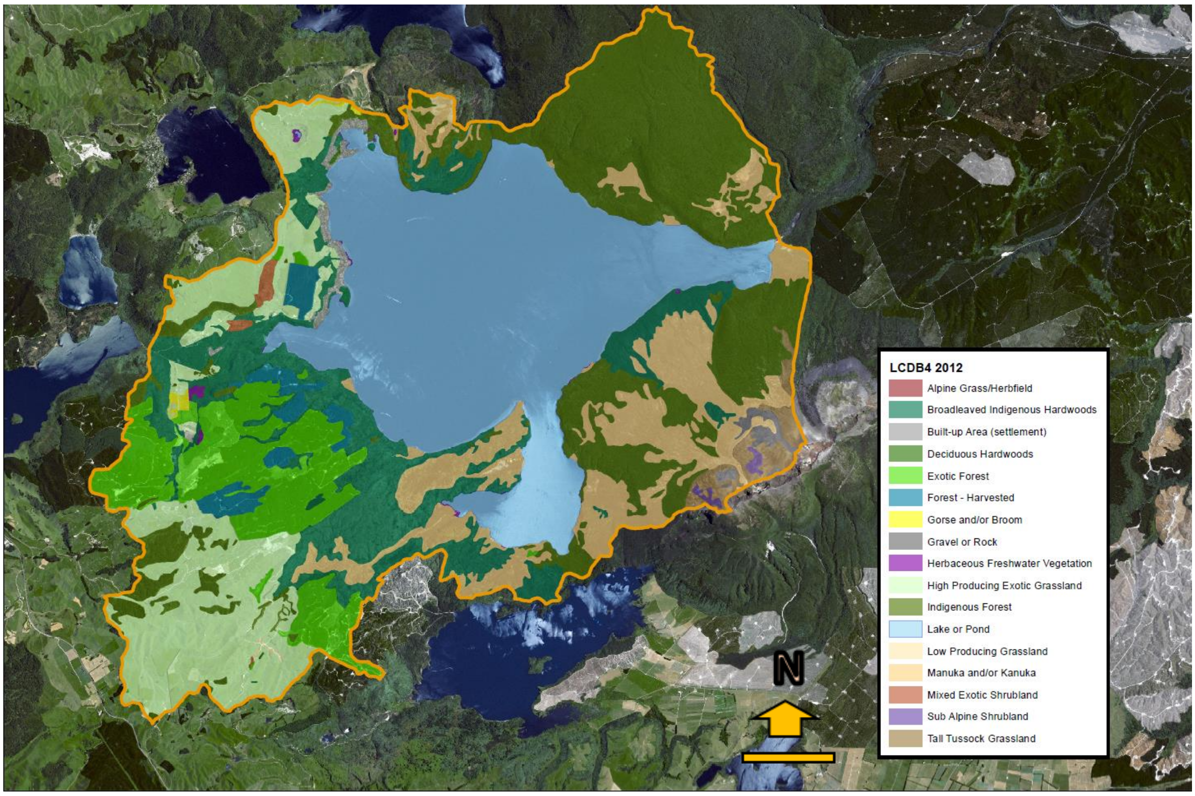

Figure 1 **Map of land use (LCDB4) in the Tarawera catchment.**

Lake Tarawera receives water, either directly or indirectly via groundwater, from seven smaller lakes in the Rotorua region and from geothermal springs on the southern and northern shores. Therefore, as well as nitrogen (N) and phosphorus (P) loads from within the immediate (surface topographical) catchment of the lake, loads received from external sources outside the immediate catchment must also be considered. BoPRC (2012) estimated loads for land use in the inner catchment only, of 67.7 t N y^{-1} and 5.6 t P y^{-1} (Appendix 2). Hamilton et al. (2006) also estimated annual loads from the greater Tarawera catchment of 84.6 t N y^{-1} and 10.4 t P y^{-1} using areal export coefficients for land use in all connected lakes and using assumed attenuation factors between lakes.

Lakeside communities at Lake Tarawera presently utilise on-site wastewater treatment (typically simple septic tanks). Failing or overloaded septic systems can be a source of faecal contamination in near-shore areas, endangering public health (Wilcock et al., 2013). While septic tank systems treat (reduce) wastewater loads to an extent, they still leach dissolved N and P which ultimately contribute to nutrient loads in nearby waters (Macintosh et al., 2011; Jayarathne, 2013; Kumar, 2016). The amount of leaching can be highly variable, although BoPRC has adopted a 'rule-of-thumb' of 3.65 kg N per resident per year and 0.37 kg P per resident per year as recommended in the review of McIntosh (2013). Where inputs from wastewater sources are substantial, they may stimulate phytoplankton production and contribute to the formation of algal blooms. The resulting reduction in light availability may increase mortality of submerged aquatic vegetation, and the eventual decomposition of phytoplankton may increase biochemical oxygen demand in the lake (Duarte, 1995).

It has been suggested that replacing on-site septic systems at Tarawera with centralised wastewater reticulation could be an effective measure for the maintenance and/or improvement of water quality at Lake Tarawera. In order to inform efforts being considered for the management of catchment sources of nutrient pollution into Lake Tarawera, the University of Waikato was commissioned by the Lake Tarawera Ratepayers Association to assess the potential impact of sewage reticulation on lake water quality in Lake Tarawera. The objective of this work is thus to address the following question:

- *What is the effect of sewage reticulation on lake water quality in Lake Tarawera, with a focus on faecal indicator bacteria (FIB) and contribution to nutrient loads?*

The present study utilises a 'mass balance' modelling approach to address this question. By comparing nutrient concentrations from on-site septic systems with other potential contributory sources of N and P loads from all sub-catchments, insight can be gained into whether a sewage reticulation system can lead to improvements in water quality in Lake Tarawera. The process of addressing the research question above also necessitates a detailed consideration of historical measurements of *E.coli* concentrations from tap water samples collected from sites around the lake. Using this approach, prevalence of microbiological non-compliance of drinking water samples could be indicative of public health risks associated with faecal contamination from poorly performing on-site treatment systems.

2.0 Methods

2.1 Study site description

2.1.1 Lake Tarawera

Lake Tarawera (38°13'S, 176°24'E) is located in the Taupo Volcanic Zone (TVZ), North Island, New Zealand, about 18 km southeast of Rotorua City, with other lakes within its receiving catchment including Lakes Okataina, Okareka, Tikitapu, Rotokakahi, Okaro and Rotomahana. It covers an area of 41 km^2, has a maximum length of 11.4 km, a maximum width of 9.0 km, and a maximum depth of 87.5 m (Win, 1975; Lowe & Green, 1987). Lake Tarawera has low productivity (i.e., it is oligotrophic), however, proliferations of cyanobacteria sometimes occur during summer (Reid, 1991; Frye & Abroad, 2008). Average surface water concentrations of total nitrogen, total phosphorus and chlorophyll *a* for the period 2010 to 2015 were 90.8 mg N m^{-3}, 19.9 mg P m^{-3}, and 1.9 mg chl *a* m^{-3}, respectively (BoPRC, unpubl. data). Tarawera's TN:TP ratio of <5:1 is very low among the Bay of

Plenty lakes (Verburg & Semadeni-Davies, 2013). At the eastern end of the lake is the outlet which flows into the Tarawera River. The Trophic Level Index (TLI; Burns, 1999) has been trending upwards for a number of years and the current value of 3.1 recorded in 2015 is well above the TLI target of 2.6 set in Bay of Plenty Regional Council's Water and Land Plan. Burns et al. (2005) suggested the lake may be in a declining state and in recent summers there have been health warnings issued for the Wairua arm due to cyanobacteria blooms.

2.1.2 Lake Tarawera catchment description

Lake Tarawera has a surface topographical catchment area of 143.4 km^2, including the lake area of 41.5 km^2 (LCDB4). Much of the catchment is relatively unaltered, with indigenous hardwood forest, and manuka/kanuka accounting for over half of all land use (Figure 1). Approximately 1800 ha of pastoral land is within the western catchment, and geothermal waters (both surface inflows and sub-surface springs) influence the lake from the south. While the main surface inflow to Tarawera is the Wairoa Stream at the western shore, Lake Tarawera receives water from several other Bay of Plenty lakes, thus it has an 'inner' catchment (described above), and 'greater' catchment which includes the six additional lakes (Figure 2). Lakes Rotokakahi and Okareka flow to Tarawera via the Te Wairoa and Waitangi Streams, respectively, and Lakes Tikitapu, Okataina and Rotomahana are connected to Tarawera by sub-surface flows. Water also seeps from Lake Rotomahana (elevation 337 m), through to Lake Tarawera (elevation 299 m) (Whiteford et al., 1996). Due to the absence of a surface outlet at Lake Rotomahana, there is also a control structure in place for the purpose of discharging excess water into Lake Tarawera when water level at Rotomahana is high. The intake structure is situated at grid reference NZMS 260 V16:107 218 and discharges to the west of the Rapatu Bay jetty at grid reference NZMS 260 V16:118 231. The maximum flow through the structure is limited to 62200 m^3 d^{-1} with a maximum rate of 0.72 m^3 s^{-1}. The relationship between Rotomahana water level and the volume of this discharge is not yet well-quantified. Lake Okaro flows to Lake Rotomahana and is thus indirectly connected to Tarawera (Figure 2). Additionally, some proportion of outflow from Lake Rerewhakakaaitu may drain to Lake Rotomahana.

2.2 Lake Model Description

Simple mass balance, 'Vollenweider'-style models were used to predict the response of lake concentrations of P and N to changes in external nutrient loads. Mean TP concentration in the lake was estimated from lake volume, the outflow rate (which combined gives residence time), lake area and total P loading, using the Vollenweider (1976) equation:

$$[\mathrm{P}]_{\mathrm{lakepred}} = (1 - R_{pred})\frac{L_p}{q_s} \qquad \text{Eq. 1}$$

where L_p is the annual external loading rate of phosphorus per area of the lake surface (mg m^{-2} y^{-1}), q_s = O/A is the annual hydraulic load (m y^{-1}), O is the annual outflow rate (m^3 y^{-1}), A is the lake surface area (m^2), and R_{pred} is the predicted lake retention coefficient (Ahlgren et al., 1988).

In order to determine the predicted lake retention coefficient, this study adopted the Vollenweider (1976) equation which found empirically that for phosphorus:

$$R_{pred} = \frac{\sqrt{T_w}}{(1+\sqrt{T_w})} \qquad \text{Eq. 2}$$

where T_w =V/O is the hydraulic residence time (y), and V is the lake volume (m^3).

The equation of Vollenweider (1976) remains the most widely applied retention model for phosphorus (Wetzel, 2001; Kalff, 2003; Brett & Benjamin, 2008). However, predicted retention for phosphorus was not assumed to apply to nitrogen, because of differences in the respective nutrient cycles, and because nitrogen can be lost from the lake by sedimentation, to the atmosphere by denitrification, and it can be fixed from the atmosphere by certain phytoplankton species. Thus in this study, we adopted the Harrison et al. (2009) equation for nitrogen retention in lakes and reservoirs:

$$R_{pred} = 1 - \exp\frac{-V_f}{q_s} \qquad \text{Eq. 3}$$

where V_f is the 'apparent settling velocity of nitrogen' with a mean value of 9.92 for total nitrogen among 80 lakes. Harrison et al. (2009) suggested that N retention in temperate lakes might be lower than for other latitudes, although differences between retention in boreal (V_f = 7.74, n = 36), temperate (V_f = 5.13, n = 35) and tropical (V_f = 9.81, n = 9) lakes were not statistically significant and the analysis by latitude did not exclude lakes where only loads for dissolved nitrogen were accounted for. The above mass balance assumes that the impact of internal loading (sediment nutrient release) is negligible. The difference obtained between predicted and observed lake concentrations was thus reported as indicative of the likely extent of internal loading.

2.3 Estimation of catchment nutrient budgets

2.3.1 Land use

Overseer™ benchmarking of agricultural land use within the Tarawera catchment was not available. Therefore, all pastoral land was assumed to be dry stock, average loss rates of 10.18 kg N ha^{-1} y^{-1} and 1.02 kg P ha^{-1} y^{-1} were applied from the average Overseer™ estimate of nutrient losses from drystock land in the catchments of other Te Arawa Lakes. For other land uses, loss rates were broadly taken from Lake Action Plans published by BoPRC for various Rotorua Lakes.

2.3.2 Geothermal inputs of nitrogen and phosphorus

Estimates of geothermal inputs to Tarawera were made following a comprehensive review of geothermal inputs to lakes in the Rotorua region.

2.3.3 Connected lakes

Nutrient loads from lakes within the greater Tarawera catchment were estimated by multiplying the outflow of these lakes, as calculated by the model of Woods et al. (2006), with the average observed surface water (<10 m) concentrations of TN and TP for the period 2009 to 2014 (BoPRC unpubl. data). Loads from Lakes Rerewhakaaitu and Okaro were not included because they are connected to

Tarawera via Lake Rotomahana. No attenuation of nutrient concentrations in transit between lakes was assumed.

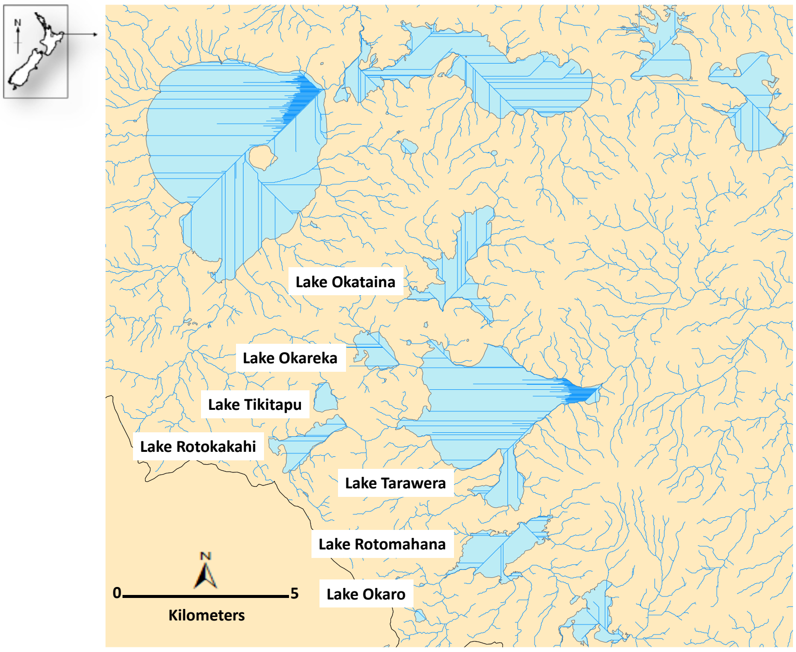

Figure 2 **Map of Lake Tarawera showing six smaller connected lakes.**

2.3.4 Wastewater

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

2.3.5 In-lake nutrient and chlorophyll concentrations

Trend analysis of monthly monitoring data for nitrogen, phosphorus and chlorophyll *a* was conducted for the period 1991 to 2015.

2.3.6 *E.coli* concentrations in the Lake Tarawera catchment

Since drinking water for Lake Tarawera residents is extracted mainly from the lake without any form of treatment (Simon Stewart and Brett Bosley, pers. comm. 2016), an assessment of drinking water quality was made with respect to the New Zealand drinking water guidelines (Table 1). *E. coli* concentrations of tap water samples collected from 1991 to 2015 were thus analysed to improve understanding on faecal contamination in drinking water sources in the catchment. Faecal coliforms in water samples were determined using the Membrane filtration (APHA, 2005) for *E. coli* . Counts were recorded as CFU/100 mL and compared to the New Zealand drinking water guidelines (Table 1). Based on an analysis of faecal bacteria in water, potential hotspots were identified by linking the locations of septic tank systems in the catchment with microbiological water quality data. With respect to recreational water quality, the existing condition of the lake was evaluated by determining the corresponding Ecosystem Health Attribute States (see Table 2) for each year in the period 2001-2014.

Table 1 **New Zealand Drinking Water Guidelines (MOH, 2005)**

Micro-organism	**Maximum acceptable value for regulatory purposes**
Escherichia coli	Less than one in 100 mL of sample

Table 2 **Lake Tarawera *E. coli* concentrations corresponding to Lake Ecosystem Health Attribute States designated in the National Policy Statement for Freshwater Management (New Zealand Government 2014).**

Attribute State	**Numeric Attribute State**	**Sampling Statistic**	**Narrative Attribute State**
A	≤260	Annual median	People are exposed to a very low risk of infection (less than 0.1% risk) from contact with water during activities with occasional immersion and some ingestion of water (such as wading and boating).
		95th percentile	People are exposed to a low risk of infection (up to 1% risk) when undertaking activities likely to involve full immersion.
B	>260 and ≤540	Annual median	People are exposed to a low risk of infection (less than 1% risk) from contact with water during activities with occasional immersion and some ingestion of water (such as wading and boating).
		95th percentile	People are exposed to a moderate risk of infection (less than 5% risk) when undertaking activities likely to involve full immersion. 540 / 100ml is the minimum acceptable state for activities likely to involve full immersion.
C	>540 and ≤1000	Annual median	People are exposed to a moderate risk of infection (less than 5% risk) from contact with water during activities with occasional immersion and some ingestion of water (such as wading and boating). People are exposed to a high risk of infection (greater than 5% risk) from contact with water during activities likely to involve immersion.
D	>1000	Annual median	People are exposed to a high risk of infection (greater than 5% risk) from contact with water during activities with occasional immersion and some ingestion of water (such as wading and boating).

2.4 Scenarios for simulating the possible effects of sewage reticulation at Lake Tarawera Catchment

A number of model simulation runs were undertaken to explore the possible effect of sewage reticulation in the Lake Tarawera catchment. The first scenario involved no wastewater reticulation in the Lake Tarawera catchment (no management action scenario) and the second involved wastewater reticulation (only sewage reticulation action scenario).

3.0 Results and Discussion

3.1 In-lake measurements (1990-2015)

A slight increase in TN and TP concentrations is evident between 1994 and 2008 (Scholes, 2010) (see Appendix 1 for the long term monitoring record for TN and TP for all depths in Lake Tarawera). Since 2009, however, there has been an abrupt decrease in TN and increase in TP. Further, variability of TN measurements appears markedly reduced. These changes occur simultaneously with a change in laboratory and analytical methods in late 2008/early 2009 (A. Spence, BOPRC, pers. comm.). Current analyses are performed in-house at BoPRC, in a lab accredited by IANZ (New Zealand's premier accreditation body), and quality control/quality assurance procedures are more robust than previous years. The BoPRC lab performs well in domestic and international inter-laboratory comparison tests, and this suggests a greater level of confidence can be placed in current analytical procedures and results (A. Spence and P. Baraclough, pers. comm.). These aspects suggest that nutrient results prior to 2009 may not be properly representative of actual concentrations and thus may not be suitable for analysis of long-term trends or for comparison with water quality targets. The TLI target for Tarawera is 2.6, and BoPRC (2012) has indicted that this was based on 1990s water quality. According to the available data, whole water column TN and TP concentrations for 1990–1999 were approximately 8.5 mg P m^{-3} and 110 mg N m^{-3}, equivalent to a TLp[2] of 2.96 and TLn[3] of 2.53, respectively.

Presented in Figure 3 is the monitoring record (2010-2015) for nutrients concentration of water samples collected at approximately 80 m and 0 to 17 m depths in Lake Tarawera. For 2010 – 2014 there were no statistically significant trends in concentrations of TN and TP (with increases occurring just prior to this period of analysis). However, there were statistically significant increases in dissolved reactive phosphorus in surface and bottom waters (3.2 and 9.4% 4yr^{-1}, respectively), and TN and TP in bottom waters (4.2 and 4.3% 4yr^{-1}, respectively) (Hamill and Scholes 2016). The high relative abundance of cyanobacteria observed in Tarawera, and occasional blooms (Reid, 1991; Frye & Abroad, 2008), is consistent with the low TN:TP ratio, despite relatively high water quality. Mean water column TN and TP concentrations are given in BoPRC (2012) as 112.3 mg N m^{-3} and 10.2 mg P m^{-3} (1999-2011 data). Mean surface concentrations for the period 2011 – 2014 were 92 mg N m^{-3} and 20 mg P m^{-3}. Therefore, in light of questions around analytical results prior to 2009 (summarised

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[2] The TLI numerical value for phosphorus

[3] The TLI numerical value for nitrogen

above) there is a need to reconsider nutrient values previously used for estimating catchment loadings into the lake (BoPRC, 2012). Monitoring data for Lake Tarawera post-2009 (after the change of lab) indicate that the period between 2012 and 2015 was characterized by considerably higher concentrations of dissolved inorganic nitrogen and phosphorus, particularly in bottom waters during warmer months

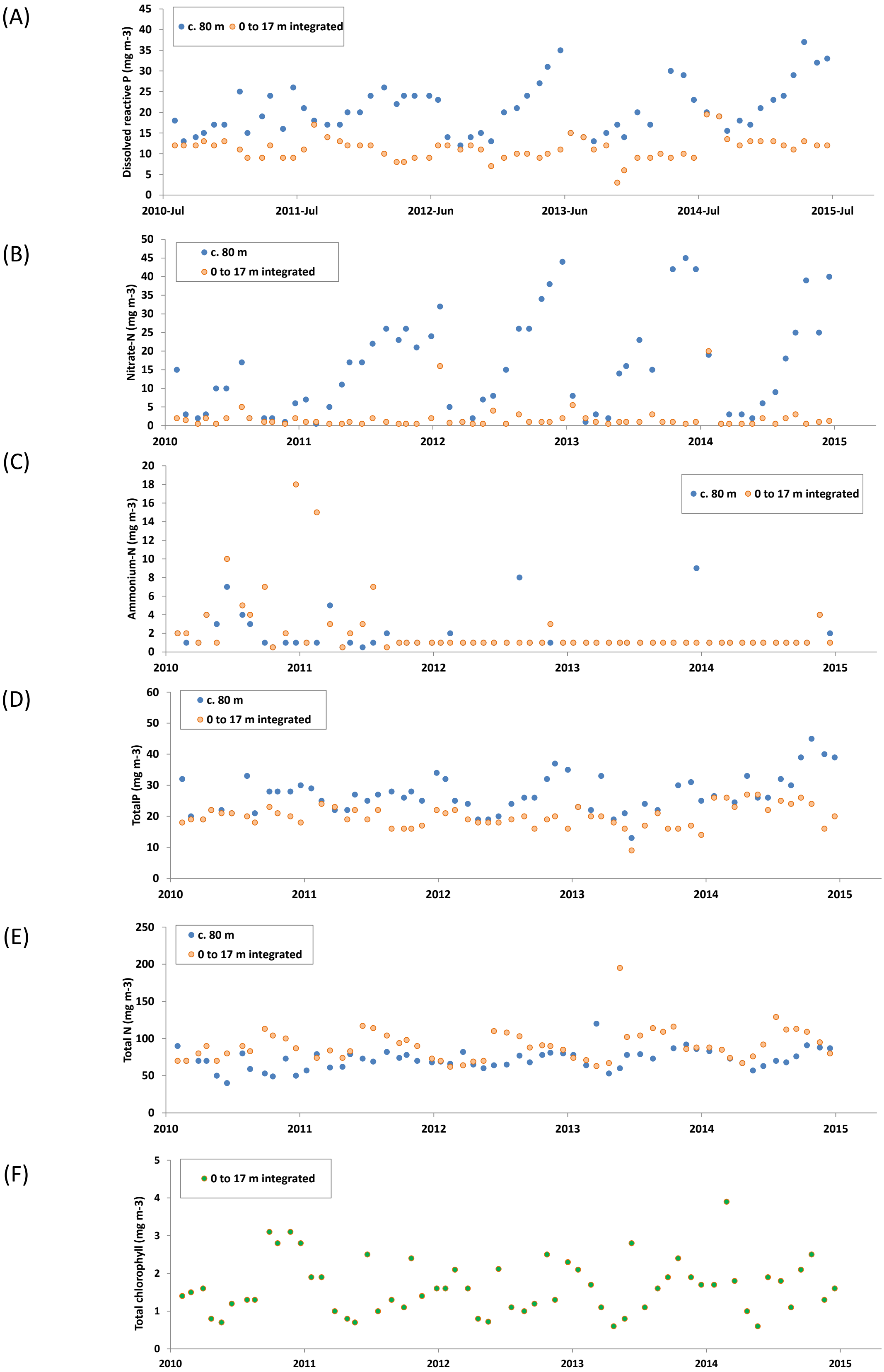

Figure 3 Post change of lab monitoring record (2010-2015) for A) dissolved reactive phosphorus and B) nitrate-nitrogen C) ammonium-nitrogen D) total phosphorus E) total nitrogen and F) total chlorophyll a in Lake Tarawera.

when the lake was stratified (Figure 3). Total nitrogen concentrations remained fairly stable between 2010 and 2015, whereas total phosphorus concentrations in 2014 to 2015 were somewhat higher than in previous years (Figure 3).

3.2 Estimation of Lake Tarawera catchment loads

3.2.1 Areal catchment load estimates

3.2.1.1 Immediate surface catchment.

The areal nutrient load estimate for the Lake Tarawera catchment from BoPRC (2012) is reproduced in Appendix 2. This estimate represented the interior (surface topographical) catchment only, did not account for geothermal inputs to the lake, and wastewater loads were based on an assumed occupancy of the equivalent of 291 full-time residents. A revised estimate of load for the surface topographical catchment is given in Table 3. Nutrient export coefficients were based on recent Overseer™ model output, and additional wastewater load was included to account for an estimated 184 household visitors, and 300 casual visitors per day (BoPRC, *pers. comm.*) Despite differences in areal nutrient loss coefficients for different land uses, the revised interior catchment load differs only slightly from the estimates of BoPRC (2012) for nitrogen, but is substantially higher for phosphorus due primarily to estimated geothermal inputs that were not accounted for in BoPRC (2012).

3.2.1.2 Geothermal sources of N and P

The areal nutrient budget of BoPRC (2012) (Appendix 2) makes no allowance for contributions of N and P from geothermal sources. Geothermal loads are difficult to quantify because flows may be subsurface, and geothermal waters are also contributed from Lake Rotomahana. A study by the Department of Chemistry at the University of Waikato in 2004 using sodium concentrations to infer the contribution of water sources concluded that 5 to 10% of the hydraulic load was from geothermal sources. Donovan & Donovan (Bioresearches, 2003) estimated a geothermal load to Tarawera of 12 t P y^{-1}, however, they only specifically identified four inflow sources with a combined estimated discharge of 0.4 m^3 s^{-1} with stated loads of 0.92 t P y^{-1} and 0.83 t N y^{-1} leaving a considerable margin of error. Monitoring of Tarawera inflows by Terry Beckett and UoW 2007 to 2014 (n = 17 samples) found average concentrations in Hot Water Beach geothermal inflow of 0.4 g P m^{-3} and 0.5 g N m^{-3}, i.e., very high concentrations of P in geothermal waters. Geothermal loads for N and P can be estimated by multiplying the observed concentrations with estimated flow (0.4 m^3 s^{-1}; or 6% hydraulic load), yielding an estimated 5 t P y^{-1} and 6.3 t N y^{-1}.

3.2.1.3 Additional loads from 'tributary' lakes.

A previous study by Hamilton et al. (2015) estimated an additional load to Lake Tarawera from Lakes Okareka, Okataina, Rerewhakaaitu, Okaro, Rotomahana, Tikitapu, and Rotokakahi of 33.5 t N y^{-1} and 4.4 t P y^{-1}. These loads were calculated by areal nutrient export rates to these lakes, with attenuation factors applied to account for net internal loss of nutrients from each lake. For the present study, estimates of mean surface and groundwater discharge to Lake Tarawera were obtained from the modelling study of White et al. (in prep), and were multiplied with mean measured total P and N concentrations for each lake to estimate the load to Lake Tarawera from each connected lake. Loads from Lakes Rerewhakaaitu and Okaro were not included because they are connected to Tarawera via Lake Rotomahana.

It seems plausible that Lake Tarawera is regionally unique in that the majority of its P load and a substantial portion of its N load appear to be derived from a combination of geothermal sources and 'tributary' lakes (Table 3, Figure 4). This may help explain the relatively high P concentrations and low TN: TP ratio in the lake.

Table 3 **Revised land use nutrient export rates and catchment loads for the greater topographical catchment of Tarawera, adapted by UoW, from BoPRC (2012), plus contributions from geothermal sources and discharge from "tributary lakes".**

Land use	Area	Area	N yield	N attenuation	N yield to lake	N load	N load	P yield	P attenuation	P yield to lake	P load	P load
(LCDB 4)	(ha)	(%)	kg N ha y^{-1}	(%)	(kg N ha y^{-1})	(kg N y^{-1})	(%)	(kg P ha y^{-1})	(%)	(kg P ha y^{-1})	(kg P y^{-1})	(%)
Broadleaved Indigenous Hardwoods	*1792.0*	12.5										
Indigenous Forest	*2989.5*	20.9										
Manuka and/or Kanuka	*1589.5*	11.1										
Sub Alpine Shrubland	*24.3*	0.2										
Tall Tussock Grassland	*190.6*	1.3										
Bush and Scrub	6586.1		3.67		3.67	**24171**	28.4	0.12		0.12	**790**	7.5
Deciduous Hardwoods	*4.2*	0.0										
Exotic Forest	*1249.2*	8.7										
Forest - Harvested	*266.7*	1.9										
Mixed Exotic Shrubland	*41.4*	0.3										
Forestry	1561.4		2.81		2.81	**4388**	5.2	0.18		0.18	**281**	2.7
Gorse and/or Broom	23.1	0.2	38.00	25	28.50	**658**	0.8	0.20		0.20	**5**	0.0
High producing Grassland	1803.5	12.6										
Low Producing Grassland	27.5	0.2										
Pastoral (Dry Stock)	1830.9		16.50	25	12.38	**22658**	26.7	2.05	50.00	1.03	**1877**	17.7
Built-up Area (settlement)	*98.8*	0.7										
Gravel or Rock	*69.9*	0.5										
Urban	168.7		3.00		3.00	**506**	0.6	0.70		0.70	**118**	1.1
Herbaceous Freshwater Vegetation	20.7	0.1	0.00		0.00	**0**	0.0	0.00		0.00	**0**	0.0
Lake Tarawera	4146.1	28.9	3.71		3.71	**15394**	18.1	0.17		0.17	**718**	6.8
Geothermal						**6300**	7.4				**5000**	47.2
Other Lakes												
Okareka						**972**	1.1				**48**	0.5
Rotokakahi						**2306**	2.7				**543**	5.1
Tikitapu						**204**	0.2				**6**	0.1
Rotomahana						**3429**	4.0				**787**	7.4
Okataina						**1149**	1.4				**133**	1.3
Wastewater (775 pp)						**2829**	3.3				**283**	2.7
Total	14337.0					**84963**	100				**10589**	100

3.3 'Manageable' sources of nutrients

To maintain or improve the water quality of Lake Tarawera it is necessary to consider the 'manageable' nutrient loads (essentially those that originate from farming activities and human sewage). These classifications influence the management and restoration initiatives that could be applied in the lake catchment.

3.3.1 Land use

Management options for a number of the nutrient sources are unlikely to yield immediate results, for example, land use change may take a number of years to have environmental effects after initiation. Managing nutrient loads from other lakes that reach Lake Tarawera will also be subjected to lags.

In the hypothetical scenario that the inner (surface topographic) catchment of Tarawera were converted to a pristine state (i.e. all native forest and scrub with no urban load), the load to Tarawera would be reduced by approximately 17.4 t N y^{-1} and 2.0 t P y^{-1} (approximately a 20% reduction of the present loads from the greater catchment, including other lakes and geothermal sources).

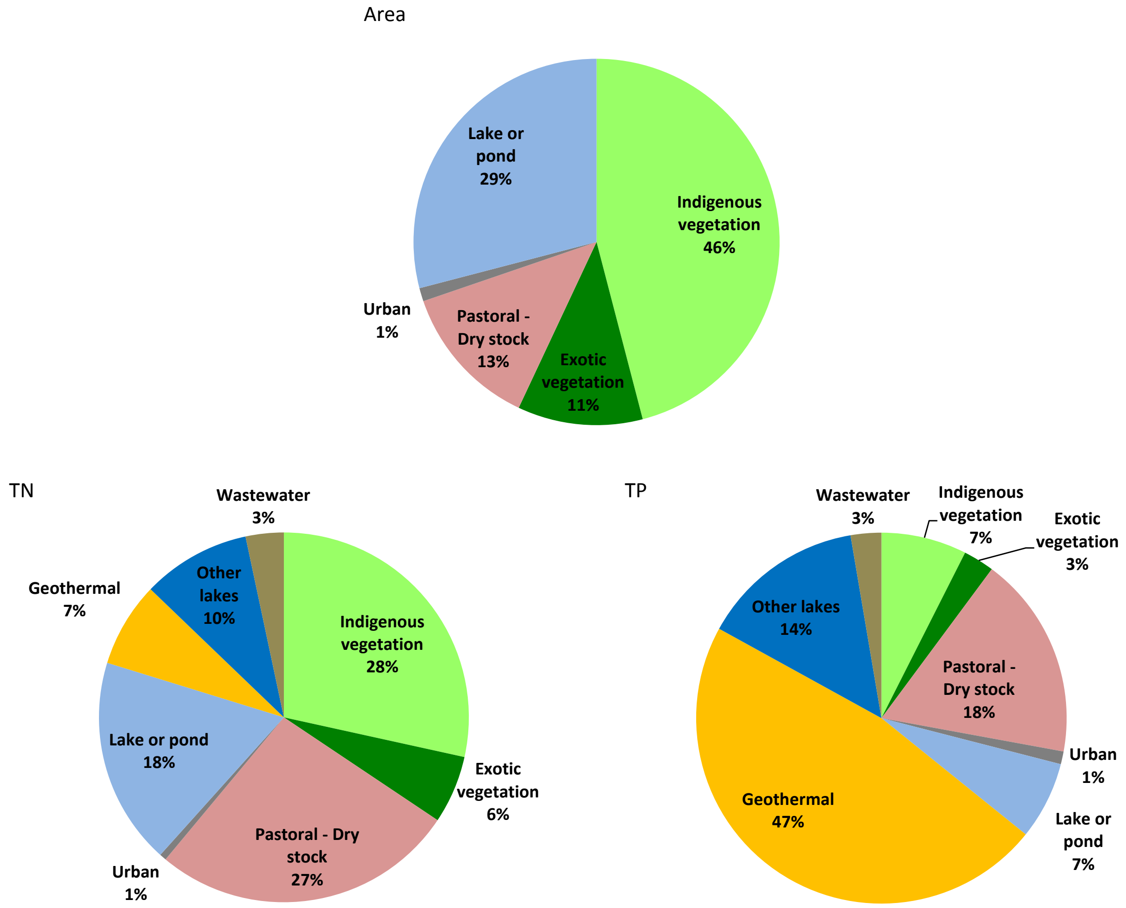

Figure 4 **Proportional contribution of different sources to total nitrogen, and total phosphorus load. Land use areas are shown for the inner catchment only, whereas the TN and TP loads presented include contributions from the five smaller (directly) connected lakes.**

3.3.2 Wastewater

From Table 3, loading from wastewater accounts for 2.9 t N y^{-1} and 0.29 t P y^{-1} (3.3% of the N load and 2.7% of the P load to Lake Tarawera, from all sources). This represents approximately 15% of the ‘manageable’ load from land use in the surface catchment only. However, reticulation of wastewater may be a desirable management action as the benefits in nutrient load reductions are likely to be immediate due to the proximity of the lake compared to other land management initiatives higher in the catchment.

3.3.3 Geothermal loads

Managing geothermal sources of nutrients that enter the lake directly may offer opportunity for more rapid gains but may be a complex and costly undertaking. Estimates of the contribution from geothermal sources and connected smaller lakes have high uncertainty due largely to difficulties in quantifying sub-surface flows. More accurate quantification of the volume of geothermal inflow could help to increase confidence in the overall nutrient budget for the lake.

3.3.4 Connected lakes

Lakes Okataina, Rotomahana and Tikitapu are at or near their TLI target (Table 4), and hence possibly provide little opportunity to reduce overall loads to Lake Tarawera. However, Lakes Rotokakahi and Okareka exceed their target TLI by 0.5 and 0.3 units respectively. Hence, management and restoration initiatives at these two lakes could realise additional benefits at Lake Tarawera.

3.4 Mass balance calculations

We evaluated the likely response of P and N nutrient concentrations in the lake given conditions of external loadings from the greater catchment, with or without sewage reticulation. In order to inform management efforts aimed at achieving a target concentration or trophic state, mass balance models can be used to estimate the catchment external load corresponding to the desired in-lake nutrient concentrations. In this study we take the reverse approach, using mass balance models to estimate the response of in-lake concentrations to changes in external load (namely, with and without sewage reticulation). Total lake outflow (and hence residence time and hydraulic load) was taken from estimates of surface and groundwater losses presented by White et al. (*in prep.*). Retention of phosphorus was estimated using the method of Vollenweider (1976) and retention of nitrogen was estimated after Harrison et al (2009), with retention coefficients of 0.73 and 0.72 for P and N, respectively (Table 5).

Modelled in-lake concentrations of both N and P were substantially lower than observed values 2010 – 2015. Differences to concentrations presented in Figure 3 may be due to either internal loading, underestimation of catchment nutrient loads (e.g., geothermal inputs or land use export) or uncertainty in estimates of nutrient or hydraulic retention. The N load to Tarawera could also be increased through N-fixation by cyanobacteria in the lake, which would produce higher concentrations in the lake.

Table 4 **Water quality in the smaller lakes connected to Lake Tarawera (Scholes and Hamill 2015).**

Lake	3-year trend	2015 TLI	Target
Okareka	Stable	3.3	3
Okaro	Improving	4.5	5
Okataina	Stable	2.9	2.6
Rerewhakaaitu	Improving	3.3	3.6
Rotokakahi	Unclear	4	3.1
Rotomahana	Unclear	4	3.9
Tikitapu	Stable	2.9	2.7
Tarawera	Declining	3.1	2.6

The 3-year trend is a the three yearly average observed from 1991-2011

Table 5 **Updated mass balance estimates of whole-catchment N and P loads**

	Units	Value	
Lake Area	m^2	41,460,000	
Lake Volume	m^3	2,273,700,000	
Outflow	$m^3 s^{-1}$	10.26	
Residence time	y	7.0	
Hydraulic load	$m\ y^{-1}$	7.8	
		TP	**TN**
Observed concentration	$mg\ m^{-3}$		
Loads			
Total load-to-lake	$t\ y^{-1}$	10.6	85.0
Wastewater	$t\ y^{-1}$	0.28	2.8
Total load-to-lake	$mg\ m^{-2}\ y^{-1}$	255.40	2049.3
Wastewater	$mg\ m^{-2}\ y^{-1}$	6.83	68.3
$\mathbf{R}_{pred}$			
Predicted concentration			
Baseline	$mg\ m^{-3}$	9.0	73.7
With reticulation	$mg\ m^{-3}$	8.7	71.2

3.5 *E.coli* trends (1991-2016)

This study analysed *E. coli* concentrations in water samples taken directly from the lake (Figure 5) as part of the BoPRC recreational water monitoring program for the period 2002-2014. Historical *E. coli* concentrations of Lake Tarawera water samples measured by BoPRC show moderate to high temporal variability with improving bacteriological quality observed in the more recent years, 2009-2014 (Figure 5). With specific reference to the National Policy Statement for Freshwater Management 2014, the *E. coli* Attribute State was A for nine out of the twelve years in the considered period (2003-2014). Attribute State A corresponds to a very low risk of infection (less than 0.1% risk) from contact with water during activities with occasional or full immersion (Table 6). Only in three years did *E.coli* concentrations correspond to either Attribute States B or C during a single year. During these three years, standard deviation was much greater than the mean, indicating the likely effect of a few outliers. These data indicate that Lake Tarawera is of satisfactory quality for recreational purposes.

However, given that drinking water for most Lake Tarawera residents is extracted from the lake without any form of treatment, this study also assessed Lake Tarawera water quality with respect to the New Zealand drinking water guidelines. This study thus examined *E.coli* concentrations from drinking water samples collected from tap water extracted from the lake without any form of treatment. Additionally, potential faecal contamination hotspots were identified by linking the locations of septic tank systems in the catchment with potential influence on microbiological quality of drinking water samples. Presented in Figure 6 is the percentage of water tests that met the 2005 Drinking-Water Standards for New Zealand 2005 (MOH, 2005). These results are based on an analysis of the faecal coliform counts in 168 drinking water samples collected at randomly selected locations in the catchment between the period 1991-2006. Locations with less than two samples collected over the 15 year period, specifically locations coded ‘262’ and ‘198’, were excluded from the analysis. On a regulatory basis, both the WHO Guidelines for Drinking Water Quality (1997) and the New Zealand drinking water guidelines stipulate that every 100 mL of tested sample must have faecal coliform counts less than one. With specific reference to the stipulated maximum acceptable value (MAV), non-compliance was prevalent at most of the sampling locations considered in this analysis, as well as among samples collected around the two of the three sampled toilets (Figure 6).

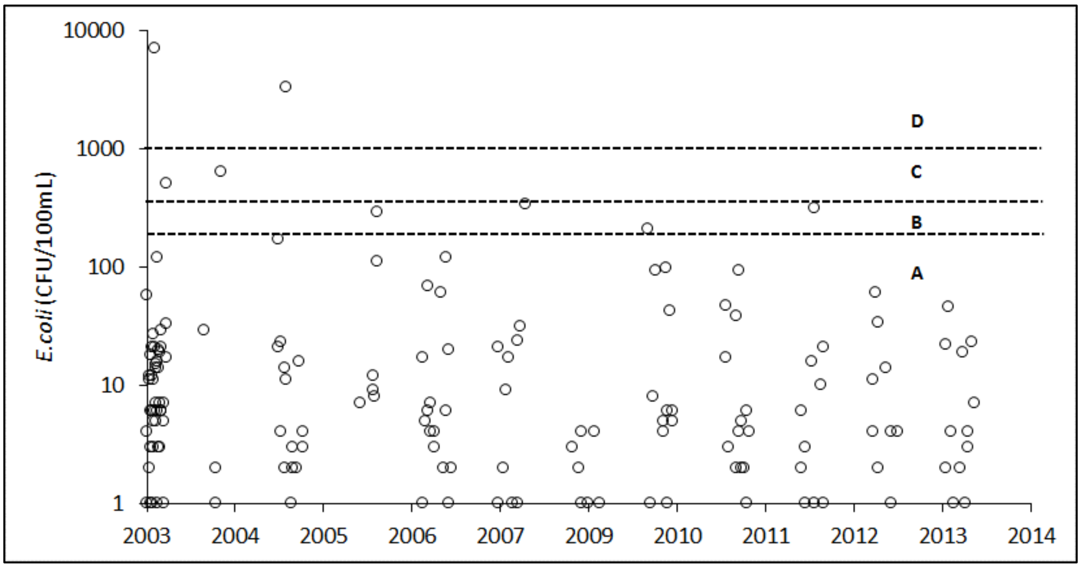

Figure 5 **Monthly measurements of *E. coli* concentration at Lake Tarawera collected by BoPRC. Dashed lines denote values that correspond to Attribute States defined in the National Policy Statement for Freshwater Management 2014.**

Table 6 **Lake Tarawera *E. coli* concentrations measured by BoPRC and associated Attribute States, as defined in the National Policy Statement for Freshwater Management 2014.**

Year	Annual Median (CFU/100mL)	95th Percentile (CFU/100mL)	Attribute State
2003	3	108	A
2004	8	211	A
2005	11	341	B
2006	18	631	C
2007	6	291	B
2008	6	93	A
2009	0.5	11	A
2010	0.75	33	A
2011	0.5	97	A
2012	0.75	11	A
2013	0.75	46	A
2014	0.5	21	A

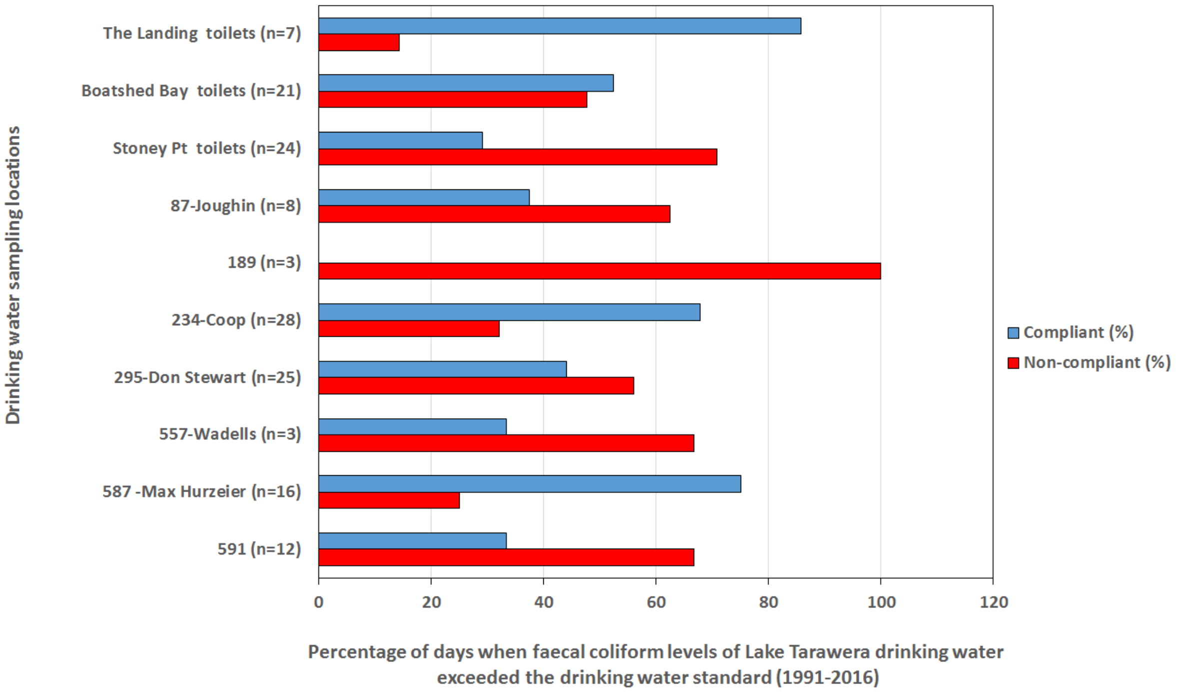

Figure 6 **Microbiological compliance and non-compliance levels of drinking water at Lake Tarawera (1991-2016).**

Only at three out of the 11 sampled locations were the proportions of compliances higher than non-compliances. More than half of the tap water samples collected from the toilet water source at Stoney Point were found to be non-compliant as the samples had higher faecal coliform counts than the maximum acceptable value. Similarly, almost 50% of tap water samples collected from the Boatshed Bay toilet were observed to be non-compliant (Table 7, Figure 7). Lakeside houses draw water from the same sources as the toilets considered in this study (e.g. Boatshed Bay). Property density seem to influence observed tap water quality. Water samples collected from The Landing toilets, situated at a location with comparatively lower number of lakeside properties presented with lower proportions of non-compliances to the New Zealand drinking water standard, compared to other toilets in locations with higher densities of lakeside properties. The total number of samples collected for faecal coliform testing at any given year was below the minimum number of samples for which a maximum permissible number of exceedances of a 95 percentile limit could be calculated (Mcbride & Ellis, 2001; McBride, 2005)(Table A1.4 in MOH (2005) requires that at least 95% of yearly scheduled samples in each supply system contain no *E. coli*).

Table 7 Summary of *E. coli* concentrations (CFU/100mL) of drinking water at Lake Tarawera catchment

Sampling location	n	Median	95% Percentile	Mean	Std. Deviation
591	12	1	10	1.667	2.741
587 (Max Hurzeier)	16	0	3	0.4375	0.8921
557 (Wadells)	3	6	7	4.333	3.786
295(Don Stewart)	25	0	7.9	1.12	2.088
234 (Coop)	28	0	5.85	0.6786	1.744
189	3	2	80	27.67	45.32
89	1	6	6	6	0
87(Joughin)	8	1	14	2.5	4.751
Stoney Pt toilets	24	1	38	4.292	9.657
Boatshed Bay toilets	21	0	40.1	3.762	9.648
The Landing toilets	7	0	7	1	2.646
N Donald	1	3	3	3	0

Figure 7 Boatshed Bay, Lake Tarawera. Tap water samples were collected from Boatshed Bay toilet which draws water from the same sources that supply water for domestic use at nearby houses (Google Map View).

The counts of faecal coliform recorded from water samples collected from selected locations within the catchment, indicate some faecal contamination of drinking water source or distribution system. A number of precautionary measures to protect public health have previously been put in place at high risk sites at the catchment, particularly the tap waters at the public toilets including the erection of signs advising people not to drink the water from the taps in the public toilets at The Landing, Boatshed Bay and Stoney Point. However, given that non-compliance was prevalent at most of the sampling locations considered in this analysis, authorities may need to look into all available options to ensure that risks to public safety are minimised. A number of successive stages of responses already exist in available literature, including intensive sampling and pollution source investigations (MOH, 2000). It seems logical that authorities may begin to channel investigative efforts towards curbing potential sources of faecal contamination within the catchment, and failed septic tanks could be one of such. This could include the commissioning of a microbial source tracking study that uses appropriate genetic markers to discriminate among the possible sources of faecal pollution in tap water available for domestic use at the Lake Tarawera catchment e.g. as was adopted in the Leonard & Gilpin (2006) study. Although no concrete evidence exists that link failed septic tanks to polluted ground water sources at the Lake Tarawera catchment, faecal coliform counts from drinking water samples collected from the lakeside houses, as well as the lakeside toilets generally presented with higher faecal counts than the maximum acceptable value. Juxtaposed with the fact that these houses draw water from the same source as the toilets considered in this study, there could be indications of undetected treatment failures in septic tanks at the lakeside properties.

Soil properties, water table location, subsurface geology and climate affect the efficiency of treatment by septic systems. Poorly functioning leach fields, faulty septic systems and overloaded systems can result in high infiltration rates, resulting in pollution of groundwater (Kumar, 2016) or in some circumstances can result in direct discharge to surface waters. Although the Australian/New Zealand Standard AS/NZS 1547:2000 defines failure of a septic tank system as an unsatisfactory performance of the system or an undesirable and unfavourable impact on the environment (Standards Australia and Standards New Zealand, AS/NZS 2000), Jayarathne et al. (2013) argued that this definition may not be particularly helpful since deciding whether or not failure has occurred tends to be based more on people's perceptions or visibly observed effects rather than on quantitative criteria. In addition, householders often knew very little about septic tank processes and their management. Given this subjectivity and knowledge gap, septic treatment failures could go undetected, particularly when the inadequately treated wastewater does not rise to the soil surface but instead merges with ground waters or the nearby lake. From a public health perspective, these considerations are important because drinking water in the catchment is sourced individually, mostly from Lake Tarawera and there is usually no treatment in place apart from a few residents who can afford point of use treatment systems.

Apart from nutrients (nitrogen and phosphorus) considered in the modelling aspects of this study, such improperly treated domestic sewage from lakeside properties may contain pathogens including bacteria, viruses, protozoa and helminths (intestinal worms and worm-like parasites) (Marin et al., 2015; Yaya-Beas et al., 2016). Bacteria, viruses and protozoans in sewage discharged without any form of treatment from lakeside properties into the lake can cause a wide variety of water-borne illnesses including diarrhoea, cholera, dysentery, typhoid, giardiasis, campylobacteriosis and cholera. In a survey of 48 septic tank systems (STS) in Australia, Ahmed et al (2005) used two pathogen strains as indicators and found a direct link between STS failure and surface water contamination. As was done in this study, traditional risk assessment often relies on the use of a faecal indicator bacteria (e.g. *E. coli*) as a proxy to infer the presence of these pathogens in water

(BoPRC, 2014). However, their suitability as a measure of recreational water risks has often been challenged due to the lack of correlation with pathogens and evidence of possible regrowth in the natural environment (Liang et al. 2015). Given these limitations, from a public health point of view, it is preferable to direct discharge to a sewage treatment plant where it passes through a combination of physical, biological, and chemical processes that remove some or most of the pollutants (Yaya-Beas et al., 2016). In a recent study on Lake Rotorua where sewage reticulation system is in place, Abell et al. (2015) reported data of bacteria concentrations measured following treatment at a centralised waste water treatment plant and found the concentrations to be very low, with a median count of zero colony forming units per 100 mL of treated effluent samples tested (Table 8).

Table 8 **Summary of *E. coli* concentrations of sewage following treatment at Lake Rotorua WWTP**

	Lake Rotorua
Statistic	**Treated sewage**
n	277
95th Percentile	6.2
Median	0
Mean	5.6
Std. Deviation	61

n= Number of values

4.0 Limitations of the study

There are important considerations for this study. In the period following the change in laboratory analysis, Lake Tarawera had an unusually low TN: TP ratio (<5:1) inferring that it might be an outlier in terms of nutrient retention dynamics (possibly increasing uncertainty in the mass balance analysis). Also, there is no method for estimating retention of nitrogen, which is subject to greater uncertainty than for P, due to processes including denitrification and N-fixation. Nutrient monitoring data seem to show evidence of internal loading (see DRP and NO_3 plots) as in-lake concentrations estimated by mass balance modelling of both N and P were c. 20% lower than observed values (2010-2015).

A few considerations come to fore when making deductions from the *E.coli* analysis. The 2005 Drinking-Water Standards for New Zealand specifies that compliance monitoring for *E. coli* must be conducted at least three monthly with a maximum interval between successive samples of 135 days. The number of samples and the intervals of sample collection herein analysed may thus be insufficient for conclusive deductions. There is the need for more frequent testing, in line with the provisions of the NZ Drinking Water Standards, as a normal response by relevant authorities and councils when consistent observations of drinking water non-compliance in a catchment/distribution zone are made.

In addition, the maximum acceptable values used as a bench mark for determining compliance and non-compliance are mainly for regulatory purposes and do not represent a dose/response relationship that can be used as the basis for determining acceptable concentrations of pathogens in drinking-water. Also, only *E.coli* data from point-of-use drinking systems (taps) were analysed. No specific data were available for *E.coli* concentrations from reservoirs within households which serve as temporary storage units for the water extracted from Lake Tarawera for domestic use. These considerations add to the uncertainties in these findings. These issues notwithstanding, it is quite clear that the majority of drinking water samples analysed during the 15 year period at Lake

Tarawera catchment were non-compliant, warranting the need for efforts aimed at reducing potential sources of faecal contamination within the catchment, including considerations for sewage reticulation in place of failed septic tanks. This could include the commissioning of a microbial source tracking study that uses appropriate genetic markers to discriminate among the possible sources of faecal pollution in tap water available for domestic use within the Lake Tarawera catchment. In the context of Lake Tarawera, these efforts for instance, could include a demonstration of the presence of human markers and an absence or very low concentration of ruminant/other warm blooded animal marker in non-compliant drinking water samples. These efforts could be put in place before and after envisioned sewage management schemes to initially, confirm the problem of human faecal contamination from faulty septic tanks and ultimately, to confirm that the sewage management efforts put in place are effective. This report has however, not made recommendations on the costs or value for money that sewage reticulation would entail. These considerations will be essential to complement our environmental investigation and underpin considerations of a reticulated sewage system for Lake Tarawera.

5.0 Conclusions

Limitations of study methodologies notwithstanding, the catchment nutrient budgets and Vollenweider modelling provide a useful context for management initiatives, including sewage reticulation. Wastewater represents a small component (<5%) of overall N and P loads to Tarawera. Nevertheless, much of the load to the lake is from sources that are difficult to mitigate (e.g. geothermal, other lakes). Therefore, wastewater reticulation could make a contribution to improving manageable sources of nutrients from the lake catchment, and may additionally mitigate public health risk associated with poorly performing on-site treatment systems.

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Personal Communications

Simon Stewart 2016. PhD Research Student, Environmental Research Institute, University of Waikato. Provided information on drinking water source at Lake Tarawera, 26 July 2016.

Brett Bosley 2016. Experienced plumber, individual water abstractions and installations on Lake Tarawera. Provided information on prevalent drinking water sources at Lake Tarawera, 26 July 2016.

Appendix 1 Long-term monitoring record for nutrients in Lake Tarawera.

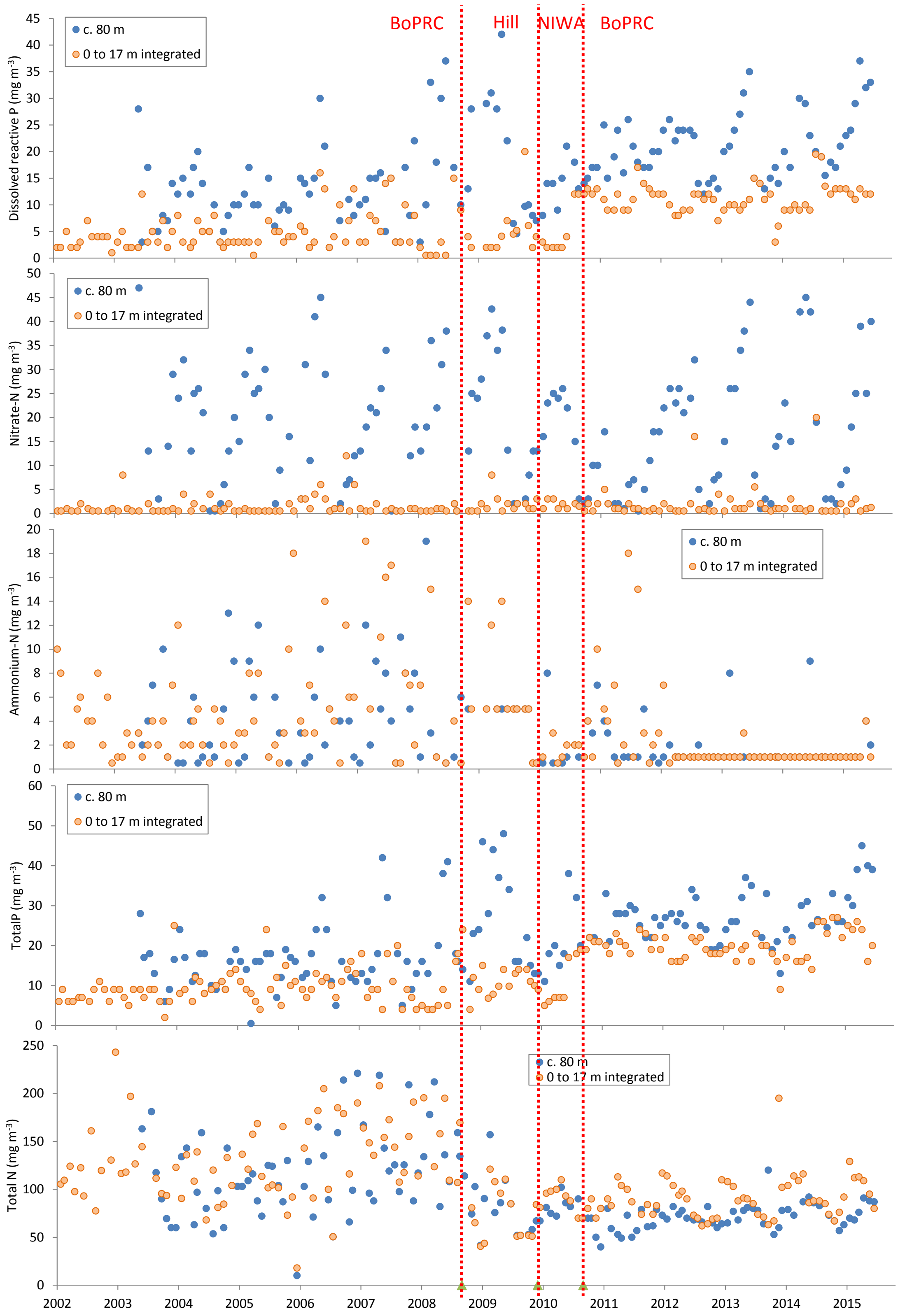

Figure 8 Long-term monitoring record for dissolved reactive phosphorus, nitrate, ammonium, total phosphorus and total nitrogen in Lake Tarawera. Dashed lines show the date of changes between laboritories used for sample analysis.

Appendix 2 Previous nutrient budget for the immediate surface topographical catchment of Lake Tarawera

Table 9 **Nutrient budget for the catchment of Lake Tarawera omitting the catchments of other lakes of the complete drainage basin) based on land-use nutrient loss estimates**

	Area	Rate of P loss	Rate of N loss	P Load	N Load
Bare ground	279.5	0.5	3	140	839
Exotic forest	1524.4	0.4	4	610	6098
Indigenous forest	6421.0	0.28	3	1798	19263
Mixed scrub/pasture	136.6	0.5	5	68	683
Beef	81.1	1	15	81	1217
Horse/lifestyle grazing	21.1	0.8	8	17	169
Recreation/other grass	50.0	0.3	4	15	200
Urban built (storm water)	93.5	0.8	8	75	748
Septic tanks (3.65 kgN/p/yr, 0.37 kgP/p/yr)	1512 people			552	5519
Rainfall on lake	4138.8	0.15	4	621	16555
Total	15704.5			5562	67710

Appendix 3 Previous whole-catchment mass balance estimates

BoPRC (2012) used a mass balance approach to estimate catchment nutrient loads of nitrogen and phosphorus to Lake Tarawera (Table 1). Total catchment loads were estimated from in-lake nutrient concentrations (median annual average from 1999 to 2011; Scholes 2011), average hydraulic loading, and assumed attenuation coefficients for N and P.

Table 10 Mass balance estimates of whole-catchment N and P loads, reproduced from BoPRC (2012)

	TP	**TN**		**C**
Lake Concentration	10.59	112.32		
	Land	Lake	Total	
Lake volume (m^3)		2273700000		
Area (ha)	10833	4138.8		
Flow (l/sec)	10.7			
Flow/yr (m^3)			337435200	**Q**
Hydraulic loading (Q/lake area A)(m/yr)			8.2	**Q/A**
Retention R (15/18+Q/A))			0.57	**R**
M=CQ/(1-R) kg/yr				**M**

where

M = estimated total load to lake

C = lake concentration: TN of 112.32 mg m^{-3} is considerably higher, and TP of 10.59 mg m^{-3} is considerably lower, than monitoring data post-2009 (TN ≈ 91 mg m^{-3} and TP ≈ 20 mg m^{-3}).

Q = Hydraulic load: The value used for hydraulic discharge in Table 3 is 10.7 m^3 s^{-1}. This comprises the measured outflow long-term average of 6.7 m^3 s^{-1}, with an additional 4 m^3 s^{-1} added to account for groundwater outflow.

R = Retention coefficient: BoPRC (2012) uses the method of Nurnberg (1984) to estimate the retention coefficient (R_{pred}) for TP of 0.57, and assumes equal retention for TN. Verburg (2013, unpubl.) notes that Nurnberg's equation had not been widely accepted or applied globally, and performs poorly for the Rotorua lakes particularly for TN. Furthermore, the value of 0.57 was derived using Q = 10.7 m^3 s^{-1} (see above).