Nutrient and water budget for Lake Tarawera

CBER Contract Report 46

Report prepared for the Lake Tarawera Ratepayers Association

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1. Executive summary

A nutrient budget has been constructed for Lake Tarawera using two techniques. One technique involved analysis of incoming stream discharges and concentrations of nutrient species (total nitrogen (TN), ammonium, nitrate, total phosphorus (TP) and phosphate) based on measurements taken at weekly to fortnightly intervals in the summer of 2005/06. The second technique involved an analysis based on the predominant land use together assigned coefficients for areal rates of nutrient export. Both techniques produced very similar nutrient load estimates of approximately 12-13 tonnes TP per year and 95-100 tonnes TN per year. On the basis of comparisons of incoming nutrient loads, discharge and nutrient concentrations in the Tarawera River outflow, and total lake volume, it is estimated that incoming water will reside in the lake for an average duration of 10 years, and that 86 % of TP and 72 % of TN will be trapped within the lake; either buried in the lake sediments or lost as nitrogen gas in the process of denitrification. A water budget constructed from stream discharges, rainfall and evaporation revealed that nearly 80 % of the water entering the lake (not including rainfall) was from sources that were not gauged as part of the summer (2005/06) stream survey; groundwater appears to be the dominant source of water for Lake Tarawera.

Nutrient analysis of stream inflows showed that geothermal inputs arising in the southern basin of the lake were comparatively enriched in ammonium, phosphate, TN and TP. Geothermal inflows accounted for less than 4 % of the total water volume entering the lake (not including rainfall) and were therefore not a major contributor to total budgets for TN and TP. By contrast, rainfall accounts for approximately 17 % of TN, but less than 5 % of TP inputs to Lake Tarawera.

The longevity of water retention in the lake, high nutrient retention rates and dominance of groundwater inflows indicate that Lake Tarawera will respond only very slowly to land use changes in its catchment. The immediate catchment area, from which water enters the lake directly via surface or sub-surface flows, is approximately 143 km^2, but water is also contributed by an additional land area of 335 km^2 which falls within six other lake catchments. These lakes play an important protective role for Lake Tarawera as they retain within their lakebed most of the nutrients derived from their catchments, with only 33 % of incoming nutrients considered to enter Lake Tarawera from the catchment of lakes Okataina, Okareka, Tikitapu, Rotokakahi and Rotomahana, 11 % for Lake Okaro and < 3 % for Lake Rerewhakaaitu. Benefits to Lake Tarawera from reductions in nutrient loading will therefore have the most marked impact within the immediate lake catchment (i.e. 143 km^2) but any reductions in nutrient loss from the outlying six lake catchments will contribute not only to improved water quality of the adjacent lake, but ultimately also to Lake Tarawera.

Trophic Level Index (TLI) targets set for Lake Tarawera by Environment Bay of Plenty were evaluated in the context of reductions in nutrient loads that would be required to meet the target. Reticulation of sewage for households in the immediate lake catchment would be unlikely to achieve the required level of nutrient reduction. On the other hand management actions for restoration of the outlying lake catchments will have a flow-on benefit in reducing nutrient loads to Lake Tarawera, and should be built into future nutrient budget projections for the lake; a sustained sound management approach for nutrient retention on land and for progressive reticulation of household sewage in the whole catchment will need to be maintained.

2. Introduction

The purpose of this study was to identify major nutrient inputs into Lake Tarawera arising from stream inflows. By creating a nutrient budget for the lake these inputs can then be managed appropriately based on increased knowledge of the hydrology and nutrient loads to the system. This information can also provide the basis of future modelling studies and to support analyses of long-term monitoring programmes being carried out on the lake and its inflows.

Water quality of Lake Tarawera is generally considered to be stable and is high relative to most other Rotorua lakes (e.g. Lake Rotoiti, Lake Rotoehu), which have shown marked trends of deterioration (Scholes and Bloxham, 2005). However, analyses of rates of oxygen depletion in bottom waters ('hypolimnetic oxygen deficit') have shown a slight increasing trend since the early 1990s (Scholes and Bloxham, 2005) and there are indications of higher chlorophyll *a* (phytoplankton) concentrations, increased total nitrogen and phosphorus concentrations and a reduction in Secchi disk depth. Changes in these indicators suggest a slight trend of declining water quality.

The quality of inflowing water is determined by the geological formations, soil type, land use, slope, runoff, rainfall and groundwater contributions arising from the catchment that supplies water. The catchment area of Lake Tarawera is around 0.7% urban, 21.1% pasture, 60.1% indigenous forest/scrub and 15.4% exotic forest (Scholes, 2005). Amongst the inflows, geothermal springs enter the lake in the southern region of the lake. Five other inflows arise from lakes completely within the catchment of Tarawera. Lake Rotokakahi and Lake Okareka have inflows to Lake Tarawera via their outflows; the Te Wairoa and Waitangi Streams respectively. The catchment of Lake Okaro and a part of the catchment of Lake Rerewhakaaitu are within the Tarawera catchment, while lakes Tikitapu, Okataina and Rotomahana are connected to Tarawera through sub-surface inflows. Table 1 provides statistics on morphometry, sub-catchment areas and land use for Lake Tarawera.

There have been few studies of nutrient inputs to Lake Tarawera. White and Cooper (1991) outlined a need to better quantify geothermal inflows, which are mostly subterranean or enter as springs in close proximity to the lake. BioResearches (2003) provide an estimate of nutrient inputs from geothermal inflows to Lake Tarawera in the context of a broader geothermal study relating to nutrient inputs to twelve Rotorua lakes. Two main geothermal sources were identified in the southern arm of the lake. These two inflows were estimated collectively to contribute 0.2 L s^{-1} of water in association with 0.92 tonnes yr^{-1} of total phosphorus and 0.83 tonnes yr^{-1} of total nitrogen. A study conducted by the Department of Chemistry at the University of Waikato in 2004, which included use of sodium ion concentrations to determine sources of water to the lake, indicated that geothermal inflows contribute between 5 and 10 % of total inflows to the lake and that the dominant source of water to the lake is sub-surface (i.e. groundwater). McIntosh (2004) carried out a nutrient budget of Lake Tarawera for the purpose of evaluating capacity for additional settlements in the immediate lake catchment. This study was used to evaluate whether Rule 11 of the Regional Council Land and Water Plan would be activated in response to additional persons residing in the catchment. McIntosh (2004) estimated that around 1,800 people could be settled in the catchment before Rule 11 was activated.

This study comprised of a monitoring programme undertaken over the summer of 2005/06. Sampling of inflows was carried out on 6 December 2005 and 13, 20 and 31 January 2006, and 7 and 15 February 2006. Measurements were made, where possible, of all inflow discharges around the lake, as well as their nutrient concentrations.

The study serves several objectives:

- To examine and quantify discharge and nutrient loads in the main surface inflows to Lake Tarawera based on in-stream measurements;
- To carry out a water balance to understand the relative contributions of geothermal, coldwater, groundwater and rainfall inputs to the lake;
- To compare results of a nutrient budget based on areal coefficients assigned to different land uses in the lake catchment, with a nutrient budget derived from the in-stream measurements.

- To consider what changes in nutrient loads would be required to conform to the Trophic Level Index prescribed for Lake Tarawera in the Regional Lake and Water Plan.

Table 1. Morphometry, sub-catchment areas and land use for Lake Tarawera (from Environment Bay of Plenty records).

Maximum water depth (m)	*87.5*	
Lake area (km^2)	*41.39*	
Immediate catchment area (not including the lake) (km^2)	*101.73*	
Land use	*Area (%)*	
Urban	*0.96*	
Pasture	*17.96*	
Native forest/scrub	*62.53*	
Exotic forest	*15.74*	
Bare ground	*2.81*	
Other lakes in catchment	*Lake area (km^2)*	*Catchment area (km^2)*
Okareka	*3.34*	*19.58*
Rotokakahi	*4.33*	*19.71*
Tikitapu	*1.44*	*6.22*
Okataina	*11.73*	*59.82*
Okaro	*0.30*	*3.89*
Rotomahana	*9.02*	*83.25*
Rerewhakaaitu	*5.17†*	*36.96†*

† Note that only part of the catchment of Lake Rerewhakaaitu contributes water to Lake Tarawera. See Section 4.3 for details.

3. Methods

3.1 *Monitoring sites.*

Monitoring sites were set up for 20 inflows in close proximity to where they enter the lake. On the basis of their discharge, these inflows were deemed to be the most important ones. Figure 1 shows the locations of the monitoring sites.

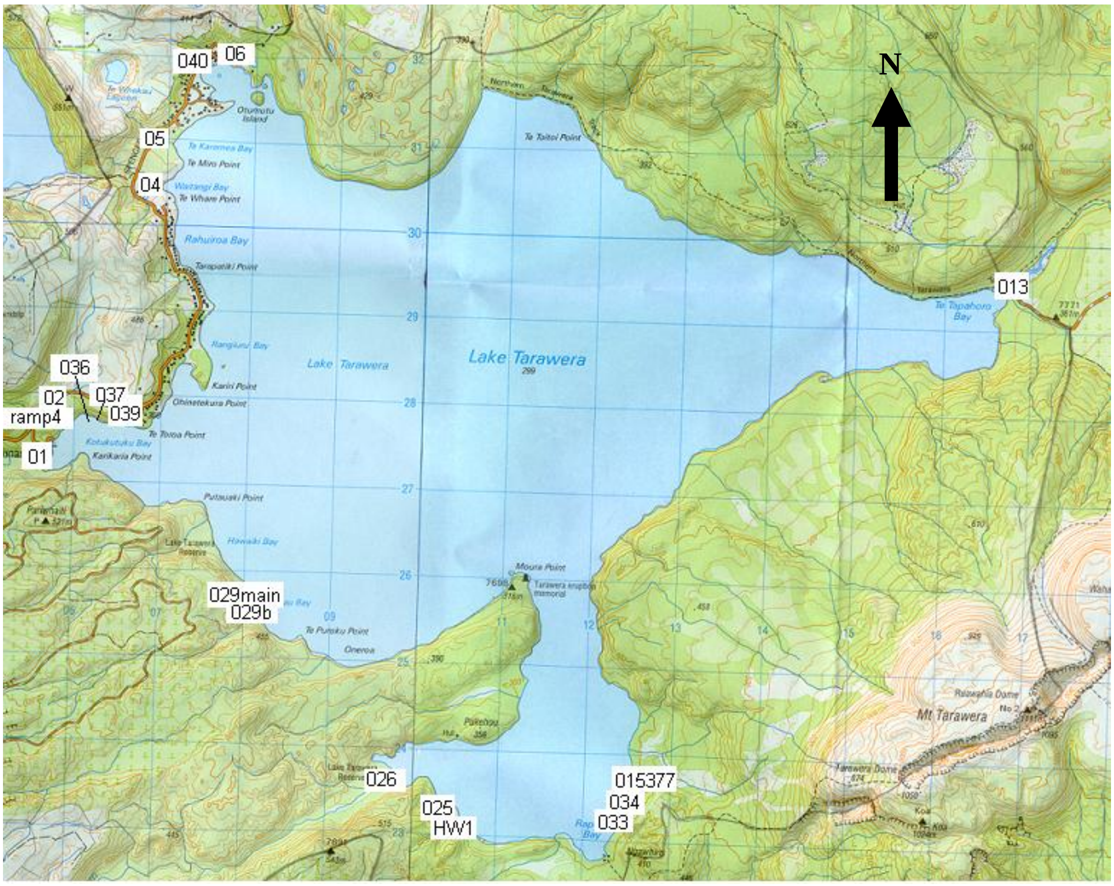

Figure 1. 2005/2006. Monitoring sites around Lake Tarawera denoted by numbers or letters on white background. Refer to Table 1 for numbers and names of stations.

The sites were monitored for flow, as well as for total and dissolved nitrogen and phosphorus species using water samples collected at each site. Sites 025 and HW1 were unable to be flow-gauged because temperatures were very high in these geothermally-derived inputs, and water quantity was low. These flows were estimated to be less than 1 L s^{-1}. Sites 033, 036, 037 and 039 were also unable to be gauged because there were not suitable gauging sites. These sites were waterfalls or steep rockslides that were too difficult to access, but their contribution was also considered small. Stage height-volume curves were established from historical data, while flow for site 015377 was derived from correlations with site 34. Table 1 lists site names and locations of the sites monitored.

Table 2. Monitoring sites used in the study (refer to Fig. 1 for general locations).

Name	Site Number	NZ Grid Reference
Te Wairoa Stream	01	U16:05742738
Orchard Stream	02	U16:05842756
Waitangi Stream	04	U16:06923046
	05	U16:071309
	06	U16:07423173
Tarawera River (Outlet)	013	V16:16742956
Tarawera Peak Stream	015377 (spring)	V16:12512408
	034 (Waterfall)	
	033 (rockslide)	V16:12492353
Hot Water Beach Spring	HW1	
Geothermal Spring	025	
Wairua Stream	026	U16:09842352
Te Puroku No.2 (of ‘Twin Creeks’)	029main	U16:08072549
Te Puroku No.1 (of ‘Twin Creeks’)	029b	
Te Wairoa Wharf Spring	ramp 4(wharf)	U16:0584 2756
	036	U16:0609 2777
	037	U16:0611 2777
	038	U16:0624 2770
	039	U16:0648 2764
Te Whekau Stream	040	U16:0739 3170

3.2 *Nutrient Analyses*

Two samples for nutrient analysis were taken in clean polyethylene sample tubes from mid-depth in the middle of the stream (Figure 2). One sample was filtered through a GF/C filter (nominal pore size 1 μm) and placed on ice for subsequent analysis of filterable nutrients, while the other sample was placed directly on ice, for subsequent analysis of total nutrients. Both sets of samples were frozen at -20°C upon return to the laboratory.

Figure 2. The second author collecting water samples for nutrient analysis in the Waitangi Stream.

Filterable nutrients were analysed on a Lachat QuickChem® Flow Injection Analyser (FIA+ 8000 Series, Zellweger Analytics, Inc.). Ammonium (NH_4) was analysed using Lachat QuickChem® Method 10-107-06-2-C. Soluble reactive phosphorus (PO_4) was analysed using Lachat QuickChem® Method 10-115-01-1-A. Oxidised nitrogen species (NO_3 and NO_2; NO_X) and nitrite (NO_2) were analysed separately using Lachat QuickChem® Method 10-107-04-1-A, where nitrate is quantitatively reduced to nitrite by passage of the sample through a copperised cadmium column. Nitrate (NO_3) was subsequently determined by subtraction of the original NO_2 concentration from the NO_X concentration. Water samples for TP and TN analysis were digested using a persulphate digestion method (Ebina *et al*. 1983) before analysis on the FIA as for SRP and NO_X.

Deionized water (>16 MΩ resistance) was used for preparing standards and reagents for nutrient analysis. To avoid contamination in the analysis, deionized water was obtained fresh daily. Stock standard solutions were prepared from analytical reagent-grade chemicals, pre-dried at 105 ºC for one hour. The stock solutions were stored in glass bottles at 4ºC in a refrigerator. Working standard solutions were prepared from serial dilutions of stock solutions with deionized water.

Laboratory reagent water blanks were analysed to demonstrate freedom from contamination. The blank was subjected to the same procedural steps as samples. Ongoing precision and recovery were verified using a mid-range calibration standard every ten samples or every analytical batch. All samples were associated with an uncontaminated method blank before the results were reported.

3.3 *Water balance*

A water balance for Lake Tarawera was determined taking into account the volume of water from the inflows (including rainfall, surface tributaries entering the lake directly and arising in close proximity to the lake from groundwater), the outflows (including the major outflow, as well as evaporation losses), and the change in lake volume arising from changes in water level. An unknown (i.e. missing) term in the equation was derived as follows:

$$U = \sum Q_{in} - Q_{out} + (P \times A) - (E \times A) - (dV/dt)$$

where U is the unknown term (m^3 day^{-1}), dV/dt is the change in volume of the lake over a period of time dt (m^3 day^{-1}), $\sum Q_{in}$ is the sum of all inflows (m^3 day^{-1}), Q_{out} is the sum of all outflows (m^3 day^{-1}), P is precipitation (m day^{-1}), E is evaporation (m day^{-1}) and A is the lake area (m^2).

3.4 *Inflow and outflow measurements*

All of the major streams entering the lake were located in a preliminary inspection by foot, and allocated a sampling number. Seventeen sites were monitored on a weekly or two-weekly basis though some sites were ephemeral. Gauging was undertaken by measuring flows at a number of locations across the stream transect using a Marsh-McBirney Model 2000 portable flow meter. Distance across the stream as well as water depth and flow were multiplied together to determine a discharge in $m^3\ s^{-1}$.

No relationship was identified between streamflow and rainfall over the monitoring days. Instead, linear interpolation between monitoring days was used to estimate streamflow when direct measurements were not available. Rainfall data was obtained from the Rotorua Airport meteorological site, and converted to volumetric units using the lake volume from Table 1. Evaporation rate was estimated from a hydrodynamic model of Lake Rotoiti that gave monthly values of evaporation based on air temperature, water temperature and relative humidity (Béya and Hamilton, 2004). A polynomial relationship was applied to the evaporation rate over the course of the year in order to interpolate measurements to daily values. The equation is:

$$E = -0.00210x^4 + 0.07328x^3 - 0.76102x^2 + 2.2607x + 3.42,\ R^2 = 0.997,$$

where x represents month of the year. There will be small differences in evaporation rate between Lake Tarawera and Lake Rotoiti, but these differences are shown below to be small relative to other components of the water budget.

Outflow to the Tarawera River was obtained from the automatic flow site of NIWA located on the Tarawera River, and was adjusted to units of $m^3\ day^{-1}$. Change in storage of the lake was obtained daily from the product of change in lake level and area of the lake (Table 1). For the purposes of the water balance calculation, a weekly average was used to reduce the short-term effects of wind and atmospheric pressure on the lake level, thereby smoothing short-term fluctuations.

3.5 *Nutrient Budget*

Discharge was multiplied by nutrient concentrations (PO_4, TP, NO_3, NH_4, TN) to derive a nutrient load for each gauged inflow. Concentrations were summed to provide a nutrient load over the gauged inflows. Total phosphorus and total nitrogen loads for rainfall were determined based on areal loads of 0.0148 and 0.396 tonnes km^2 yr^{-1}, respectively. These areal loads have been widely used by Environment Bay of Plenty in nutrient load budgets for several other Rotorua lakes, but are based on measurements taken several years ago in other regions of the Central Volcanic Plateau. Similarly, areal nutrient loads for different land uses have been derived mostly from figures used by Environment Bay of Plenty and are near the middle of the range of values given in a comprehensive review of nutrient losses for different land uses given in Meneer *et al*. (2005).

4. Results

4.1 *Water budget*

Results of the water budget are provided in Figure 3 for losses of water (outflows and evaporation) and in Figure 4 for gains of water (gauged inflows, rainfall and ungauged inflows).

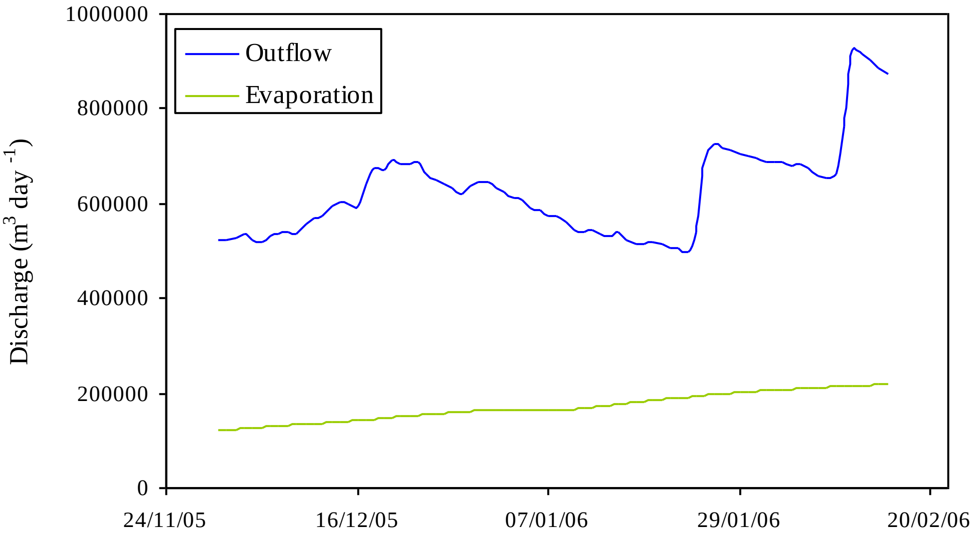

Figure 3. Lake outflow and evaporation for the study period.

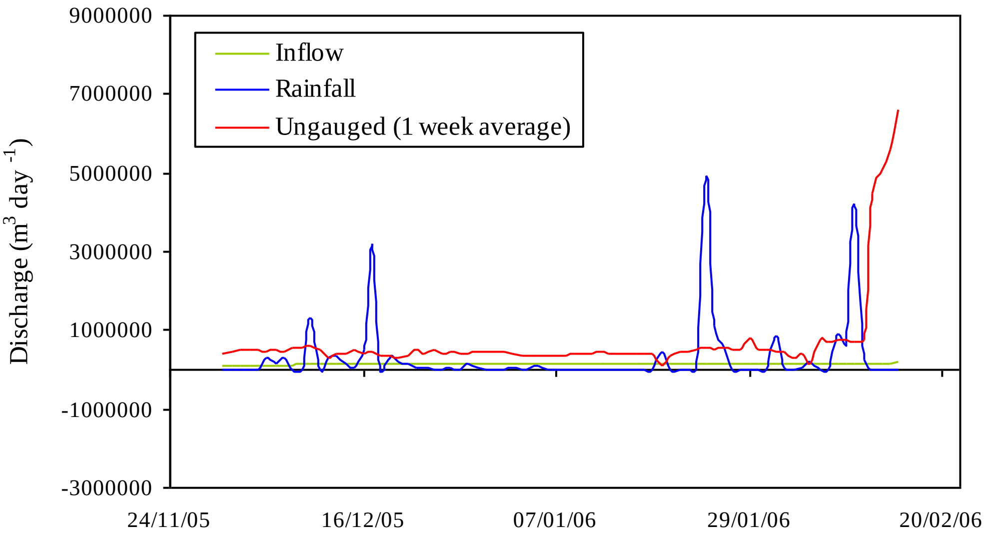

Figure 4. Total gauged inflow volume, daily rainfall and weekly averaged residual (ungauged inflow) for the study period.

It should be kept in mind that ungauged inflows were derived as the missing term in the water balance. On a daily basis, ungauged inflows were highly variable and sometimes negative, but these variations were smoothed by using a weekly running average; a time scale that most likely reflects some of the inertia in lake response to rainfall, and adjusts for wind and atmospheric effects that influence lake water levels over a shorter time scale.

Two major rainfall events (R > 10 cm day^{-1}) occurred over the sampling period. The second event (peak on 8 February) was more prolonged, with rainfall spread over 3 consecutive days, and appeared to be the major factor driving the rapid increase in flow from the ungauged catchment at the end of the study period. The lack of response to the earlier large rainfall event (19 January) most likely relates not only to the lack of rainfall on the preceding and subsequent days, but also to the inertia of the catchment response, i.e., the time for the catchment to become ‘wetted up’ and for the tributaries to become responsive to rainfall.

From Figures 3 and 4, it is evident that ungauged inflows are a very important constituent of water inputs to Lake Tarawera. On average gauged inflows represent 23 % of the discharge of the outflow, with ungauged outflows representing 104 % (i.e. > 100 % because of the additional loss term of evaporation in the water balance).

4.2 *Nutrients in stream inflows*

Concentrations of nutrients in stream inflows to Lake Tarawera are shown in Figures 5 and 6. The values have been derived over the entire study period by linear interpolation of weekly or fortnightly measurements in each stream. Inflows that are derived from the two lakes immediately upstream of Lake Tarawera, Rotokakahi and Okareka, are low in soluble nutrients (PO_4, NO_3 and NH_4) and total phosphorus (TP), and have moderate levels of total nitrogen (TN). By contrast, inflows from Tarawera Peak Stream are relatively high in both PO_4 and TP, and have moderate levels of NO_3 (100-200 mg m^{-3}); the latter nutrient constitutes the dominant form of TN. Ammonium was a minor constituent of each of the stream inflows except for the Te Puroku No.1, where its concentration was around 100 mg m^{-3}.

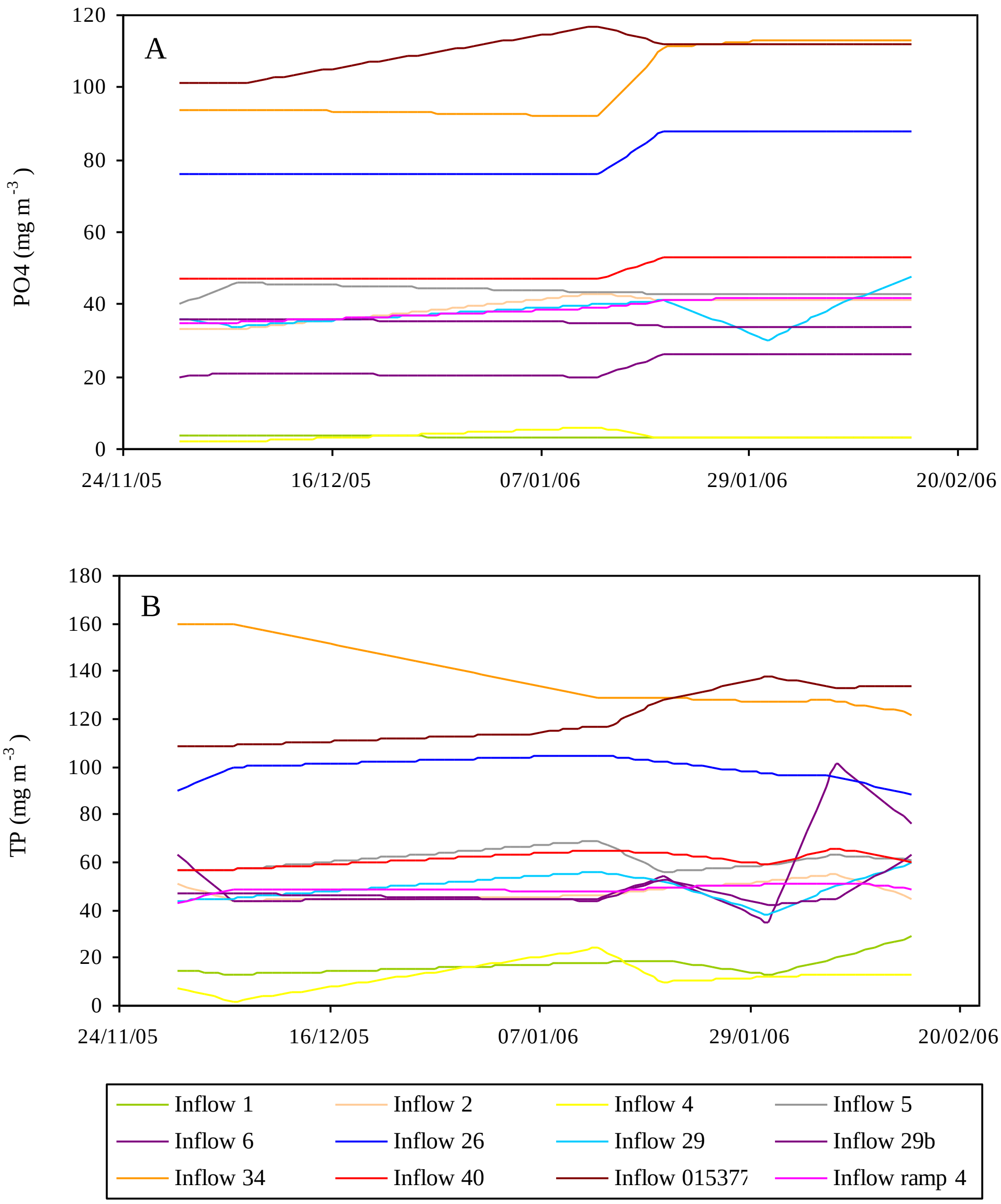

Figure 5. Concentrations of A) phosphate and B) total phosphorus for all measured inflows.

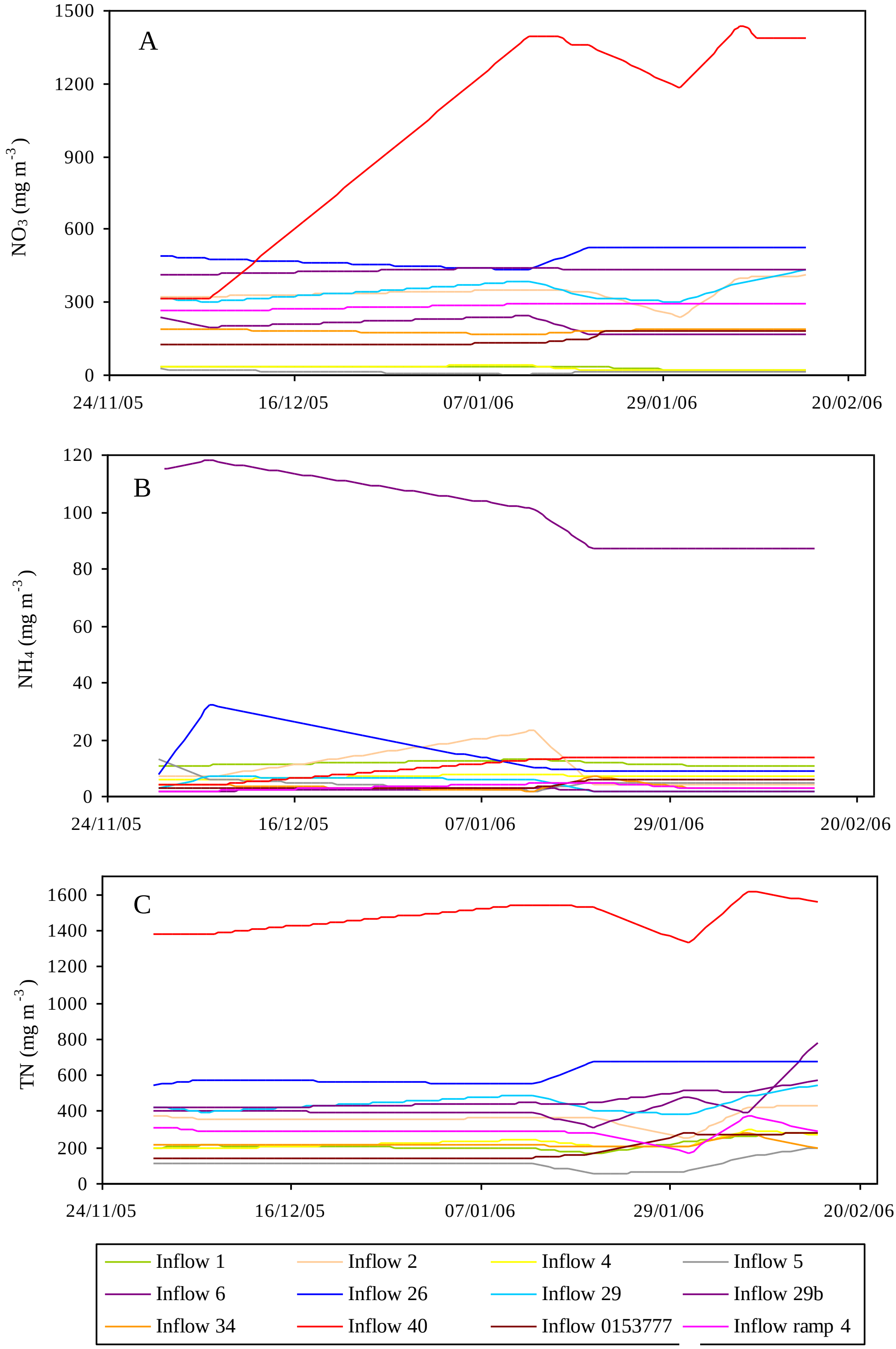

Figure 6. Concentrations of A) nitrate, B) ammonium and C) total nitrogen for all measured inflows.

The major geothermal inflow, Wairua Stream (No. 26), had a mean discharge of 208 L s^{-1} and was moderately enriched in phosphorus (TP approximately 100 mg mg^{-3}), most of which was in the form of PO_4, and was the second most enriched inflow in terms of TN (c. 600 mg m^{-3}), most of which was in the form of NO_3. A small coldwater inflow (No. 40) near Te Whekau Stream was clearly the most enriched inflow in terms of nitrogen (c. 1500 mg m^{-3}), and it had intermediate levels of TP relative to the other inflows.

Nutrient loads for the stream inflows have been derived on a daily basis and are presented as a mean value over the study period in Figure 7. In the case of phosphorus inputs there is no single dominant inflow. Te Puroku (Nos 29 and 29b) and Tarawera Peak Stream (No. 34) collectively dominate the loads of TP, each contributing c. 700 kg yr^{-1}, most of which is in the form of PO_4. Geothermal inputs from the Wairua Stream are the next major stream load but represent less than one-half of loads of TP from the three main inflows.

Rainfall is also a major constituent of phosphorus loads to Lake Tarawera. The figure for rainfall is based on an areal deposition rate of TP of 0.0148 tonnes km^{-2} and no consideration is made as to the relative partitioning of phosphorus between particulate and dissolved phases. Most phosphorus from areal deposition is likely to be contributed by dust and leaf litter and areal deposition rates will therefore vary between lakes. Nevertheless areal deposition of phosphorus may be of the order of individual contributions by the three largest stream inflows.

By far the largest contribution to phosphorus to Lake Tarawera is the ‘unknown’ term. This component represents a discharge to the lake of around 7 m^3 s^{-1}, and if assumed to have a volumetrically averaged phosphorus concentration of all of the gauged stream inflows (c. 51 mg m^{-3}), represents a load of 9.13 tonnes yr^{-1} (Table 3). For comparison, the gauged coldwater inflows and Wairua Stream contribute 2.3 and 0.66 tonnes yr^{-1} respectively (Table 3)

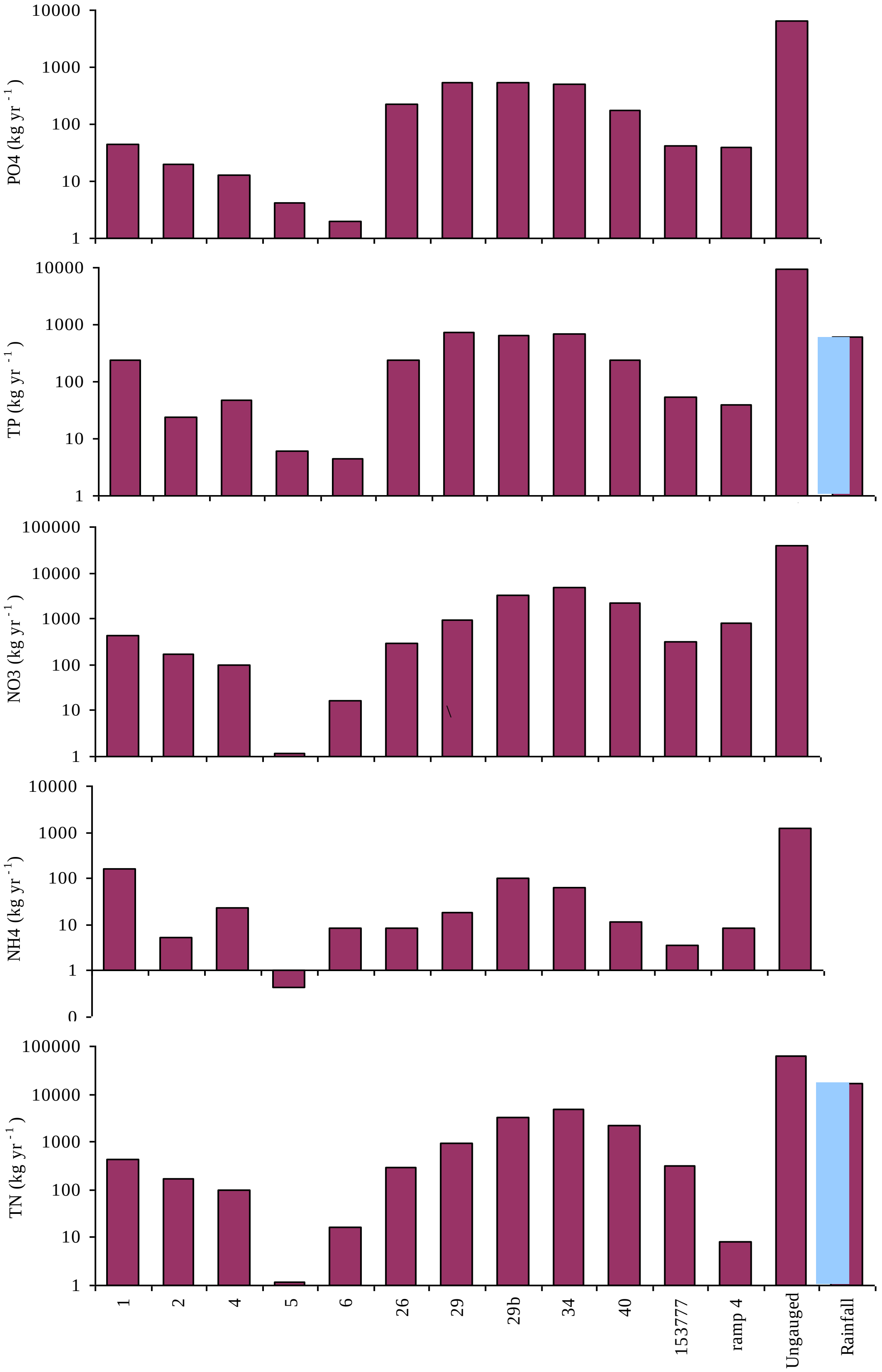

Figure 7. Nutrient load per year from all inflows (derived from the 3-month study period) and rainfall for A) phosphate, B) total phosphorus, C) nitrate, D) ammonium and E) total nitrogen. Note that the nutrient loads are presented on a log scale.

Table 3. Nutrient concentrations and loads for components of the Lake Tarawera water balance.

	Volume (m^3 yr^{-1})	Concentration (mg m^{-3})					Load (T yr^{-1})				
		PO4	TP	NO3	NH4	TN	PO4	TP	NO3	NH4	TN
Inflow coldwater	44367429.00	36.18	51.82	223.99	7.00	344.47	1.61	2.30	9.94	0.31	15.28
Inflow Hotwater	7815599.00	68.14	84.08	409.02	12.90	510.96	0.53	0.66	3.20	0.10	3.99
Ungauged	176212692.50	36.18*	51.82*	223.99*	7.00*	344.47*	6.37*	9.13*	39.46*	1.23*	60.70*
Rainfall								0.61			16.22
Subtotal Inflows								3.56			35.50
Outflow	228255998.50		7.59			116.81		1.73			26.66
Retention time (years)	9.96										

** Nutrient loads for the ungauged inflows have been derived by assuming that the concentrations of TP and TN are identical to those of the coldwater inflows.*

The Tarawera Peak Stream (No. 34) is clearly the dominant source of gauged nitrogen loads to the lake. Ammonium loads appear high for inflow Te Wairoa Stream, but are in fact a minor contributor to the total nitrogen loads. Except for Te Puroku No.1 Stream, ammonium contributes little to the total nitrogen concentration and nitrate is the dominant nitrogen species. The individual gauged contributions to TN are small, however, relative to rainfall. The areal deposition of TN in rainfall of 0.396 kg km^{-2} was applied to estimate the total load to the lake of 16.22 tonnes yr^{-1}, which is comparable to the combined contribution of TN from gauged inflows (Table 3). Gibbs (NIWA, pers. comm.) has recently found considerably elevated levels of atmospheric deposition in the Taupo catchment compared with data collected in the 1970s and 1980s, but it was considered premature for the purposes of this report, to extrapolate those data to the present study. Contributions from areal deposition are, however, dwarfed by those from the ungauged inflows, which ertr estimated by applying the discharge by the volumetric mean total nitrogen concentration for all the gauged coldwater inflows (344 mg m^{-3} for TN).

Based on a comparison on all nitrogen and phosphorus loads entering Lake Tarawera, and the discharge of nitrogen and phosphorus through the outflow using assumed mean concentrations of 7.59 mg m^{-3} for TP and 116.81 mg m^{-3} for TN (Table 3), it is estimated that around 86 % of phosphorus entering the lake is retained within it, and around 72 % of nitrogen. Water resides within the lake for approximately 10 years, a period of time very similar to the water residence time of Lake Taupo. The total nutrient loads given in Table 1 are comparable to those estimated by Bioresearches (2003) for TN but are less for TP by around 5 tonnes yr^{-1}.

Lake Tarawera has been assigned a target value for its Trophic Level Index (TLI) of 2.6 under the Regional Council Land and Water Plan. In recent years Lake Tarawera's TLI has been around 0.15 to 0.3 units above this value. If it is assumed that the TLI should decrease by c. 0.2 units in order to conform to the assigned target, then this would necessitate decreasing concentrations of TP from 7.59 to 6.48 mg m^{-3}, and concentrations of TN from 116.81 to 100.2 mg mg^{-3}. This necessitates a considerable reduction in nutrient load to the lake given the very high retention coefficients for both phosphorus and nitrogen that are given above. If it is assumed that there are approximately 104 households with an average occupancy of 2.8 people per household that are currently on septic tank systems, then their combined load can be estimated to be 204 kg yr^{-1} for TP and 1063 kg yr^{-1} for TN, using contributions of 0.7 kg TP person^{-1} yr^{-1} and 3.65 kg TN person^{-1} yr^{-1}. For this particular case there is assumed to be no retention of TP in soil between the septic tank and the lake. An important question to address is whether removing septic tanks and replacing them with a reticulated sewage system would address the current TLI state, which is slightly elevated relative to the target of 2.6. It is possible to determine the change in mass loading required to reduce the TLI from:

$$M = \frac{CQ}{1-R}$$

where M is the change in mass (kg yr^{-1}), C is the change in the outflow concentration (i.e. 1.11 mg m^{-3} for TP and 16.61 mg m^{-3} for TN), Q is the outflow discharge (equivalent to 7.24 m^3 s^{-1}) and R is the retention coefficient (0.86 for TP and 0.72 for TN). According to the above equation, in order to achieve a 0.2 reduction in the TLI it would be necessary to remove 1.86 tonnes yr^{-1} of TP from the current load and 13.7 tonnes yr^{-1} for TN; considerably greater than is likely to be achieved from removal of septic tanks alone. These figures for the required reduction can be compared with the current total load of 12.69 tonnes yr^{-1} of TP and 96.2 tonnes yr^{-1} for TN based on Table 3. In other words the reduction required represents 15 % of the current load for TP and 14 % for TN. It should be kept in mind, of course, that rainfall contributes around 5 % of the TP load and 17 % of the TN load, and that much of the Lake Tarawera catchment is currently undeveloped.

4.3 *Nutrient loads based on land use*

The catchment that inputs water directly to Lake Tarawera, whether through surface water or groundwater connections, is approximately 102 km^2. Nutrient yields for land uses within this catchment are assumed to have no attenuation from the assigned areal nutrient yield coefficients for different land uses (i.e., Factor = 1, Table 4). It was also assumed that there was no attenuation from septic tank inputs that enter the Te Wairoa Stream from the Buried Village; this input has been allocated together with nutrient inputs arising from Lake Rotokakahi in Table 4.

Outside of the immediate catchment of Lake Tarawera there are additional sources of water that first enter other lakes before Tarawera. These sources arise from lakes Rotomahana, Tikitapu, Rotokakahi, Okataina, Rerewhakaaitu and Okaro. Nutrients that enter these lakes are deposited mostly to their bottom sediments or, in the case of nitrogen, are also lost to the atmosphere through the process of denitrification. Average values from a number of detailed nutrient budget studies indicate that around two-thirds of nutrients are either 'lost' to the sediments or to the atmosphere. For this reason a factor of 0.33 (one-third) is applied to incoming nutrients for outlying lake catchments of Lake Tarawera; Rotomahana, Tikitapu, Rotokakahi and Okataina.

Lakes Rerewhakaaitu and Okaro are further complicated by the fact that nutrients in outflows from these lakes are attenuated first of all by Lake Rotomahana, before water enters Lake Tarawera, and only part of Lake Rerewhakaaitu lies within the larger Lake Tarawera catchment. For this reason a factor of 0.109 was applied to nutrient loads from the Lake Okaro catchment, to represent attenuation through Lake Okaro and then Lake Rotomahana (i.e., 0.33 x 0.33). For Lake Rerewhakaaitu there is no data to verify how much water from this lake catchment ultimately enters Lake Tarawera. We assumed that 50 % of water from the Lake Rerewhakaaitu catchment contributes inflow to Lake Tarawera (i.e., a multiplier of 0.5) and, when combined with attenuation of nutrients through Lake Rerewhakaaitu (multiplier = 0.33) and Lake Rotomahana (multiplier = 0.33), there is only a small fraction (0.5 x 0.33 x 0.33 = 0.027), 5.4 %, of nutrient inputs to Lake Rerewhakaaitu that ultimately reach Lake Tarawera.

Table 4. Nutrient budget for Lake Tarawera based on areal nutrient loads for different land uses in the immediate catchment (Lake Tarawera with Factor = 1) and outlying parts of the catchment which include other lakes (Factor varying from 0.036 to 0.33). The Factor term represents retention of nutrients in lake sediments en route to Lake Tarawera (see text for details). Inputs from septic tanks are based on approximations of 3.65 kg N per person per year and 0.7 kg P per person per year. Inputs of land use, catchment area and nutrient yields are mostly consistent with values used by Environment Bay of Plenty in their analyses of different nutrient areal loads based on the predominant land use.

Lake	**Land Use**	**Land use**	**Catchment area**		**Nutrient yields**		**Nutrient load**		**Factor**	**Tarawera input**	
		%	ha	km^2	(tN/km^2/yr)	(tP/km^2/yr)	N (t/yr)	P (t/yr)		N (t/yr)	P (t/yr)
Tarawera	Native forest	62.53	6361.31	63.61	0.250	0.04	15.903	2.545	1.00	15.903	2.545
	Exotic forest	15.74	1601.26	16.01	0.250	0.04	4.003	0.641	1.00	4.003	0.641
	Pasture (mixed)	17.96	1827.11	18.27	0.700	0.100	12.790	1.827	1.00	12.790	1.827
	Urban	0.96	97.66	0.98	0.290	0.066	0.283	0.064	1.00	0.283	0.064
	Septic tanks (104 houses x 2.8 occupancy)						1.063	0.204	1.00	1.063	0.204
	Bare ground	2.81	285.87	2.86	0.25	0.05	0.715	0.143	1.00	0.715	0.143
	Lake/rainfall		4138.56	41.39	0.396	0.0148	16.389	0.613	1.00	16.389	0.613
	Total	100.00	10173.21	101.73			50.431	5.893		51.146	6.036
Okareka	Pasture/Grassland	37.96	613	6.13	0.7	0.1	4.291	0.613	0.33	1.416	0.202
	Native forest	42.91	693	6.93	0.25	0.04	1.733	0.277	0.33	0.572	0.091
	Exotic forest	7.80	126	1.26	0.25	0.04	0.315	0.050	0.33	0.104	0.017
	Scrub mixed	4.64	75	0.75	0.25	0.04	0.188	0.030	0.33	0.062	0.010
	Mixed woody vegetation	2.72	44	0.44	0.25	0.04	0.110	0.018	0.33	0.036	0.006
	Wetlands	0.31	5	0.05	0	0	0.000	0.000	0.33	0.000	0.000
	Septic tanks (288 houses, 2.3 occupancy)						2.418	0.464	0.33	0.798	0.153
	Urban	2.85	46	0.46	0.29	0.066	0.133	0.030	0.33	0.044	0.010
	Bare ground	0.80	13	0.13	0.25	0.05	0.033	0.007	0.33	0.011	0.002
	Lake/rainfall		334	3.34	0.396	0.0148	1.323	0.049	0.33	0.436	0.016
	Total	100.00	1615	16.15			10.542	1.538		3.479	0.508
Okaro	Sheep/beef	66.45	237.5	2.375	0.7	0.11	1.663	0.261	0.109	0.181	0.028
	Deer	11.9	42.8	0.428	0.6	0.15	0.257	0.064	0.109	0.028	0.007
	Dairy	10.7	38.3	0.383	1.5	0.18	0.575	0.069	0.109	0.063	0.008
	Exotic forest	5.6	19.9	0.199	0.25	0.04	0.050	0.008	0.109	0.005	0.001
	Scrub	3.7	13.2	0.132	0.25	0.04	0.033	0.005	0.109	0.004	0.001
	Wetland	0.45	1.4	0.014	0	0	0.000	0.000	0.109	0.000	0.000
	Other	1.2	4.3	0.043	0.25	0.04	0.011	0.002	0.109	0.001	0.000
	Lake/rainfall		32	0.32	0.396	0.0148	0.127	0.005	0.109	0.014	0.000
	Total	100	357.4	3.574			2.714	0.414		0.296	0.122

Rotokakahi	Pasture	27.8	547.94	5.48	0.7	0.1	3.836	0.548	0.330	1.266	0.181
	Native forest	25.7	506.55	5.07	0.25	0.04	1.266	0.203	0.330	0.418	0.067
	Exoic forest	46.5	916.52	9.17	0.25	0.04	2.291	0.367	0.330	0.756	0.121
	Septic (50 pp @ Buried Village)						0.183	0.035	1.000	0.183	0.035
	Lake/rainfall		433	4.33	0.396	0.0148	7.805	0.292	0.330	2.576	0.096
	Total	100	1971.00	19.71			15.381	1.444		5.198	0.500
Okataina	Native forest	84.7	5066.75	50.6675	0.25	0.04	12.667	2.027	0.330	4.180	0.669
	Exotic forest	5.7	340.974	3.40974	0.25	0.04	0.852	0.136	0.330	0.281	0.045
	Pasture	9.6	574.272	5.74272	0.7	0.1	4.020	0.574	0.330	1.327	0.190
	Septic (30 pp @ lodge)						0.110	0.021	0.330	0.036	0.007
	Lake/rainfall		1173	11.73	0.396	0.0148	4.645	0.174	0.330	1.533	0.057
	Total	100	5407.73	54.0773			22.294	2.932		7.357	0.968
Tikitapu	Native forest	79.2	492.62	4.926	0.25	0.04	1.232	0.197	0.330	0.406	0.065
	Exotic forest	17.3	107.61	1.076	0.25	0.04	0.269	0.043	0.330	0.089	0.014
	Pasture/ grassed recreation	3.5	21.77	0.218	0.7	0.1	0.152	0.022	0.330	0.050	0.007
	Septic (545 @ camp ground)						1.995	0.382	0.330	0.654	0.131
	Lake/rainfall		144	1.44	0.396	0.0148	0.570	0.006	0.330	0.188	0.002
	Total	100	622	6.22			2.406	0.303		0.794	0.100
Rotomahana	Pasture	41.4	3446.55	34.4655	0.7	0.1	24.126	3.447	0.330	7.962	1.137
	Native forest	42.7	3554.78	35.5478	0.25	0.04	8.887	1.422	0.330	2.933	0.469
	Exotic forest	14.1	1173.83	11.7383	0.25	0.04	2.935	0.470	0.330	0.968	0.155
	Unassigned (wetlands etc.)	1.8	149.85	1.4985	0.25	0.04	0.375	0.060	0.330	0.124	0.020
	Lake/rainfall		902	9.02	0.396	0.0148	3.572	0.133	0.330	1.179	0.044
	Total		8325	83.25			39.894	5.531		13.165	1.825
Rerewhakaaitu	Native forest	6.2	229.15	2.2915	0.25	0.04	0.573	0.092	0.054	0.031	0.005
	Exotic forest	14.7	543.31	5.433	0.25	0.04	1.358	0.217	0.054	0.074	0.012
	Pasture	76.7	2834.83	28.348	1.5	0.18	42.522	5.103	0.054	2.315	0.278
	Wetlands	1.4	51.74	0.517	0	0	0.000	0.000	0.054	0.000	0.000
	Urban	1	36.96	0.37	0.29	0.066	0.107	0.024	0.054	0.006	0.001
	Septic (estimate 250 people)						0.913	0.175	0.054	0.050	0.010
	Lake/rainfall		517	5.17	0.396	0.0148	2.047	0.077	0.054	0.111	0.004
	Total	100	3696	36.96			47.521	5.688		2.587	0.310
Grand total										**84.62**	**10.41**

The catchment area of Lake Tarawera can be defined in a variety of ways:

1) Water contributed via surface water or groundwater inflows that enter the lake directly, representing an area of 101.7 km^2;
2) The immediate catchment of 101.7 km^2 as defined in 1) above, and additional catchment land area of 335.4 km^2 representing lakes with boundaries partially or totally within the wider Lake Tarawera catchment area (including the correction factor of 0.5 applied to the catchment area of Lake Rerewhakaaitu), for a total catchment area of 478.5 km^2;
3) As for 2) above, but also including the outlying lake water surface areas of 27.1 km^2, yielding a total area of 505.6 km^2.

It should be emphasised that the various nutrient yield coefficients used in Table 4 are simple approximations and that there are many additional factors (e.g. soil type, slope and grazing intensity for pastoral land use) that will produce highly variable nutrient yields (see Meneer *et al.* (2005) for a comprehensive review). Furthermore estimates of contributions from septic tanks are based on rough values for average household number of people, occupancy rates and soil attenuation rates. Estimates for Lake Tikitapu were based on design criteria for sewage reticulation, while people contributing to septic tanks from the Buried Village (categorised in Table 4 under inputs from Lake Rotokakahi) may be considerably greater than 50. There will also be a strong seasonal signal in leaching rates associated with occupancy of households and tourist accommodation and facilities (e.g. the lodge at Lake Okataina, toilet and camping ground facilities at Lake Tikitapu, and Buried Village).

The total nutrient load to Lake Tarawera based on the predominant land use and assigned nutrient yield coefficients is 84.1 and 10.4 tonnes yr^{-1} for total nitrogen and total phosphorus, respectively. These values compare with those estimated from stream inflow gauging and nutrient samples of 96.2 and 12.7 tonnes yr^{-1} for total nitrogen and total phosphorus, respectively. Part of this difference may be explained if there were higher areal deposition rates of nutrients that followed the trend for Lake Taupo (Gibbs, pers. com) but this would influence nutrient inputs only from the outlying lakes as both methods (streamflow gauging and land use coefficients) use the same areal deposition rate for Lake Tarawera itself.

5. Discussion

The catchment of Lake Tarawera is unusual in having such a large number of other lakes within it. This situation will to some extent buffer Lake Tarawera from land use changes within the other lake catchments, due to retention of nutrients within the sediments of these lakes. It will, however, necessitate considerations of effects on Lake Tarawera water quality of land use and lake water quality in the six contributing lakes. Internal loads arising from lake sediments, e.g. in response to loss of oxygen and anoxia, have the potential to influence the nutrient budgets derived from this study as they were not taken into consideration in the calculations.

Lake Tarawera has a relatively high retention coefficient for total phosphorus (0.86) and for total nitrogen (0.72 for the low areal deposition of TN and 0.67 for the higher value). These values mean that it is difficult to alter nutrient concentrations in Lake Tarawera substantially while land use remains similar to present. Options of changing land use and replacing septic tanks with a reticulated sewage system will tend to have incremental changes on lake water quality due to the relatively long residence times in the lake (approximately 10 years). Although the current Trophic Level Index (TLI) is only slightly elevated in Lake Tarawera, it will nevertheless be important to develop strategies required to reduce lake nutrient loads, time frames on which these reductions might be achieved and on which the lake nutrient concentrations will respond.

There are no especially distinctive patterns in nutrient concentrations in the inflows to Lake Tarawera. The geothermal Wairua Stream had slightly elevated concentrations of all nutrient species, but not especially so relative to, for example, many of the geothermal inflows to Lake Rotorua. Te Whekau Stream did have relatively high concentrations of ammonium, however, and it may be useful to track the source of ammonium to this stream as nitrate is generally the dominant species in most coldwater inflows to Rotorua lakes. Concentrations of both soluble reactive phosphorus and total phosphorus are slightly elevated in many of the stream inflows to Lake Tarawera though notably not in inflows arising from lakes Rotokakahi and

Okareka where much of the phosphorus is likely to sediment out in the quiescent lake waters. One interpretation of the elevated stream phosphorus levels in the other inflows is that the phosphorus arises from old-age groundwater in which there has been dissolution of sorbed phosphorus from the bedrock material. In this context it would be useful to know more about the nature of the source water (i.e. age) and catchment delineation of the Tarawera Peak and Te Poroku stream inflows, as well as a small stream inflow (No. 40) near the Te Whakau Stream.

Lake Tarawera has a very high phosphorus retention coefficient (0.86). Factors that likely contribute to this are the long hydraulic residence time (c. 10 years), and the oligotrophic (low productivity) status of the lake which probably results in considerable demand and internal recycling of phosphorus. It is interesting to note that the surface sediments of Lake Tarawera are the most enriched of any of the Rotorua lakes (D. Trolle, PhD study at the University of Waikato), corresponding to moderate loads of phosphorus from the lake catchment and high phosphorus retention within the lake. Much of the phosphorus entering Lake Tarawera is in dissolved form which is probably symptomatic of relatively low concentrations of suspended sediments which would otherwise adsorb the phosphorus and contribute it to the lake in particulate form.

Estimates of nutrient loads from stream inflow sampling and from areal nutrient yields assigned for different land uses are remarkably similar and offer some support for the results from stream sampling, even though this part of the study was undertaken over a relatively short period of time in 2005/06. The areal yields of nutrients serve to re-emphasise the interconnectedness of Lake Tarawera and other lakes in the district. The results also point to a potentially large aquifer system whose quality will, in the long-term, play a major role in determining the water quality of Lake Tarawera. It is quite possible that the catchment boundaries of the groundwater aquifer will differ from the boundaries of the surface water catchment. Considerable knowledge has been gained about the groundwater system of Lake Rotorua as a result of a series of studies by Geological & Nuclear Sciences, and a similarly well designed study may provide important knowledge about the influence of groundwater on lakes Tikitapu, Rotokakahi, Okareka, Okataina, Okaro and Rerewhakaaitu, as well as Lake Tarawera, as groundwater is clearly the dominant discharge into the latter lake.

The interconnectedness of Lake Tarawera with the six other contributing lakes also suggests that the domain for managing nutrient loads should extend beyond the immediate catchment boundary (143 km^2) of Lake Tarawera. Control of nutrient exports within the immediate Tarawera catchment and in Te Wairoa Stream will be most effective overall (Factor = 1, refer to Table 4), but of particular significance is the contribution of nutrients from bottom sediments of the other contributing lakes. Some of these lakes (e.g. Okaro) are already highly degraded and have large internal nutrient loads (i.e. arising from the bottom sediments) that are enhanced by deoxygenation of bottom waters. Furthermore, there is evidence of some deoxygenation in bottom waters of Okareka, Tikitapu, Rotokakahi and Okataina (Hamilton, 2004). Large releases of nutrients from anoxic bottom sediments will be in dissolved form and therefore not attenuated in the same way as nutrients arising from within catchments of each of these lakes, for which an attenuation factor of 0.33 is applied (Table 4). This analysis therefore serves to emphasise:

1) that optimisation is required of on-land retention of nutrients for all six contributing lakes, as well as within the catchment of Lake Tarawera itself,
2) that sewage reticulation works in any of these lakes will benefit Lake Tarawera by reducing nutrient inputs,
3) and that Lake Tarawera will respond only very slowly to changes in nutrient inputs.

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8. Appendices

Working data for the stream sample and areally derived nutrient budgets can be found on the CD attached with the master copy of this report, or requested from The University of Waikato (davidh@waikato.ac.nz).