

ANALYSIS OF CATCHMENT HYDROLOGY AND NUTRIENT LOADS FOR LAKES ROTORUA AND ROTOITI



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Executive Summary

A water and nutrient budget has been derived from lakes Rotorua and Rotoiti to complement an earlier report to the Lakes Water Quality Society that considered only internal (bottom sediment-derived) sources of nutrients for these two lakes. Twenty-six inflows to Lake Rotorua that have been monitored for varying periods are considered in this report. The combined annual mean discharge of these inflows varies between 12 and 17 m³ s⁻¹ depending on the time period selected, which likely reflects long-term variations in rainfall and groundwater levels. Correlations of discharge in the Utuhina Stream with discharges of other major inflows were generally significant and reinforce the concept that discharges from individual streams respond in a synchronous fashion across the catchment of Lake Rotorua. Greater than 90% of the discharge is contributed by six streams that are predominantly spring-fed; Hamurana, Awahou, Utuhina, Waiteti, Puarenga and Ngongotaha. Geothermal inflows with elevated nutrient concentrations are an important contributor of the remaining minor stream inflows (< 1 m³ s⁻¹), which all have mean discharges less than 1 m³ s⁻¹. Flow-weighted mean total phosphorus (TP) and total nitrogen (TN) concentrations for the minor inflows are therefore relatively high at 0.145 g TP m⁻³ and 2.192 g TN m⁻³, compared with the six major inflows, which each have mean concentrations less than 0.1 g TP m⁻³ and 1.5 g TN m⁻³. By virtue of dominance by discharge, however, the six major streams are also the dominant contributors to the nutrient load, collectively producing just over 80% of the phosphorus and nitrogen that enters Lake Rotorua from all of the gauged inflows. The contribution of ungauged stream inflows to Lake Rotorua was estimated as the missing term in a water budget that included discharge from the gauged stream inflows, inputs from rainfall, losses from evaporation and discharge to the Ohau Channel of approximately 17 m³ s⁻¹ depending on the time frame selected for the analysis. Ungauged stream inflows contribute approximately 15% of the total incoming water to Lake Rotorua and, in order to construct a relatively complete nutrient budget for the lake, were assumed to have nutrient concentrations equal to the mean concentrations of the minor inflows. The nutrient budget, which included terms for release from the bottom sediments of 24 tonnes TP yr⁻¹ and 308 tonnes TN yr⁻¹ to account for longer periods of stratification and deoxygenation, indicated that approximately 80% of TP and 76% of TN entering the lake is retained through sedimentation or is lost to the atmosphere through denitrification in the case of TN.

Lake Rotoiti has one major inflow, the Ohau Channel, of which approximately 30% is short-circuited directly to the Kaituna River outflow. Other gauged inflows contribute approximately $0.6 \text{ m}^3 \text{ s}^{-1}$ to the lake, while the residual term estimated from the water balance, representing groundwater and other ungauged inflows, is estimated to be $3.8 \text{ m}^3 \text{ s}^{-1}$. A nutrient budget was constructed for Lake Rotoiti, using contributions from the Ohau Channel of 13.3 tonnes TP yr^{-1} and 164 tonnes TN yr^{-1} after accounting for the extent of short-circuiting of this inflow to the Kaituna River. Ungauged inflow concentrations were set to the flow-weighted values of minor gauged streams of $0.081 \text{ g TP m}^{-3}$ and $1.265 \text{ g TN m}^{-3}$. It is noteworthy that the relatively low nutrient levels in the volumetrically dominant Waiiti Stream had by far the largest influence on the flow-weighted concentration, while far smaller volumes contributed by three geothermal sources, the Parengarenga, Otutara and Ruahine streams, had high concentrations of total phosphorus ($> 0.26 \text{ g m}^{-3}$) and exceptionally high levels of total nitrogen ($> 14.9 \text{ g m}^{-3}$). Additional contributions to the nutrient budget were from internal loading during seasonal stratification, calculated previously to be 20 tonnes TP yr^{-1} and 50 tonnes TN yr^{-1} , losses from denitrification which averaged out at 50 tonnes TN yr^{-1} from prior calculations, and a relatively small contribution from rainfall. From these figures, the retention of TP was 28.7 tonnes yr^{-1} and for TN, only 15.4 tonnes yr^{-1} , with the loss due to denitrification matching the input due to internal loading. A hypothetical consideration of the effects on nutrients of Ohau Channel diversion, assuming all other fluxes are unaffected by the diversion, resulted in a reduction of TP retained in the lake to 10.9 tonnes TP yr^{-1} while for TN the lake would export 153 tonnes yr^{-1} .

Acknowledgments

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1 General Introduction

The objective of this report is to summarise information on catchment nutrient loads to lakes Rotorua and Rotoiti, and to generate information for the application of ecological models to these lakes. Inflows and outflows, as well as nutrient mass loads are required at daily resolution by the model to observe inter-annual variations within each of the lakes. This report supplements an earlier report presented to the Lakes Water Quality Society that examined internal nutrient loads in lakes Rotorua and Rotoiti (Hamilton *et al.*, 2004).

2 Lake Rotorua

2.1 Background

The information below has been collated from scientific papers to provide a general overview of Lake Rotorua. Meteorology, lake inflows and outflows, water levels, catchment areas and land uses are considered in this review.

2.1.1 History

Maori settled around Lake Rotorua from about 1350, but the city settlement only underwent substantial growth around the 1890s. Native vegetation around the lake's edge was milled for timber and cleared for farming, and with urban development, septic tanks were installed. This development resulted in an increased nutrient load flowing from the catchments into the lake. Excess nitrogen and phosphorus has stimulated the growth of phytoplankton and has eventually led to poor water clarity and blue-green algal blooms, though introduced species (e.g. oxygen weed such as *Lagarosiphon*) have also played a role. Health warnings are now issued routinely during summer for parts of Lake Rotorua in response to blue-green algal cell counts exceeding recommended recreational limits.

The linkage of the lakes Rotorua and Rotoiti, through the Ohau Channel, makes management of Lake Rotoiti, in particular, very complex. Approximately 70% of the nitrogen and phosphorus that flows into Lake Rotoiti comes from Lake Rotorua. Work to reduce nutrient loads on the two lakes commenced in the mid 1970s as part of the Upper Kaituna Catchment Control Scheme. These works around Lake Rotorua included: 514 km of retirement fencing, retirement of 4000 ha of land, and planting of 400,000 plants and 260,000 production trees. Around Lake Rotoiti there has also been 16 km of fencing undertaken and exclusion of stock from 140 ha of its watercourse and catchment.

There was also an earlier plan to pipe the treated sewage from the city of Rotorua to the Kaituna River. A Treaty of Waitangi claim, however, prevented this and instead, Rotorua District Council built a modern nutrient stripping plant to treat the effluent before it was sprayed onto a part of the Whakarewarewa Forest. This occurred in 1991 and was regarded as 'leading edge' technology. Although there have been problems in meeting the reduced guideline of 30 tonnes of

nitrogen and 3 tonnes of phosphorus flowing to the lake each year from the irrigated effluent, this target is currently being achieved, particularly following recent modifications in technology and forest irrigation practice. The net result has been a reduction of nitrogen and phosphorus to the lake of 120 tonnes and 27 tonnes per year respectively, compared with 1990 levels.

Ongoing monitoring has shown that while nitrogen inputs from sewage have declined, there has been a marked increase (70 tonnes/year or more) in nitrogen flowing from groundwater and entering as stream inputs to the lake compared with 1990 (Rutherford, 2004). A similar phenomenon has been identified in Lake Taupo where groundwater is comparatively 'old' (often 50 years or more in individual streams) and the impacts of land use change have been delayed by the groundwater reservoir (Morgenstern et al., 2004).

Lake Rotorua is currently a productive trout fishery and is also used for swimming and boating, and is one of the main tourist attractions for the wider region.

2.1.2 Location

Rotorua is situated in North Island of New Zealand, in the Bay of Plenty District (Figure 1). Rotorua city is located at the southern end of the lake (Figure 2). Its geographic coordinates are 176°15'E, 38°5'S and altitude is 271 m above sea level. Rotorua city has a population of around 60,000.

2.1.3 Geology

Lake Rotorua is situated in an ancient volcanic caldera. The Rotorua caldera is circular in shape and about 16 km in diameter. The caldera was formed about 140,000 years ago as the Mamaku Ignimbrite erupted. The ignimbrite (welded and non-welded pyroclastic flows) covers about 4,000 km² and is the youngest and most widespread ignimbrite in the Taupo Volcanic Zone. Rhyolite lava domes were extruded after the caldera formed. The Whakarewarewa geothermal area contains numerous geysers, hot springs, and boiling mud pools.

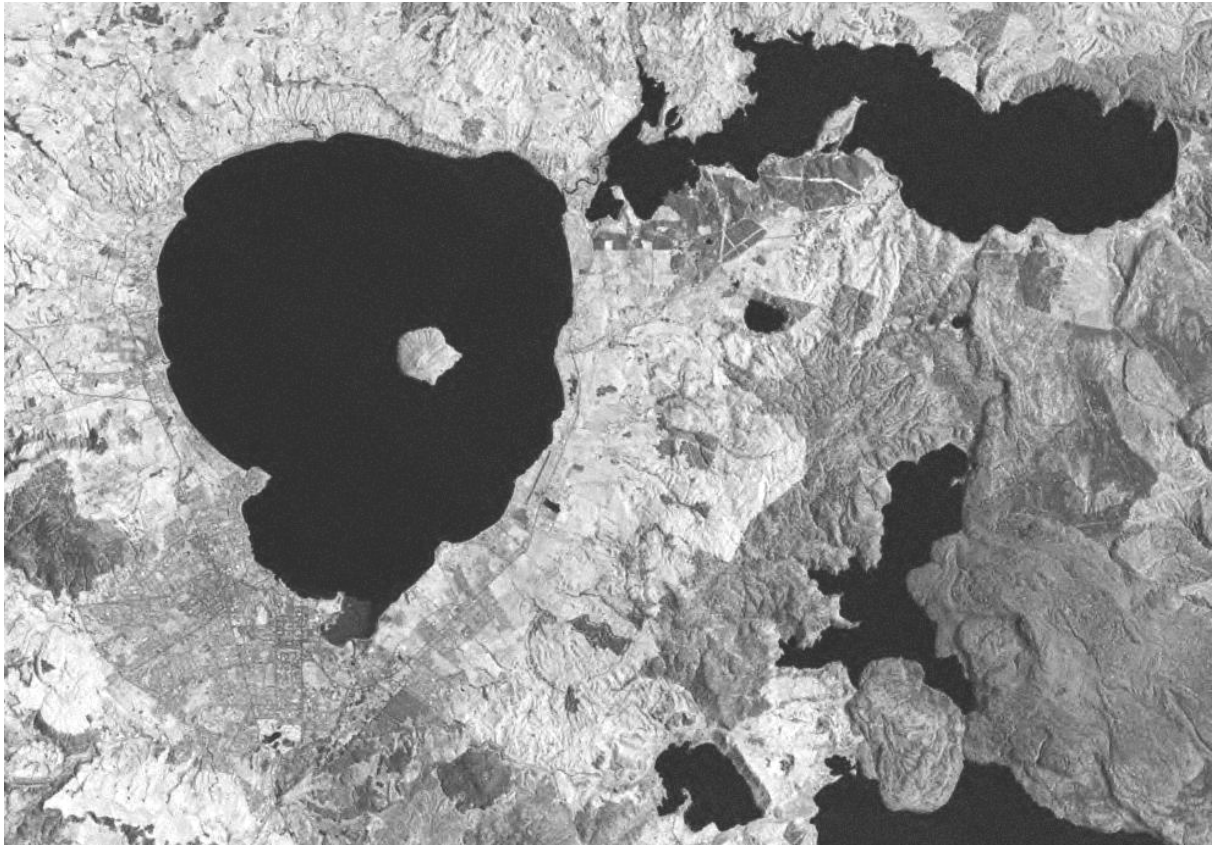


Figure 2. Aerial view of Lake Rotorua (centre-left), the Ohau Channel and the Lake Rotoiti (up-right). (Source: <https://zulu.ssc.nasa.gov>.)

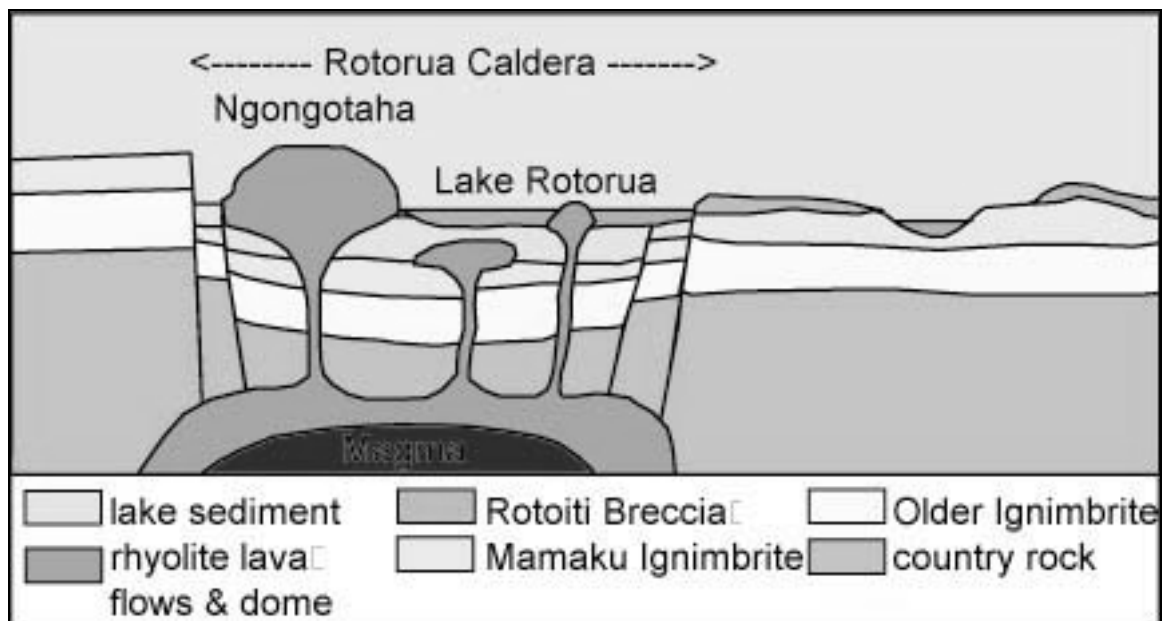


Figure 3. Simplified cross-section of the Rotorua caldera. (Source: http://volcano.und.nodak.edu/vwdocs/volc_images/australia/new_zealand/rotorua.html.)

2.1.4 Morphometry

Table 1 shows the main morphometric parameters of Lake Rotorua. A bathymetric map of the lake is shown in Figure 4.

Table 1. Morphometric parameters for Lake Rotorua

Lake Area	80 km ²
Lake Volume	802 Hm ³
Catchment Area	424 km ²
Length	12 km
Average Diameter	10 km
Maximum depth	25 m (Note: small 44m crater)
Mean depth	10.5m

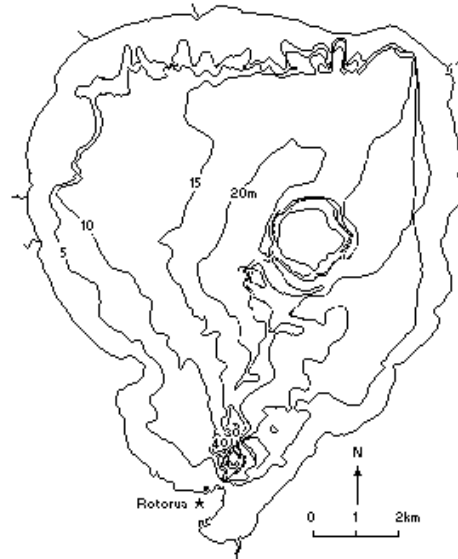


Figure 4. Bathymetric map of Lake Rotorua. (Source: <http://www.ilec.or.jp/database/oce/oce-03.html>.)

2.1.5 Hydrology

Lake Rotorua is fed by many small streams, with the main inflow being Hamurana Springs. There is only one outflow, the Ohau Channel, which enters Lake Rotoiti. The water residence time of Lake Rotorua is about 1.2 years. Figure 5 shows the major catchment areas associated with the major streams and Table 2 shows the land uses within the respective catchments. There are extensive large catchments on the north-west of the lake, but the exact extent of some of these catchments is somewhat arbitrary since the extent of contributing groundwater is difficult to elucidate but is the subject of ongoing investigation.

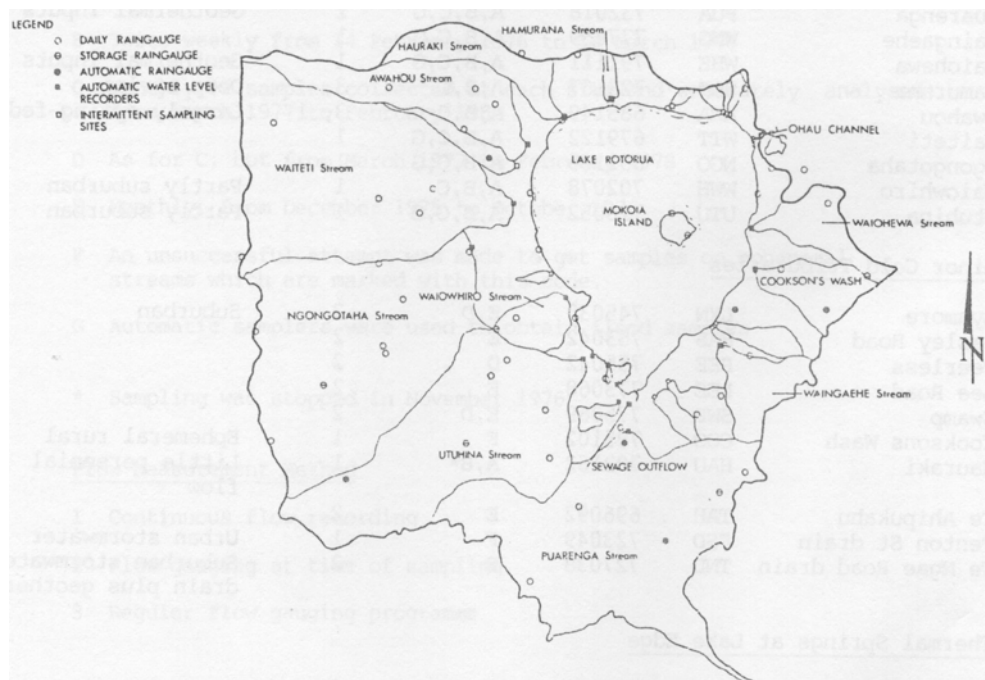


Figure 5. Sub-catchments of Lake Rotorua. (Source: Hoare 1987).

Table 2. Sub-catchment land use area (Ha) for the major inflows to Lake Rotorua. Data are given to two significant figures only to illustrate the relatively small contributions of some land uses in some of the sub-catchments.

Sub-catchment	Bare Ground	Forest-Indigenous	Forest-Planted	Horticulture	Pasture-Exotic	Scrub - Mixed	Urban	Urban-Open Spaces	Water	Wetland-Inland
Awahou	34.93	600.07	632.07		1364.00	175.55				31.18
Awahou Point		28.70		3.52	104.43				1.50	
Hamurana		118.90	14.21		524.79	30.45			4.05	
Hauraki		147.16	172.32	0.49	930.15	48.27			0.07	
Kaituna					0.01					
Lake Rotokawa			0.06		0.59		0.01		5.42	
Lake Rotorua	0.41	9.55			4.29	19.49	21.38	1.80	7989.5	0.34
Mangorewa		0.00	4.89		5.08	0.18				
Mission Bay	32.46	207.33	13.58		531.33	28.27			15.26	
Mokoia Island		122.07			2.87	2.60			9.58	
Motutara	5.61					22.55	185.81	69.21	1.88	
Ngongotaha		2855.43	881.15		3758.60	192.23	57.83	8.69		
Ngongotaha township					4.12	0.02	53.65	16.70		
Pohue Bay	29.14	60.67	83.10		260.39	18.32			8.45	
Puarenga	13.58	866.71	3143.31		3197.91	310.93	337.36	172.37	9.29	8.59
Rotokawa	28.99	255.46	37.41		1783.08	127.72	127.55		17.66	15.69
Utuhina		1594.72	1060.21		1871.78	10.40	1109.2	284.32	0.00	
Waimehia	5.55	98.52			976.40	53.70	19.48		0.05	
Waingaehe		38.77	152.82		793.54	27.32	45.58		0.20	
Waiohewa	41.32	268.83	66.86		751.55	69.19			0.02	
Waiowhiro		119.78	23.66		686.70	101.86	487.72	56.56	1.17	
Waitawa	0.82		41.86		678.81	26.24	326.58	18.75	15.09	8.74
Waiteti	59.65	2034.80	107.86		4139.93	418.32	52.17	8.04		47.19
Whangamarino	0.34				0.78				0.01	
Grand Total	252.8	9427.5	6435.4	4.0	22371.1	1683.6	2824.3	636.4	8079.2	111.7

2.1.6 Hydrodynamics

Lake Rotorua is a eutrophic polymictic lake with brief periods of stratification (days to weeks) during the summer, interspersed with well mixed conditions. The annual temperature range is 8-23°C.

2.2 Water Balance

A water balance was constructed as part of this study and to run the hydrodynamic model DYRESM. It was first necessary to carry out a water balance in order to determine indirectly the total lake inflows based on the other constituents of the water balance. The water balance was initially developed for the time period Jan-1992 to Dec-1995. However, this was later extended to include Oct-1967 to Nov-2003. A monthly mean evaporation rate was applied to the latter period, since the meteorological data for the Rotorua Airport meteorological station extended back only as far as 1980.

2.2.1 Available Data

The available data to carry out the water balance included:

Ohau Channel Outflow: this is the only surface outflow from the lake and the daily record is relatively complete. Missing data were completed by linear interpolation between the closest available data (Figure 6).

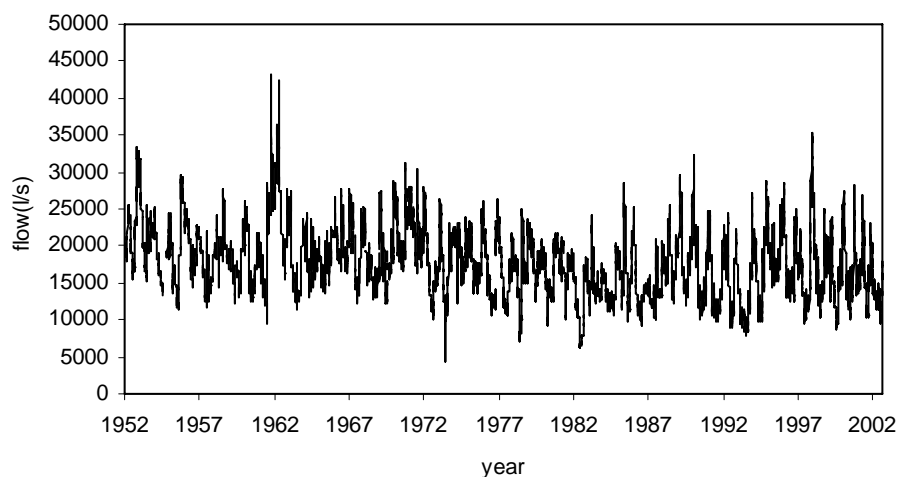


Figure 6. Daily flow in the Ohau Channel, 1952-1967.

Rainfall: the “Kaituna at Whakarewarewa” station has a very complete rainfall record, from 1899 to 2004. Two periods of missing data (< 7 days) were substituted with rainfall values of zero. The mean total annual rainfall at this station is approximately 1.5m.

Water Level: the “Lake Rotorua at Mission Bay” and “Lake Rotorua at Lake Rotorua Wharf” stations have been used to record lake levels from 1934 to date. The first station was used to develop the water balance calculation (see Figure 7).

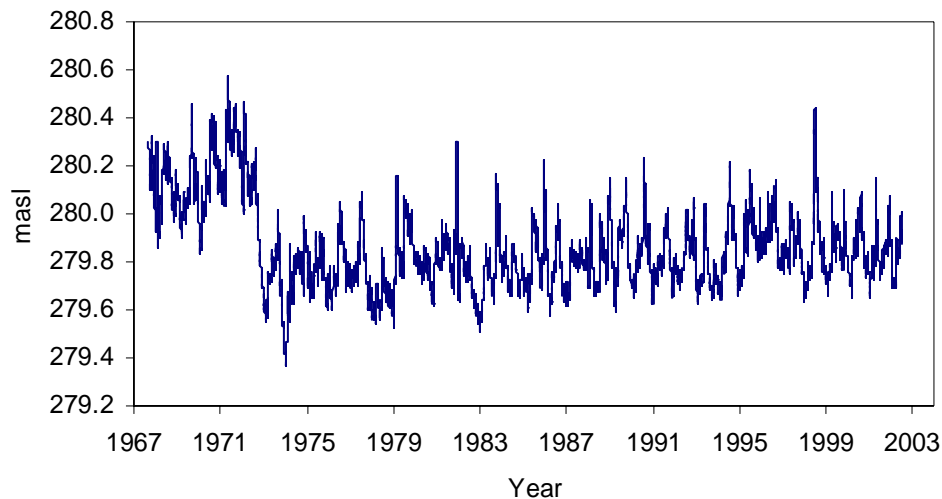


Figure 7. Time series in Lake Rotorua of water levels as meters above sea level (October 1967 – July 2002).

The effect of dredging and the ultimate implementation of a 'cut' in the Ohau Channel to reduce the relatively high water levels in Lake Rotorua immediately preceding this time are clearly illustrated in the water level record of Figure 7 (around 1972). The recommended maximum and minimum water levels of 280.071 and 279.461m, respectively, have been in operation by the Bay of Plenty Catchment Commission (and subsequently Environment Bay of Plenty) since shortly after that time (see copy of electronic mail from John McIntosh, Appendix 1).

Bathymetry: Based on the record of water level, the difference between the maximum and minimum throughout the whole record is less than 1.5m. The relatively small adjustments in lake area exposed to evaporation and rainfall were therefore not taken into account, and volumes contributed from rainfall and evaporation were estimated using a lake surface area of 79.0 km².

2.2.2 Estimated Data

2.2.2.1 Evaporation

The section describes the methodology used to determine lakewater evaporation and follows the description given in the Science Manual available through <http://www2.cwr.uwa.edu.au/~ttfadmin/>. The latent (evaporative) heat flux was estimated as (Fischer et al. 1979, Equation (1)):

$$Q_{lh} = \min\left(0, \frac{0.622}{P} C_L \rho_A L_E U_a (e_a - e_s(T_s)) \Delta t\right) \quad (1)$$

Where P is the atmospheric pressure in hectapascals, C_L is the latent heat transfer coefficient ($= 1.3 \times 10^{-3}$) for wind speed at the reference height of 10 m, ρ_A the density of air in kg m^{-3} , L_E the latent heat of evaporation of water ($= 2.453 \times 10^6 \text{ J kg}^{-1}$), U_a is the wind speed in m s^{-1} at the reference height of 10 m, e_a the vapour pressure of the air, and e_s the saturation vapour pressure at the water surface temperature T_s , both vapour pressures are measured in hectapascals. The condition that $Q_{lh} \leq 0$ is to remove condensation effects.

The saturated vapour pressure e_s is calculated using the Magnus-Tetens formula (TVA 1972, Equation 2):

$$e_s(T_s) = \exp\left[2.3026 \left(\frac{7.5T_s}{T_s + 237.3} + 0.7858\right)\right] \quad (2)$$

The change in mass in the surface layer (layer number N) due to latent heat flux is calculated as

$$\Delta M_N^{(lh)} = \frac{-Q_{lh} A_N}{L_V} \quad (3)$$

where A_N is the area of the surface layer and $L_V = 2.258 \times 10^9 \text{ J kg}^{-1}$ is the latent heat of vaporisation for water.

To estimate the surface temperature of water in the lake, a cosine model was developed of lake water temperature versus time was developed using a least squares fit:

$$T_s = A \cos(\omega t + \varphi) + T_0 \quad (4)$$

Where T_s is the estimated water temperature, A is the amplitude calculated from the least squares fit, ω is the angular frequency and equal to $2\pi/365$ (the year period), ϕ is the phase angle such that 21 December gives the maximum cosine value, T_0 is the mean water temperature estimated from the least squares method, and t is time in days. Figure 8 shows a comparison between the model temperatures and the field data.

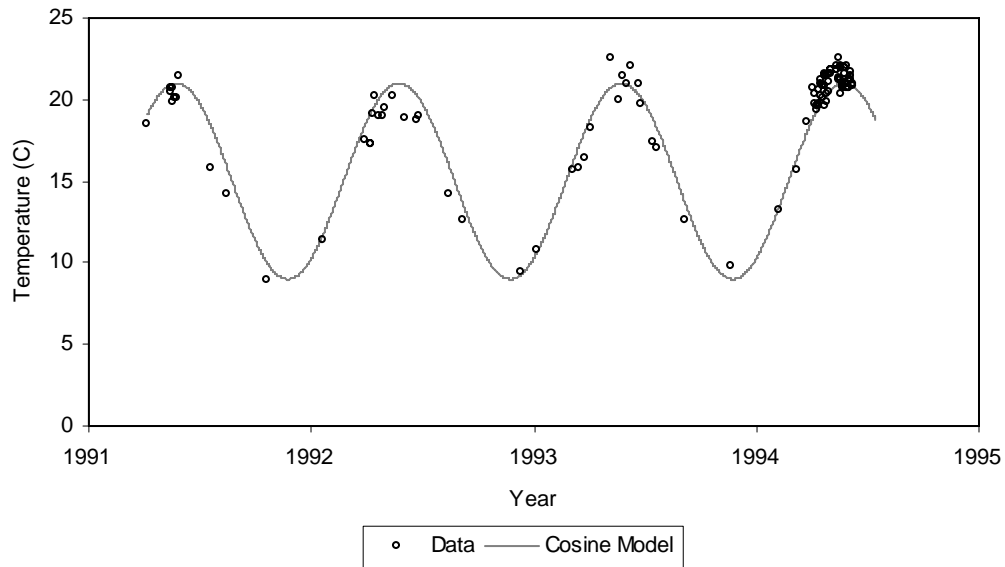


Figure 8. Water surface temperatures in Lake Rotorua. Continuous line shows the cosine function adjusted to surface data and circles show field data.

A sensitivity analysis was undertaken for the A and T_0 parameters (Table 3). Water temperature is a critical component of the evaporation rate. A variation of only 2 or 3°C produces a variation of around 30-40 % in the evaporation rate. The selected value of T_0 is also highly important.

Table 3. Sensitivity analysis of A and T_0 parameters. Figures in bold are selected values.

A	To	Evap mm/year	% difference
4	15	1197	-4%
5	15	1221	-2%
6	15	1251	0%
7	15	1288	3%
8	15	1334	7%
6	13	882	30%
6	14	1059	15%
6	16	1456	16%
6	17	1673	34%
8	17	1757	40%

Other meteorological data required for estimates of the latent heat flux in Equation (1) were available Rotorua Airport Meteorological Station.

2.2.2.2 Inflow Calculations

With estimates of the contribution to the water balance of evaporation, it is possible to determine the total inflow volume using the following equation:

$$\frac{\partial V}{\partial t} = V_{in} - V_{out} = Inflows + Rain - Outflow - Evaporation \quad (5)$$

$\frac{\partial V}{\partial t}$ can be approximated by $\frac{\Delta V}{\Delta t} = \frac{A(L(t+1) - L(t))}{\Delta t}$, where A is the lake area (assumed to be 79.0 km²), and $L(t)$ is the water level at time t in days.

With these assumptions the total volume of the inflows can be calculated for the period 1967-2003. To rectify any numerical problems and bias errors, e.g., negative inflow values on some days, it was necessary to use 7-day averaged data (Figure 9 and 10). The average daily inflow was estimated to be 12,795 L/s for 1992-1995 (see Figure 9) and 16,459 L/s for 1967-2003 (see Figure 10).

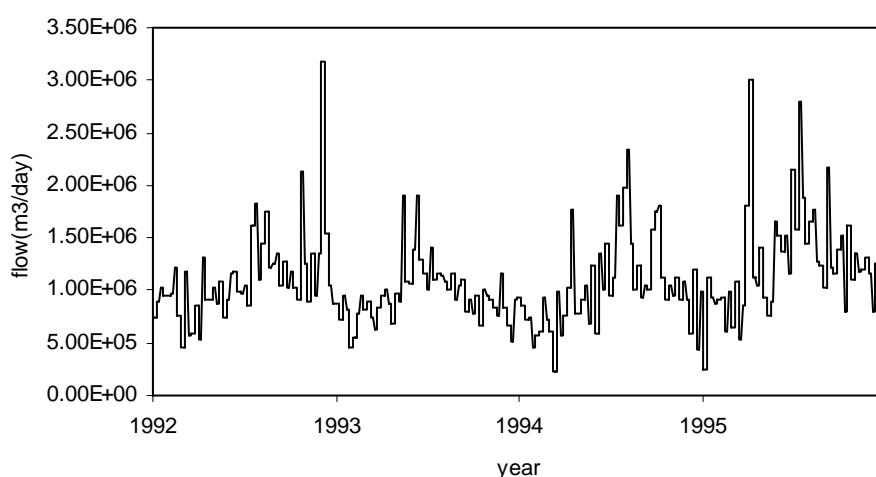


Figure 9. Total daily inflow (7-day average) into Lake Rotorua estimated from the water balance of 1992-1995.

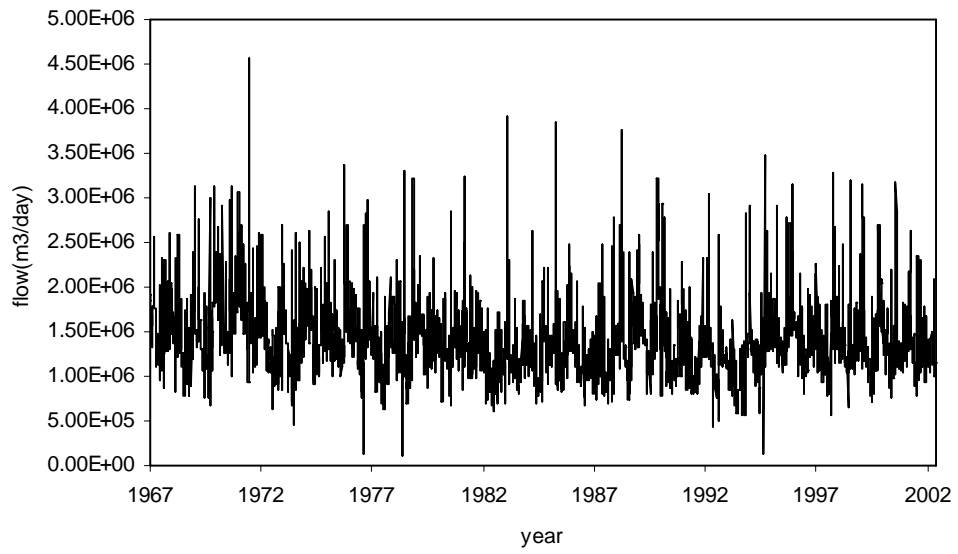


Figure 10. Total daily inflow (7-day average) into Lake Rotorua estimated from the water balance of 1967-2003.

2.3 Catchment Analysis

This section outlines the steps taken to obtain accurate flow estimates for the individual inflows to Lake Rotorua. The main inflows are Awahou, Hamurana, Ngongotaha, Puarenga, Utuhina, Waingaehe, Waiohewa, Waiowhiro and Waiteti. Figures 11 and 12 show the availability of information and the discharge for each of the streams. The highest frequency of discharge measurements is in the period 1992-1994.

Table 4. Flow from main inflows to Lake Rotorua based on the available data (see Figure 11).

Stream Name	Station Name	Mean flow (L/s)	Measure Type
Awahou	Awahou at Tauranga Direct Road	1708.3	C
Basley	Basley Road Stream	9.47	G
Black	Black Stream	6.12	G
Cooksons	Cooksons Wash SH Culvert	0.83	G
Fenton	Fenton Street Drain	0.13	G
Hamurana	Hamurana at Hamurana Rd Br	2475.8	G
Hauraki	Hauraki Fryer	5.19	G
Lee	Lee Rd Trib.	20.67	G
Lynmore	Lynmore Stream	52.78	G
Ngongotaha	Ngongotaha Stream	1792.8	F
Pipe	Pipe Stream	3.03	G
Polynesian North	Polynesian Springs - North	11.39	G
Polynesian South	Polynesian Springs - South	1.14	G
Puarenga	Puarenga Stream at F.R.I Station	1768.1	F
Roto-a-tamaheke	Roto-a-tamaheke at Path	28.0	C-F
Sewer	Sewer Stream	13.75	G
Springs	Springs Outlet	1.54	G
Swamp	Swamp	31.22	G
Te Ahipukahu	Te Ahipukahu Trib.	61.72	G
Te Ngae	Te Ngae Road Drain	25.67	G
Tunuhopu	Tunuhopu Springs	6.58	G
Utuhina	Utuhina River at S.H. Bridge	1968.5	F
Waingaehe	Waingaehe Stream at SH Bridge	221.3	F
Waiohewa	Waiohewa at SH Bridge	310.5	C
Waiowhiro	Waiowhiro Bonningtons Farm	322.6	C
Waiteti	Waiteti at Tauranga Rd Br	1266.9	F
Total		12114	
C=Chart recorder F=Punch Tape recorder G=Gaugings only			

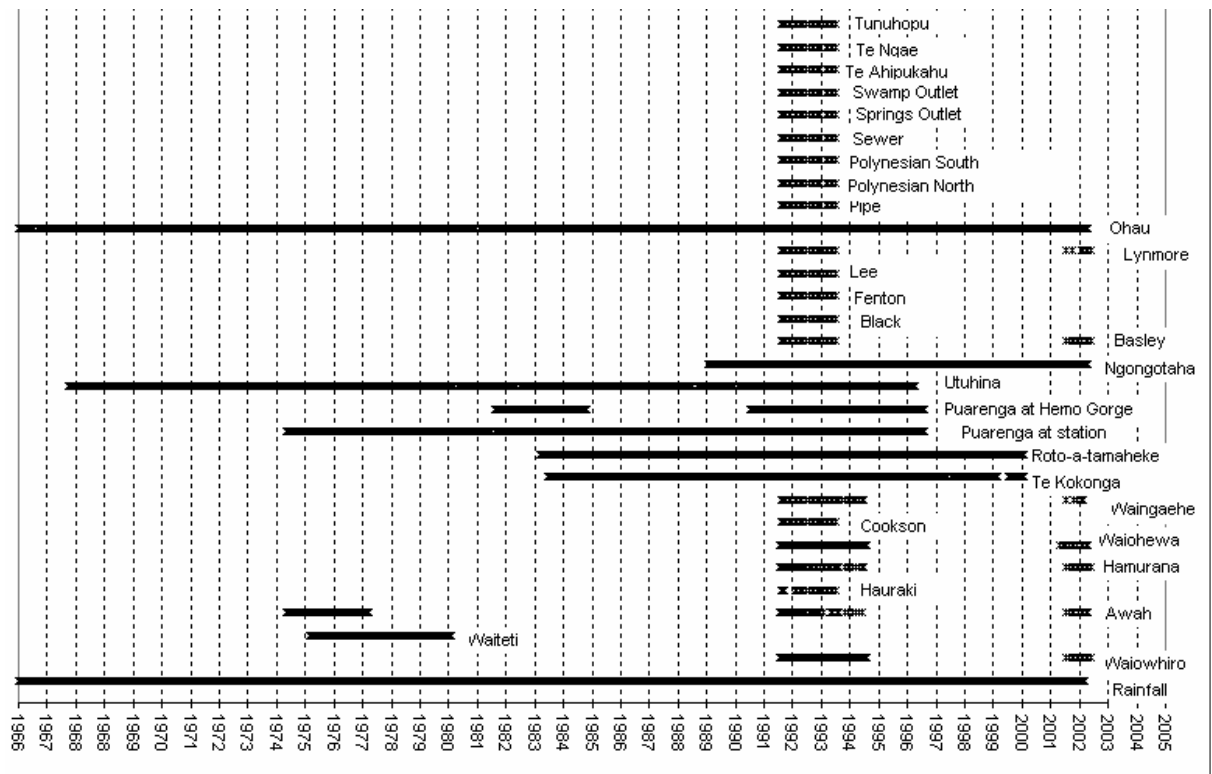


Figure 11. Data availability of Lake Rotorua stream flows.

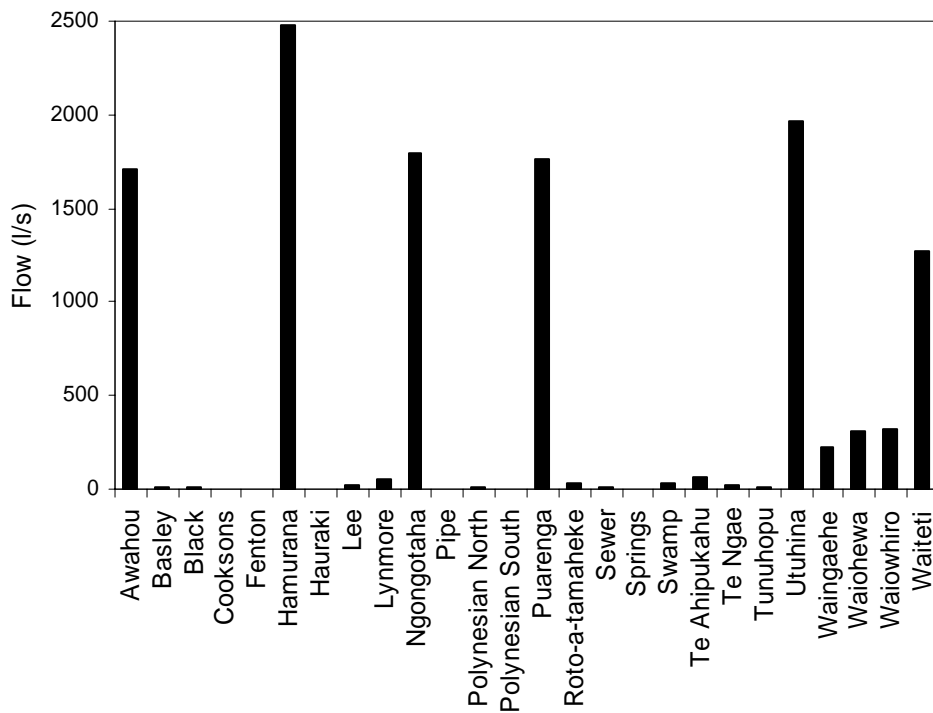


Figure 12. Mean daily flows to Lake Rotorua.

In some cases discharge measurements were not made at the entry to the lake, but any variation between this point and the gauging point could generally be considered negligible. The Hamurana Stream is the largest inflow and is almost entirely spring-fed. Its catchment area is small compared with other streams and it seems improbable that the contribution to the streamflow arises solely from the sub-catchment represented by Figure 5. It is likely that neighbouring basins and a more extensive catchment contribute to this inflow (Morgenstern, 2004).

Figure 13 and Figure 14 show the time series for the major and minor stream inflows, respectively, as a time series over periods when data are available. Collectively, Ngongotaha and Hamurana contribute 35% of the total inflow to Lake Rotorua (Figure 12). These streams have the poorest correlations, however, of the continuously gauged stream stations with any of the other stations and this clearly has an impact on the accuracy of the water and nutrient balance.

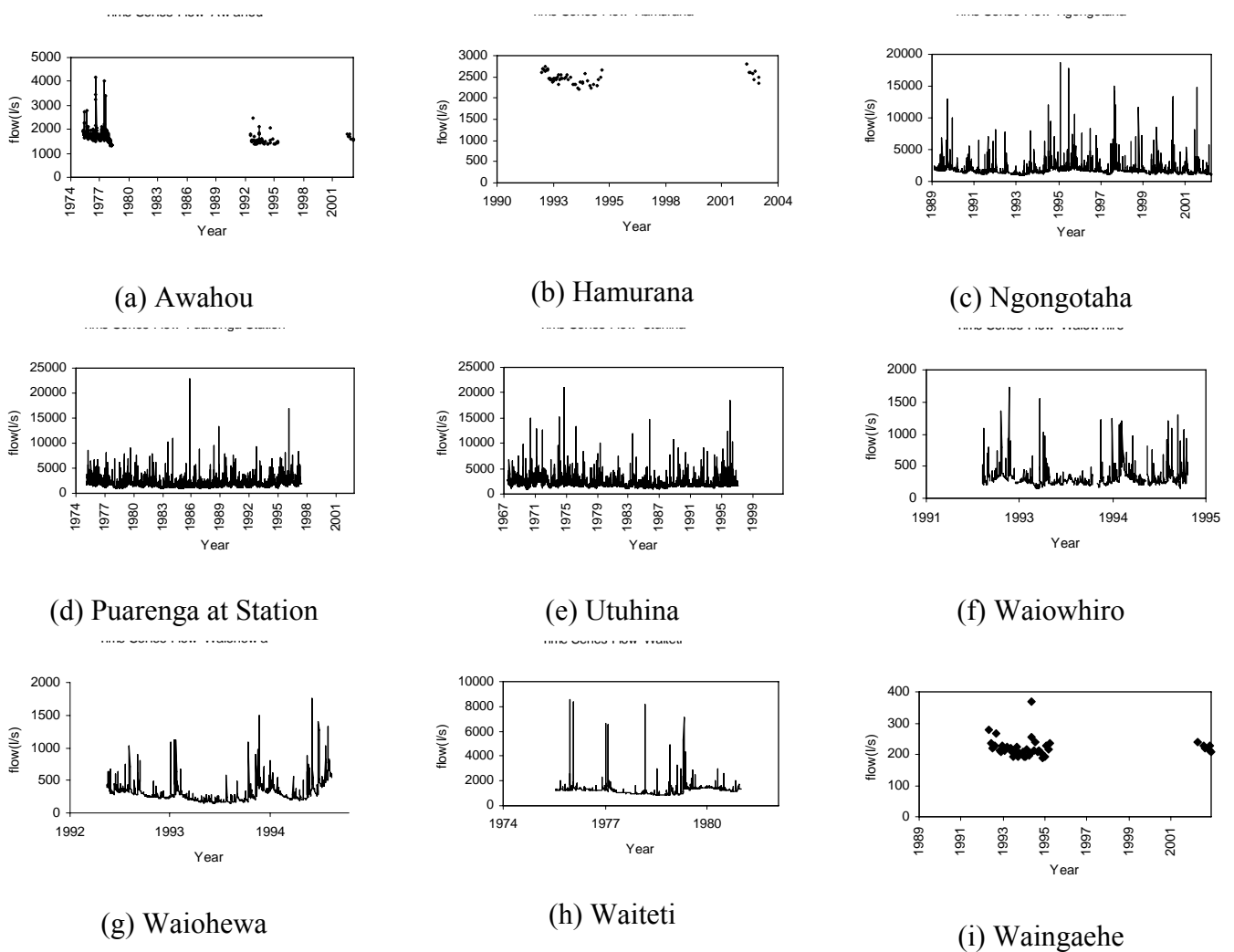


Figure 13. Time series of flow in the major tributaries to Lake Rotorua.

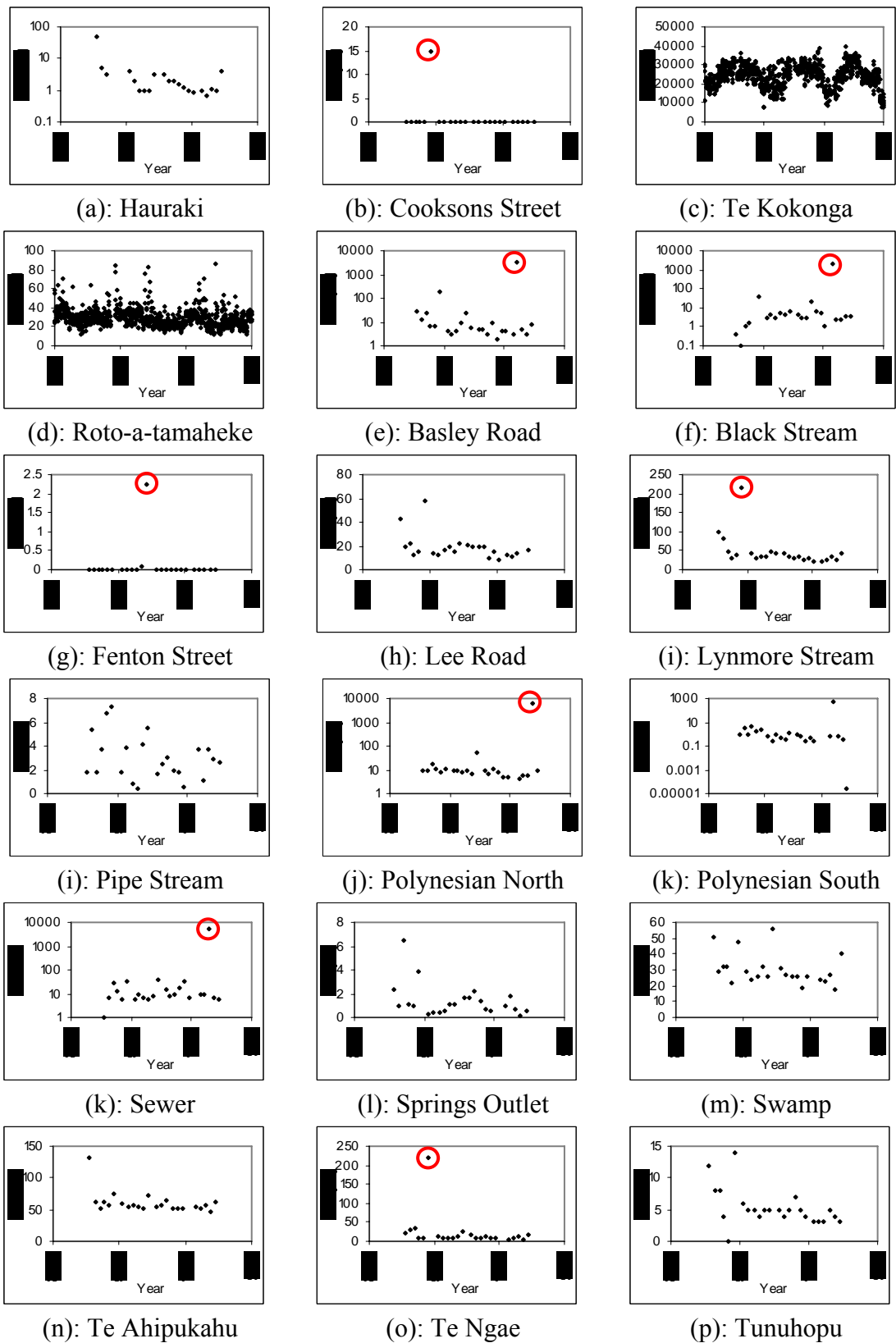


Figure 14. Time series of flow in the minor tributaries to Lake Rotorua. Note: discharge in Te Kokonga Stream may be is over-estimated by three orders of magnitude, and it is therefore excluded from the analysis. Other high values excluded are circled.

2.3.1 Flow Correlations

In order to extend the inflow time series to cover an extensive period over which data have been collected and to eventually extend the period of hydrodynamic modelling for Lake Rotorua, correlations were carried out of daily and 30-day averaged flows. Tables 5 and 6 show the correlation coefficient matrix between all of the inflows. Values of the correlation coefficient that exceed 0.65 are denoted by bold font.

The Waiowhiro, Puarenga and Waiohewa flows are closely correlated with the Utohina flow. The significance of this correlation is that the Utohina record extends from 1967 until 1997.

In order to estimate flows for streams where the record was intermittent, 30-day averaged correlations were also carried out (Table 6). This analysis has been used to estimate missing data from non-continuous records based on the appropriate correlation from the continuous data. It is evident that, overall, correlations of Utohina with other inflows are consistently better than for other streams, based on both daily and 30-day averaged data. Tables 7 and 8 summarise the highest correlated station flow and the correlation of flow in the Utohina Stream for the main tributaries to Lake Rotorua, based on daily and 30-day averaged data respectively. Flow in most of the major streams can be estimated from the continuous flow data. Ngongotaha and Hamurana streams show low correlation coefficients, however, and cannot be estimated using this method.

Table 5. Correlation coefficients for daily flow data.

Correlation Matrix Daily Data	Waiteti at Tauranga Rd	0.82
	Waikohiro Bonningtons	0.00
	Waiohewa at SH Bridge	0.13
	Waingaehe Stream at	0.69
	Utuhina River at S.H. Bridge	0.84
	Tunuhopu Springs	0.37
	Te Ngae Road Drain	0.10
	Te Kokonga at Bath House	0.10
	Te Ahiopekahu Trib	0.80
	Swamp	0.66
	Springs Outlet	0.26
	Sewer Stream	-0.27
	Roto-a-tamaheke at	0.63
	Rainfall mm	0.02
	Puaranga Stream at	0.46
	Puaranga at Herra Gorge	0.05
	Polmesian Springs -	0.20
	Polmesian Springs -	-0.32
	Pipe Stream	0.08
	Oahu Channel	0.36
	Ngongotaha Stream	0.46
	Lynmore Stream	0.16
	Lee Rd Trib	0.40
	Hauraki Fryer	0.74
	Hamurana at Hamurana Rd	0.46
	Fenton Street Drain	0.26
	Cooksons Wash	0.01
	Black Stream	-0.10
	Basley Road Stream	0.02
	Awahou at Tauranga	0.02
	Awahou at Tauranga Direct Road	0.01
	Basley Road Stream	-0.05
Black Stream	-0.10	
Cooksons Wash SH Culvert	0.01	
Fenton Street Drain	0.26	
Hamurana at Hamurana Rd Br	0.74	
Hauraki Fryer	0.46	
Lee Rd Trib	0.40	
Lynmore Stream	0.16	
Ngongotaha Stream	0.46	
Oahu Channel	0.36	
Pipe Stream	0.08	
Polmesian Springs - North	-0.32	
Polmesian Springs - South	0.20	
Puaranga at Herra Gorge	0.05	
Puaranga Stream at F.R.I Station	0.46	
Rainfall mm	0.02	
Roto-a-tamaheke at Path	0.63	
Sewer Stream	-0.27	
Springs Outlet	0.26	
Swamp	0.66	
Te Ahiopekahu Trib	0.80	
Te Kokonga at Bath House	0.10	
Te Ngae Road Drain	0.05	
Tunuhopu Springs	0.37	
Utuhina River at S.H. Bridge	0.84	
Waingaehe Stream at SH Bridge	0.69	
Waiohewa at SH Bridge	0.13	
Waikohiro Bonningtons	0.00	
Waiteti at Tauranga Rd	0.82	

Table 6. Correlation coefficients for 30-day averaged flow data.

Correlation Matrix 30 Days Averaged Data		Waiwhiro Bonningtons	Waikawa at SH Bridge	Waingaehe Stream at SH	Utuhina River at S.H. Bridge	Tunuhapu Springs	Total Rain(mm)	Te Ngae Road Drain	Te Kokonga at Bath House	Te Ahipukahu Trib.	Swamp	Springs Outlet	Sewer Stream	Roto-a-tamaheke at	Puarenga Stream at F.R.I	Puarenga at Hemo Gorge	Polynesian Springs - South	Polynesian Springs - North	Pipe Stream	Ohau Channel	Ngongotaha Stream	Lynmore Stream	Lee Rd Trib.	Hauraki Fryer	Hamurana at Hamurana Rd	Fenton Street Drain	Cooksons Wash SH Culvert	Black Stream	Basley Road Stream	Awahou at Tauranga Direct	
Awahou at Tauranga Direct Road		0.46	0.48	0.46	0.46	0.28	0.25	-0.03	0.35	0.28	0.36	0.07	-0.26	0.41	0.44	0.29	0.29	0.51	0.56	0.41	0.02	0.08	0.37	0.81	0.45	-0.07	-0.16	-0.08	-0.08		
Basley Road Stream	-0.08		0.53	0.48	0.46	0.28	0.25	-0.03	0.35	0.28	0.36	0.07	-0.26	0.41	0.44	0.29	0.29	0.51	0.56	0.41	0.02	0.08	0.37	0.81	0.45	-0.07	-0.16	-0.08	-0.08		
Black Stream	-0.16	-0.05		0.48	0.46	0.28	0.25	-0.03	0.35	0.28	0.36	0.07	-0.26	0.41	0.44	0.29	0.29	0.51	0.56	0.41	0.02	0.08	0.37	0.81	0.45	-0.07	-0.16	-0.08	-0.08		
Cooksons Wash SH Culvert	-0.07	0.00	-0.03		0.48	0.28	0.25	-0.03	0.35	0.28	0.36	0.07	-0.26	0.41	0.44	0.29	0.29	0.51	0.56	0.41	0.02	0.08	0.37	0.81	0.45	-0.07	-0.16	-0.08	-0.08		
Fenton Street Drain	0.46	0.48	0.46		0.46	0.28	0.25	-0.03	0.35	0.28	0.36	0.07	-0.26	0.41	0.44	0.29	0.29	0.51	0.56	0.41	0.02	0.08	0.37	0.81	0.45	-0.07	-0.16	-0.08	-0.08		
Hamurana at Hamurana Rd	0.61	0.33	-0.25	-0.01		0.46	0.28	0.25	-0.03	0.35	0.28	0.07	-0.26	0.41	0.44	0.29	0.29	0.51	0.56	0.41	0.02	0.08	0.37	0.81	0.45	-0.07	-0.16	-0.08	-0.08		
Hauraki Fryer	0.37	-0.11	-0.10			0.46	0.28	0.25	-0.03	0.35	0.28	0.07	-0.26	0.41	0.44	0.29	0.29	0.51	0.56	0.41	0.02	0.08	0.37	0.81	0.45	-0.07	-0.16	-0.08	-0.08		
Lee Rd Trib.	0.08	-0.13	-0.14			0.46	0.28	0.25	-0.03	0.35	0.28	0.07	-0.26	0.41	0.44	0.29	0.29	0.51	0.56	0.41	0.02	0.08	0.37	0.81	0.45	-0.07	-0.16	-0.08	-0.08		
Lynmore Stream	0.02	-0.05	-0.12			0.46	0.28	0.25	-0.03	0.35	0.28	0.07	-0.26	0.41	0.44	0.29	0.29	0.51	0.56	0.41	0.02	0.08	0.37	0.81	0.45	-0.07	-0.16	-0.08	-0.08		
Ngongotaha Stream	0.41	-0.20	-0.28			0.46	0.28	0.25	-0.03	0.35	0.28	0.07	-0.26	0.41	0.44	0.29	0.29	0.51	0.56	0.41	0.02	0.08	0.37	0.81	0.45	-0.07	-0.16	-0.08	-0.08		
Ohau Channel	0.61	-0.24	-0.27			0.46	0.28	0.25	-0.03	0.35	0.28	0.07	-0.26	0.41	0.44	0.29	0.29	0.51	0.56	0.41	0.02	0.08	0.37	0.81	0.45	-0.07	-0.16	-0.08	-0.08		
Pipe Stream	0.65	-0.21	-0.10			0.46	0.28	0.25	-0.03	0.35	0.28	0.07	-0.26	0.41	0.44	0.29	0.29	0.51	0.56	0.41	0.02	0.08	0.37	0.81	0.45	-0.07	-0.16	-0.08	-0.08		
Polynesian Springs - North	-0.30	-0.05	-0.05			0.46	0.28	0.25	-0.03	0.35	0.28	0.07	-0.26	0.41	0.44	0.29	0.29	0.51	0.56	0.41	0.02	0.08	0.37	0.81	0.45	-0.07	-0.16	-0.08	-0.08		
Polynesian Springs - South	0.28	1.00	-0.05	-0.06	-0.41		0.46	0.28	0.25	-0.03	0.35	0.28	0.07	0.41	0.44	0.29	0.29	0.51	0.56	0.41	0.02	0.08	0.37	0.81	0.45	-0.07	-0.16	-0.08	-0.08		
Puarenga at Hemo Gorge	0.44	-0.19	-0.28	0.61	0.27	0.41		0.46	0.28	0.25	-0.03	0.35	0.28	0.08	0.44	0.29	0.29	0.51	0.56	0.41	0.02	0.08	0.37	0.81	0.45	-0.07	-0.16	-0.08	-0.08		
Puarenga Stream at F.R.I Station	0.41	-0.20	-0.26	0.60	0.34	0.40	0.34		0.46	0.28	0.25	-0.03	0.35	0.28	0.08	0.44	0.29	0.29	0.51	0.56	0.41	0.02	0.08	0.37	0.81	0.45	-0.07	-0.16	-0.08		
Roto-a-tamaheke at Path	0.23	0.20	0.14	0.59	0.20	0.04	0.35	0.01		0.46	0.28	0.25	-0.03	0.35	0.28	0.08	0.44	0.29	0.29	0.51	0.56	0.41	0.02	0.08	0.37	0.81	0.45	-0.07	-0.16		
Sewer Stream	-0.26	-0.05	-0.05	-0.05	-0.46	-0.09	-0.11	-0.07	-0.09		0.46	0.28	0.25	-0.03	0.35	0.28	0.08	0.44	0.29	0.29	0.51	0.56	0.41	0.02	0.08	0.37	0.81	0.45	-0.07		
Springs Outlet	0.07	0.00	-0.07	0.40	-0.06	0.42	0.11	0.63	0.46	0.32		0.46	0.28	0.25	-0.03	0.35	0.28	0.08	0.44	0.29	0.29	0.51	0.56	0.41	0.02	0.08	0.37	0.81	0.45		
Swamp	0.36	-0.16	-0.14	0.44	0.64	0.25	0.41	0.68	0.56	0.41	0.68		0.46	0.28	0.25	-0.03	0.35	0.28	0.08	0.44	0.29	0.29	0.51	0.56	0.41	0.02	0.08	0.37	0.81		
Te Ahipukahu Trib.	0.36	-0.10	-0.09	0.32	0.27	0.43	0.20	0.61	0.16	0.18	0.16	0.18		0.46	0.28	0.25	-0.03	0.35	0.28	0.08	0.44	0.29	0.29	0.51	0.56	0.41	0.02	0.08	0.37		
Te Kokonga at Bath House	0.36	-0.26	-0.42	-0.08	0.17	0.61	0.16	0.18	0.16	0.18	0.16	0.18	0.18		0.46	0.28	0.25	-0.03	0.35	0.28	0.08	0.44	0.29	0.29	0.51	0.56	0.41	0.02	0.08		
Te Ngae Road Drain	-0.03	-0.03	-0.08	0.59	0.01	0.07	0.48	0.32	0.56	0.48	0.32	0.56	0.48	0.32		0.46	0.28	0.25	-0.03	0.35	0.28	0.08	0.44	0.29	0.29	0.51	0.56	0.41	0.02		
Total Rain(mm)	0.25	0.12	-0.17	0.57	0.31	0.04	0.30	0.23	0.71	0.70	0.84	0.88	0.50	0.21	0.84		0.46	0.28	0.25	-0.03	0.35	0.28	0.08	0.44	0.29	0.29	0.51	0.56	0.41		
Utuhina River at S.H. Bridge	0.46	-0.14	-0.16	0.68	0.36	0.26	0.56	0.48	0.32	0.56	0.48	0.32	0.56	0.48	0.32	0.56		0.46	0.28	0.25	-0.03	0.35	0.28	0.08	0.44	0.29	0.29	0.51	0.56		
Waingaehe Stream at SH Bridge	0.48	-0.26	-0.08	0.61	0.11	0.42	0.72	0.74	0.72	0.74	0.72	0.74	0.72	0.74	0.72	0.74	0.72		0.46	0.28	0.25	-0.03	0.35	0.28	0.08	0.44	0.29	0.29	0.51		
Waiwhiro Bonningtons Farm	0.65	-0.20	-0.15	0.82	0.26	0.42	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68		0.46	0.28	0.25	-0.03	0.35	0.28	0.08	0.44	0.29	0.29	0.51	
Waikawa at SH Bridge	0.53	-0.20	-0.20	0.44	0.33	0.42	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62		0.46	0.28	0.25	-0.03	0.35	0.28	0.08	0.44	0.29	0.29	0.51
Waikawa at Tauranga Rd Br	0.68	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	

Table 7. Summary of correlation coefficients (*r*) based on daily data.

Stream Station	Highest Correlated Station	Highest r-value	Utuhina r-value
Rainfall (mm)	Ngongotaha Stream	0.43	0.02
Awahou at Tauranga Direct Road	Waiteti at Tauranga Rd Br	0.82	0.64
Basley Road Stream	Awahou at Tauranga Direct Road	0.02	-0.13
Black Stream	Waiohewa at SHBridge	0.31	0.06
Cooksons Wash SHCulvert	Rainfall mm	0.69	0.01
Fenton Street Drain	Waiowhiro Bonningtons Farm	0.92	0.9
Hamurana at Hamurana Rd Br	Ohau Channel	0.52	0.21
Hauraki Fryer	Ngongotaha Stream	0.99	0.06
Lee Rd Trib.	Rainfall mm	0.81	0.15
Lynmore Stream	Rainfall mm	0.8	0.12
Ngongotaha Stream	Awahou at Tauranga Direct Road	0.48	0.32
Ohau Channel	Waiohewa at SHBridge	0.68	0.6
Pipe Stream	Utuhina River at S.H. Bridge	0.51	0.51
Polynesian Springs - North	Te Kokonga at Bath House	0.46	-0.06
Polynesian Springs - South	Waiowhiro Bonningtons Farm	0.22	-0.13
Puarenga at Hemo Gorge	Puarenga Stream at F.R.I Station	0.99	0.91
Puarenga Stream at F.R.I Station	Puarenga at Hemo Gorge	0.99	0.89
Roto-a-tamaheke at Path	Awahou at Tauranga Direct Road	0.53	0.05
Sewer Stream	Roto-a-tamaheke at Path	0.21	-0.02
Springs Outlet	Rainfall mm	0.44	0.01
Swamp	Awahou at Tauranga Direct Road	0.66	0.61
Te Ahipukahu Trib.	Ngongotaha Stream	0.96	0.24
Te Kokonga at Bath House	Ohau Channel	0.22	0.14
Te Ngae Road Drain	Rainfall mm	0.75	0.09
Tunuhopu Springs	Rainfall mm	0.77	0.04
Utuhina River at S.H. Bridge	Puarenga at Hemo Gorge	0.91	1.0
Waingaehe Stream at SHBridge	Ngongotaha Stream	0.66	0.6
Waiohewa at SHBridge	Puarenga at Hemo Gorge	0.86	0.83
Waiowhiro Bonningtons Farm	Utuhina River at S.H. Bridge	0.89	0.89
Waiteti at Tauranga Rd Br	Awahou at Tauranga Direct Road	0.82	0.76

Table 8. Summary of correlation coefficients (*r*) based on 30-day averaged data.

Stream Name	Highest Correlated Station	Highest r-value	Utuhina r-value
Total Rain (mm)	Waiowhiro Bonningtons Farm	0.68	0.5
Awahou at Tauranga Direct Road	Waiteti at Tauranga Rd Br	0.66	0.46
Basley Road Stream	Roto-a-tamaheke at Path	0.2	-0.14
Black Stream	Roto-a-tamaheke at Path	0.14	-0.16
Cooksons Wash SHCulvert	Waiowhiro Bonningtons Farm	0.62	0.58
Fenton Street Drain	Awahou at Tauranga Direct Road	0.45	0.36
Hamurana at Hamurana Rd Br	Awahou at Tauranga Direct Road	0.61	0.26
Hauraki Fryer	Ngongotaha Stream	0.76	0.55
Lee Rd Trib.	Puarenga at Hemo Gorge	0.75	0.71
Lynmore Stream	Puarenga at Hemo Gorge	0.74	0.7
Ngongotaha Stream	Puarenga at Hemo Gorge	0.87	0.84
Ohau Channel	Puarenga at Hemo Gorge	0.84	0.82
Pipe Stream	Utuhina River at S.H. Bridge	0.71	0.71
Polynesian Springs - North	Te Kokonga at Bath House	0.36	-0.01
Polynesian Springs - South	Awahou at Tauranga Direct Road	0.29	-0.16
Puarenga at Hemo Gorge	Puarenga Stream at F.R.I Station	0.99	0.88
Puarenga Stream at F.R.I Station	Puarenga at Hemo Gorge	0.99	0.88
Roto-a-tamaheke at Path	Waiohewa at SHBridge	0.37	0.05
Sewer Stream	Total Rain(mm)	0.16	0.07
Springs Outlet	Ohau Channel	0.57	0.4
Swamp	Puarenga Stream at F.R.I Station	0.76	0.73
Te Ahipukahu Trib.	Ngongotaha Stream	0.77	0.65
Te Kokonga at Bath House	Awahou at Tauranga Direct Road	0.35	0.25
Te Ngae Road Drain	Puarenga at Hemo Gorge	0.7	0.66
Tunuhopu Springs	Puarenga Stream at F.R.I Station	0.57	0.51
Utuhina River at S.H. Bridge	Waiowhiro Bonningtons Farm	0.92	1.0
Waingaehe Stream at SHBridge	Utuhina River at S.H. Bridge	0.81	0.81
Waiohewa at SHBridge	Puarenga Stream at F.R.I Station	0.91	0.87
Waiowhiro Bonningtons Farm	Utuhina River at S.H. Bridge	0.92	0.92
Waiteti at Tauranga Rd Br	Puarenga Stream at F.R.I Station	0.77	0.66

2.3.2 Estimates of flow

The correlations of the preceding section may be used to obtain flow estimates for the major tributaries to Lake Rotorua. The minor inflows contribute less than 8% the total water entering the lake and detailed estimates to obtain a complete water balance are not carried out here. The Utuhina station was used in order to complete the major stream records shown in Figure 13. This gauging station shows good correlations with most of the major streams (Table 8) and has the longest record of discharge.

1. *Utuhina*: The data record was completed with a combination of mean values and linear interpolation between missing data (Figure 15). Mean values were used when the difference between the last and first continuous values was <100 L/s. For the remaining cases, linear interpolation was used.

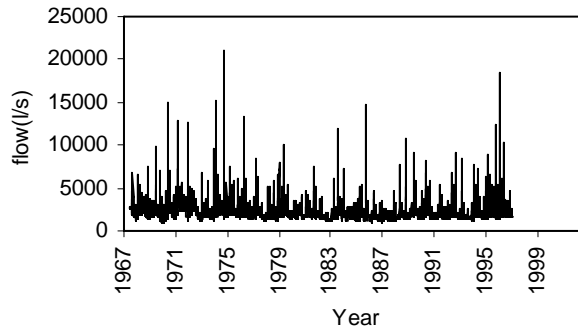


Figure 15. Time series of Utuhina inflows.

2. *Awahou*: These flow data were estimated from those of the Utuhina station (Figure 16). The correlation coefficient (r) with the Utuhina daily flow is 0.67 ($r^2 = 0.41$) (Figure 17).

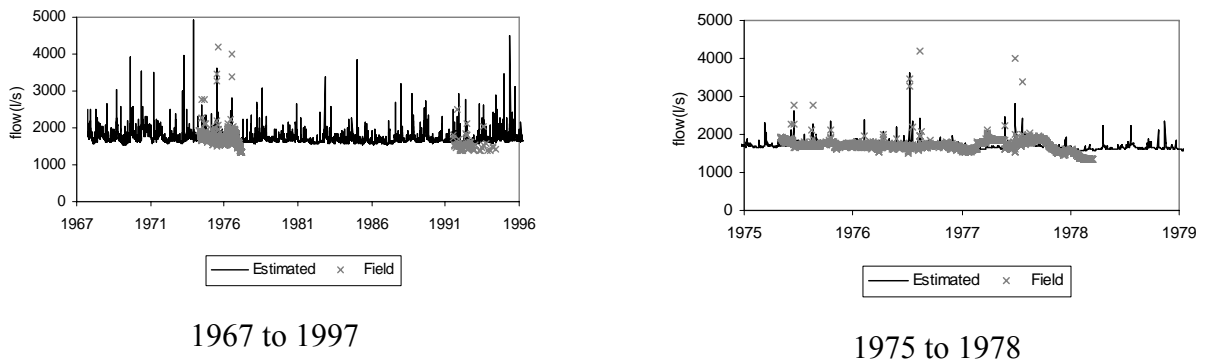


Figure 16. Time series of estimated and measured time series of flows for the Awahou.

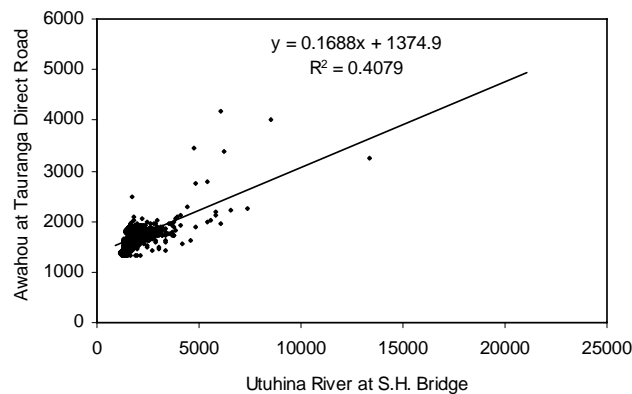


Figure 17. Daily flow correlation between the Awahou and Utuhina inflows.

3. *Hamurana*: The dominant influence of groundwater in the Hamurana Spring means that discharge in this inflow is poorly correlated with any other inflow. For this inflow the discharge was set to a constant equal to the long-term mean value (2475 L/s). Natural variations in discharge may be partly reflected in the groundwater flux estimates that are made below. A trend line fit to variations in this inflow through the monitoring period is not significantly different from zero and indicates that over the limited period of monitoring, there is no discernible trend in discharge (Figure 18).

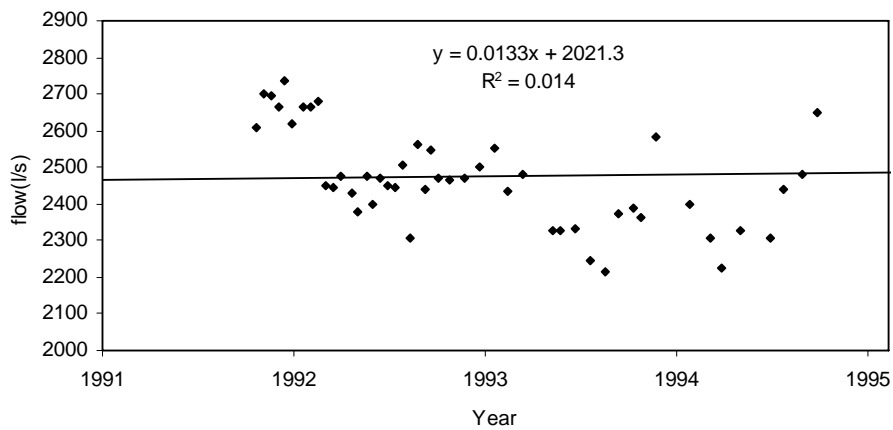


Figure 18. Time series of discharge in Hamurana Spring inflow.

4. *Ngongotaha*: Discharge for this stream (Figure 19) is poorly correlated with any of the continuous daily data records, but shows a reasonable correlation ($r = 0.84$) with the 30-day averaged flows for the Uthina Station ($r^2 = 0.71$, Figure 20). This correlation was used to estimate flows on a continuous basis.

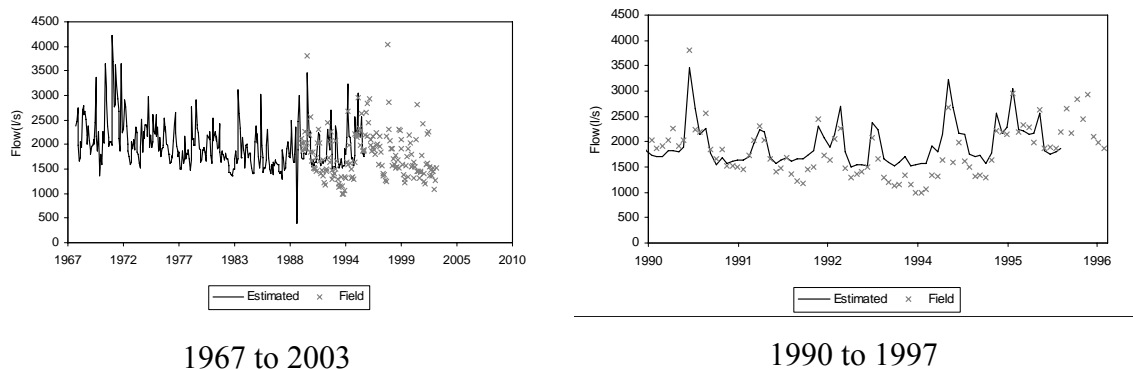


Figure 19. Time series of estimated and measured flows for the Ngongotaha Stream.

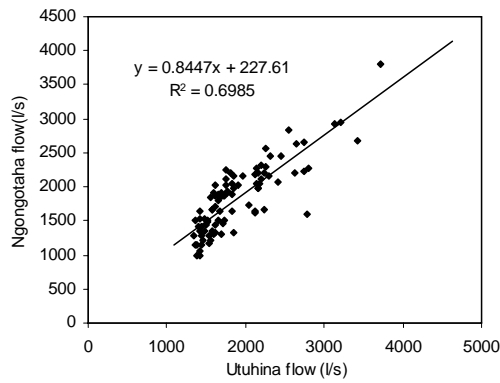


Figure 20. Daily flow correlation between the Ngongotaha and Utuhina stream inflows.

5. *Puarenga at Hemo Gorge*: The broken sequence of records for discharge from this inflow between 1982 and 1997 (Figure 21) was estimated from the close correlation with the Utuhina daily record (Figure 22).

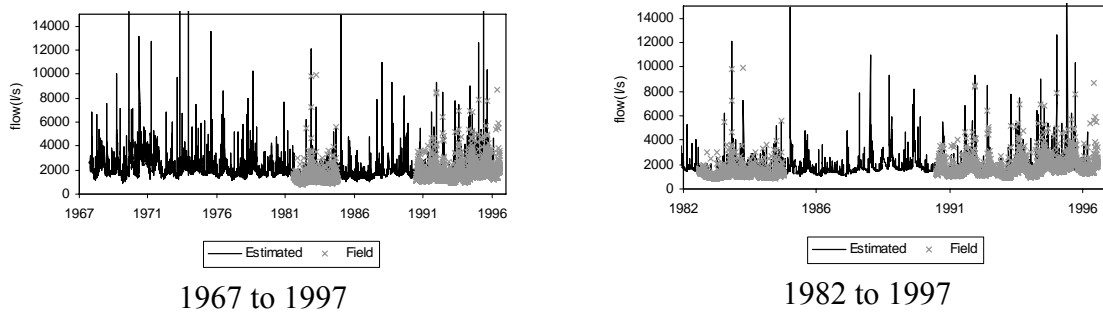


Figure 21. Time series of estimated and measured flows for the Puarenga at Hemo Gorge.

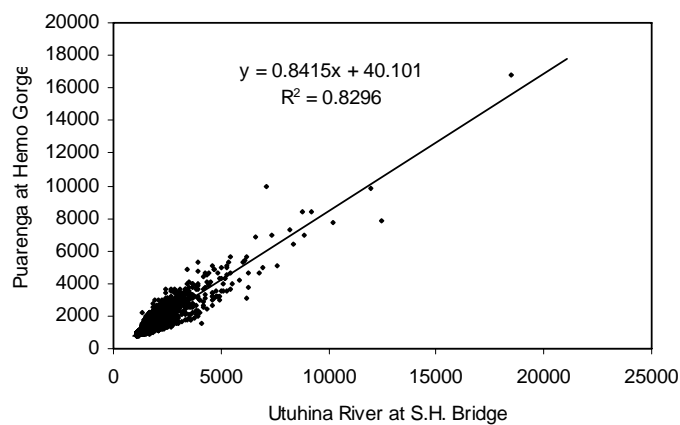


Figure 22. Daily flow correlation between the Puarenga at Hemo Gorge and the Utuhina Stream inflows.

6. *Puarenga*: This stream had continuous flow data series from 1975 to 1997 (Figure 23). Missing data extending back to 1967 were estimated from the Utuhina daily flow time series which were closely correlated with Puarenga (Figure 24).

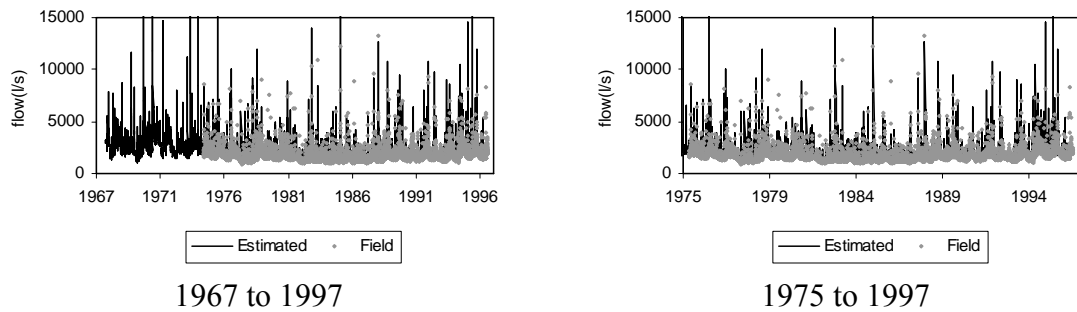


Figure 23. Time series of estimated and measured flows for the Puarenga.

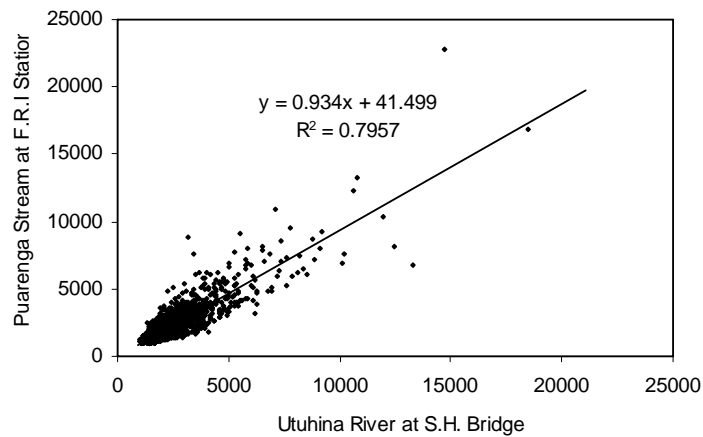


Figure 24. Daily flow correlation between the Puarenga and Utuhina stream inflows.

7. *Waingaehe*: The inflow record for this inflow is fairly continuous from 1992 to 1995 but doesn't commence again until 2001 (Figure 25). For this reason flow estimates were made with 30-day averaged data from the Utuhina Stream inflow (Figure 26).

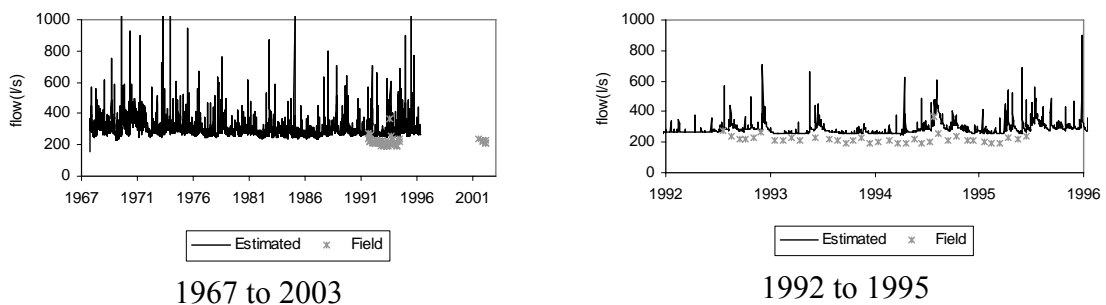


Figure 25. Time series of estimated and measured discharges for the Waingaehe inflow.

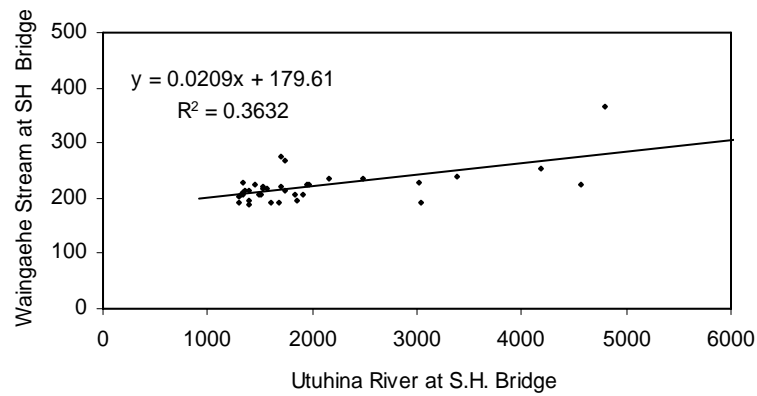


Figure 26. Correlation of 30-day average flows in the Waingaehe Stream versus the Utuhina.

8. *Waiohewa*: The relatively continuous data for this inflow, from 1992 to 1995, were extended between 1967 and 1997 (Figure 27) using the relatively high correlation coefficient ($r = 0.834$) with the Utuhina Stream inflow (Figure 28).

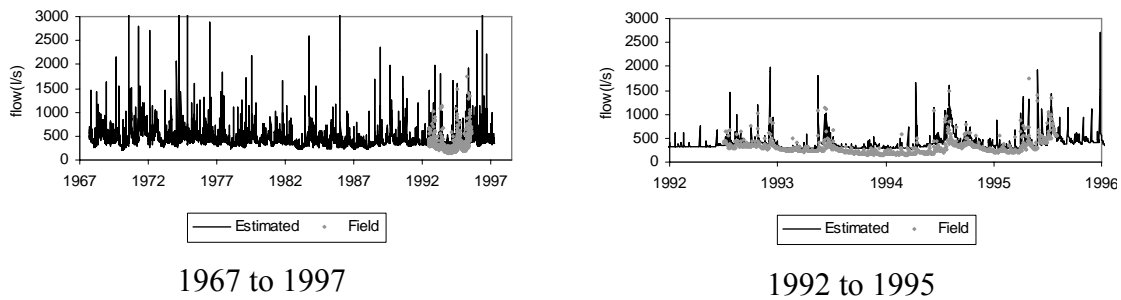


Figure 27. Time series of estimated and measured discharges for the Waiohewa Stream.

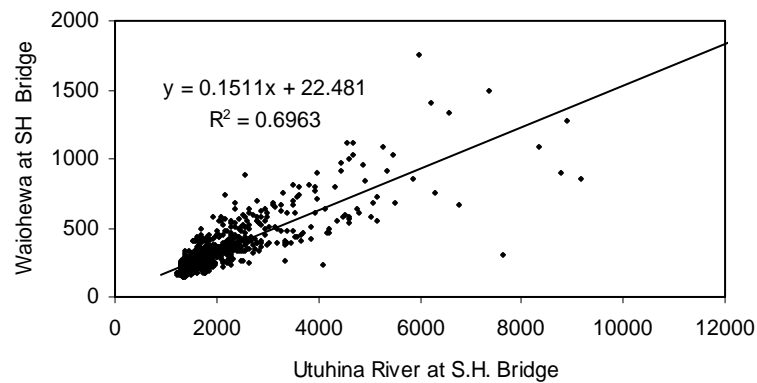


Figure 28. Correlation of daily flows in the Waiohewa versus Utuhina.

9. *Waiowhiro*: This stream was estimated from the Utuhina daily time series. The data are available as a continuous daily record from 1992 to 1995 (Figure 29) and there is a close correlation with the Utuhina discharge (Figure 30).

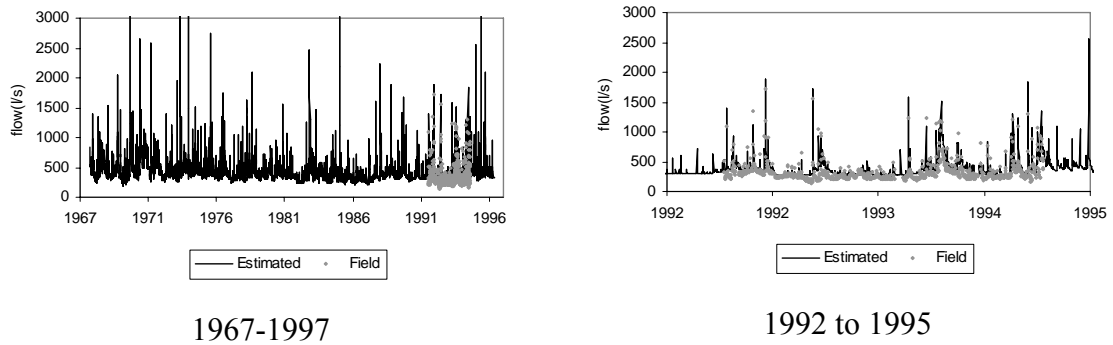


Figure 29. Time series of estimated and measured discharges for the Waiowhiro Stream.

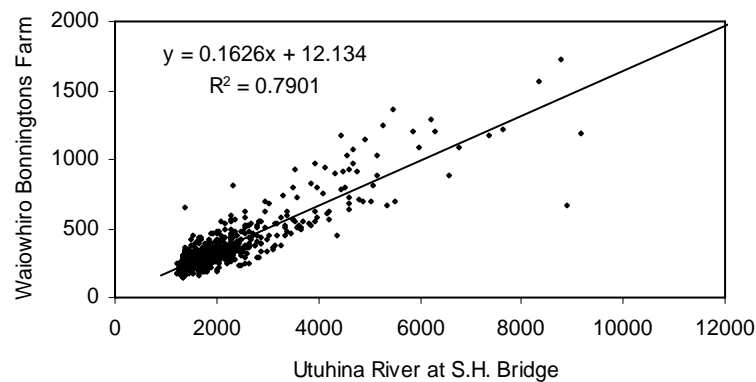


Figure 30. Correlation of daily flows in the Waiowhiro versus Utuhina.

10. *Waiteti*: There is a relatively continuous data set for this inflow from 1976 to 1981 (Figure 31). The discharge was derived from the Utuhina daily record despite the highest correlation which was with the Puarenga Station. This was done to be consistent with preceding calculations. The correlation coefficient of the Waiteti with the Utuhina is 0.76 (Figure 32).

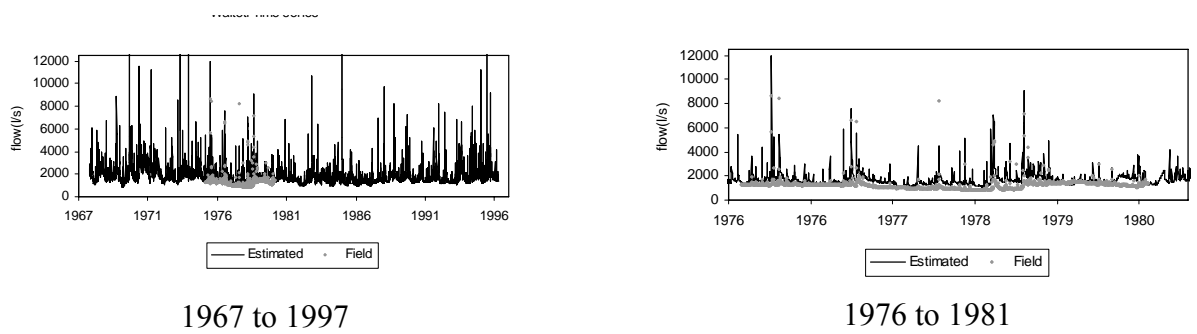


Figure 31. Time series of estimated and measured discharges for the Waiteti Stream.

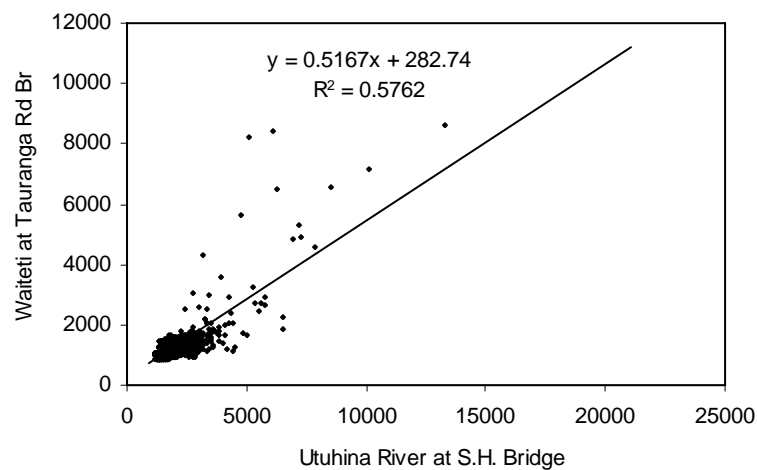


Figure 32. Correlation of daily flows in the Waiteti Stream versus the Utuhina Stream.

2.3.3 Groundwater Estimation

The net groundwater flux into Lake Rotorua was estimated from the difference between the total estimated surface inflows (minor and major) and the inflow calculated from the lake water balance, though in reality this value may include a component of ungauged and local surface flows. On average, the total of the individual surface inflows is 14,063 L/s and the total from the water balance is 16,459 L/s for the period 1967-2003. The difference between these two values is 2,396 L/s, i.e., 15% of the total incoming water to the lake. Figure 33 shows the estimated mean groundwater flux and the mean rainfall over the same period, using 5-yearly mean values. This duration of averaging was used to avoid numerical errors associated with the wide variation of flows and negative values generated because Hamurana and the minor streams were estimated as

constants during the whole period. Groundwater fluctuations on this time scale tend to be coincident with fluctuations in rainfall as shown in Figure 33.

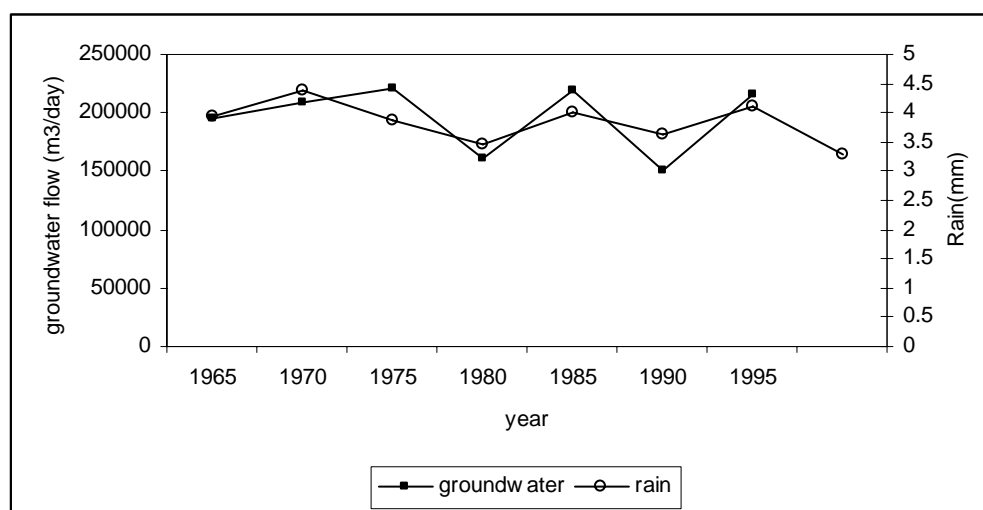


Figure 33. Net daily groundwater flow and daily rainfall. Values are means for the preceding 5 years.

2.3.4 Nutrient Loads

Estimates of nutrient loads into Lake Rotorua are important to identify any trends through time and to identify key catchments or land uses that influence the loads. These estimates will ultimately be an integral part of the water quality modelling that will be undertaken with the water quality model DYRESM-CAEDYM. Total phosphorus and total nitrogen in inflows were measured over the dates shown in Figure 34.

Table 9 shows averages for a range of parameters for the main stream inflows to Lake Rotorua. Total nitrogen (TN) was estimated from the sum of total Kjeldahl nitrogen (TKN) and NO_3 . No attempt was made to correct for sampling bias associated with timing or duration of collection of samples. The Waiohewa Stream has very high concentrations of total nitrogen that reflect correspondingly high levels of ammonium (NH_4) derived originally from geothermal sources. Similarly, levels of TP are high in geothermally-derived inflows (e.g. Polynesian Springs), but do not appear to co-vary with TN. These streams tend to be warm ($> 30^\circ\text{C}$) with low concentrations of dissolved oxygen. Bar graphs of total nitrogen and total phosphorus, shown in Figures 35 and 36 respectively, illustrate graphically the very large variations in nutrient concentrations from the different sources.

Nutrient loads were calculated using mean concentrations of TP and TN for each of the tributaries (Table 9), and multiplying this value by the mean tributary flow. The Awahou Stream is the dominant contributor of nitrogen, with nearly 16% of the total load. Other important contributors are the Utuhina, Puarenga, Ngongotaha and Hamurana Streams. Hamurana Springs is the dominant contributor of phosphorus to the lake with 18.5% of the total load. This is followed by the Utuhina, Puarenga and Awahou Streams. The tributary loadings of TN and TP are shown graphically in Figures 37 and 38 respectively.

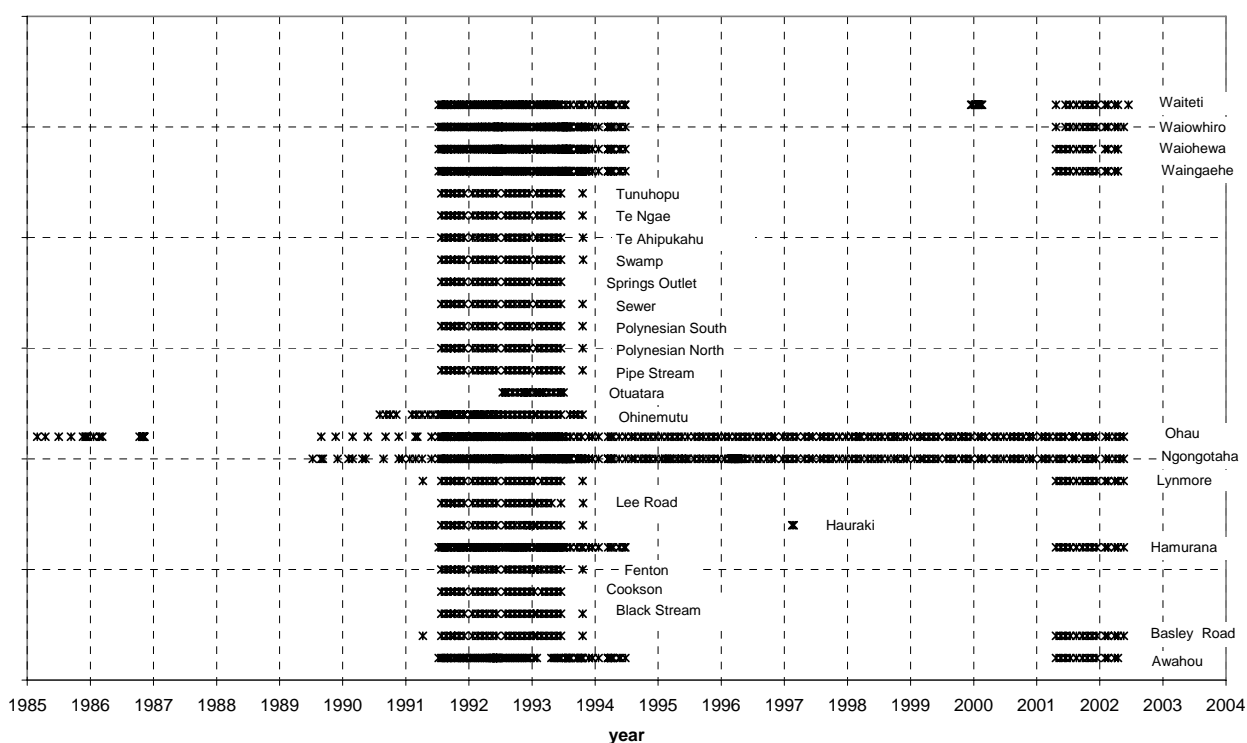


Figure 34. Availability of information on for nutrient concentration in inflows to Lake Rotorua.

Table 9. Mean values for selected water quality parameters for Lake Rotorua inflows. (See data availability of Figure 34 for averaging period).

Stream Name	Flow L/sec	TP mg/m ³	TN mg/m ³	DO mg/l	Temp. °C	Cond. (mS/m)	SS mg/m ³	Turb. NTU	BOD g/m ³	pH
Awahou Stream	1708.3	88.7	1286.2	8.86	12.51	8.77	8.60	0.66	0.54	6.60
Basley Road Stream	9.5	60.2	2629.6	9.44	14.86	12.33	1.66	1.83	0.77	7.11
Black Stream	6.1	333.5	1824.5	3.10	25.90	89.03				5.30
Cookson's Wash	0.8	556.5	2814.0			2.00				6.10
Fenton Street Drain	0.1	73.0	719.8	0.70	15.90	24.78				4.60
Hamurana Stream	2475.8	83.0	699.2	9.55	12.26	8.03	0.89	0.66	0.59	6.62
Hauraki	5.2	50.4	633.9	6.80	13.00	7.06				6.35
Lee Rd Trib.	20.7	89.4	2287.6			13.81				6.75
Lynmore Stream	52.8	87.5	3514.5	9.50	14.58	12.71	3.78	6.78	0.96	7.08
Ngongotaha Stream	1792.8	69.1	1033.8	7.97	11.90	7.27	22.66	4.78	0.75	7.00
Ohinemutu Springs	10.2	96.5	474.9	1.80	45.00	148.55				7.80
Pipe Stream	3.0	210.8	575.9	0.20	24.50	148.51				5.95
Polynesian Springs Nth	11.4	270.9	1333.4	0.40	42.00	233.14				3.25
Polynesian Springs Sth	1.1	397.6	524.7	2.80	36.10	107.52				4.85
Puarenga	1768.1	108.1	1163.6	9.25	16.11	24.89	39.53	7.12	0.88	6.64
Sewer Stream	13.8	330.7	263.5	2.20	31.20	142.67				6.50
Springs Outlet	1.5	362.0	1510.0			156.63				2.60
Swamp	31.2	56.7	2878.0			14.77				6.40
Te Ahipukahu Trib.	61.7	43.6	1147.4	9.60	13.10	6.53				6.70
Te Ngae Road Drain	25.7	333.0	872.2	10.20	23.20	123.91				3.40
Tunuhopu Springs	6.6	212.5	708.7	6.40	39.70	126.04				7.45
Utuhina Stream	1968.5	98.7	1048.3	9.35	14.04		46.35			6.91
Waingaehe Stream	221.3	169.0	1743.2	9.27	15.54	12.27	106.00	1.81	0.41	7.28
Waiohewa Stream	310.5	167.0	3741.2	8.52	14.32	16.88	75.31	7.39	2.14	6.61
Waiowhiro Stream	322.6	119.2	1265.1	9.89	13.02	6.96	43.00	1.66	0.66	6.80
Waiteti Stream	1266.9	64.1	1344.8	9.74	11.98	7.95	21.29	2.22	0.71	6.94

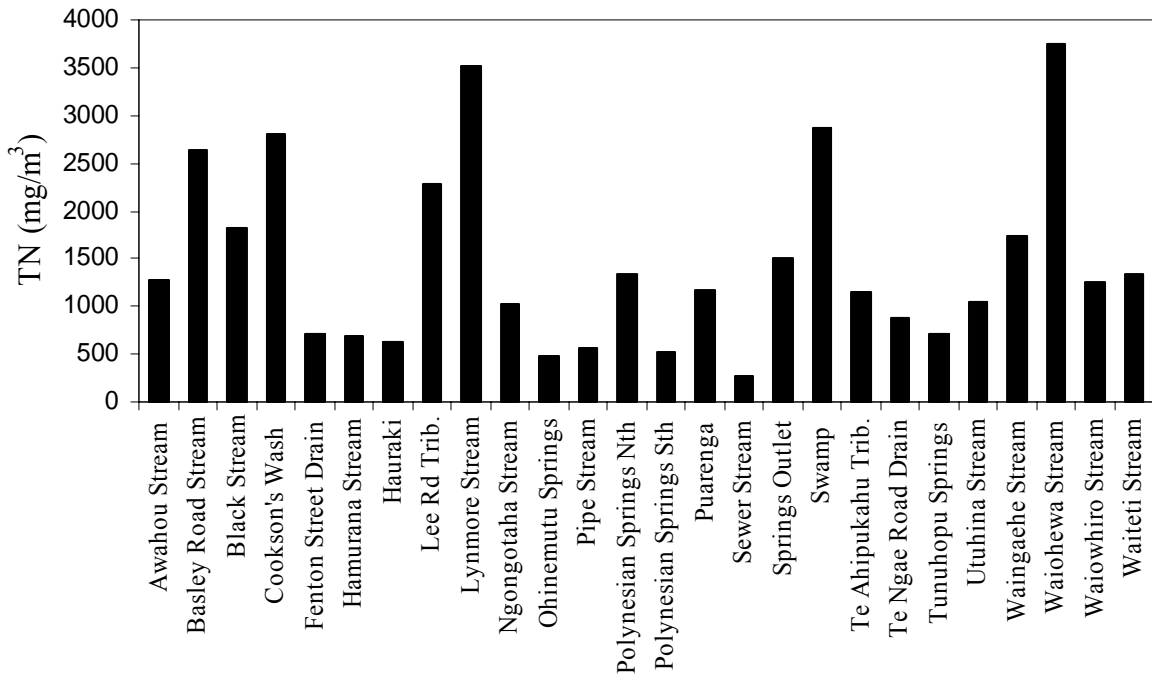


Figure 35. Mean concentrations of total nitrogen for inflows to Lake Rotorua.

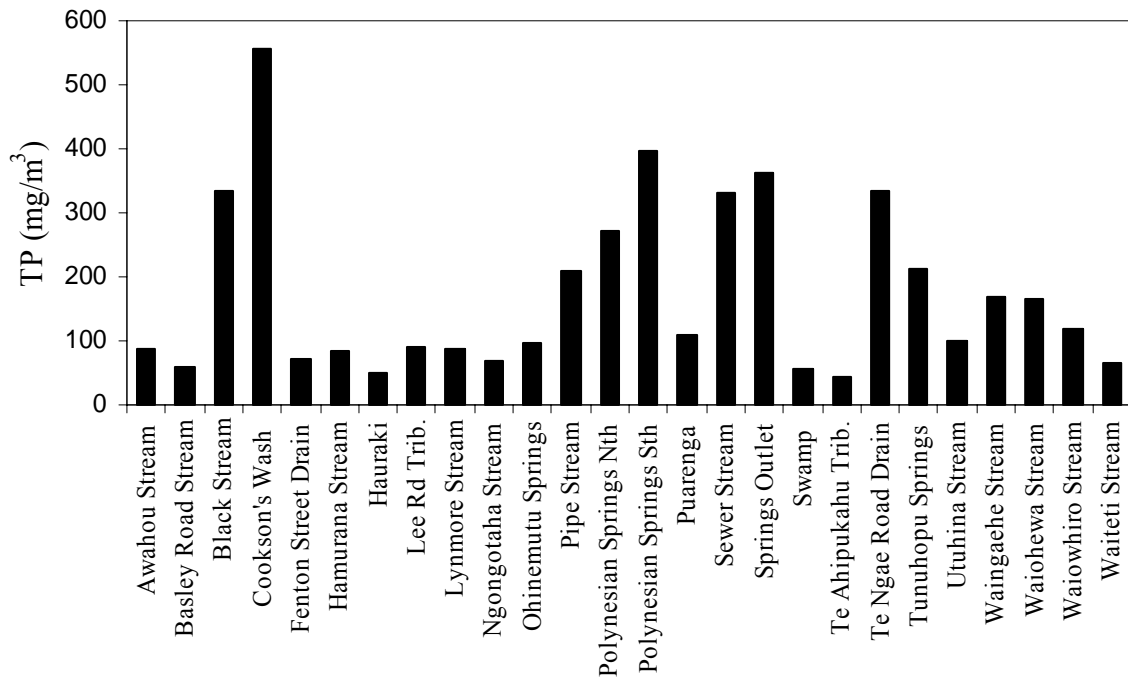


Figure 36. Mean concentrations of total phosphorus for inflows to Lake Rotorua.

Table 10. Annual average nutrient loads in tributaries to Lake Rotorua. Comparisons of loads derived from this study are made against 1976-77 (Hoare, 1987), 1984-85 (Rutherford et al., 1989) and 2002 (Rutherford, 2004).

Stream Name	TN Load		TP Load	
	tons/year	%	tons/year	%
Awahou Stream	69.29	15.6	4.78	13.7
Basley Road Stream	0.79	0.2	0.02	0.1
Black Stream	0.35	0.1	0.06	0.2
Cookson's Wash	0.07	0.0	0.01	0.0
Fenton Street Drain	0.00	0.0	0.00	0.0
Hamurana Stream	54.60	12.3	6.48	18.5
Hauraki	0.10	0.0	0.01	0.0
Lee Rd Trib.	1.49	0.3	0.06	0.2
Lynmore Stream	5.85	1.3	0.15	0.4
Ngongotaha Stream	58.45	13.2	3.91	11.2
Ohinemutu Springs	0.15	0.0	0.03	0.1
Pipe Stream	0.06	0.0	0.02	0.1
Polynesian Springs Nth	0.48	0.1	0.10	0.3
Polynesian Springs Sth	0.02	0.0	0.01	0.0
Puarenga	64.88	14.6	6.03	17.2
Sewer Stream	0.11	0.0	0.14	0.4
Springs Outlet	0.07	0.0	0.02	0.1
Swamp	2.83	0.6	0.06	0.2
Te Ahipukahu Trib.	2.23	0.5	0.08	0.2
Te Ngae Road Drain	0.71	0.2	0.27	0.8
Tunuhopu Springs	0.15	0.0	0.04	0.1
Utuhina Stream	65.08	14.7	6.13	17.5
Waingaehe Stream	12.17	2.7	1.18	3.4
Waiohewa Stream	36.63	8.3	1.64	4.7
Waiowhiro Stream	12.87	2.9	1.21	3.5
Waiteti Stream	53.73	12.1	2.56	7.3
Total - this analysis	443	100	35	100
Total - 1976-77	485		34	
Total - 1984-85	415		34	
Total - 2002	660		35	

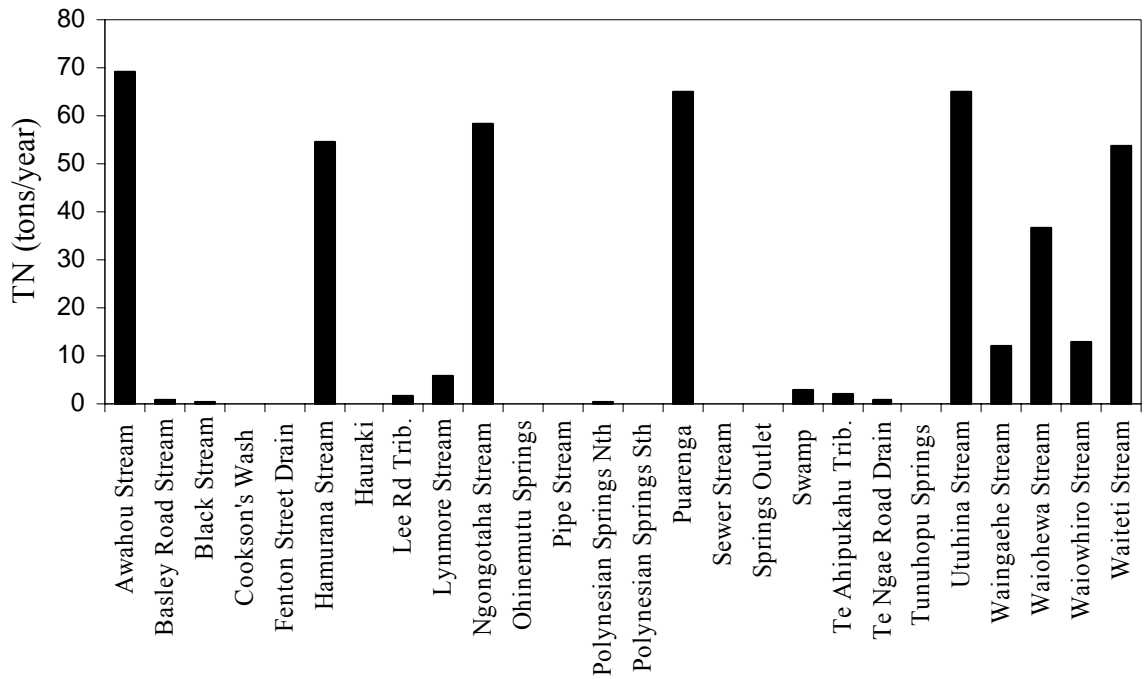


Figure 37. Loads of total nitrogen for tributaries to Lake Rotorua.

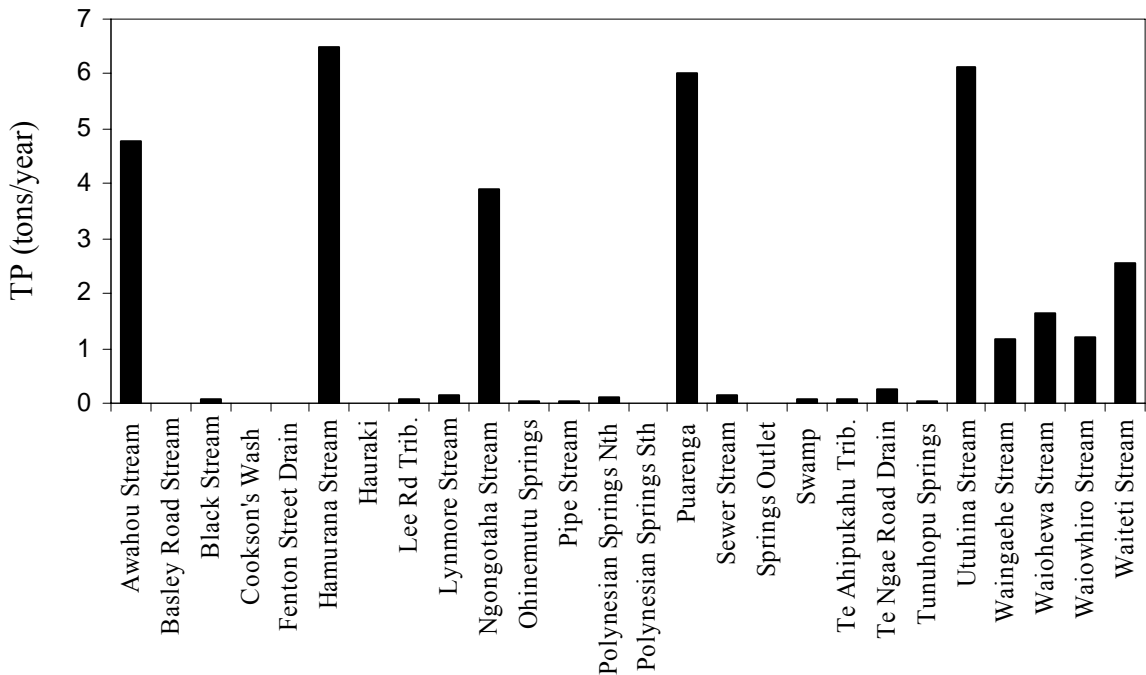


Figure 38. Loads of total phosphorus for tributaries to Lake Rotorua.

The comparisons of total nutrient loads to Lake Rotorua across years should be interpreted cautiously because of the different time frames that have been used for the analysis. The data

prior to 1990 include a substantial component due to direct inputs of treated wastewater to Lake Rotorua. The data for the present analysis include several time scales but are perhaps most representative of data from around 1991-94 when there was the greatest availability of data (refer to Figure 34), while the data from Rutherford (2004) are specific to 2002. It is apparent that there are some deviations in TN loads between the 2002 study (Rutherford, 2004) and our study, but we cannot differentiate the extent to which these deviations are a result of the different time periods used for calculations or different calculation methodologies.

It is now possible to put together a summary of loads contributed from various sources (Table 11), including gauged stream inflows, the residual stream inflow derived from the water balance, evaporation, rainfall, Ohau Channel outflow and internal loading. Gauged inflow volumes were taken from the total value given in Table 9. The residual volume (ungauged, mostly groundwater) was taken to be 15% of the gauged stream inflow based on the long-term mean (see above). Thus the Ohau Channel outflow is lower than presented in Table 15, reflecting the slightly lower rainfall and inflow volumes for the period given in Table 9. Evaporation was assumed to be only a loss of water and not of solutes. Rainfall was assigned an areal deposition rate of $3.7 \text{ kg N ha}^{-1} \text{ yr}^{-1}$, a value representative of the mean of measurements within the Lake Taupo catchment in the late 1970s, 1980s and in 1997 (White and Downes, 1977; Schouten, 1983; Timperley and Vigor-Brown, 1985; Dyck et al., 1987; Nicol et al., 1997), and $0.17 \text{ kg P ha}^{-1} \text{ yr}^{-1}$ (Schouten, 1983); both values are very close to values previously assigned to Lake Rotorua by Hoare (1987). The ungauged stream inflows were derived from the flow-weighted mean concentration of all gauged Rotorua stream inflows which had discharge less than $1 \text{ m}^3 \text{ s}^{-1}$. This produces relatively high flow-weighted mean concentrations of $145.3 \text{ mg TP m}^{-3}$ and $2192 \text{ mg TN m}^{-3}$, which partly reflects the contributions to the load from gauged geothermal inflows, which have high nutrient concentrations.

The results of the nutrient budget indicate that gauged inflows contribute nearly 50% of the total nutrient load for all inflows, internal loads contribute just over 30%, and ungauged inflows nearly 20%. It is also highly significant that there is a high retention or loss of nitrogen and phosphorus from the lake, other than through the Ohau Channel. The higher retention of phosphorus does not reflect an additional term for atmospheric loss of incoming nitrogen via denitrification; the retention/loss term for nitrogen would otherwise be expected to be larger. It should also be noted that this estimate of retention may vary from year to year because it includes three stratification events based on data for 2002-3 (Hamilton et al., 2004) and could be

conservative because it does not include additional inputs due to sediment resuspension (Stephens et al., 2004). On the other hand the estimate of losses of nutrients via the Ohau Channel may have some bias according to whether samples have captured the true frequency of sediment (and particulate nutrient) resuspension events and stratification events that increase nutrient levels in the Channel (see Stephens et al., 2004). Nevertheless, only around 25% of the incoming nutrients to Lake Rotorua will actually exit via the Ohau Channel; the remainder being retained in the bottom sediments or, in the case of nitrogen, being denitrified.

Table 11. Summary of nutrient budget for Lake Rotorua. The retained/lost value represents net retention (e.g. by sedimentation for TP and TN) or loss (e.g. by denitrification for TN) of nutrients in the lake. 'Internal' represents the internal load due to sediment release events during periods of stratification (from Hamilton et al., 2004). It does not include effects of sediment resuspension on nutrients. Percentages of total phosphorus and total nitrogen imports to and exports from the lake are given and compared in the retained/lost row.

Variable	Flow (m³ s⁻¹)	TP (tonnes yr⁻¹)	% TP	TN (tonnes yr⁻¹)	% TN
<i>Inflows</i>					
Rainfall	3.8	1.3	1.8	29.2	3.0
Gauged inflows	12.1	35.0	47.9	443.2	45.5
Ungauged inflows	2.8	12.8	17.5	193.7	19.9
Internal	N/A	24.0	32.8	308.0	31.6
Total inflows	18.7	73.1	100	974.1	100
<i>Outflows</i>					
Evaporation	3.1	0	0	0	0
Ohau outflow	15.6	19.3	100	236.2	100
Total outflows	18.7	19.3	100	236.2	100
<i>Net</i>					
Retained/lost	0	60.21	82.4	737.9	75.8

3 Lake Rotoiti

3.1 Background

Relevant background information for Lake Rotoiti is presented in this section. As much of the historical and geological information on Lake Rotorua (Chapter 2) is also relevant to Lake Rotoiti, this information is not repeated here.

3.1.1 Location

Lake Rotoiti is located in the Rotorua area on the eastern side of Lake Rotorua (refer to Figs 1 and 2). Its approximate coordinates are 38°02'S and 176°24'E. The dominant inflow is through the Ohau Channel and the only major outflow is via the Kaituna River in the north-west region of the lake.

3.1.2 Morphometry

Table 12 shows relevant morphometric parameters for Lake Rotoiti. The lake bed is characterised by many irregularities (Figure 39) that influence water motion and propagation of internal waves in the lake (Hamilton and Uraoka, 2005). There is a relatively shallow western basin and a deeper eastern basin in which there is a deep hole extending to 124m.

Table 12. Morphometry of Lake Rotoiti. Source: www.envbop.govt.nz and data from Figure 39.

Lake Area	33.48 km ²
Lake Volume	1071.5 Hm ³
Catchment Area	120.56 km ²
Length	13 km
Mean width	2.5 km (approx)
Max depth	120 m
Mean depth	31.53 m

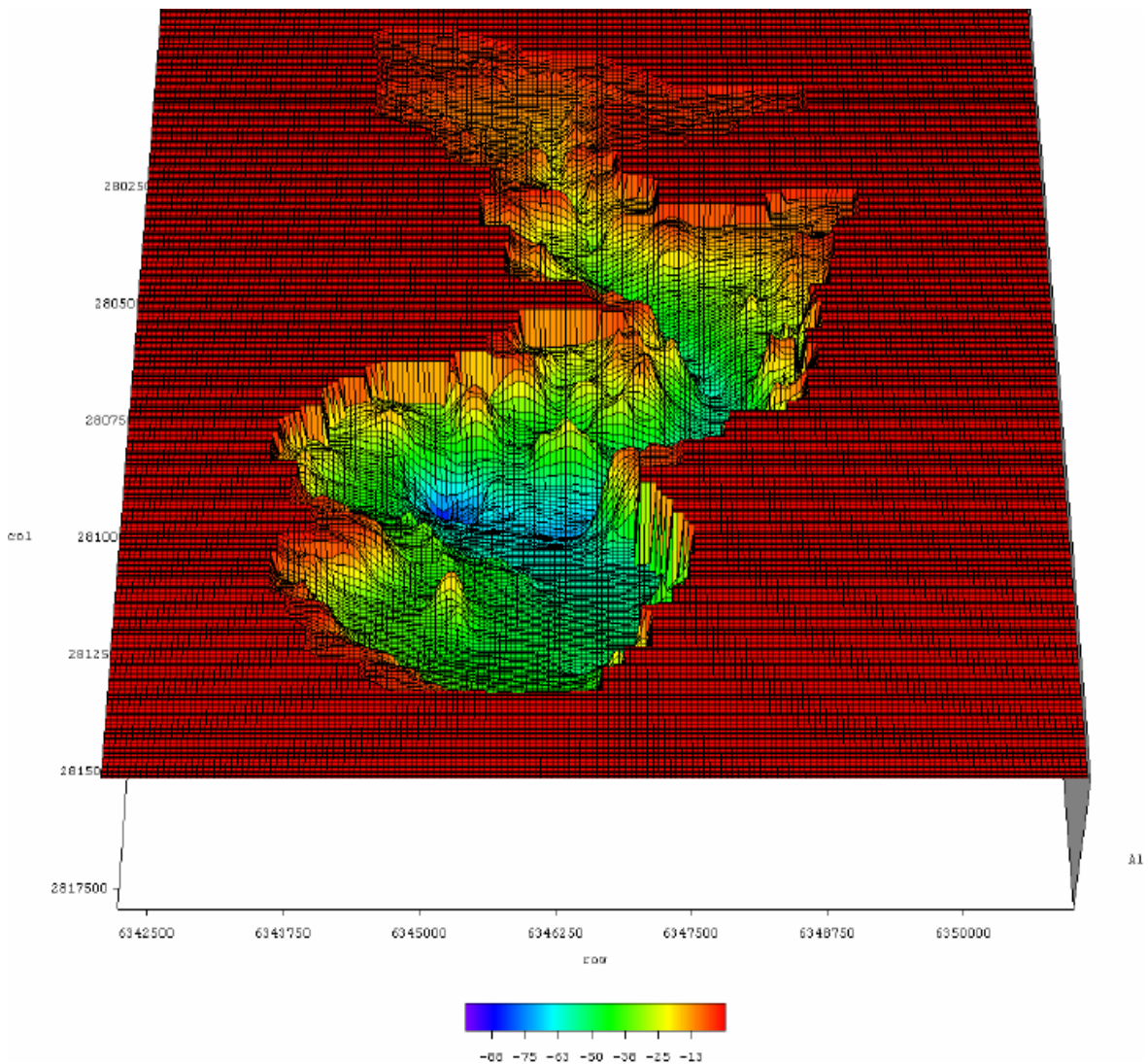


Figure 39. Bathymetry of Lake Rotoiti viewed from the eastern end of the lake. The 'col' and 'row' axis labels refer to longitude and latitude values (UTM coordinates in m), respectively. Vertical elevations are given with respect to an assigned value of 279.20 m for the lake shoreline, with elevations exceeding this value coloured red.

3.1.3 Hydrology

The hydrology of Lake Rotoiti is dominated by the Ohau Channel, the only surface outflow from Lake Rotorua. The lake has only one outflow, the Kaituna River, which is situated in the north-western region of the lake, relatively close to the Ohau Channel inflow. The Ohau Channel either 'short circuits' directly to the Kaituna River or intrudes in an easterly direction as an interflow or underflow towards the main basin of Lake Rotoiti (for details see Hamilton and Uraoka, 2005). The surface flow, interflow and underflow conditions have been the subject of detailed studies,

and relative frequencies of each occurrence have been quantified for considerations of diversion of the Ohau Channel away from Lake Rotoiti (Vincent et al., 1986; Hamilton and Uraoka, 2005).

The residence time of Lake Rotoiti is on average approximately 1.5 years. However, the main inflow discharges mostly to the smaller western basin and may flow directly to the Kaituna outflow, suggesting that residence times for this basin may be in the order of a few weeks of months, compared with the deeper eastern basin where residence times will be considerably longer than 1.5 years.

3.1.4 Water Quality

Lake Rotoiti is a monomictic lake with a stratification period extending from October to June and an annual range of water temperatures generally from 9 to 21°C. During the stratified period bottom waters become anoxic and dissolved reactive phosphorus and ammonium concentrations increase in these waters. The lake has previously been considered to be in a stable mesotrophic state (Burns et al., 1997), with moderate nutrient levels and a mean Secchi depth around 5m, but there appears to have been a significant adverse shift in water quality commencing in the 2002-3 summer, when Secchi disk depths were regularly below 2m in the main lake basin.

Hamilton et al. (2004) have previously quantified internal loads of nutrients during the stratified period in Lake Rotoiti. Based on several years of data, the average increase in dissolved reactive phosphorus is approximately 20 tonnes over the stratified period, and the average increase in ammonium is around 50 tonnes. The anoxia of bottom waters also leads to a brief period of denitrification when nitrate is chemically reduced and lost from bottom waters, resulting in a loss of nitrogen in the range of 40 to 83 tonnes (Hamilton et al., 2004).

3.2 Water Balance

A water balance was carried out for Lake Rotoiti to determine the total flow into the lake. Daily water level and inflow and outflow volumes were used to develop the water balance. Evaporation was calculated using the same methodology adopted for Lake Rotorua, and using the mean lake area (Table 12) to derive a volumetric contribution. Rainfall data correspond to the station “Kaituna at Whakarewarewa” (see Chapter 2) were also multiplied by the mean lake area to produce the volumetric contribution from this source.

3.2.1 Water Levels

Lake Rotoiti water level has been recorded at the station “Kaituna at Lake Rotoiti Outlet”, from 1906 to date. The statistics are relatively complete. Missing data were filled using mean values (typically 4-5 points) from the closest set of available data. Figure 40. 40 shows the time series of water levels and indicates that since the early 1980s, water level has been more stable. Major modifications to the outlet at Kaituna occurred mostly around 1979.

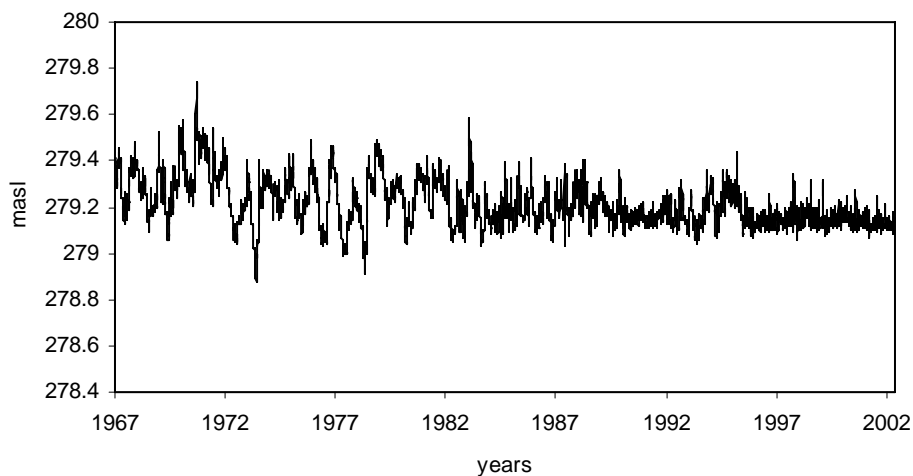


Figure 40. Water Level at the Lake Rotoiti station ‘Kaituna at Lake Rotoiti Outlet’

3.2.2 Outflow

A relatively complete daily data flow record for the Kaituna outflow from Lake Rotoiti is available from 1956 to date. Missing data were also filled using mean values (typically 4-5 points) from the closest available data. From 1981, the NIWA station “Kaituna at Taaheke”

became available and these data have been used in preference to the “Kaituna River at the outlet” station (Figure 41), which does not accurately represent the Kaituna River flow following changes to the outlet structure in 1979 (refer to Figure 40).

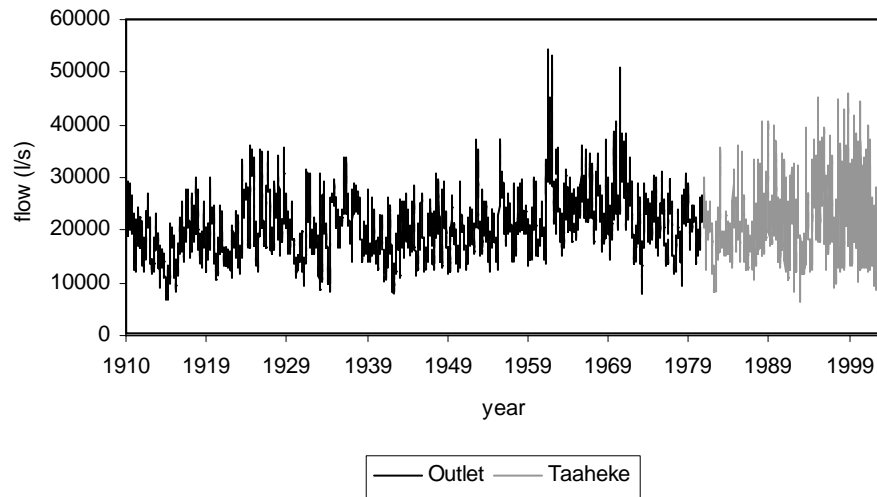


Figure 41. Time series of discharge in the Kaituna River.

3.2.3 Evaporation

Evaporation was estimated in the identical manner to that used for the Lake Rotorua water balance. The mean daily surface water temperature used in calculation of evaporation was estimated empirically as a cosine function using a mean surface water temperature of 15°C centred around late January and a fluctuation of up to $\pm 5.1^{\circ}\text{C}$ in the annual cycle. Evaporation was then calculated as a mean each monthly value (Figure 42).

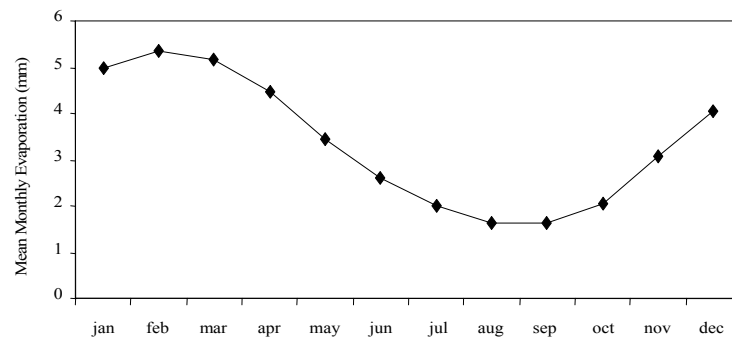


Figure 42. Mean monthly evaporation rate for Lake Rotoiti, calculated from daily average values.

3.2.4 Rainfall

The contribution of rainfall to the lake water volume was estimated from the station “Kaituna at Whakarewarewa”. This rainfall was multiplied by the mean lake surface area, with no adjustment of lake area for changes in water level, to obtain the volumetric contribution due to rainfall.

3.2.5 Inflows

The main inflow to Lake Rotoiti is via the Ohau Channel. Its flow has been recorded daily, from 1934 to date, and averages $16.91 \text{ m}^3 \text{ s}^{-1}$ ($1,461,000 \text{ m}^3 \text{ day}^{-1}$). This flow rate can be compared with the mean outflow from Lake Rotoiti of $21.35 \text{ m}^3 \text{ s}^{-1}$ ($1,845,000 \text{ m}^3 \text{ day}^{-1}$), indicating that 79% of the total inflow to the lake is from the Ohau Channel. Figure 43 shows the time series of total inflow to Lake Rotoiti obtained from the water balance.

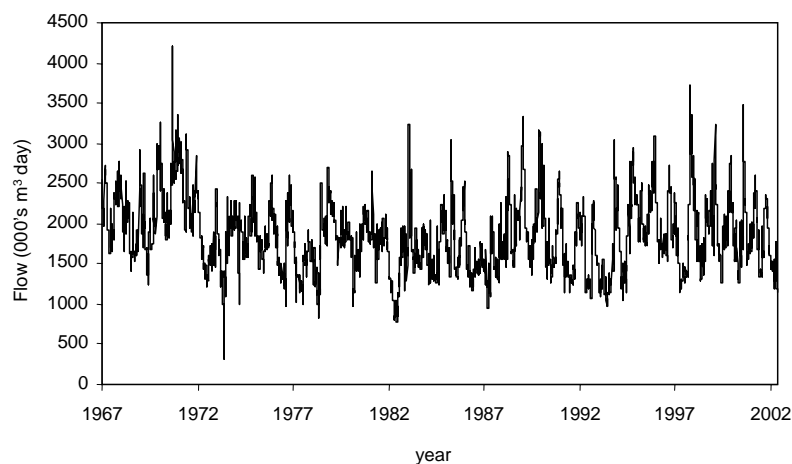


Figure 43. Time series of total inflow to Lake Rotoiti estimated from a water balance.

The difference between the calculated total inflow to Lake Rotoiti, based on the water balance, and the Ohau Channel should always be positive, reflecting other inflows from the Rotoiti catchment, including net groundwater flow. Negative values were obtained over short (mostly

daily) durations (Figure 44), however, indicating that the resolution of measurements is sometimes insufficient to produce an accurate water balance at the selected daily temporal resolution. For example, water levels may fluctuate over the lake on a daily basis due to the effects of wind, resulting in short-term inaccuracies in the water balance. In order to correct this problem a 30-day moving average was used for the water balance though it should be noted that in the short term (e.g. the time scale of flood events) the peaks and troughs in the data will not be accurately captured. The 30-day average residual value, representing all inflows to Rotoiti except for the Ohau Channel, is shown in Figure 44. One of the features of this figure is the abrupt jump in the time series in 1979, corresponding to engineering works on the Kaituna outflow.

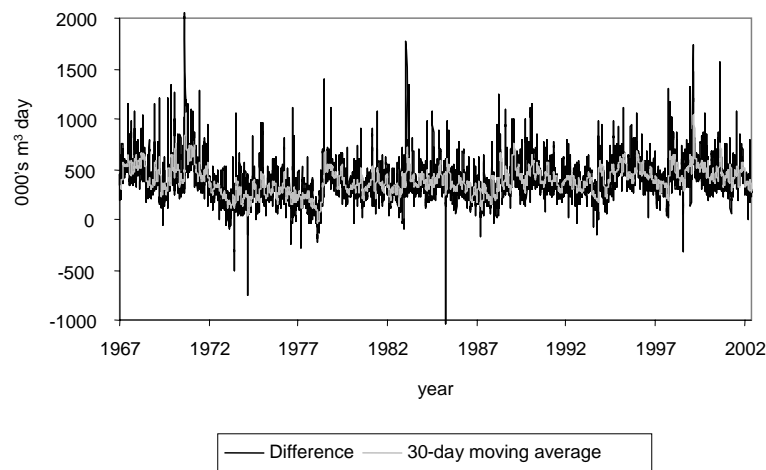


Figure 44. Time series of 'residual' water flow to Lake Rotoiti, representing contributions of all inflows to the lake except the Ohau Channel.

3.3 Catchment Analysis

This section describes information relevant to the catchment analysis such as: land use and inflow temperatures and discharges. Correlations of flow with other parameters are also examined in this section.

3.3.1 Land uses

Land uses in the Rotoiti catchment are summarised in Tables 13 and 14. Land use is mixed and relatively evenly distributed between plantation forestry, indigenous forests and pasture. A comparatively small area of the catchment is urbanised. It should be noted that the assigned catchment does not include Lake Rotorua, which contributes nearly 80% of the lake inflow. It is also possible to examine changes in the Lake Rotoiti catchment land cover for the years 1975, 1986 and 1996. Indigenous forestry has expanded rapidly in the Lake Rotoiti catchment and appears to have replaced a considerable area of land previously in pasture, though it appears likely that the area of indigenous forestry has now largely stabilised. Regular updates of current data, including use of satellite data will help to elucidate general trends and rates of change of land use in the Lake Rotoiti catchment.

Table 13. Catchment land cover for Lake Rotoiti in 1996.

Land cover	Lake Rotoiti area (Ha)
Bare Ground	68.0
Forest – Indigenous	3247.1
Forest – Planted	3115.1
Horticulture	448.9
Pasture – Exotic	2007.6
Scrub – Mixed + Exotic	51.2
Urban	46.1
Urban - Open Spaces	46.0
Water	3460.5
Wetlands – Inland	20.9
Total	12511.4

Table 14. Land cover changes for Lake Rotoiti between 1975 and 1996.

Landcover	1996 Area (Ha)	1986 area (Ha)	1975 area (Ha)	% difference 1975-1996
Forest - Indigenous	3247	2890	4111	-21
Forest – Planted	3115	635	0	Increase
Pasture – Exotic	2007	4012	2990	-33
Scrub	448	1233	1869	-76
Urban	92	0	0	Increase
Water	3460	3463	3488	0

3.3.2 Stream Information

There are six stream inflows to Lake Rotoiti, not including the Ohau Channel, that have been gauged for various durations since 1992. Figure 45 shows the location of these inflows, as well as other inflows which are not gauged, and Table 15 shows the mean flow rates and their percentage contribution to the total flow. From Table 15 it is evident that around 18% of the inflow is unaccounted for. This flow may be assumed to be due to the ungauged surface inflows as well as groundwater from both cold-water and geothermal sources. The availability of flow data for the various gauged streams can be assessed in Figure 46. A reasonably intensive period of gauging is evident in the period 1992-1994, and these data have provided much of what is known about flow and composition of several of the smaller stream inflows.

Detailed analysis of streamflows for Lake Rotoiti have been carried out for only four streams: Ohau Channel, Kaituna River, Waiiti and Te Toroa. All other gauged stream inflows had discharges less than 25 L s^{-1} and because of the small number of measurements recorded for these streams, the statistical significance of correlations was likely to have been jeopardised (i.e. $p > 0.01$). Figure 47 shows flows in the three largest gauged inflow streams, Ohau Channel, Waiiti and Te Toroa, as well as in the Kaituna River. The discharge record for these streams is relatively complete though slightly more sporadic (approximately 2-weekly) for Te Toroa.

Table 15. Mean (based on all available measurements) stream discharges for inflows and outflows to Lake Rotoiti.

Stream	Flow ($L s^{-1}$)	% inflow
Hauparu Stream	21.0	0.1
Ohau Channel	16911.0	79.2
Ruato	15.7	0.07
Tapuaeharuru	7.6	0.04
Parengarenga	9.0	0.04
Ruahine	15.7	0.07
Otuatara Springs	1.8	0.0
Taupo Stream	4.8	2.6
Tawhakarere Stream	7.1	3.4
Te Toroa Stream	53.8	0.2
Waititi Spring	458.4	2.2
Kaituna (outflow)	21572.5	-
Sum of surface inflows	17505.9	82.0
Water Balance Outflow	21354.0	100.0
Net of other inflows	1822.2	18.0

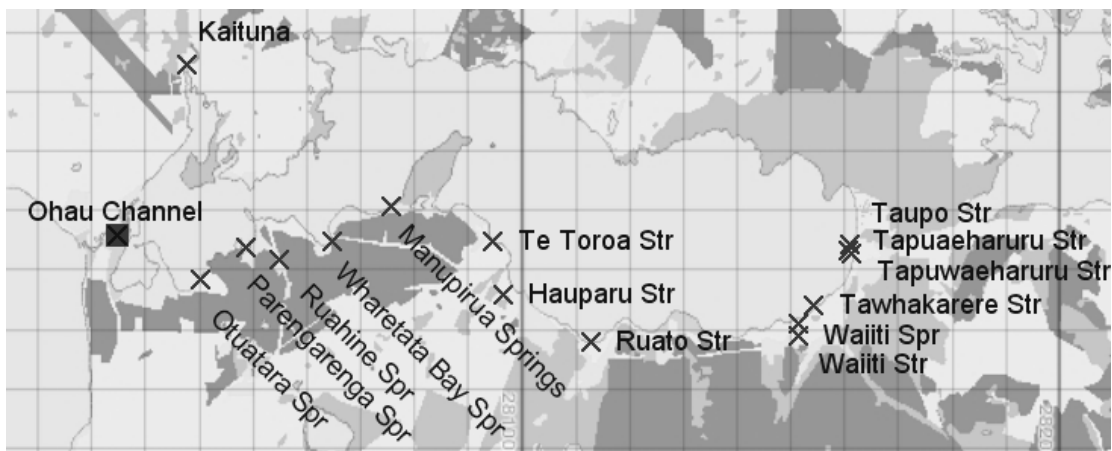


Figure 45. Location of surface inflows to Lake Rotoiti, and the Kaituna outflow.

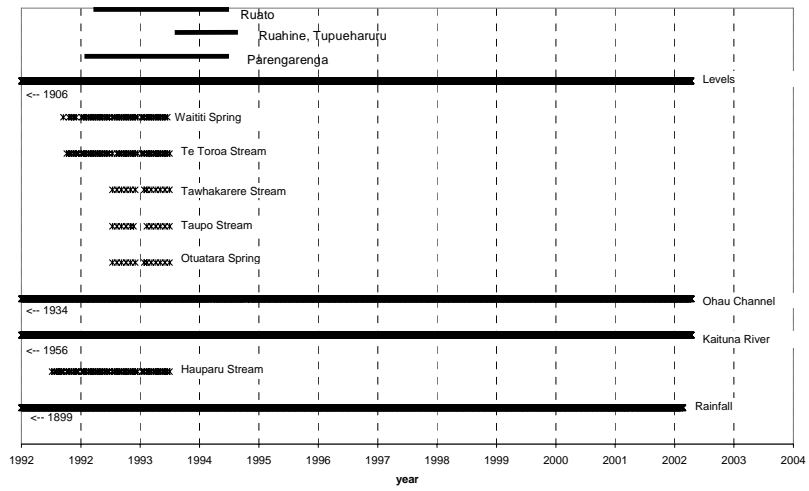


Figure 46. Availability of information relating to stream inflows to Lake Rotoiti, the Kaituna outflow, water level and rainfall.

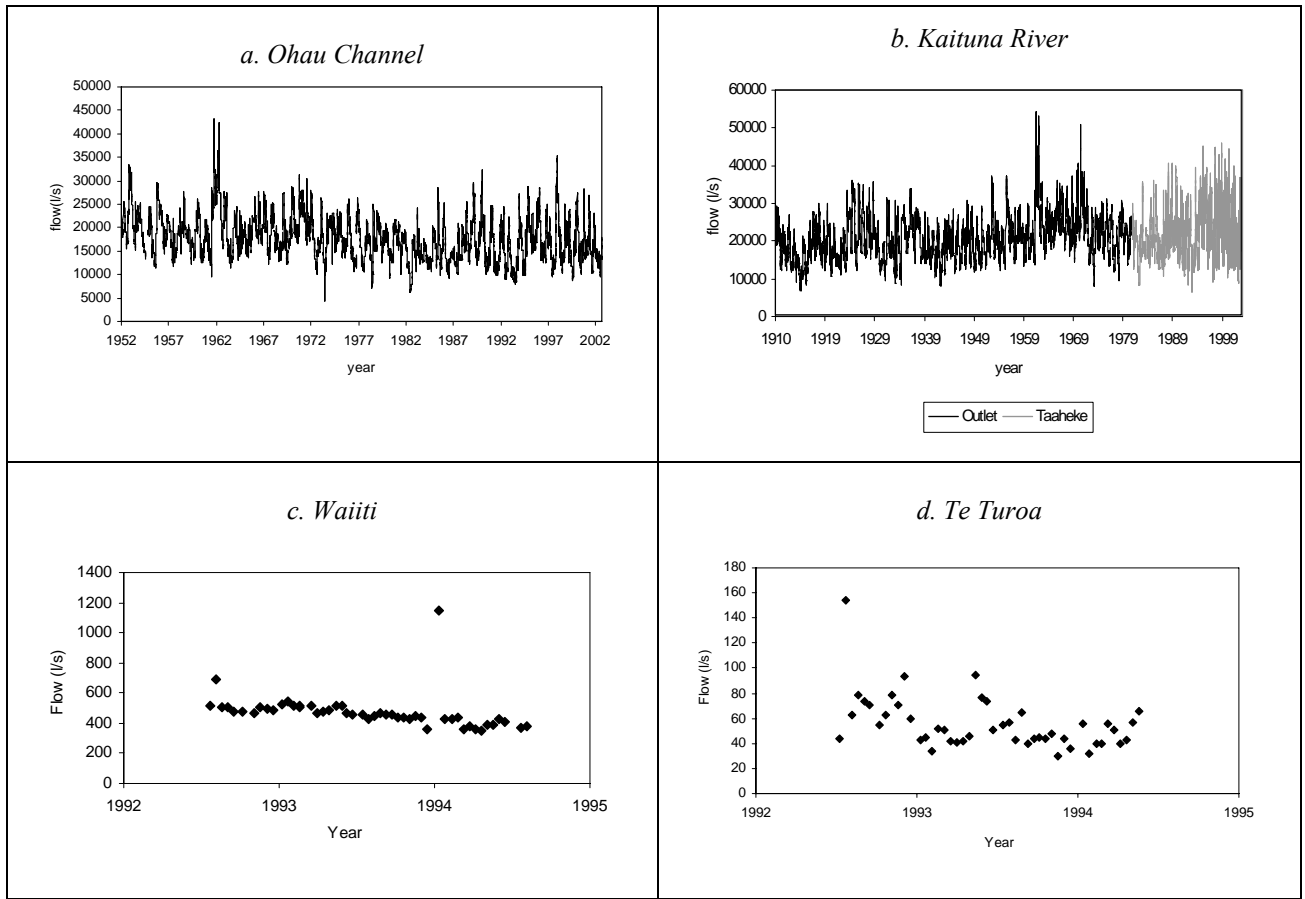


Figure 47. Time series of discharge in Lake Rotoiti inflows.

Correlations between the major streamflows and rainfall were set up using daily and 30-day averaged flow data (Tables 16 and 17 respectively). Correlation coefficients (r) greater than 0.65 are denoted in bold. Rainfall is a relatively poor predictor of streamflows at the two time scales, though correlation coefficient values increase considerably, with the exception of Waiiti Stream, at the monthly time scale. Daily and monthly flows in Te Toroa Stream were closely related to flow in the Ohau Channel ($r = 0.84$ and 0.92 , respectively). A visual comparison of this relationship for the daily flows is given in Figure 48. The relatively high correlation coefficient between flows in Te Toroa Stream and in the Kaituna River can probably be attributed to the moderately high correlation coefficients ($r \geq 0.67$) between daily and monthly flows in the Ohau Channel and the Kaituna River. Considerations of temperature in streamflows (see below) provide further insights into the relationships between discharges in each of the streamflows and also with rainfall; temperature in Te Turoa shows moderate variation over the year (approximately 10°C) that reflects a combination of spring flows and surface runoff (hence $r =$

0.49 between monthly rainfall and flow for this stream) while Waititi is spring-fed, with temperatures almost invariant at 14 to 16°C ($r = 0.02$ for monthly rainfall vs streamflow).

Table 16. Daily flow and rainfall correlation coefficients for major gauged Rotoiti streams. Values greater than 0.65 are denoted in bold font.

Daily Correlations	Rainfall	Ohau Channel	Te Turoa Stream	Waititi Spring	Kaituna
Rainfall	1.00				
Ohau Channel	0.06	1.00			
Te Turoa Stream	0.16	0.84	1.00		
Waititi Spring	0.11	0.08	0.03	1.00	
Kaituna	0.07	0.77	0.58	0.07	1.00

Table 17. Monthly streamflow and rainfall correlation coefficients. Values greater than 0.65 are denoted in bold font.

30 Day Averaged	Rainfall	Ohau Channel	Te Turoa Stream	Waititi Spring	Kaituna
Rainfall	1.00				
Ohau Channel	0.35	1.00			
Te Turoa Stream	0.49	0.92	1.00		
Waititi Spring	0.02	0.04	-0.04	1.00	
Kaituna	0.28	0.67	0.63	-0.18	1.00

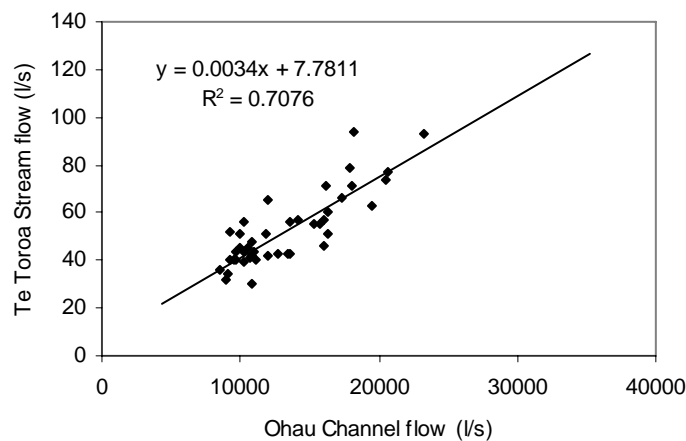


Figure 48. Relationship between daily flow in Te Turoa and Ohau Channel.

3.3.3 Stream Inflow Temperatures

The Ohau Channel temperature is extremely important to the dynamics of Lake Rotoiti because it is a major influence on whether this inflow intrudes into the lake as a buoyant overflow, as an interflow or as an underflow. For the case of a buoyant overflow, there is an increased likelihood of ‘short circuiting’ of the inflow to the Kaituna River outflow, depending on wind velocity, surface currents and the temperature structure in the lake itself (Hamilton and Uraoka, 2005). Temperature in the Ohau Channel may vary during the day due to heat exchange with the atmosphere and solar radiation, particularly where the water is derived from the relatively shallow shelf region of Lake Rotorua, as well as through the Ohau Channel itself. Temperature data for the Ohau Channel was correlated with air temperature measured at Rotorua Airport for times corresponding to the time of sampling of the Channel (Figure 49). Air temperature explained 80% of the variation in the temperature of water in the Ohau Channel.

Temperatures were also examined in other stream inflows using mean values. Variability of temperature was also taken into account to provide some insight into the source of water (i.e. spring-fed, surface inflows or geothermal inflows). Table 18 shows the mean water temperature, the approximate range of water temperature for the inflows to Lake Rotoiti. Streams such as Otuatara had water temperatures that were relatively cool for a geothermal spring, reflecting a dilution influence of coldwater springs or the relatively small flow rate that resulted in cooling of the geothermal water prior to the point of sampling.

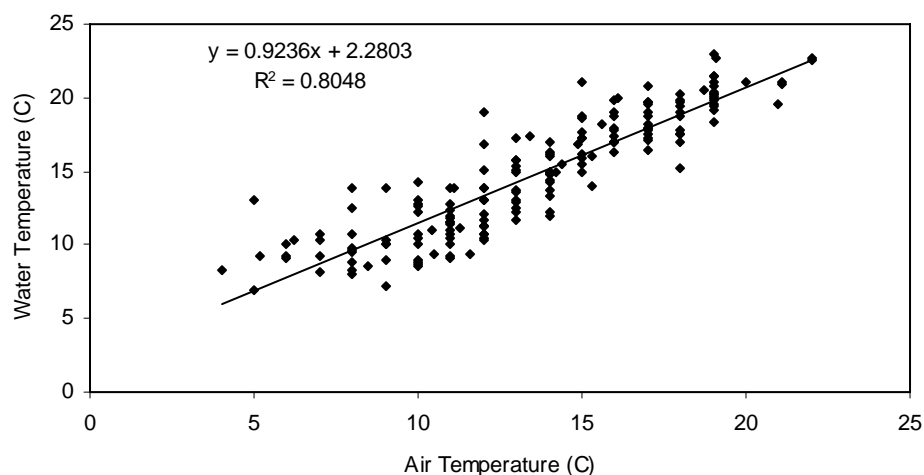


Figure 49. Relationship between air temperature at Rotorua airport and water temperature in the Ohau Channel.

Table 18. Mean flow, mean temperature, approximate temperature range and likely source of water based on temperature for gauged inflows to Lake Rotoiti.

Stream name	Mean flow (L s ⁻¹)	Mean temperature (°C)	Temperature range (°C)	Likely dominant water source
Tawhakarere	7.1	14.3	Minimal	Spring
Ruato	15.7	13.8	Minimal	Spring
Ruahine	15.7	27.0	Minimal	Geothermal spring
Tapuaeharuru	7.6	11.3, 12.1 (two samples only)	Not established	Not established
Taupo	4.8	9.2	Minimal	Spring
Waiiti	472	14.9	Minimal	Spring
Otuatara	1.84	21.2	Minimal	Geothermal spring
Parengarenga	9.0	28.8	Minimal	Geothermal spring
Hauparu	21.0	13.7	± 4	Surface water
Te Toroa	56.0	14.9	± 5	Surface water

3.3.4 Stream Inflow Nutrients

In order to derive a nutrient budget for Lake Rotoiti, the product of flow and nutrient concentration was calculated for the Ohau Channel. Because of the comparative paucity of measurements in the other smaller inflows, the product of mean flow and mean nutrient concentration over all measurements was used to derive a nutrient load for each stream. Table 19 shows the mean nutrient concentrations for each of the minor streams and also presents mean concentrations of dissolved oxygen and suspended solids, as well as pH. Geothermal streams are clearly evident as having low pH; Ruahine, Otuatara and Parengarenga. These streams also have slightly depressed levels of dissolved oxygen (mean < 7 mg L⁻¹). They are also clearly distinguished by their nutrient signature; mean total phosphorus concentrations are greater than 0.1 mg L⁻¹, with approximately half of this phosphorus is dissolved reactive form. Mean levels of total nitrogen are exceptionally high, particularly in the Otuatara Stream (47.20 mg L⁻¹) and while ammonium dominates the nitrogen species in the other two geothermal flows, there appears to be a substantial (nearly 50%) organic nitrogen component in the Otuatara Stream. These results support the observations presented in Table 18 that identify three gauged geothermal inflows, and clearly also reinforce the view that these sources of water are laden with nutrients, both phosphorus and nitrogen species, and have particularly high concentrations of

ammonium. A visual comparison of the data for total nitrogen and total phosphorus is given in Figure 50.

Table 19. Mean concentrations of dissolved oxygen, pH, and concentrations of dissolved reactive phosphorus, total phosphorus, ammonium, nitrate and total nitrogen in minor input streams to Lake Rotoiti.

Stream name	DO [mg L ⁻¹]	pH	SS [mg L ⁻¹]	DRP [mg L ⁻¹]	TP [mg L ⁻¹]	NH ₄ [mg L ⁻¹]	NO ₃ [mg L ⁻¹]	TN [mg L ⁻¹]
Tawhakarere	9.1	7.0	7.9	0.061	0.070	0.020	0.066	0.273
Ruato	9.6	7.4	3.1	0.047	0.050	0.031	0.071	0.249
Ruahine	6.7	2.7	3.4	0.135	0.269	10.74	0.218	14.91
Tapuaeharuru	10.1	7.4	10.8	0.050	0.057	0.010	0.084	0.223
Taupo	13.2	7.1	9.5	0.065	0.123	0.032	0.063	0.351
Waiiti	9.0	6.5	1.5	0.072	0.073	0.015	0.063	0.333
Otuatura	5.5	2.3	0.4	0.290	0.290	25.45	0.270	47.20
Parengarenga	5.9	2.5	4.0	0.137	0.292	19.54	0.370	21.72
Hauparu	9.5	7.3	80.9	0.053	0.112	0.048	1.083	1.771
Te Turoa	9.3	7.2	9.7	0.033	0.052	0.041	2.001	0.936

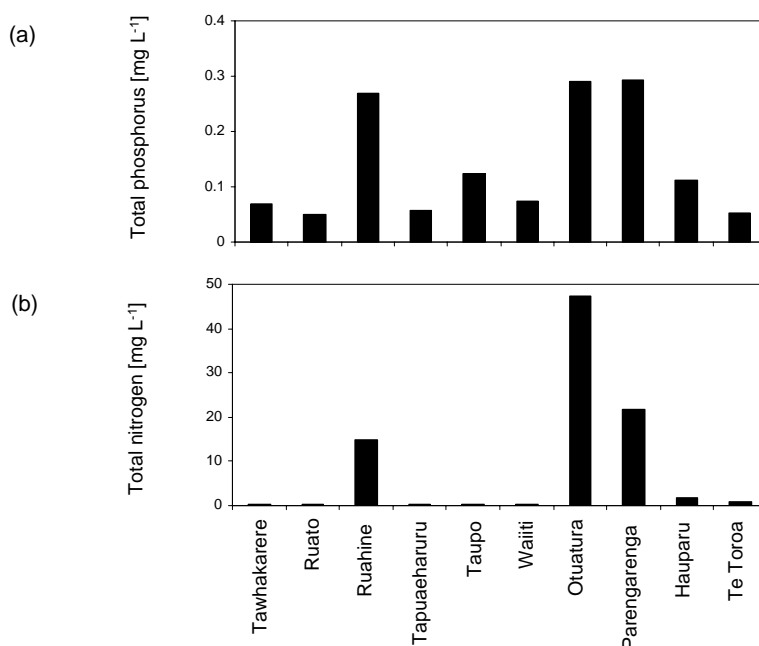


Figure 50. Mean concentrations of total phosphorus and total nitrogen in minor input streams to Lake Rotoiti.

Concentrations of total phosphorus and total nitrogen from 1995 to the beginning of 2003 are shown in Figure 51a and 51b, respectively. Total phosphorus and total nitrogen concentrations were correlated ($r = 0.45$, $p < 0.01$) and the time series shows a number of peaks in the two

nutrients, with the peaks often characterised by increased nutrient concentrations immediately beforehand and afterwards. Nutrient loads were calculated in the first instance simply as the product of discharge and concentration for each sampling day, followed by determination of an annual mean for these days. Table 20 presents the annual mean loads of total phosphorus and total nitrogen calculated on this basis. It is difficult to ascertain at this stage whether inter-annual variations are significant or are simply brought about by smaller time scale fluctuations that bias the result, but there should not be significant seasonal basis because the sampling interval is relatively constant at one month. More recent high frequency sampling of the Ohau Channel (Hoare, 1987; Gibbs et al., 2003) could be examined in detail to assess the temporal scale of fluctuations in nutrient loads. Averaged over all samples collected from 1995 to 2003, the mean annual load of total phosphorus is 19.3 tonnes and for total nitrogen, 236.2 tonnes. The mass ratio of TN:TP is therefore 12.2.

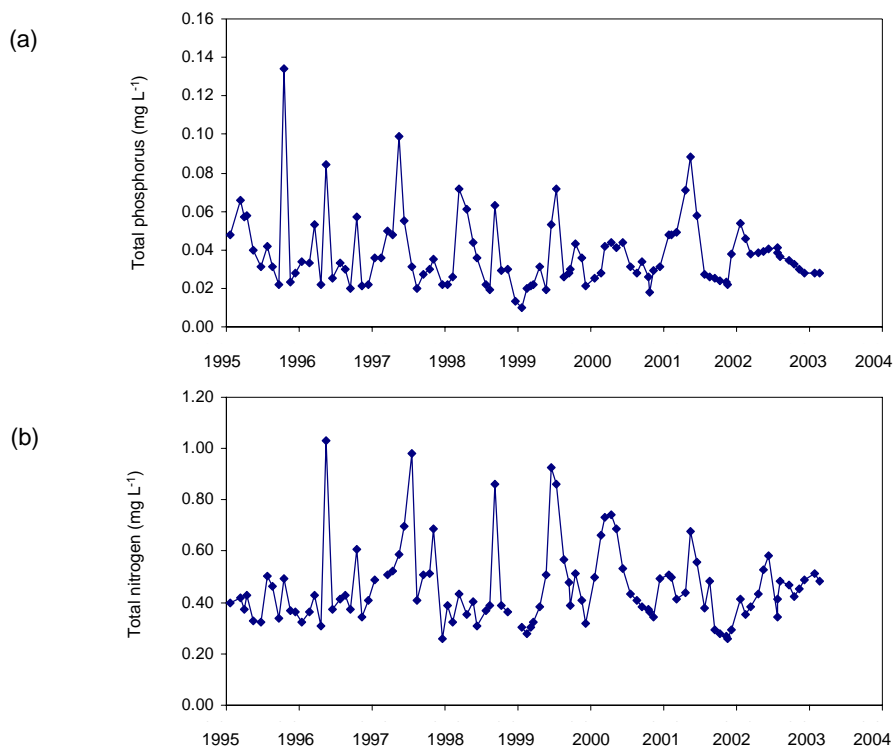


Figure 51. Mean concentrations of total phosphorus and total nitrogen in minor input streams to Lake Rotoiti.

It is now possible to make comparisons of relative nutrient inputs to Lake Rotoiti from all incoming streams, including the Ohau Channel (Figure 52, Table 20). The Ohau Channel is clearly the dominant inflow in terms of nutrient loads.

Table 20. Annual loads of total nitrogen and total phosphorus from the Ohau Channel.

Year	Total P (tonnes)	Total N (tonnes)
1995	27.0	230.2
1996	21.9	275.9
1997	21.4	313.4
1998	19.2	243.3
1999	13.5	205.8
2000	14.3	225.9
2001	19.9	195.0
2002	18.6	217.7

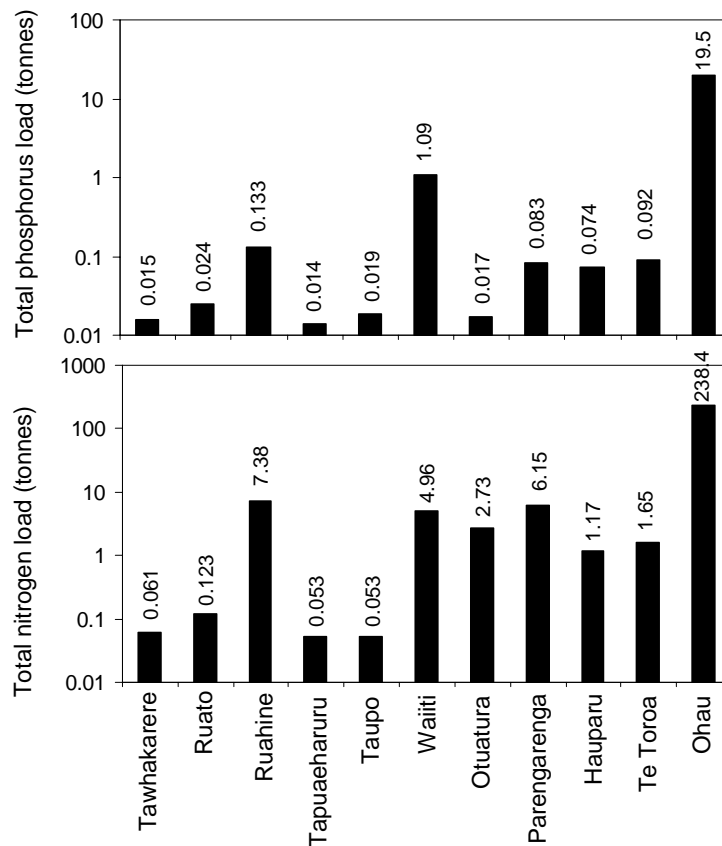


Figure 52. Nutrient loads for all gauged stream inflows to Lake Rotoiti.

Based on the above data and assigning mean nutrient concentrations to the Kaituna outflow and for the ungauged inflows, as well as for internal loading, it is possible to produce a relatively complete nutrient budget for Lake Rotoiti (Table 21). The Kaituna discharge was derived from the water balance (see above) and from a relatively complete sequence of data on nutrient concentrations in the 'Rotoiti outflow to Kaituna station' from 1995-99. The latter data gave a mean TP concentration of 0.024 g m^{-3} and mean TN concentration of 0.338 g m^{-3} . The lake area was taken to be 33.48 km^2 (Table 12) and areal deposition rates for TN and TP were set to be identical to those used for Rotorua (3.7 and $0.17 \text{ kg ha}^{-1} \text{ yr}^{-1}$ respectively). Gauged inflows, not including the Ohau Channel, discharge $0.60 \text{ m}^3 \text{ s}^{-1}$ of water to the lake (sum of constituents from Table 18) and $1.56 \text{ tonnes yr}^{-1}$ of TP and $24.3 \text{ tonnes yr}^{-1}$ of TN (sum of values given in Figure 52). The flow weighted mean concentration for these inflows is $0.081 \text{ g TP m}^{-3}$ and $1.265 \text{ g TN m}^{-3}$, which was applied to derive the concentration of nutrients from ungauged inflows to Lake Rotoiti. Based on the Lake Rotoiti water balance and using estimates of rainfall and evaporation at rates identical to Rotorua (with the appropriate areal adjustment), ungauged inflows were estimated to contribute $3.76 \text{ m}^3 \text{ s}^{-1}$ to the lake. Discharge and nutrient loads for the Ohau Channel were based on the nutrient budget values for Lake Rotorua (Table 11), but only 69% of this load was used in the nutrient budget in order to reflect the surface overflow conditions in the Ohau Channel, which results in only approximately 20% of the Ohau Channel inflow entering the main basin of Lake Rotoiti (refer to Hamilton and Uraoka, 2005). Internal loads of nutrients from release events during seasonal stratification, as well as seasonal hypolimnetic losses of nitrogen from denitrification as a result of anoxia, were taken from Hamilton et al. (2004).

For Lake Rotoiti there is a substantially lower retention of nutrients than in Lake Rotorua. The substantial loss of nitrogen via denitrification most likely results in a far lower retention of nitrogen compared with phosphorus. Seasonal release of nutrients into the hypolimnion over the stratified period most likely also offsets the retention from natural sedimentation of particulate nutrients to the lake bed. This imbalance between nitrogen and phosphorus retention is accentuated to an even greater extent with a hypothetical case of diversion of the Ohau Channel, assuming all other fluxes remain constant; net retention of phosphorus decreases from 28.7 to $10.9 \text{ tonnes yr}^{-1}$, while nitrogen is 'mined' from the lake, with the amount retained changing from 15.4 to $-153.1 \text{ tonnes yr}^{-1}$.

Table 21. Summary of nutrient budget for Lake Rotoiti. The retained/lost value represents net retention (e.g. by sedimentation for TP and TN). 'Internal' represents the internal load due to sediment release events during periods of stratification (from Hamilton et al., 2003). Percentages of total phosphorus and total nitrogen imports to and exports from the lake are given and compared in the retained/lost row.

Variable	Flow (m ³ s ⁻¹)	TP (tonnes yr ⁻¹)	% TP	TN (tonnes yr ⁻¹)	% TN
<i>Inflows</i>					
Rainfall	1.61	0.55	1.2	12.4	4.3
Gauged minor inflows	0.6	1.56	3.5	24.5	8.4
Ohau inflow	16.91	13.3	29.5	164	56.4
Ungauged inflows	3.76	9.6	21.3	40.1	13.8
Internal	N/A	20	44.4	50	17.2
Total inflows	22.88	45.0	100	291	100
<i>Outflows</i>					
Evaporation	1.31	0	0	0	0
Kaituna outflow	21.57	16.3	100	230.1	82.1
Denitrification	N/A	N/A	N/A	50	17.9
Total outflows	22.88	16.3	100	280.1	100
<i>Net</i>					
Retained	0	63.8	60.5	3.7	18.2

4 References

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Appendix 1

Extract from electronic mail from John McIntosh, November-2003:

Lake Rotorua Data Archive.

Intermittent level records were collected from 1934 to 1952 at the Rotorua town wharf and these have been archived on the NIWA database as site 14615. From 1952 to March 1966 the wharf staff gauge was read regularly and the levels have been transferred to the existing monitoring site at Mission Bay 14625. Flow ratings for the Ohau channel were established from intermittent gaugings at the channel. From 1966 a permanent lake level recorder was established at Mission Bay and this became the official lake level record. Both sites are surveyed into Moturiki datum. NIWA and its predecessors are the recording authority.

Ohau Channel Flow Measurement.

The channel had occasional gaugings to 1966 and approximate ratings were created on the basis of these and the relationship with gaugings at the outlet of Lake Rotoiti. From 1966 when the recorder was installed, gauging frequency increased so that the quality of the ratings improved significantly. The rating changes at Ohau Channel are attributable to a number of influences. They are; natural changes in the channel bed, Lake Rotoiti levels, the lake outlet control area, dredging of the channel and the construction of an outlet control.

Lake Level Control.

The lake outflows through the Ohau Channel up to 1971 had virtually no man made manipulation. Rainfall was the significant influence on lake level and in high rainfall years the lake flooded low lying areas. In 1962 the Bay of Plenty experienced one of the highest rainfalls in a 12 month period. The impact can be seen on the lake level plot. Again in 1970-71 high rainfall was experienced but this time the authorities decide to act and the Ohau Channel was dredged over the period January to October 1972 to increase flows. The channel was modified further with a cut in September 1973. The 1972-73 period had very low rainfall and the impact on the lake caused many complaints at the shoreline and in very shallow places. One example was the Hamurana jetty which could not be accessed so a channel was blown in the lakebed. To reduce the outflow and ensure

some control, rock gabions were installed in 1974. These were then changed as required to maintain the lake at a reasonable level. The BOP Catchment Commission then established a recommended maximum and minimum which continue to the present. The maximum, in the present datum, is 280.071 metres and the minimum is 279.461. In April 1989 the gabions were replaced with a concrete control and removable stoplogs. The result is that the lake level has rarely been exceeded or lowered below these recommendations since 1974 and extreme events are required to move the lake level outside these limits. Analysis of the record since 1952 in ten year periods defines the time that these limits are exceeded. From 1952 to the end of 1959 the maximum was exceeded 22% of the time (576 days) and it did not drop below the minimum. From 1960 to the end of 1969 the maximum was exceeded 54 % of the time (1909 days) and it did not drop below the minimum. From 1970 to the end of 1979 the maximum was exceeded 21% of the time (768 days). This occurred prior to the channel dredging and the installation of the control. The lake dropped below the minimum for approximately 1% of the time (47 days). Again this occurred prior to the installation of the control. From 1980 to the end of 1989 the maximum was exceeded 2.1% of the time (75 days) and it did not drop below the minimum. From 1990 to the end of 1999 the maximum was exceeded 4.8 % of the time (173 days) and it did not drop below the minimum. From 2000 to the present the maximum was exceeded 1.0% of the time (11 days) and it did not drop below the minimum.