INFLOWS TO LAKE ROTORUA

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ABSTRACT

A water balance study of Lake Rotorua establishes that about 66% of the total input of water to the lake is from nine streams, 22% is from direct rainfall and 2% from minor tributaries. Unmeasured sources might be 10% of the total input. Flow distribution curves for major streams show that floods are relatively unimportant to the annual water balance of the lake.

INTRODUCTION

Lake Rotorua is situated on the edge of the central volcanic plateau of the North Island of New Zealand (Fig. 1). The lake has an area of about 81 km², and its mean depth is about 10.5 m. The topography and soils of catchments draining into the lake are dominated by products of volcanic eruptions (Healy, 1963). Porous and permeable ash layers cover the surface to a depth of several tens of metres in places, absorbing a very large proportion of the rainfall without becoming saturated. Overland flow is therefore infrequent. Many of the catchments have fractured ignimbrite or other permeable volcanic rocks which act as

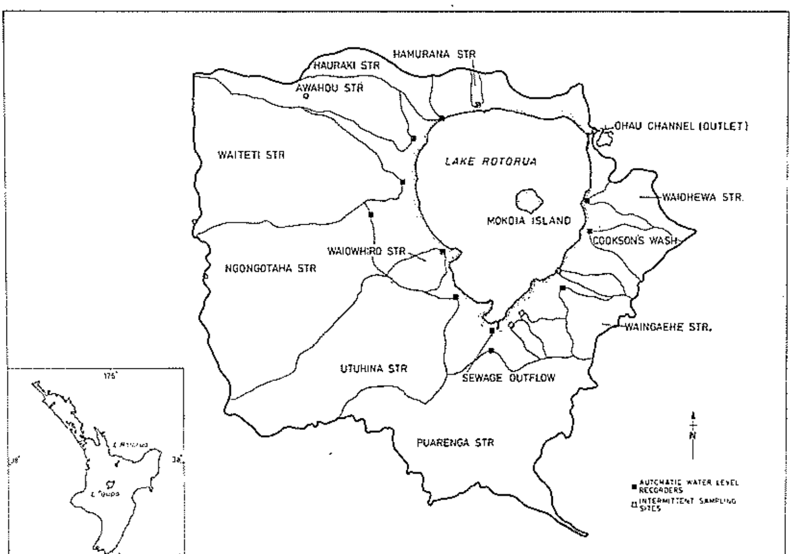

FIG. 1—Catchments used in the study.

aquifers capable of storing water for up to 15 years before the water emerges at springs (Taylor *et al.*, 1977).

The appearance and use of Lake Rotorua are threatened by eutrophication (White, 1977) and major engineering works have been proposed to correct this problem (Bay of Plenty Catchment Commission, 1975). To estimate the probable effects of these works, detailed studies of the input of nutrient to the lake have been made (White *et al.*, 1978; Hoare, 1980); these studies justified collecting the flow data described in this paper.

The key issues are:

(a) What are the average flows of each tributary?
(b) How is the flow distributed in time?
(c) How much of the total input into the lake is accounted for by the measured flows?

METHODS

The nine most important flow measuring sites used are shown in Figure 1 and Table 1. The lake level and flow at Utuhina have been recorded for 10 years. In 1975 the other sites listed in Table 1 were established to ensure detailed records for nutrient input studies. Unless the channel was naturally stable, recorder sites had some form of bed control constructed to ensure stable rating curves (Table 1). Hamurana Stream is the largest single input, but it is fed by a spring just above the lake level, so that its level is controlled by lake level and a flow rating curve can not be determined easily. The flow at this site changes very slowly with time, and the site has a very small surface catchment area, so its flow can be measured by monthly flow gaugings. Standard gauging techniques were used to calibrate the recorder sites, and methods outlined by Thompson and Wrigley (1976) were used to calculate flows and flow distributions.

Sewage discharges and small streams from geothermal springs may have high concentrations of salts. Nutrient studies have to consider

TABLE 1—Flows at major sites.

Stream name	Map ref. N76:	Catchment area, km^2	Record type	Bed control	1976 Mean flow (l/s)
Waingaehe	777059	9.6	F	Rock channel	2050
Puarenga	732018	74.8	F	Metal weir	274
Waiohewa	791111	11.1	C	Rock bed	413
Hamurana	728167	—	G	None	3080
Awahou	685149	21.5	C	Rock bed	1664
Waiteti	679122	71.0	F	Wooden weir	1391
Ngongotaha	662105	73.3	F	None	1977
Waiowhiro	702078	4.4	C	Rock weir	415
Utuhina	710052	59.6	F	None	2040

Notes: C = Chart recorder.
F = Punch tape recorder.
G = Gaugings only.

these streams in case the mass flow of a particular nutrient is high even though the stream's contribution of water is small. About 15 such minor streams were gauged monthly during 1976 and 1977.

Rainfall measurements were made by voluntary raingauge readers who took daily readings at 25 sites which gave a good coverage of the whole catchment. These sites and methods were checked by technical staff of the Ministry of Works and Development's Water and Soil Division. Additional data came from 6 storage gauges (checked monthly) and four automatic recording raingauges. Average rainfall over the lake was determined by calculating isohyets and then integrating the volume of rainfall over the lake area.

Open water evaporation from the lake was calculated by applying the factor 0.69 (Finkelstein, 1973) to pan evaporation data from Rotorua Airport (N.Z. Meteorological Service, 1976). This should be reasonably accurate for annual average evaporation figures, according to Finkelstein, but will overestimate short-term summer evaporation rates and underestimate short-term winter evaporation rates.

RESULTS

Six streams each supply 7-15% of the total inflow, and three streams each supply 1-2% of the inflow (Table 1). Other measured streams each supply less than 0.3% and Rotorua City sewage supplies 0.6%. Flows plus data on meteorology and lake level were used to prepare a water budget for the lake for the year 1976 (Table 2). About 90% of the estimated total inflow is accounted for by direct measurements. In addition, short-term water budgets were determined for rainless periods in summer and winter (Table 2), and showed that less than 5% of the annual average inflow rate could be attributed to inflow from unmeasured springs. Rainfall into the lake was 22% of the input and estimated evaporation was 10% of the output.

TABLE 2—Water Budget of Lake Rotorua (Average flow, m^3/s).

		Dry periods	
	1976 Annual	February 12-21, 1976	May 29-June 10, 1976
Major sites	13.3	12.8	12.3
Minor sites	0.4	0.4	0.4
Rain	4.5	0.0	0.0
Total Measured Inflow	18.2	13.2	12.7
Ohau Channel	17.9	17.0	16.4
Evaporation	2.0	3.8	0.7
Increase in Storage	0.4	−6.7	−3.8
Total Estimated Inflow	20.3	14.1	13.3
Unmeasured Inflow	2.1	0.9	0.6

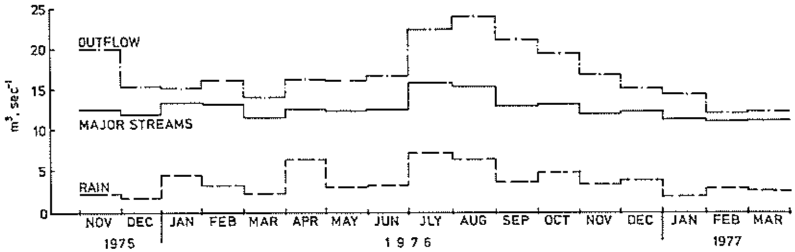

FIG. 2—Monthly mean flow into and out of the lake (m^3/s).

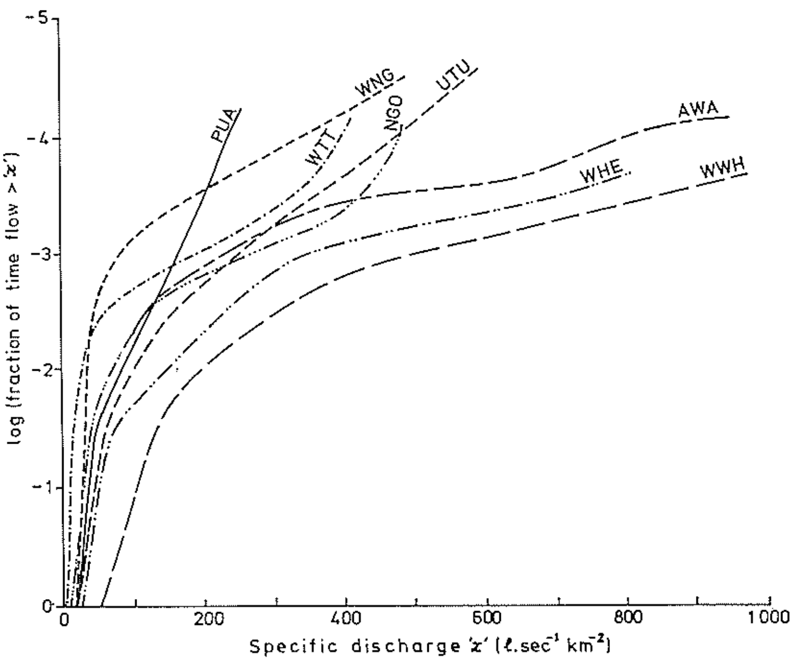

FIG. 3—Time distribution of specific discharges in tributaries of Lake Rotorua. The data is from May 1975 to April 1977, except for the Utuhina which is from September 1967 to May 1977.

The monthly means of the sum of the flows of streams, the outflow and the rainfall showed a seasonal variation (Fig. 2), being most noticeable in the outflow, which presumably reflects the seasonal variation in evaporation from the lake surface.

The time distribution of the flow of any stream may be illustrated by plotting the logarithm of the fraction of time that the flow rate exceeds a value Q, against Q. This is done for 1976-1977 flow records from eight major sites in Figure 3, where specific discharge has been

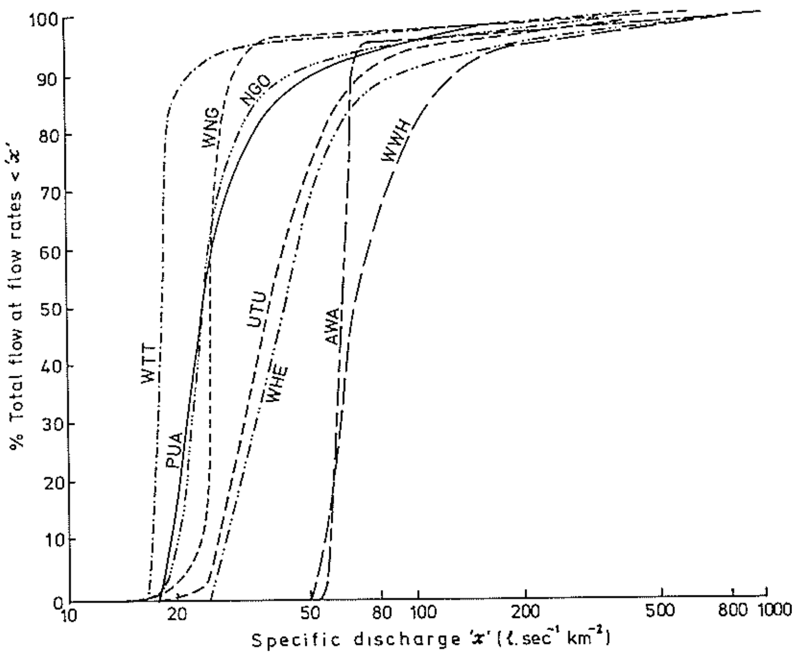

FIG. 4—The relative flows of the tributaries of Lake Rotorua, as a function of the specific discharge below which the specified proportion of the flow occurs.

calculated from measured flow and the apparent catchment area. High specific discharges occur, but only for very short times.

Studies of water quality are often concerned with the volume of water being transported at flows greater than any given flow. Only a small percentage of the total volume of water is transported at flows greater than twice the minimum flow on all the major sites (Fig. 4).

It would be expected that sites as close as these would show similar variations in flow from month to month. The correlation matrix for monthly average flow from January 1976 to December 1977 is shown in Table 3 along with the standard deviation of the monthly average flow rate and the mean of the monthly flow at each site for this period. The flows are sometimes very well correlated, but not always.

The time covered by the measurements on most of these streams is very short, and the period may not represent average conditions. Comparison of annual values for mean flow in the Utuhina Stream and rainfall at Whakarewarewa over a 10 year period (N.Z. Meterological Service, 1967-1976) indicates that 1976 total rainfall (1510 mm) was near the average for this period (1540 mm) (Fig. 5). The 1976 mean flow in the Utuhina (1.997 m^3/s) was 11% lower than the 10 year mean flow rate of 2.247 m^3/s. H. Freestone (unpublished MWD report) has used a correlation with the Lake Rotoiti outlet record, to estimate the 1906-1972

TABLE 3—Statistics of monthly stream flow, January 1976-December 1977.

			Correlation Coefficients												
Stream name	Code	Rain*	Utu	Wtt	Pua	Ngo	Wwh	Whe	Wng	Awa	Ham		Mean	SD	C
Utuhina	Utu	0.743	1	.927	.920	.912	.886	.717	.658	.566	(.105)		1949	329	17
Waiteti	Wtt	0.635		1	.823	.909	.894	.833	.537	(.387)	(−.058)		1366	146	11
Puarenga	Pua	0.754			1	.851	.897	.736	.743	.557	(.151)		1964	288	15
Ngongotaha	Ngo	0.707				1	.723	.494	.502	.532	(−.013)		1978	364	18
Waiowhiro	Wwh	0.557					1	.833	.688	(.420)	(.081)		380	84	22
Waiohewa	Whe	0.552						1	.832	.485	(.119)		358	78	22
Waingaehe	Wng	0.195							1	(.345)	(.286)		266	21	8
Awahou	Awa	(0.011)								1	(−.167)		1627	130	8
Hamurana	Ham	(0.096)									1		3023	96	3

* At Whakarewarewa.
( ) Indicates r not significantly different from zero at 95% confidence level.
SD = Standard deviation of monthly means.
C = Coefficient of variation, %.

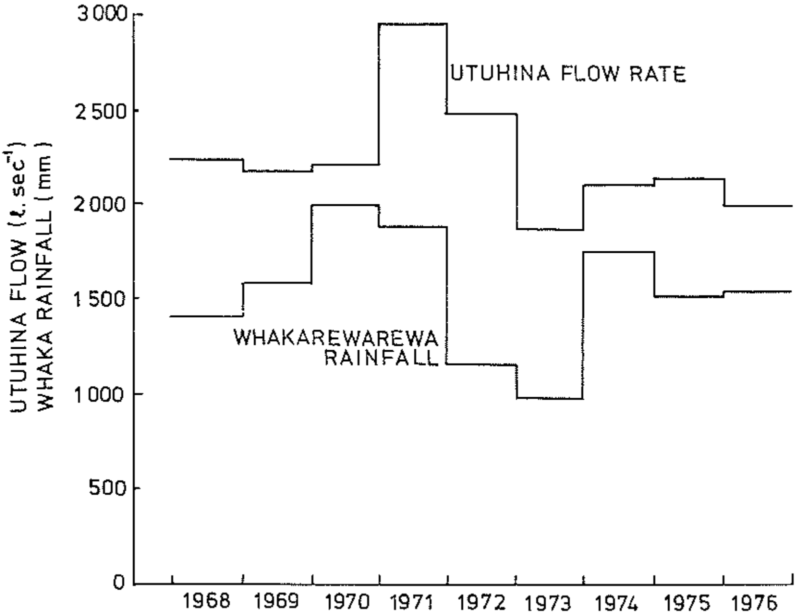

FIG. 5—The annual flow of the Utuhina Stream and the annual precipitation at Whakarewarewa, from 1968-1976.

mean flow of the Utuhina as 2.045 m^3/s. The correlation between annual mean runoff and annual mean rainfall is not significant at the 5% level ($r = 0.40$), because of storage effects. The short length of record prevents analysis of storage delays but multiple regression of flow on both the present and previous year's rainfall gives

$$R = 0.175\,P + 0.364\,P' + 406$$

where annual rainfall P (mm) and rainfall of the previous year, P′ (mm) are related to the runoff R (mm). The multiple correlation coefficient is 0.78.

In the Rotorua catchment the rainfall is considerably lower in the south than the north, and the distribution for 1976 is shown in Figure 6. The mean rainfall in the lake was 1750 mm, 1.19 times the rainfall at the airport and 1.16 times the Whakarewarewa rainfall.

DISCUSSION

Fish (1975) reported flows for 1967-1970 for most of the major inflows to Lake Rotorua. He did not have flow recorders on most sites, so could not account for flood flow. He quotes the Rotorua airport average rainfall for 1967-1970 as 1537 mm/yr, whereas in 1975 and 1976 the rainfall at the airport was 1556 and 1471 mm. One would expect Fish's estimates to be lower because of the lack of flood flow, but this is possibly compensated by a 4% higher rainfall. In fact, Fish's estimates

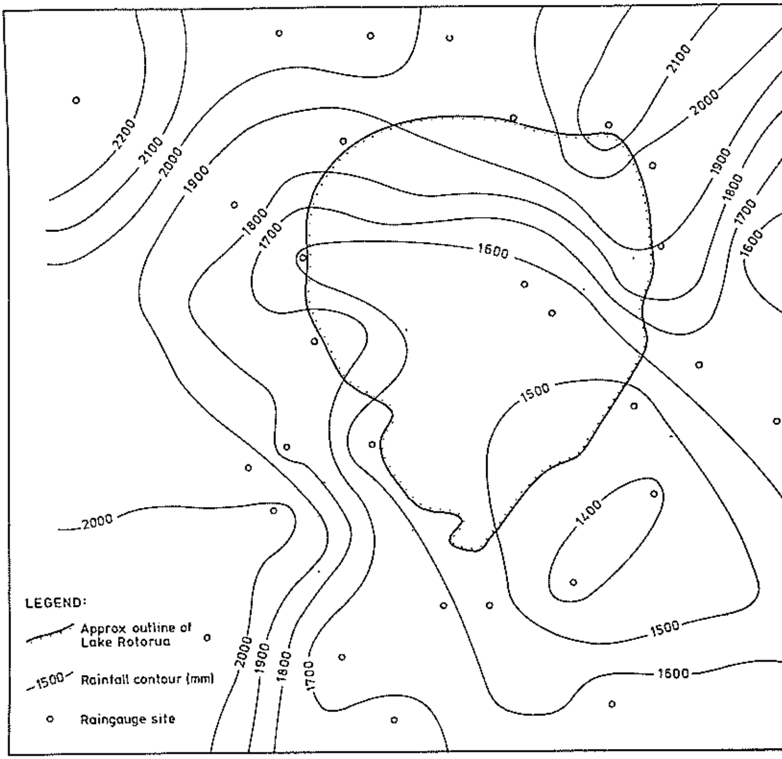

FIG. 6—Isohyets for the Lake Rotorua catchment, 1976.

are about 10% higher for most sites, except Hamurana which is the same within 1% and Puarenga which is 6% lower than the 1976 flow.

The 1976 water balance in Table 2 shows that if the measured inflows are compared with the measured outflow, change in storage and estimated evaporation, there remains 2.1 m^3/s of estimated inflow not measured at the sites listed in Table 1. This is about 10% of the estimated total inflow.

One would not expect complete balance, for about 69 km^2 of low lying land and ephemeral catchments near the lake have been left out of the flow estimate. The runoff from the unmeasured areas occurs partly as flood flow in ephemeral channels and partly as continuous flow from lakeside springs, and from underwater springs (John and Lock, 1977). To distinguish these, short-term balances for rainless periods in summer and winter are also shown in Table 2. The unmeasured flow is about 0.7 m^3/s, and appears to be larger in summer than in winter, but the precision of the short-term evaporation estimate is such that the differences are not significant. Since changes in lake temperature lag changes in pan temperature, the summer evaporation is probably overestimated and this alone could account for the differences.

There must be unmeasured inflow from sources which flow only for a short time after rain, and this will include part of the runoff from urban areas. If we take the average rainfall on the unmeasured areas to equal the average rainfall on the lake, and assume than 800 mm of water is lost by evaporation and interception, then the runoff from 69 km^2 amounts to just 2.1 m^3/s. The exact agreement is fortuitous, but clearly the water balance of the lake can be explained well by the measurements.

Pittams (1968) concluded from rainfall measurements that substantially more water was entering the lake than could be measured in the outflow stream, but this study shows that this is not the case.

The monthly mean data in Figure 2 shows that, although rainfall can double between one month and the next, this causes only a 25% increase in monthly discharge of the streams in winter, and less in summer. This is because, as shown in Figure 4, only a small proportion of the total flow runs off at high flow. This same storage effect persists even in the annual flow values, as shown by the Utuhina flow record.

At least three distinct types of flow distribution curves occur (Fig. 3), with the Awahou, Waiohewa and Waiowhiro having very high specific discharge for short time periods, and the Puarenga having notably little of its total time spent at high specific discharge. Thompson and Adams (1979) used this form of plot because according to the theory of statistical extremes the flows should be able to be extrapolated by straight lines. This does appear to be the case. They normalised the flow axis by using the mean flow rather than catchment area, but this was purely for convenience (S. M. Thompson, pers. comm.).

The correlation between the monthly average flow at some sites is much closer than at others (Table 3). The average flows of the Utuhina, Waiteti, Puarenga, Ngongotaha, Waiowhiro, and Waiohewa are strongly correlated, while those of the Waingaehe, Awahou, and Hamurana are progressively less correlated with those of other sites. These latter sites have small coefficients of variation C_v (i.e. the standard deviation divided by the mean) because the majority of their flow comes from deep springs, which are not affected by recent rainfall. Even on the other sites the coefficient of variation is small (15-20%). What variation does occur is partly correlated with monthly rainfall ($r = 0.7$ to 0.8).

To monitor nutrient load on the lake it is necessary to estimate the volume of water flowing in each stream, as well as to measure the concentration of nutrients. The concentrations of nutrients in the base flow of these tributaries of Lake Rotorua are only slightly dependent on flow rate, but some do show seasonal variations (Hoare, in preparation). In this case then, the monthly mean is a useful statistic of the flow. Since the monthly mean concentrations can be estimated only within about 10% from the few samples it is practical to collect, it is necessary to obtain the monthly mean flow only to a similiar level of precision. Hamurana Stream has a coefficient of variation of 3% (Table 3), so that the monthly mean flow seldom differs by more than 6% from the annual flow, allowing the annual mean flow to be used in water quality calculations.

The data in Table 3 may be used to devise equations to predict the flow at one site from that at any other, on a monthly basis. The precision of prediction depends on the correlation coefficient between the two sites, and also on the variance of the flow rate of the stream whose flow is to be predicted. It can be shown from the expression given by Snedecor and Cochran (1976, p. 155), that the standard deviation of an estimate divided by the mean is approximately $\sqrt[2]{(1-r^2)}$ times the coefficient of variation providing that a reasonably large number of data points were used in the regression (say, more than 20), and that the particular value is not too far from the mean value. If the Utuhina site were used to predict flows at all the other sites, then the standard deviation for the predicted flows would be 15% of the mean flow for the Waiohewa, and 10% or less of the mean flow at the other sites.

CONCLUSIONS

The data presented give the flows for most of the tributaries of Lake Rotorua for 1976, and allow the estimation of monthly average flows of all streams if some are known. Utuhina Stream is a good base station because it has a long record and correlates well with other stations. The precision of such estimates is such that in most cases the standard deviation of an estimated monthly flow is less than 10% of the mean flow.

Most of the volume of water is transported by the streams at flows less than twice the minimum flow, so that floods are relatively unimportant to the water budget of the lake. The water storage of the catchments is very great, so much so, that annual runoff may not be significantly correlated with annual rainfall.

Nine major rivers account for about 66% of the total input of water to the lake, direct rainfall 22%, and the minor tributaries 2%. Runoff from unmeasured portions of the catchment is, by difference, 10% of the total input, or about 15% of the measured river flow.

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