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# WATER BALANCE OF LAKE ROTOITI, NORTH ISLAND: FLOODS AND SHORT-CIRCUITING OF INFLOWS FROM LAKE ROTORUA

Robert H. Spigel

*Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand*

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## ABSTRACT

The water balance of Lake Rotoiti, North Island, New Zealand, is examined to clarify the role of floods and residual flows in the transport of Lake Rotorua water into the main body of Lake Rotoiti. A 28-year (1957–1984) data set for inflows, outflows, water levels, rainfall and evaporation is used to construct a long-term monthly water balance and to compare daily flows for the entire study period. Four storms are examined in detail to explain observed lake level rises during the storms. The transport of Lake Rotorua water to Lake Rotoiti during storms is negligible compared with transport governed by density currents, and lake level rises during storms are a response more to rainfall on the lake than to inflows from Lake Rotorua. The residual term in the water balance reflects groundwater input, resulting in a net westward flow through the lake. In the absence of density currents this flow reinforces the tendency of Lake Rotorua water to short-circuit (i.e. to flow directly to the outlet of Lake Rotoiti without mixing with the main body of the lake) because of the proximity of the lake inlet and outlet at the western end of the lake.

## INTRODUCTION

Vincent et al (1984) have documented the decline of water quality of Lake Rotoiti (North Island), implicating inflow from nearby Lake Rotorua via a short connecting channel, the Ohau Channel (Fig. 1), as a contributing factor to the decline. Lake Rotorua is a shallow eutrophic lake (Rutherford 1984) that receives the treated sewage effluent from Rotorua city (population 48,300). A study of the inflow dynamics of the Ohau Channel by Vincent et al (1986) shows that buoyancy effects arising from temperature differences between the Ohau Channel inflow and epilimnion of Lake Rotoiti largely determine the fate of Lake Rotorua water in Lake Rotoiti. When the temperature of the inflow is colder than that of Lake Rotoiti's epilimnion by approximately 0.5° C or more, the inflow plunges and enters the main basin of Lake Rotoiti as a density current on the lake bottom or as an intrusion near the thermocline. In contrast, warmer inflows remain on the surface as overflows and, in the absence of strong westerly winds, are short-circuited to Lake Rotoiti's outlet to the Kaituna River, adjacent to the inlet from the Ohau Channel in the shallow western basin of the lake (Fig. 1). Similar short-circuiting has been documented in a New York lake by Englert and Stewart (1983).

This paper discusses aspects of the water balance of Lake Rotoiti relevant to the transport of Lake Rotorua water to Lake Rotoiti. The water balance

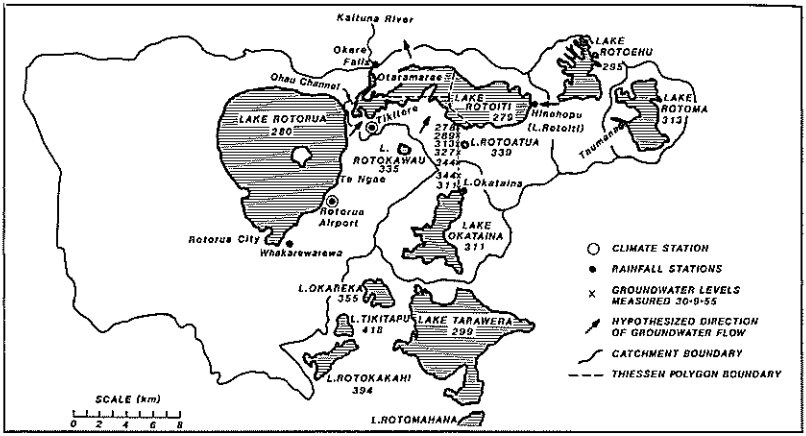

FIG 1—Rotorua district lakes, showing sub-catchment boundaries based on surface topography, rainfall and climate stations, water surface elevations and hypothesized direction of groundwater flows for the Rotoiti catchment.

treats Lake Rotoiti as a single control volume, and relates inflows and outflows to changes in lake storage through the equation for conservation of volume. No fluid dynamics other than conservation of volume are involved, hence buoyancy effects are not considered. This latter aspect has been discussed by Vincent et al (1986) and is the subject of other papers in preparation. The water balance helps explain two aspects of the transport of Lake Rotorua water to Lake Rotoiti.

First, the water balance shows that there must be, on average, residual westward flow of water through the lake of 3.6–7.9 $m^3/s$, composed of groundwater, baseflow from small streams other than the Ohau Channel, and storm runoff. As a result of this residual flow, the outflow from the lake to the Kaituna River is almost always greater than the inflow from the Ohau Channel. Such a net westward flow would reinforce the tendency of warmer, less dense Ohau Channel inflows to short-circuit directly to the lake outlet at the western end of the lake.

Second, the transport to Lake Rotorua water into Lake Rotoiti has been identified as a cause of deteriorating water quality in Lake Rotoiti (Vincent et al. 1984). Lakeside residents are concerned that during floods the control gates at Lake Rotoiti's outlet may be used to detain floodwaters from the Lake Rotorua catchment, resulting in a greater-than-normal influx of poor quality Lake Rotorua water to Lake Rotoiti. Lake level rises during storms have been attributed by some residents to flood flows from Lake Rotorua. While the water balance cannot provide information on the path taken by Lake Rotorua floodwater entering Lake Rotoiti, it does clearly show that during floods outflow from Lake Rotoiti almost always exceeds inflow from Lake Rotorua. Transport of Lake Rotorua water by floods to Lake Rotoiti is negligible compared to the prolonged inflows due to density differences. Moreover, daily water balances for four storms indicate that rises in lake levels during storms are much more closely correlated with rainfall on the lake than with inflows from the Ohau Channel.

## LAKE ROTOITI AND ITS CATCHMENT

Lake Rotoiti is one of the group of lakes in the Rotorua district formed by volcanic activity within the Taupo Volcanic Zone in the central North Island, New Zealand. The lake is approximately 14 km long and of variable width less than 3.5 km. It has a surface area of 34.35 km$^2$ and a volume of 1.135 (10$^9$) m$^3$ (by planimetry from Irwin 1969, Irwin and de L. Main 1982), giving a mean depth of 33.0 m. However, depths in the main eastern basin are much greater, of the order of 60 m, with a hole of small areal extent ($<$ 1 km$^2$) more than 120 m deep. A major geothermal heat source is associated with this hole (Calhaem 1973), while numerous high temperature geothermal springs occur along the southeastern lake boundary (Cole and Nairn 1975). The lake becomes shallower to the west, with the main body of the lake separated by a constriction in width from a wide shallow (ca. 10 m deep) western basin into which flows the only major inflow, the Ohau Channel from Lake Rotorua (mean flow 18.0 m$^3$/s). The lake outlet is practically adjacent to the inlet (Fig. 1); outflow to the Kaituna River (mean flow 22.8 m$^3$/s) until 1982 was via a natural control over rock sills to Okere Falls. In 1982 adjustable gates were installed upstream of the falls to control lake levels upstream of the gates and flood flows downstream (cf. Bay of Plenty Catchment Commission 1975).

The Rotorua lakes region is characterised by warm, humid summers and mild winters; annual rainfall is in the range of 1500 to 2500 mm with a winter maximum. Prevailing winds are from the southwest but occasional strong gales and heavy rains sweep the region from the east or northwest. Rainfall is highest near Lake Rotoma and decreases south and west of Lake Rotoiti, New Zealand Meteorological Service (1983a).

The geology of the region is volcanic in orgin, and has been described by Healy (1963) as well as in several New Zealand Government publications (e.g. N.Z. Ministry of Works 1962, Blaschke 1985, Ewart and Healy 1965, Suggate et al 1978), with a useful summary by Nairn (1975). The large, deep eastern basin of Lake Rotoiti lies on the rim of the Haroharo caldera, a complex structure also containing parts of the lake basins of Okataina, Tarawera, Rotoma, and Rotomahana (Nairn 1981). The western half of Lake Rotoiti fills an old river channel formed by headward erosion at a time when the Haroharo complex drained to the east by way of the valley now occupied by the Tarawera River (Healy 1975). Subsequent eruptions ($<$ 20,000 years ago) within the caldera blocked the eastward drainage, causing Lake Rotoiti to fill and the Rotorua-Rotoiti system to drain northward by way of the Kaituna River. Steep cliffs of rhyolite on the northern shore, and of ignimbrite on the southern shore bound Lake Rotoiti, and are striking reminders of the lake's volcanic origins. Elsewhere the volcanic rock is overlain by successive layers of pumice and ash of total thickness up to 100 m arising from successive explosive eruptions within the Haroharo and neighbouring volcanic complexes. With the exception of a relatively impermeable capping of Rotomahana muds in the southeastern quarter of the catchment, the soils and underlying deposits of the Rotoiti catchment are generally porous and highly permeable (Nairn 1975). As a result infiltration rates are high and overland flow is rarely observed (Freestone 1974, Hoare 1980). However, changes in land use from woody vegetation to pasture with subsequent soil compaction can lead to greatly increased runoff (Selby 1972).

Subsurface flows play a major role in the hydrology of the lake and its catchment. With the exception of the Ohau Channel, all surface flows into the lake are small ($< 1\ m^3/s$) and dominated by springs (Freestone 1982). Even the definition of a lake catchment is made problematical by subsurface flow. Catchment boundaries are sketched in Fig. 1 based on surface topographic features (see also Nairn 1975 and Pittams 1968). The purely local catchment surrounding Lake Rotoiti was estimated by Nairn (1975) to have an area (including the lake) of 119 $km^2$, giving a land area of 84.7 $km^2$. With the exception of some residential development on the western lakeshore, most of the catchment is either farmland (42.8% pasture, 8.3% pasture and scrub) or indigenous forest (49.4%; Nairn 1975). However, the catchment defined as the surface area draining to the lake outlet at Okere Falls also includes the Lake Rotorua catchment (area 355 $km^2$) and possibly parts of the catchments surrounding Lake Rotoehu, Lake Rotoma, and Lake Okataina. These latter three lakes have no surface outlets and probably drain underground partly through the Rotoiti catchment and eventually to the Kaituna River (Pittams 1968). This hypothesis is supported by the relative lake levels (Fig. 1) as well as by groundwater levels measured in 1955 on a line between Lake Okataina and Lake Rotoiti during investigation drilling for the Kaituna Power Development (N.Z. Ministry of Works and Development 1964, I. Innes, personal communication). These levels (Fig. 1) clearly indicate an hydraulic gradient toward Lake Rotoiti. The 1 m discrepancy between lake level and groundwater level near the southern shore of Lake Rotoiti is probably not significant and could involve local effects, temporal effects, or drawdown from pumping in nearby wells. Near the northwest shore groundwater levels were nearly 37 m below the lake surface level, and the hydraulic gradient on the line north from the lake dropped steadily away from the lake (N.Z. Ministry of Works and Development 1964; I. Innes, personal communication). The implications of these observations for the water balance and for transport within the lake will be discussed later. Directions of hypothesized groundwater flows are indicated on Fig. 1.

## WATER BALANCE

### *General Considerations*

The water balance of Lake Rotoiti has been discussed by Pittams (1968), Freestone (1982) and to a lesser extent by Fish (1975). In addition, the relation of water levels in Lakes Rotorua and Rotoiti to flows in the Ohau Channel and Kaituna River has been extensively investigated by the N.Z. Ministry of Works and Development in connection with proposals for controlling water levels in the two lakes. This work is documented in several Ministry of Works and Development reports and is summarised briefly by Best and Wilshere (1973). The calculations presented here are independent of the studies mentioned above, none of which focuses specifically on issues raised in this paper.

The water balance of Lake Rotoiti may be expressed in terms of an equation relating rate of change in storage in the lake to flows into and out of the lake, including rainfall and evaporation, as:

$$\frac{dS}{dt} = Q_O - Q_K + Q_{GW} + Q_{BF} + Q_{SRO} + P - E \quad (1)$$

where S = lake storage and dS/dt = rate of change in lake storage, $Q_O$ = Ohau Channel flow entering the lake, $Q_K$ = Kaituna River flow leaving the lake, $Q_{GW}$ = net groundwater flow into the lake, $Q_{BF}$ = baseflow or dry weather flow into the lake from surface streams and springs, $Q_{SRO}$ = storm runoff from the lake catchment during periods of rainfall, P = rainfall on the lake surface, and E = evaporation. Equation 1 can be approximated by a simple forward finite difference scheme in which dS/dt is replaced by $\Delta S/\Delta t = (S(t + \Delta t) - S(t))/\Delta t$ over the time step $\Delta t$, and all the terms on the right hand side are evaluated at time t.

The results presented below are based on a 28-year data set for 1957–1984 inclusive, using flow and lake level data stored on the N.Z. Ministry of Works and Development Time Dependent Data (TIDEDA) archive and acquisition system, and rainfall and evaporation pan data from the N.Z. Meteorological Service. Change in lake storage was calculated from lake level records as $\Delta S = A\Delta h$, where $\Delta h$ is change in lake level and A = lake surface area (34.35 $km^2$). Rainfall data from rain gauge sites (Fig. 1) at Okere Falls, Tikitere, Lake Okataina, Lake Rotoiti (near Hinehopu), Rotorua Airport, Whakarewarewa, and Taumana (at Lake Rotoma) were used to compute rainfall over the lake. None of the above stations provided daily data covering the full study period, but by correlation if was possible to construct a 28-year sequence on monthly totals for the full study period for the stations at Okere Falls, Tikitere, Lake Okataina, and Lake Rotoiti (see Appendix). Rainfall over the lake was then computed as the weighted average rainfall at the above four stations using weighting factors 0.299, 0.150, 0.036, 0.515 respectively as determined by the method of Thiessen polygons (Linsley et al. 1975). The correlations also were used to establish shorter daily records for selected floods discussed below. Lake evaporation was estimated as the product of Rotorua pan evaporation multiplied by a pan coefficient of 0.75 (Linsley et al. 1975). Where daily evaporation pan data were unavailable, the figures for mean monthly pan evaporation for 1967–1980 (N.Z. Met. Service 1983b) were used. The terms $Q_{GW}$, $Q_{BF}$, and $Q_{SRO}$ for groundwater flow, baseflow, and storm runoff constituted the unknowns in Eq. 1; these terms are discussed below.

### *Monthly Water Balance 1957–1984*

Freestone (1982) has estimated an average value for baseflow ($Q_{BF}$) as 0.8 $m^3/s$ from an extensive set of measurements made in 1973–1974 of all known surface streams and springs entering Lake Rotoiti. He estimated storm runoff from the lake catchment ($Q_{SRO}$) as 0.3 $m^3/s$ and gave a figure of 2.0 $m^3/s$ for unmeasured inputs, which included net groundwater flow ($Q_{GW}$) plus any measurement errors. Pittams (1968) estimated groundwater flow to Lake Rotoiti from Lake Rotoehu alone as 1.8 $m^3/s$; further inputs of groundwater from the southern and southwestern sides of the lake are possible. Groundwater levels measured along the Okataina tunnel line during investigation drilling for the Kaituna Power Development show the groundwater table sloping downward toward Lake Rotoiti from a point roughly 700 m north of Lake Okataina, indicating groundwater flow toward Lake Rotoiti. However, groundwater levels to the north of Otaramarae were below the lake surface elevation, indicating that Lake Rotoiti is probably contributing to groundwater on its northwestern shore.

For this study, inflows due to net groundwater inflow, baseflow, and storm runoff were grouped together as a single unknown residual term, and the water

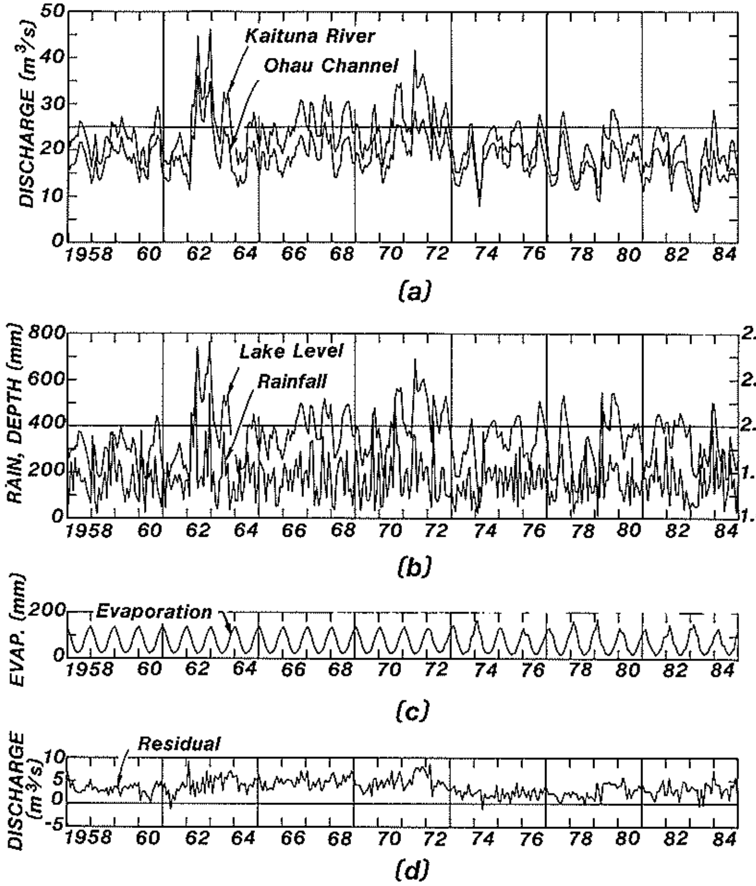

FIG 2—Monthly water balance components, Lake Rotoiti, 1957–1984.

(a) Monthly mean flows in the Ohau Channel and in the Kaituna River at Okere Falls (1957–1981) and at Taaheke (1982–1984), from the Ministry of Works and Development Time Dependent Data (TIDEDA) archive.

(b) Monthly rainfall; monthly mean lake levels (from TIDEDA) with a value of zero corresponding to 277.315 m above sea level (Moturiki datum).

(c) Monthly evaporation.

(d) Water balance residual, including groundwater inflow, baseflow, storm runoff, and errors in measured terms.

balance equation (Eq. 1) was solved month by month for the period 1957–1984 for this residual term. The residual term incorporates errors in all measured terms as well. The mean values for all components over this period were: $Q_O = 18.04$ m$^3$/s, $Q_K = 22.82$ m$^3$/s, P = 2010 mm/yr (2.19 m$^3$/s), E = 880 mm/yr (0.96 m$^3$/s), and $Q_{GW} + Q_{BF} + Q_{SRO} + \epsilon = 3.55$ m$^3$/s, where $\epsilon$ includes errors in all measured terms. The mean rate of change in storage over the entire period was negligible ($<$ 1 mm); mean lake level was 279.165 m above sea level (Moturiki datum). The value of 3.55 m$^3$/s for the mean residual flow is consistent with

Freestone's estimates. Furthermore, as most of the groundwater input must enter the lake on its southern and eastern shores (see above), the residual flow must result in a net westward transport through the lake to the outlet at Okere Falls. This flow reinforces the tendency for short circuiting of the inflow to the outlet under conditions of overflow, or when there is no temperature difference between the inflow and the lake.

The monthly variations in the water balance are illustrated in Figure 2 which shows flows, lake levels, rainfall, evaporation and the residual term as functions of time over the 28-year study period. A remarkable feature of the monthly variations is the relative steadiness of the residual term when compared with the large fluctuations in the measured terms. Fluctuations in the residual term are evident (Fig. 2), but these are of the order of errors expected in the measured terms in the water balance.

Two kinds of errors occur in the water balance calculations. First are random errors associated with the measured terms. The rainfall term is computed as a weighted average of four values, some or all of which have been derived by regression. The standard errors associated with the regressions are of the order of 40 mm/mo (0.52 $m^3/s$) for each station, giving an error (as the square root of the sum of squares) for four stations of ± 1.1 $m^3/s$. Evaporation pan estimates for lake evaporation are notoriously inaccurate, and before 1972 only mean monthly values (rather than actual values) were used in the calculations. Fortunately evaporation is a minor term in the balance. Assuming an accuracy of ± 100% gives an error estimate for evaporation of ± 1.0 $m^3/s$. Assuming relative accuracies for the Kaituna River and Ohau Channel flows of ± 5% and ± 10% respectively (the rating for the Ohau Channel is much less stable than for the Kaituna River) gives errors of ± 1.1 $m^3/s$ and ± 1.8 $m^3/s$ respectively. The total error, estimated as the square root of the sum of squares of the individual errors, is ± 2.5 $m^3/s$. This is of the same order as the standard deviation calculated for the residual term, 1.85 $m^3/s$.

The second kind of error involves the difficulties in measuring the discharge in the Ohau Channel associated with backwater effects from Lake Rotoiti, erosion and deposition in the Ohau Channel, alterations to the entrance to the Ohau Channel in Lake Rotorua, and the changing rating curve for the Ohau Channel. These problems have been studied by staff of the N.Z. Ministry of Works and Development and are beyond the scope of this paper. Best and Wilshere (1973) estimate a mean flow in the Ohau Channel for the period 1 September 1952 — 31 December 1971 of 13.73 $m^3/s$ while the mean flow from TIDEDA for the same period is 19.38 $m^3/s$. Best and Wilshere's results do not extend beyond 1971, while the frequency of Ohau Channel stream gaugings and consequent updating of rating curves from TIDEDA increased dramatically after 1971. Hence the reliability of Ohau Channel discharges increased significantly following 1971. However, an upper limit for the residual term can be calculated from Best and Wilshere's estimate of 13.73 $m^3/s$ for mean Ohau Channel flow instead of the value 18.04 given earlier. This yields a value for the residual of 7.86 $m^3/s$. Hence this second kind of error reinforces the conclusion that a net westward flow occurs in Lake Rotoiti, tending to reinforce short circuiting during periods when underflow or interflow do not occur.

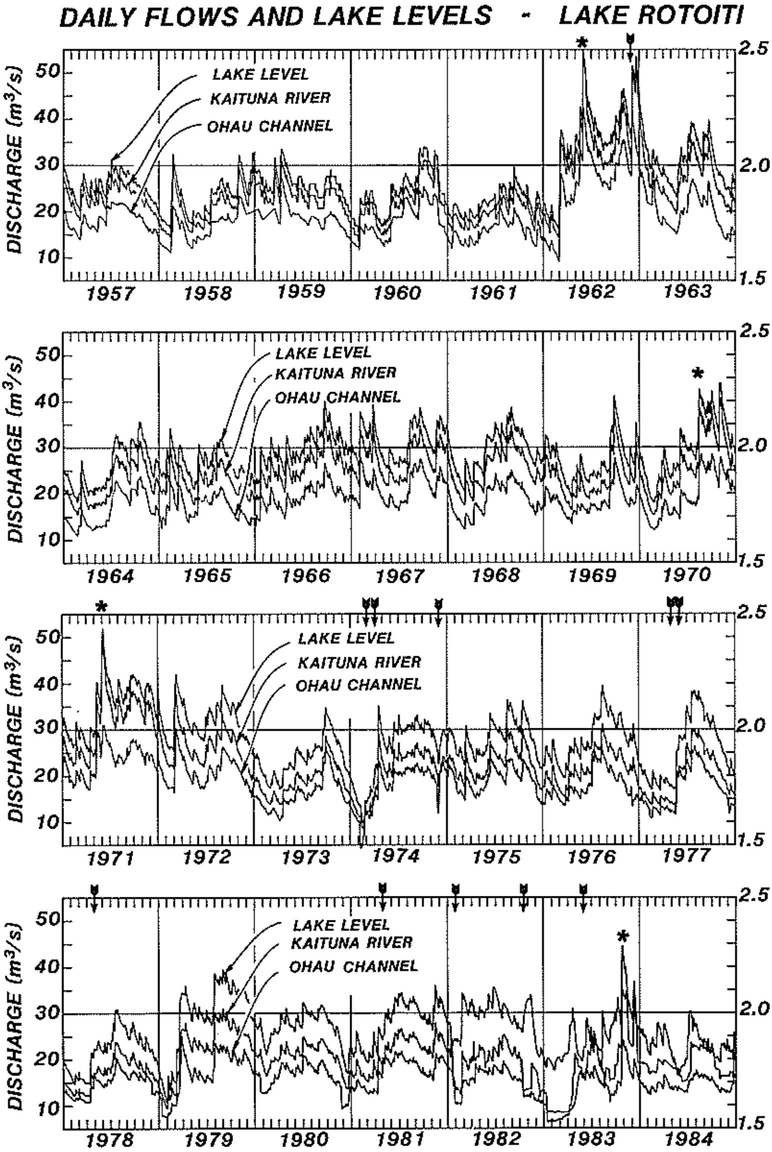

FIG 3—Daily flows in the Ohau Channel and in the Kaituna River at Okere Falls (1957–1981) and at Taaheke (1982–1984), and daily lake levels in Lake Rotoiti. All data are from Ministry of Works and Development Time Dependent Data (TIDEDA) archive. A lake level of zero corresponds to an elevation of 277.315 m above sea level (Moturiki datum). Small arrows mark periods when Ohau Channel flow exceeds Kaituna River flow; asterisks mark storms examined in more detail in the text.

*Flood Flows*

During storms flow rates increase in the Ohau Channel and the Kaituna River, and the water level of Lake Rotoiti rises. A 10 mm rise in the lake surface corresponds to an increase in lake storage volume of approximately $0.344 \times 10^6$ $m^3$. How much of this increase in volume is Lake Rotorua water, and how does this contribution compare with the less visible but more frequent underflow and interflow? To answer these questions two approaches were used. First, the 1957–1984 28-year daily time series of flows and lake levels was examined for events in which inflow to Lake Rotoiti from the Ohau Channel exceeded lake outflow to the Kaituna River. A daily time step provided adequate resolution since the time to peak of floods in the Ohau Channel is of the order of one to three days. Secondly, four floods chosen from the 28-year record were examined in detail by means of a daily water balance to relate changes in lake levels during storms to flows, rainfall, evaporation and storm runoff from the lake catchment.

The 28-year time-series are shown in Figure 3; Kaituna River flow prior to the installation of a control structure at Okere Falls in 1982 is calculated by applying a conventional stage/discharge rating to the lake levels; thereafter flow is a function of both lake level and gate setting. The periods during which Ohau Channel inflow exceeded Kaituna River outflow are marked with arrows in Fig. 3 and the net volumes of inflow are summarised in Table 1. The net inflow volume, i.e., the difference between Ohau Channel inflow and Kaituna River outflow during periods when inflow exceeded outflow, provides a measure

TABLE 1—Yearly summary of events in which discharge in Ohau Channel ($Q_O$) exceeds the discharge in the Kaituna River at Okere Falls ($Q_K$).

| Year | Net inflow volume $10^6 m^3$ (1) | Equivalent depth mm (2) | Fraction of total lake volume (3) | Number of days $Q_O > Q_K$ | Dates |
|---|---|---|---|---|---|
| 1962 | .0971 | 2.8 | 8.56 ($10^{-5}$) | 1 | 4 Dec |
| 1974 | 1.5612 | 45.4 | 1.37 ($10^{-3}$) | 18 | 25 Feb–6 Mar<br>27 Mar–1 Apr $Q_O < \bar{Q}_O$ (4)<br>6–7 Dec |
| 1977 | .4103 | 11.9 | 3.62 ($10^{-4}$) | 8 | 17 May<br>26 May–1 Jun $Q_O < \bar{Q}_O$ (4) |
| 1978 | .0082 | 0.2 | 7.23 ($10^{-6}$) | 1 | 30 Apr $Q_O < \bar{Q}_O$ (4) |
| 1981 | .3777 | 11.0 | 3.33 ($10^{-4}$) | 5 | 30 Apr–4 May |
| 1982 | .9688 | 28.2 | 8.53 ($10^{-4}$) | 9 | 20–26 Jan<br>14–15 Oct $Q_O < \bar{Q}_O$ (4) |
| 1983 | .0175 | 0.5 | 1.54 ($10^{-5}$) | 2 | 27–28 May $Q_O < \bar{Q}_O$ (4) |

1 ($Q_O - Q_K$) × time interval over which flow occurs.

2 Net inflow volume divided by lake surface area (34.35 $km^2$).

3 Net inflow volume divided by lake volume (1135.1 ($10^6$) $m^3$).

4 Indicates that on these days the Ohau Channel flow was less than average (18.04 $m^3/s$); i.e. these are low flow rather than high flow events.

of the transport of flood waters from Lake Rotorua to Lake Rotoiti as distinct from transport due to the effects of density differences. Two interesting points emerge from Table 1. First, events in which Ohau Channel discharge exceeded Kaituna River outflow are infrequent and the net flow volumes are relatively small; second, most of these events (Table 1) relate to low flows rather than flood flows. In the 28 years of record (10227 days) there were only 44 days on which Ohau channel inflow exceeded Kaituna River outflow, i.e., $Q_O > Q_K$ only 0.43% of the time. In 35 of these 44 days, Ohau Channel inflow was below average. The total volume of net inflow over 28 years was 3.44 $(10^6)$ $m^3$, corresponding to 0.3% of total lake volume. For 1974, the year of maximum net inflow, 0.14% of the total lake volume entered as net inflow over a period of 18 nonconsecutive days. By comparison, it is estimated by Vincent et al (1986) that in 1985 underflow or interflow occurred 60% of the time, corresponding to a volume of 280 $(10^6)$ $m^3$, or 25% of the total lake volume. There is no reason to think that 1985 was an atypical year. While the figures presented above do not represent precise estimates of transport by either floods or density currents, the relative magnitudes make it quite clear that transport of Lake Rotorua water to Lake Rotoiti by floods is negligible compared to transport by underflow and interflow.

The rise in lake surface level in Lake Rotoiti during storms cannot, therefore, be attributed to an excess of Ohau Channel inflow over Kaituna River outflow. Lake level rise in storms occurs in response not only to flows in the Kaituna River and Ohau Channel, but also to rainfall on the lake and storm runoff from rain falling on the lake catchment. To illustrate these processes in more detail four events were chosen from the 28-year record corresponding to the largest Ohau Channel flow in each of the four 7-year periods depicted in Figure 3. The events are plotted in detail in Figure 4, which includes cumulative rainfall and evaporation. The results are summarised in Table 2, which gives peak flow rates, maximum lake level rise, total rainfall prior to peak lake level, and an estimate for the runoff/rainfall ratio (storm runoff volume for the lake catchment divided by total rain volume falling on the lake catchment). The runoff/rainfall ratio was estimated using measured daily values of rainfall, evaporation, lake

TABLE 2—Summary of daily water balance results for four storms.

| Dates | Maximum Ohau Ch. flow $m^3/s$ | Maximum Kaituna R. flow $m^3/s$ | Maximum rise in lake level mm | Rainfall before peak flow mm | Runoff/ Rainfall ratio |
|---|---|---|---|---|---|
| 13 May–23 June 1962 | 42.49 | 54.03 | 394 | 544 | .06 |
| 11 Aug–16 Sept 1970 | 26.05 | 39.07 | 258 | 253 | .14 |
| 29 May–4 July 1971 | 31.14 | 51.19 | 333 | 468 | .23 |
| 20 Oct–25 Nov 1983 | 23.95 | 35.19 | 340 | 453 | .03 |

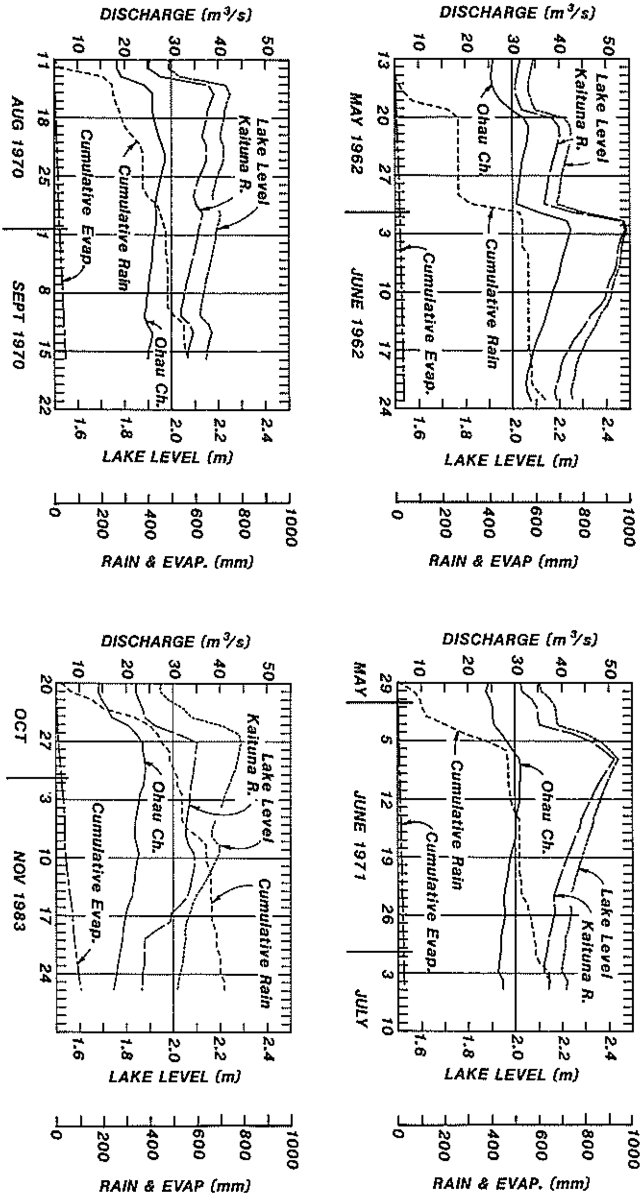

FIG 4—Water balance components for four storms (marked with asterisks in Fig. 3) using daily data as described in Figure 3. Cumulative rainfall and evaporation are plotted but the residual term is not shown. Note the close correlation between rainfall and lake level.

levels and flows and assuming a constant value for combined baseflow and net groundwater inflow of 2.8 $m^3/s$ (Freestone 1982). Storm runoff was expressed as a fraction of total rainfall volume falling on the lake catchment (area — 84.7 $km^2$). The water balance (Eq. 1) was solved by trial and error with a daily time step using different estimates for the runoff/rainfall ratio until a balance over the storm was achieved. The values of the runoff/rainfall ratio ranged from 3% to 23% with a mean value of 12%.

## CONCLUSION

Average values for the components of the monthly water balance of Lake Rotoiti for the 28-year period 1957–1984 have been computed as: Ohau Channel inflow, 18.04 $m^3/s$; Kaituna River outflow, 22.82 $m^3/s$; rainfall on the lake, 2010 mm/yr (2.19 $m^3/s$); evaporation from the lake, 880 mm/yr (0.96 $m^3/s$); and a residual inflow term incorporating surface water (excluding the Ohau Channel) and groundwater inputs from the lake catchment, plus any errors in measured terms, 3.55 $m^3/s$. Mean rate of change in lake storage over the 28-year period was negligible. The 3.55 $m^3/s$ residual inflow results in a net westward flow through Lake Rotoiti to the lake outlet at Okere Falls. When there is no plunging of the Ohau Channel inflow as density currents, the westward lake current reinforces the tendency of the inflow to short-circuit to the outlet (i.e. to flow directly to the outlet without entering the main body of the lake) because of the proximity of the lake inlet and outlet (cf. Englert and Stewart, 1983). Short-circuiting is possible only for overflows or when temperature differences between lake and inflows are negligible (difference $< 0.5°C$; see Vincent et al 1986), for approximately 40% of the year; for the remaining 60% of the year temperature differences cause Ohau Channel inflows to plunge as density currents in to Lake Rotoiti.

The contribution of Lake Rotorua water to Lake Rotoiti by flooding is negligible compared to the contribution by underflow or interflow. Detailed examination of the water balance for four floods shows that net inputs of Lake Rotorua water to Lake Rotoiti have negligible effect on the rise in lake levels observed during storms. These rises are much more closely correlated with rainfall on the lake than with river inflow (Fig. 4).

## ACKNOWLEDGEMENTS

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This study forms part of a broader study on the limnology of Lake Rotoiti and the impact of the Ohau Channel inflow, a study carried out by scientists from the Taupo Research Laboratory, Division of Marine and Freshwater Sciences (now Division of Water Science) of the N.Z. Department of Scientific and Industrial Research. Financial support came from a research grant on River Inflows to Lakes from the National Water and Soil Conservation Authority, through the Water and Soil Division of the N.Z. Ministry of Works and Development; this support is gratefully acknowledged.

## APPENDIX

### *Estimating rainfall for the lake and its catchment*

Monthly rainfall over the lake was computed as the weighted average of rainfall at the four stations Okere Falls, Lake Rotoiti, Lake Okataina and Tikitere, using weighting factors 0.299, 0.515, 0.036 and 0.150, respectively (Fig. 1). However, complete records were not available at these stations for the total study period January 1957–December 1985; periods of record are summarised in Table A1. Missing records were filled in by simple correlation as detailed in Table A2. The monthly regression equations also were used where required to form daily rainfall records for the four storms depicted in Fig. 4.

TABLE A1—Period of record for stations used in estimating rainfall for Lake Rotoiti and its local catchment.

| Rainfall Station | Period of Record |
|---|---|
| Okere Falls | Apr 54 — Jul 57*<br>Sep 57 — Nov 57*<br>Jan 58 — Nov 58*<br>Sep 59 — Dec 59*<br>Feb 60 — Nov 60*<br>Sep 74 — Present |
| Lake Rotoiti | Jan 68 — Dec 75* |
| Lake Okataina | Jan 57 — May 74<br>Jul 75 — Nov 75<br>Jan 76 — Apr 76<br>Oct 76 — Jul 78 |
| Tikitere | Aug 77 — Present |
| Rotorua Airport | Dec 63 — Present |
| Whakarewarewa | Jan 57 — Dec 81 |
| Taumana | Jul 63 — Jan 83<br>Dec 83 — Present |

* Monthly totals only

See Figure 1 in main text for location of stations.

TABLE A2—Correlation for missing rainfall data

| (1) Y | (2) X | Period of Missing Record | (3) A | (4) B | (5) S (mm/mo) | (6) R |
|---|---|---|---|---|---|---|
| Okere Falls | Lake Okataina | Aug 57–Dec 57<br>Dec 58–Aug 59<br>Jan 60<br>Dec 60–May 74 | 15.8075 | 0.82529 | 29.03 | .9399 |
| | Rotorua Airport | Jun 74–Aug 74 | 5.3516 | 1.3206 | 31.36 | .9361 |
| Lake Rotoiti | Lake Okataina | Jan 57–Jun 63 | 4.9476 | 1.0630 | 50.34 | .9158 |
| | Taumana | Jul 63–Dec 67<br>Jan 76–Jan 83 | 7.3263 | 0.94015 | 35.23 | .9542 |
| | Okere Falls | Feb 83–Nov 83 | 29.0256 | 0.84514 | 46.20 | .8488 |
| | Taumana | Dec 83–Dec 85 | 7.3263 | 0.94015 | 35.23 | .9542 |
| Lake Okataina | Rotorua Airport | Jun 74–Jun 75<br>Dec 75<br>May 76–Aug 76 | 3.6642 | 1.3076 | 38.80 | .9215 |
| | Tikitere | Aug 78–Dec 85 | 3.1250 | 1.2947 | 22.80 | .9809 |
| Tikitere | Whakarewarewa | Jan 57–Nov 63 | -8.1166 | 1.2810 | 30.85 | .9273 |
| | Rotorua Airport | Dec 63–Jul 77 | -20.6685 | 1.3482 | 20.24 | .9706 |

1 & 2 Y = dependent variable, X = independent variable in regression for monthly rainfall
3 & 4 A, B are regression coefficients in Y = A + BX for X, Y in mm/month
5 S = standard error of the regression (mm/month)
6 R = sample correlation coefficient

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