PRELIMINARY WATER BALANCE STUDIES OF THE ROTORUA LAKES

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ABSTRACT

An approximate quantitative statement of rainfall, evapotranspiration, lake levels, ground-water storage, and outflow, for lakes Rotoma, Rotoehu, Rotorua, and Rotoiti in the Rotorua–Bay of Plenty area of the North Island of New Zealand (Fig. 1) is given.

All basic relationships were investigated using data from Lake Rotoma, a lake which has no open outlet. Individual techniques, with possible sources and magnitudes of error, are discussed in detail, and future investigations suggested.

Techniques found valid for Rotoma have been applied to Rotoehu which similarly has no open outlet, and to Rotorua and Rotoiti, both of which do have river outflows. The annual water balances for these lakes are included for comparison with Rotoma.

INTRODUCTION

For some years, lakes which have no open outlet have been of interest for investigations of losses by seepage and underground flow, and for investigations of the response of lake levels to rainfall. North and east of Rotorua (Fig. 1) a group of lakes is contained in volcanic basins which often have no outlets. The geological structure is of rhyolite dome and flow form with an ash and breccia mantle. Extensive ignimbrite sheets also occur, one of which, sloping northwards to the coast, is of considerable importance.

These lakes comprise two major systems of which the simpler, including Rotoma, Rotoehu, Rotorua, and Rotoiti, drains to the north by way of the Kaituna River (Fig. 1). The other drains to the east by way of the Tarawera River.

Rotoma, the most easterly lake in the area, is the most suitable of all Rotorua lakes for intensive investigations as it is the highest above sea level, has the largest proportion of lake area to total catchment area, and is the most accessible.

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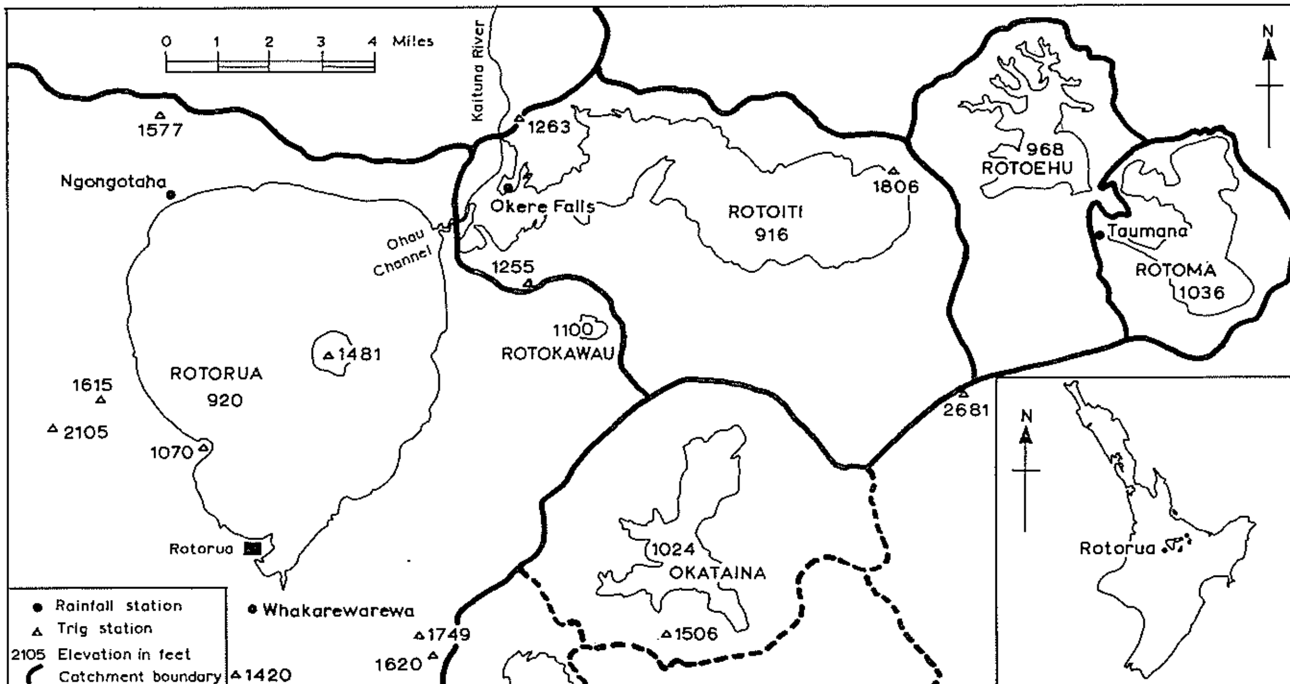

Fig. 1 — The Kaituna system of the Rotorua lakes. Trig heights and lake elevations are given as feet above sea level. Inset: locations of the Rotorua lakes.

These studies form part of the water-resource investigations made by the Ministry of Works in this area. Records and measurements of lake levels and outlet flows for all lakes have been collected and maintained by the Department. All available data from Rotoma and Rotoehu with comparable records from Rotorua and Rotoiti have been summarized in this paper (Rotorua records began in 1934 and Rotoiti in 1906). Additional instruments were installed in Rotoma in 1967.

METHOD

Basically the water-balance method for a lake with no open outlet, such as Rotoma, involves one input (rainfall), two outputs (seepage and evapotranspiration), and two storages (the lake and its land catchment). The volume lost from the lake by seepage and evapotranspiration must be balanced by rainfall and withdrawal from land storage, otherwise the lake level would fall.

To establish a water balance, four assumptions have been made:

(i) That all rain falling on the catchment is either ultimately stored in the lake, adds to the ground water, or is evapotranspired.

(ii) That evapotranspiration from the catchment can be approximated by values of evaporation and evapotranspiration obtained at Taupo and Rotorua respectively (Taupo is 40 miles south of Rotorua).

(iii) That ground-water storage changes at a constant rate of 0.33 inch for every inch change in the lake level.

(iv) That outflow is constant.

The basic time unit used for calculation is the month; monthly values are added to produce annual water balances. Values for the individual parameters are determined in the following manner:

Precipitation (P) is based directly on rain-gauge records. Where a network contains more than one gauge, the catchment rainfall is the average of the monthly totals from each without any attempt to weight for area, altitude, or exposure.

Evapotranspiration (Et) comprises lake evaporation (E) and land evapotranspiration (El) related by:

$$El = k \times E \text{ (where k is a seasonal constant)}$$

and combined in the ratio of land area to lake area for the catchment. The following seasonal constants were obtained by comparing monthly values of evapotranspiration for 1962 to 1965, calculated by the Thornthwaite method for Whakarewarewa, with evaporation measured by the sunken pan at Taupo:

Dec, Jan, Feb	0.7
Mar, Apr, May, Sep, Oct, Nov	0.8
Jun, Jul, Aug	0.9

From 1953 to 1961, Thornthwaite values for Whakarewarewa were used as a basis for calculation for all catchments. Subsequently the Taupo values have been used as well. No actual values are available for 1966.

Effective rainfall (Eff. P) is the volume of water being added to the lake system. It is convenient first to subtract evapotranspiration from measured rainfall and then to use a scale factor to condense the remainder into the lake area.

Change in lake level representing difference in storage (ΔS) is the difference between successive staff gauge readings, expressed in inches. The sign convention is positive for a rise in lake level, and the initial level, in inches, is given at the top of each set of tabulations. Lake level changes were recorded by weekly, sometimes daily, readings. Automatic-recorder records are available only from 1965 for Rotoma, Rotoehu, and Rotorua (1942 for Rotoiti). There are large gaps in all records.

Land storage ($0.33\Delta S$) is the volume of water involved in the rise or fall of the ground-water table. It is assumed to be constant for all catchments, and vertical changes are assumed to be directly related to changes in lake level. As the total volume stored depends on the land area of the catchment, a scale factor (land area:lake area) is used in all storage calculations. The value of 0.33 is thought to be a realistic estimate for ignimbrite, and is derived from soil physical data for pumice where each inch could take 0.5 inch of ground water.

Outflow (Q) is derived from measurements and estimation. All known springs have been gauged but the total discharge can only be a guide as there may well be others. A realistic estimation can be obtained from periods of no rain. At such times outflow and evapotranspiration must balance the drop in lake level and reduction of land storage. The different values for outflow can be combined to give an average for water-balance calculations using constant outflow.

The lake balance is derived by subtracting change in lake level, land storage, and outflow, from the effective rainfall.

The catchment imbalance is derived by applying a scale factor to the lake balance — the actual scale factor being the lake area divided by total catchment area (the inverse of that used for effective rainfall). The magnitude of the catchment imbalance is an indication of the errors involved in the method.

TABLE 1 — Water balances for Rotoma (all data in inches).

	P	*Et*	*P-Et*	*Eff. P* (2.558P)*	ΔS (31.20)†	$0.33\Delta S$ ($0.50\Delta S$)‡	*Q*	*Lake balance*	*Catchment imbalance*
1953 (10 months)	83.99	20.64	63.35	162.05	+33.00	+16.50	122.40	− 9.85	−3.85
1954	84.09	29.51	54.58	139.62	− 2.70	− 1.35	146.00	− 2.33	−0.91
1955 (15 months)	101.82	41.08	60.74	155.37	−25.50	−12.75	182.40	+11.22	+4.39
1956 (9 months)	102.58	20.06	82.52	211.09	+72.96	+36.48	122.40	−20.75	−8.11
1957	67.78	27.60	40.18	102.78	−44.16	−22.08	146.00	+23.02	+9.00
1958	85.14	29.81	55.33	141.53	− 9.00	− 4.50	146.00	+ 9.03	+3.53
1959	74.68	28.74	45.94	117.51	−13.20	− 6.60	146.00	− 8.69	−3.40
1960	92.51	27.65	64.86	165.91	+12.60	+ 6.30	146.40	+ 0.61	+0.24
1961	76.17	28.34	47.83	122.35	−14.40	− 7.20	146.00	− 2.05	−0.80
1962	148.65	28.02	120.63	308.57	+96.00	+48.00	146.00	+18.57	+7.26
1963	78.00	30.12	47.88	122.48	−31.80	−15.90	146.00	+24.18	+9.45
1964	83.90	30.46	53.44	136.70	−17.40	− 8.70	146.40	+16.40	+6.41
1965	77.74	32.85	44.89	114.83	−13.92	− 6.96	146.00	−10.29	−4.02
1966	98.51	(30.00)	68.51	175.25	+25.80	+12.90	146.00	− 9.45	−3.69
Overall				2176.04	+68.28	+34.14	2034.00	+39.62	+15.49

* $2.558P = 11.0 \times (P - Et)/4.3$.
† 31.20=Lake level on staff gauge at beginning of study (in inches).
‡ $0.50\Delta S = 0.33 \times 6.7/4.3$.

RESULTS

Rotoma

Table 1 gives water balances for Rotoma for 14 years. An overall balance is added to indicate the total percentage error involved. Rotoma has a lake area of 4.3 square miles in a total catchment area of 11.0 square miles. Thus the scale factor for effective rainfall is 2.558. Similarly, the scale factor for ground water storage is 6.7 : 4.3, so that for each inch change in the lake level the ground-water storage will change by $6.7 \times 0.33/4.3$, or 0.5 inch.

Two points merit special attention: firstly, the overall imbalance shows an average error of less than one percent of the effective rainfall; secondly, the balances fluctuate between positive and negative but neither the sign nor the magnitude can be correlated with specific factors for individual years. Even with possible errors and many approximations the method gives an acceptable starting point.

Elimination of approximations presents real difficulties. Early returns from four daily manual rain gauges installed around the catchment in May 1967 indicate that the mean catchment rainfall may not differ greatly from the Taumana value used previously, though storm variability is considerable. Ground-water storage cannot be measured but fluctuations are assumed to be small and related to lake level changes. At present, land storage cannot be calculated without holding outflow constant, though it is thought that both are variable.

If outflow is not constant it should be chiefly dependent on lake height, perhaps logarithmically, but it need not be a simple relationship. Correlation was tested by calculating 72 outflows using the no-rainfall method and plotting against gauge height. A sequence through 1963 suggests a progressive trend, with outflow being related to the gauge height four months earlier.

Accuracy is not sufficient to warrant calculation of variable annual run-off, especially since the time lag may be different for each of the three known springs. Measured outflows (three springs were gauged in May 1964 and again in October 1966) account for 42 cusecs or 122 inches/year, while deduced outflows average 48 cusecs or 146 inches/year. The latter value has been used.

Rotoehu

A method that applies to Rotoma may also apply to Rotoehu. Table 2 gives water balances for Rotoehu for 13 years, of which two have been combined owing to lack of records. The area of Lake Rotoehu is 3.0 square miles in a total catchment area of 19.0 square miles.

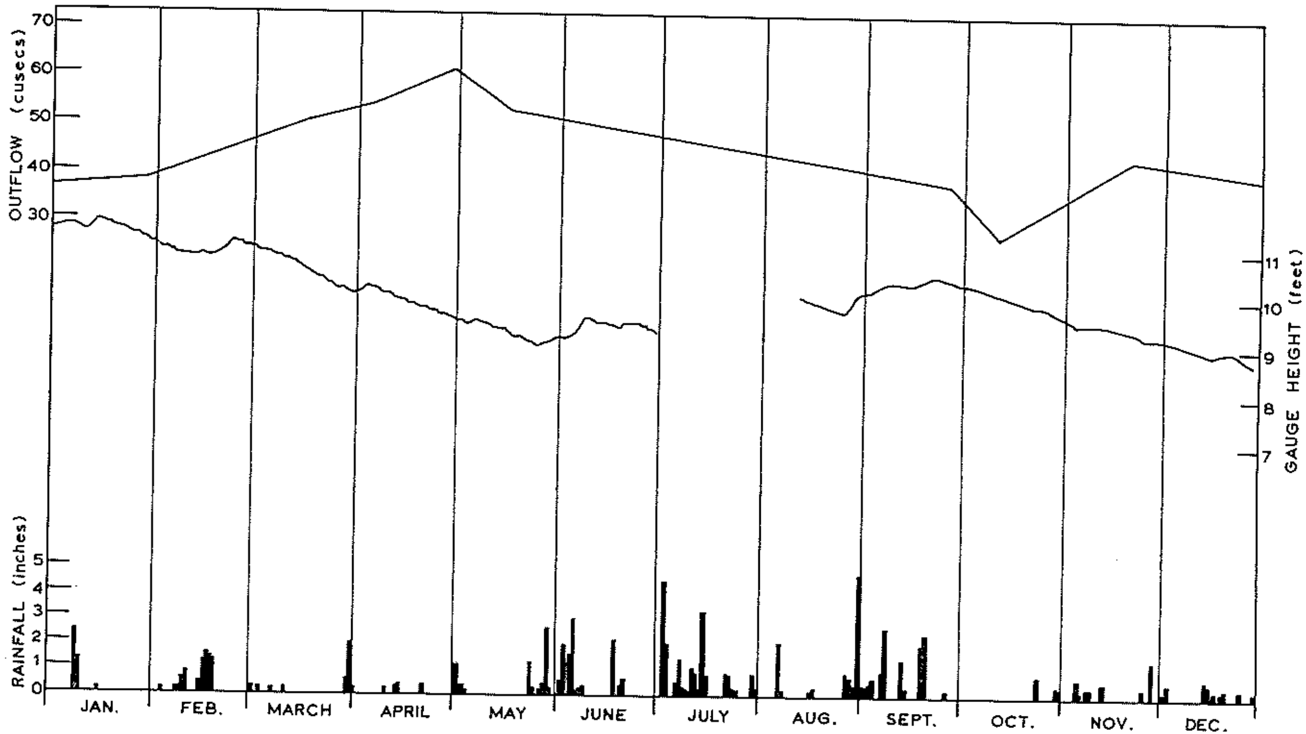

Fig. 2 — 1963 relationships for Rotoma showing rainfall, lake level, and calculated outflow.

TABLE 2 — Water balances for Rotoehu (all data in inches). Catchment area 19.0 square miles.

	P Rotoma	*Et*	*P-Et*	*Eff. P (6.4P)* *	*Rotoma Inflow*	*ΔS (27.60)* †	*0.33ΔS (1.81ΔS)* ‡	*Q*	*Catchment imbalance*
1954	84.09	27.56	56.53	361.79	84.90	+ 7.20	+13.03	274.00	+ 83.85
1955	78.11	27.41	50.70	324.48	84.90	− 1.20	− 2.17	274.00	+ 76.31
1956	126.29	29.71	96.58	618.11	85.10	+27.60	+49.96	274.50	+193.13
1957	67.78	25.87	41.91	268.22	84.90	−18.00	−32.58	274.00	+ 71.33
1958	85.14	27.73	57.41	367.42	84.90	+ 3.60	+ 6.52	274.00	+ 92.51
1959	74.68	26.85	47.83	306.11	84.90	− 9.60	−17.38	274.00	+ 79.19
1960–61 (2 years)	168.68	52.40	116.28	744.19	170.00	−19.80	−35.84	548.50	+231.73
1962	148.65	26.16	122.49	783.94	84.90	+46.80	+84.71	274.00	+254.83
1963	78.00	28.20	49.80	318.72	84.90	−18.60	−33.67	274.00	+100.04
1964	83.90	28.51	55.39	354.50	85.10	− 1.20	− 2.17	274.50	+ 92.66
1965	77.74	30.78	46.96	300.54	84.90	− 6.00	−10.86	274.00	+ 70.56
1966	98.51	(30.00)	68,51	438.46	84.90	+21.12	+38.23	274.00	+104.56

* 6.4P=19.0×(P—Et)/3.0.
† 27.60=Lake level on staff gauge at beginning of study (in inches).
‡ 1.81ΔS=0.33×16.0/3.0.

The Taumana rainfall totals are considered to be fairly representative of rainfall for the Rotoehu catchment. The inflow from Rotoma has been assumed to be 84.90 inches/year, being the combined flow of two springs as measured on the two occasions (1964 and 1966).

Only one outflow is known and has been measured (4.20 cusecs) but the no-rainfall calculation requires a total outflow of about 60 cusecs (274 inches/year), some 50 cusecs of which are assumed to flow into Rotoiti.

The cumulative large positive imbalance indicates either that too much water is entering the lake system or that not enough is leaving (or that the answer is a combination of both).

Outflow is already limited by the rate at which the lake falls, and it cannot be increased by 50 percent without evidence that withdrawal from ground-water storage is increased by about 400 percent. Considering the shape and size of the catchment, this seems most unlikely.

Similarly, the rainfall would need to be reduced by almost 50 percent to achieve overall balance, and this cannot be justified in any way. The probable answer is that the true catchment area is about half the apparent area, the remainder contributing either to Rotoiti, or to the Tarawera River, or to both.

Table 3 gives a 13-year water balance for Rotoehu using a catchment area of 10 square miles.

This gives a result very closely comparable to that from Rotoma. A calculation using a catchment area of nine square miles gives an overall imbalance of −39.72 inches, indicating that the area is larger than that. The true area would therefore appear to be between nine and 10 square miles. Most fluctuations can again probably be explained by variable outflow and storage relationships.

Rotorua

It is now interesting to look at Lake Rotorua since it has a measurable outlet and only the land storage factor is unknown. It also has a much larger rain-gauge network (although its catchment area is much larger also), but only the three rain gauges with complete records from January 1953 or earlier have been used to calculate the rainfall factor. The area of Lake Rotorua is 31.5 square miles in a total catchment area of 198.0 square miles.

Table 4 gives a 12-year water balance.

TABLE 3 — Water balances for Rotochu all data in inches). Catchment area 10.0 square miles.

	P Rotoma	Et	P-Et	Eff. P (3.33P)*	Rotoma inflow	ΔS (27.60)†	0.33ΔS (0.70ΔS)‡	Q	Catchment imbalance
1954	84.09	29.00	55.90	186.15	84.90	+ 7.20	+ 5.04	274.00	− 4.56
1955	78.11	28.84	49.27	164.07	84.90	− 1.20	− 0.84	274.00	− 6.90
1956	126.29	31.25	95.04	316.48	85.10	+27.60	+19.32	274.50	+13.38
1957	67.78	27.16	40.62	135.26	84.90	−18.00	−12.60	274.00	− 6.97
1958	85.14	29.07	56.07	186.71	84.90	+ 3.60	+ 2.52	274.00	− 2.55
1959	74.68	28.25	46.43	154.61	84.90	− 9.60	− 6.72	274.00	− 5.45
1960–61 (2 years)	168.68	55.06	113.62	378.35	170.00	−19.80	−13.86	548.50	+10.05
1962	148.65	27.51	121.14	403.40	84.90	+46.80	+32.76	274.00	+40.42
1963	78.00	29.63	48.37	161.07	84.90	−18.60	−13.02	274.00	+ 1.08
1964	63.90	29.96	53.94	179.62	85.10	− 1.20	− 0.84	274.50	− 2.32
1965	77.74	32.32	45.42	151.25	84.90	− 6.00	− 4.20	274.00	− 8.30
1966	98.51	31.00	67.51	224.81	84.90	+21.12	+14.78	274.00	− 0.06
Overall									+27.82

* 3.33P=10.0—(P—Et)/3.0.
† 27.60=Lake level on staff gauge at beginning of study (in inches).
‡ 0.70ΔS=0.33×7.0/3.0.

TABLE 4 — Water balances for Rotorua (all data in inches).

	P	*Et*	*P-Et*	*Eff. P* (*6.29P*) *	ΔS (*186.00*) †	$0.33\Delta S$ ($1.76\Delta S$) ‡	*Q*	*Lake balance*	*Catchment imbalance*
1953	81.56	25.45	56.11	352.93	− 8.40	− 14.78	250.45	+125.66	+ 19.98
1954	70.84	27.59	43.25	272.04	− 3.00	− 5.28	208.58	+ 71.74	+ 11.41
1955	67.98	27.45	40.53	254.93	+ 3.00	+ 5.28	189.88	+ 56.77	+ 9.03
1956	102.57	29.75	72.82	458.04	+ 8.64	+15.21	268.47	+165.72	+ 26.35
1957	64.78	25.90	38.88	244.55	− 11.16	− 19.64	225.36	+ 49.99	+ 7.95
1958	79.69	27.76	51.93	326.64	+13.32	+23.44	223.11	+ 66.77	+ 10.62
1959	66.84	26.88	39.96	251.35	− 13.20	− 23.23	230.54	+ 57.24	+ 9.10
1960	70.83	25.89	44.94	282.67	+ 1.20	+ 2.11	223.76	+ 55.60	+ 8.84
1961	68.23	26.58	41.65	261.98	+ 3.60	+ 6.34	200.86	+ 51.18	+ 8.14
1962	122.25	26.19	96.06	604.22	+ 21.12	+37.17	400.17	+145.76	+ 23.18
1963	64.21	28.23	35.98	226.31	− 17.52	− 30.84	312.92	− 134.97	− 21.46
1964	78.26	28.54	49.72	312.74	+ 3.36	+ 5.91	258.81	+ 44.66	+ 7.10
Overall									+120.24

* 6.29P=198.0×(P—Et)/31.5.
† 186.00=Lake level on staff gauge at beginning of study (in inches).
‡ 1.76ΔS=0.33×166.5/31.5

Three factors probably contribute to the overall imbalance and to the degree of fluctuation:

(i) The catchment mean rainfall may not be represented by the three rain gauges chosen. The imbalance can be over-corrected by using Whakarewarewa rain-gauge data only (overall catchment imbalance of −32.86 inches) but the same pattern persists.

(ii) The catchment area for the small lake Rotokawau may in fact not be part of the Rotorua catchment. This has not been tested but would reduce the effective rainfall scale factor very slightly.

(iii) The land storage factor, probably very complex considering the size of the catchment, may not be adequately represented by a constant proportion of the change in lake level.

Rotoiti

Rotoiti is the most complex of all the water-balance studies but allows some check on certain hypotheses for both Rotoehu and Rotorua. Rainfall from the Okere Falls rain gauge was used from 1955 to 1958 inclusive. For other years the mean of Whakarewarewa and Rotoma rainfall values was taken. A constant inflow is added from Rotoehu (50 cusecs or 53 inches/year) and a fluctuating inflow added from Rotorua (via Ohau channel). The outflow is the Kaituna River. The area of Lake Rotoiti is 13.0 square miles in a total catchment area of 46.0 square miles.

The initial tabulation of a 12-year water balance for Rotoiti gave an overall catchment imbalance of −185.00 inches with only 1962 of the 12 years having a positive imbalance. Table 5 shows the 12 years, with the catchment enlarged to include the nine square miles excluded from the Rotoehu catchment.

This overall imbalance represents less than one percent of the total effective rainfall involved.

CONCLUSIONS

It is possible to tabulate an approximate water balance for a lake using five basic components. This is sufficient to give a critical appraisal of interrelationships within the system and to test the accuracy of estimates for unmeasured components. Inadequacies within any particular system are clearly defined and remedies can be applied to the method without increasing the number of assumptions or breaking natural laws. Disagreement between geographical and hydrological boundaries, where this exists, is emphasized by the scale factor applied to rainfall.

TABLE 5 — Water balances for Rotoiti (all data in inches). Catchment area 55.0 square miles.

	P	*Et*	*Eff. P* (4.23*P*)*	*Rotoehu inflow*	*Rotorua inflow*	ΔS (78.00)†	0.33ΔS (1.08ΔS)‡	*Q*	*Catchment imbalance*
1953	77.66	26.36	217.00	53.00	606.84	− 4.20	− 4.54	917.59	− 7.55
1954	67.34	28.61	163.83	53.00	505.39	+ 2.40	+ 2.59	829.90	−26.59
1955	67.39	28.46	164.67	53.00	460.08	+ 2.16	+ 2.33	725.51	−12.33
1956	101.32	30.83	298.17	53.00	650.50	+ 0.60	+ 0.65	995.47	+ 1.17
1957	65.56	26.81	163.91	53.00	546.05	0.00	0.00	846.60	−19.74
1958	66.84	28.71	161.29	53.00	540.60	−12.96	−14.00	758.92	+ 5.41
1959	64.81	27.87	156.26	53.00	558.60	+ 4.80	+ 5.18	863.31	−24.88
1960	74.31	26.83	200.84	53.00	542.17	+ 1.80	+ 1.94	801.82	− 2.25
1961	64.23	27.52	155.28	53.00	486.58	− 0.60	− 0.65	718.20	− 5.19
1962	125.12	27.15	414.41	53.00	969.61	+19.20	+20.74	1227.86	+39.94
1963	67.95	29.24	163.74	53.00	758.21	−16.20	−17.50	1052.29	−10.30
1964	71.92	29.57	179.14	53.00	627.10	+ 0.60	+ 0.65	854.16	+ 0.90
Overall									−63.21

* 4.23P=55.0×(P—Et)/13.0.
† 78.00=Lake level on staff gauge at beginning of study (in inches).
‡ 1.08ΔS=0.33×42.0/13.0.

For Rotoma in particular the method appears to have been successful. Even though records are incomplete and certain important data are not available, it has been possible to scrutinize individual components, while overall the degree of error has proved to be less than one percent of effective rainfall. Remarks applicable to Rotoma in general apply to the other lakes as well, although additional complications are involved.

The approach used has obvious limitations, the most important being:

(i) errors in rainfall measurement,
(ii) discrepancies between evapotranspiration as calculated and true catchment evapotranspiration,
(iii) errors in lake level measurement, especially where gaps occur in records,
(iv) lack of knowledge of ground-water storage,
(v) lack of knowledge of seepages comprising outflows.

Future effort by the Ministry of Works in its water-resource investigations will be concentrated on lakes Rotoma and Rotoiti, these having the highest proportion of lake to catchment area. Current investigations concern:

Rainfall — clarification of storm patterns. The final network will give more accurate catchment mean rainfalls.

Evapotranspiration — establishment of true lake evaporation from Rotoma.

Ground-water storage — investigations of response to a change in lake level using the ground-water levels in test bores between lakes Rotoiti and Okataina.

Outflows — investigation of spring behaviour using gaugings around Rotoma, and radioactive tracers to establish time of travel between the lake and individual springs.

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