Dissolved Loads of Rivers and Surface Water Quantity/Quality Relationships
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Budget of water and its constituents for Lake Taupo (New Zealand)

C. J. SCHOUTEN
Department of Geography, State University of
Utrecht, PO Box 80.115, 3508 TC Utrecht,
The Netherlands

ABSTRACT Outputs of water and its constituents from streams draining into Lake Taupo were investigated over the period 1976-1979. Special attention was given to the effects of volcanic processes and of the activities of man. The water budget showed that about 95% of the outflow of Lake Taupo can be accounted for by surface inflows and direct precipitation to the lake. About 60% of the chloride and sodium cannot be attributed to measurable sources, and is presumably of geothermal origin; most of these geothermal springs are believed to enter below the lake. Hydroelectric power schemes have resulted in a 16% increase in lake outflow, but not in important changes of the loading of nitrogen and phosphorus components. Further increases in nitrate-N outputs of the basin as a result of agriculture or forestry threatens the trophic status of Lake Taupo.

Bilan hydrologique et ses composantes pour le lac Taupo (Nouvelle Zélande)

RESUME Les apports en eau et les matières en solution dans les cours d'eau se jetant dans le lac Taupo ont été étudiés pour la période 1976-1979. On a accordé une attention toute spéciale aux effets des processus volcaniques et des activités de l'homme. Le bilan hydrologique montre que 95% des apports au lac Taupo peut être porté au compte de l'écoulement de surface et des précipitations directes sur le lac. Environs 60% du chlore et du sodium ne peut pas été attribué à des apports mesurables et est probablement d'origine géothermique; la plupart de ces sources géothermiques sont supposée rejoindre l'eau du lac par le fond. Les aménagements hydroélectriques donnent lieu à un accroîssement de 16% des apports au lac mais n' apportent pas de modification importante dans la charge d'azote et de phosphore. Une augmentation supplémentaire en azote (nitrates) résultant des activités agricoles et forestières menace l'état trophique du lac Taupo.

INTRODUCTION

Lake Taupo (175°50'E, 38°50'S), which is with an area of 616 km^2 the largest lake of New Zealand, is an important water resource serving recreation, electricity-supply and drinking water purposes. Considerable changes have recently taken place in its drainage area as a result of deforestation, hydropower development, modern agriculture and recreation. It is the aim of this investigation to assess the impact of the activities of man upon the streams and to evaluate potential threats to the oligotrophic status of Lake Taupo.

Physical characteristics of Lake Taupo and Lake Rotoaira

Lake Taupo (Fig.1) is at an altitude of about 357 m and has an average range in lake level of 2 m. It has a mean depth of 97 m with a maximum of 163 m. The volume is *c.* 600 x $10^8 m^3$. With an outflow of 146 m^3s^{-1} the average residence time is about 13 years.

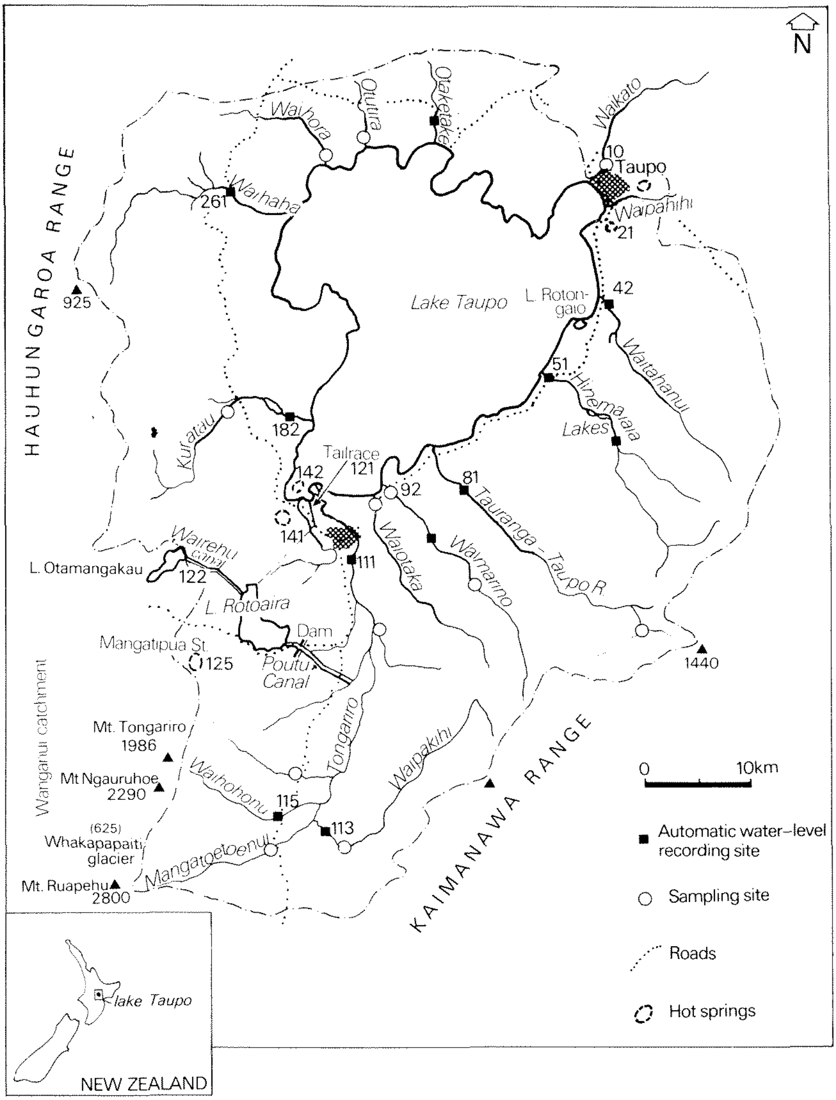

FIG.1 Lake Taupo basin.

Lake Rotoaira is the second biggest lake in the basin; its altitude is 565 m, its area 15 km^2 and it has a volume of about 1.24 x $10^8 m^3$. Lake Rotoaira forms the reservoir for the Tokaanu Power Station, which was constructed as part of the Tongariro Power Development scheme. Lake Rotoaira was a natural lake, but its level was raised a few metres to accommodate water, diverted from the Tongariro and Wanganui rivers.

Geographical characteristics of the Lake Taupo basin

Lake Taupo is situated in the Volcanic Plateau of the central North Island, it has a total catchment area (excluding the lake) of 2670 km^2. The lake and its surroundings are the product of Quaternary volcanic activity and accompanying subsidence. The underlying geology consists of consolidated rhyolitic formations such as ignimbrites, dacites and breccias, while the southern part consists of andesitic deposits (Fig.2(a)). Permian-Mesozoic greywacke blocks form the

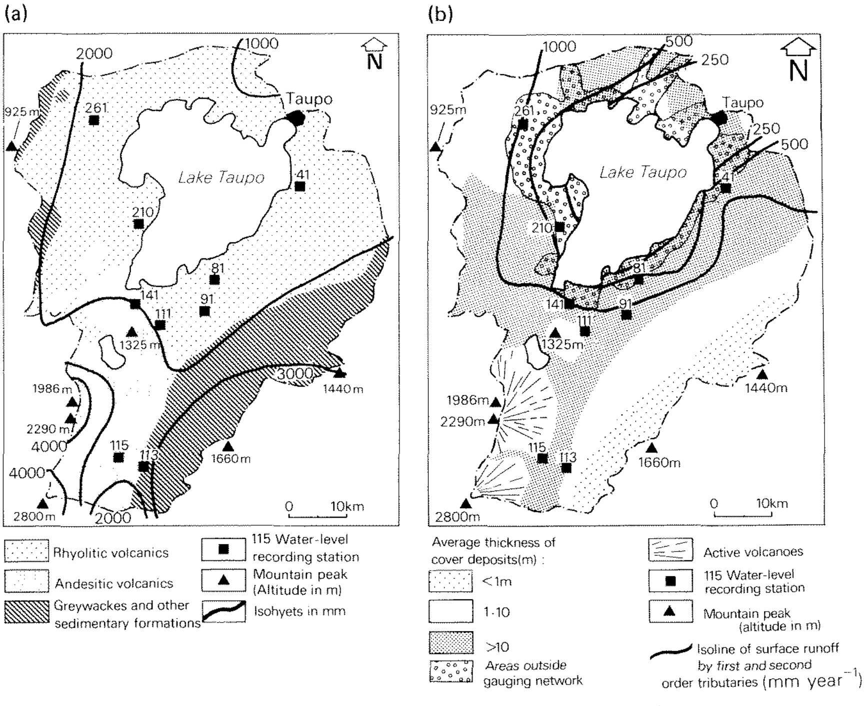

FIG.2 Basal lithology of the Lake Taupo basin and isohyets (a), average thickness of the cover deposits and areas outside the network of regular flow measurements with isolines of surface flow (b).

basin divide to the east and the west. In the Lake Taupo basin the cover deposits consist of tephra (lapilli and various ashes) deposited by volcanic activity during the last 20 000 years. In the lower parts surrounding Lake Taupo cover deposits may reach an average thickness of between 10 and 20 m, whereas in the highlands the cover deposits are generally shallow, with an average thickness of less than 2 m (Fig.2(b)). In all, *c.* 1500 km^2 of the Lake Taupo basin are covered by 5 m or more tephra, mainly Taupo pumice. Thick deposits are also found in the larger valleys like the Tongariro valley. To the south an increasing proportion of the tephra consists of andesitic ashes from the Tongariro volcanoes, of which Mt Ngauruhoe (2290 m) and Mt Ruapehu (2800 m) are still active. In the permeable volcanic deposits groundwater forms the main source of surface flow all year round and in several parts of the basin, especially to the north and northeast of Lake Taupo, less than half of the expected runoff is drained by the surface streams.

The lowlands were originally covered by scrub and podocarp/hardwood forests (Fig.3), but since 1960 large areas have been developed into agricultural grassland or exotic pine plantations. Dense mixed podocarp/hardwood forests still exist along the southern and western sides of Lake Taupo. The ranges to the east are covered by beech forests *(Nothofagus spp)*. The Tongariro volcanoes are covered by scrub with some patches of beech forest on the lower parts; they are virtually bare at higher elevations. Precipitation (Fig.2(a)) increases with height from around 1100 mm year^{-1} at the northern lake margin to more than 3000 mm year^{-1} in the high mountain ranges south of Lake Taupo. Seasonal variation is small with a maximum in winter. Soils throughout the Lake Taupo catchment have developed from volcanic ashes. In the International Soil Classification these soils can be grouped under Vitric Andosols, characterized by a coarse texture and excessive drainage.

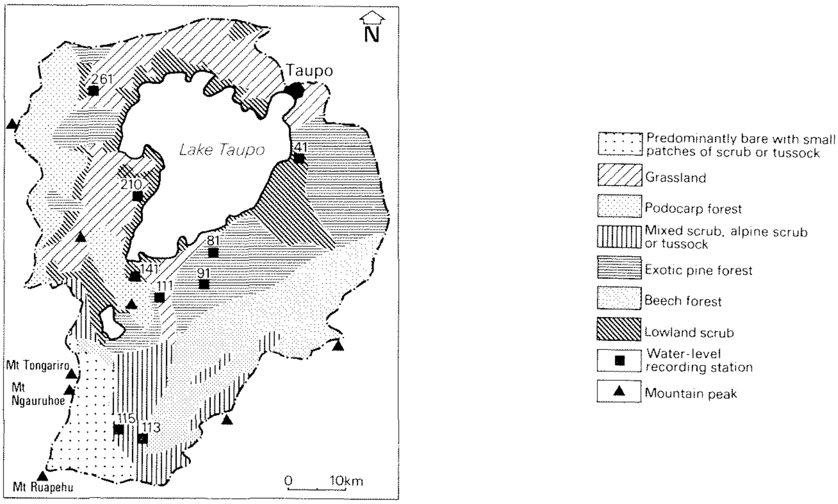

FIG.3 Vegetation and land use of the Lake Taupo basin.

The Tongariro Power Development scheme

For the period before 1971 a mean discharge of 129 m^{3}s^{-1} was produced from the basin including the lake (3289 km^2). The Tongariro River was the largest single inflow with a mean discharge of

54 m^3s^{-1} and a drainage area of 786 km^2. All other natural streams entering Lake Taupo have discharges well below 10 m^3s^{-1}. Substantial changes have taken place in the hydrology since 1972. This is a result of the Tongariro Power Development scheme (TPD). The Wairehu Canal was constructed to connect the Wanganui River from outside the Lake Taupo basin with Lake Rotoaira. The upper Wanganui itself receives additional water from outside its basin from streams draining the southern slopes of Mt Ruapehu which are diverted through canals and aquaducts. Before 1981, about 20 m^3s^{-1} of additional water from outside the natural Lake Taupo basin flowed through the Wairehu Canal (Fig.1) into Lake Rotoaira, but after this date even more water entered the Lake Taupo basin through tunnels drilled in the Kaimanawa Ranges. This water flows into the Tongariro River which is partly channelled into Lake Rotoaira through the Poutu Canal. A dam that controls the natural outlet of Lake Rotoaira was constructed (Poutu River Dam) and the new additional input into Lake Rotoaira plus some of the original inputs are used to generate electricity in the Tokaanu Power Station which receives its water from Lake Rotoaira through a tunnel. The Tokaanu Power Station disposes of its water through the Tailrace directly into Lake Taupo. Thus the Tailrace water forms a mixture of water originating from the Tongariro River and from external sources. The mean discharge of the Tailrace flow (40 m^3s^{-1}) now exceeds that of the Tongariro River and has become the largest single source of water into Lake Taupo.

METHODS

Hydrological observations

Records of lake level and outflow are available since 1905. Since 1941 the outflow of Lake Taupo has been artificially controlled. From the beginning of 1976 until early 1979 about 50 sites, spread around the Lake Taupo basin, were sampled regularly. Samples were taken in polythene bottles and frozen as soon as possible after being taken, almost invariably within 5 h. Special attention was given to the sampling of floods in order to provide data on particulate matter outputs. Rainfall records and the flow records of all permanent and temporary automated stations are available from the Ministry of Works and Development in Wellington. In order to obtain annual outputs, some smaller inflows were gauged regularly and their flow correlated to those of nearby stations on streams of similar characteristics. Precipitation and runoff data from 1977 were used to construct a water balance and output budget.

Chemical analyses

Samples were analysed routinely for dissolved reactive phosphorus (DRP) defined as phosphorus which passes through a membrane filter of 0.45 µm pore size and is hydrolysed to orthophosphate under the conditions of the test (Van Schouwenburg & Wallinga, 1967). Total dissolved phosphorus (TDP) and total phosphorus (TP) were analysed after sulphuric acid/potassium persulphate digestion in an autoclave, and then as for DRP. It was found that on virtually all occasions the difference between TDP and DRP was only very small and often negative, implying that the difference between TP and DRP (PP) was mainly of a particulate nature in the Lake Taupo region. Nitrate (NO_3-N) was measured by automated colorimetric analysis for nitrite after hydrazine reduction (Kamphake *et al.*, 1967), and ammonia (NH_4-N) was measured by colorimetric analysis involving indophenol blue. Dissolved inorganic nitrogen (DIN) has been defined as the sum of nitrate-N and ammonia-N. Total kjeldahl nitrogen was measured after digestion of the unfiltered sample with sulphuric acid/potassium/zirconium sulphate mixture (Glowa, 1974) in the same manner as ammonia. The difference between total kjeldahl nitrogen and ammonia nitrogen is defined as organic nitrogen (org-N). Chloride, silica and alkalinity were measured by automated colorimetric analyses and sulphate by turbidimetric analyses as barium sulphate. Metals were measured by atomic absorbtion using caesium chloride as a releasing agent. Suspended matter was measured by filtration through a Whatman GFC filter.

Calculations

In most cases the annual output was calculated with the aid of the observed relationships between the concentrations of materials transported by streams and discharge, in combination with the flow duration curves for 1977. Data for all measured sites are available in Schouten *et al.* (1981).

RESULTS

The water balance of Lake Taupo

A water budget for Lake Taupo may be formulated as:

$$\text{inflow} = \text{outflow} + \text{change in storage} \qquad (1)$$

The components of the inflow that are distinguished at Lake Taupo are the surface inflows (Q_{surf}), subsurface inflows (Q_{sub}) and the direct precipitation on the Lake (P_L). Components of the outflow are the lake outflow through the Taupo Gates (O_L) and the open water evaporation (E_L). By substitution of the various components into equation (1) the following equation results:

$$Q_{surf} + Q_{sub} + P_L = O_L + S + E_L \qquad (2)$$

where S = change in lake storage.

Surface inflows All of the single inflows with a mean discharge in excess of 0.5 m^3s^{-1} and many other smaller streams were either automatically recorded or gauged adequately to obtain their mean annual flows. The total drainage area of these measured stream systems comprises 89% of the total land area of the Lake Taupo basin. The mean total surface flow measured from this area amounted to 127 m^3s^{-1}. The fraction of the basin for which the surface inputs were not measured (288 km^2) consisted partly of the areas downstream of the recording stations on the main streams and partly of areas close to the lake that were drained by small, often ephemeral streams. These areas are mostly situated in a region with moderate precipitation and underlain by permeable volcanic formations (Fig.2(b)). It is therefore not possible to estimate the annual surface flow contribution of these areas from the difference between rainfall and evapotranspiration. From all the existing data collected during the course of the investigations, a map (Fig.2(b)) has been constructed of the surface runoff contribution of the first and second order tributaries in the region. The pattern that emerged from this type of hydrological mapping was rather regular and much of the inadequately measured area is in the region of very low surface runoff contributions. In order to estimate the missing surface inflow, the areas outside the regularly measured catchments were grouped into four classes of surface runoff production according to Fig.2(b), and the class mean of runoff was multiplied by the class area. The resulting estimate of missing surface runoff was *c.* 4 m^3s^{-1}, and this brings the total of surface inflows up to 131 ± 3 m^3s^{-1}, for which the error of estimate is merely the result of the error in the five largest inflows producing more than 80% of the 131 m^3s^{-1}.

Direct precipitation inputs to the lake Precipitation data from five stations close to the shores of Lake Taupo and spread around it were used to estimate a mean precipitation for the lake surface. The highest measured rainfall close to the lake was at Turangi with 1600 mm, the station with the lowest amount was at Taupo Township, with a little over 1100 mm. A weighted mean for the lake was about 1300 mm which is equivalent to about 25 ± 2 m^3s^{-1}.

Lake outflow and storage There is no reason to believe that any significant subsurface outflow occurs from Lake Taupo. The surface outlet of Lake Taupo is at Taupo Township, where the outflow is controlled by gates. During 1977 the measured outflow of the lake was 146 ± 1 m^3s^{-1}. The lake level was 260 mm higher at the end of 1977 than at the beginning. The equivalent change in storage is *c.* 5 m^3s^{-1}.

Open water evaporation The open water evaporation for Lake Taupo has been obtained by multiplying the open pan evaporation by a factor of 0.69 (Finkelstein, 1961). The annual variation in open water evaporation is small and therefore the long term average of 700 mm or 13 m^3s^{-1} is used for 1977 (±1 m^3s^{-1}).

Subsurface inflows Insufficient work has been carried out to quantify directly the total groundwater inputs into Lake Taupo. Springs and seepages are clearly visible at or just below the water level around the lake. At Waihi and Taupo Township hot mineralized springs can be observed within the lake. From the water balance studies it could be deduced that in many parts of the volcanic formations surround Lake Taupo a considerable proportion of the net precipitation leaves the area as subsurface flow. The aquifers in the areas north of Turangi are largely rhyolitic volcanic deposits and fluviatile gravels and sands. To the south of Turangi the andesitic debris and ashes that surround the Tongariro Mountains are also very important. Much more closed hydrological systems are formed in the greywacke mountain ranges and the steep volcanic highlands of Mt Ruapehu and Mt Tongariro. A rough estimate of the total direct subsurface inflows into Lake Taupo could be obtained by substitution of all the measured or estimated components into equation (2). This produces a deficit value of 8 m^3s^{-1} that may be attributed to subsurface inflows. If the error of estimate in the total inflows is *c.* 3 m^3s^{-1} and the error of the sum of outflow and evaporation is *c.* 2 m^3s^{-1}, then the possible error in this subsurface inflow estimate may be as high at 5 m^3s^{-1}.

Geochemistry of the waters in the Lake Taupo basin

Atmospheric pollution such as acid rain and high nitrate concentrations are virtually absent in the part of the world where Lake Taupo is situated. There is no industry and modern agriculture forms a relatively new development within the Lake Taupo basin and has had relatively little effect upon the waters of the region. In the Lake Taupo basin, the streams that are not influenced by geothermal inputs may be regarded as belonging to the most pure and unpolluted waters in the world. On the basis of their chemical composition and origin, the waters in the Lake Taupo basin may be separated into two major groups of the volcanic waters and the non-volcanic waters.

Volcanic waters The volcanic waters in the Lake Taupo area belong to the chloride sulphate type of waters in which Cl^- and SO_4^{2-} form the predominant anions (Fig.4) and HCO_3^- forms less than 80% of the anionic composition. These waters are also recognizable by their raised levels of total dissolved solids, and sometimes by their low pH or high temperatures (Table 1). Volcanic waters are the product of the solution of rocks by water, containing fumarolic HCl, H_2S, CO_2 etc. under high temperature and pressure, followed by subsequent mixing with meteoric waters. If the rocks involved in these processes are of an andesitic nature, the predominant cation will be Ca^{2+} and the divalent cations will be in excess of the monovalent cations (Fig.4). If the rocks involved are of a rhyolitic nature or greywacke then the predominant cation is Na^+ with the monovalent cations in excess of the bivalent ones. Volcanic waters of the Na type occur in the Tokaanu and Taupo geothermal fields. Both the Tokaanu Stream and Waipahihi Stream are strongly affected by geothermal springs, with chloride as the dominant anion (Table 1, columns 1 and 2). Volcanic waters of the Ca type occur in the Tongariro Mountains. Streams, such as the Waiohohnu or Mangatoetoenui, and the Wairehu Canal are strongly affected by volcanic waters, and bicarbonate forms less than 80% of their anionic composition. Very acidic SO_4 and Cl waters occur around the summit of Mt Ruapehu and in the crater lake itself (Table 1, column 4). Some volcanic waters contain more than 5000 mg m^{-3} of ammonia-N resulting from the solution of fumarolic NH_3 (Ketetahi geothermal springs).

Non-volcanic waters (Table 2) The non-volcanic waters in the Lake Taupo area belong to the bicarbonate type of waters in which

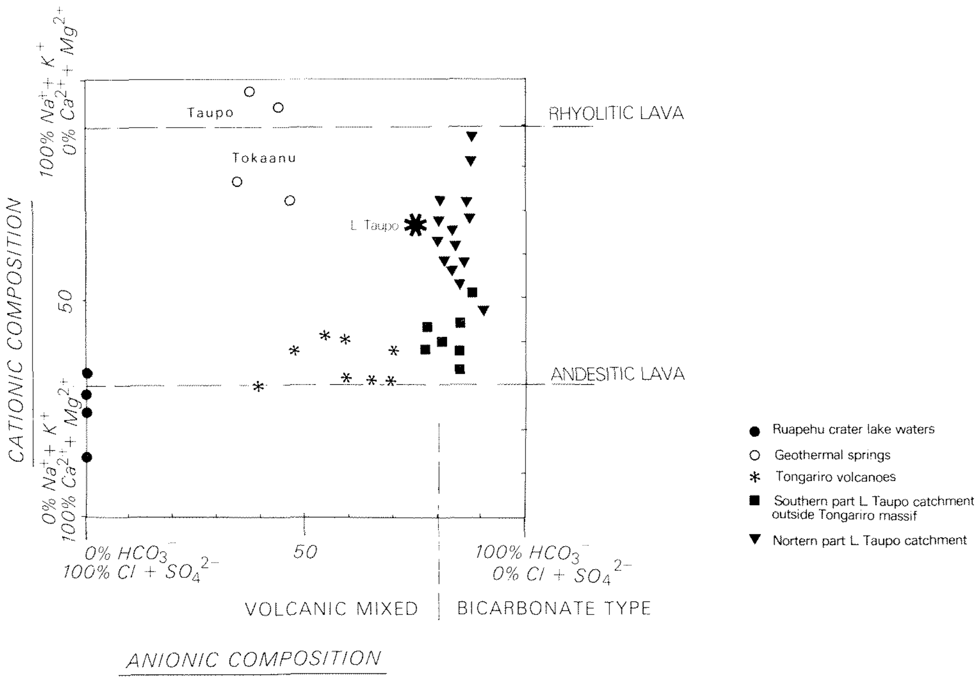

FIG.4 Ionic composition of the waters in the Lake Taupo basin.

bicarbonate forms more than 80% of the anionic composition (Fig.4). These waters are the product of the mixing and interaction of the precipitation (minus interception/evaporation) with the vegetation, the soil-rock complex and dry fallout of solutes. In the high rainfall areas the mean total dissolved solids concentrations are

TABLE 1 Flow-weighted mean concentrations of the volcanic waters in the Lake Taupo basin

NAME:	Waipahihi St* (geothermal)	Tokaanu St* (geothermal)	Mangatipua Stream	Whakapapaiti Glacier	Waihohonu River	Wairehu Canal
SITE no:	21	142	125	625	115	122
$\bar{q}$ ($m^3 s^{-1}$)	0.01	0.05	0.1	0.005	6.0	20.5
Temp (°C)	>60	>60	-	0.2	8.4	10.3
Susp. matt. ($g\ m^{-3}$)	-	-	-	10000	280	-
DRP ($mg\ m^{-3}$)	200	-	4	0	13.6	6.8
PP ($mg\ m^{-3}$)	-	-	20	130	53	20
NO_3-N ($mg\ m^{-3}$)	-	-	500	13	7	
NH_4-N ($mg\ m^{-3}$)	2000	2200	5000	15	6	7
Org-N ($mg\ m^{-3}$)	-	-	1000	-	105	144
Cl ($g\ m^{-3}$)	720	1500	1.1	0.5	4.1	6.0
HCO_3 ($g\ m^{-3}$)	580	100	44	0	18.2	36
SO_4 ($g\ m^{-3}$)	190	130	45	68	11.4	20
Na ($g\ m^{-3}$)	1200	760	8.5	2.2	3.8	7.3
K ($g\ m^{-3}$)	160	50	4.2	0.4	1.5	2.9
Ca ($g\ m^{-3}$)	13	120	16	16	6.6	11
Mg ($g\ m^{-3}$)	6	15	4.5	1.1	1.8	3.4
H_4SiO_4 ($g\ m^{-3}$)	160	460	16	0.8	13	30
pH ($g\ m^{-3}$)	7	7.5	-	3.7		
TYPE	NaCl	NaCl	$CaSO_4$	$CaSO_4$	$CaSO_4$/ mixed	$CaSO_4$/ mixed

* Obtained by subtraction of the non-geothermal part from the total outputs.

TABLE 2 Flow-weighted mean concentrations of non-volcanic and mixed-bicarbonate waters in the Lake Taupo basin

NAME: SITE no.	Waipakihi River 113	Waitahanui River 42	Waihaha River 261	Kuratau River 182	Lake Rotoaira Tokaanu Power St. 121	Lake Taupo at outlet 10
$\bar{q}$ ($m^3 s^{-1}$)	8.8	6.8	6.1	7.0	41.5	146
Temp (°C)	8.9	11.3	10.5	12.9	11.9	15.5
Susp. matt. ($g\ m^{-3}$)	30	15	37	(50)	4	1
DRP ($mg\ m^{-3}$)	3.6	62	16	8.8	7.5	2.5
PP ($mg\ m^{-3}$)	28	15	36	30	12	5.7
NO_3-N ($mg\ m^{-3}$)	28	205	230	400	5.4	3.1
NH_4-N ($mg\ m^{-3}$)	9	13	11	13	12	8.6
Org-N ($mg\ m^{-3}$)	100	105	204	225	119	82
Cl ($g\ m^{-3}$)	1.3	3.0	3.6	3.8	6.4	9.2
HCO_3 ($g\ m^{-3}$)	13	34	18	24	42	44.6
SO_4 ($g\ m^{-3}$)	1.0	2.0	1.0	0.7	13.6	5.7
Na ($g\ m^{-3}$)	1.9	8.3	4.4	4.5	8.3	15.2
K ($g\ m^{-3}$)	0.3	1.5	1.2	1.6	2.0	2.2
Ca ($g\ m^{-3}$)	3.2	3.1	2.5	2.9	8.6	6.6
Mg ($g\ m^{-3}$)	0.4	0.9	0.8	1.4	3.8	2.3
H_4SiO_4 ($g\ m^{-3}$)	5.9	36.	13.	30.	19.	17.
TYPE	$CaCO_3$	$NaHCO_3$	$NaHCO_3$	$NaHCO_3$	mixed	mixed

frequently below 40 g m^{-3}, in the low rainfall areas mean concentrations are around 80 g m^{-3}. In areas where the tephra cover and subsoils are of a rhyolitic nature or greywacke, Na^+ forms the most important cation and the monovalent cations are in excess of the divalent cations (Fig.4 and Table 2, column 2). In areas where the tephra or subsoils are of an andesitic nature, Ca^{2+} forms the most important cation and the divalent cations are in excess the monovalent (Fig. 4 and Table 2, column 1). In the Kaimanawa greywacke ranges for instance, the southwestern parts are covered by thick andesitic ashes from the Tongariro volcanoes but such ashes become thinner to the north. The percentage of divalent cations increases from <40% in the area around Taupo Township (42, Table 2) to >60% in the streams draining the Kaimanawa Ranges (113, Table 2) in the south. DRP concentrations range between 200 and 2 mg m^{-3}. There is no relationship between land use and DRP content of the streams in the Lake Taupo basin. High concentration levels are possibly related to the existence of certain tephra deposits. The DIN concentrations of the non-volcanic waters are an expression of the effects of vegetation, vegetational history and human land uses. In well established forest the mean DIN concentrations remain below 200 mg m^{-3}, in areas of alpine scrub and tussock grassland below 50 mg m^{-3}, while in areas of highly productive agricultural grasslands, urban settlements or recently logged native forests, concentrations range between 500 and 1500 mg m^{-3}.

Budget of constituents of water

On the basis of the measured streamflow outputs, the water balance, and data on regional concentration levels of various water constituents, it is possible to construct for Lake Taupo a budget of materials transported by water. As virtually all of the measurements were carried out on the streamflow component of the budget, it will be necessary to make a number of assumptions in order to estimate the other budget components such as subsurface and atmospheric inputs. The residence time of water in Lake Taupo is about 13 years.

TABLE 3 Percentage contributions of the main streams to the total measured surface inputs into Lake Taupo for 1977

Site no. and name	$\bar{q}$	Q_s	DRP	PP	NO_3-N	NH_4-N	Org-N	Cl	HCO_3	SO_4	Na	Ca	H_4SiO_4	Area
142 Tokaanu St.	1	<1	3	2	3	8	1	13	2	1	6	2	4	34.8
121 Tailrace Tokaanu Power station	33	4	14	13	2	30	25	43	44	66	42	47	30	-
111 Tongariro R.	25	58	23	41	6	23	21	18	24	24	16	29	28	785.5
92 Waimarino R.	3	3	1	3	3	2	3	1	1	<1	1	2	1	78.9
81 Tauranga - Taupo R.	7	7	5	5	6	4	8	3	4	2	4	4	4	199.5
51 Hinemaiaia R.	5	1	7	4	3	3	4	2	3	1	4	2	3	105.4
42 Waitahanui R.	7	3	24	3	13	7	5	4	7	2	9	4	12	304.2
261 Waihaha R.	5	5	4	6	12	4	7	4	3	1	3	2	3	132.9
182 Kuratau R.	6	7	3	5	23	6	8	4	5	1	4	3	8	194.7
Total measured surface inputs	127 ($m^3 s^{-1}$)	164 ($t x 10^3$)	72 (t)	123 (t)	375 (t)	52 (t)	620 (t)	19 ($t x 10^3$)	125 ($t x 10^3$)	27 ($t x 10^3$)	26 ($t x 10^3$)	24 ($t x 10^3$)	85 ($t x 10^3$)	2385 (km^2)

The effects of the Tongariro Power Development scheme (TPD) is expected to take several years to produce a steady change in the loading of the outflow. However, from the changes in the loading which have resulted from the TPD scheme so far, it can be calculated that the expected final changes in lake water concentrations, will be very small, if measurable. Therefore, concentration levels measured at Taupo Gates during 1977-1978 are considered to represent the steady state condition for Lake Taupo. A budget for the dissolved constituents of a lake may be considered in a similar way to the water balance (equation (1)), but special attention has to be given to the occurrence of various processes (biological uptake and transformations, or ion-exchange with particulate matter, sedimentation, etc.) which take place within the lake.

Contributions from surface streams (Table 3) All of the streams that were automatically recorded or gauged regularly were also sampled sufficiently often to enable calculation of annual outputs of materials (Schouten *et al.*, 1981). The samples obtained elsewhere were compared with the samples of frequently measured inflows and were found to be very similar in chemical composition to other small streams draining rhyolitic volcanic deposits, mainly pumice, around the lake. By using the annual outputs of small riparian catchments such as the Omori, Otaketake, Whangamata, Waipehi and Waitetoko streams, flow-weighted annual mean concentrations considered representative for such areas could be calculated (Table 4). The output of streamflow constituents from the missing 288 km^2 of lake catchment was then estimated by multiplying the regional flow-weighted concentrations by the annual water yield based on a total flow rate of 4 m^{3}s^{-1}. The amounts thus obtained were added to the sum of the inputs from measured surface inflows and are presented in the first column of Table 5.

TABLE 4 Flow-weighted mean concentrations in nine streams draining small rhyolitic catchments around Lake Taupo (total area = 297 km^2, total discharge = 5.6 m^{3}s^{-1})

DRP (1)	PP (1)	NO_3-N (1)	NH_4-N (1)	Org-N (1)	Cl (2)	HCO_3 (2)	SO_4 (2)	Na (2)	K (2)	Ca (2)	Mg (2)	H_4SiO_4 (2)	Susp. matt. (2)
52	36	250	14	270	3.2	30	1.9	6.9	1.6	3.6	1.4	27	47

(1) Value in mg m^{-3}
(2) Value in g m^{-3}

Contributions from the atmosphere The direct atmospheric contribution consists of input of nutrients and other matter dissolved in precipitation or suspended in the air. No measurements of these have been carried out as part of the Lake Taupo project, but use is made of the measurements reported by others. At Taupo the annual input from the atmosphere of DRP is 13 kg km^{-2}, of ammonia-N is 252 kg km^{-2} and of nitrate-N is 119 kg km^{-2} (White & Downes, 1977). Fish (1976) also measured the total P and total N in a number of

TABLE 5 Budget of water and its dissolved and suspended constituents for Lake Taupo in 1977

	Surface streams*	Airborne*	Groundwater*		Total*	Lake† outflow	Storage†	Sedimentation and biological uptake†
			Rural	Geothermal				
$\bar{q}$ ($m^3 s^{-1}$)	131	12	7	1	151	146	5	–
Q_S (t x 10^3)	170	0			170	4	<1	166
DRP (t)	79	8	9	1	97	12	<1	85
PP (t)	127	3	3		133	26	1	106
NH_4-N (t)	54	160	3	50	267	40	1	226
NO_3-N (t)	407	70	105		582	14	1	567
Org-N (t)	654	180	20		854	378	13	463
Cl (t x 10^3)	20	2	1	21	44	42	2	
HCO_3 (t x 10^3)	129	?	8	20-77?	214	206	8	?
SO_4 (t x 10^3)	27	<1	1	4	32	26	1	5
Na (t x 10^3)	27	1	2	42	72	70	2	
K (t x 10^3)	6.6	<1	<1	3	10	10	<1	
Ca (t x 10^3)	25	<1	1	5	31	30	1	
Mg (t x 10^3)	8.9	<1	<1	1	10	11	<1	
H_4SiO_4 (t x 10^3)	88	<1	6	10	104	79	3	22

* *Inputs.*
† *Outputs.*

atmospheric input samples taken at Rotorua. About 75% of the phosphorus in these samples was DRP and 56% of the total nitrogen was inorganic. These results were applied to the P and N results from Taupo to obtain the particulate and organic fractions. No measurements of the major ion inputs from the atmosphere have been carried out in the Lake Taupo basin. Miller (1961, 1963) investigated nutrient cycling and the chemical composition of rainwater at Taita near Wellington in New Zealand. He observed that the relatively high chloride input all appeared in the drainage (16 t km^{-2} year^{-1}). In most lithologies there is very little chloride present, and from the Taita and similar studies elsewhere (Swank & Douglass, 1975; Verstraten, 1977) it may be concluded that atmospheric inputs of chloride are about equal to the catchment outputs. Stream systems that are affected by chloride inputs from volcanic origin are, of course, exceptions. The range of Cl$^-$ concentrations measured within the bicarbonate-type streams in the Taupo basin is very small, and a regional flow-weighted mean chloride concentration (3.1 g m^{-3}) was calculated from the outputs in surface flow and the specific chloride yield was estimated at 3.2 t km^{-2} year^{-1}. As might be expected from its inland situation, the atmospheric chloride precipitation rate will be considerably smaller at Taupo than at Taita. By assuming that the chemical precipitation rate for Lake Taupo is the same as that estimated for the nearby catchments, and that the ratios between chloride and the other major ions in the atmospheric precipitation at Taupo are about the same as at Taita, the input of major ions to Lake Taupo may be estimated from the measurements of Miller (1963) at Taita, and are presented in column 2 of Table 5.

Output and temporary storage of materials The output from, and storage of ions in Lake Taupo for 1977 was estimated by multiplying the annual water output by the mean concentration of ions in the samples taken at Taupo gates (column 6 + 7, Table 5).

Inputs from subsurface flow Except for the urbanized area of Taupo Township (John *et al.*, 1978; Gibbs, in preparation) and for the geothermal springs, no investigations on the chemistry of the groundwater resources around Lake Taupo have been carried out. The average concentration in the groundwater around the lake could only be obtained from the concentrations in the surface streams. It is assumed that, for those constituents which are not much affected by in-stream biological processes, concentrations measured during extended periods of base flow recession are comparable to those in the groundwater. In order to estimate a regional mean groundwater concentration level for the various constituents, an area-weighted mean value was calculated from the baseflows of spring-fed streams originating in the areas covered by more than 10 m of tephra (Fig.2 (b)).

Direct geothermal contributions to the lake It is obvious from the budget calculations that the sum of the output and increase in storage of Cl^-, Na^+ and HCO_3^- are not matched by the sum of the inputs from surface streams and direct atmospheric contributions. Only two small surface inflows of the lake exhibited Cl^- concentrations higher than the 9 g m^{-3} measured in Lake Taupo. Also the Na^+ output was considerably higher than the known inputs, indicating the possibility of inputs from springs discharging volcanic waters of the sodium-chloride type. McColl (1975) noted the large discrepancy between the Na^+ concentrations within Lake Taupo and those in the major inflows. He suggested the existence of hot springs somewhere in the lake, to explain this discrepancy. The existance of geothermal springs below Lake Taupo is not surprising when it is recognized that the lake lies across a complex fault system which is accompanied by volcanic and geothermal activity. From Mt Ruapehu this fault system can be followed to Mt Tongarito (Ketetahi geothermal field), Lake Rotoaira, the Tokaanu-Waihi geothermal field, Taupo and Wairakei. It is believed that the geothermal activity of Waihi and Taupo is continued below parts of the lake. The chloride budget of Lake Taupo implies that there is an unmeasured input of about 670 g s^{-1} of chloride. In the geothermal fields around Lake Taupo the maximum observed Cl^- concentrations range between 400 and 800 g m^{-3}, so the average discharge of geothermal water from springs at the shores and within Lake Taupo must be at least 1 m^3s^{-1}. In agreement with the average composition of geothermal waters and fumaroles there also exists an excess of Na^+ and HCO_3^- in the Lake Taupo outflows. In Table 5 the geothermal contributions directly to the lake have been calculated using the mean composition of the geothermal fraction of the Waipahihi St. (21, Table 1). The non-geothermal fraction of the groundwater inputs directly to Lake Taupo have been estimated at 7 m^3s^{-1} while the geothermal discharge was taken as 1 m^3s^{-1} (Table 5).

Deposition of materials in Lake Taupo Most of the gravel, sand, silt and other particulate matter transported by the rivers to the lake does not reach the outlet. The coarse debris is deposited in river deltas whereas clay and other fine suspended particles may be transported far into the lake before settling. A continuous stream of fine organic matter, largely consisting of dead algae together with inorganic suspended matter, is sinking to the lake bottom and forming a fine mud. Frequent volcanic eruptions in the region have deposited volcanic ash-layers which enable the measurement of rates of deposition of mud. Rawlence & Reay (1976) measured an average deposition rate of mud of 260 g m^{-2} $year^{-1}$ in some deep parts of Lake Taupo and this would be equivalent to approximately 100 000 t $year^{-1}$ for the whole lake. A considerable part of the dissolved phosphorus, nitrogen and reactive silica inputs remain behind within the lake (Table 5), and most of it has probably been taken up by plants, and deposited in the lake mud.

DISCUSSION

The impact of Holocene and recent volcanic processes

Major ions The effects of volcanic processes are summarized in Table 6. Geothermal springs add large quantities of Cl^-, Na^+, HCO_3^- and other major ions to Lake Taupo and possibly to Lake Rotoaira.

TABLE 6 Proportional effects of important environmental processes upon the loadings of Lake Taupo

Annual loading (1977)		*Recent volcanic eruptions and geothermal waters (%)*	*Agriculture forestry urbanization (%)*	*Hydropower development (%)*
Q_S	170×10^3 t $year^{-1}$	40	5	decrease*
Diss.load	518×10^3 t $year^{-1}$	38	n.s.	15
DRP	97 t $year^{-1}$	28	n.s.	n.s.
DIN	849 t $year^{-1}$	10	35	n.s.

n.s. not significant.
** c. 300 x 10^3 t $year^{-1}$ before the TPD scheme came to effect.*

They exert a strong effect upon a number of surface streams in the Taupo basin. It can be calculated that about 60% of the Na^+ and Cl^- loading of Lake Taupo originates from geothermal springs, mainly those below the lake. A similar origin may be attributed to about one third of the K^+ and smaller proportions of the other major ions and SiO_2. The specific output of dissolved material from the Tongariro Mountains is about 127 t km^{-2} $year^{-1}$, which is double the output from the Kaimanawa Ranges. The difference is attributed to volcanic sources. The effect of volcanic sources on the yield of each of the major ions was roughly estimated by subtracting the yield of each ion per square kilometer in the Kaimanawa Ranges from those measured in the Tongariro Volcanic Massif, and multiplying the results by the Tongariro catchment area (470 km^2). More than half the SO_4^{2-} load of Lake Taupo originates from the Tongariro Volcanoes as well as a considerable amount of Ca^{2+} and SiO_2.

DRP outputs and volcanism The concentrations and outputs of DRP in the Lake Taupo basin cannot be correlated to present land use, land-use history or the presence of volcanic water of any kind

(42, Table 2). Careful mapping of outputs and concentrations measured in first and second order streams revealed that these generally decreased with increasing distance from the area between Taupo Township and Lake Rotongaio. In this area are situated the old eruption centres of the Taupo pumice eruptions (130 AD). The very high DRP outputs close to these centres, some of which were in excess of 50 kg km^{-2} $year^{-1}$, are not likely to be derived from Taupo pumice itself, since P-levels in this pumice are not very high. It is suggested that one of the many rhyolitic tephra originating from the Taupo-Rotongaio centres forms the source of the elevated DRP outputs.

Suspended matter and volcanism Very high suspended matter outputs originate from the slopes of the active volcanoes, especially from Mt Ruapehu. Large volumes of unconsolidated sandy volcanic deposits are prone to erosion which is accelerated by the high rainfall, lack of vegetation, and harsh climate. Recent ash eruptions provide the headwaters of the Tongariro River with a continuous supply of suspended matter, making this river by far the largest source of suspended matter for both Lake Rotoaira and Lake Taupo (Tables 3 and 5). The specific outputs of suspended matter of catchments on the slopes of Mt Ruapehu range between 200 and 900 t km^{-2} $year^{-1}$. In the high rainfall areas in the rest of the Lake Taupo catchment, the specific outputs remain below 75 t km^{-2} $year^{-1}$. Of the total mass of suspended matter that is generated annually within the Lake Taupo basin and deposited in both Lake Taupo and Lake Rotoaira about 75% originates from the slopes of Mt Ruapehu and Mt Ngauruhoe.

Forestry, agricultural and human occupation effects upon the loading

Most of the active use of land in the Lake Taupo basin is carried out in rhyolitic lowland areas which are highly permeable and receive a relatively moderate rainfall (Figs 2(a) and (b)). The undisturbed forests are in the less permeable greywacke ranges with high rainfall. This makes a comparison of the effects of land use upon catchment outputs very complicated and if the differences are small, impossible.

DIN outputs resulting from land use The only nutrient that has consistently higher concentrations and often higher outputs in areas of strongly modified vegetation, such as logged native forests or agricultural grasslands, is nitrate-N. Levels of nitrate-N in excess of 1000 mg m^{-3} in groundwater springs and in excess of 500 mg m^{-3} in surface streams have been measured in agricultural grasslands to the north and west of Lake Taupo, and in most streams draining the Hauhungaroa Ranges downstream of the logged forests. Occasionally these high concentrations occur in the foothills of the northern Kaimanawa Ranges and coincide with the areas where large environmental changes have taken place during the last 50 years. Several of the western catchments have total N outputs in excess of the estimated atmospheric contribution (*c.* 670 kg km^{-2} $year^{-1}$). In these catchments the original virgin podocarp forests have been replaced by agricultural grasslands, secondary scrub or exotic pine plantations. The nitrogen outputs of the grazed pastures are not systematically different from those containing secondary scrub or exotic pines, possibly because the nitrate is released from decomposing organic matter in the humus-rich forest soils, which are not in equilibrium with the present vegetation. This may also explain the lower DIN concentrations in the streams draining the basins around the northern shores of Lake Taupo, which have a much longer history of deforestation. This area was already in scrub before 1840 and has been burnt frequently during the past, leaving behind little easily decomposable organic matter.

The urban effects upon the loading of Lake Taupo are concentrated mainly around Taupo Township. Most of the septic tank effluents from the houses in the settlements around Lake Taupo drain directly to the lake and do not affect the larger streams in the area. Gibbs (in preparation) estimated the contribution of DIN to the lake from the septic tanks at Taupo Township to be about 40 t year^{-1}. To account for additional settlements around the lake, the total urban DIN inputs were estimated to be about 60 t year^{-1}. Relatively low DIN concentrations and outputs (75-300 kg km^{-2}year^{-1}) were measured from streams draining undisturbed forests. Extremely low outputs of DIN occur in the Tongariro highlands (below 30 kg km^{-2}year^{-1}). Because the principal sources of water for Lake Taupo originate from areas with low to very low DIN outputs the total loading of DIN is exceptionally low, certainly when compared to lakes in Europe or North America. The effect of human activities upon DIN loading was estimated by subtracting from the observed basin outputs the outputs that would have been expected from similar sized basins in the original vegetation (*c*. 300 t km^{-2}year^{-1}). Virtually all of the excess of DIN calculated in this way was derived from the western tributaries and a little from the urban inputs.

Land-use effects upon suspended matter loading Large scale transformations of the original forest and scrub vegetation into agricultural grassland and *Pinus radiata* plantations, have taken place during the last 25 years in the Lake Taupo basin. Exotic forestry developments are still going on and the enormous scale of the discing operations can be seen from satellite pictures. The impact of these developments upon suspended matter loading of the streams is only very small. Agencies involved in the forestry developments have not always consistently applied the guidelines for the protection of the soils and stream courses. Roads are often close to stream channels and block normally dry channels. The average output of suspended matter of streams draining these catchments under development was generally below 50 t km^{-2}year^{-1}, and for most land to the north and northeast of the lake was below 25 t km^{-2}year^{-1}, which is lower than found for areas in native forest, which are however on steeper land. This contradiction, between poor soil conservation practices, and little measurable effect on the streams draining these areas, is caused by the exceptionally high infiltration rates and permeabilities of the deep ash and lapilli deposits.

The effects of the Tongariro Power Development project

Dissolved load The effect of the additional loading from the Wairehu canal upon the concentrations of most of the major ions in Lake Taupo will be small. Only relatively large quantities of additional SO_4^{2-} may have resulted in a final increase of about 2 g m^{-3}, while at the same time concentrations of Na^+ and Cl^- each may have dropped by about 1 g m^{-3}. The increase in loading of dissolved matter of Lake Taupo was about 17%.

Effects of the TPD scheme upon dissolved N and P The outflow of Lake Rotoaira (Tokaanu Power Station Tailrace, 121) contains water originating from the original Lake Taupo basin (Tongariro River) and water from external sources (Wairehu Canal). Its chemistry is however, not a simple mixture of these waters. During the period of storage in Lake Rotoaira various lake processes, such as algal growth and sedimentation have caused considerable changes. The average dissolved N and P concentrations in the input of Lake Taupo have in fact dropped as a result of the TPD scheme while the loading is about the same as before (Table 7).

Suspended matter inputs and the TPD As a consequence of the inputs through the Poutu Canal, the suspended matter loading of Lake Rotoaira has increased by a factor of 20. Although the water entering through the Wairehu Canal originates from sources extremely rich in suspended matter (Mt Ruapehu), the suspended load is considerably smaller than that of the Poutu Canal. Possibly, part of the suspended load from the Wanganui River is deposited in Lake Otomangakau (Fig.1) before it reaches the Wairehu Canal. As a result of deposition of suspended matter from the Poutu Canal in Lake Rotoaira, the suspended matter loading of Lake Taupo has decreased by approximately 45% since 1972. A large fraction of the particulate and organic phosphorus (PP) from the streams in the Lake Taupo area, is inorganically bound to suspended matter and therefore the PP

TABLE 7 Specific loadings of P and N constituents and hydrological factors of importance for eutrophication (Vollenweider, 1975) for Lake Taupo

	White & Downes	*This investigation:*	
	pre-TPD	*pre-TPD**	*post-TPD*
Discharge ($m^3 s^{-1}$)	143	143	164
Water residence time (T_W) *(years)*	13.0	13.2	11.5
$\bar{z}/T_W$ ($m\ year^{-1}$)		7.3	8.4
DRP ($g\ m^{-2} year^{-1}$)	0.191	0.154	0.157
PP ($g\ m^{-2} year^{-1}$)	0.09	0.240	0.215
TP ($g\ m^{-2} year^{-1}$)	0.281	0.394	0.373
DIN ($g\ m^{-2} year^{-1}$)	1.07	1.40	1.38
Org-N ($g\ m^{-2} year^{-1}$)	1.15	1.35	1.39
TN ($g\ m^{-2} year^{-1}$)	2.22	2.75	2.77

**Based on water quality data of period 1976-1977 applied to the pre-TPD hydrological situation.*

loading of Lake Taupo has also decreased as a result of the TPD diversions (Table 7).

The trophic status of Lake Taupo

White & Downes (1977) stated that there could be no doubt, on the basis of algal and chlorophyll content, total phosphorus content, water clarity and dissolved oxygen depletion in the hypolimnion, that Lake Taupo could be classified as an oligotrophic lake. Paerl (1977) measured the annual pattern of *in situ* primary productivity by the ^{14}C method and concluded on the basis of a mean rate of 0.7 mg C $m^{-3}h^{-1}$ that Lake Taupo represents an oligotrophic situation. On the basis of phosphorus loadings, lake depth and water residence time (Vollenweider, 1975), Lake Taupo is situated well within a cluster of lakes that are mesotrophic. White & Downes (1977) suggested the reason why the mesotrophic status predicted from the P budget has not been realized, is most probably that nitrogen has been limited as well. Vollenweider (1968) reported that nitrogen may be limiting for algal growth if the ratio N:P is less than 15. Although the pre-TPD nutrient loadings estimated by White & Downes, are somewhat different from the estimates in this investigation (Table 7), they give similar conclusions concerning the trophic status of Lake Taupo. Before and after the effects of the TPD were felt the ratio N:P for Lake Taupo ranged between 7 and 9, depending on what part of the TN and TP was taken as being available for algal growth. The TPD scheme has lead to minor changes in nutrient loading and mean depth of annual water load ($\bar{z}/T_W$) for Lake Taupo (Table 7). However, these changes are unlikely to be followed by a change in the trophic status of the lake. The N:P has remained the same and according to the P loading (Vollenweider, 1975) its mesotrophic potential has not changed either. If Lake Taupo is N-limited, increasing deforestation of the Hauhungaroa Ranges and increasing N loading from agricultural and urban areas may threaten the present oligotrophic state of Lake Taupo.

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REFERENCES

Finkelstein, J. (1961) Estimation of open water evaporation in New Zealand. *NZ J. Sci.* 4 (3), 506-521.
Fish, G.R. (1976) Nitrogen and phosphorus analysis of rainfall at Rotorua (New Zealand). *J. Hydrol. (NZ)* 15 (1).
Gibbs, M.M. (in preparation) Groundwater input to Lake Taupo (New

Zealand): nitrogen and phosphorus inputs from Taupo Township.

Glowa, W (1974) Zirconium dioxide, a new catalyst in Kjeldahl method for total nitrogen determination. *J. Ass. Analyt. Chem.* 57, 1228-1251.

John, P.J., Gibbs, M.M. & Downes, M.T. (1978) Groundwater quality along the eastern shores of Lake Taupo, 1975-76. *NZ J. Mar. Freshwat. Res.* 12 (1), 59-66.

Kamphake, L.J., Hannah, S.A. & Cohen, J.M. (1967) Automated analysis for nitrate by hydrazine reduction. *Wat. Res.* 1, 205-216.

McColl, R.H.S. (1975) Chemical and biological conditions in lakes of the volcanic Plateau. In: *New Zealand Lakes* (ed. by V.H.Jolly & J.M.A.Brown), Auckland University Press/ Oxford University Press.

Mahon, W.A.J. & Klyen, L.E. (1968) Chemistry of the Tokaanu-Waihi hydrothermal area. *NZ J. Sci.* 11, 140-158.

Miller, R.B. (1961) The chemical composition of rainwater at Taita, New Zealand 1956-1958. *NZ J.Sci.* 4, 844-853.

Miller, R.B. (1963) Plant nutrients in hard beech III, the cycle of nutrients. *NZ J.Sci.* 6, 388-413.

Paerl, H.W. (1977) Annual primary productivity in Lake Taupo. *NZ Limnol. Soc. Newsletter no. 13,* p.20.

Rawlence, D.J. & Reay, P.F. (1976) Diatom numbers and phosphorus levels in deepwater sediment from Lake Taupo, New Zealand. *NZ J. Mar. Freshwat. Res.* 10 (4), 589-595.

Sarbutt, J.V. (1964) A chemical survey of the hot spring and drillhole waters of Taupo Borough. *NZ J. Sci.* 7 (4), 491-505.

Schouten, C.J., Terzaghi, W. & Gordon, Y. (1981) Summaries of water quality and mass-transport data for the Lake Taupo catchment. *Water and Soil Division, Ministry of Works and Development, Miscellaneous Publication no. 24, National Water and Soil Conservation Organization, Wellington, NZ.*

Schouten, C.J. (1983) Volcanic cover deposits and streamflow behaviour in the Central North Island of New Zealand. *Geol. en Mijnb.* 3.

Selby, M.J. (1972) The relationships between land use and erosion in the Central North Island, New Zealand. *J. Hydrol. (NZ)* 11 (2), 73-85.

Swank, W.T. & Douglass, J.E. (1975) Nutrient flux in undisturbed and manipulated ecosystems in the Southern Appalachian Mountains. In: *The Hydrological Characteristics of River Basins* (Proc. Tokyo Symp., December 1975). IAHS Publ. no. 117.

Van Schouwenburg, J.C. & Wallinga, I. (1967) The rapid determination of phosphorus in presence of arsenic, silicon and germanium. *Analyt. Chimica Acta* 37, 271-274.

Verstraten, J.M. (1977) Chemical erosion in a forested watershed in the Oesling, Luxembourg. *Earth Surf. Processes* 2, 175-184.

Vollenweider, R.A. (1968) *Scientific Fundamentals of the Eutrophication of Lakes and Flowing Waters, with Particular Reference to Nitrogen and Phosphorus as Factors in Eutrophication.* OECD, Paris, 160 pp.

Vollenweider, R.A. (1975) Input-output models with special references to the phosphorus loading concept in limnology. *Schweiz, Z. Hydrol.* 37, 53-84.

White, E. & Downes, T. (1977) Preliminary assessment of nutrient loads on Lake Taupo. *NZ J. Mar. Freshwat. Res.* 11 (2), 341-356.

White, E. (1977) The Tongariro Power Development and its effect on Lake Rotoaira. *NZ Limnol. Soc. Newsletter no. 13*.