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Eutrophication processes regulated by a plunging river inflow

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Abstract

Lake Rotoiti (North Island, New Zealand) is a deep mesotrophic lake that has declined in water quality over the last 30 years. The main river entering the lake was identified as the primary enrichment source, but its interaction with the surrounding lakewater varied with season and time of day. During winter the river was colder than the lake and penetrated 6–8 km into the main basin as an underflow. In summer the river often entered as a plunging inflow during the early morning, but it warmed during the day, and in the afternoon entered the lake as a buoyant jet that flowed directly to a nearby outlet river. From continuous temperature measurements in the inflow and lake surface it was estimated that the river plunged and penetrated the lake as an interflow or underflow for 60.2% of the year. This translated into 31% of the N and 64% of the P loading on the lake. The river also injected phytoplankton into the main basin of Lake Rotoiti, including populations of bloom-forming cyanobacteria. The underflow was the dominant term in calculating the hydraulic flushing time of the main basin, and also made a large contribution of dissolved oxygen to the subsurface waters. These complex interactions between Lake Rotoiti and its inflowing river were controlled by small temperature differences (<3 °C), and had wide-ranging implications in the eutrophication process.

Introduction

When a stream or river enters a lake its pathway of flow is largely controlled by the density difference between its water and that of the surrounding lakewater. Inflows that are warmer than the lake tend to move across the surface as an overflow before being dispersed into the mixed layer. Colder inflows enter the lake and then plunge to flow across the bottom as an underflow. Such currents may separate at the point of neutral buoyancy to penetrate into the water column as an interflow. All three types of input-derived flows increase in size by entraining water from the surrounding lake as they enter (Fischer *et al.*, 1979).

Although these input patterns are understood in qualitative terms there have been few case studies which have examined their quantitative importance for the transfer of materials into and within a lake. Internal waves modified a plunging inflow to Lake Mead and resulted in a 10% transfer of the entering nutrients to the surface mixed layer (Fischer & Smith, 1983). Diurnal changes in the water temperature of a turbid river entering a large glacial lake resulted in variations in the extent of underflow and mixing with the surrounding lakewater (Irwin & Pickrill, 1982). At Silver Lake, New York, the main river inflow remained as a buoyant jet that short-circuited directly to the outflow (Englert & Stewart, 1983). The Jordan River penetrates 5–6 km into Lake Kinneret as an underflow during the coolest 2–3 months, and for the remainder of the year floats over and mixes with the surface waters of the lake (Serruya, 1978). A density inflow to a small eutrophic lake generated a net upwelling and associated nutrient transfers through the upper layers of the waterbody (Imberger & Spigel, 1987). The seasonal dynamics of physical structure in Kootenay Lake, British Columbia is substantially influenced by two rivers that at certain times of year penetrate into the lake as plunging inflows (Carmack *et al.*, 1986). At each of these study sites the inflow-derived density currents may be expected to have major implications for the ecological dynamics of the lake.

In the present study we examined the importance of a plunging inflow to the enrichment processes operating in Lake Rotoiti, a deep mesotrophic lake in the Central North Island of New Zealand. Previous investigations of this lake have emphasised internal biogeochemical processes (e.g. Priscu, 1986) but there had been little attention directed towards the external inputs. Lake Rotoiti has experienced a persistent decline in water quality over the last 30 years (Vincent *et al.*, 1986). Attention became focussed on the dominant hydraulic input to the lake, a river flowing in from a nearby eutrophic waterbody. Our detailed hydrodynamic measurements (summarized here) indicated that this riverine inflow penetrated the lake as density currents that varied with season and time of day. These currents had a wide-ranging influence on eutrophication in Lake Rotoiti by greatly modifying its hydrology, nutrient loading, algal growth, oxygen distribution and other ecosystem characteristics.

Study site

Lake Rotoiti is located on the central volcanic plateau of the North Island, New Zealand at latitude 38° 02′ S, longitude 176° 24′ E (Fig. 1). It has a maximum depth of 120 m, a mean depth of 33.1 m, and an area of 34.35 × 10^6 m^2. The lake is monomictic with stratification from October to May, and winter mixing from June to September

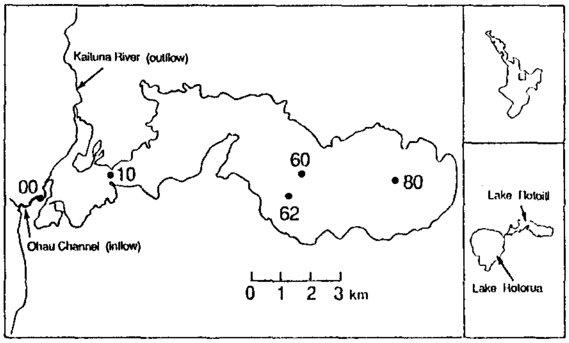

Fig. 1. Location of sampling sites on Lake Rotoiti, Central North Island.

(Fig. 2). The only major river input to the lake is called the Ohau Channel and flows into the shallow western basin of Lake Rotoiti from a nearly (2 km) eutrophic lake, Lake Rotorua. The outflow from Lake Rotoiti, the Kaituna River, also lies at the western end of the lake, 2.6 km from the inflow (Fig. 2). For 28 years of records from 1957 to 1984 the average annual discharges were 18.04 m^3 s^{-1} from the Ohau Channel and 22.80 m^3 s^{-1} for the Kaituna River. Throughout this record it was extremely rare for the daily Ohau discharge to exceed the Kaituna discharge, the difference being made up from small surface streams, springs and groundwater inflow entering the lake largely on its southern and eastern shores. Spigel (1989) estimated the remaining terms in the lake's water balance as: rainfall 2010 mm yr^{-1} (2.19 m^3 s^{-1}), evaporation

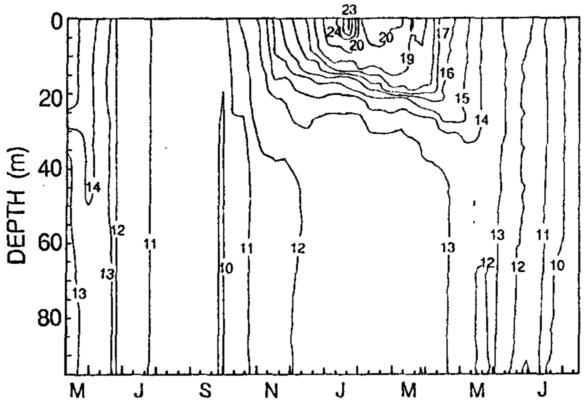

Fig. 2. Seasonal variation in temperature in Lake Rotoiti, 1982/83, at site 62.

880 mm yr^{-1} (0.96 $m^3 s^{-1}$) and all residual inflows 3.55 $m^3 s^{-1}$. The residual inflows include surface springs and streams (other than the Ohau Channel) and net groundwater inflow. The geology of the region is volcanic in origin, and the soils and underlying deposits of the Rotoiti catchment are generally porous and highly permeable, allowing subsurface flows to play a role in the hydrology of the lake. Freestone (1982) estimated average dry weather surface inflow as 0.8 $m^3 s^{-1}$ and net groundwater inflow as 2.0 $m^3 s^{-1}$, with the remaining inflow being due to storm runoff. Since most of the residual flow occurs around the shores of the larger, deeper eastern basin, there is almost always a net flow from east to west through the lake to balance the deficit between Kaituna River outflow and Ohau Channel inflow.

Methods

Physical measurements for this study centred on the small differences in temperature between the inflow and the lake which controlled the density current effects. Two underwater thermistors were installed in the middle of the Ohau Channel at Mourea Bridge (station 00, Fig. 1), one at 0.2 m below the surface, and one at 0.2 m above the channel bottom (about 2.0 m depth). A third thermistor was used to measure air temperature. The measurements were recorded at 30 min intervals on a Tasman solid state data logger. Temperature data were recorded concurrently in the lake at station 10 (Fig. 1) with an *in situ* Aanderaa thermistor chain, the thermistors set at 5.5, 7.7, 9.9, 12.1, 14.3, 16.5, 18.7, 20.9, 23.1, 25.3 and 28 m below the water surface. The bottom thermistor was approximately 1 m above the lakefloor. The precision of the thermistors at both stations was ± 0.05 °C. In conjunction with the temperature measurements three recording current meters were also moored at station 10, approximately 50 m to the west of the thermistor chain. These were positioned at 5.5 m, 17 m and 28 m and they logged current speed, direction and temperature at 60 min intervals. The lake instruments were retrieved from the lake at 3 monthly intervals and were then downloaded, serviced and redeployed 1 to 2 days later. The calibration of the lake thermistors was checked at each 3 month deployment. The Ohau Channel calibration was checked against measurements with a mercury thermometer every two weeks. The lake and channel measurements were made continuously from July 1985 to August 1986.

A series of 3 dye release experiments was performed to more precisely track the Ohau Channel inflow. Five litres (July, 1985) or 15 litres (morning and afternoon releases in February, 1986) of Rhodamine WT dye (20% concentration) were poured as a line across the Ohau Channel 50 m from its entry point to Lake Rotoiti. The dye was immediately stirred into the water using the propeller of the boat. It was then tracked using a submersible pump connected to a Turner Designs fluorometer that had been calibrated against known concentrations of dye. During the February releases the surface dye distribution was tracked from the air and continuously recorded on video film.

Additional limnological variables were measured at two-weekly intervals at three stations in Lake Rotoiti (10, 62, 80; Fig. 1) over 1984 to 1986 to compare against the Ohau Channel and also to detect east-west gradients. Samples for chlorophyll *a*, phytoplankton enumeration, and nutrients were always taken from 0, 5, 10 and 15 m and mixed together to provide an integrated measure for the euphotic zone. These samples were collected in duplicate for each station, with a second water bottle cast at each depth.

Subsamples for chlorophyll *a* analysis were filtered on to 42.5 mm Whatman GF/C glass fibre filters that were stored frozen and subsequently ground in 90% acetone with a Teflon tissue grinder. The extract was cleared by centrifugation and assayed by spectrofluorometry before and after acidification (Strickland & Parsons, 1968). Subsamples for phytoplankton enumeration were preserved with Lugol's iodine in the field and subsequently filtered on to Millipore 0.45 μm, 25 mm diameter membranes. These were mounted on glass slides, cleared with 25% glutaraldehyde (modification of Dozier & Richerson,

1978) and then examined by light microscopy. For reactive nutrient analysis samples were filtered through lake water-washed GF/C filters and then stored frozen. Dissolved reactive phosphorus (DRP), ammonium and nitrate were subsequently analysed on a Technicon II Autoanalyzer as described in Howard-Williams *et al.* (1983). For particulate *N* and *P* analysis samples were filtered onto acid-washed GF/C filters that were Kjeldahl-digested and then analysed as in Howard-Williams *et al.* (1983).

Results and discussion

Inflow hydrodynamics

The hydrodynamic data set for this study will be analysed in full elsewhere (R.H. Spigel *et al.*, in prep.), but is summarized here as a background to the input calculations. A comparison of Ohau Channel (station 00) and Lake Rotoiti near-surface (5.5 m, station 10) temperatures showed that for prolonged periods during the year there were density differences favouring underflow. The main period of underflow conditions were the winter months from May to September. Detailed temperature profiling over this winter period consistently showed a cold water accumulation in the deep eastern basin, with the isotherms tracing the bathymetry of the lake from west (Ohau Channel) to east (Fig. 3). At this time of year the bottom (28 m) current meter moored at site 10 showed a persistent flow of cold water from west (Ohau channel) to east (Eastern Basin) with maximum velocities approaching 15 cm s^{-1} (Fig. 4). At 17 m depth the current was weaker and intermittent but invariably to the east, while the 5.5 m

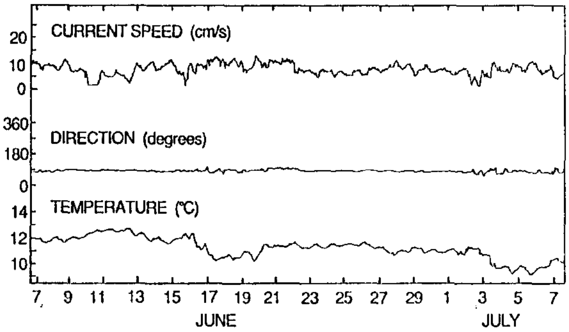

Fig. 4. The bottom current at site 10, June–July, 1986. The instrument was moored at 28 m depth, with measurements every hour.

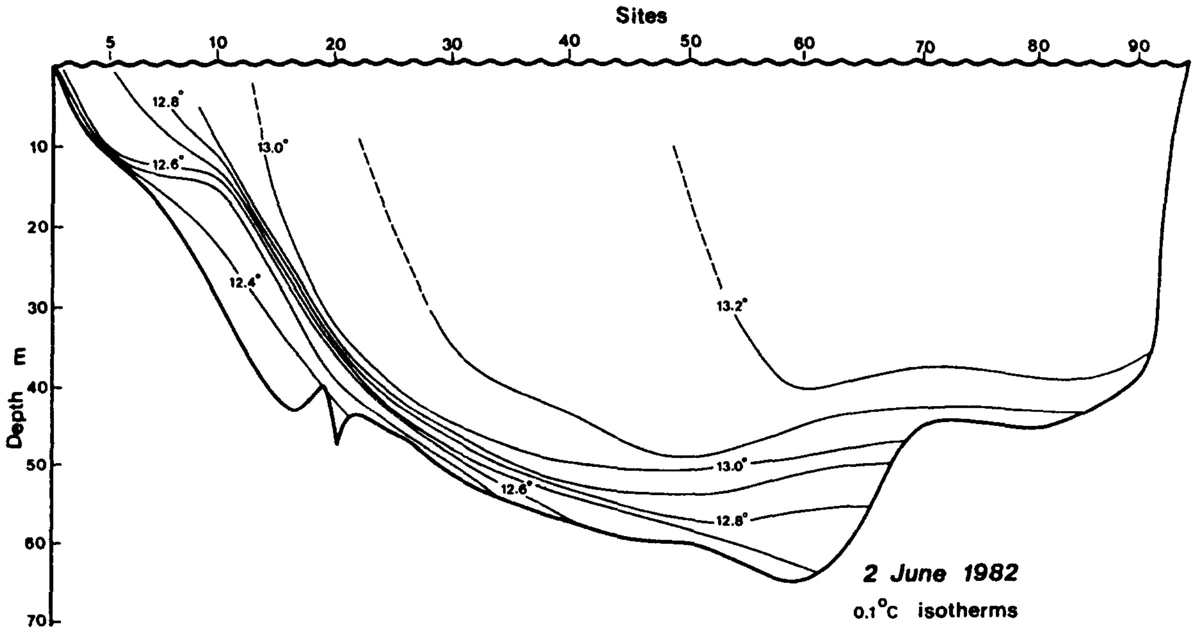

Fig. 3. Temperature section for Lake Rotoiti, 2 June, 1982.

current meter showed a low velocity return flow to the west.

In addition to the seasonal changes in water temperature our measurements in the Ohau Channel consistently revealed large daily fluctuations. Fig. 5 shows typical portions of the data set. The temperatures generally followed a pronounced 24 hour periodicity with an amplitude of 1–3 °C. Minimum temperatures were typically recorded just before sunrise and maximum temperatures occurred in the mid to late afternoon. This diel cycle appeared to be induced by solar heating of the shallow inshore water of Lake Rotorua in the vicinity of the Ohau Channel inflow (M.M. Gibbs & W.F. Vincent, unpublished data).

The series of dye release experiments confirmed that the underflow at site 10 during winter was derived from the Ohau Channel, and that during late summer when the inflow temperature crossed the lakewater temperatures each day underflow occurred during the morning while overflow occurred during the afternoon. In the experiment during overflow conditions the dye cloud from the Ohau Channel stayed near the surface and moved towards the outflow of the lake, the Kaituna River. During interflow conditions the dye cloud moved approximately 200 m into the lake beyond the river mouth and then plunged beneath the surface. It moved along the lake bed, but then lifted off and proceeded eastwards as a discrete inflow plume within the metalimnion towards site 10 and the main body of the lake.

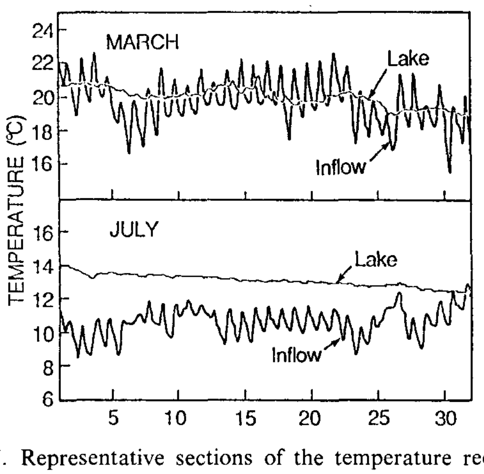

Fig. 5. Representative sections of the temperature record from the Ohau Channel and Lake Rotoiti (5.5 m, site 10).

To quantify the net effect of these seasonal and diel patterns of temperature change we calculated the hours of underflow (and/or interflow) each day and summed these over each month of the year. Our criterion for underflow was a positive instantaneous temperature difference of 0.2 °C or greater between the lake thermistor reading at 5.5 m and the near-surface Ohau Channel thermistor reading. This criterion was selected on the basis that 0.2 °C was the smallest temperature difference consistently associated with an episode of eastward flow in the current meter records. Underflow conditions ranged from virtually the entire month in May, June, July and August to only 20% of December (Table 1). For the 12 month period July 1985 to June 1986 underflow conditions operated for 60.2% of the time, equivalent to a continuous underflow period of 7.25 months.

Hydraulic residence time

The hydraulic residence time (T) for Lake Rotoiti can be defined as:

$$T = V/(rQ + R + I)$$

where V = volume of the lake
= 1135.1×10^6 m^3
Q = discharge of the Ohau Channel
r = fraction of the Ohau discharge penetrating into the Eastern Basin
R = rainfall over the lake
I = input of water to the lake from springs, streams (excluding the Ohau Channel), overland flow and groundwater.

Using the Kaituna River outflow discharge, the Ohau Channel discharge and precipitation data for 1985 the above terms were estimated as Q = 14.8 m^3 s^{-1}, R = 2.5 m^3 s^{-1} and I = 3.2 m^3 s^{-1} (details in Spigel, 1989). For r = 0.6 as above, T = 2.5 years. From the value of

Table 1. Cumulative hours of negative (underflow/interflow) zero and positive (overflow) temperature differences between the Ohau Channel (station 00) and station 10 (5.5 m) in Lake Rotoiti. Data are for July 1985 to June 1986.

Month	Negative	Hours zero	Positive	% underflow
January	361	23.5	359.5	49
February	146	24	502	22
March	449.5	20	274.5	60
April	524.5	18	177.5	73
May	671	16	53	91
June	720	1	0	100
July	731.5	5.5	7	98
August	641.5	19	83.5	86
September	506	22	192	70
October	169.5	28	546.5	23
November	213.5	17.5	489	30
December	147.5	26	570.5	20
Total	5281.5	220.5	3255.0	60

$Q \cdot r/V$ we calculate that 24.6% of the total volume of Lake Rotoiti was replaced by Ohau Channel water over the 12 month period.

Nutrient loading

The Ohau Channel inflow contained high levels of dissolved inorganic nitrogen (DIN) but comparable levels of dissolved reactive phosphorus to those in Lake Rotoiti. For all samples collected between 1984 and 1986 the dissolved nutrients averaged (mean $\pm$ 2 SE from monthly means): 67 $\pm$ 32 mg NO_3-N m^{-3}, 19 $\pm$ 6 mg NH_4-N m^{-3} and 11 $\pm$ 2 mg DRP m^{-3}. Over the same period of time the surface waters of Lake Rotoiti at station 62 averaged 3 mg NO_3-N m^{-3}, 9 mg NH_4-N m^{-3} and 12 mg DRP m^{-3}. As the large standard error estimates indicate there was considerable variation in the nutrient content of the channel inflow between months. The largest variation was in nitrate concentrations which were higher during the winter months (Fig. 6), the period of continuous underflow.

To further evaluate the impact of the Ohau Channel underflow as a source of nitrogen and phosphorus enrichment a nutrient budget was calculated for the Lake Rotoiti basin. For this analysis we calculated the input of nitrate, ammonium, phosphate, particulate-N and particulate-P in the Ohau Channel for the 7 months when underflow penetration operated most frequently (March to September, $r > 0.5$ for each of these months). We calculated the mass flow of water from the channel each month using the 1985 mean flow of 14.8 $m^3 s^{-1}$ multiplied by the proportion of hours of underflow for that month. The monthly average nutrient concentration estimates were derived from 1 to 6 measurements in the Ohau Channel each month. A single sampling of 13 other small spring or stream inputs to the lake for nutrient analysis was performed on 9 Feb 1985. Direct precipitation on the surface of Lake Rotoiti was estimated as 2.5 $m^3 s^{-1}$ for 1985 (see above). The nitrogen and phosphorus content of this precipitation was estimated using the measurements of White & Downes (1977) at Lake Taupo. The total remaining input, i.e. the residual term for 1985 water balance (see above), was 3.2 $m^3 s^{-1}$. Of this inflow 0.1 $m^3 s^{-1}$ was presumed to be from geothermal springs. On 9 February we sampled the 4 major geothermal springs and for these the discharge totalled about 0.07 $m^3 s^{-1}$. Nutrient samples were also obtained on this date for 9 small stream and cold spring inputs to the lake and these analyses were used to estimate the nutrient loading on the lake from the residual inflows.

In this budget analysis the Ohau Channel appeared to contribute one third of the total biologically available nitrogen to Lake Rotoiti and almost two thirds of the phosphorus (Table 2). The residual inflows provided most of the remaining phosphorus, but the hot spring inputs contained very high levels of ammonia (up to 15000 mg N m^{-3}) and contributed almost a quarter of the nitrogen input to the lake.

Although terms in this budget are limited by the paucity of nutrient and hydrological data, the analysis clearly identifies the Ohau Channel underflow as a major input of both N and P to the main basin of Lake Rotoiti. The percentage contribution by underflow in Table 2 is likely to

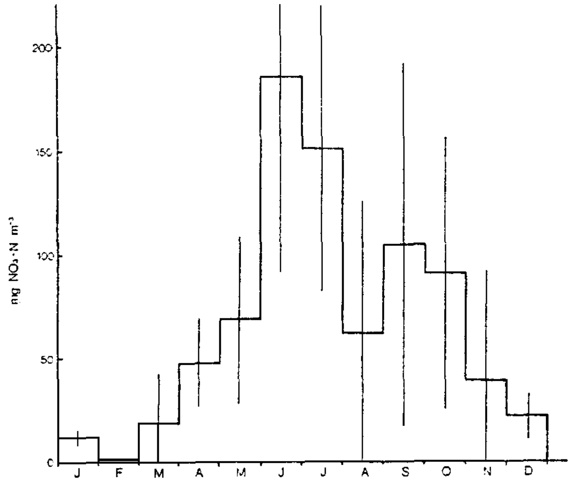

Fig. 6. Nitrate levels in the Ohau Channel. Data have been pooled from 1 to 6 samples per month over 1984 to 1986. Vertical bars represent ±2 standard errors.

under-estimate nutrient loading from the Ohau Channel into the main basin as it does not include the direct injection of nutrients by interflow during the months from October to February, which total 20% of underflow conditions. Nor does it include Lake Rotorua water near the Ohau Channel delta that is entrained during plunging; this may have been especially important during the period of diel cycling between interflow and overflow. This budget may also exaggerate the importance of the geothermal inputs to the total N and P economy of the lake. The hot springs are located at the eastern edge of the western basin and since they are much warmer than the lake water they will flow out into Lake Rotoiti as a buoyant overflow. Given the net movement of surface water of the lake towards the west much of this geothermal input may be carried directly to the Kaituna River, with little opportunity for transfer into the main body of Lake Rotoiti.

Algal enrichment

The Ohau Channel inflow had a potential influence on algal growth in Lake Rotoiti by three mechanisms:

(i) Penetration of nutrients from Lake Rotorua into the Eastern Basin via the Ohau Channel underflow, which were then used for phytoplankton growth throughout the lake.
(ii) Overflow and mixing of nutrients from Lake Rotorua in the vicinity of the Ohau Channel delta, which could then be used for phytoplankton growth in the Western Basin.
(iii) Direct transfer of algal populations that had grown in Lake Rotorua.

Table 2. Nutrient budget estimates for Lake Rotoiti. All values are in tonnes per annum. NH_4 = ammonium; NO_3 = nitrate; PN = particulate nitrogen; DRP = dissolved reactive phosphorus; PP = particulate phosphorus.

Nutrient	Contribution			Precipitation	Total
	Ohau underflow	Residual inflows	Hot springs		
Nitrogen					
NH_4-N	4.9	0.5	41.6	15.8	62.8
NO_3-N	22.1	46.1	<0.1	5.5	73.7
PN	21.3	–	–	–	21.3
DIN + PN	48.3	46.4	41.6	21.3	157.8
% total	31%	29%	26%	14%	100%
Phosphorus					
DRP	2.72	3.05	0.13	0.67	6.57
PP	4.15	–	–	–	4.15
DRP + PP	6.87	3.05	0.13	0.67	10.72
% total	64%	28%	1%	6%	100%

Comparison of nutrient levels along the west-east axis of Lake Rotoiti suggests that the second mechanism was most likely to have operated during summer when there was intermittent interflow and overflow through the 24 hour cycle (Table 3). During the period October to March (inclusive) concentrations of ammonium and nitrate often declined from west to east (site 10 > site 62 > site 80). During the winter months this pattern was lost and nutrient levels were sometimes higher at sites 62 and 80. These elevated concentrations in the main basin reflected the mixing of deep nutrient-rich water into the surface region of the lake during winter, as well as the injection of nutrients from Lake Rotorua into the main basin by the density underflow at that time of year.

The temporal pattern of nutrient distribution was likely to be a dominant factor regulating the changes in algal biomass in the lake both over time and along the W-E axis. Chlorophyll *a* concentrations were highest in the main basin during winter mixing (Fig. 7). This mid year peak in algal biomass (mostly diatoms, Fig. 8) is a feature of many of the Central North Island lakes in which nutrients accumulate in the hypolimnion during summer and then are entrained into the euphotic zone during deep-mixing in autumn and winter (see Vincent *et al.*, 1984). In Lake Rotoiti, however, this winter algal growth may have been amplified by the large input of nitrate, ammonium

Table 3. Nutrient levels in Lake Rotoiti surface waters over 1984 for summer (Jan, Feb, Mar, Oct, Nov, Dec) and winter (April–Sept). Each value is in mg m^{-3} and is the average of monthly means ± 2 SE.

	Summer	Winter
NH_4-N		
Site 10	16.2 ± 2.5	5.0 ± 1.4
Site 80	7.3 ± 1.3	8.5 ± 5.8
NO_3-N		
Site 10	21.7 ± 16.8	5.7 ± 1.6
Site 80	2.9 ± 1.9	7.3 ± 9.3
DRP		
Site 10	10.8 ± 4.4	11.8 ± 5.5
Site 80	9.8 ± 6.7	18.3 ± 8.7

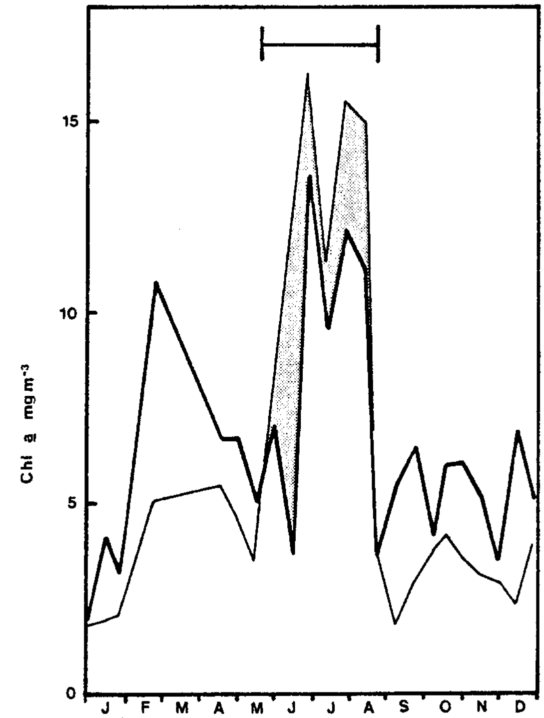

Fig. 7. Seasonal variation in the chlorophyll *a* content of the surface waters of Lake Rotoiti at the western (site 10, thick line) and eastern (site 80, thin line) ends of the lake. The bar indicates the mid-winter period.

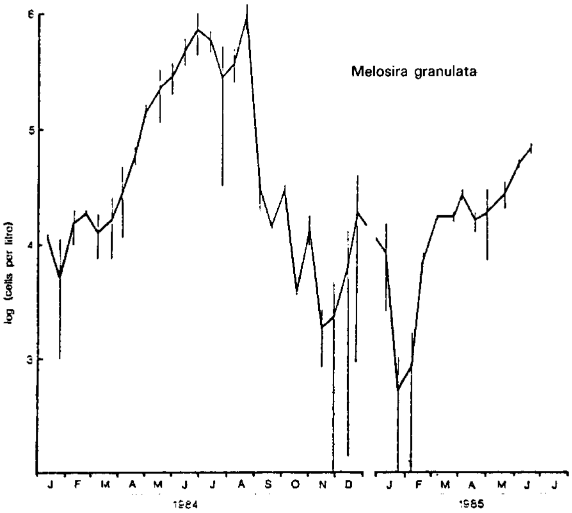

Fig. 8. Winter growth of the diatom *Melosira granulata* which gave rise to the annual maximum of algal biomass in Lake Rotoiti. Each value is the mean for duplicate integrated samples ± 2 S.E. at site 62.

and DRP in the underflow from the Ohau Channel. The winter growth of phytoplankton was abruptly terminated in spring. With the onset of more stable water conditions the large diatoms which dominated the winter phytoplankton community sank out of the euphotic zone (Fig. 8) and provided a major input of BOD to the bottom waters and sediments of the lake. Subsequent to the collapse of the winter bloom the chlorophyll *a* in the Eastern Basin remained at much lower concentrations until the next autumn (Fig. 7). Much higher chlorophyll *a* levels, however, were recorded in the western end of the lake at this time of year. In part this may have reflected the local input of Ohau Channel nutrients by intermittent overflow in summer as well as overflowing geothermal inputs to the western basin. Additionally, however, this elevated summer biomass in the Western Basin may have been derived directly from the algae contained within Ohau Channel water. Chlorophyll *a* levels were examined in the Ohau Channel throughout 1984. High values were frequently recorded in summer, and low values in winter (Fig. 9a), implying that the high algal content of western basin in summer may in part have been the direct result of the input of algae from Lake Rotorua. A comparison of these inputs expressed as a % of the chlorophyll *a* concentrations in the main body of the lake further emphasises their importance in summer but not winter (Fig. 9b).

Cyanobacterial inoculum

Bloom-forming cyanobacteria were often recorded throughout Lake Rotoiti, but concentrations in excess of 10^5 cells l^{-1} occurred for only brief

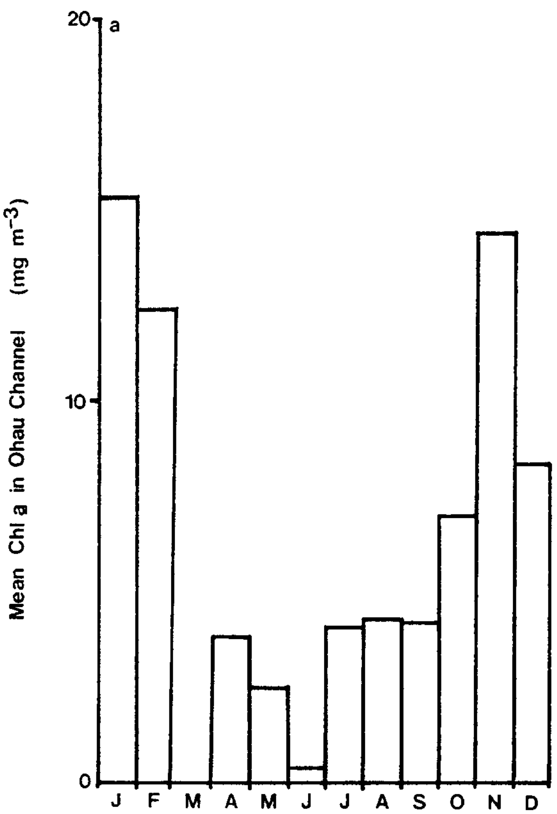

Fig. 9a. Chlorophyll *a* concentration in the Ohau Channel inflow. Each value is the mean of two sampling dates each month in 1984.

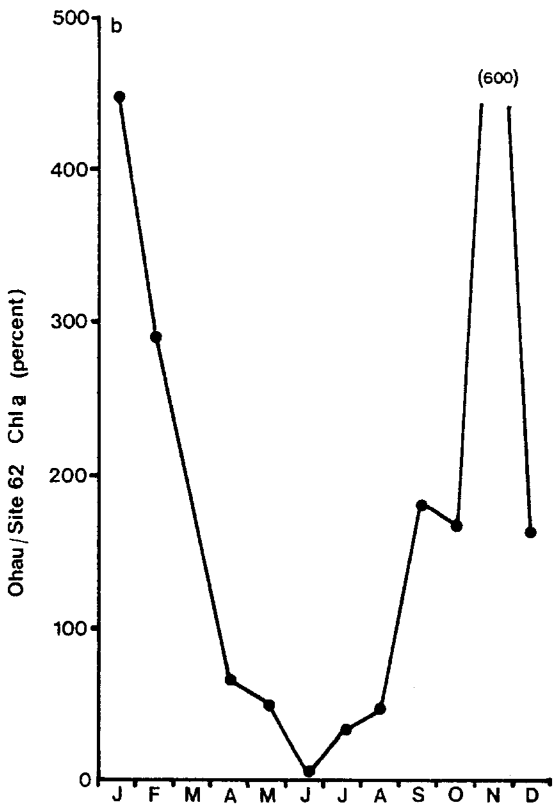

Fig. 9b. Chlorophyll *a* concentration in the Ohau Channel expressed as a percentage of the chlorophyll *a* concentration at site 62 in Lake Rotoiti on the same date.

periods of time each year (Fig. 10). These episodes of blue-green abundance were highly variable from year to year in their population size, species composition and timing, although October–November and March–April were the more common periods for blooms to develop (Fig. 10). The appearance of these phytoplankton in Lake Rotoiti corresponded with elevated populations of the same cyanobacterial species in the Ohau Channel. In March–April 1984 *Anabaena flos-aquae* bloomed on Lake Rotoiti, and was present in high concentration in the Ohau Channel (Fig. 11). In March–April 1985 both *Anabaena flos-aquae* and *Microcystis aeruginosa* were identified in the Ohau Channel, and the same two species were responsible for a blue-green algal bloom on the lake (Fig. 10). In both years the concentrations of the blue-greens were much higher in the channel than in the lake water. If these inputs had been maintained for a month they would have contributed a sizeable inoculum by interflow to the main body of the lake – equivalent to 10% of the *Anabaena* populations in mid April 1984 and 20% of the *Microcystis* populations in mid April 1985 (Fig. 11). The direct inoculation of blue-greens from Lake Rotorua into Lake Rotoiti was also implied by the low concentrations of *Anabaena* and *Microcystis* at the site most distant from the Ohau Channel (site 80, Fig. 11, data for *Anabaena* in 1985 not shown).

Oxygen effects

The presence of algal material in the Ohau Channel implies that it carried a biological oxygen

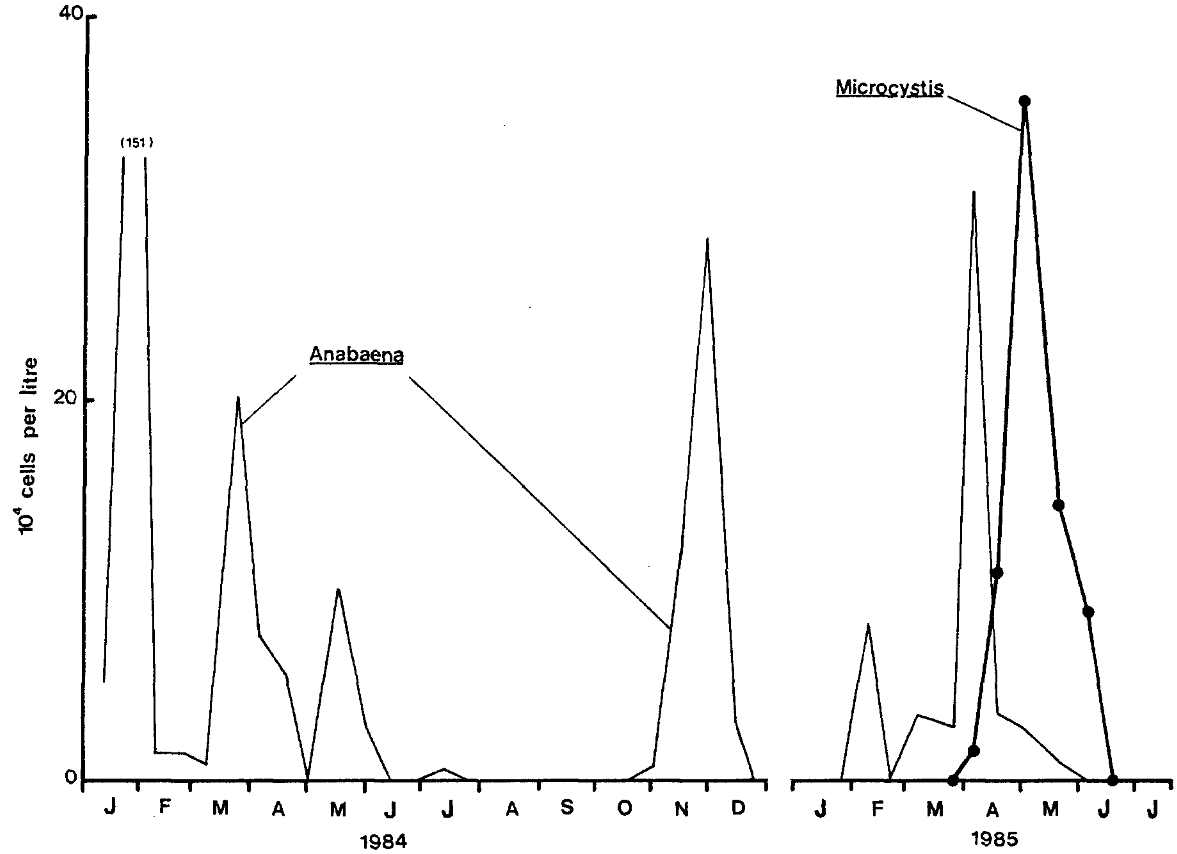

Fig. 10. Growth of cyanobacteria in Lake Rotoiti, site 62. Each value is the mean of duplicate samples integrated from 0, 5, 10 and 15 m depth.

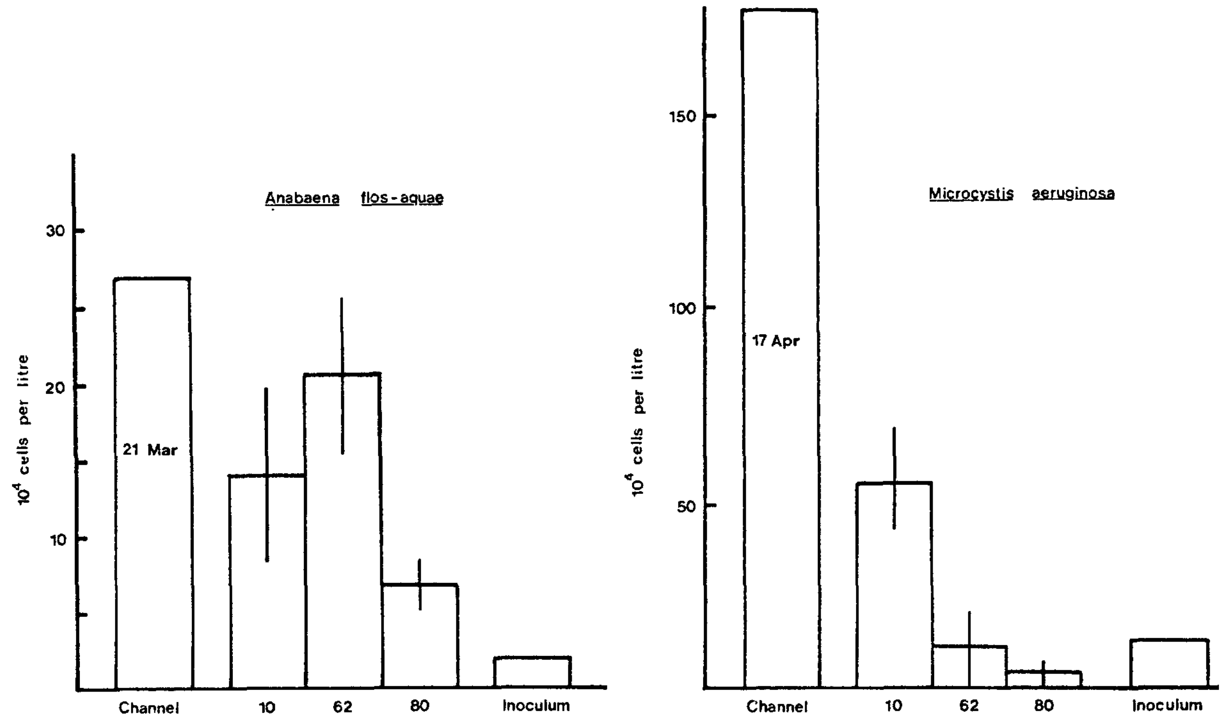

Fig. 11. Concentrations of cyanobacteria at three sites in Lake Rotoiti and in the Ohau Channel. The *Anabaena flos-aquae* data are for April 14, 1984 (lake) or March 21, 1984. The *Microcystis aeruginosa* data are for April 17, 1985 at all sites. The inoculum was calculated as the amount of cyanobacteria entering the lake by interflow over one month divided by the volume of the epilimnion of the lake (0–15 m).

demand (BOD) that would hasten the deoxygenation of the receiving water, Lake Rotoiti. Over the sampling period 1984 to 1985 the highest seston nitrogen and phosphorus values recorded in the Ohau Channel water were 261 mg N m^{-3} and 39 mg P m^{-3} on Nov 7, 1985. Assuming that all of this material was in the form of algal cells and that the stoichiometry of decomposition followed the Redfield equation (Redfield *et al.*, 1963) then the ratio of oxygen consumed to particulate organic nitrogen and particulate organic phosphorus would be 19.2 and 142 by weight. The November 7 particulate values translate into a BOD of 5.0 and 5.5 g O_2 m^{-3}. This range is at best an approximation because algal particulates in the Central North Island are often enriched in P (which will overestimate the BOD) and low in N (which will underestimate BOD). However, these values are well below the saturation level of oxygen that would be carried in by the Ohau Channel which varied from 11.7 g O_2 m^{-3} in August (7 °C) to 8.4 g m^{-3} in February (22 °C).

Typically the Ohau Channel contained much lower levels of particulates than in the November sampling. During the main period of underflow (March–September) the PN and PP averaged 96 mg m^{-3} and 18 mg m^{-3}. These translate into a total BOD of 1.8–2.6 g O_2 m^{-3}, up to about 25% of the oxygen dissolved in the inflowing water at that time of year. By entraining water as it plunged the Ohau Channel brought much larger quantities of oxygen into the main basin of the lake. Laboratory studies of a physical model of this system gave initial dilution factors of 3 to 6 (Leong, 1988) which compared favourably with field measurements based on temperature or dye measurements (R.H. Spigel, unpublished). The entrained lakewater also contained algae and had an associated BOD, but like the inflow itself this BOD would potentially consume less than 25%

of the dissolved oxygen. Thus the Ohau Channel provided much more oxygen to the mid-level and bottom waters of Lake Rotoiti than that required to decompose its algal particulate load. At the 1985 discharge average of $14.8\ m^3\ s^{-1}$, 50% interflow penetration, 25% BOD, a measured entrainment factor of 3.5 and a dissolved oxygen content of $9\ g\ m^{-3}$ the Ohau Channel input would have delivered 15.1 tonnes of oxygen per day, and recharged the metalimnion (15–30 m) to $1.4\ g\ m^{-3}$ each month. Part of this oxygen may have also been transported downward into the bottom water by mixing aided by the weak, geothermally driven circulation that operates in the hypolimnion of this lake (Priscu *et al.*, 1986).

The seasonal timing of oxygenation by the interflow mechanism may be especially critical for the internal nutrient dynamics of Lake Rotoiti. With the onset of stratification particulate nitrogen material entering the hypolimnion and sediments is decomposed to ammonium and then subsequently oxidised to nitrate. Later in the stratified period the hypolimnion becomes completely anoxic and the nitrate-nitrogen is lost from the lake by denitrification (Downes, 1987). With increasing eutrophication the period of anoxia has begun earlier during stratification (Vincent *et al.*, 1984). Without the injection of interflowing oxygen much less ammonium would be oxidised to nitrate and denitrification losses would be reduced with a corresponding increase in the internal nitrogen load during winter circulation. Application of a simulation model to Lake Rotoiti has indicated that without the penetrating underflow the hypolimnion would become anoxic 75 days earlier than observed in the present study (Gibbs, 1986) which would potentially eliminate the period of nitrification required to generate the NO_3 substrate for hypolimnetic denitrification. By delaying the onset of anoxia the interflow oxygenation would also have had other beneficial effects on the lake water quality, such as reducing the period of H_2S and DRP accumulation in the hypolimnion.

Conclusions

The main river entering Lake Rotoiti had both positive and negative influences on the lake that were largely controlled by the pattern of density current flow. When the Ohau Channel water was warmer than the lake surface the inflow was short-circuited directly to the outlet. At other times of year or times of day when the Ohau Channel water was cooler than Lake Rotoiti it entered the lake as a plunging inflow which then penetrated 6–8 km into the main basin as an interflow or underflow. This inflowing current brought with it a substantial load of nutrients and algae, but it also increased the hydraulic flushing and oxygenation of the lake. There has been pressure exerted on the lake management authority by residents and environmental groups to divert the Ohau Channel directly to the Kaituna River outlet and thereby eliminate the enrichment effects of this inflow. The magnitude of the flushing and oxygenation effects reported here showed that such a course of action would have deleterious short-term effects, and would only be advised if the Ohau Channel water from Lake Rotorua continued to deteriorate substantially.

Understanding the eutrophication process in Lake Rotoiti has required that the lake and inflowing river be considered component parts of a tightly coupled system. In this system, and probably in other lakes with river inflows, the nature of that coupling (underflow/interflow/overflow) changes at timescales ranging from seasonal to time-of-day, and has a major influence on the nutrient distribution and associated biological properties of the lake.

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