Lake Rotoiti – Ohau Channel: assessment of effects of engineering options on water quality

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Lake Rotoiti – Ohau Channel: assessment of effects of engineering options on water quality

Max Gibbs
Ian Hawes
Scott Stephens

Prepared for

Environment Bay of Plenty
Rotorua District Council

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National Institute of Water & Atmospheric Research Ltd
Gate 10, Silverdale Road, Hamilton
P O Box 11115, Hamilton, New Zealand
Phone +64-7-856 7026, Fax +64-7-856 0151
www.niwa.co.nz

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Reviewed by:	*Approved for release by:*
Dr David Hamilton	Dr David Roper

Formatting checked

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Executive Summary

This report was commissioned by Environment Bay of Plenty and Rotorua District Council to collate current knowledge on water quality and hydrodynamics of the Lake Rotorua – Lake Rotoiti system with a view to identifying impacts of three proposed engineering solutions, modelling requirements, and gaps in the current knowledge.

The information on which this report is based is limited. Detailed information on the limnology of Lake Rotoiti was based on intensive studies undertaken by the DSIR in 1980-81, supplemented with less intensive studies in 2001-03, and limited monitoring data for other years. Details of hydraulic connections between the lakes are based on a single year of study in 1985-86 and processes at the margins of Lake Rotorua that affect the quality of the water entering Lake Rotoiti have been investigated only in 1990. The information is therefore not recent, but is also restricted to a single or few years, thus precluding an understanding of inter-annual variations. Conclusions drawn therefore tend to be generalities rather than provide specific outcomes.

The Ohau Channel is the single largest source of water and nutrients to Lake Rotoiti. The nature of the connection between the Ohau Channel and Lake Rotoiti is complex, and depends on the temperature differential between lake and channel. In summer, the inflow is warmer and less dense than the lake, floats on the surface as a relatively discrete **overflow**, and mostly short-circuits directly to the Kaituna River. In winter and spring, the inflow is colder and denser than the lake, and the Ohau Channel water flows eastwards as an **underflow** along the bottom of the lake or may insert at some intermediate depth. In autumn, the Ohau Channel water is denser than the surface lake waters, but less dense than the deep lake water, and forms an **interflow** within the temperature gradient that separates surface and deep waters. Overall in 1985-86 40% of flow was estimated to be diverted down the Kaituna River.

The underflow has a number of effects on Lake Rotoiti. It assists with the oxygenation of the bottom of Lake Rotoiti during winter and spring, and may occasionally add oxygen to the deep waters in winter. The quantitative effect of this oxygenation appears to vary from year to year; the qualitative effect is to retard the onset of anoxia (no oxygen) in the deep part of the lake. The underflow also delivers biochemical oxygen demand (BOD) and nutrients to the eastern basin of Lake Rotoiti. Finally the underflow drives a return flow in the surface of the lake that assists with flushing water out of the eastern basin of Lake Rotoiti. Current data are inadequate to quantify most of these effects an detailed hydrodynamic modelling, coupled with a field campaign to obtain suitable verification data, are required to quantify these effects.

Even with the oxygen supplied by the underflow, the bottom waters of Lake Rotoiti become anoxic each year. Accompanying this is an accumulation of inorganic nutrients, both N and P. P accumulates steadily over the stratification period, while N undergoes a sequence of changes. First N accumulates as NH_4-N, then this is nitrified to NO_3-N by microbial activity, until oxygen runs out. Finally, after the onset of anoxia, denitrification dominates and most of the accumulated NO_3-N is lost as N_2 or N_2O gas. This process effectively removes N from the lake, perhaps by as much as 100 t y^{-1}, and ensures that accumulated N at the end of stratification is primarily as NH_4-N. At the onset of winter mixing, the accumulated DRP and NH_4-N are mixed through the water column and once again become available for plant growth.

The interflow is likely to be most prevalent during late summer. At this time it is likely to have an adverse effect on the eastern basin, through advection of nutrients and an algal inoculum from Lake Rotorua to metalimnion around the base of the photic zone, at the same time displacing low-nutrient surface water via the Kaituna outflow. At the same time the circulation induced by the interflow will be flushing rapidly the western basin with water from the east. The interflow will be most effective in promoting algal proliferation in he eastern basin if it coincides with a period of high nutrient concentrations in Lake Rotorua (usually at the end of a stratification/mixing cycle).

A diversion structure to ensure that all of the Ohau Channel flow is diverted to the Kaituna River will eliminate both underflow and interflow. The beneficial effects of this will be a net reduction of nutrient and algal flux to the eastern basin of Lake Rotoiti; total diversion would reduce the annual N and P loads by 181 tonnes and 25 tonnes, or 73% and 76%, respectively. The primary adverse effects will be reductions in flushing rate and oxygen delivery. The consequences of reduced flushing during underflow and interflow are likely to be complex and require further modelling to quantify. The consequences of flushing on nutrients depends on the relative concentrations of underflow and return flow water. Based on comparisons of nutrients between Ohau Channel and Rotoiti surface water, in winter, flushing is likely to have little net effect on TN or TP, whereas in late summer flushing by the interflow will be a net input of both TN and TP to the surface of eastern Lake Rotoiti.

An optimal diversion strategy might be to divert only during the interflow period, as this appears to be the time when maximum adverse impact might be expected, because at this time nutrients and algal inocula are delivered to the upper lake waters.

Oxygenation of the deep water of Lake Rotoiti has also been suggested as a remediation option. This would have similar effects with or without diversion. Maintenance of oxygen at 5 g m^{-3} in deep water would favour the accumulation of NO_3-N over NH_4-N and likely reduce the loss of N through denitrification, but there is uncertainty about the effects on dissolved reactive phosphorus (DRP). It would much reduce the N loss through denitrification. The result at the end of the stratified period is likely to be mixing of high concentration NO_3-N and DRP bottom waters with surface waters, which would potentially fuel a winter/spring algal (probably diatom-dominated) proliferation. A combination of oxygenation and diversion of interflows is likely to have the most beneficial effects on the lake.

The quality of the water entering the Ohau Channel is determined by the background quality of Lake Rotorua water, suspension of particulate materials in shallow water, and long-shore advection of water from nearby tributaries. Physically re-modelling of the entrance to the Ohau Channel, in a way that will minimise the entrainment of suspended sediments, can improve the quality of the water by reducing particulate N and P concentrations. The suggestion of constructing 200 m long groynes to effectively move the Ohau Channel inlet offshore, out of the sediment suspension zone, appears to be a good option. Coarse estimates suggest sediment transport through the Ohau Channel could be reduced by as much as 10,000 tonnes per year, or 85%, based on limited 1990 data. The primary adverse effect will be the need to clear sediment accumulation from behind the groynes. The effect cannot be assessed quantitatively at this stage; detailed experimental work and modelling of the resuspension process is first required.

Engineering options that reduce the load of nutrients to Lake Rotoiti can be expected to show results of medium time frames. Halving of the nutrient load may be achieved, and while internal load may take time to reduce, as was observed immediately after the removal sewage discharge from Lake Rotorua, there should be some immediate benefit. Combining the diversion with oxygenation has the added advantage of ensuring high NO_3-N supply, and reducing the likelihood of cyanbacterial blooms, rather increasing the potential for spring stripping of nutrients from the epilimnion via diatoms.

Okawa Bay is a small, shallow embayment isolated from the western basin of Lake Rotoiti. Water quality problems have occurred there for many years. Diversion of the Ohau Channel through Okawa Bay would drastically increase the flushing of water from the bay, and the water would essentially become Lake Rotorua water. On average, water would spend just over 1 day in Okawa Bay before exiting to the western basin. The consequences of any such diversion on the subsequent distribution of water exiting Okawa Bay (i.e. underflow/interflow) would depend on exact conformation of the diversion and any modifications to the bay (i.e., additional exit point), and would require careful modelling, supported by field data verification.

1 INTRODUCTION

During the 1980s a considerable amount of research was undertaken by the Taupo Research Laboratory (DSIR) into the accelerated eutrophication of Lake Rotoiti. There was clear evidence of deteriorating water quality in the period 1960-1980. It was identified that the lake was strongly affected by the poor condition of Lake Rotorua in that it received a high proportion of its nutrient load from Rotorua via the Ohau Channel. Research showed that the nature of the Rotorua-Rotoiti connection via the Ohau Channel was complex; while it contributes to the decline of Rotoiti through delivery of nutrients and cyanobacteria, it also has a number of beneficial effects. At the time it was hoped that remedial actions for Rotorua, including sewage diversion and riparian retirement, would benefit Rotoiti. In practice the quality of Lake Rotorua has improved only slightly since then and, until 2002-03, Lake Rotoiti was showing a similar trend. There is some evidence of an increased frequency and severity of blue-green algal blooms in recent years and in 2002-03 there was a prolonged cyanobacterial bloom in Lake Rotoiti which seriously impacted on lake values.

Long-term engineering options currently under discussion seek to modify the connection between the two lakes, in an effort to isolate the eutrophication of Lake Rotorua from Rotoiti. Three engineering options at the Ohau Channel that have been proposed by Environment Bay of Plenty to restore the water quality of Lake Rotoiti (Environment Bay of Plenty File note 3365 LO4) are as follows:

1. "*Channel extension into Lake Rotorua littoral zone – removal of BOD and sediment/nutrient loading. Capture sediment at the Ohau Channel Rotorua by gates or other device at the throat of the structure is also a likely component of the component*."
2. "*Permanent or intermittent diversion structure – diversion of Ohau Channel underflow at Rotoiti lake end, to Kaituna River*."
3. "*Okawa Bay: a) diversion of Ohau Channel under a range of flows and/or flow periods to Okawa Bay; b) connect to western basin (includes a component of a)?); c) the effect of diversion to Okawa Bay on temperature of water*."

"*Engineering solutions to take into account the role of lake oxygenation as a possible remedial measure*."

NIWA was commissioned by Environment Bay of Plenty and Rotorua District Council to assess the likely effects of these engineering options on the water quality of

Lake Rotoiti. Specifically NIWA was asked "*to collate current knowledge on water quality and hydrodynamics of the Lake Rotorua – Lake Rotoiti system with a view to identifying impacts of three proposed engineering solutions, modelling requirements, and gaps in the current knowledge.*" Additional points to be considered were:

- Time frames – short, intermediate, long term.
- Oxygenation – Rotorua and Rotoiti possibilities – impacts?
- Need to examine nutrient balance for Rotorua – Rotoiti combined
- Other modelling to be examined, question of level of modelling that can be achieved in short time-frame.

The first part of this report summarises the state of understanding of the Rotoiti-Rotorua connection, and includes indications of possible change in this system, since the initial research (1980s) was undertaken, and possible reasons underlying recent blooms.

The second part of this report provides an overview of the likely impact of the three engineering options on ecological processes in Lake Rotoiti. Although each of these options is considered separately, combinations of these three engineering options are possible. The effect of diversion of part or all of the Ohau Channel flow to Okawa Bay on temperature of water entering the western basin and consequently, the likely effect on underflow condition, is considered in general terms based on previous modelling.

Gaps in the current understanding have been identified along with modelling requirements and the need to collect validation data, as discussed with Environment Bay of Plenty at a meeting in Rotorua, 21 November 2003 (Environment BoP file reference RARAP 3365 L04; 24 November 2003).

In general, a 'weight-of-evidence' approach is used to assess the likely effects of the proposed engineering options, drawing from both past and present research and monitoring studies, and personal experience with these and other lakes.

2 OVERVIEW OF CURRENT KNOWLEDGE

The basic concepts of a hydraulic coupling between Lake Rotorua and Lake Rotoiti and the intrusion of Lake Rotorua water into the eastern end of Lake Rotoiti as an underflow, are generally accepted. However, the hydrodynamics of this coupling are extremely complex and it is of fundamental importance to understand the existing hydrology before imposing a new hydraulic regime as an engineering option. Consequently, the following hydrology section (2.1) is presented in detail.

2.1 Hydrology

Lake Rotoiti, North Island, lies in the Central Volcanic Plateau of the North Island of New Zealand and is one of the deepest Rotorua Lakes. The lake is a drowned river valley formed 11,850-20,000 years ago when lava flows dammed the drainage system through the Okataina caldera (Pickrill et al. 1992). The morphological information on Lake Rotoiti, separated into the three main basins, is presented in Table 1.

Table 1 Lake morphological data:

Eastern Basin		
	Surface Area	29.58 km^2
	Area below 30 m	20.38 km^2
	Volume	1.094×10^9 m3
	Volume below 30m	0.356×10^9 m^3
	Maximum depth [vent]	120 m
	Maximum basin depth	90 m
	Mean depth [whole lake]	33 m
	Thermal stratification depth	22-32 m
	Thermal stratification period	September – June
Western Basin		
	Surface Area	4.35 km^2
	Volume	16.5×10^6 m^3
	Maximum depth	35 m
Okawa Bay		
	Surface area	0.45 km^2
	Volume	1.8×10^6 m^3
	Maximum depth	6.5 m
	Mean depth	4.0 m

The lake receives water from a number of small cold streams from the eastern catchment and several hot geothermal streams from the western catchment. Lake Rotoiti also has a large hydrothermal field and a geothermal vent in the bottom of the eastern basin, west of Gisborne Point, which potentially contributes geothermal fluid. This vent is surrounded by a large [area covers several km^2] gas bubble field with numerous columns of hydrothermal gas bubbles rising to the surface (Pickrill et al. 1992; Gibbs 1992). Initial estimates of the heat input at c.140 MW (Calhaem 1973), were subsequently corrected to c.10-20 MW (Priscu et al. 1986) to allow for the heat pumping effect of sequential stratification and mixing events during spring, before thermal stratification stabilised. About 10 MW of that heat is thought to be a conductive heat flux through the lake bed in the centre of the eastern basin, as estimated by Calhaem (1973). The remaining 10 MW may be associated with other lake bed geothermal fields such as that found by Pickrill et al. (1992), who describe a geothermal influence in the bed of Lake Rotoiti west of Tumoana Point, where the lake "bed is broken by occasional pockmarks and holes, probably vents for hydrothermal fluids and gases". This area also has a gas field (M. Gibbs, NIWA, pers. obs.). The lack of any increase in concentration of geothermal salts (e.g. chloride and sulphate) in the hypolimnion of Lake Rotoiti through the stratified period indicates minimal geothermal fluid inputs through the bed of the lake, but does not preclude heated groundwater or steam, which potentially contain high concentrations of ammoniacal-nitrogen (NH_4-N).

Cold stream inputs to the lake total 3.4 $m^3\ s^{-1}$ and there is likely to be a groundwater component of c. 2 $m^3\ s^{-1}$ (e.g. Freestone 1982; Spigel 1989) entering the lake from the eastern catchment. This gives a net discharge of c. 5.4 $m^3\ s^{-1}$ from the eastern end of the lake. Several geothermal springs in the catchment discharge into Lake Rotoiti along the southern shores as hot streams (>45ºC) between Okawa Bay and the Manupirua Hot springs east of Tumoana Point. These have relatively low flows (0.005-0.010 $m^3\ s^{-1}$) but often at very high NH_4-N and dissolved reactive phosphorus (DRP) concentrations (Table 2). Because of the buoyancy of these hot water inputs and the net westwards flow from the eastern basin of the lake, nutrients from these sources are more likely to affect the water quality of the western than the eastern basin.

Table 2 Nutrient concentrations (mg m^{-3}), estimated flow 'Q' (L s^{-1}), and temperature ('H' = hot; 'C' = cold) in surface streams entering Lake Rotoiti, based on Taupo Research Laboratory, DSIR, February 1985 data. (Not all streams sampled).

Stream	Q	Temp	DRP	DOP	NO_3-N	NH_4-N	DON
Te Arero Bay (west)	5	C	17.8	6.2	2.2	3.2	205
Te Arero Bay (north)	30	C	110	14.3	1715	0.4	34.6
Hinihopu pipe	5	C	2.1	6.8	320	17.8	265
Hinihopu (south)	15	C	31.2	18.4	135	7.4	285
Waiti	1500	C	54.2	9.8	165	2.6	40.8
Rauto Bay	50	C	29.6	10.0	130	1.2	61.5
Haupara Bay	20	C	15.1	8.3	665	5.1	160
Moose Lodge	10	C	19.5	10.1	600	2.3	195
Haupara	20	C	1.4	3.0	520	3.6	90
Manupirua Springs	5	H	53.4	4.8	<0.5	2875	13
Wharetata A	10	H	33.6	2.7	1.1	11370	121
Wharetata B	20	H	36.4	3.6	46.5	26630	420
Parengarenga	30	H	96	<1	34.8	11860	5
Ohau Channel	18000	C	10.6	9.3	1.5	205	225

The main inflow to Lake Rotoiti is the outlet river from Lake Rotorua via the Ohau Channel [present mean flow = 15 m^3 s^{-1}], which enters the western basin of Lake Rotoiti 2.6 km from the outlet, the Kaituna River. Combined with the stream and groundwater inflow, the average discharge from Lake Rotoiti to the Kaituna River outlet is about 20.4 m^3 s^{-1}. Early studies of Lake Rotoiti (e.g. Fish 1969, 1971) suggested that the Ohau Channel inflow did not influence the lake beyond the western basin but short-circuited to the Kaituna River outlet (Fig. 1). However, subsequent studies in the 1980s determined that, while the Ohau Channel flow did short circuit to the Kaituna River outlet in summer, in winter the Ohau Channel inflow formed a thermally-induced density current or underflow which flowed along the lake bed in the western basin down the old river channel towards the eastern end of the lake (Vincent et al. 1986; and related papers).

High resolution seismic reflection profiles (7 kHz) confirmed that the drowned river system channelled inflowing water into the eastern basin of Lake Rotoiti, scouring and depositing sediments and maintaining an active sublacustrine channel in the former river valley (Pickrill et al. 1992).

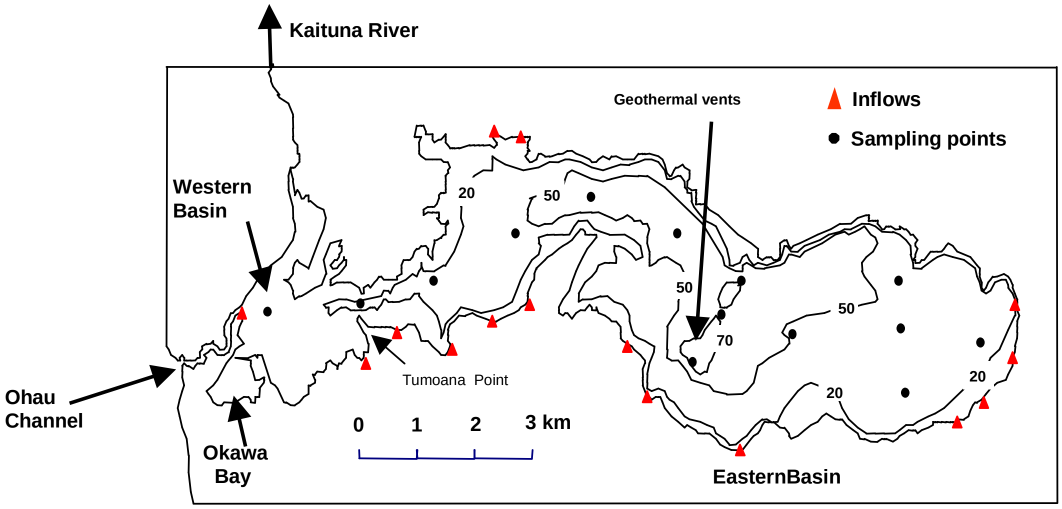


Fig. 1 Schematic map of Lake Rotoiti showing 20, 50, and 70 m depth contours and the positions of the various inflows and sampling points, and the geothermal vent.

2.1.1 Density currents

Density currents are a key component of the hydrology of Lake Rotoiti. The condition is caused by a thermal difference between the Ohau Channel water draining from Lake Rotorua and the water in the western basin of Lake Rotoiti. This is due to the tendency for Lake Rotorua to cool more than Lake Rotoiti in winter (Fish, 1975) but mostly due to the warming or cooling of Lake Rotorua water as it crosses the 600 m wide shallow shelf [<1 m deep] before entering the Ohau Channel. Because that shelf is so shallow, the temperature of this water changes much faster than the temperature of the water in the western basin of Lake Rotoiti. All water passing through the Ohau Channel must cross this shallow shelf and thus experiences heating during the day and cooling at night. When the Ohau channel water is warmer than the western basin, it is less dense [more buoyant] and floats on the top of the western basin water [**overflow** condition]. When the Ohau Channel water is colder than the western basin of Lake Rotoiti, it is more dense [less buoyant] and sinks to the bottom of the western basin [**underflow** or **interflow** condition].

During the year, the temperature-induced density differences between the two lakes shift from continuous underflow condition in winter to continuous overflow in summer. Based on the difference between temperatures in the Ohau Channel measured at Mourea Bridge and in the western basin measured at a depth of 5 m in 1985-86 (Fig. 2), it was estimated that overflow occurred for 40% of the year.

There have been no subsequent estimates of the overflow period and data do not exist with which to make such estimates.

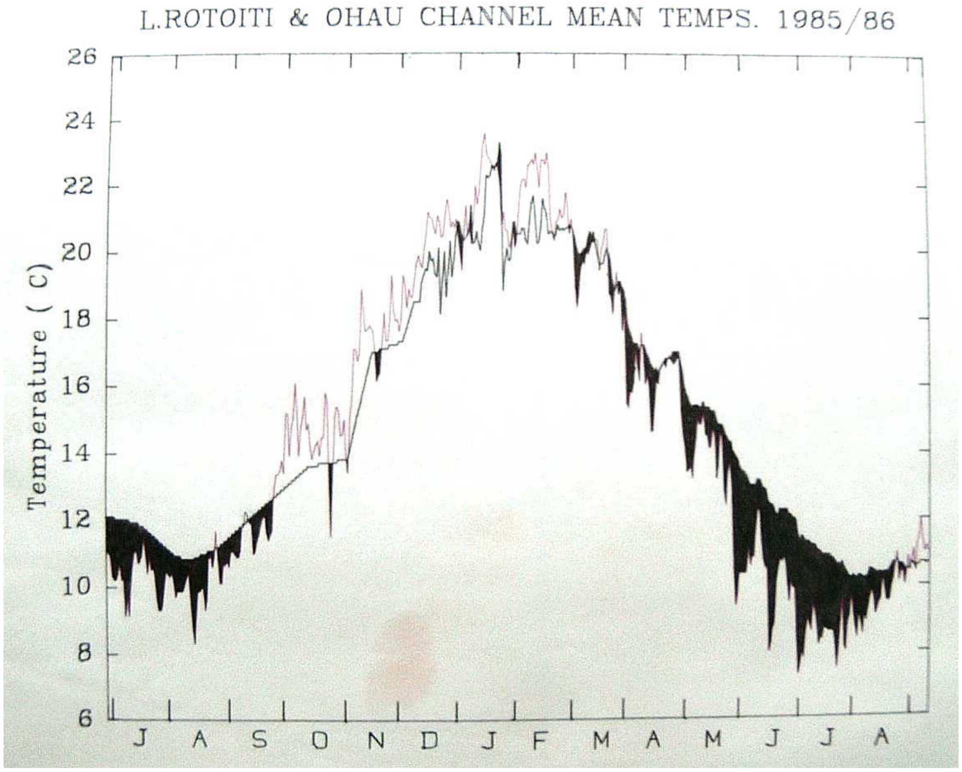


Fig. 2 Temperature (6 hr means) in the Ohau Channel (red line) and Lake Rotoiti at 5 m (black line), measured in 1985-86. Shading between these lines indicates periods of underflow or interflow. Intermittent interflow periods can occur during summer if the night temperatures are very cold.

2.1.2 Entrainment and mixing

Lake Rotorua water enters the western basin of Lake Rotoiti as a jet and because of this, the water is entrained from the western basin of the lake into a much larger density current (Fig. 3). The amount of entrainment can be calculated (Jirka & Watanabe 1980) using the temperature-induced density difference between the Ohau Channel and western basin waters, the slope of the lake bed at the Ohau Channel delta, and the velocity of the water as it enters the western basin (>0.2 m s^{-1}). Theoretical entrainment factors are about 5. From a dye tracer study in 1986, the density current moving into the eastern basin was estimated to be about 70 m^3 s^{-1} (Spigel 1989), or a factor of 4.5.5.

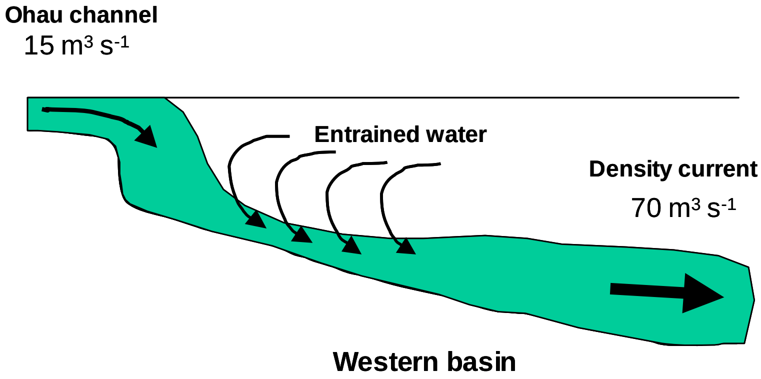


Fig. 3 Stylised flow diagram of entrainment of western basin water into the Ohau Channel discharge into Lake Rotoiti.

2.1.3 Underflow, interflow, and overflow

When conditions exist that allow water to form a plunging density current, i.e., the Ohau Channel temperature is less than the temperature at a depth of 5 m in the western basin (Fig. 2), the resultant current sinks to the lake bed in the western basin as an **underflow** (Fig. 4A). This underflow may be dense enough to sink right to the bottom of the eastern basin. However, the density current, particularly after entrainment of western basin water may be colder than the epilimnion but not the hypolimnion in the eastern basin of Lake Rotoiti. Since the downwards force of gravity only applies when the density current is heavier than the surrounding water, when the density current reaches a depth where its density matches that of the lake water, the current lifts off the lake bed and inserts at that depth as an **interflow** within the metalimnion (Fig. 4B). The density current then propagates across the lake at that depth as an intrusion layer, driven by the hydraulic inertia of the density current itself.

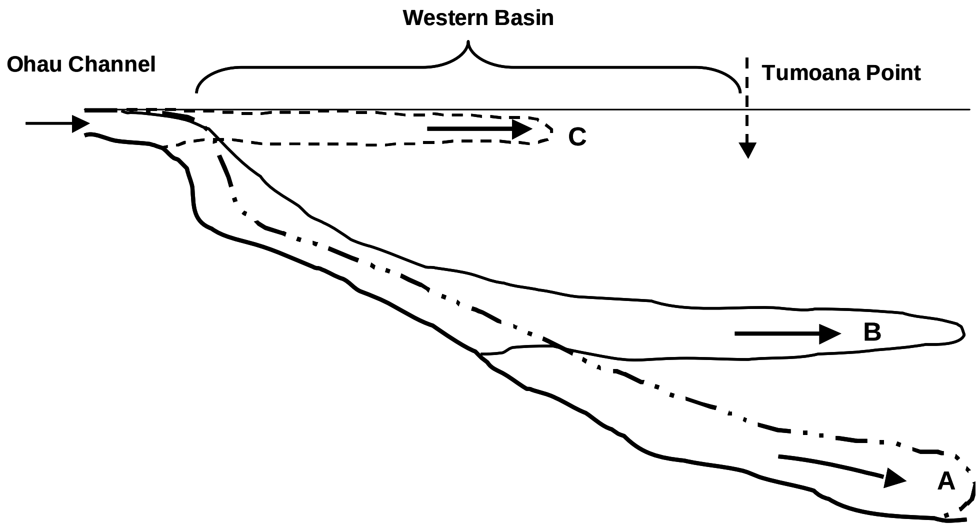


Fig. 4 Stylised flow diagram of **A**) underflow, **B**) interflow, and **C**) overflow. Interflow begins as an underflow in the western basin but lifts off the lake bed at a depth of equal temperature-induced density before leaving the western basin through the narrows at Tumoana Point. The interflow can be at any depth between underflow and overflow.

Bottom temperatures in Lake Rotoiti tend to be close to 11°C during the fully mixed period in winter. Once thermal stratification is set up in Lake Rotoiti (approximately in October), bottom temperatures begin slowly rising, reaching 13°C by late summer stratification. Figure 2 therefore suggests that the inflow may be cold enough to underflow to the lake bottom in June-August (perhaps extending into September), but that for most of the rest of the year an interflow into the metalimnion or an overflow is most likely. There is a period in spring and autumn when interflow and overflow may occur on a daily basis, with colder night temperatures inducing underflow in the morning, but warmer days inducing overflow in the afternoon.

Winter water column temperature structure in 1981/82), contoured from transects of temperature profile data taken on the same day (Gibbs 1988), demonstrate how the cold density current can reach the centre of the eastern basin, flowing along the bed of the lake (Fig. 5A). When the lake was stratified, and the inflow was cooler than surface waters in April 1982, the contoured data shows how the density current intruded as an interflow within the metalimnion (Fig. 5B), causing it to thicken.

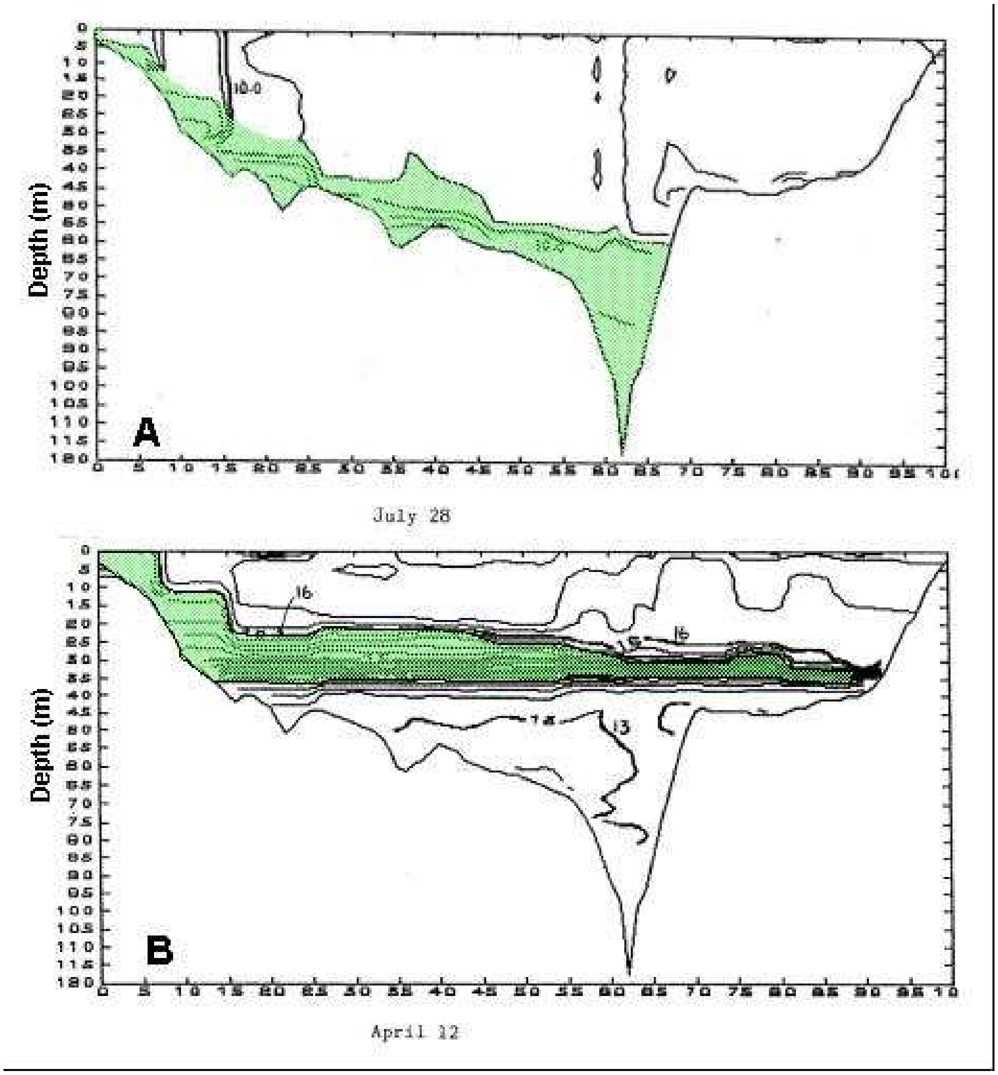


Fig. 5 **A**) Contoured temperature data (28 July 1982) showing a cold layer (highlighted) on the bed of Lake Rotoiti attributable to underflow. **B**) Contoured temperature data (12 April 1982) showing the intrusion of the density current (highlighted) into the thermocline as an interflow. X-axis about 700 m per division. Tumoana Point is at position 10.

When the Ohau Channel water temperature is warmer than the 5 m depth temperature of the western basin of Lake Rotoiti, the Lake Rotorua water is likely to float on the surface as a buoyant overflow (Fig. 4C). Under calm and easterly wind conditions, this overflow is most likely to short-circuit to the Kaituna River outlet. However, coupled with a moderate westerly wind, it is possible that the overflow could be driven into the eastern basin of Lake Rotoiti as a surface flow. An example of this was seen in the contoured temperature data in spring 1981 (Fig. 6).

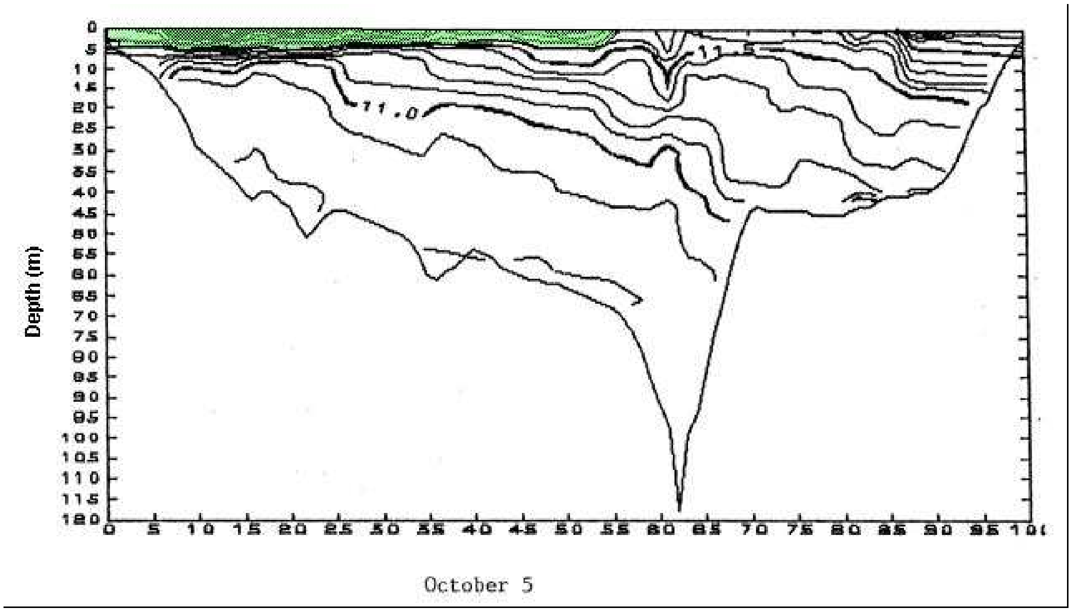


Fig. 6 Contoured temperature data (5 October 1981) showing an apparent warm surface layer (highlighted) extending from the western basin into the eastern basin of Lake Rotoiti. X-axis about 700 m per division. Tumoana Point is at position 10.

2.1.3. Ohau Channel temperature

The 1985-86 temperature data set shows that, during summer, there are daily temperature excursions when the Ohau Channel water temperature switches between being colder and warmer than the 5 m depth in the western bay of Lake Rotoiti, and hence between interflowing and overflowing (Fig. 7). Note that in the dataset shown by Fig. 7, underflow is unlikely, as the minimum inflow temperature never approaches that needed (<12°C) to penetrate the thermocline to the hypolimnion in March. This diurnal temperature variation, although rapid, is not a sudden switch from one condition to the other. Consequently, for part of the day the density current probably interflows into the metalimnion, advecting nutrients and algae from Lake Rotorua and the western basin into the eastern basin of Lake Rotoiti.

It has been speculated that much of the diurnal change in temperature occurs during passage of water across the shallow shelf [<1.0 m deep] in Lake Rotorua immediately offshore from the Ohau Channel outlet. To test this hypothesis, water temperatures were measured in summer and winter 1990 at midday, at 50 m intervals across the

600 m wide shelf under windy (summer) and calm (summer and winter) conditions (Fig. 8).

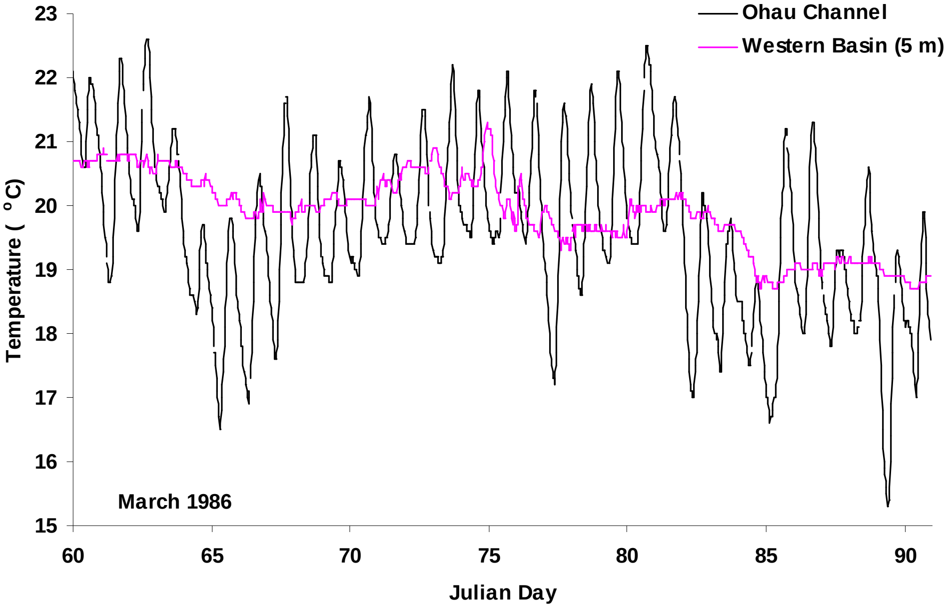


Fig. 7 Diurnal temperature variations in the Ohau Channel (black line) relative to the 5 m depth in the western basin of Lake Rotoiti (red line) in March 1986. Data recorded at 30 minute intervals. While a negative temperature differential may cause the Lake Rotorua water to flow into the eastern basin, the range of possible insertion depths for interflow includes the epilimnion - below 5 m but above the thermocline at 22-32 m.

In calm conditions in winter, there was a 3.5ºC gradient across the shallow zone, decreasing from the open lake towards the Ohau Channel outlet. In calm conditions in summer, the temperature across the shelf varied <1ºC from open lake to inshore (Fig. 8, black line). The windy conditions in summer were measured 5 days after the calm (Fig. 8, red line) and at this time there was an apparent decreasing temperature gradient of about 2ºC from the open lake towards the Ohau Channel outlet. Minimum temperatures coincided with the most turbulent zones at the 600 m drop-off and inshore. Temperatures 100-400 m offshore seem least affected by the wind.

These data confirm that large temperature changes can occur as the water moves across the shelf and into the Ohau Channel. The large diurnal change in air temperature at Rotorua, however, may have a much greater effect at different times of the day, causing the large diurnal temperature fluctuations in the Ohau Channel (Fig. 7). Further cooling or warming may occur during the 2-hour passage of water through the channel itself.

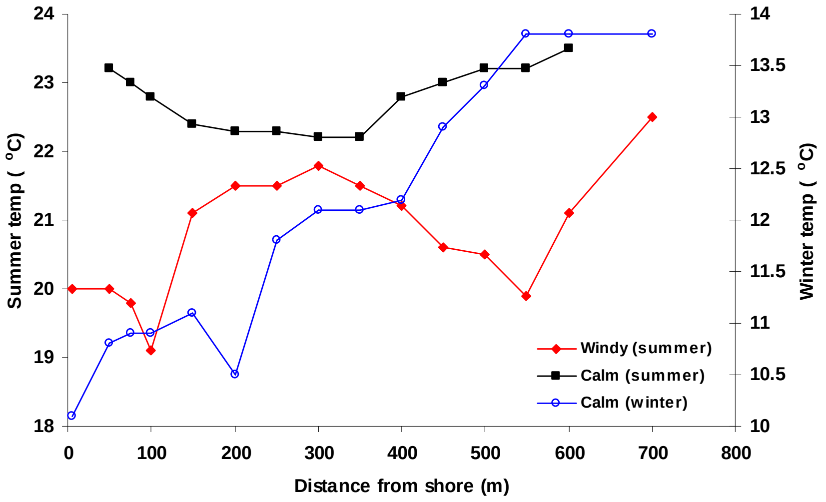


Fig. 8 Cross-shelf temperature structure in Lake Rotorua adjacent to the Ohau Channel outlet under calm and windy conditions in summer (left hand axis), and in relatively calm conditions in winter (right hand axis). Expanded scales are used to provide better resolution.

Although it has been assumed that rapid heating and cooling of the water flowing over the shallow littoral zone before it enters the Ohau Channel are responsible for the large diurnal temperature fluctuations in the Ohau Channel (e.g. Fig. 7), only the cross shelf temperature data (Fig. 8) are available to demonstrate this phenomenon.

2.1.4. Effects of underflows and interflows

The effects of a plunging stream inflow of 70 m^3 s^{-1} of water on Lake Rotoiti are substantial. When underflowing to the bottom of the lake during the winter, this flow will drive a return flow of 75 m^3 s^{-1} and will replace this volume of eastern Rotoiti water with a mixture of western basin and Rotorua water (Fig. 9). The increased return flow includes the volume of water from the eastern catchment. It is from this return flow that the c. 20 $m^3 s^{-1}$ discharge to the Kaituna River outlet is drawn.

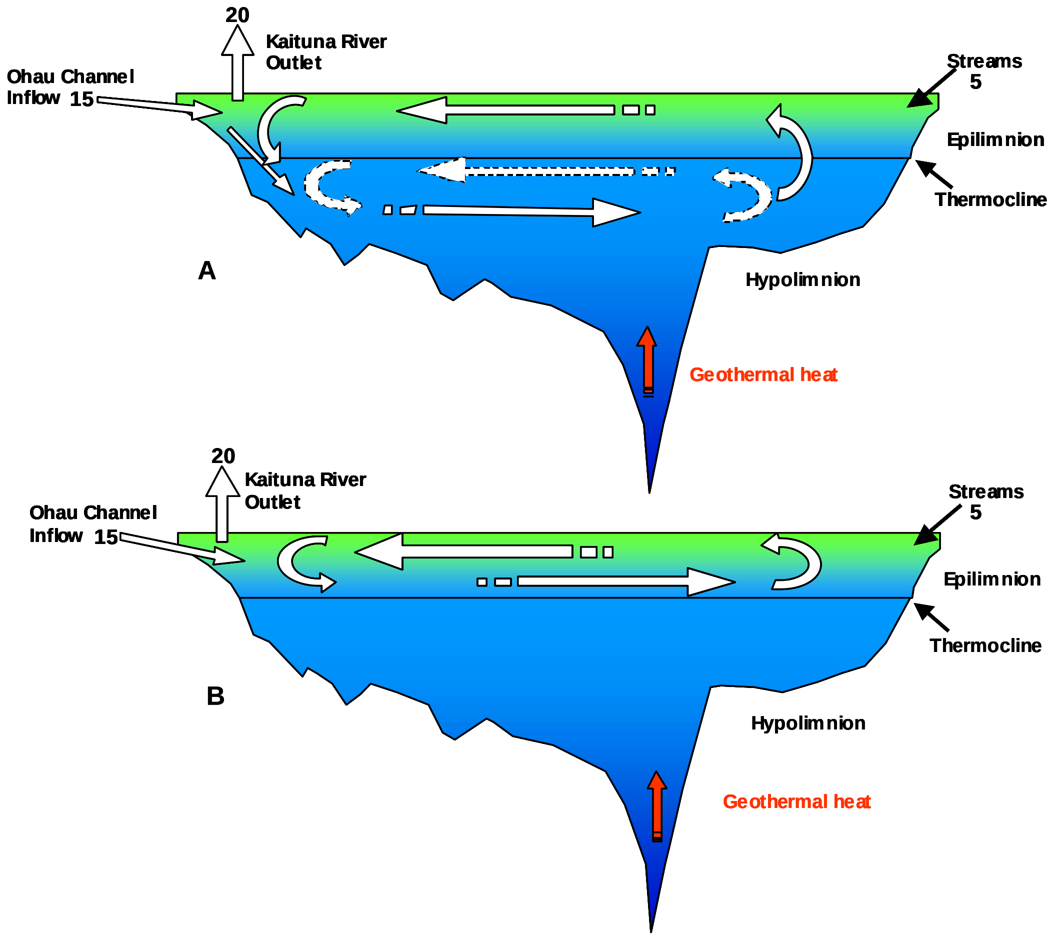


Fig. 9 Stylised flow diagrams of likely circulation patterns **A**) during periods of underflow into the hypolimnion or interflow onto the lower metalimnion [which are likely to occur mainly during spring and late autumn] and **B**) during periods of interflow into the base of the epilimnion [during late spring and summer]. During underflow and interflow into the hypolimnion or metalimnion (**A**) a conveyor-belt flow pattern is likely with a large return current upwelling into the epilimnion. There may also be a smaller complementary return current in the hypolimnion near the thermocline. During interflow into the epilimnion (**B**) all the circulation is likely to be in the upper water column. Geothermal heat stirring will be superimposed on these flows.

During stratified periods when the density plume interflows, the effects will be more complex. When the interflow is warm it will tend to flow into the upper part of the metalimnion of Rotoiti, will be susceptible to entrainment into the epilimnion and will drive an epilimnetic circulation (Fig. 9). When the interflow is cooler, it will insert deeper into the metalimnion, displacing water upwards to drive the return current (Fig. 10). When inserting low into the metalimnion, the interflow will tend to broaden the temperature–depth gradient (c.f. Fig. 5B), reducing stability and thus become vulnerable to incorporation into the hypolimnion during high energy events (such as strong wind set-ups leading to internal waves and seiching). This process is enhanced in Lake Rotoiti by the geothermal convective circulation set up in the hypolimnion. The geothermal heat source in the eastern basin of Lake Rotoiti provides a rising warm-water plume above the vent in the centre of the lake (Gibbs 1992) which draws colder replacement water along the lake bed towards the vent (e.g. Fig. 5A) and drives weak convective circulation currents elsewhere. While this current is slow and flow will typically be laminar (R Spigel, pers. comm.), when combined with wind or other disturbance of the thermocline, sufficient turbulence may be induced to episodically mix the bottom of the metalimnion into the hypolimnion.

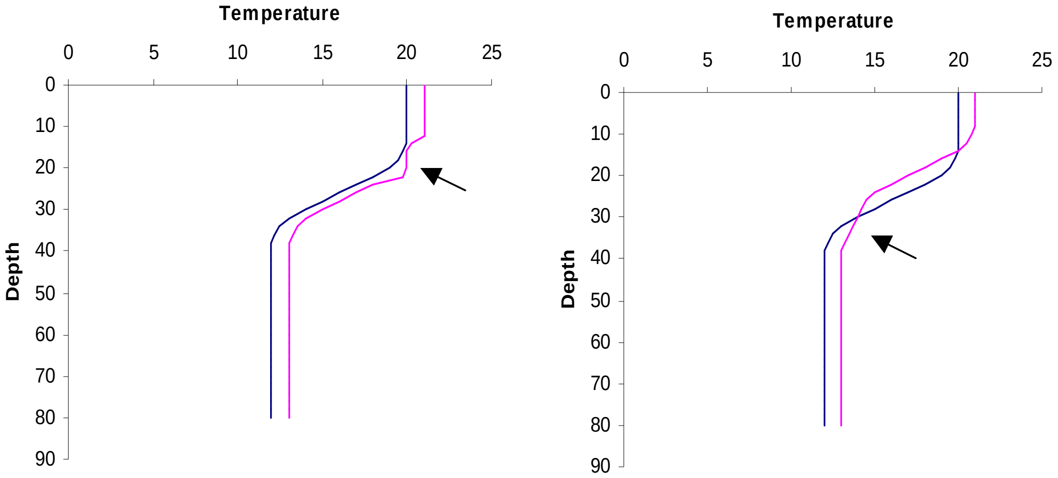


Fig. 10 Schematic example of the effects on temperature structure of interflow shallow (left) and deep (right) into the metalimnion. In both cases the arrow marks the interflow, the pink line is post-insertion, and this has been offset 1°C to the right for clarity. In the left hand example, wind stress is likely to mix the interflow into the epilimnion, in the right hand case, wind stress and geothermal convection may mix it into the hypolimnion – or it may stay where it is.

The consequences of underflow at 1985-86 levels were calculated in terms of residence time, volume displacement, and external nutrient load on Lake Rotoiti, based on data from Taupo Research Lab, DSIR, 1980s studies (Table 3). With no underflow, or complete short-circuiting of the Ohau Channel to the Kaituna River, the theoretical mean residence time of the eastern basin of Lake Rotoiti would be about 6.3 years, assuming a net westward flow from the eastern basin of 5.4 $m^3 s^{-1}$ due to the surface stream and groundwater inflows. This flow regime would give the western basin a residence time of about 35 days. With the 1985-86 under/interflow condition and the present mean 15 $m^3 s^{-1}$ inflow for 60% of the year, the theoretical mean residence time for the eastern basin reduces to 2.4 years and that of the western basin to about 2 days. However, during stratification to 20 m, the return flow of 75 $m^3 s^{-1}$ from the epilimnion of the eastern basin will theoretically displace the epilimnion volume in just over 100 days.

Annually, more than 70% of the N and P that flows into Lake Rotoiti comes from Lake Rotorua via the Ohau Channel, but only around 60% of this will enter the eastern basin of the lake as, for 40% of the year (1985-86 estimate), that load short circuits to the Kaituna River outlet. For up to half of the time that the under/interflow is operating the lake is likely to be well mixed and for the remainder of the time the lake is stratified. Nutrients entering during the well mixed phase (June-September) are likely to be distributed throughout the lake. During the stratified condition (October-April) nutrients are likely to interflow to the metalimnion or epilimnion. It is not possible at this stage to determine what proportion of the interflowing nutrient load will ultimately be delivered to the epi-, meta- or hypolimnion. However, as discussed above, because of the entrainment of surface water into the plunging density current, the temperature of the plume is likely to tend to approach that of the upper water and the interflow is most likely to inject into the upper part of the metalimnion. From here it is likely to interact with the epilimnion, and enhance primary production (including provision of nutrients and an algal inoculum from Lake Rotorua). Figure 2 indicates that late summer (March-April) is the time that interflows will be most frequent. The over/inter/underflow dynamics will be dependent on temperature differentials between inflowing and lake water, stratification set-up and wind forcing, thus is likely to vary from year to year according to prevailing weather conditions.

Table 3 Effects of under/interflow on Lake Rotoiti, as at 1985-86

Period	225 days (60% of year)
Timing	March to October
Volume	26% of lake each year
Residence time	2.4 yr (c.f. 6.3 yr without underflow)
Nutrient load	31% N
(eastern basin)	64% P
Oxygen input	13 tonnes per day (Rotorua water only)

2.1.4 Underflow-interflow and Oxygen

Oxygen concentration declines in the hypolimnion of a lake during the stratified period as a result of respiration and microbial decomposition of organic matter. The rate of reduction reflects the availability of microbial substrates, usually dominated by settled phytoplankton. Thus oxygen depletion integrates all biological processes occurring in the lake and provides a relative measure of lake water quality over the previous year. The poorer the water quality, the higher the flux of organic material to the sediment, and the faster the hypolimnetic oxygen depletion (HOD) (Burns 1995); if sufficiently high the hypolimnion can become anoxic, i.e. devoid of oxygen, before the next mixing event. A key question associated with the underflow-interflow in Lake Rotoiti is the extent to which dissolved oxygen (DO) is transported into the meta- and hypolimnion. Any injection of oxygen to the hypolimnion will in part off-set the consumption by decomposition processes in the bottom waters. The oxygen potentially transported in the Lake Rotorua water inflow amounts to about 13 tonnes per day (Table 3) and the effect of entrainment of Western Basin water into the density current may increase this to c. 50 tonnes per day (1985-86 data).

During the isothermal period, which usually comprises two to three months in June-September, persistent underflow is indicated by the temperature differential between the Ohau Channel and Lake Rotoiti. During this period underflow assists with the re-oxygenation of the lake to the amount of 13 tonnes day^{-1}, equivalent over 90 days to just over 1 g m^{-3} over the entire lake volume. The remainder of reoxygenation will come from mixing with oxygenated surface water and atmospheric equilibration. However, even during apparently isothermal conditions, intermittent stratification ensures that full mixing does not occur all of the time, and the deep underflow of oxygen, which will include that coming with the entrained surface water from the western basin (i.e. a total of 50 t oxygen day^{-1}), may be disproportionately important to reoxygenation of the deeper part of the lake during the winter period in the absence of subsequent wind induced complete mixing.

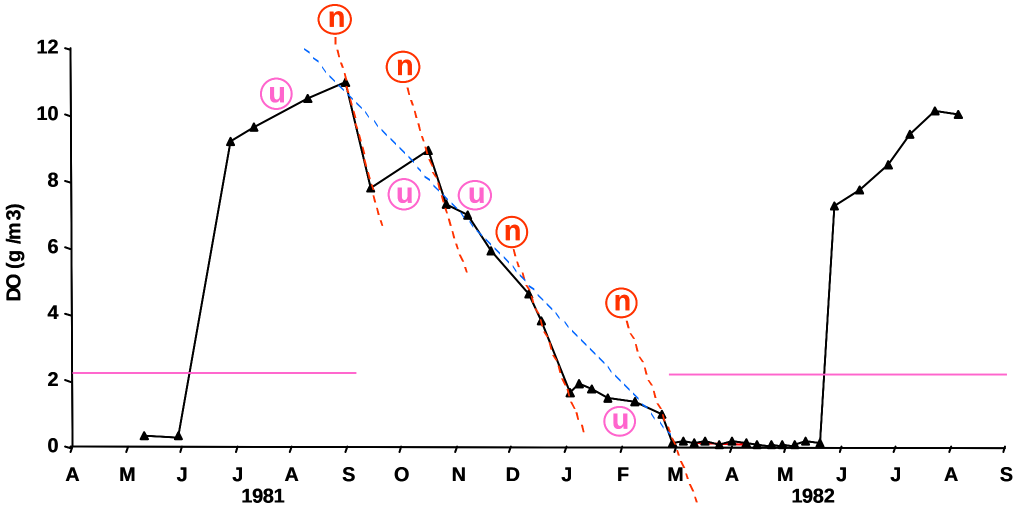


Fig. 11 Estimation of net and absolute hypolimnetic oxygen demand (HOD) based on 1981-82 data at 60m. The blue broken line is a regression through all data points above 1 g O_2 m^{-3} after stratification begins and the slope of this line gives a net HOD rate of 0.076 g O_2 m^{-3} day^{-1}. The data include periods of reduced apparent oxygen consumption and even concentration increase. This could represent underflow, interflow or intermittent deep mixing. The red broken lines marked with a circled 'n' are thought to coincide with periods of little delivery of oxygen to deep water, thus giving an indication of the absolute HOD rate (0.136 g O_2 m^{-3} day^{-1}). The pink circled 'u's indicate periods of intermittent underflow/interflow. The pink lines represent the period in 1985-86 (note a different year to oxygen data) when temperature differences between the Ohau Channel and Lake Rotoiti were adequate to drive density currents (see Fig. 2). In March and April interflow may have occurred, whereas at other times underflow was most likely.

The duration of the mixed period and underflow of the Ohau Channel water are likely to be critically important in determining the extent to which reoxygenation of the deep water occurs, due to the combined effects of the duration of underflow and time and opportunity for atmospheric equilibration.

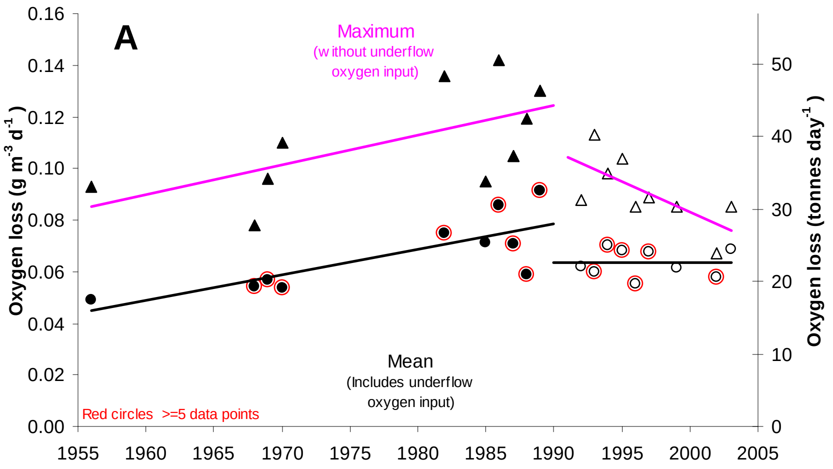
It is possible that some interflowing oxygen may also reach the hypolimnion during the stratified period. The intensive oxygen profile data collected in 1981-82 shows that the rate of oxygen decline in the deep waters of the lake was not constant over time (Fig. 11). In September and early October, intermittent stratification appears to have allowed oxygen depletion to start, though by late October the lake was strongly stratified and cumulative depletion began. However, even after October, variations in the rate of oxygen depletion still occurred.

During early stratification it is possible for interflows to deliver oxygen directly to the upper hypolimnion. However, as discussed above, once stratification is well established the opportunity for interflows to penetrate into the hypolimnion is lost although if these penetrate sufficiently deeply into the metalimnion, they potentially deliver oxygen to the hypolimnion through thermal convection (see above).

If this scenario of hypolimnetic isolation with intermittent oxygenation events is correct, the highest rates of oxygen depletion (0.136 g m^{-3} day^{-1} in Figure 11) may be thought of as the absolute rate of HOD, when no oxygen entrainment from the Ohau Channel inflow was occurring. Over longer time intervals, this absolute rate is reduced by oxygen entrainment, resulting in a lower average rate (0.076 g m^{-3} day^{-1} in Figure 11), which is the net or mean HOD rate. The difference between absolute and mean rates (0.060 g m^{-3} day^{-1} in Fig. 8) should therefore be the average amount of oxygen entrained from metalimnion during the period of depletion. The potential for metalimnion-hypolimnion exchange will depend on the turbulence generating forces as well as the extent to which deep interflows occur.

The long term oxygen data set for Lake Rotoiti (1955 to 2003) is less comprehensive than that for 1981-82, but allows for estimation of absolute and mean HOD rates for several years. These should provide an assessment of long-term change in lake water quality. Surmises based on absolute HOD rates require care, since these are necessarily based on very few (sometimes only two) data points. Given this proviso, changes in the absolute HOD rate should reflect changes in lake water quality, while differences between mean and absolute HOD rates will include the net effects of oxygen transport via density currents from the Ohau Channel.

The mean and absolute HOD rates (Fig. 12A) show an apparent increase from 1955 to the mid 1980s, with the absolute HOD rate almost double the mean HOD rate. This increase is consistent with a trend of decreasing water quality in both Lakes Rotorua and Rotoiti. The mean and the absolute HOD rates increase at about the same rate during this period, implying that the amount of oxygen transported in the density current each spring is comparable between years.



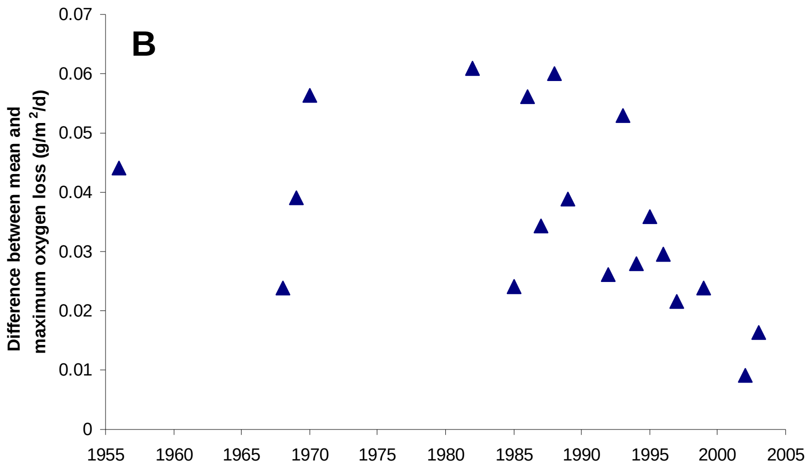


Fig. 12 **A**) Mean and absolute hypolimnetic oxygen depletion (HOD) rates in Lake Rotoiti from 1955 to 2003, calculated from 50-60 m data as per Figure 11. Trend lines (black = mean; pink = absolute) are divided at 1991 with solid symbols before and hollow symbols after that date. Sewage diversion from Lake Rotorua began in 1991. Symbols for mean HOD rates use 5 or more data points in the annual regression. Note: absolute HOD rates often use only 2 data points when underflow is assumed to be minimal or not occurring and hence there may be large error terms. **B**) Difference between absolute and mean HOD rates.

From the 1990s to present, the mean HOD rate has remained essentially unchanged while the absolute HOD rate shows an apparent declining trend. The difference between absolute and mean HOD has been highly variable, but particularly low in recent years (Fig. 12). This suggests a trend of improving water quality in the 1990s (declining absolute HOD) but also a reduction in the amount of oxygen being transported in the density current (reduced difference between absolute and mean) and therefore, by inference, a reduction in the advection of oxygen by underflow-interflow into the hypolimnion.

Given the paucity of data in some years, these estimates may contain substantial errors. In particular, long periods between data points in some years make the probability of obtaining a period unaffected by oxygen entrainment, that is approaching absolute HOD, unlikely. However, if the absolute HOD rates were still increasing, at least one value in recent years would be expected to be in the range of the earlier trend line.

The implication of improvement in water quality from the HOD data is not consistent with the apparent increase in cyanobacterial blooms in recent years. These tend to imply deteriorating water quality, when high biomass should deliver abundant organic matter to the lake floor and invoke high HOD rates. The potential explanation for these apparently contradictory observations could simply be the change in algal species composition. Analysis of algal species composition suggests that while there had been a general dominance by diatoms over the 10 years since 1990 (Burns et al. 1998; Wilding 2000), there has been a proliferation of cyanobacteria blooms in the last 2-3 years in the western basin embayments of Lake Rotoiti. A significant difference between cyanobacteria and diatoms is that the former can be positively buoyant, while the latter sink. Thus a cyanobacterial bloom may deliver less organic matter to deep water than an equivalent diatom biomass, thus generating less HOD.

An example of this effect was seen as a rapid decline in absolute HOD rates in Lake Taupo (Gibbs 2002, p11) following change in winter bloom dominance from the diatom, *Aulacoseira granulata*, which rapidly sediments in the deeper parts of the lake, to the buoyant colonial green, *Botryococcus braunii*. Other factors may have also contributed at Lake Taupo, as volcanic ash from the Mount Ruapehu eruptions appeared to 'trigger' the species shift.

2.1.5 Climate variability effects on underflow

It was identified in section 2.1.4 that climate variability could cause a change in the under/interflow condition from that measured in 1985-86. In this section we compare two years, 1981-82 and 2001-02 to determine whether, based on our understanding of the dynamics of the underflow, different climatic conditions are likely to have affected the underflow regime. We focus on two key elements, night time temperature and thermal structure of Lake Rotoiti.

Night time air temperatures. Low night time temperatures rapidly cool the shallow waters adjacent to the Ohau Channel outlet and in the channel itself, thus increase the depth to which the underflow-interflow will insert into the eastern basin of Lake Rotoiti. Monthly mean minimum daily air temperatures at Rotorua airport (Fig. 13A) show that minimum air temperatures were up to 4.5ºC warmer in June 2002 than in 1982, and the monthly mean minimum was often more than 1ºC warmer in 2002. This was particularly evident during winter. A similar pattern of warmer monthly mean maximum day temperature was also found (Fig. 13B). Our expectation would therefore be that in 2001-02, interflow would be favoured over underflow during early stratification, and this would restrict oxygenation of the deep waters. Conversely, in 2002-03, when spring temperatures were cooler, the opposite might have been expected.

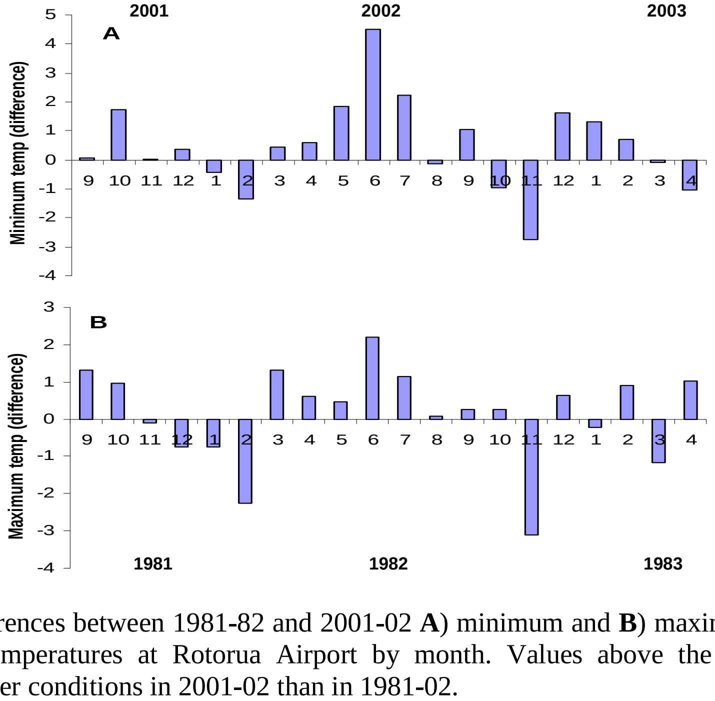


Fig. 13 Differences between 1981-82 and 2001-02 **A**) minimum and **B**) maximum mean daily air temperatures at Rotorua Airport by month. Values above the x-axis indicate warmer conditions in 2001-02 than in 1981-02.

Temperature structure in Lake Rotoiti. The temperature structure of Lake Rotoiti was assessed by comparing contoured temperature profile data from 1981-82 with similar data collected in 2001-02 (Fig. 14). These plots indicate that the mixed period was very short in 2001, and that Lake Rotoiti thermally stratified about 1 month earlier in 2001-02 than in 1981-82. This would again be consistent with warmer air temperatures in 2001-02 (Fig. 13). Earlier stratification implies less downwards mixing of heat into the hypolimnion during mixing (c.f. section 2.1 Hydrology: Priscu et al. 1986), and consequently the hypolimnion appears to be slightly colder in 2001-02 than in 1981-82 (Fig. 14). Detail of the difference in hypolimnion temperature can be seen in vertical temperature-depth profiles in the eastern basin of Lake Rotoiti in summer (February–March) (Fig. 15). These data indicate that the hypolimnion was about 1ºC colder in 2002 than in 1982. In autumn, stratification persisted slightly longer in 2002 than 1982, and winter cooling in 1982 was much more rapid.

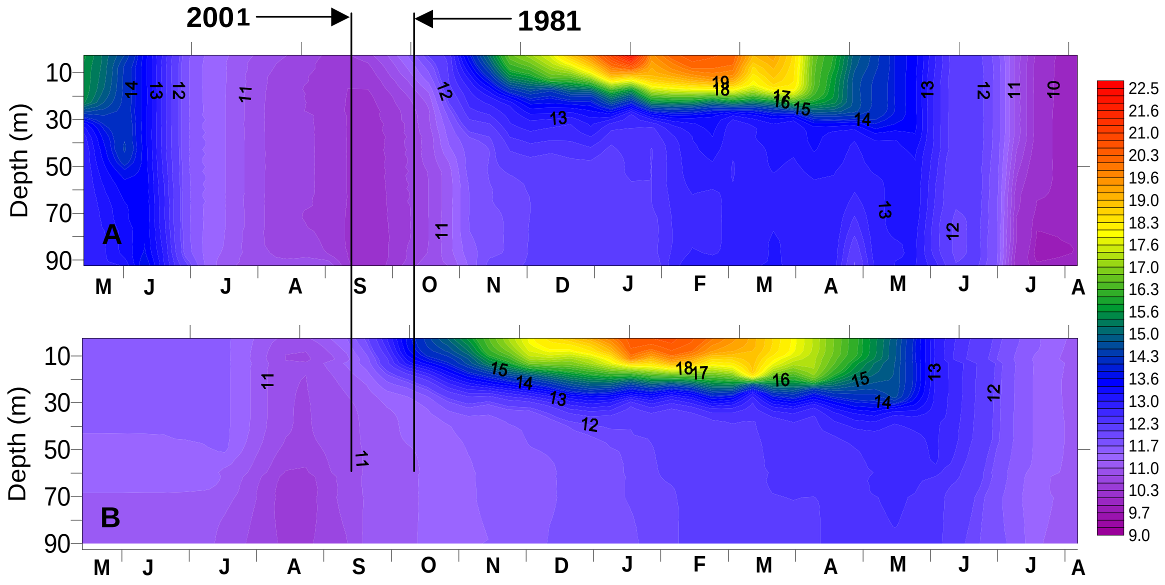


Fig. 14 Contoured temperature plots of Lake Rotoiti, eastern basin in **A**), 1981-82 and **B**), 2001-02 showing the onset of stratification to be about 1 month earlier in 2001 than 1981. The data also indicate a colder hypolimnion in 2001-02. (X-axis = month of year, temperature units in degrees centigrade, contouring by Surfer32 with linear Krigging).

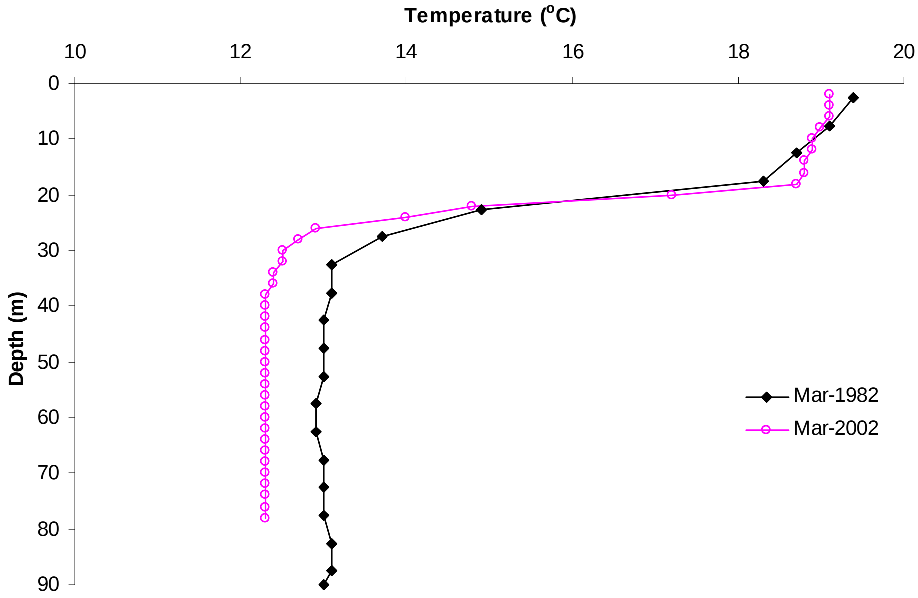


Fig. 15 Temperature profiles in the eastern basin of Lake Rotoiti from 1982 and 2002, showing the cooling of the hypolimnion between years.

These data provide compelling evidence of climate difference between the two comparison years, which can be expected to have influenced the dynamics of the hydraulic connections between the Ohau Channel and Lake Rotoiti. As the differences show an increase in winter minimum air temperatures, the Ohau Channel water is likely to have been **warmer** in 2001-02 than in 1981-82. Conversely, the temperature of the hypolimnion was around 1ºC **colder** in 2001-02 than in 1981-82. The resultant temperature differential driving the underflow condition must therefore be less in 2001-02 than in 1981-82, which implies shorter duration of winter underflow and longer periods of overflow/interflow in 2001-02. The net effect would be a reduction the DO mass transport into the hypolimnion of Lake Rotoiti.

Given this potential degree of variability in the under/interflow condition, predictions of the likely effects of the engineering structures based on the historical water quality data for Lake Rotoiti will have a high degree of uncertainty and, at best, provide general rather than specific terms.

2.1.6 Summary.

- The single largest inflow to Lake Rotoiti, and its greatest potential nutrient source, is from Lake Rotorua via the Ohau Channel.

- Passage across the extensive shallow shelf offshore of the entrance to the Ohau Channel tends to cool the channel water in winter and warm it in summer. It can contribute to a 4-degree diurnal fluctuation in channel temperature.

- Temperature differentials between the Ohau Channel and the Western Basin of Lake Rotoiti determine the fate of the Ohau Channel water. When the channel is warmer than the lake, inflows form a surface overflow, and under most conditions will short-circuit to the Kaituna River. In 1986 this occurred 40% of the time.

- When the inflow is sufficiently cooler than the western basin water, the density difference causes the inflow to flow along the bottom of the lake. As it does so it entrains 4-5 times its volume of western basin lake water to form a density current of up to 70 m^3 s^{-1}. This density current will rise from the lake bed when it encounters water of similar density. Under winter conditions, the density current can form a true underflow and reach the deepest parts of the lake.

- Once thermal stratification has set up in Lake Rotoiti, the density current tends to be an interflow, inserting into the metalimnion at a depth determined by temperature differentials.

- Underflows and interflows can be significant in delivering oxygen to the meta- and hypolimnia, and offsetting oxygen consumption by microbial respiration.

- The dynamics of overflows, interflows and underflows are strongly dependent on climate. Year-to-year variations in temperature and wind regimes are likely to result in major differences in the duration of plunging density currents and insertion depths.

2.2 Quality of water entering the Ohau Channel

The Ohau Channel discharge into the western basin of Lake Rotoiti is the driving force behind the density current which underflows or interflows into the eastern basin of the lake. It is also the greatest single external source of nutrients entering Lake Rotoiti (Table 2) and has been implicated as at least partially responsible for eutrophication in that lake (Vincent et al. 1986). While the ultimate source of that water is Lake Rotorua, the immediate source is the broad shallow shelf between the entrance to the Ohau Channel and the deep open waters of the lake. Measurements made in 1990 (Gibbs 1991) found that this littoral zone was less than 1 m deep for almost 600 m from shore and that it was subject to episodic fluctuations of turbidity and particulate nutrient concentrations associated with sediment disturbance during strong on-shore wind events. The suspended solids, organic material (a measure of BOD load) and the nutrients generated by the wind induced disturbance of these littoral zone sediments, were being drawn into the Ohau Channel and subsequently discharged into the western basin of Lake Rotoiti.

In this section we review the data on water quality in and close to the Ohau Channel and attempt to assess the overall importance of the shallow zone in supplying nutrients, in order to determine the feasibility of reducing nutrient loading to Lake Rotoiti by managing the Ohau Channel.

2.2.1 Ohau Channel (1990)

Data from a one week time-series sampling of the effects of a wind event on the Ohau Channel in winter 1990 (Fig. 16) show the close relationship between wind speed and the particulate components of the nutrient load i.e., suspended solids (SS), organic carbon (as loss on ignition), total phosphorus (TP) and total nitrogen (TN). Winds of 5 m s^{-1} generated an increase in particulate load, but the effect of a very strong wind (in excess of 12 m s^{-1}) produced a much more dramatic result. These data also show that the DRP and DIN components (Fig. 16C, D) were not well correlated with wind speed. Mass transport estimates are shown in Table 4 as the total amount for that week and as an estimate of likely base-load for the week in the absence of a wind event, extrapolating from the low wind period data.

Table 4. Estimated total and base-load sediment and nutrient mass transport (tonnes) through the Ohau Channel in a 7-day period in winter 1990.

	SS	Organic	TN	DIN	TP	DRP
Total for week	227.4	59.9	7.0	1.9	0.82	0.12
Base-load for week	34.8	24.9	3.9	0.9	0.36	0.09

Evaluation of the time-series data (Fig. 16, 17) show that there were strong correlations between organic matter, TN and TP ($r^2 > 0.9$ in each case). TN and TP were also correlated ($r^2 = 0.913$ - if the point with anomalously high nitrate was ignored), and the average ratio of TN:TP was 9.4, consistent with the stoichiometry of a source dominated by planktonic algae [TN:TP ratios of sediment in Lake Rotorua are approximately 4:1]. There was also a good correlation between organic matter and SS, though this showed some indication of a curvilinear response at high SS values (Figure 16B). The flattening of the SS vs organic matter curve at highest SS, coupled with the more rapid fall of SS than organic matter after the peak wind event, suggest that a proportion of the SS peak may be inorganic-rich bed material from very close to the entrance to the Ohau Channel that is suspended only under the most vigorous conditions.

We can conclude from these data that strong wind events increase the load of suspended solids, including organic material, particulate N and particulate P to the Ohau channel.

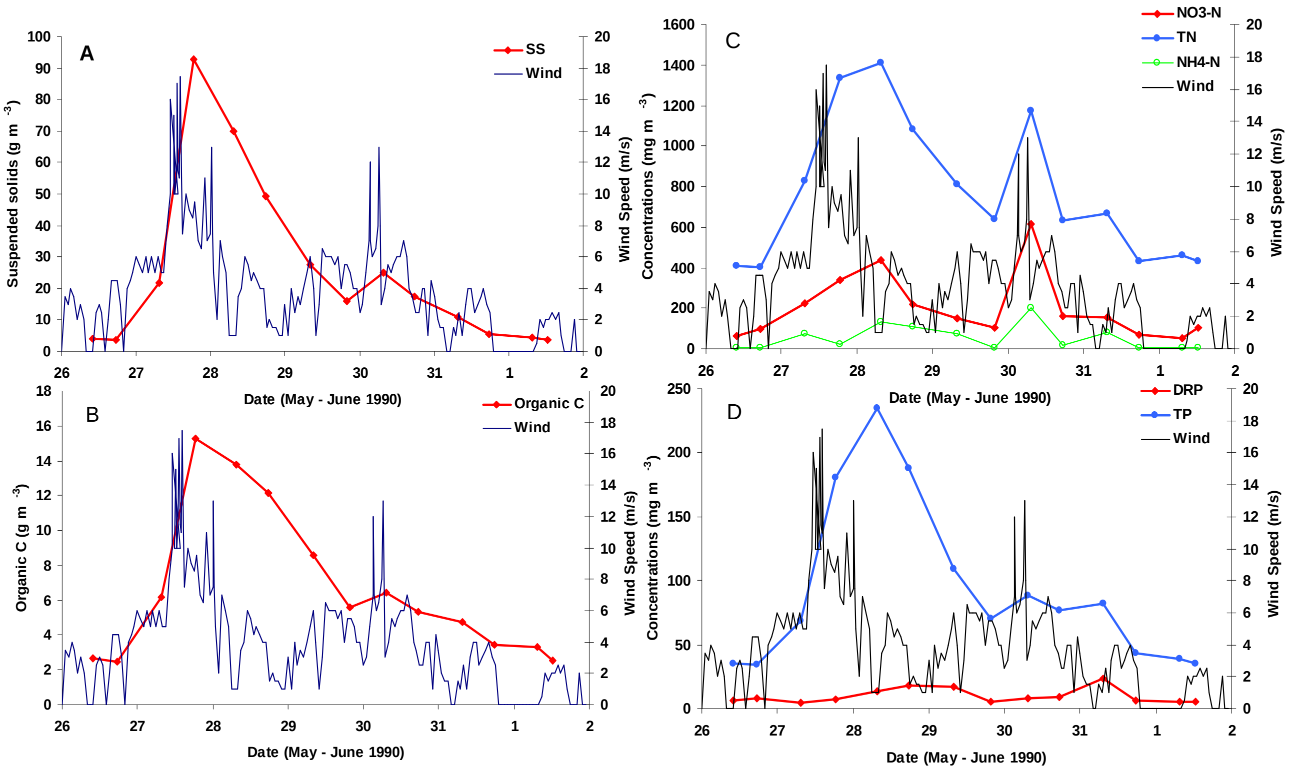


Fig. 16 Time series suspended solids and nutrient concentration data in the Ohau Channel relative to westerly wind speed across Lake Rotorua. Grab samples were taken from within the Ohau Channel about 100 m downstream of the control structure at the inlet end. Wind speed was taken from Rotorua Airport weather station and converted to m s^{-1} from knots assuming 1 m s^{-1} = 2 knots. Organic C is the loss on ignition of the dry suspended solids.

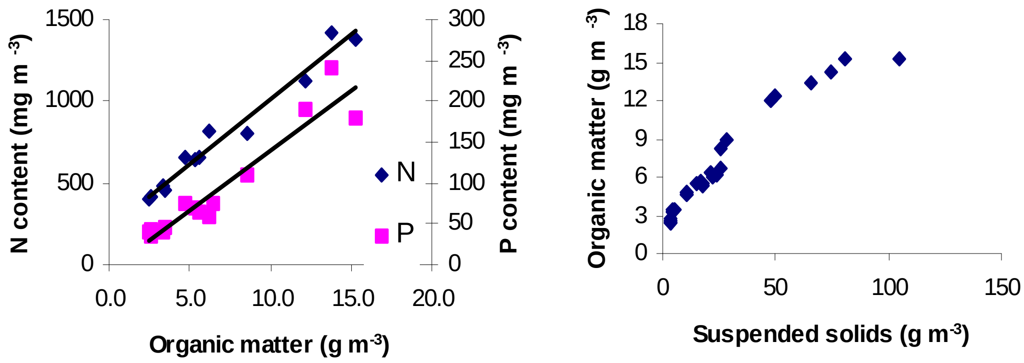


Fig. 17 **A**) Relationships between organic matter, TN and TP in Ohau Channel samples (left) and **B**) between SS concentration and Organic matter.

2.2.2 Origin of particulates and nutrients

Effects of wind stress on sediments and nutrients in the shallow littoral zone in Lake Rotorua adjacent to the entrance to the Ohau Channel have only been measured in one study in 1990 (Gibbs 1991).

Some indication of the origins of the particulates advected into the Ohau Channel under wind stress can be obtained from cross-shelf observations undertaken in the 1990 study. In general, there are four possible sources of material, none of which is mutually exclusive. These are;

- the offshore shelf break, some 600 m offshore where the open water waves first encounter the shallow shelf
- the wave wash zone immediately at the opening of the Ohau Channel,
- advection of offshore organic particulates (e.g. phytoplankton)
- long-shore drift of suspended wave-wash material.

Examination of concentration data of dissolved and particulate materials in a transect across the shallow littoral zone adjacent to the Ohau Channel entrance under calm and windy conditions in summer 1990 (Figs. 18A, C, D) shows that most of the increased concentration under wind stress occurred within 200 m of shore. While there was also an increase at the lakeward shelf-break, this increase did not appear to propagate across the shelf and there was a marked dip in concentration of particulates in the centre of the shelf.

Of the dissolved inorganic nutrients, DRP, NO_3-N, and NH_4-N, only NO_3-N concentrations showed any increase towards the shore under windy conditions (Fig. 18B) and concentrations were generally low and comparable with open water concentrations in Lake Rotorua. In the case of NO_3-N the sudden increase at the lake edge was a single high datum and cannot be adequately explained by resuspension.

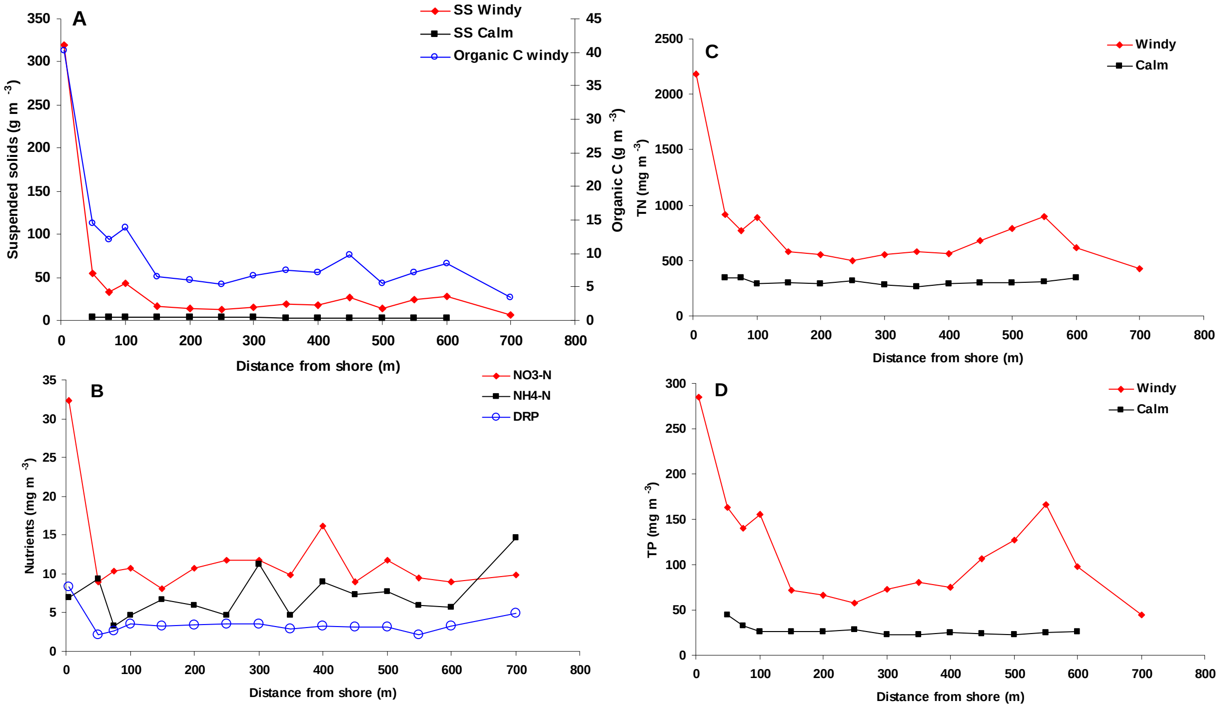


Fig. 18 Cross shelf concentrations under calm and windy (7-10 m s^{-1}) westerly wind speeds across Lake Rotorua in summer 1990. Nutrient data (B) are for windy conditions.

From the cross shelf data we can conclude that much of the sediment and organic load associated with onshore wind events is generated close to shore. These data do not rule out some degree of onshore advection of material from deeper water or long-shore drift.

Longshore transport

Long-shore transport of DRP and other nutrients from the Hamurana Springs would require a clockwise circulation current while, to receive drift from the Waiohewa Stream, requires a counter-clockwise circulation current. Currents in lakes are driven by wind and planetary rotation. From planetary rotation the expectation would be for a clockwise circulation in a large circular lake in the southern hemisphere, especially as it has a central island to focus the current flow. However, drift patterns of sulphur plumes from Sulphur Point indicate a counter-clockwise flow (Gibbs, personal observations). It is likely that under most conditions wind plays a major role in determining currents close to the shore.

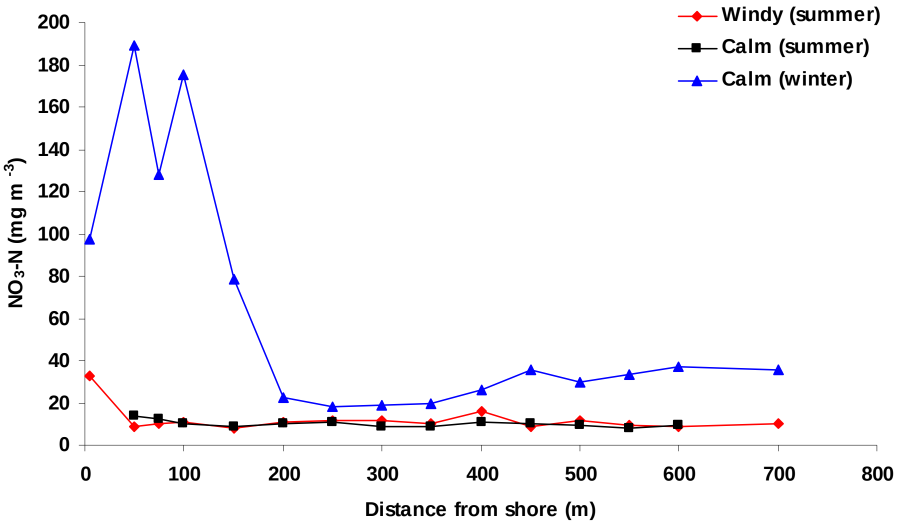


Fig. 19 Cross shelf concentrations of nitrate-N (NO_3-N) in summer and winter 1990, at the entrance to the Ohau Channel.

Possible evidence of long-shore currents can be seen in the cross shelf NO_3-N concentrations in winter (Fig. 19). High NO_3-N concentrations in-shore in winter appear to be much too high to be due to groundwater discharge or sediment remineralisation, particularly as no such effect was evident in the summer data. As there is no obvious link to the open lake water concentration, it is perhaps most likely that the NO_3-N came from northerly long-shore transport of a plume of Waiohewa Stream water, which is known to have very high DIN concentrations from geothermal sources. Such events will be weather-dependent, and are likely to be episodic.

A second aspect of long-shore transport is the movement of sediment along beaches through swash and drift processes. The position of the Ohau Channel outlet in the NE corner of the lake suggests that sediment transport by long-shore drift will be towards the outlet under westerly or south-westerly wind stress. This sediment drift towards the outlet replaces material lost down the outflow, and may contribute directly to the outflow load.

Lake Rotorua as a nutrient source

Comparison of Environment Bay of Plenty time-series nutrient data in the Ohau Channel with available data from the open waters of Lake Rotorua (Fig. 20) shows that there is often an increase in DRP in the Ohau Channel associated with a DRP concentration increase in the lake. These data, together with the absence of any relationship between DRP and SS in the channel (section 2.2.3), confirm that changes in DRP in the offshore waters of the lake are a more important source of DRP to the outflow rather than changes due to processes in the near-shore zone.

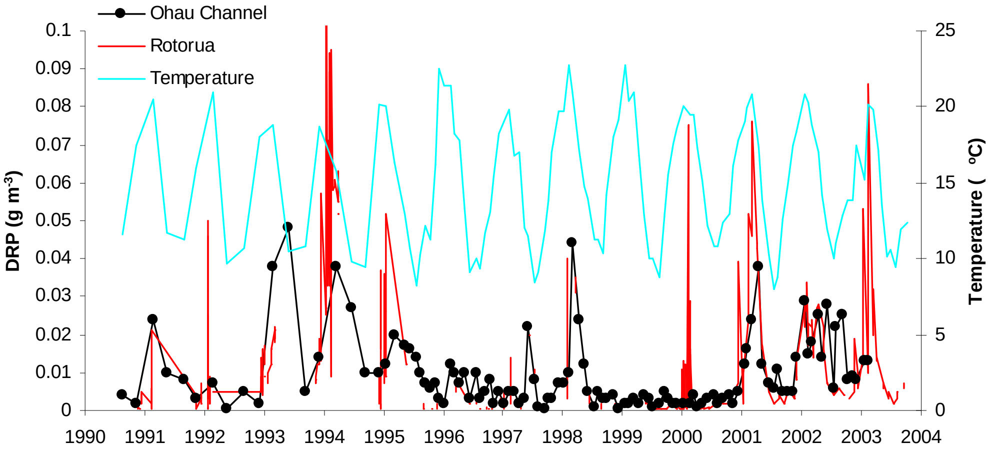


Fig 20 Time-series DRP concentrations in Lake Rotorua and the Ohau Channel showing episodic events indicated by high DRP concentrations in the lake and the movement of that water through the Ohau Channel. Temperature data from the Ohau Channel are used to indicate the seasonal cycle. The lake data include multiple depths on the same day.

The timing of the appearance of the elevated DRP concentrations in the lake in summer after a period of low oxygen (data not shown) is consistent with it being from sediment release and hypolimnetic accumulation during intermittent stratification events in Lake Rotorua. That the DRP concentration in the Ohau Channel is less than that in the open lake is consistent with it only occurring once stratification breaks down and some degree of dilution occurs. There is also evidence (not shown) of the DRP moving through the western basin of Lake Rotoiti to the Kaituna River in summer when overflow conditions are expected for the Ohau Channel discharge (Wilding 2000) and into the hypolimnion of Lake Rotoiti (section 2.3 below).

2.2.3 Long term monitoring of Ohau Channel water

Long term monitoring data from Environment Bay of Plenty includes approximately monthly sampling at a site on the Ohau Channel at Mourea Bridge. While the site is about 1 hr flow time downstream of the Ohau Channel entrance, it provides further information on nutrient passage.

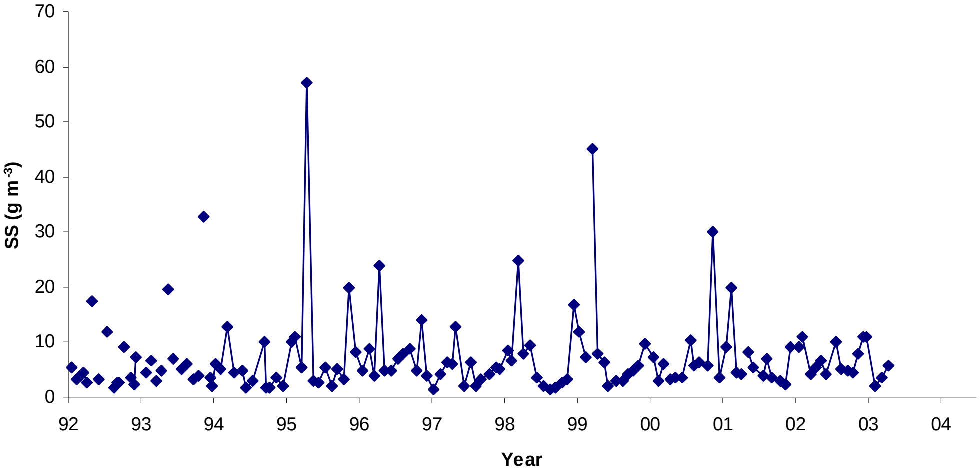


Fig. 21 Time series of suspended sediment concentrations in the Ohau Channel at Mourea Bridge.

Although this monitoring programme was not designed to determine the peak loads of sediments associated with wind events, the sampling picked up a number of high SS concentration events exceeding 10 g m^{-3} against a background SS concentration of 2-3 g m^{-3} (Fig. 21). There is a high probability that other events will have occurred but not been captured due to the infrequent sampling.

Comparison of SS with N and P concentrations of the Ohau Channel shows no relationship between SS and either DRP or NH_4-N (Fig. 22). While PN and PP were not measured, the difference between TKN (Total Kjeldahl N) and NH_4-N will estimate particulate + organic N, and TP – DRP will estimate particulate + organic P. These derived N and P values tend to increase with increasing SS. While the presence of DON and DOP will complicate this relationship, it supports previous data that indicate the major near-shore effect as being on particulate, rather than dissolved inorganic, nutrients. Average ratios of non-inorganic N:P were 12:1, again consistent with the organic material being primarily algal-derived. [Sediment non-inorganic N:P ratios are more likely to be around 4:1].

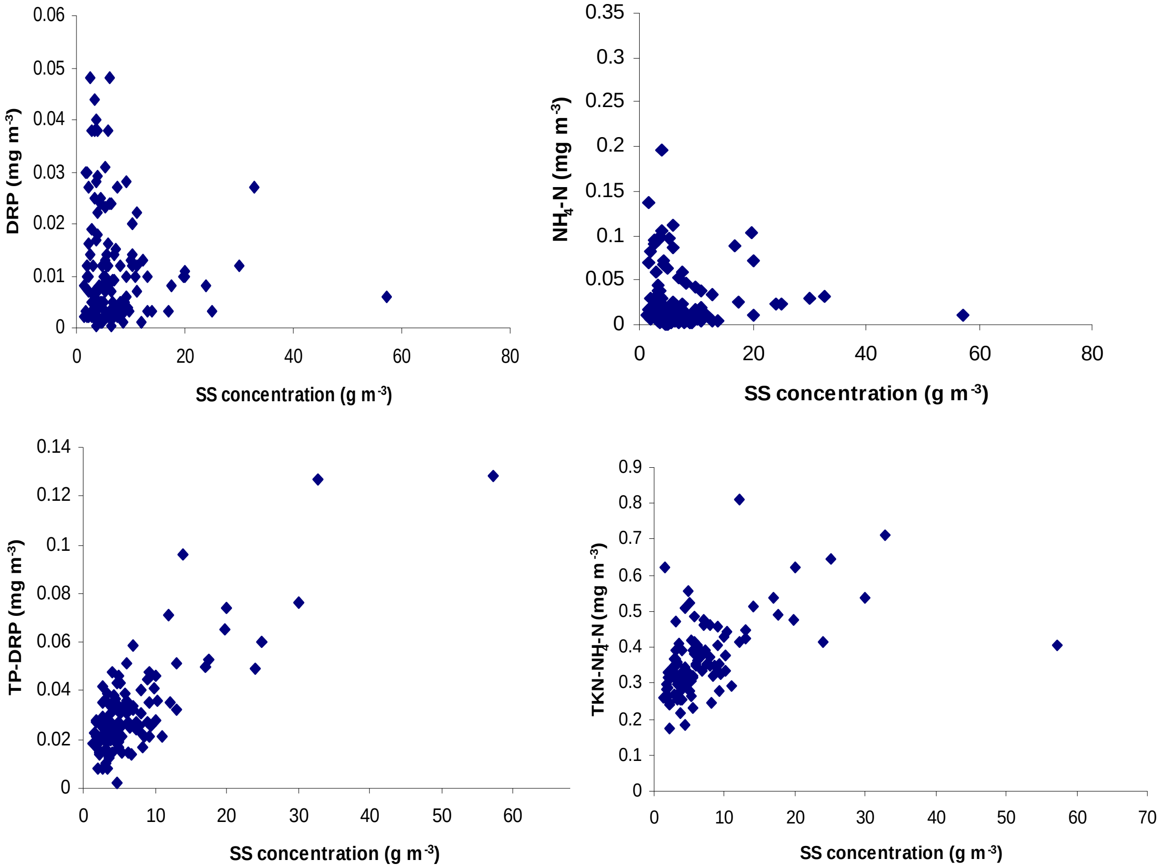


Fig. 22 Relationships between suspended sediment (SS), DRP, NH_4-N and best estimates of organic N and P concentrations in the Ohau Channel monitoring data. Particulate N and P concentrations were not measured, but TKN–NH_4-N will estimate organic plus particulate N, while TP-DRP will estimate organic plus particulate P. TKN is total Kjeldahl Nitrogen. Insufficient NO_3-N data are available to include in this analysis.

The lack of strong relationships between DRP or NH_4 and SS suggests that there is an alternative source for these other than release from the disturbed sediment across the shallow littoral zone. Possible sources would be a long-shore transport as a discreet plume of water from nutrient-rich inflows, either the cold Hamurana Spring to the north west or the geothermally-influenced Waiohewa Stream to the south, or pulses of nutrients from Lake Rotorua.

2.2.4 Climate effects - wind

While climate difference effects were demonstrated for temperature (Fig. 13), changes in wind strength and direction in recent years can also be demonstrated. A wind rose incorporating all data from 1991 to 2003 (Fig. 23) shows that most of the strong winds come from the southerly through westerly or north to north-easterly direction. They also show that winds of >12 m s^{-1}, that elicited such high loads of suspended material in figure 16, are rare. Between 1990 and 2002 there were, on average, 29 days per year when mean daily wind speed exceeded 5 m s^{-1}, two days a year when it exceeded 7.5 m s^{-1} and no days when it exceeded 10 m s^{-1}. These statistics refer to daily means and imply fluctuations between higher and lower velocities on any day.

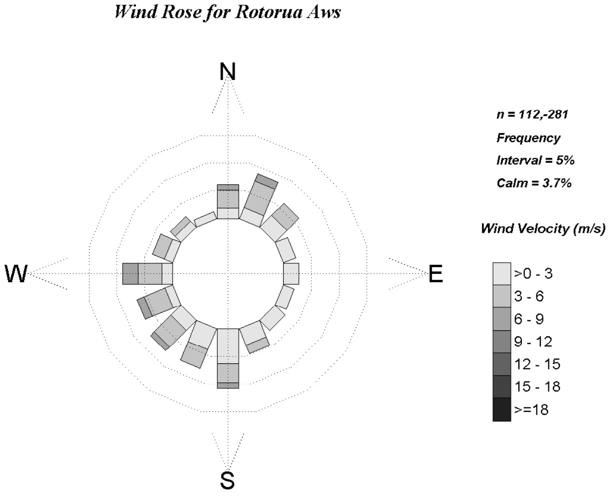


Fig. 23 Wind rose for Lake Rotorua based on Rotorua Airport data from 1991-2003**.**

Closer examination of the 1990 data (Fig. 16) shows that the very high velocity wind events that caused the high suspended materials loads only occurred for a few hours but the suspended material concentrations remained high for more than a day. This indicates that sediment suspended by strong wind may be maintained in suspension by weaker winds. Preliminary evaluation of the 1991-2003 wind data versus suspended solids in the Ohau Channel suggests that a minimum threshold value of about 3 m s^{-1} is required to initiate suspension, i.e., break the cohesion of the sediments due to packing and binding by microbial exudates etc., before the sediment particles can be suspended. This is likely to be important for estimating loads transported through the Ohau Channel. Any model used will have to include evaluation of the wind history prior to assigning a likely suspension or sediment transport load to a measured wind stress.

Table 5 summarises the mean hourly wind speed data in hours by year from all directions and gives the peak mean hourly wind speed for each year. Individual wind gusts will exceed the mean hourly wind speed but may be more or less important than the sustained wind stress for the hourly period for lake set-up and wind wave generation. Wind speeds above 10 m s^{-1} were almost always from the southerly quarters.

Table 5 Summary of mean hourly wind speed in hours at Rotorua Airport between 1990 and 2003. Peak data refer to the peak mean hourly wind-speed rather than peak gust. Wind speed separation at 3 m s^{-1} is the nominal threshold for suspension.

Year	1991*	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003*
<3 m s^{-1}	1298	3178	3248	3049	3112	3040	3249	3058	3507	3050	3057	2953	2742
3-5 m s^{-1}	1485	3521	3377	3449	3327	3296	3177	3115	3149	3360	3267	3167	2262
5-8 m s^{-1}	890	1836	1810	1893	1954	1900	1926	2126	1809	2022	1679	2099	1275
8-10 m s^{-1}	106	207	199	269	287	362	297	393	233	284	238	382	183
>10 m s^{-1}	12	34	52	54	43	103	96	58	50	60	60	137	60
Peak m s^{-1}	12.9	12.9	14.9	14.9	14.4	18.5	14.4	17	14.4	16.5	14.4	16.5	15.4

* Incomplete year

2.2.5 Summary

- The source water moving through the Ohau Channel is derived from the broad shallow part of the littoral zone adjacent to the entrance to the Ohau Channel.
- Wind events from the west suspend sediments close to the Ohau Channel entrance and allow them to pass through the Ohau Channel into the western basin of Lake Rotoiti.
- Sediment suspended by short duration (hours) bursts of strong winds may remain in suspension for considerable periods after the wind velocity drops.
- A wind stress of about 3 m s^{-1} is required to break sediment cohesion and initiate suspension of sediment particles.

- SS, organic carbon, TP and TN concentrations appear to be increased by wind-induced disturbance of the shallow littoral zone sediments within about 100 m from shore.
- During a one-week study in 1990, which incorporated a large wind event, wind induced sediment disturbance accounted for about 85% of the SS, 60% of the organic carbon, and 50% of the TP, TN, and DIN loads passing through the Ohau Channel. Wind events of this size are likely to occur episodically, with a frequency of tens per year. Lesser wind events will also cause re-suspension; though at present insufficient data area available to establish the wind stress-resuspension relationship.
- DRP concentrations appear to be influenced by nutrient cycling events in the main body of Lake Rotorua. At times, base loads of DRP and NO_3-N may be enhanced by long-shore transport of nutrients from either Hamurana Springs or the Waiohewa Stream.

2.3 Limnology of Lake Rotoiti

In order to understand the impacts of possible management options on water quality in Lake Rotoiti it is important to understand the basic limnology of the lake, and in particular the complex biogeochemical pathways that control the nutrient concentrations and species within the lake. In this section we summarise the current understanding, focussing on the roles of the under/interflow and dissolved oxygen.

2.3.1 Overview

Lake Rotoiti is a deep monomictic[1] lake with biological and chemical cycles which follow the general patterns of similar lakes. Typically the lake thermally stratifies in spring (September-October) and destratifies in autumn with mixing in winter (June) when the lake is once more isothermal. During the stratified period, nutrients released from the sediments by biogeochemical processes accumulate in the hypolimnion. These are mixed throughout the lake in winter and are the nutrient supply that drives primary production in the lake in the following spring.

During the period when underflow conditions occur, that is primarily in winter, Lake Rotorua water is transported into the deep waters of the main eastern basin of Lake Rotoiti. When interflow is occurring, Lake Rotorua water is transported into the metalimnion of Rotoiti. Consequently, the water quality of Lake Rotoiti is strongly influenced by that of Lake Rotorua. These effects will be direct, because of the nutrient and phytoplankton load in the Lake Rotorua water, as well as indirect, because of the effect of the oxygen and BOD load in the density current on the biogeochemical processes in the hypolimnion. The range of possible effects will depend on the quality of the Lake Rotorua water at the time and whether it is transported into the hypolimnion, metalimnion or the epilimnion of Lake Rotoiti.

Algal productivity in the Rotorua lakes is sensitive to the availability of the plant growth nutrients nitrogen (N), as ammoniacal-N (NH_4-N) and nitrate-N (NO_3-N) — together these are referred to as dissolved inorganic-N (DIN), and phosphorus (P), as dissolved reactive P (DRP). There has been much debate as to whether N or P is the nutrient most likely to limit algal growth and it is generally agreed that for most of the year, N is more likely to limit algal growth than P. This relationship can change during winter when the accumulated nutrients from the hypolimnion mix throughout the lake, and for a brief period P may become limiting until the excess N is utilised.

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[1] Monomictic means the lake thermally stratifies and subsequently mixes once each year

In Lake Rotoiti, suggestions of a recent reduction in the ratio of N:P has become more important as nuisance blue-green algal species, which potentially have access to atmospheric nitrogen, may have an advantage over other species when the lake is strongly N-limited. Dominance by blue-green algal species is not a problem until they start to grow rapidly and their cell numbers exceed 2,000 cells/ mL, when the water is unsuitable for drinking due to unpleasant taste, odour, and potential toxicity problems (very low), or 15,000 cells/mL, when the water may be unsuitable for general contact recreation and stock watering. When these buoyant algae form surface scums, they are said to be a blue-green algal bloom.

2.3.2 In-lake processes

Most in-lake processes are regulated to some extent by the availability of oxygen. Following thermal stratification in spring, microbial decomposition processes consume oxygen and nutrients begin to accumulate in the hypolimnion. Dissolved inorganic nitrogen (DIN) and DRP normally come from decomposing organic matter and these are continuously released at a low rate from the sediments. Processes governing DRP and nitrogenous compounds are initially similar, but there are significant differences that emerge, particularly as oxygen is depleted (Priscu et al., 1986). In many lakes, release of DRP from sediments is enhanced under conditions of low oxygen concentration through dissolution of DRP bound up with insoluble Mn (IV) and Fe (III) oxides, as these are reduced to soluble Mn(II) and Fe(II) compounds. Nitrogen liberated through decomposition is initially released as NH_4-N, which, in the presence of oxygen, is oxidised to NO_3-N by nitrifying bacteria. This is often associated with the oxidised sediment surficial layer, but can also occur in the water column. Once oxygen is depleted the microbial community undergoes a shift and denitrifying bacteria reduce NO_3-N to the gases N_2O and N_2, which may then be lost to the system.

In most lake hypolimnia, all of these redox-related processes can occur simultaneously, but in different depth strata. Typically oxygen depletion is most rapid in deep waters, and denitrification can occur in anoxic waters at depth while nitrification may still be active at shallower depths. However, the existence of thermal convection within the Rotoiti hypolimnion reduces the extent to which vertical separation of microbial processes can occur. Some stratification of biogeochemical processes still occurs in the metalimnion (Priscu et al., 1986), but much less so within the hypolimnion.

2.3.2.1 DRP in Lake Rotoiti

In 1981-82, DRP concentrations in hypolimnion of Lake Rotoiti (Fig. 24) began to increase about the time thermal stratification stabilised and the underflow-interflow-overflow condition had switched mainly to an overflow condition, and continued at a similar rate all summer. This increase is therefore internally generated rather than a result of inflow. The rate of DRP increase in the stratified period of 1981 was very constant, at 0.38 mg m^{-3} d^{-1} (r^2 = 0.9, n = 25). Such constant rates against a background of declining oxygen argue against significant release of DRP through redox chemistry, in contrast to the “classical” situation described in section 2.3.2 above.

The sudden decrease in DRP concentration in June is consistent with winter mixing and dilution associated with dispersion throughout the lake water column and, potentially, incorporation into particulates. At mixing, similar concentrations of DRP (15 mg m^{-3}) were seen in surface and 60 m water, though during the stratified period surface DRP was reduced to approximately 2 mg m^{-3} (data not shown).

2.3.2.2 DIN in Lake Rotoiti

In 1981-82, the seasonal cycle of DIN accumulation in the hypolimnion showed an initial accumulation of NH_4-N in the hypolimnion after thermal stratification had stabilized and while the water column was still well oxygenated. (Fig. 25). This initial rate of accumulation was 3 mg m^{-3} d^{-1}, approximately eight times the rate of DRP accumulation. A stochiometry of 8:1 is consistent with mineralisation of algal derived material. Accumulation of NH_4-N in the presence of oxygen implies low populations of nitrifying bacteria at the sediment-water interface and within the water column at this stage of the annual cycle.

Critical evaluation of the timing of the DIN components (Fig. 25) shows that NH_4-N accumulation begins in mid-October, when stratification was intermittent and underflow could still be occurring. This is slightly before DRP began to accumulate in November (Fig. 24) and may be evidence of a hypolimnetic source of NH_4-N other than mineralisation, for example the underflow itself or geothermal water.

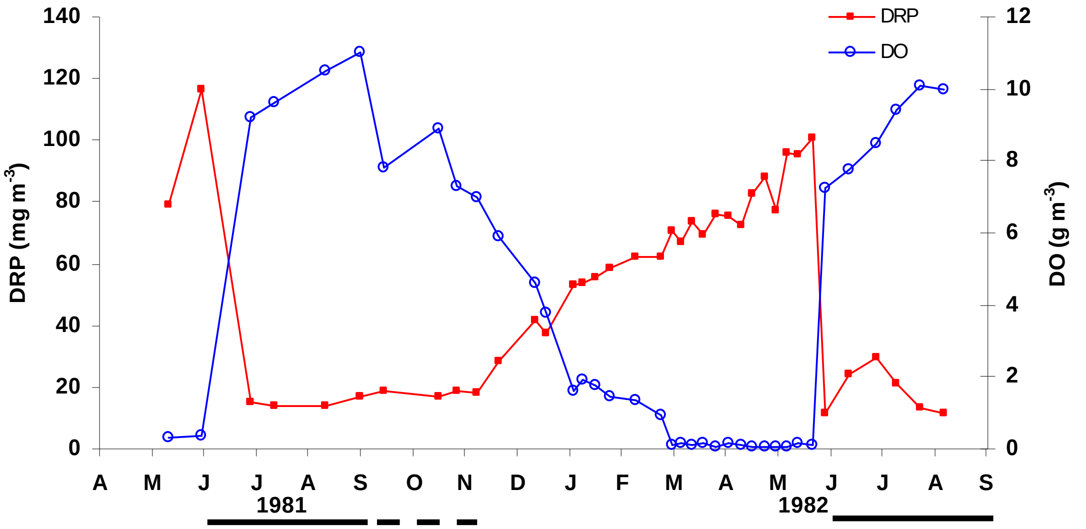

Fig. 24 Annual cycle of dissolved reactive phosphorus (DRP) in the hypolimnion (at 60 m) of Lake Rotoiti in 1981-82 relative to dissolved oxygen (DO) concentrations. Solid black bars indicate mixed period, dashed black bar indicates intermittent stratification and mixing events.

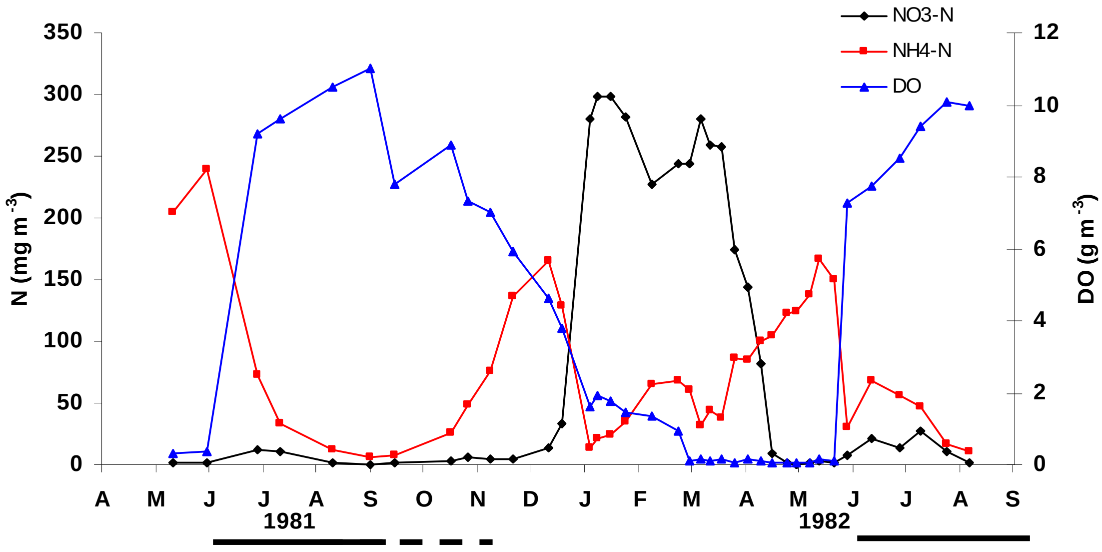

Fig. 25 Annual cycle of nitrate-N (NO_3-N) and ammoniacal-N (NH_4-N) in the hypolimnion (at 60 m) of Lake Rotoiti in 1981-82 relative to dissolved oxygen (DO). Solid black bars indicate mixed period, dashed black bar indicates intermittent stratification and mixing events. The sudden rise in DO in 1981 and in 1982 indicates complete lake mixing in winter.

The sudden loss of NH_4-N and appearance of NO_3-N in late December is consistent with onset of nitrification in the water column. The nitrification event in December-January would have consumed 1 mg m^{-3} of oxygen, perhaps responsible for the apparent increase in rate of oxygen decline at that time. For the next 2 months, until March, oxygen, NO_3-N and NH_4-N were all present in the hypolimnion and there was net accumulation of NH_4-N, but no net accumulation of NO_3-N. The hypolimnion suddenly became anoxic in March and one month later the accumulated NO_3-N was lost through denitrification (Downes 1988). Estimates of the amount of N lost, based on the volume of the hypolimnion and decline in NO_3-N, suggst that as much as 100 t may be lost through this process. After the lake mixed in June 1982, NH_4-N concentrations dropped rapidly, as would be expected by dilution and uptake, and largely paralleled DRP.

The data for DRP and DIN (Figs. 24, 25) appear to show accumulation of these nutrients in the hypolimnion as if they were suddenly being released from the sediments after stratification. There is no biological or geochemical reason for this given that the hypolimnion is still well oxygenated when the accumulation begins. In reality, DRP and DIN are continuously released from the sediments at about the same rate throughout the year but during the mixed period, these nutrients are dispersed throughout the lake water column and can be taken up and utilised by algae for primary production. Stratification largely isolates the bottom waters from the productive surface waters, preventing utilisation of the nutrients by algae and allowing the nutrients to accumulate. The question of timing and magnitude of release of DRP and NH_4-N from the sediments of Lake Rotoiti is an important one, since this defines the internal load of these nutrients. The data that currently exist do not allow a definitive statement to be made as to how release rates change with stratification and hypoxia.

2.3.3 Comparison 1981-82 with 2001-02

A comparison of 1981-82 and 2001-02 data shows remarkable similarities between these years, as well as some interesting differences. Most differences can be attributed to a paucity of data in 2001-02 compared to the intensive sampling of 1981-82

2.3.3.1 Oxygen

Comparison of dissolved oxygen concentrations for 1981-82 and 2001-02 (Fig. 26) show that the two data sets are essentially the same in both timing after the onset of stratification and for the rate of oxygen loss from the hypolimnion. This is consistent with observations made previously (Fig. 14).

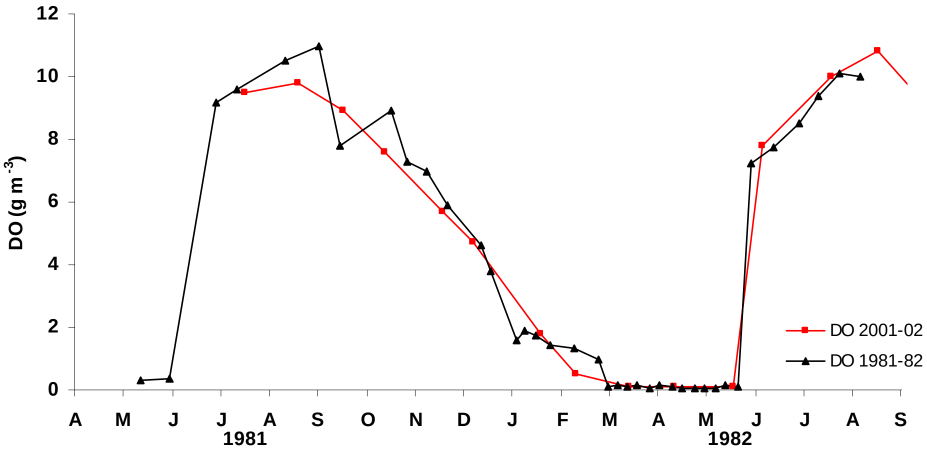

Fig. 26 Comparison of annual dissolved oxygen (DO) cycle in the hypolimnion of Lake Rotoiti in 1981-82 and 2001-02.

The greatest difference between the 2 years is the lack of variability in the 2001-02 data. This may simply reflect fewer sampling dates or it could be a function of less underflow-interflow transporting oxygen into the hypolimnion during the stratified period. In particular the apparent injections of oxygen in January/February of 1982 did not occur in 2001-02.

While underflows are highly unlikely at this time of year, it may be that mixing of metalimnetic water into the hypolimnion may be responsible. Notwithstanding this, contoured bathythermograph data (Gibbs 1988) show a cold water (<12 ºC) layer on the lake bed between December 1981 and March 1982 on most occasions.

Comparison of contoured data from the oxygen profiles for 1981-82 and 2001-02 (Fig. 27) appears to show more spring mixing events in 1981, delaying the onset of stratification relative to 2001-02. While these apparent differences may be related to less frequent sampling in 2001-02, injection of oxygen into the hypolimnion during the stratified period left measurable effects in the DO contour plot for 1981-82 (Fig. 27A).

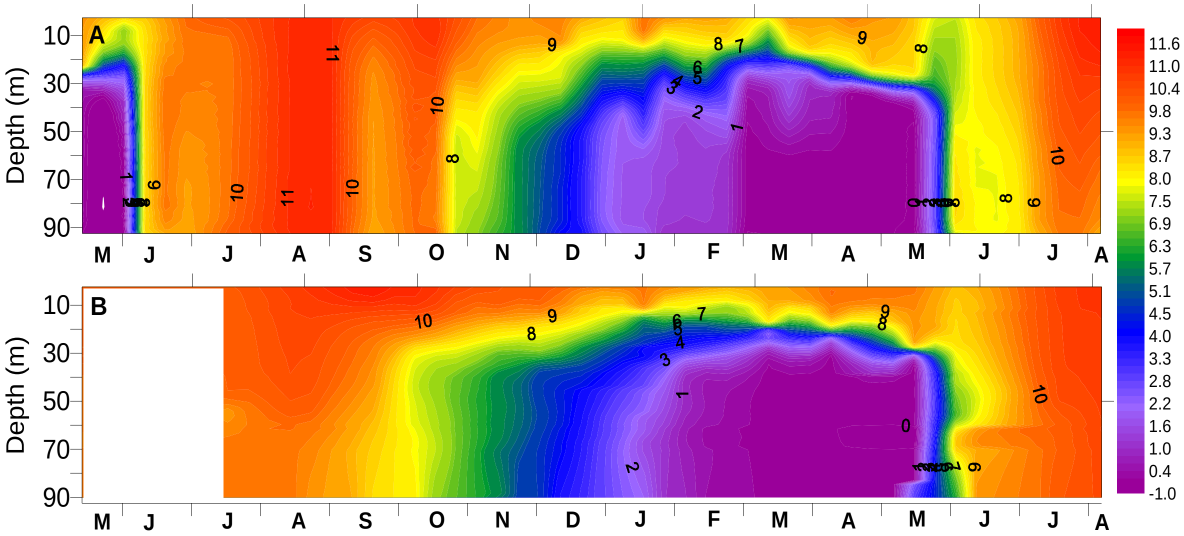

Fig. 27 Contoured oxygen data from **A**) 1981-82 and **B**), from 2001-02 using Surfer32 and linear Krigging for interpolation of measurements.

Obvious differences include the incomplete oxygenation to the bottom of the lake during winter mixing in 2001, and the absence in 2002 of oxygen injection into the hypolimnion during a spring mixing event (cf. 1981). Other indications of oxygen entrainment into the hypolimnion in summer (January and February) 1982 are also not seen in the 2001-02 data set. An apparent consequence of this may be an earlier occurrence of anoxic conditions higher in the water column in 2002, and less oxygen ultimately available to drive nitrification. If these differences are real, they support earlier suggestions that climate difference may affect the period of underflow and period and/or depth of insertion of interflows. Depth of insertion of interflows may affect the extent to which interflows ultimately interact with the epilimnion or hypolimnion (section 2.1.5).

2.3.3.2 DRP

Comparison of DRP concentrations in the hypolimnion for 1981-82 and 2001-02 (Fig. 28) show that, while the rate of accumulation is essentially the same, the start of that accumulation in 2001 begins about a month earlier than in 1981. Assuming the DRP increase begins when thermal stratification is stable, this is consistent with the onset of stratification about one month earlier in 2001 than in 1981 (Fig. 14).

Another major difference between the 2 years is that there is a substantial reduction in the DRP concentrations in late summer (April) in 2002, well before winter mixing in June (Fig. 27). The bottom water DRP concentrations continued to fall in winter mixing, but then began to rise while the lake was still re-oxygenating.

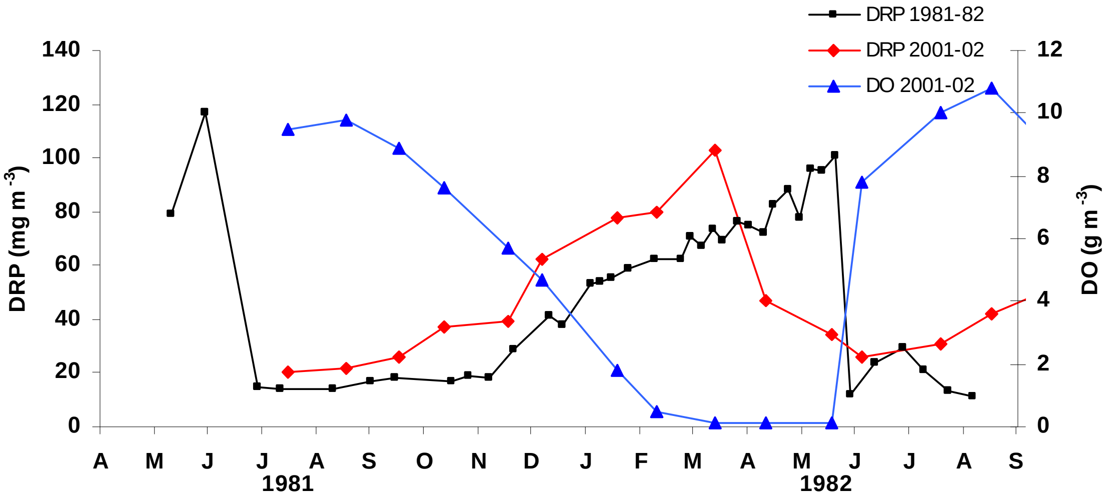

Fig. 28 Comparison of the annual DRP cycle in 1981-82 and 2001-02 relative to the 2001-02 DO cycle. [Sample depths 50-60m]

Although it is possible that sample handling procedures may have compromised these samples, this is very unlikely and the overall pattern suggests a strong external influence on the lake in autumn 2002. While there is no evidence of stratification breakdown in April 2002 (Fig. 14B), and there was no increase in oxygen, the sudden reduction in DRP concentrations may indicate entrainment of low-DRP water from the metalimnion associated with geothermal stirring or an interflow at that time. The contoured 2001-02 oxygen data indicate the lake didn't completely re-oxygenate in winter 2001 and the higher DRP concentrations in June and July 2002 may be associated with incomplete mixing.

2.3.3.3 DIN

Comparison of NH_4-N and NO_3-N concentrations in the hypolimnion for 1981-82 and 2001-02 (Fig. 29) show that, while the overall patterns of accumulation are essentially the same, there are differences in timing and magnitude which indicate that different processes may have been operating between 2001-02 and 1981-82.

Apart from higher levels of NH_4-N during the mixed period and possibly an earlier decline before mixing in winter 2002, there is essentially no difference between the two NH_4-N data sets even though they are 20 years apart in time (Fig. 29A). Conversely, there are substantial differences between the two NO_3-N data sets (Fig. 29B). In 2001 the NO_3-N concentration begins to increase in September when stratification first stabilises, then continues to increase through to February 2002 before declining to zero in April. The apparent difference may be inter-annual variability because NO_3-N data in 2002-03 do not show such high values in spring.

Of some significance is the similarity in the overall DIN species concentrations between the two data sets 20 years apart. The expectation for a lake experiencing advancing eutrophication would be for the amount or the rate of accumulation of NH_4-N in the hypolimnion to increase with time – which does not appear to be the case.

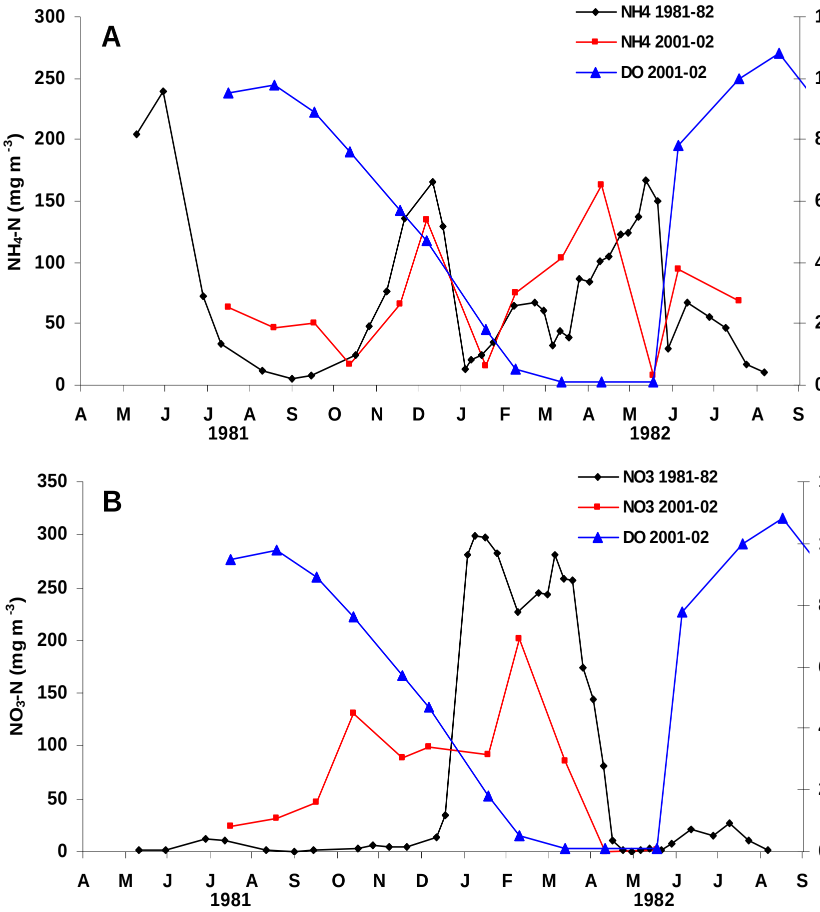

Fig. 29 Comparison of the 1981-82 and 2001-02 data for A), NH_4-N and B),NO_3-N relative to the 2001-02 DO cycle. [Sample depths 50-60m]

2.3.3.4 Algal biomass

Chlorophyll *a* (chla) concentrations provide an indication of algal biomass in the water column. Average chla concentrations in the upper 10 m of water column of the eastern basin of Lake Rotoiti were higher in 1981-82 than in 2001-02 (Fig. 30). The major differences between these years were the major diatom bloom of *Aulacoseira granulata* (formerly *Melosira granulata*) in spring 1981, which was a lesser event in 2001 and 2002, and the blue-green algal bloom of *Anabaena sp*. and *Microcystis aeruginosa* which produced a peak in the chla in late summer 1982, but not in 2002.

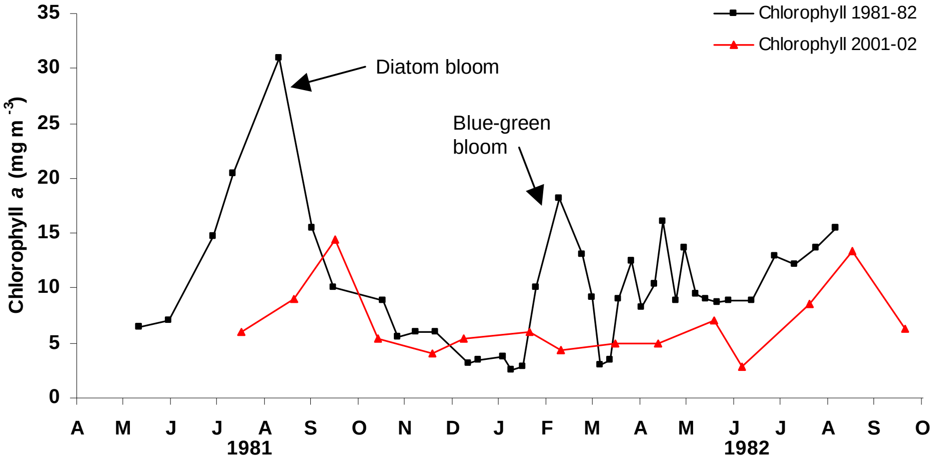

Fig. 30 Comparison of annual chlorophyll *a* concentrations in the upper 10 m of water column in the eastern basin of Lake Rotoiti in 1981-82 and 2001-02.

Blue-green algal blooms of public concern were found mainly in the western embayments of Lake Rotoiti (Okawa and Te Weta Bays) in summer 2002 and 2003. The spread of the bloom to the eastern basin occurred in 2003 (Fig. 31). The time-series chla data since 1991 from the western basin and eastern basin show a typical level of about 8 mg m^{-3} in both basins and the sudden increase to over 50 mg m^{-3} in the eastern basin in summer 2003. The chla concentrations in Okawa Bay (Fig. 31) exceeded 100 mg m^{-3} in 2002 and almost reached 250 mg m^{-3} in summer 2003.

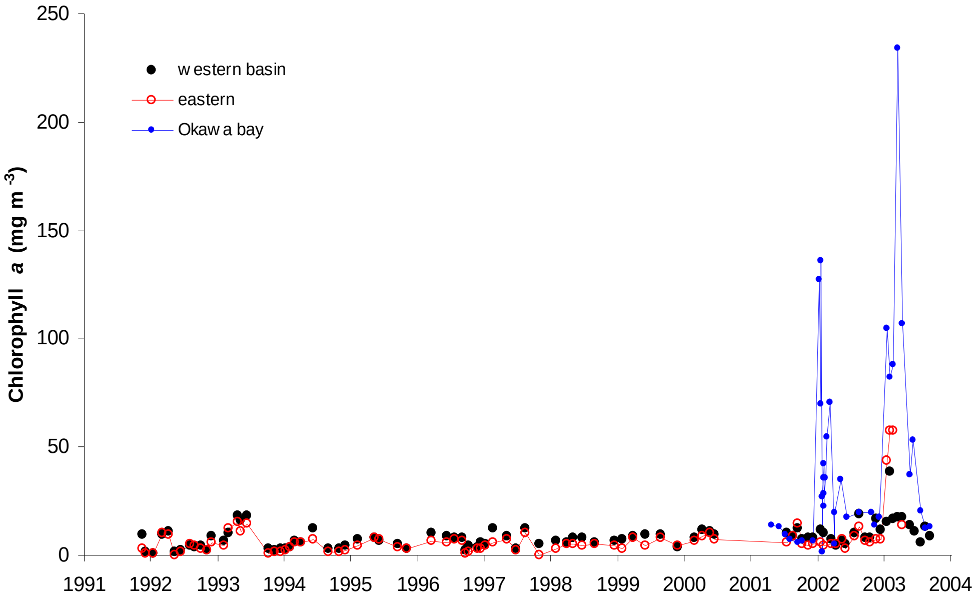

Fig. 31 Time-series chlorophyll *a* concentrations in the western and eastern basins from 1991-2003 and in Okawa Bay in summers of 2002 and 2003.

Development of algal blooms in sheltered embayments such as Okawa Bay is common and consequently, the increase in chla in the eastern basin could be attributed to the spread of the bloom from Okawa Bay through the western basin to the eastern basin of the lake. However, peak chla concentrations were higher in the eastern basin than the western (Fig. 31) so some growth must have occurred there.

The stoichiometry of algal growth means that development of 50 mg m^{-3} of chla would require an approximately similar amount of P, and about 500 mg m^{-3} of N. Understanding the origins of these nutrients in 2003 may help in understanding the cause of the blooms. Suggestions have been made that algal blooms in Lake Rotoiti may be linked to sediment release events in Lake Rotorua and the subsequent advection of this N and P, as well as algal inocula though the Ohau Channel and into the eastern basin. To achieve this would require the conjunction of mobilisation of high concentrations of nutrients through breakdown of stratification in Lake Rotorua with a period of interflow into the metalimnion in Lake Rotoiti, or wind-driven overflow. As breakdown of stratification is likely to accompany a strong wind event, this conjunction is seemingly possible. Data to examine linkages between Lake Rotorua DRP releases and chlorophyll *a* concentration in the western and eastern basins of Lake Rotoiti are limited to events in 1993, 1994 and 2003 (Fig. 32). The small release in 1993 was accompanied by chlorophyll *a* increases in Rotorua, and Rotoiti (both basins) but the large 1994 release event in Lake Rotorua was not.

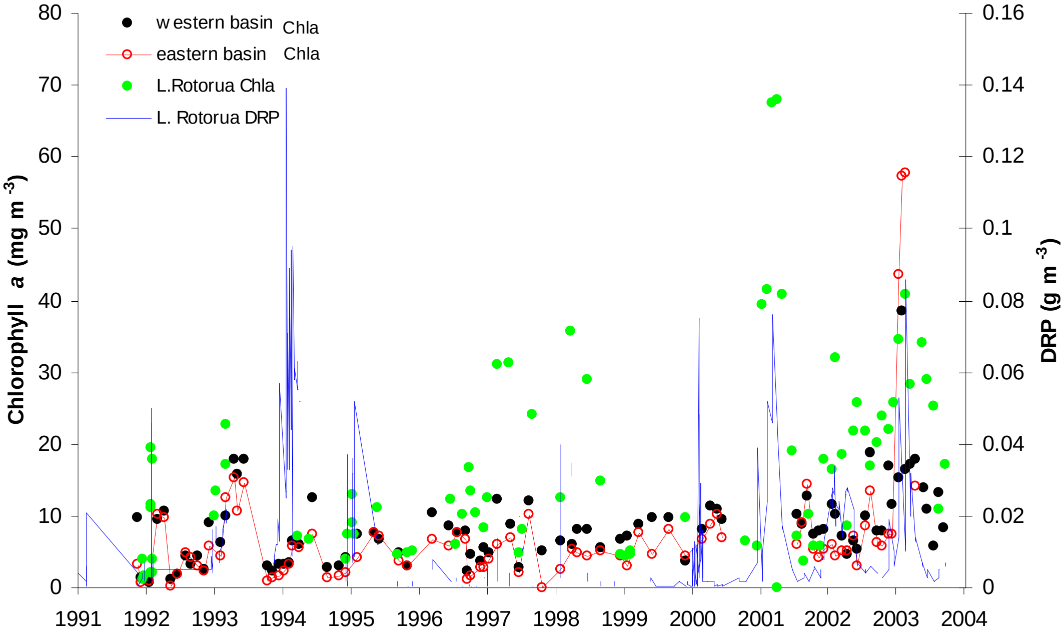

Fig. 32 Time-series relationship between DRP release events in Lake Rotorua in summer and chlorophyll *a* concentrations in Lake Rotorua and the western and eastern basins of Lake Rotoiti.

There are indications of chlorophyll *a* increases in Lake Rotorua associated with the DRP release events in that lake. However, although there are some corresponding chlorophyll *a* increases in the western basin of Lake Rotoiti, the chlorophyll *a* values there are much less than measured in Lake Rotorua. The chlorophyll *a* values in the eastern basin are lower than in the western basin except for the summer of 2003.

These data may be interpreted to indicate that the algal bloom in the eastern basin of Lake Rotoiti in 2003 was an unusual event. Winter nutrient accumulation would not seem to be sufficiently different to 1982 to expect such an event, and an external supply of nutrients may be implicated. Nitrogen fixation by heterocystous cyanobacteria is an attractive option, though interflows may also be implicated. The long-term monitoring data are not sufficiently robust to exclude or include the possibility of a direct link between events in Lake Rotorua and algal blooms in Lake Rotoiti.

2.3.4 Okawa Bay

Okawa Bay is a small, shallow embayment (Table 1) isolated from the side of the western basin of Lake Rotoiti (Fig. 1). The bay is noted for its calm conditions and for this reason it was used as landing place for the logs processed in the Rotoiti Timber Milling Company Ltd mill established in 1919 — the present Okawa Bay resort stands where the saw mill once stood and the present launching ramp is where the logs were dragged ashore (c.f. Auckland Weekly News, p42-43, 13 February, 1935). It is thought that large quantities of native timber sawdust were dumped into the bay from time to time.

Table 6 Okawa Bay nutrient loads in kg day^{-1} (t y^{-1}) from external and internal sources (Ray et al. 2002)

Catchment	TN	2.0	(0.7)	TP	0.2	(0.07)
Septic tank	TN	4.0	(1.5)	TP	1.2	(0.44)
Internal Loads:						
Summer *	DIN	23-124	(8.3-46)	DRP	1.2-15	(0.43-5.6)
Winter	DIN	11-30	(4-10.8)	DRP	0.2-3.6	(0.07-1.3)
Annual mean	DIN	17-77	(6-28)	DRP	0.7-9.3	(0.3-3.5)

Water quality problems have long been known in Okawa Bay. A recent study (Ray et al., 2002) identified internal load as a major contributor to the N and P load to Okawa bay (Table 6). A study 1972 (Fish & Bryers 1973) to investigate the likely effects of diverting the Ohau Channel through the bay as a method of improving the water quality of the bay through enhanced flushing. During that study, monthly data showed frequent loss of oxygen from the lower water column in summer (minimum recorded concentration of 6 mg l^{-1}), indicating that the bay was stratified. The 1972 stratification event was followed by an algal bloom of about 50 mg m^{-3} chla, though no such bloom was evident in 1973 (Fig. 33). In 2002 and 2003 oxygen depletion events also occurred, with at least one period of anoxia. The biomass of subsequent algal blooms was 3-5 times higher than in 1972 (Figs. 31 and 33).

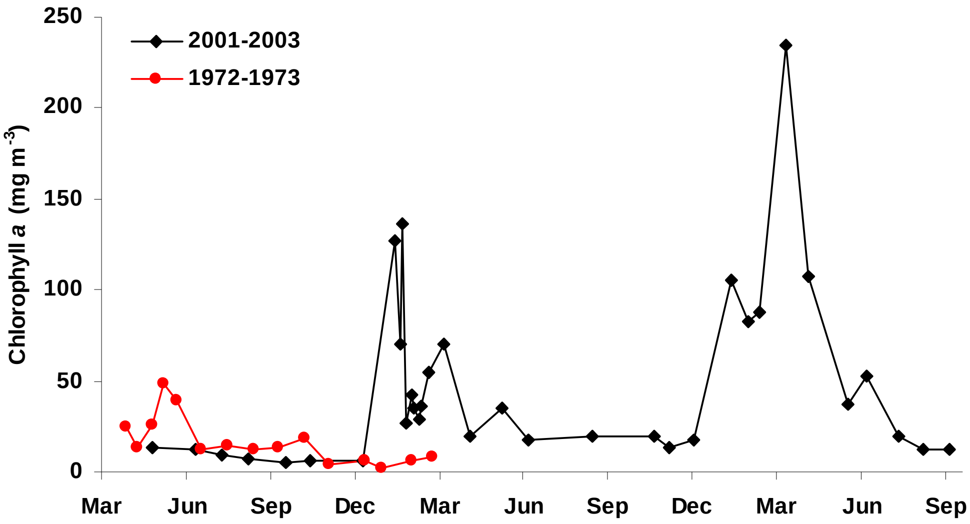

Fig. 33 Chlorophyll *a* concentrations in Okawa Bay in 1972 compared with 2002 and 2003.

The position of Okawa Bay – sheltered from the predominant south and westerly winds and the lack of exchange with the open waters of the western basin of Lake Rotoiti – means that nutrients released from the sediments are primarily available for primary production within the confines of the bay. The hydrodynamic studies by Ray et al. (2002) indicated that the exchange rate was low, and potentially as slow as 712 days, which allows the algae ample time for growth. Wind induced circulation potentially increased the exchange rate to about 3.7 days, which we would expect to prevent bloom development or disperse any existing bloom. Figure 33 suggests that conditions were calm enough in 2001-03 during summer to permit bloom development.

The hydrodynamic study included a simulation of the effect of introducing a 1 m^3 s^{-1} flow from the Ohau Channel to enhance the exchange rate of Okawa Bay. This was estimated to increase the exchange rate to about 18 days without wind-induced circulation or 3.1 days with the wind-induced circulation and exchange. Without wind, this is still insufficient to prevent the development of blue-green blooms.

Considering the climate changes noted above (section 2.2.4), warmer weather with longer periods of westerly winds will tend to favour more frequent anoxic events in summer and consequently, greater nutrient release and potentially more intensive blue-green algal blooms.

3 ASSESSMENT OF EFFECTS

3.1 Groyne structures into Lake Rotorua

Section 2.2 described the quality of the source water entering the Ohau Channel and by implication the western basin of Lake Rotorua. The water quality is affected by on-shore winds, which disturb the shallow sediments adjacent to the Ohau Channel outlet from Lake Rotorua and by the background quality of Lake Rotorua. The cross shelf data (Fig. 18) show that there is a node point about 200 m offshore where the wind effect is minimal. The concept behind the groyne structures into Lake Rotorua is to draw water from this zone rather than the more turbid inshore waters and thus reduce the sediment and nutrient loads passing through the Ohau Channel into Lake Rotoiti.

3.1.1 Effects on nutrient loads

Table 7 lists the proportion of suspended solids and nutrients in the Ohau Channel water that could be attributed to wind disturbance of the littoral sediments. They are derived from comparisons of concentrations 50 and 200 m from the Ohau Channel entrance (summer, Figures 17, 18), and from elevations over baseline as measured over a week in the Ohau Channel just downstream of the entrance weir (winter, Figure 16). If the groyne structure eliminated resuspension, this represents the quantitative reduction in nutrient flux that might be achieved

Table 7. Estimated % sediment and nutrient reductions that might be achieved by the proposed groyne structures in summer and winter. (ND= not determined)

	SS	Org-C	BOD	TN	DIN	TP	DRP
Summer (windy)	93	78	49	66	27	71	33
Winter (Ohau Ch)	85	59	ND	45	55	57	24

There is clearly a difference between these estimates, which probably reflects the method of calculation as well as the short-term measurement frquency. They may not be representative of the “typical” response to a wind-induced disturbance of the sediments. However, there are no other data which can be used to estimate the likely benefits of the groyne structures in terms of reduction of sediment and particulate nutrient loads. The small improvement in the DIN and DRP loads is also unlikely to be typical as these dissolved components are more likely to be derived from stratification events in Lake Rotorua or long-shore drift from the Hamurana or Waiohewa Streams than wind-induced disturbance of the sediments adjacent to the Ohau Channel entrance.

The winter estimate (Table 7) does not include any element which allows the difference between near-shore and offshore sediment and nutrient loads to be estimated and hence is only an indication of the difference in the loads between windy and calm conditions. While the 1990 data (Table 4) can only be reliably used to estimate the likely sediment and nutrient loads passing through the Ohau Channel that week, extrapolating the weekly data for a full year may give an indication of the maximum potential loads that might be transported e.g. sediment loads could be as much as 12,000 tonnes per year. From annual wind speed records (Table 5) it is apparent that the strong winds encountered in winter 1990 are not typical of the whole year and indeed, may not be reached at all in some years. Consequently, the annual loads associated with wind-induced disturbance of the sediments are likely to be less, but by how much is unknown.

3.1.1.1 Summary

Based on the existing knowledge, it is likely that implementing the groyne structure engineering option will substantially improve the water quality passing through the Ohau Channel in terms of the annual sediment, BOD, and total N and P input loads to Lake Rotoiti. There are likely to be lesser reductions in the annual loads of DIN and DRP as these can originate from sources other than wind-induced sediment disturbance, i.e., sediment release events in summer within the main body of Lake Rotorua and possibly long shore drift of these nutrients from either the Hamurana Springs or the Waiohewa Stream.

Adverse effects of the groynes will be accumulation of sediment and detritus (i.e., algal blooms, drifting weed, etc.) behind the structures on the lake shore and the requirement for periodic clearance and disposal. It is not certain whether preventing sediment movement into the Ohau Channel will result in rapid build up of sediment behind the groynes, or whether wind-induced suspension will be a relatively local effect once the current associated with the Ohau channel intake has been moved off-shore (i.e., the sediment is suspended but settles in the same general area).

3.1.2 Effects on temperature

There is evidence (section 2.1.3) of cross-shelf cooling of 2-3ºC during summer and edge water cooling in winter of about 3-4ºC relative to the open lake. However, the differences in temperature between 50 m and 200 m off-shore are small (Fig. 8) and it is likely that water temperatures in the Ohau Channel would not change substantially if the groyne structures extend to 200 m from shore. Thus there is no expectation that the groyne structures would substantially affect the hydraulic link between lakes Rotorua and Rotoiti. However, to extend the groynes across the full width of the shallow littoral zone to draw open lake water would potentially raise the Ohau Channel temperatures during winter and have a profound effect on the downstream underflow-interflow condition in Lake Rotoiti. Water taken from the open lake in winter is not subjected to night time cooling as it crosses the shallow shelf and thus has the thermal inertia of the main body of the lake to reduce temperature fluctuations.

3.1.3 Physical effects on the lake bed

There is currently no data available to assess the likely effects of the groynes on the lake bed at their termination off-shore. At 200 m off-shore, the lake depth is still less than 1m and hence wave action breaking against the groyne structures could enhance sediment resuspension and cause bed scouring if the currents induced between the groynes is sufficient to keep the sand in suspension, i.e., greater than 0.2 m s^{-1}. This is an engineering design feature beyond the scope of this report. Extension of the groynes to the edge of the shelf (600 m off shore) would increase the water depth to over 1.5 m at the entrance reducing the wave energy effects on the lake bed, and proportionally lowering the current speed between the groynes thus reducing the potential bed erosion.

A detailed model of the near-shore zone with hind-casting with a range of wind conditions is needed to more accurately quantify particulate loads and effects of the groyne structures once the design details are known. Validation data will be needed for a range of wind conditions and to evaluate potential long-shore drift.

3.2 Diversion structure in Lake Rotoiti

3.2.1 Hydrodynamics

Section 2.1 described the hydraulic coupling between Lake Rotorua and Lake Rotoiti. It also described the importance of the temperature differential between these lakes in determining where the Lake Rotorua water travels after leaving the Ohau Channel and its effect on the hydrodynamics of Lake Rotoiti. It clarifies the status of the so-called "underflow" condition. This is not a simple switch but a complex glissade of temperature-induced density conditions which cause the inflowing Lake Rotorua water to flow along the eastern basin lake bed in winter, over the surface of the western basin and mostly to the Kaituna River outlet at the height of summer, and insert as an interflow at any depth of equal density in between those two extremes.

The hydrodynamics of entrainment and the implied in-lake circulation patterns of the resultant density currents are also described in terms of likely effects on hydraulic exchange rates or residence times in the western and eastern basins of Lake Rotoiti. In 1985-86, the entrainment factor measured was 4.5 but this is dependent on the physical conditions of the inflow jet and the temperature induced density difference between the inflow and the lake water. As the temperature differential decreases, the entrainment and thus mixing increases, approaching "infinite" mixing when there is no density difference.

By definition, the quality of the water in the density current is proportional to the quality of the source water from the Ohau Channel and the water entrained from the western basin of Lake Rotoiti. At an entrainment factor of 4.5, the density current consists of 1 part Lake Rotorua water and 3.5 parts western basin water. Consequently, the water quality of the western basin of Lake Rotoiti dominates the nutrient mass transport in the density currents and circulation through the eastern basin of the lake. Changes in that water quality derived from the groyne structures (section 3.1) are likely have a long-term flow-on effect on the water quality of Lake Rotoiti.

It is unlikely that during underflow conditions, the density current will transport the entire nutrient load from the Ohau Channel directly into the eastern basin of Lake Rotoiti. This is because the reduction in velocity associated with water entering the western basin and the entrainment into the plume will allow most of the heavier particulate material to sediment out of the flow. This material will be biogeochemically processed in the sediments of the western basin and may subsequently be released as dissolved nutrients. These can then either be entrained into the density current and moved into the eastern basin, utilised within the western basin, or advected in surface water to the eastern basin or the Kaituna River. Remineralisation of Lake Rotorua nutrients from the western basin sediments is likely to be a significant source of nutrient enrichment to the eastern basin, though as yet it has not been measured.

While the possibility of diurnal alternation between underflow and overflow at the Ohau Channel discharge into the western basin of Lake Rotoiti was known, little consideration had previously been given to consequences of small density changes associated with climate-induced temperature differences, especially at night. These have the potential to cause a shift in the proportion of interflow entering the hypolimnion and epilimnion of the eastern basin of Lake Rotoiti. Consequently, assessments of the likely effects of the diversion engineering option (2) must be couched in general terms rather than specific terms on the basis of current data availability.

3.2.2 Summary of the effects of the density flows

The effects of the coupling between lakes Rotorua and Rotoiti are complex and variable, depending on the exact dynamics of the day. Overflow to the Kaituna River is the simplest condition, which tends to occur in summer and to favour;

- Increased lake-wide residence time in both eastern and western basins
- Minimal flow of Rotorua nutrients to Rotoiti
- Minimal flow of western basin nutrients to the eastern basin
- Reduced reoxygenation during overturn
- No possibility of oxygen injection to the hypolimnion in spring,

Underflow into the hypolimnion tends to occur in winter and;

- Enhances oxygenation of deep waters,
- Delivers Rotorua and western basin nutrients to the eastern basin

- Enhances winter flushing of the eastern and western basins

Interflow occurs primarily in spring and autumn. Effects tend to vary with the depth of insertion, but in general interflow;

- Generates a return flow of ~75 m^{-3} s^{-1} from the epilimnion of the eastern basin[*]

- Enhances flushing of the eastern, and particularly the western basins

- Injects nutrients and algae into the metalimnion, which will tend to be mixed into the epilimnion and may promote algal growth

- May enhance oxygen flux to the hypolimnion

Thus, all three primary scenarios have both beneficial and adverse impacts on Lake Rotoiti. In the following sections we generalise on the likely impacts of diversion of the Ohau Channel into the Kaituna River, with and without oxygenation of the hypolimnion.

Oxygenation is intended to be sufficient to maintain a minimum oxygen concentration of 5 g m^{-3} in the hypolimnion throughout the stratified period, as discussed at the meeting 21 November 2003 at Environment Bay of Plenty offices, Rotorua.

3.2.3 Assessment

Because of the climate change / difference uncertainties identified (sections 2.1.5 and 2.2.4), and the flow-on effects of a groyne structure at the Lake Rotorua end of the Ohau Channel, the effects of diversion of the Ohau Channel to the Kaituna River outlet are best treated by weight of evidence of likely benefits versus disadvantages with and without the groyne structures. The effects of the diversion on the water quality of Lake Rotoiti are likely to include the following:

- A complete removal of the load of total nutrients, potential algal inoculum, and BOD directly into eastern basin of Lake Rotoiti from Lake Rotorua. Based on the estimates of Donovan & Don (1991), total diversion would

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[*] Assumes an entrainment factor of 4.5. This is likely to increase with reducing temperature differentials.

result in a reduction of 181 tonnes and 25 tonnes, or 73% and 76% of the annual N and P loads, respectively, on the eastern basin of Lake Rotoiti. As these loads are implicated in the decline of Lake Rotoiti water quality, their removal should be beneficial to the long-term water quality of Lake Rotoiti.

- A complete removal of the oxygen supply in the density current to the hypolimnion. As oxygen regulates many of the in-lake processes, this may be a disadvantage. However, given the evidence of recent differences in the hydraulic regime, this may not be critical and could potentially be replaced by oxygenation.

- The extent to which diversion or oxygenation is likely to affect the rate of DRP accumulation in the short term is not clear from the current data. This depends on the uncertain extent to which redox potential of the overlying water affects DRP release. If the supply of organic material to the lake sediments is reduced through long term nutrient load reduction, this will slowly decline (decades).

- Diversion will not immediately affect DIN regeneration, though the potential for reduced spring oxygen supply may result in less oxygen available for nitrification. This would reduce the amount of N that could later be lost through denitrification, thus allowing a slight increase in the accumulation of NH_4-N. With oxygenation to 5 g m^{-3}, however, this effect would not occur, rather remineralised N would tend to accumulate as NO_3-N, with less lost through denitrification than under the current regime.

- The two points above suggest that, after winter mixing, in the post-diversion + oxygenation scenario the lake would be left with concentrations of DRP and NO_3-N broadly similar to those at present. Winter/spring blooms of diatoms normally occur under such conditions in New Zealand North Island lakes, and sedimentation of the diatoms is likely to remove a higher proportion of nutrients from the epilimnion, leaving relatively clear water.

- Diversion will result in a substantial reduction in the annual nutrient and BOD load to the sediments of the western basin of Lake Rotoiti. Potentially, diversion will reduce the sediment load to the western basin by as much as 10,000 tonnes per annum. This must be beneficial to the western basin as there will be less regeneration of the associated nutrients. It will also benefit the local embayments — Te Weta Bay and Okawa Bay — as the water entering the bays will have lower nutrient concentrations than at present. As nutrients drive the production of algal blooms, in the long term, the future expectation would be for a reduction the magnitude of algal blooms as the nutrient reservoir in the bay sediments is slowly depleted. Conditions in the bays will remain favourable to blue-green algae for some time, and once blue-green algal blooms have occurred, there is always a greater chance that these will occur again given the "right" conditions.

- A transfer of the total nutrients, potential algal inoculum, and BOD load more directly to the Kaituna River. Current indirect flow from the Ohau to the Katuna, even during overflow conditions, may trap these components in Lake Rotoiti. This is likely to have immediate and persistent adverse effects on the Kaituna River. However, given that the construction of groynes in Lake Rotorua is likely to substantially reduce the loads of these components through the Ohau Channel, implementation of both engineering options may cancel the adverse effects on the Kaituna River.

- A decrease in the net hydraulic exchange or residence time from 2.3 years to 6.4 years in the eastern basin. As hydraulic exchange is the main mechanism for removing nutrients and restoring a degraded lake, reducing the exchange rate by almost 3-fold must be regarded as disadvantageous. However, this disadvantageous effect would only result if the underflows had a net negative effect on nutrient concentration – if they introduced more nutrients than they displace it would not occur. At present the underflows may be a net source of nutrients. Should attempts to reduce nutrient concentrations in the underflows be effective, the situation could be reversed. The balance of these effects requires further modelling to elucidate.

Most negative impacts tend to be associated with shallow interflows. These dilute the eastern basin water with lower quality Lake Rotorua / western basin water in spring and autumn. The only beneficial effect is through enhanced exchange rates and reduced residence times, though a net gain of nutrients by this route is expected all the while summer N and P in Rotorua exceed Rotoiti. An intermittent diversion to be active only during interflows may be a valid option, though further modelling would be required to validate this and engineering assessments required to assess its practicality.

There can be no clear-cut statement on the benefits of the diversion of the Ohau Channel to the Kaituna River as there are too many unknowns and climatic differences in recent years that may have changed the hydraulic regime from what was conceptualised in the 1980s, to a new regime. It can be said that if the groynes, diversion, and oxygenation options are implemented together, there is likely to be a substantial improvement in the water quality of Lake Rotoiti in both the short and long term.

This does not mean to say that there will not be algal blooms in the future. There is a legacy of nutrients in the sediments of Lake Rotoiti which can only very slowly be depleted or buried. Conditions will occasionally favour the release of these and thus a bloom may develop. The changes to the limnology may, however, favour another algal species rather than blue-greens.

To improve the assessment of the likely effects of these engineering options, the system needs to be modelled and validation data is needed for the present conditions.

3.3 Okawa Bay diversion option

Section 2.3.4 described Okawa Bay with respect its water quality and the history that most likely led to the deterioration that has been evident for many years. The data clearly show that nutrient cycling from the sediments dominates the nutrient supply to this embayment and hence internal loads drive the algal productivity in the bay. The hydrodynamics of the bay were previously modelled for an inflow of 1 m^3 s^{-1} of Ohau Channel water with wind-induced exchange flows of up to 5 m^3 s^{-1}. This was sufficient to achieve an exchange rate where blue-green algal could grow but not develop to bloom abundances. Modelling the 1 m^3 s^{-1} diversion with exchange flows of 10 m^3 s^{-1} increased the exchange rate to 1.7 days which was further beneficial in reducing algal accumulation (Ray et al. 2002), and is likely to result in Okawa Bay water being little worse than western basin water. The impact of this rapid flushing on the western basin has not been assessed, but it would presumably represent an additional source of nutrients at least in the short term.

Diversion of the whole Ohau Channel flow through Okawa Bay requires a different scenario as the 15 m^3 s^{-1} inflow would most likely prevent wind-induced exchange currents and thus eliminate the advection of the residual nutrient load and algal biomass from the western basin into Okawa Bay. The whole Ohau Channel diversion would increase the exchange rate to 1.2 days and thus the water quality would most likely become similar to that of Lake Rotorua.

The likely effects of the diversion would depend on the design and positioning of the diversion channel into Okawa Bay and whether there was an additional or alternative outlet cut through the isthmus between the land and the cemetery on Motutawa Point.

A potential effect of this diversion would be to alter the temperature of the Ohau Channel water and also the hydraulic regime sufficiently to eliminate the possibility of density current formation for the water as it moves into the western basin. This scenario would result in the whole nutrient load from Lake Rotorua circulating in the western basin where it might be blown by westerly winds into the surface waters of the eastern basin.

One important consideration is that diversion of the Ohau Channel through Okawa Bay would almost certainly preclude control of the water and diversion to the Kaituna River outlet as an option. However, modelling may demonstrate that, in combination with the groyne structures in Lake Rotorua, to reduce sediment and nutrient loads, and an alternative exit from Okawa Bay, this option may enhance the exchange rate through the western basin and provide a long-term improvement in overall water quality at the western end of Lake Rotoiti. Oxygenation and other considerations for the eastern basin as for the diversion to the Kaituna River option (section 3.2) would still apply.

Much of the above is informed speculation and a 3-D model of these scenarios would be required to provide a more informed evaluation of effects.

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