Okawa Bay Water Quality Study

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Authors
David Ray
Max Gibbs
Niall Broekhuizen
Kit Rutherford
Scott Stephens

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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 Sandy Elliott	Dr Kit Rutherford

Formatting checked

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Executive Summary

In recent years Okawa Bay has periodically experienced algal blooms during spring and summer, which on occasion have required warning signs to be erected by Rotorua District Council (RDC) advising against contact recreation. In an effort to reduce these blooms, RDC is investigating the options of replacing the septic tanks around Okawa Bay with a sewerage scheme, and/or diverting some flow from the Ohau Channel into Okawa Bay to improve water quality in the Bay. RDC engaged NIWA to assess how much these management options would improve water quality in the Bay.

The results of our field work and computer modelling indicate that, in the short term (i.e., <10 years), the removal of sewage and a 1 $m^3 s^{-1}$ diversion flow from the Ohau Channel would reduce typical summer algae concentrations by only about 15%. There are two main reasons for this finding:

a. The inflow of nutrients from the bed of Okawa Bay presently dominates the nutrient load on the Bay.

b. There is a large 'exchange flow' between Okawa Bay and the Western Basin of Lake Rotoiti, which limits the effectiveness of sewage removal and the Ohau Channel diversion.

The algal bloom problem in Okawa Bay is strongly influenced by the shallow, sheltered nature of the Bay. We have not modelled the situation when blooms occur because there is insufficient information about the release of nutrients from the lake bed or exchange flow during blooms. However, in our opinion removal of sewage will not affect blooms in the short term because of the large nutrient releases from the bed. We also believe that the diversion flow of 1 $m^3 s^{-1}$ will not affect blooms because it will not reduce the residence time of the Bay sufficiently.

It is more difficult to predict how the management options would affect algal blooms in the long term. However, it has been shown in other lakes that there is a link between sewage inputs and the amount of nutrients released from the lake bed. For example, modelling of Lake Rotorua suggests that over time the release of nutrients from the lake bed will reduce, and water quality will gradually improve, although these changes will probably take a matter of decades. This process may also operate in Okawa Bay on a similar time frame.

Furthermore, water quality in Okawa Bay is strongly affected by the water quality in the Western Basin because of the large exchange flow between the two water bodies. As water quality in Lake Rotorua (and hence the Western Basin) gradually improves, we would expect flow-on benefits in Okawa Bay.

In conclusion:

1. In the short-term (i.e., <10 years) the removal of sewage and/or the introduction of a 1 $m^3 s^{-1}$ diversion flow from the Ohau Channel is unlikely to substantially reduce algal blooms in Okawa Bay.

2. In the long term: (a) improvements in water quality in Lake Rotorua and the Western Basin, and (b) removal of sewage inputs to Okawa Bay (which should reduce the amount of nutrient released from the lake bed) are likely to benefit Okawa Bay, although these improvements have not been quantified.

Technical Summary

Introduction

Okawa Bay is a small (45 ha) shallow (maximum depth 5 m) embayment connected by a narrow channel to the Western Basin of Lake Rotoiti. It is close to the Ohau Channel, through which Lake Rotorua discharges into the Western Basin.

In recent years Okawa Bay has periodically experienced algal blooms during spring and summer. On occasions the concentration of blue-green algae has reached a level that required warning signs to be erected by Rotorua District Council (RDC) advising against contact recreation.

It has been suggested that the blooms could be caused by the input of nutrients from sewage disposal systems around the Bay. Because of this, RDC is investigating the option of reticulating the sewage and providing a treatment and disposal system. RDC is also considering diverting some flow from the Ohau Channel into Okawa Bay, in an attempt to improve water quality by reducing the residence time of the Bay and raising dissolved oxygen levels, thereby reducing sediment nutrient releases.

Before finally committing to the sewerage scheme or diversion flow, RDC wishes to clarify (as much as is possible) how much these management options would improve water quality in the Bay. NIWA was engaged by RDC to address these questions.

Our study included monitoring currents and temperature (8 to 28 March 2002 and 22 July to 7 August), wind measurements (18 January to 28 March), and intensive field investigations (19 to 22 February and 22 to 26 July). Results from these field studies, together with water quality data provided by Environment B·O·P, were used to develop a nutrient/phytoplankton computer model. The model was then used to make predictions about the potential for water quality improvements from the proposed management options.

History of blooms at Okawa Bay

We have been unable to locate any quantitative information on the water quality of Okawa Bay prior to 1997. This makes the assessment of long-term water quality trends in the Bay difficult. However, anecdotal evidence suggests that Okawa Bay was relatively stable prior to 1980, with good water clarity and extensive macrophyte (weed) beds. The Bay has been subject to significant fluctuations in both water clarity and macrophyte abundance since the early 1980s to the present day. Blue green algal blooms (some severe) have occurred during the summer months in most years since regular monitoring by Environment B·O·P began in 1997.

Possible causes of blooms

Recent algal blooms in Okawa Bay have been more serious than in the Western Basin of Lake Rotoiti. Possible reasons that we have considered include:

1. The input of nutrients from sewage disposal systems around the Bay.
2. Nutrient-rich ‘warm’ geothermal and/or ‘cold’ groundwater inflows to the Bay.
3. A long residence time of water in the Bay resulting from small inflows, which allows time for algal biomass to build up.
4. The Bay is relatively shallow which means that the full depth of the water column receives enough light for phytoplankton growth, whereas this occurs in only the top half of the water column in the Western Basin.
5. Episodic anaerobic nutrient releases from the sediments of Okawa Bay during summer. Because of its sheltered nature, stratification and anaerobic sediment nutrient release events are more likely in the Bay than in the Western Basin. Because the Bay is shallow, any nutrient release from the lake bed results in greater water-column-average concentrations within the Bay than in the Western Basin. As a result, phytoplankton growth rates may be higher.

Results of fieldwork

We deployed benthic chambers in summer and winter (19-22 February and 22-26 July) to measure nutrient releases from the lake bed, and found a persistent aerobic release of nutrients from the sediments during both periods. We have used the results of these deployments to calculate the release rate of nutrients from the sediments across the whole bed of the Bay, as follows:

	Summer	**Winter**	**Annual average**
NH_4-N	23-124 kg N day^{-1}	11-30 kg N day^{-1}	17-77 kg N day^{-1}
DRP	1.2-15 kg P day^{-1}	0.2-3.6 kg P day^{-1}	0.7-9.3 kg P day^{-1}

The larger estimated nutrient release in the summer is consistent with the effect of increased temperature on biological processes.

It is important to note that our summer field work did not coincide with a severe algal bloom, such as the one that occurred between 16 and 21 January 2002, although algal concentrations during the field work were high (about 35 mg m^{-3} chla). Our field work results are instead representative of typical summer conditions.

The expected nitrogen inflow from the catchment (excluding septic tanks), given the catchment area and land use is 2 kg day^{-1}, while the inflow from sewage is estimated to be 4 kg day^{-1}. Therefore our estimates of annual-average nutrient releases from the bed are much larger (4 to 19-fold) than inputs to the lake from the septic tanks.

Our fieldwork has largely discounted the possibility of the bed nutrient release being sourced from geothermal or cold water springs. We postulate that a sediment nutrient ‘pool’ has built up over many years, probably as algae and macrophytes die and sink onto the lake bed. This sediment ‘pool’ is likely to be continually recycling between the water column and the sediments. We have measured only the release of nutrients from the sediments to the water column; deposition will also be occurring (e.g., in autumn when the macrophytes die back and decompose on the lake bed, and when algae sink and die after a bloom).

We also assessed the exchange flow between Okawa Bay and the Western Basin using current meters, drogues and dye releases. These measurements suggested an exchange flow during March and August of between 0 and 10 $m^3 s^{-1}$, with a mean flow of about 5 $m^3 s^{-1}$. We developed an uncalibrated hydrodynamic model to assess how much this exchange flow mixes with the whole body of the Bay. Results from the model suggest that, while wind is blowing, there is likely to be considerable horizontal mixing of the waters within the Bay. This conclusion is supported by water quality measurements at three different locations in the Bay.

Results of nutrient/phytoplankton modelling

Using data from our benthic chamber and exchange flow measurements under typical summer conditions, computer nutrient/phytoplankton modelling indicates that, in the short term (i.e., <10 years), removing sewage and introducing a 1 $m^3 s^{-1}$ diversion flow from the Ohau Channel will only reduce algal concentrations in the Bay by about 15%. There are two main reasons for this finding.

1. The bed inflow of nutrients (as inferred from our chamber measurements) dominates the nutrient load on the Bay, and was assumed to be unaffected by sewage removal or diversion.
2. The high exchange flow between the Bay and the Western Basin limits the effectiveness of local initiatives such as sewage removal and the Ohau Channel diversion.

Discussion

Our computer model predictions are sensitive to nutrient inflow through the lake bed. Environment B·O·P has measured large bed nutrient releases in the Bay during summer stratification, probably as a result of sediment anoxia, but we did not observe this phenomenon during our study. Nutrients released from the bed at such times are likely to aggravate algal blooms. Our modelling assumed a constant release rate from the bed, set equal to the average value measured in late February 2002. If nutrient releases are higher than this value (e.g., because of lake stratification and anoxia), then higher algal bloom biomass may occur than we have predicted. Conversely, if bed nutrient releases are lower (e.g., if they decrease over time as a result of management) then lower bloom biomass may occur.

We have not modelled the situation when blooms occur because there is insufficient information about the release of nutrients from the lake bed or exchange flow during blooms (our field work was carried out during typical summer conditions rather than during bottom-water anoxia or severe bloom conditions). However, in our opinion removal of sewage will not affect blooms in the short term because of the large nutrient releases from the bed. We also believe that, even if there is little exchange flow during bloom conditions, the diversion flow of 1 m^3 s^{-1} will not affect blooms because it will not reduce the residence time of the Bay sufficiently. With a diversion flow of 1 m^3 s^{-1} and no exchange flow, the residence time of the Bay would be approximately 18 days, while the algae population can double in one or two days.

Total nitrogen concentrations are consistently lower in the Western Basin (c. 400 mg m^{-3}) than in Okawa Bay (c. 600 mg m^{-3}). This difference implies that there is a net export of many tonnes of nitrogen from Okawa Bay into Lake Rotoiti via the exchange flow between the two water bodies. An important unanswered question is why the export of nitrogen is so high, given that the catchment and septic tank nutrient load to Okawa Bay is estimated to be only 6 kg N day^{-1} (2.2 t N yr^{-1}). There are two possible explanations: either (1) nutrient release is currently ‘mining’ historic nutrient out of the bed sediments in Okawa Bay, or (2) there is an unidentified source of nutrient replenishment. The latter could include settling of algae blown into Okawa Bay from Lake Rotoiti and/or rooted macrophytes that obtain nutrients from deep within the lake sediments and then release them into the lake when they die.

If nutrient is currently being ‘mined’ from the sediment and external nutrient loads are reduced (e.g., by reduced inputs from Lake Rotorua, and/or diverting septic tanks away from the Bay), then over time sediment nutrient levels and hence nutrient release rates can be expected to decrease. It has been shown in other lakes that reducing sewage inputs can reduce sediment nutrient releases, but the response time is often very long. For example, in Lake Rotorua it is predicted that reductions in sediment release are unlikely to be detectable for 10-20 years and are not expected to reach pre-1970s levels for c. 100 years after sewage diversion. The same process may occur in Okawa Bay in a similar time frame, but it was not possible to quantify this in this study.

Our computer model predictions are also sensitive to exchange flows at the Okawa Bay entrance. If water quality is low in the surface waters of the Western Basin (e.g., because Ohau Channel water accumulates on the surface) this adversely affects water quality in Okawa Bay. Conversely, high quality water in the Western Basin (e.g., because Ohau Channel water plunges into the bottom waters of the Western Basin) benefits Okawa Bay. Sewage diversion away from Lake Rotorua has resulted in improved water quality in the Ohau Channel and this trend can be expected to continue slowly over time as sediment nutrients decline in Lake Rotorua. We have postulated that nutrients from the Western Basin may accumulate in Okawa Bay (either through settling or uptake by macrophytes). Therefore as water quality gradually improves in the Western Basin, we would expect benefits in Okawa Bay.

Conclusions

1. In the short-term (i.e., <10 years) the removal of sewage and/or a diversion flow of 1 m^3 s^{-1} from the Ohau Channel is unlikely to substantially reduce algal blooms in Okawa Bay.

2. The reasons are that: (a) nutrient release from the lake bed currently dominates the nutrient load; (b) the high exchange flow between the Bay and the Western Basin limits the

effectiveness of the proposed management options; and (c) even when exchange flows are small, a 1 $m^3 s^{-1}$ diversion flow would not sufficiently reduce the residence time of the Bay.

3. In the long term: (a) improvements in water quality in Lake Rotorua and the Western Basin, and (b) removal of sewage inputs to Okawa Bay (which should reduce nutrient releases from the lake bed) are likely to benefit Okawa Bay, although these improvements have not been quantified.

1. Introduction

1.1 Background to the study

Okawa Bay is located at the western end of Lake Rotoiti (Figure 1.1). The Bay has an area of about 45 ha, and is almost completely encircled by land, with a narrow (c. 150 m) channel to the main body of Lake Rotoiti. There are no major surface water inflows to the Bay, and the catchment area is only about 115 ha (including the Bay itself).

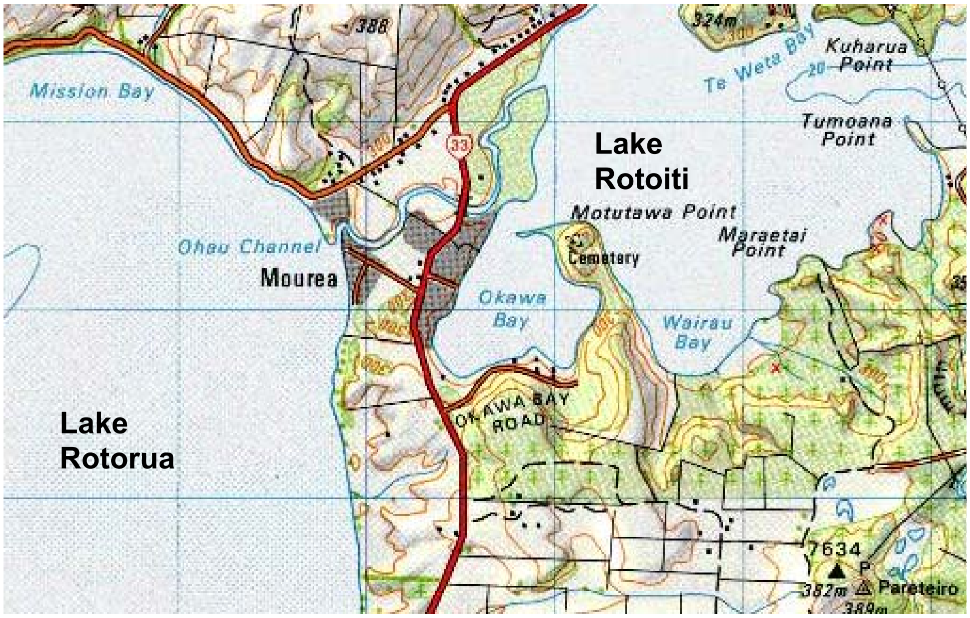


Figure 1.1: Okawa Bay locality plan

The maximum depth in the Bay is approximately 5 m, and the volume is approximately 1,600,000 m^3. A bathymetric map of Okawa Bay was plotted during our preliminary investigations in 2001, and is shown in Figure 1.2.

There are a number of private dwellings on the western and southern shores of the Bay. In addition, there is a resort lodge at the south-western corner of the Bay (the Okawa Bay Lake Resort), and a Marae located to the west of the entrance to the Bay. The residences and Marae are serviced by septic tanks. The Okawa Bay Lake Resort has a wastewater treatment system that discharges into the Bay.

In recent years Okawa Bay has periodically experienced algal blooms during spring/summer (Wilding 2000). These vary in duration and intensity, probably depending on a range of climatic conditions. On occasion, the concentrations of blue-green algae reach a level that requires warning signs to be erected by Rotorua District Council (RDC) to advise against contact recreation.

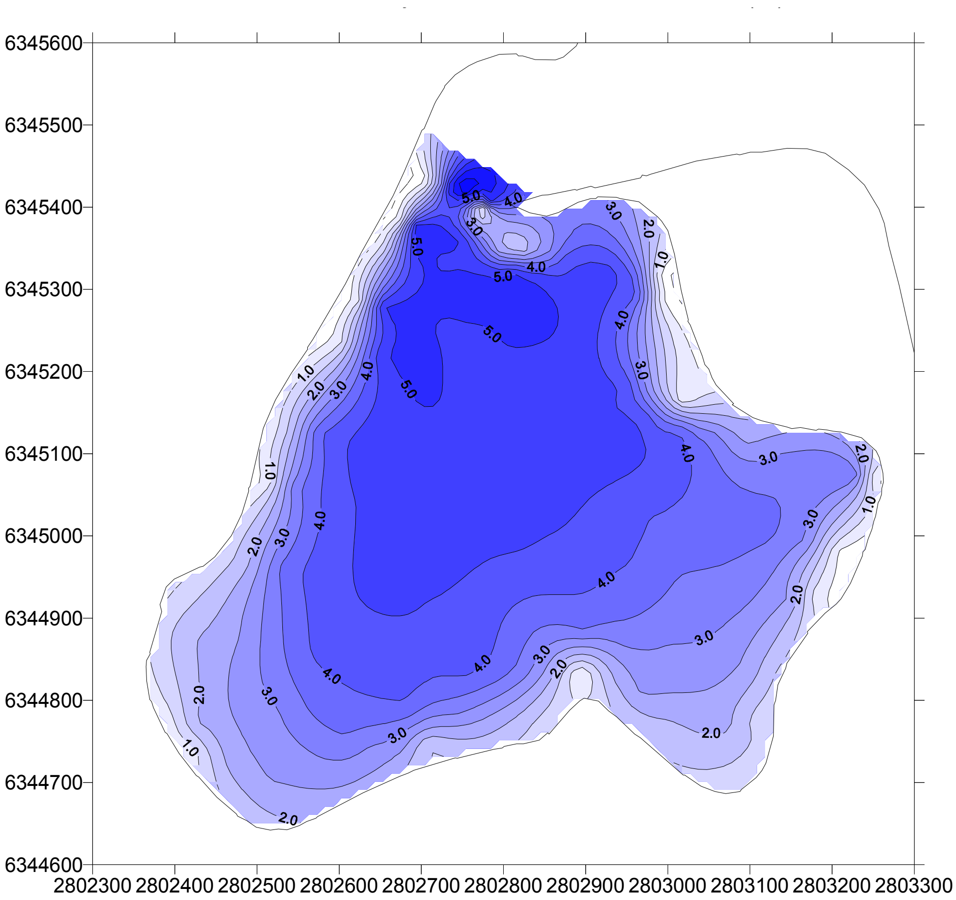


Figure 1.2: Depth contours for Okawa Bay (0.5 metre intervals), measured by NIWA in 2001. X and Y axes show NZMS map co-ordinates (100 m per division).

The reasons for the algal blooms are uncertain. One factor that has been considered by RDC is the input of nutrients from sewage disposal systems around the Bay. Because of this, RDC is investigating the option of reticulating the septic tank discharges and diverting the discharges to a disposal site outside the Okawa Bay catchment.

Furthermore, RDC is considering diverting a proportion of the flow from the Ohau Channel into Okawa Bay. The Ohau Channel is the outlet from Lake Rotorua to Lake Rotoiti (Figure 1.1). A diversion of about 1 m^3 s^{-1} of the Ohau Channel flow is proposed, about 5% of the Ohau Channel mean flow of 18 m^3 s^{-1}. Theoretically, addition of the diversion flow from the Ohau Channel has the potential to improve the water quality of Okawa Bay by three mechanisms. Firstly, the diversion flow could substantially decrease the residence time of water in the Bay. This would increase the rate of export of phytoplankton from the Bay into Lake Rotoiti. Secondly, if 'cleaner' (i.e., with lower nutrient and phytoplankton concentrations), the diversion flow would dilute the Okawa Bay nutrients and phytoplankton. Thirdly, because the Ohau Channel water is oxygen rich, it is possible that diversion of this water into Okawa Bay would reduce the frequency of periods in which the bottom waters of Okawa Bay become anoxic. This might be expected to be beneficial, because anoxia results in the release of nutrient from lake sediments.

Before RDC finally commits to the sewerage scheme and/or the Ohau Channel partial diversion, the Council wishes to clarify (as much as is possible): how much these changes would improve water quality in the Bay, and how long such changes might take. NIWA was engaged by RDC to address these questions.

We carried out some preliminary investigations in 2001 (reported in Ray et al. 2002), summarised as follows.

- A desk-top assessment of the nitrogen budget for the Bay was conducted, including inputs from sewage disposal systems, catchment runoff, geothermal springs and rain falling directly into the Bay. This assessment concluded that septic tanks and treated effluent from the Okawa Bay Resort Lodge contribute up to about two-thirds of the total nitrogen input to the Bay from the sources considered.

- The possibility of nutrient inputs into the bed of the Bay via geothermal springs was investigated by measuring conductivity and temperature throughout the Bay, and direct inspections by divers. This investigation suggested that geothermal springs are unlikely to be a dominant factor in the input of nutrients into the Bay, although some geothermal input could not be ruled out.

- A preliminary assessment of the changes to the water quality of the Bay that might be induced by removing sewage disposal inputs and/or introducing a diverted flow from the Ohau Channel was made using the Vollenweider equation. This assessment suggested that because (1) septic tanks were thought to dominate nutrient inputs to the Bay and (2) the diversion flow would greatly reduce the residence time, these options should benefit long-term water quality in the Bay, although it was emphasised that this conclusion was very tentative.

This report presents the results of more detailed investigations based on field measurements, and supported by computer modelling. The investigations were carried out in two stages; during February and July 2002.

RDC also asked NIWA to review historical information to clarify how water quality in the Bay has changed over the past 30 to 40 years. We have addressed this question in Section 1.2, below.

1.2 Review of historical information on Okawa Bay water quality

We have been unable to locate any quantitative information on the water quality of Okawa Bay prior to 1997. This makes the assessment of long-term water quality trends in the Bay difficult. However, NIWA does have records of some quantitative surveys of macrophytes (large aquatic plants) in the Bay carried out by MAF during the 1980s and 1990s, and the staff who carried out these surveys (Rohan Wells and John Clayton) have been interviewed. We have also interviewed a number of other people, most of them with scientific expertise, who have inspected the Bay at various times between the late 1960s to the present day. Environment B·O·P have also been carrying out surveys of blue green algae since 1997.

Aerial photography from 1981 shows that at that time there was a similar pattern of residential development to that of today, except that empty lots present in 1981 have since been built on, and the motor camp at the western side of the Bay has been replaced by the Okawa Bay Lake Resort complex. We have not been able to source any records of development prior to 1981, but the previous owner of the motor camp recalls there being few houses around the Bay in 1970, with a proliferation of development occurring between 1970 and 1980 (pers. comm. Michie).

It is likely that prior to the 1960s most of the Bay would have been covered with native charophytes, with some exotic *Elodea canadensis* (introduced to New Zealand in the 1930s). These plants tended to have a stabilising influence on New Zealand lakes, preventing stirring up of the soft bed sediments and maintaining relatively clear water. During the 1950s and 1960s, exotic, invasive weed species were introduced into many New Zealand lakes including the Rotorua Lakes, either accidentally or deliberately. These aggressive weeds gradually displaced the *Elodea* and native charophytes. The exotic species cause a number of lake management problems, such as interfering with boating and swimming. They also generally have rapid growth in the spring and summer, followed by die-off in the late summer and autumn, when the decaying plants sink to the lake bed. This fluctuating pattern of weed growth can lead to lake instability and occasional weed ‘crashes’.

Surveys of macrophytes were undertaken during the late 1960s. At that time and through the 1970s water clarity was generally good, with diving visibility between 4 and 5 m at times (pers. comm. Coffey). The owner of the motor camp between 1972 and 1982 recalls that, although the lake bed was always muddy, the water clarity was generally good for swimming. Algal blooms did not cause problems for users of the Bay during this time (pers. comm. Michie).

A number of macrophyte surveys were carried out by MAF staff between 1981 and 1985 as part of weed control trials. At that time *Lagarosiphon major* (an exotic invasive weed) dominated the lake in water depths between 1m and 5m. Native charophytes were also present at depths greater than about 5m. The surveys showed a degree of variation in plant abundance over these years, perhaps with a tendency of declining abundance towards the mid 1980s. Water clarity was very good at this time, with diving visibility of about 4m, although there was often a lot of rotting weed in the shallows (i.e., at water depths less than 1m). There was also a very pronounced thermocline evident at times during the summer, at a depth of about 4m (pers. comm. Wells).

In the late 1980s the weed beds 'crashed' (i.e., the majority of the beds died off) and water clarity declined, with diving visibility falling to about 0.5m (pers. comm. Coffey). A local resident recalls that at this time he was unable to see the lake bed at the end of his jetty, a depth of about 1.2m (pers. comm. Gill). An aerial photograph in 1989 shows a complete absence of weed beds. Echograms (underwater surveys carried out using sonar) show an absence of weeds through the early 1990s.

Water clarity began to improve again in the early 1990s, with diving visibility reaching about 2m in 1995 (pers. comm. Coffey). The weed beds gradually re-established during this time, but with the dominant species changing from *Lagarosiphon* to *Ceratophyllum demersum* (hornwort). Hornwort is more tolerant of low clarity waters, and also tends to die away more during the winter than *Lagarosiphon.*

In March 1998 the weed beds again crashed, with hypereutrophic conditions developing (pers. comm. Wells). Since 2000 the weed beds have again recovered, and now cover a large part of the lake bed. While hornwort is still the dominant species, charophytes are also evident (pers. comm. Taumoepeau). In spite of the abundance of algae, diving visibility is reasonable, being about 1 m in the summer and about 1.5-2 m in the winter.

Blue-green algae in Okawa Bay have been monitored by Environment B·O·P since 1997 (Wilding 2000). An 'alert trigger' of 15,000 blue-green algae cells per mL has been adopted by Environment B·O·P as indicating unsuitability for contact recreation. This figure was exceeded on 20 monitoring occasions in the five-year period between March 1997 and July 2002, at the following times:

- 16 April 1998
- 3 February to 22 March 1999 (5 consecutive measurements)
- 27 May 1999
- 23 June to 20 July 1999 (2 consecutive measurements)
- 13 to 19 January 2000 (2 consecutive measurements)

- 15 February to 29 March 2000 (4 consecutive measurements)
- 11 December 2000
- 16 to 21 January 2002 (2 consecutive measurements)
- 5 to 20 March 2002 (2 consecutive measurements)

Thus the worst blooms appear to have occurred in the late summers/early autumn of 1999, 2000 and 2002.

In summary, Okawa Bay appears to have been relatively stable prior to 1980, with good water clarity and extensive macrophyte beds, although these beds increasingly required controlling to allow for boating activities. The Bay has been subject to significant fluctuations in both water clarity and macrophyte abundance since the early 1980s to the present day. Blue green algal blooms (some severe) have occurred during the summer months in most years since regular monitoring began in 1997.

2. Methodology

As noted in Section 1.1, this report is based on the results of two sets of field work, carried out in February and July 2002, respectively. The methodology used for the two sets of work are described in the following subsections.

2.1 Environment B·O·P water quality monitoring, December 2001 to February 2002

Environment B·O·P has been monitoring water quality in Okawa Bay at monthly intervals since April 2001 (NZMS260 U15: 0278 4506 – see Figure 2.1). In support of this investigation, the frequency of this sampling was increased to weekly between 8 January and 22 February 2002. A further sampling site in the Western Basin of Lake Rotoiti was also added (location NZMS260 U15: 0366 4592). Samples were collected at depths of 1 m and 4 m in Okawa Bay and 1 m and 9 m in the Western Basin. Parameters measured included:

- Total kjeldahl nitrogen (TKN), nitrate nitrogen (NO_3-N), ammoniacal nitrogen (NH_4-N), total phosphorus (TP), dissolved reactive phosphorus (DRP), chlorophyll *a* (chl a), turbidity and pH. We also inferred total nitrogen (TN) concentrations by summing TKN and NO_3-N.

- Secchi depth (a measure of water clarity).

- The temperature and dissolved oxygen profile between the surface and the lake bed.

Environment B·O·P also carries out routine monthly sampling and nutrient analyses of water in the Ohau Channel (U15: 0250 4560).

All analyses are carried out by Environment B·O·P's water quality laboratory.

2.2 Wind measurements

Seiching in Lake Rotoiti (changes in water level between one end of the lake and the other caused by winds) could be an important factor in Okawa Bay water quality, since it could affect the flow of water into and out of the Bay from the main body of Lake Rotoiti. We therefore set up a wind gauge to the east of State Highway 33, near the Ohau Channel (Figure 2.1). Wind speed and direction at a height of 6 m above ground level was recorded at 10-minute intervals (average and maximum) from 18 January 2002 to 28 March 2002.

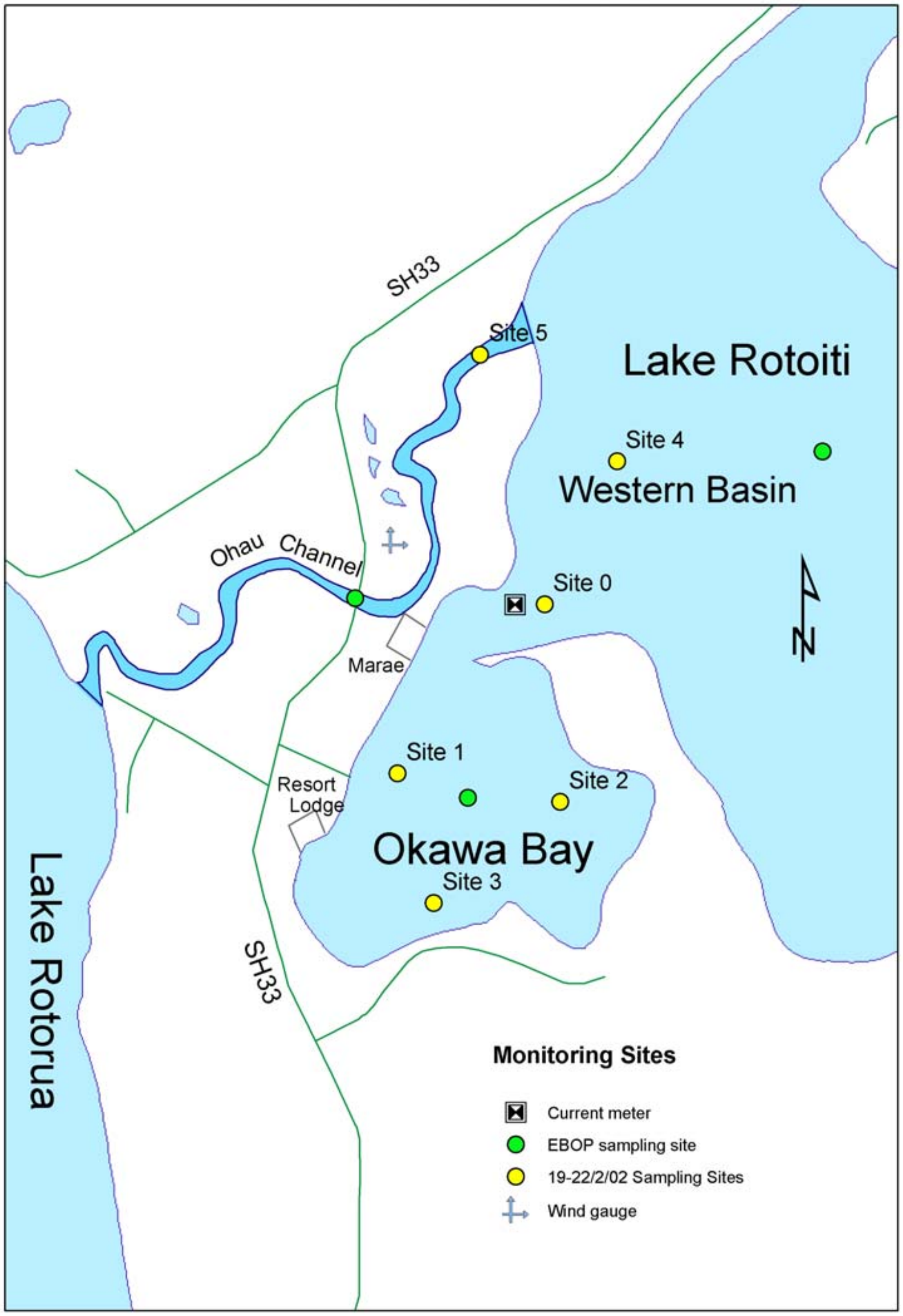


Figure 2.1: Measurement instrument and water sampling locations.

2.3 Current measurements at entrance to Okawa Bay

2.3.1 S4 current measurements, February-March 2002

To assist with the estimation of water flow into and out of the Bay, we deployed an S4 current meter about 0.5 m above the lake bed, in the entrance of the Ohau Channel (NZMS260 U15: 2802897E 6345539N – see Figure 2.1). Water depth at this location was 5.7 m. The meter measured current velocity every 0.5 s for one minute and recorded the average of these readings. This process was repeated every 5 minutes (i.e., one-minute averaged readings were recorded every 5 minutes). Temperature thermistors were also placed at the S4 (i.e., near the bottom) and near the water surface. These logged temperature at 5-minute intervals.

2.3.2 ADP current measurements, July-August 2002

An ADP (Acoustic Doppler Profiler) current meter was deployed in the Okawa Channel about 0.5 m above the lakebed at NZMS260 U15: 2802913E 6345499N. Water depth at this location was 5.8 m. The instrument measured current velocity every 0.5 s for one minute and recorded the average of these readings. This process was repeated every 5 minutes (i.e., one-minute averaged readings were recorded every 5 minutes).

2.3.3 Hydrodynamic modelling

A three-dimensional numerical model was set up to help conceptualise patterns of flow in Okawa Bay and its exchange with Lake Rotoiti (Figure 2.2). Wind-driven currents were simulated using the Danish Hydraulics Institute three-dimensional model MIKE 3, with 5 × 1 m layers in the vertical. To focus on Okawa Bay, a fine-scale 30 m grid (Figure 2.3) was nested inside the larger 90 m grid (Figure 2.2). The model was forced at the water surface by applying wind measured at Rotorua Airport uniformly over the water surface. The model included temperature stratification, with the uppermost vertical layer having an initial temperature of 21°C, and other layers 19°C. No additional temperature inputs were included, so the stratification broke down with time as currents mixed the upper and lower layers. The model was not calibrated against the ADP measurements due to time constraints, so the current magnitudes are somewhat over-predicted. But the measured and modelled flow patterns are close enough to be confident that the model can be used to demonstrate wind-induced flow patterns in Okawa Bay.

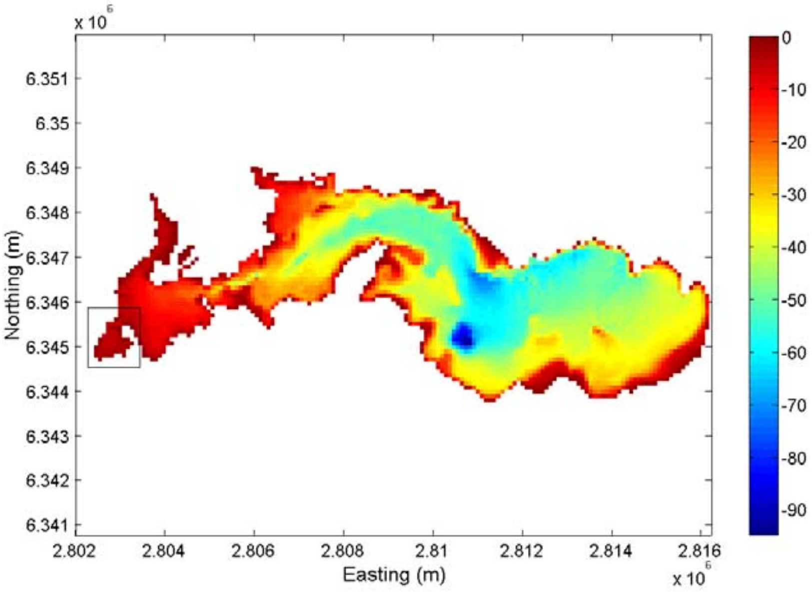


Figure 2.2: Lake Rotoiti 90 m model bathymetry grid. The colour scale indicates depth (m), while the box shows the location of the 30 m Okawa Bay grid.

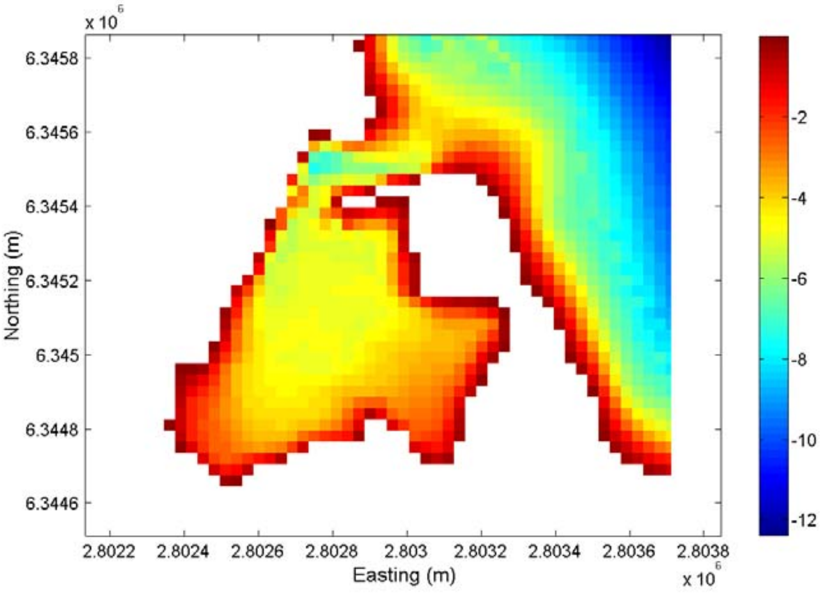


Figure 2.3: Okawa Bay 30 m model bathymetry grid. The colour scale indicates depth (m).

2.4 Intensive field investigations, 19-22 February 2002 and 22-26 July 2002

During the weeks of 19 to 22 February and 22-26 July 2002, we carried out a range of investigations, as follows.

2.4.1 Lake bed nutrient release experiment

Lake bed sediments contain a large reservoir of nutrients, accumulated over many years through deposition of organic matter from aquatic plants (both algae and macrophytes). When dissolved oxygen levels are high, microbial decomposition processes in the sediments continuously and slowly release the stored nitrogen and phosphorus as inorganic nutrients (ammoniacal nitrogen and dissolved reactive phosphorus) into the overlying water column. When dissolved oxygen levels are low or zero, the rate of release increases dramatically such that the overlying water column rapidly becomes nutrient enriched. Low oxygen conditions typically occur when a lake thermally stratifies in the summer – i.e., when the lake surface warms to an extent that there is a distinct separation between the upper and lower waters. Sediment nutrient release can have a large influence on the concentration of dissolved nutrients in the water column, and thus plant growth (in particular, algal blooms).

We assessed the potential for such nutrient releases using a well-proven benthic chamber technique (Burns et al. 1996; Gibbs 2001). In February, six weighted benthic chambers (0.5 m square) fitted with plastic domes and pulsed recirculation stirrers were lowered to the lake bed to enclose an area of sediment. The sharp edges to the chamber frames were expected to cut through any macrophytes and into the sediments to form a seal, preventing the transfer of water or dissolved oxygen into or out of the chamber. In July, we used divers to install the chambers and ensure the chambers were sealed to the sediments correctly. During the July deployment, flow measurements were also made from each chamber and again 4 days later prior to retrieval (see “Chamber flow measurements” below).

Two chambers were deployed at each site, one transparent (the ‘light’ chamber), the other covered with black plastic sheeting to prevent any light penetration (the ‘dark’ chamber). Water samples are taken from the chambers via 3 mm I.D. nylon tubes using a suction pump at regular intervals, for analysis of dissolved nutrients and dissolved oxygen. Microbial and plant respiration uses up the dissolved oxygen in the chamber until the water becomes anoxic. Oxygen depletion usually happens more rapidly in the dark chamber, since trapped plants are prevented from photosynthesising. Light and dark bottles, containing near-bottom ambient lake water and no air bubbles, were tied to the outside of the chambers just before deployment and incubated with the chambers. The water in the bottles was analysed at the beginning and end of the experiment for dissolved oxygen and nutrients. The data from these bottles is used to correct the chamber results for any effects of water column processes. The chambers were deployed at three sites at 2 pm on Tuesday 19 February (Figure 2.1). The last samples were retrieved at approximately 6 pm on Wednesday 20 February.

Dissolved oxygen was measured immediately on collection and all water samples were filtered for nutrients within 2 hours of the samples being taken.

We considered the option of taking sediment core samples and analysing the sediment for nutrients. The main purpose of this would have been to provide an estimate of the nutrient store in the sediments and thus how long nutrient release would continue if there were no further significant inputs of nutrients to the sediments. However, any estimate of the time for future sediment nutrient release would be very approximate, since it is very difficult to assess how much of the nutrients in the sediments will be released to the overlying water column. The retrieval of sediment cores and analysis for nutrients would have also involved considerable extra costs to the project. Therefore we did not believe that sediment coring was warranted. Sediment cores could be taken in the future if it were considered a worthwhile exercise.

2.4.2 Chamber flow measurements

During the February measurements, we obtained some unexpected results which raised the possibility that there was a substantial groundwater flow into the chambers (refer to results in Section 3). Therefore in July we measured the actual flow from each chamber at the beginning and end of the incubation period. To do this the divers fitted a dual tap, “T” piece in place of the pulse stirrer on top of the chamber. Any water entering the chamber through the sediments must displace water from the chamber via this “T” piece. By switching the taps, any water flow was diverted into a soft flexible collection bag. The volume collected in a measured time was related to the area of lake bed enclosed by the chamber and calculated as a flow in litres per square metre per hour. Two measurements were made from each chamber before and again after the 4-day incubation period. After measuring the initial flows, the divers fitted the pulsed stirrers and the incubation began.

2.4.3 NIWA water quality measurements

Depth-integrated water samples were collected daily by NIWA at six sites (Figure 2.1): three within the Bay (Sites 1 to 3), one in the Bay entrance channel (Site 0), one in the Western Basin of Lake Rotoiti (Site 4), and one in the Ohau Channel (Site 5). The samples were filtered on site and analysed for dissolved and total nitrogen and phosphorus, and chlorophyll *a* (chl a). Secchi depth was measured at the same time.

2.4.4 Phytoplankton incubation experiment

This experiment was designed to assess the response of phytoplankton in the water column to increases in nitrate concentration. Two 20 L transparent plastic bags were filled with lake water. One of the bottles was spiked with a concentrated nitrate solution to increase nitrate-nitrogen concentration by 100 mg m^{-3}. The bottles were deployed on 19 February near the lake bed at Site 1, at a water depth of approximately 4.5 m (Figure 2.1). The chl a concentration was measured in samples from each bottle before and 24 hours after deployment. These were not repeated in winter as low temperatures and ambient light levels would be unlikely to support any rapid growth.

2.4.5 Drogue tracking

We used 10 drogues to assess the movement of water into and out of the Bay at different depths below the surface. The drogue is a plastic float with a 0.5 m^2 plastic curtain hung below the float. The drogue is dropped into the water and its position fixed at intervals using GPS, which accurately locates position to within one metre. The drogue follows the movement of the water at the depth of the curtain. Wind effects are usually fairly minimal because little of the drogue is exposed above the water surface (although some wind drag can occur during strong winds and weak subsurface currents). The curtain can be hung at different depths to assess water movements at different depths. For most of the time, 6 of the drogues had curtains 0.8 m below the surface, and the other 4 drogues had curtains 1.5 m below the surface. One drogue had its curtain depth increased to 3 m. Greater depths are impractical because the curtains tend to get caught up in weeds.

2.4.6 Dye tracer study

Two dye tracer experiments were conducted in July to help corroborate instrument (ADP) current measurements. About 200 ml of dilute non-toxic Rhodamine WT dye (diluted 1:50 in water) was released simultaneously at each of three depths: (1) on the surface, (2) 2 m below the surface and (3) 1 m above the sediments. To achieve this, the dye was placed in balloons which were attached to a light mooring line and subsequently burst by dropping a weight with sharp spikes down the line. The surface dye was released by inverting a container of the dye just below the surface. The movement of the dye was tracked either visually (surface) or using a Richard Brancker Research profiler fitted with a Rhodamine fluorometer (surface and subsurface). The position of each measurement was logged from a differential GPS system. An estimate of velocity was made from the distance travelled by the leading edge of the dye plume during a measured time interval.

Two dye releases were made under opposing wind flows. The first on 23 July with a NE wind blowing into Okawa Bay, and the second on 25 July with a SW wind blowing out of Okawa Bay.

2.5 Nutrient/phytoplankton modelling

2.5.1 Overview of model

We developed a computer model for nutrient/phytoplankton/detritus dynamics to predict how the proposed removal of septic tanks and/or introduction of the diversion flow might influence phytoplankton dynamics within Okawa Bay in the short term. This model is an extension of previous NIWA lake nutrient models used for Lake Rotorua and a number of other New Zealand water bodies. A full mathematical description of the model, together with parameter values, is provided in Appendix 3.

The model includes explicit representations of the dynamics of nutrients (dissolved inorganic nitrogen, DIN, and dissolved reactive phosphorus, DRP), phytoplankton abundance (as a carbon concentration) and organic detrital abundance (as carbon concentration). 'Detritus' is essentially dead algae and other dead organic matter (e.g., macrophytes) containing organic nutrients. The model assumes the Bay to be "well mixed" (no horizontal or vertical gradients in any of the properties of interest).

Phytoplankton are assumed to have fixed N:C, P:C and *Chlorophyll a*:C ratios. The instantaneous phytoplankton gross-growth rate is determined by the most limiting of: the light intensity, DIN or DRP concentrations. Phytoplankton are assumed to be neutrally buoyant, but suffer a mortality of 10% d^{-1}. Carbon and nitrogen within phytoplankton cells that die is assumed to pass into the pool of suspended organic detritus. In contrast, only 90% the cell phosphorus (which is much more labile) is assumed to pass into the detrital pool, the remaining 10% is assumed to pass directly into DRP. Detritus is assumed to remineralise (releasing CO_2 and DIN at a rate of 5% d^{-1} (Enríquez 1993) and to sink at a speed of 0.1 m d^{-1} (Smayda 1970)). Detritus sedimenting onto the lake-floor is lost from the system. The nutrient returns from sedimented detritus are specified *a priori* as benthic boundary conditions (see below).

2.5.2 Boundary Conditions

In addition to internal recycling of material within Okawa Bay (as a result of phytoplankton growth and death), the Bay also exchanges materials with the wider area. The model includes boundary inflows to represent inputs from:

1. Diffuse sources entering Okawa Bay via groundwater inflow

2. Nutrient release from the sediments (derived from our benthic chamber measurements)

3. Rainfall
4. Septic tank inputs
5. Ohau Channel diversion into Okawa Bay
6. Exchange of water with the rest of Lake Rotoiti

In each case, we assume that the water-input is matched by a corresponding output flow into the Western Basin of Lake Rotoiti which carries nutrients, detritus and phytoplankton with it. Nutrient and phytoplankton concentrations in the boundary inputs are taken to be the average of those measured by NIWA within the corresponding inflow. Detritus cannot be measured directly because it is not easy to separate living material from detrital material. Thus, we derive an approximate detrital concentration (mg C m^{-3}) by subtracting the sum of nitrate-nitrogen and phytoplankton concentration (expressed as nitrogen) from the measured total nitrogen content of the water, and assuming the detrital N:C ratio to be the same as that of the phytoplankton.

Between Okawa Bay and the Western Basin of Rotoiti, incoming water is assumed to have the measured characteristics of Rotoiti water, whilst outgoing water has the simulated characteristics of Okawa Bay.

Simulations are made for the summer period only. Thus, for simplicity, we assume constant water-temperature (20 °C) and day length (14 hours). The instantaneous intensity of photosynthetically active radiation at the water-surface is assumed to follow a half-sinusoid (rising from zero at dawn, to 1200 $\mu E\ m^{-2}\ s^{-1}$ at solar midday, and falling to zero once more at dusk). Within the lake, light intensity is depth-dependent. The light-attenuation coefficient is assumed to have two components: a constant ‘background’ term (reflecting scattering by particulates and subsequent attenuation by water and dissolved organic materials) and a term reflecting light-absorption by chlorophyll.

2.5.3 Model Calibration

In addition to the parameters governing the physical nature of Okawa Bay (depth, surface area, temperature etc) and its boundary conditions (flows and concentrations), the model has 15 parameters governing nutrient, detritus and phytoplankton within the Bay. We fixed 12 of these to literature-derived values and fitted the remaining three (half-saturation concentrations for phytoplankton growth upon DIN, phytoplankton N:C and P:C ratios) by calibrating to the field measurements made over February 19-22, 2002. Boundary and initial conditions were defined by the corresponding averages from our field measurements.

2.5.4 Scenario Simulations

Once the model had been calibrated, we ran several simulations designed to either: (a) examine the consequences of the proposed management scenarios, or (b) examine the sensitivity of the model to some of the model's parameters.

We examined the following management scenarios:

1. removal of septic tank discharges without addition of a flushing flow into Okawa Bay

2. addition of the diversion flow without removal of the septic tank discharges

3. addition of the diversion flow and removal of the septic tank discharges. In this case, we made two simulations. The first assumed the diversion flow to have high DIN, DRP and chlorophyll concentrations, the second assumed much lower concentrations (those which we measured during February 2002).

With respect to examining the model's parameter sensitivity, we made the following simulations (these simulations assumed the presence of a 1 $m^3 s^{-1}$ diversion flow and septic tank inputs to be zero):

1. simulation assuming the rate of water exchange between Okawa Bay and the Western Basin of Rotoiti was 0 $m^3 s^{-1}$ (c.f. estimated mean of ~ 5 $m^3 s^{-1}$).

2. simulation assuming the rate of water exchange between Okawa Bay and the Western Basin of Rotoiti was 10 $m^3 s^{-1}$.

3. simulation assuming 'low' chlorophyll concentrations in the Western Basin of Rotoiti (~ 2.5 mg Chl m^{-3}, the minimum summertime value (observed on 6 January 1982) in fortnightly sampling of the Western Basin of Rotoiti during 1981/1982: Gibbs unpublished data). We also adopted the concentrations of DIN, DRP and detrital carbon measured on that date.

3. Results

3.1 Preliminary estimates of nutrient inputs and residence times

3.1.1 Nutrient inputs to Okawa Bay

Our estimate of the inputs of N and P from septic tanks to Okawa Bay are summarised in Table 3.1.

Table 3.1: Estimate of N & P inputs to septic tanks and Lake Resort, Okawa Bay

Source	Population equivalent (averaged over a year)	Estimated N input to septic tanks per year (TN, t/yr)	Estimated P input to septic tanks per year (TP, t/yr)
Houses	270 (90 houses)	0.99	0.30
Okawa Bay Lake Resort	120 (15 timeshares, plus 42 hotel rooms, plus staff)	0.44	0.13
Marae	10 (guess)	0.05	0.01
Total	400	1.48	0.44

The assumptions used in Table 3.1 are as follows.

- Number of dwellings estimated using cadastral plans and aerial photos.
- Average of 3 persons per dwelling, all year round.
- TN load taken as 10 g N/person/day.
- TP load taken as 3 g P/person/day.

It is considered that there will be little removal of nitrogen in the Lake Resort wastewater treatment system, so we have conservatively assumed no removal. Table 3.1 may slightly over-estimate nitrogen inputs because: (1) some nitrogen may be retained in the septic tanks and removed during tank cleaning; and (2) some nitrate from sewage may be removed by denitrification from groundwater prior to discharge into Okawa Bay. We have (conservatively) ignored these N losses. Phosphorus in the septic tank leachate will tend to adsorbed onto soil particles as it leaves the disposal field. The pumice soils in the Rotorua area generally have high P adsorption capacity. However, over time the soils will become saturated with P, and some leaching of P to the lake will occur. This will be more pronounced where disposal fields are close to the groundwater table (i.e., where the soils near the disposal field are saturated). We have assumed that 70% of the phosphorus is lost between the septic tank and the Bay, i.e., that the mass load of phosphorus to the Bay is 0.3 x 0.45 = 0.14 t yr^{-1}.

For estimating N inputs to Okawa Bay from other sources, we have drawn on data used in previous studies of the Lake Rotorua catchment. Our preliminary N and P budgets are presented in Tables 3.2 and 3.3. It should be noted that there will be some inaccuracies in using the Rotorua data for Okawa Bay, but this is the best data available.

Table 3.2: Estimated N inputs to Okawa Bay.

Source	**Catchment area (km^2)**	**TN specific yield (t N km^{-2} yr^{-1})**	**Total TN load (t N yr^{-1})**
Pastoral landuse	0.56	0.7[1]	0.39
Urban landuse (excluding septic tanks)	0.16	0.8[2]	0.13
Rainfall directly into Bay	0.44	0.4[3]	0.18
Total (excluding septic tanks)			**0.70**
Septic tanks & Resort Lodge			1.48
Total (including septic tanks)			**2.18**

[1] from Williamson et al. (1996)
[2] from Williamson (1993)
[3] from Hoare (1987)

Table 3.3: Estimated P inputs to Okawa Bay.

Source	**Catchment area (km^2)**	**TP specific yield (t P km^{-2} yr^{-1})**	**Total TP load (t P yr^{-1})**
Pastoral landuse	0.56	0.09[1]	0.050
Urban landuse (excluding septic tanks)	0.16	0.08[2]	0.013
Rainfall directly into Bay	0.44	0.015	0.007
Total (excluding septic tanks)			**0.070**
Septic tanks & Resort Lodge			0.14[4]
Total (including septic tanks)			**0.21**

[1] from Williamson et al. (1996)
[2] from Williamson (1993)
[3] from Hoare (1987)
[4] assumes 30% of P entering septic tanks reaches Okawa Bay

From our benthic chamber experiments, we inferred nutrient inputs from the lake bed that were much higher than the total inputs listed in Tables 3.2 and 3.3. This is addressed in Section 3.7.

3.1.2 Residence time

We calculated the theoretical residence time for the Bay, assuming that the only inflow to the Bay is rainfall less evapotranspiration (ET), as follows:

Okawa Bay volume: 1,600,000 m^3

Okawa Bay catchment area: 1,150,000 m^2 (including the Bay itself)

Average annual rainfall: 1,500 mm yr^{-1}

Average annual ET: 800 mm yr^{-1}

$\Rightarrow$ rainfall – ET inflow = 1,150,000 x (1,500 – 800)/1000

= 805,000 $m^3\ yr^{-1}$

= 0.026 $m^3\ s^{-1}$

$\Rightarrow$ residence time = 1,600,000/805,000

= 2.0 years

If the 1 $m^3\ s^{-1}$ diversion flow from the Ohau Channel is introduced, this would theoretically reduce the residence time to 18 days. It is because of this large theoretical reduction in residence time that the option of introducing the flow diversion is worthy of serious consideration.

However, the above approach assumes that there is *no* exchange flow between Okawa Bay and the Western Basin. We measured a substantial exchange flow during our field investigations of February and July 2002, and the implications of this exchange flow on the residence time are addressed in Section 3.4.5.

3.2 Wind measurements, February 2002

A frequency histogram for wind direction for the period 18 January to 28 March 2002 is presented in Figure 3.1. This shows that, as expected, wind direction is predominantly from the west and southwest (between 200º and 280º) and northeast (20º to 70º).

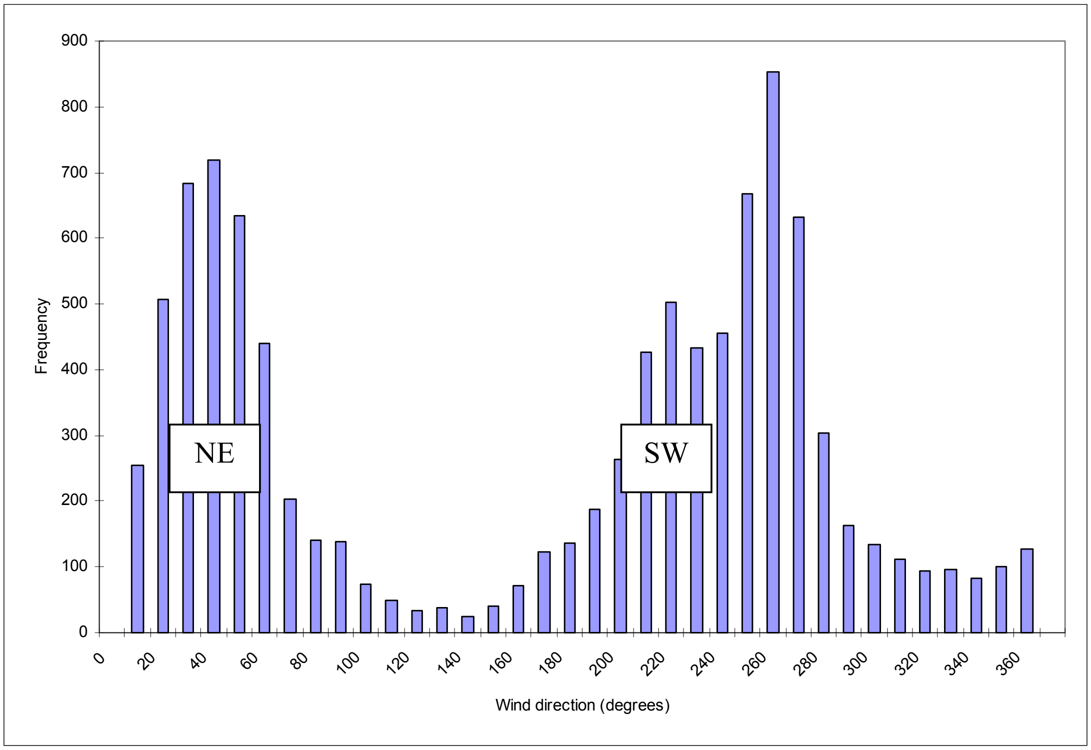


Figure 3.1: Wind direction frequency histogram for the period 18 January to 28 March 2002. The graph shows the number of times that wind direction, averaged over a 10-minute period, was in a certain direction. 360º (or 0º) is northerly wind.

The time history of wind speed and direction for the period of the intensive field measurements (19 to 22 February) is shown in Figure 3.2. A steady south-westerly wind of approximately 5 m s^{-1} (10 knots) blew for most of the first day (19 February). After the first day the wind speed dropped to between 2 and 4 m s^{-1}, and wind direction was more variable.

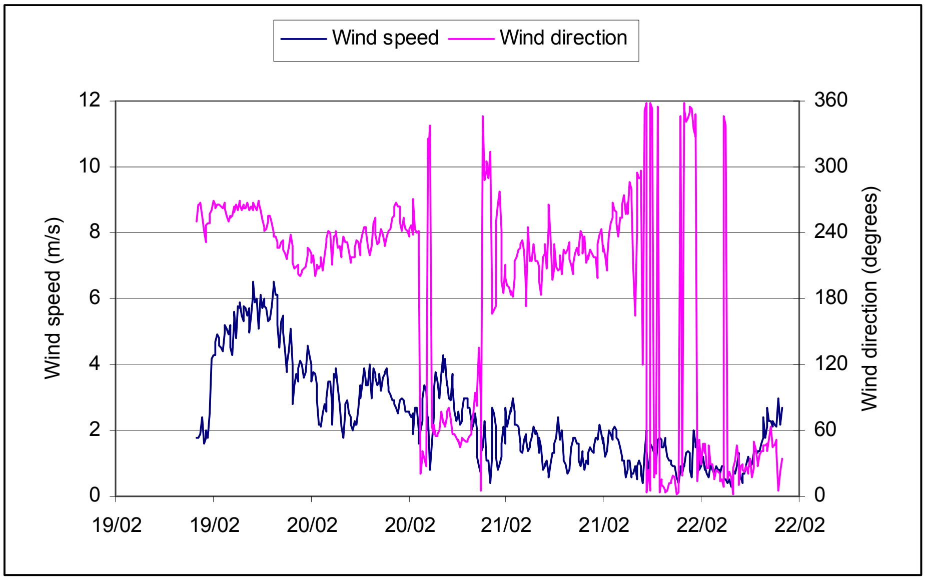


Figure 3.2: Wind speed and direction measurements for the period of intensive field work, 19 to 22 February 2002. 1 m/s equates to approximately 2 knots.

3.3 Okawa Bay and Western Basin temperature measurements

Environment B·O·P measured temperature/depth profiles at Okawa Bay and the Western Basin from 13 December 2001 to 22 February 2002. The results are presented in Figures 3.3 to 3.5. Thermal stratification is evident in the Bay (and to a lesser extent in the Western Basin), particularly between 22 and 31 January 2002.

The plots show that the temperature/depth profiles often differed between the Bay and the Western Basin. Such temperature differences are likely to affect the rate of exchange of water between the two water bodies. For example, on 13 December the water below 4 m depth in the Western Basin was nearly 1 °C colder than water at the same depth in Okawa Bay. This colder water is more dense, and in the absence of any other forcing factors (e.g., wind set up or seiching), this colder water would 'slide' horizontally into the Bay, displacing the warmer, lighter Okawa Bay bottom waters upwards. On 13 December we would expect there to have been a flow into the Bay from the Western Basin along the bottom of the entrance channel. Such a flow would induce a surface flow out of the Bay. From 22-31 January Okawa Bay bottom waters were cooler (by 1-3 ^{o}C) than waters at the same depth in the Western Basin (e.g., 24 January). On these days we would expect there to have been a flow out of the Bay into the Western Basin along the bottom of the entrance channel. Such a flow would induce a surface flow into the Bay. Currents into and out of the Bay were not measured on the same days as temperature profiles, and so we can only make inferences about the likely direction of flow. It is not possible to estimate the magnitude of exchange flows on these days.

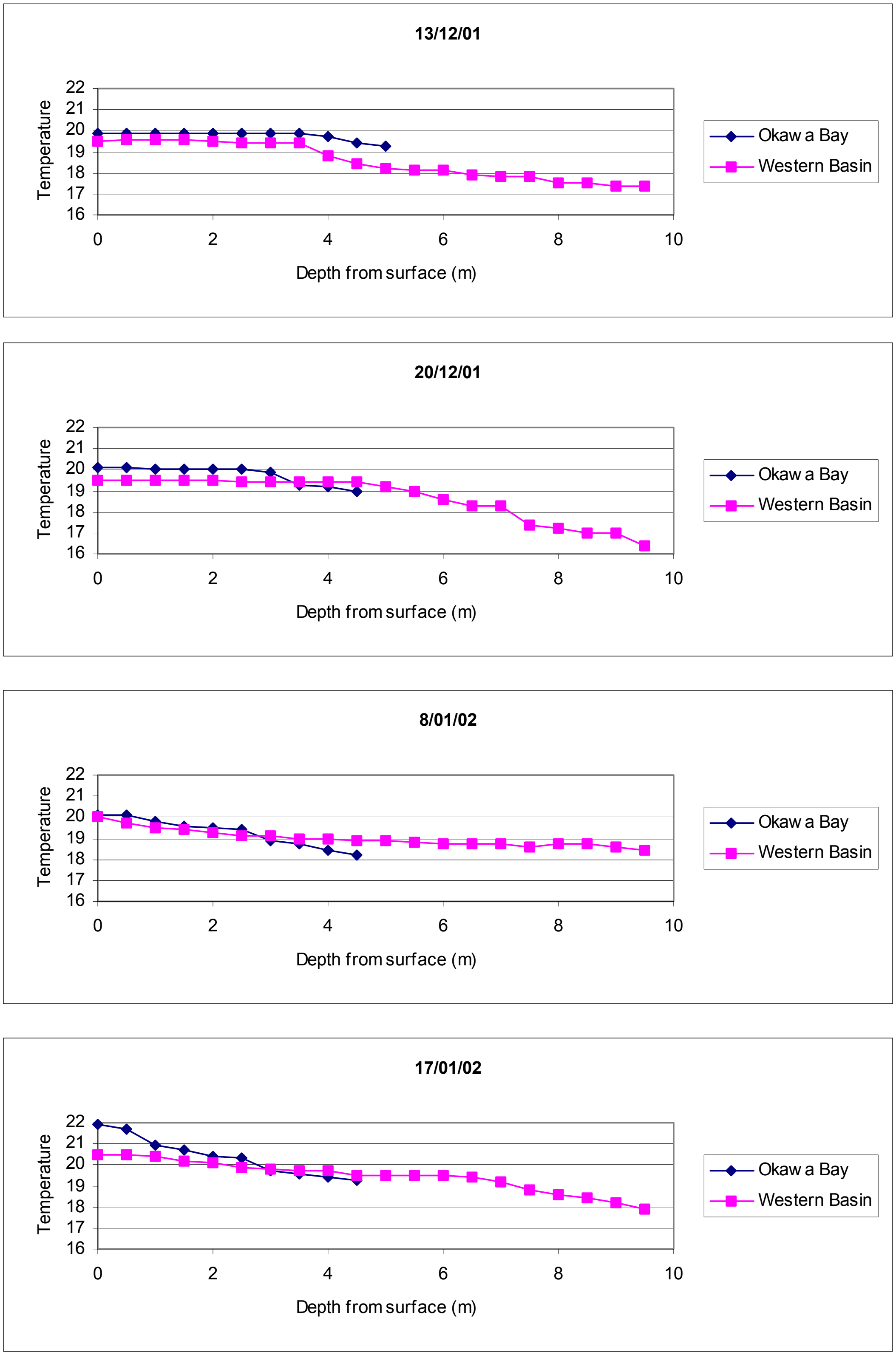


Figure 3.3: Temperature/depth profiles in Okawa Bay and Western Basin, 13/12/01 to 17/01/02.

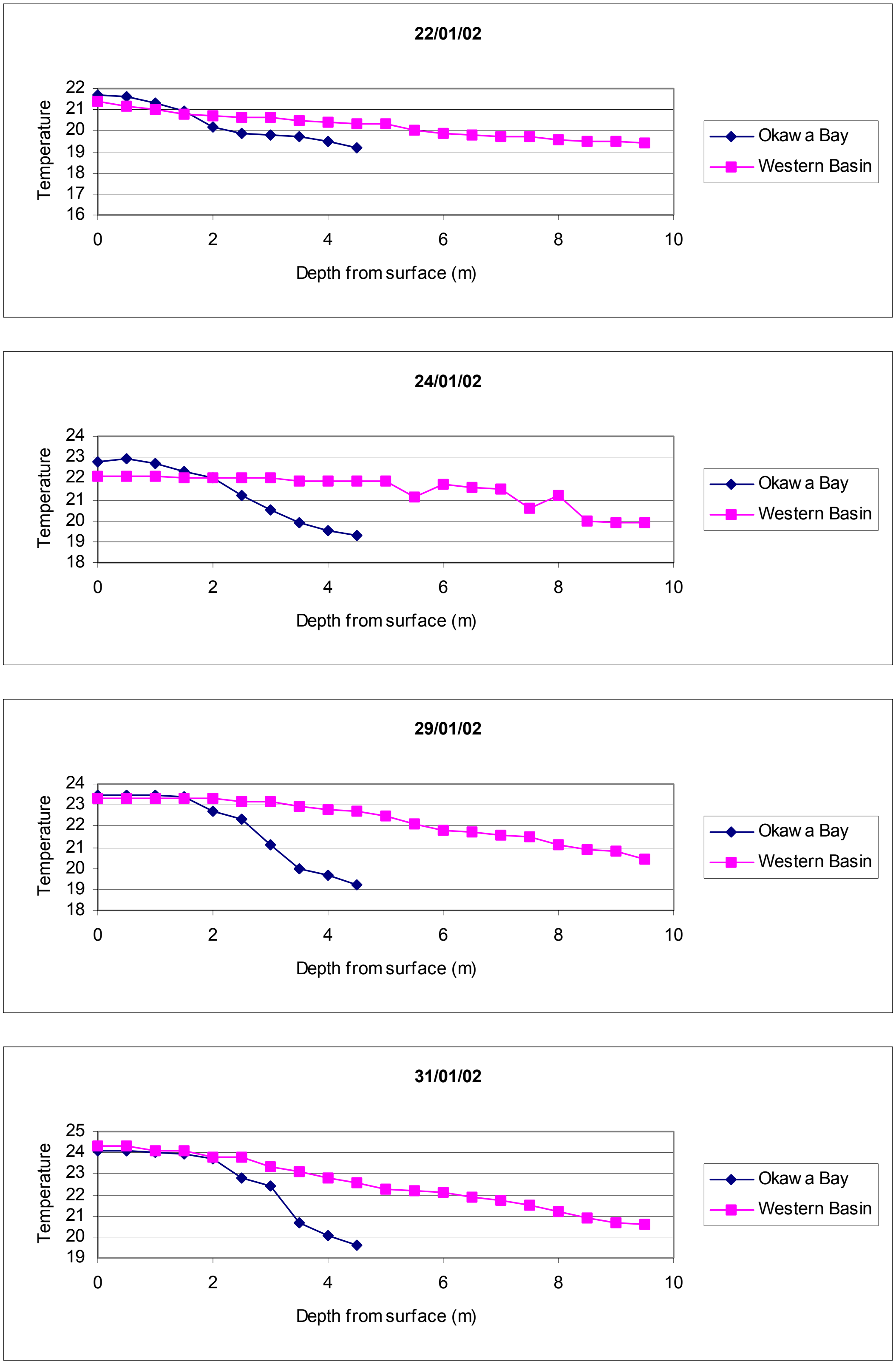


Figure 3.4: Temperature/depth profiles in Okawa Bay and Western Basin, 22/01/02 to 31/01/02.

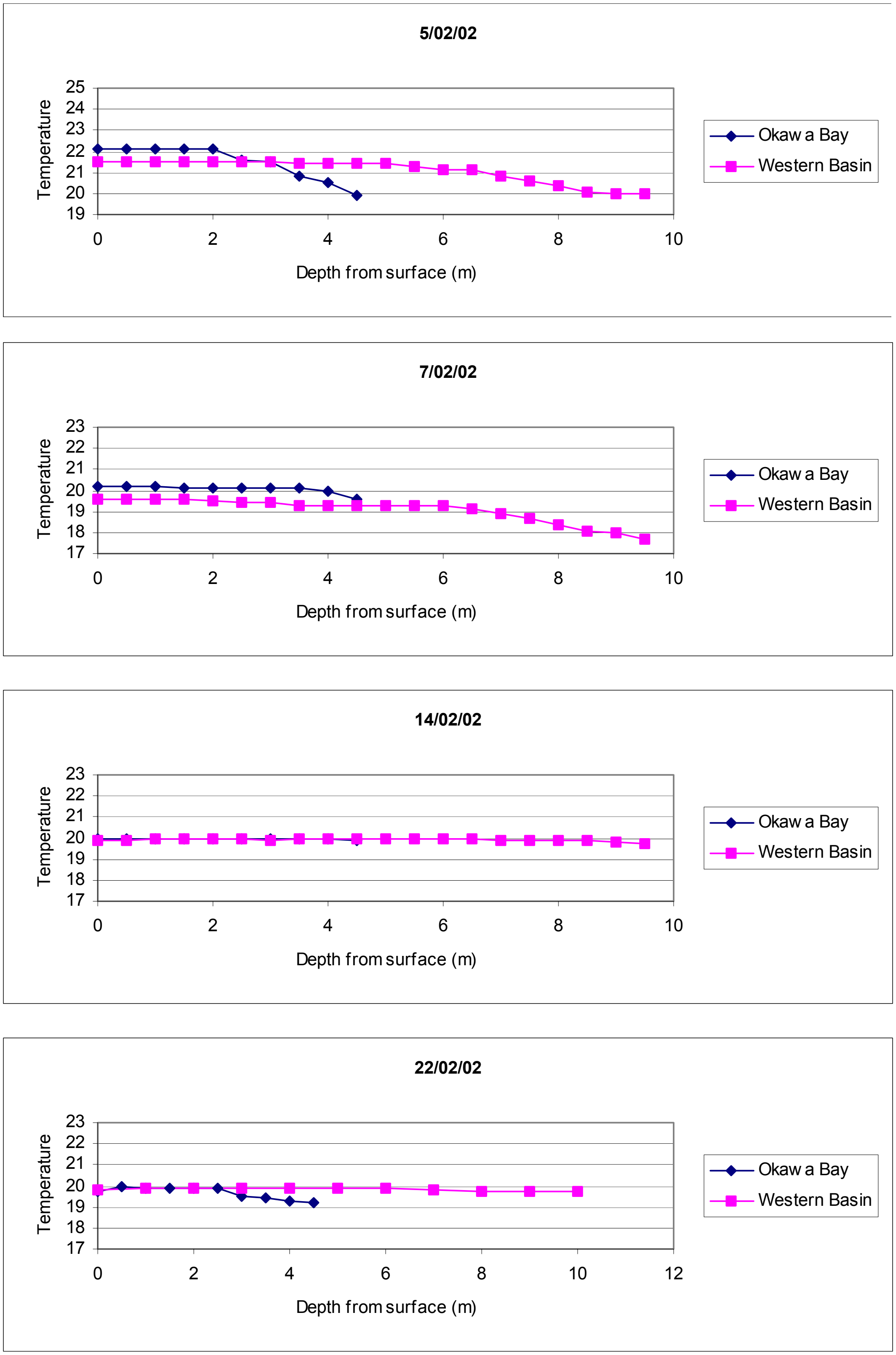


Figure 3.5: Temperature/depth profiles in Okawa Bay and Western Basin, 5/02/02 to 22/02/02.

During the periods of observed stratification, Environment B·O·P also measured high nutrient concentrations in the bottom waters. This is discussed in more detail in Section 3.8.1.

3.4 Current measurements at entrance to Okawa Bay

3.4.1 S4 current meter deployment, March 2002

The S4 current meter sited near the lake bed in the entrance to Okawa Bay in early February malfunctioned, and all measurements for 22 February – 8 March were lost. A new S4 was deployed from 8-28 March. Current and wind speeds are plotted in Figure 3.6.

The temperature measurements show that the channel was often stratified (with lower bottom than surface temperature). However, mixing occurred on 15-16 and 17-19 March when winds were strong. The channel stratified again on 20 March, but the bottom temperature was approximately 1 °C cooler than prior to 16 March. This suggests that there had probably been an exchange of water with cooler waters, perhaps from the deeper waters of the Western Basin.

Average current velocity was about 3 cm s^{-1}. The manufacturers rate the current meter as accurate to +/- 1 cm s^{-1}. A frequency histogram for the current direction is shown in Figure 3.7. This shows that the water flow near the bottom was almost always from the north east (about 50º). Thus the predominant bottom current at the entrance was into the Bay from the Western Basin of Lake Rotoiti.

Temperature profiles in the Bay and Western Basin (described above) indicate density differences that are likely to have induced bottom flows either into (13 December) or out of (22-31 January) the Bay. When the S4 current meter was deployed, temperature profiles were measured at the entrance (Figure 3.6) but not in the Western Basin. Consequently, it is not possible to corroborate whether temperature differences induce flow at the entrance, or to quantify the relationship.

If the water level within Okawa Bay remains constant, then an inflow along the bottom must be balanced by an equivalent outflow near the surface. Drogue tracking at the entrance (19-20 February) was not done during the S4 deployment (8-27 March). Nevertheless on 19-20 February surface drogues invariably moved out of the Bay (Section 3.4.2). This is consistent with there being a bottom current into the Bay (as was measured by the current meter on 8-27 March) and an induced surface flow out of the Bay.

The current meter and drogue results suggest that there is a two-layer flow structure at the entrance, which results in a net exchange of water between the Bay and the Western Basin.

The main purpose of the current meter was to quantify the exchange rate between the Bay and the Western Basin. The channel cross section at the S4 deployment is shown on Figure 3.8. If we assume that: (1) the meter measures the average velocity over the lower 1-3 m of the entrance channel; and (2) the channel width at this depth averages about 100 m, then a current velocity of 3 cm s^{-1} implies an exchange flow rate of between 3 and 9 m^3 s^{-1}.

There is obviously considerable uncertainty in this estimate of the exchange flow. In addition the exchange flow is likely to vary with time, depending on wind and temperature differences between Okawa Bay and the Western Basin. To improve our understanding of the exchange flows, we measured velocities again in July/August using an ADP. An ADP measures velocities over most of the depth of the water column, unlike an S4 which measures velocities only within a small distance of the instrument. Furthermore, the ADP used was more accurate at low velocity measurements. Therefore the results of the ADP (refer to Section 3.4.4) should be considered more reliable than those of the S4.

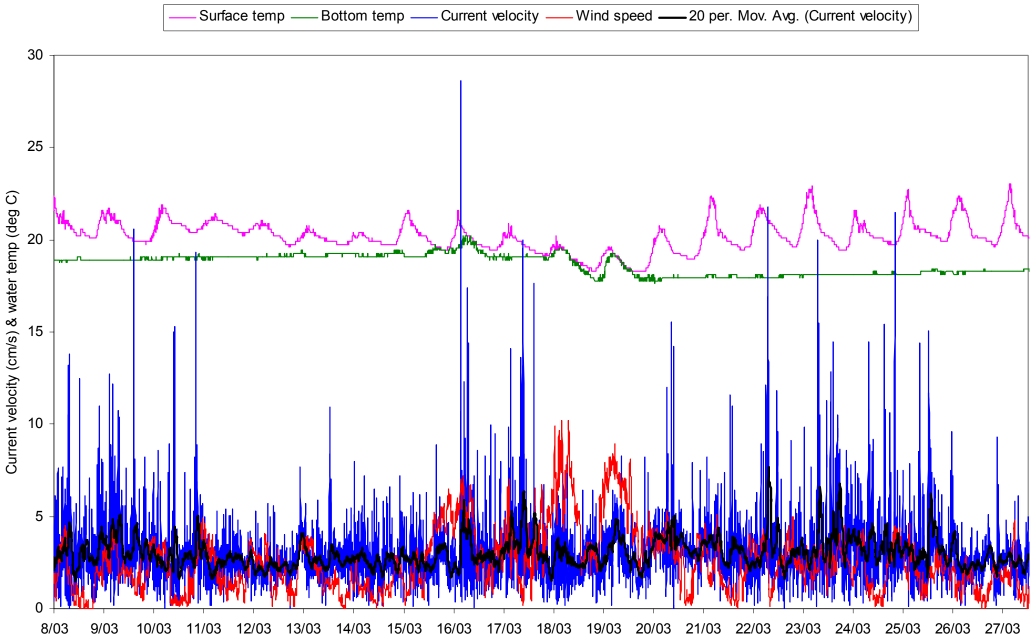


Figure 3.6: Near-bottom current velocity and bottom and surface temperature at the entrance to Okawa Bay, plus wind speed (in m s^{-1}) near the Bay, 8 to 28 March 2002. The current results show the 5-minute average current velocity. The black line shows a moving average of the previous 20 current velocity measurements (i.e., 100-minute average).

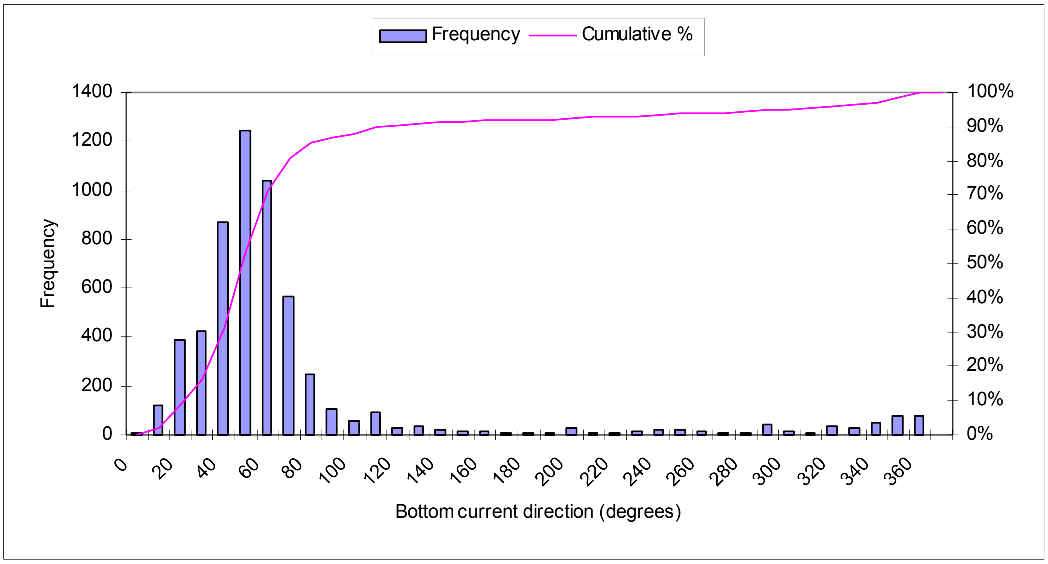


Figure 3.7: Frequency histogram for near-bottom current direction at the entrance to Okawa Bay for the period 8 to 28 March 2002. The graph shows the number of times that current direction, averaged over a 5-minute period, was in a certain direction. 360º (or 0º) is current direction from the north.

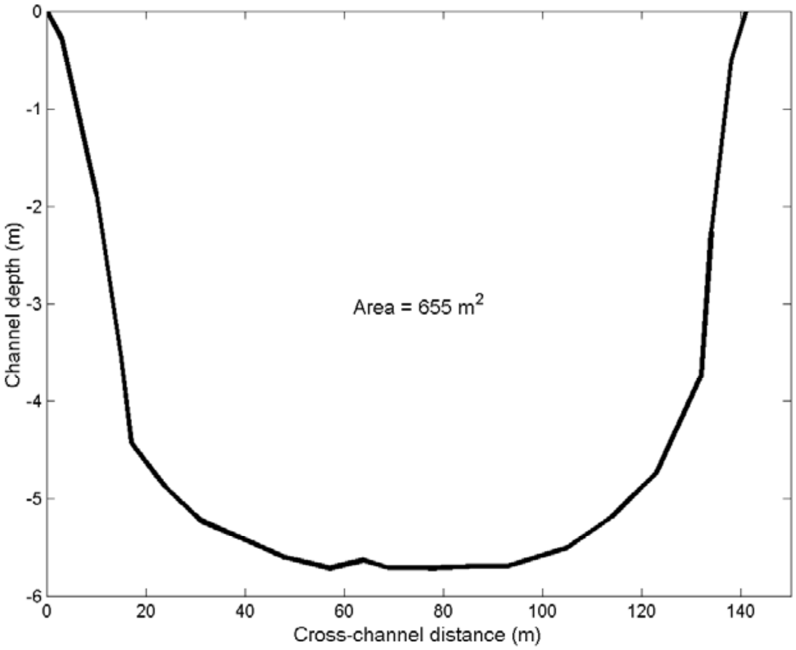


Figure 3.8: Channel cross section at S4 deployment site.

3.4.2 Drogue tracking, February 2002

The movements of drogues in the vicinity of the Okawa Bay inlet channel are shown in Appendix 4. One of the drogue plots is presented in Figure 3.9. This shows drogue movements during the second day of the drogue tracking, when winds were lighter (and hence drogue movement would have been least influenced by wind).

Figure 3.9 shows a pronounced movement of the shallow drogues (blue lines) out of the Bay, while the mid-depth drogues (red lines) remained fairly stationary. The mid-depth drogues curtains were approximately 1500 mm below the surface, while the shallow drogues curtains were approximately 600 mm below the surface. Thus the ‘mid-depth’ drogues in fact had their curtains at less than half the depth of the channel (channel depth was between 5 and 6 m). Deeper curtains were impractical because of fouling on weeds.

The minimal movement of the mid-depth drogues suggests that the water at the mid depth of the channel was fairly stationary, while shallow water was flowing out of the Bay and, to maintain equilibrium, the bottom waters (say 4 to 6 m below the surface) would have been flowing into the Bay. This observation tends to support the results obtained from the S4 current meter, which showed that the bottom waters most frequently flowed into the Bay (and hence to maintain equilibrium, the surface waters had to be flowing out of the Bay).

The three shallow drogues shown in Figure 3.9 moved ~100 m in ~40 minutes (i.e., at velocities of ~4 cm s^{-1}). This estimate of surface velocity is comparable with the average bottom water velocity (~ 3 cm s^{-1}) measured by the S4 current meter.

The other drogue tracking plots shown in Appendix 4 showed similar trends of faster velocities at the surface compared with at mid-depth. Current directions also differed at the different depths.

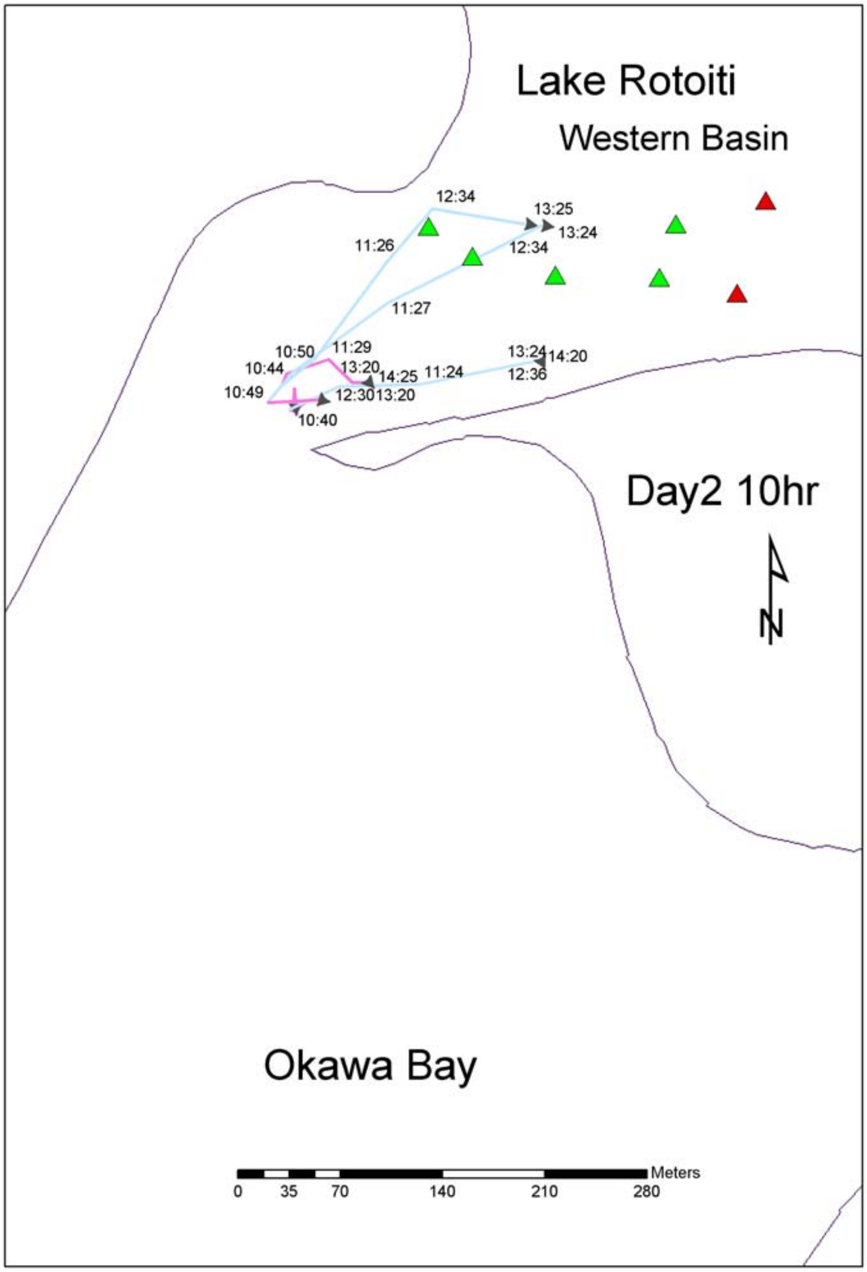


Figure 3.9: Movement of drogues deployed in Okawa Bay inlet channel, 20 February 2002. Blue lines indicate routes of shallow drogues, red lines indicate routes of mid-depth drogues. Arrows indicate end positions. Green and red triangles show location of permanent channel buoys (red triangles indicate left side of channel for vessels entering the Bay, green triangles indicate right side of channel). All drogues remained in the deep water channel, except for two of the shallow drogues, which eventually drifted into the shallows to the north of the channel. Wind was light south-westerly, 2 to 3 m s^{-1} (4 to 6 knots).

3.4.3 Dye tracking, July 2002

The objective of the dye tracer experiment was to confirm instrument measurements in July 2002 of water movement in and out of Okawa Bay through the entrance channel, near the surface and at depth. In March, the current meter data indicated that flow velocities were likely to be low and near the threshold of detection. They also indicated that there may be considerable short-term to-and-fro movement associated with seiching. Dye tracing has the advantage of integrating movement of water over a long period and hence will give the net movement of water even if it were seiching in and out of the bay. The two dye tracking experiments indicated that net cross-entrance flows were small but persistent and dependent on the surface wind stress for magnitude and direction.

On 23 July, with a NE wind blowing into Okawa Bay, the surface dye plume moved down wind into Okawa Bay (Figure 3.10). It rapidly dispersed and was no longer detectable after about 30 minutes. The dye travelled about 35 m in 10 minutes, which implies a surface layer velocity of about 5 to 6 cm s^{-1} (although this must be regarded as very approximate due to the rapid dispersion of the dye). Conversely, the subsurface plumes (at depths of 2 m and 5 m) were tracked for over 2 hours as they moved slowly up-wind out of Okawa Bay along the entrance channel (Figure 3.10). The leading edge travelled 120 m in 2.25 hr giving an estimated flow velocity of 1.5 cm s^{-1} over that period.

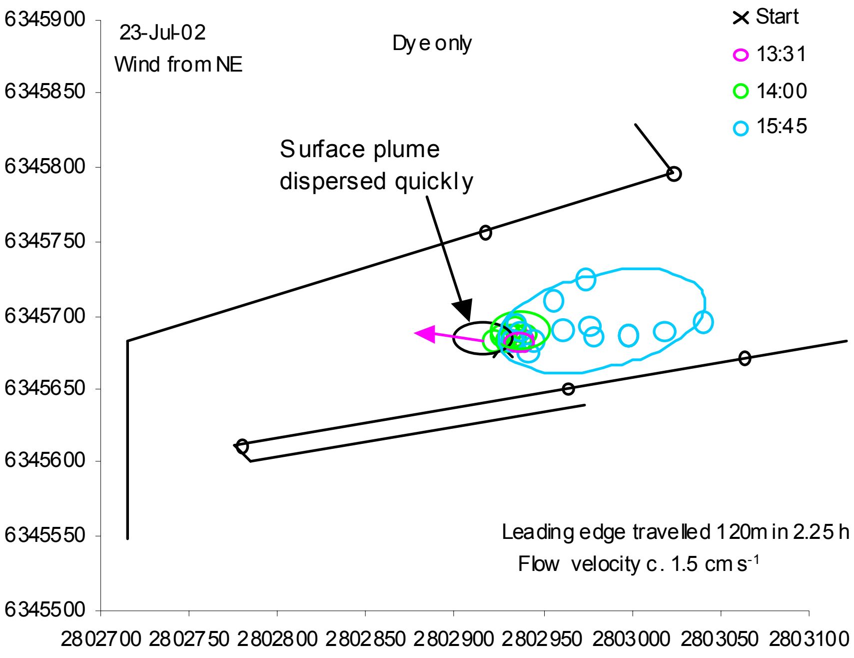


Figure 3.10: Dye tracking, 23 July 2002. Black lines indicate outline of Okawa Bay inlet channel.

On 25 July, with a SW wind blowing out of Okawa Bay, the surface dye plume moved rapidly down-wind out of the bay (Figure 3.11), rapidly dispersing, and was no longer detectable after about 20 minutes. The dye travelled about 55 m in 8 minutes, implying a surface layer velocity of about 10 to 12 m s^{-1}. Conversely, the subsurface dye plumes moved slowly up-wind into Okawa Bay along the entrance channel. (Figure 3.11). The leading edge of the dye travelled 250 m in 2.5 hr giving an estimated flow velocity of 2.8 cm s^{-1}.

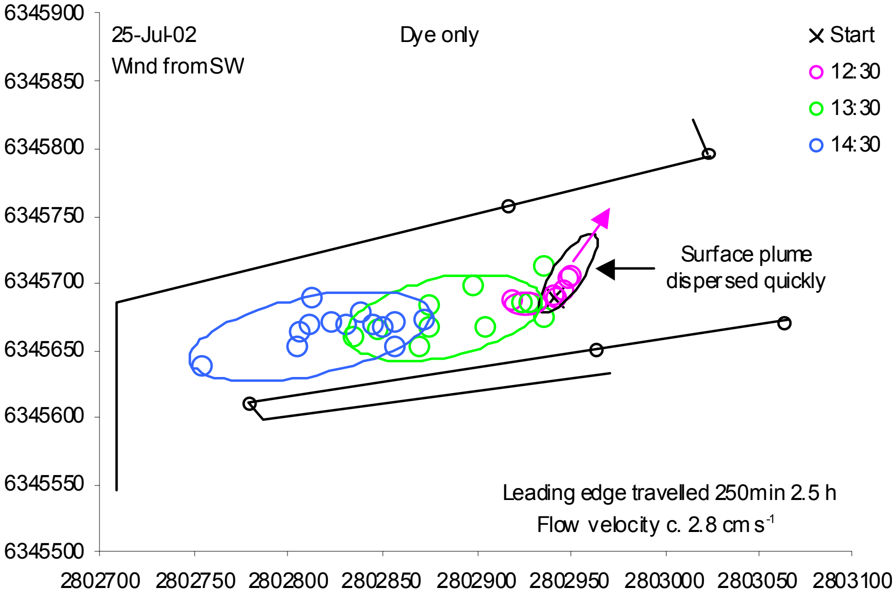


Figure 3.11: Dye tracking, 25 July 2002. Black lines indicate outline of Okawa Bay inlet channel.

3.4.4 ADP current meter deployment July/August 2002

Currents measured by the Acoustic Doppler profiler (ADP) are shown in Figure 3.12. The ADP was deployed on the lakebed at 5.8 m depth, looking upward through the water column. The ADP measures currents by emitting sound beams that reflect back to the instrument off particles that are moving with the water currents. The current velocity is then calculated from the Doppler shift principle, and currents can be calculated at multiple distances from the ADP. In this deployment the ADP was set up to calculate water velocity at 1 m intervals, giving measurement locations (bins) of 1.5, 2.5, 3.5, 4.5 and 5.5 m above the lakebed. Unfortunately, the near-surface measurements are interfered with by sound reflecting off the water surface and must be discarded, leaving valid readings from approximately 1.3, 2.3, 3.3 and 4.3 m below the surface (Figure 3.12).

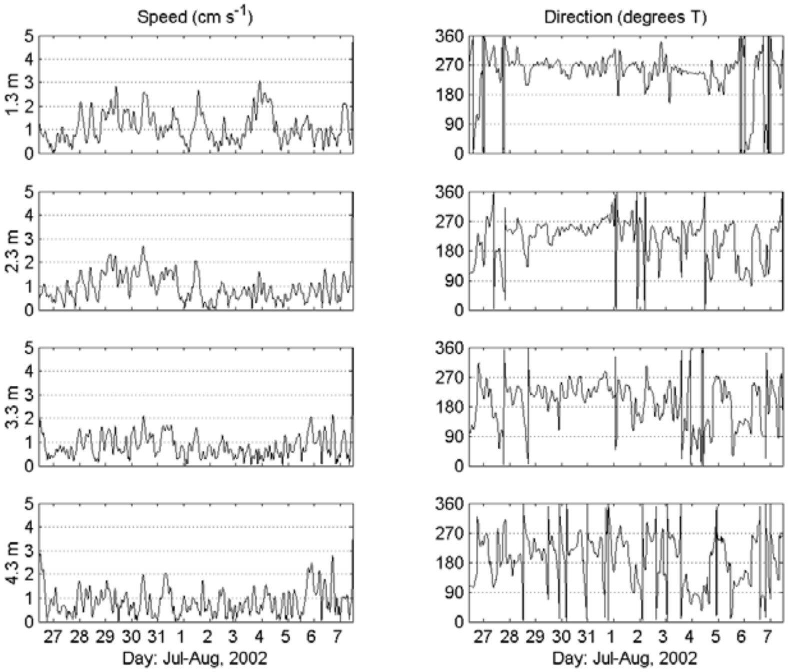


Figure 3.12: Current speed and direction for depths centred at 1.3, 2.3, 3.3 and 4.3 m below the surface. Current directions are in true-vectors ("going-to") convention. Measurements were collected at 5-minute intervals, but a 1-hour running-average window has been applied to smooth the curve. The running average damps out extreme fluctuations, raw speeds are ± 1 cm s^{-1}, speeds less than this occurred during 8% of the deployment.

Currents with speeds lower than the ADP detection limit (<0.5 cm s^{-1}) occurred during only 8% of the deployment, so the channel is generally an active flow region, as would be expected for a narrow channel joining two larger basins. Over the deployment period, currents at 1.3 m depth were predominantly towards the SW, flowing into the bay, while near-bottom currents had a larger NE (outflowing) proportion (Figure 3.13A). On the whole, currents in the ADP measurement range (below 1 m) flowed SW, into Okawa Bay (Figure 3.13B). Periods of horizontal shear occurred when the near-surface currents flowed in the opposite direction to the near-bed currents, and these are typical of wind-driven flows in enclosed bays. A shear event is evident in Figure 3.13, on 4-5 August under winds from the easterly quarter (Figure 3.14), where along-channel flows differed in speed by around 4 cm s^{-1} between 1.3 and 4.3 m depth. This pattern was seen in the ADP record for faster currents (those above 2 cm s^{-1}), water often flowed into the bay at 1.3 m and out of the bay near the lakebed. This demonstrates that entrance flow can be strongly sheared (flow in opposite directions in the top and bottom layers). This was also inferred from bottom currents (S4 current meter) and surface currents (drogues) measured in February (Sections 3.4.1 and 3.4.2), from dye-tracer experiments (Figures 3.10 and 3.11), and from numerical model predictions (Figure 3.16).

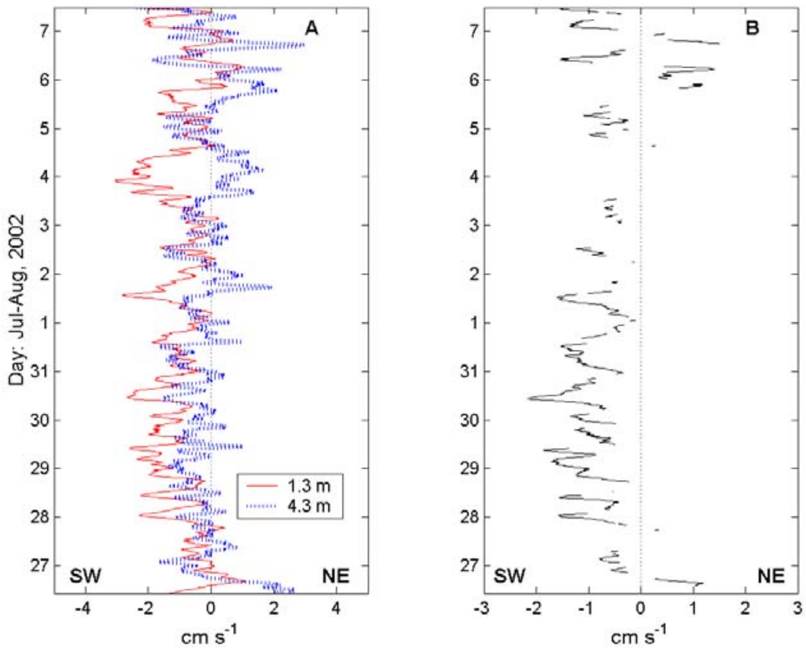


Figure 3.13: Magnitude of the along-channel (59 – 239 °T) current component measured by the ADP : A) at 1.3 and 4.3 m below the water surface; B) depth-averaged – only plotted when currents at all 4 measurement depths flowed in the same along-channel direction. Positive currents were flowing toward the northeast (59°), and negative towards the southwest (239°). An obvious two-layer flow exists on 3-4 August and a smaller one occurs on 1-2 Aug, but currents are flowing in much the same along-channel direction for most of the deployment. Means SW- and NE-directed depth-averaged (plot B) were –0.95 and 0.78 cm s^{-1} respectively.

Typically, currents are exchanged through the bay entrance in a two-layer flow, water can be flowing into the bay at the surface and out near the lakebed, known as return-flows. Since the channel is the only entrance/exit to Okawa Bay, these types of return-flows are expected to be common. One reason that they are not commonly seen in the ADP data (Figures 3.12 and 3.13) may be that the ADP did not easily pick up the surface wind-driven current. Due to sound reflection off the water surface, the ADP measurements do not include the upper 1 m, where wind-driven currents are likely to be strongest. (The wind-driven current decreases logarithmically with depth and would be small at 1.3 m below the water surface, where the shallowest measurement was centred). This helps to explain an anomaly in the data: during the ADP deployment the measured currents were directed mostly into Okawa Bay when southerly winds were blowing (Figure 3.12), yet a northerly-directed wind-driven surface current would have been expected, and water levels were dropping in the bay (Figure 3.15), inferring a net outflow. Numerical model results show a surface flow in the wind direction and bottom-return-flows lower in the water column, in the same direction as the ADP (Figure 3.16).

The ADP measurements (Figures 3.12 and 3.13) can be related to wind forcing (Figure 3.14) as follows. A southerly wind blew from 27 July to 1 Aug, which would have induced a surface current (in the upper 1 m) flowing out (to NE) of Okawa Bay. If water level remains the same, then there has to be a return flow into the bay (to SW) lower in the water column, such as measured by the ADP (Figures 3.12 and 3.13). On 4 August a NE wind blew, which is expected to drive a surface current to the SW. The NE wind has a relatively long fetch into Okawa Bay compared to other wind directions, so it can set up a strong surface current that may extend deeper into the water column and be measured by the ADP. This is probably the cause of the measured current shear of 4 Aug, a wind-driven current flowing to the SW measured at 1.3 m, and a corresponding bottom-return-flow seen at 4.3 m (Figure 3.13). The depth-averaged flow to the NE on 6 August (Figure 3.13) is likely to be a return-flow induced by the strong SE wind (Figure 3.14), but could also be related to water level changes (see below).

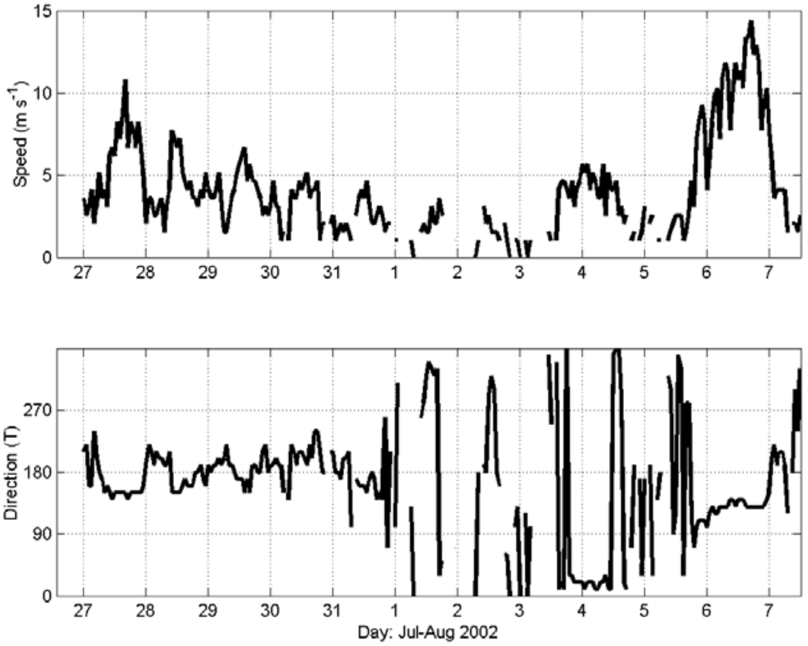


Figure 3.14: Wind measured at Rotorua Airport weather station, 176.3°E, 38.1°S. Wind directions are in meteorological ("coming-from") convention.

A calculation of the mean exchange flow through the channel can be made if we assume that the mean SW-directed depth-averaged current of 0.95 cm s^{-1} (Figure 3.13) is a return-flow balanced by a wind-driven surface current in the upper 1 m of the water column. The channel cross-sectional area of 655 m^2, of which the upper 1 m has an area of 130 m^2. The mean discharge of the depth-averaged return-flow is therefore 5 m^3 s^{-1} (0.0095 m s^{-1} x 525 m^2), which gives a flushing time for Okawa Bay of 3.7 days (1,600,000 m^3 ÷ 5 m^3 s^{-1}).

Assuming the surface wind-driven current exactly balances this, the corresponding mean wind-driven near-surface current speed is 3.8 cm s^{-1} (5 m^3 s^{-1} ÷ 130 m^2), which is ~1% of the mean wind speed (4 m s^{-1}) during the deployment. Further estimates of the surface wind-driven currents can be made based on drogue experiments and from the literature. In February, drogues (with 1 m-square sails centred at about 0.75 m) gave surface-layer speed estimates of ~4 cm s^{-1} in 2-3 m s^{-1} winds, about 1.5% of the wind speed. Magnitudes of wind-driven ocean currents at the water surface are typically about 3% of the wind speed. (The Open University 1989), but are often 1-2% in coastal situations due to bottom frictional effects (Prandle & Matthews 1990). Recent measurements in the Hauraki Gulf showed that wind-driven currents are around 0.7-1.1% of the wind-speed when averaged over the surface 1 m of the water column (Stephens 2001). Taking the mean and maximum measured winds of 4 and 14 m s^{-1} (Figure 3.14) and applying a 0.7%-relationship (used lower end of the range because fetch is very limited), then mean and maximum currents averaged over the upper 1 m would have been 3 and 10 cm s^{-1}, values which compare favourably to the estimate based on measured currents.

Assuming a maximum near-surface flow of 10 cm s^{-1} gives a near-surface exchange flow of 13 m^3 s^{-1}, which would translate into a maximum current speed of 2.5 cm s^{-1} in the lower water column (depth averaged), a value that compares closely to the measured currents (Figure 3.12). The maximum exchange flow gives a flushing time for Okawa Bay of 1.4 days.

The wind affects water levels as well as currents. In enclosed water bodies, wind stress will create pressure gradients by setting water up against the downwind lake edge, and this effect can be seen by comparing wind and water level records. Water levels measured inside Okawa Bay, in Lake Rotoiti near the outlet gates, and in the Kaituna River at Taaheke (Figure 3.15), can be compared with winds (Figure 3.14). In the absence of rain, water levels dropped gradually from 27 July to 2 Aug, but small water level changes of order 5 mm occurred associated with southerly wind pulses (compare Figures 3.14 and 3.15). On 2 August the Lake Rotoiti outlet gate was raised to hold water (seen as a downward discontinuity in the Kaituna River levels), causing water levels in the lake and Okawa Bay to stabilise, and then rise rapidly during rainfall, with ~ 11 mm rain on 4 Aug.

The measured currents appear to result from the direct influence of wind stress on the water surface, and not from the associated water level changes. However, there was a flow event through the Okawa channel that may have been related to the lowering of the outlet gate. The outlet gate was lowered on the afternoon of 5 August (seen as an upward discontinuity in the Kaituna River levels) and water levels dropped away in Lake Rotoiti, but were maintained for a short period in Okawa Bay, presumably by the 9 m s^{-1} easterly wind (Figure 3.15). This period of initial lake-lowering on 6 August was the only time of consistent outflowing (NE) current throughout the entire water column, as measured by the ADP (Figure 3.13B).

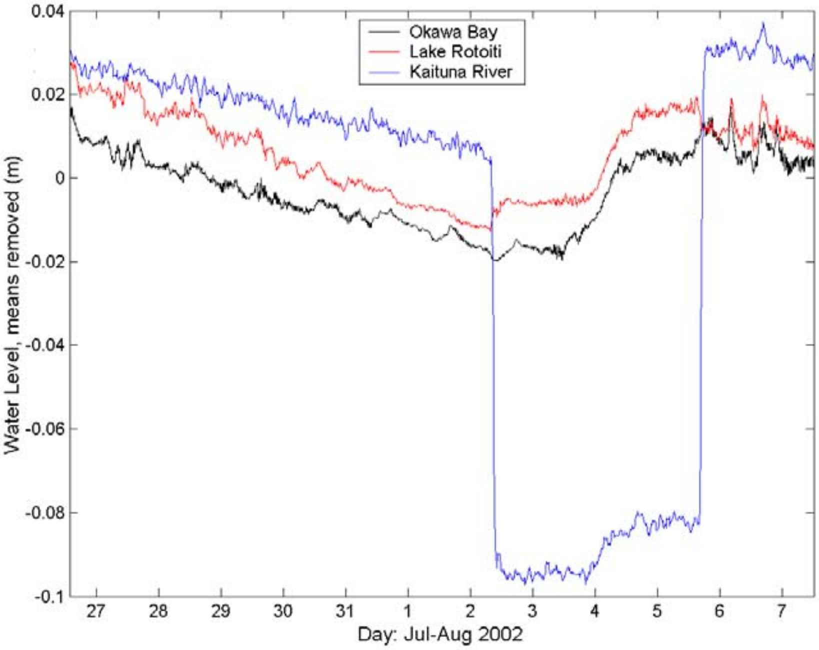


Figure 3.15: Water levels recorded at Okawa Bay entrance, Lake Rotoiti outlet and the Kaituna River at Taaheke, with means removed. The discontinuities in the Kaituna River levels correspond to changes in the Lake Rotoiti outlet gate, which feeds the Kaituna River.

3.4.5 Assessment of mixing within Okawa Bay using hydrodynamic model

The flushing times calculated above quantify the time water spends within Okawa Bay assuming that the bay is well-mixed. An important question is the extent to which water flowing in and out of the entrance mixes with water in the main body of Okawa Bay. It is possible that the currents measured in the entrance channel might not penetrate very far into Okawa Bay once the constriction of the channel eases. Thus when ‘new’ water flows into Okawa Bay in the surface layer, it might tend to pond on the surface just inside the entrance. If there is very little mixing within the Bay at the time (e.g., negligible wind mixing, stable water levels and no significant density differences that might induce circulation), then this ‘new’ water would likely be entrained into the near-bottom flow and carried back out through the entrance. In this situation water from the southern and eastern shores of Okawa Bay may not have the opportunity to mix with water flowing in and out through the entrance and its residence time may be much longer than the estimates given above. However, if mixing within Okawa Bay is rapid (e.g., because of wind-induced circulations and/or because temperature (density) differences between the inflowing water and water within the Bay induce density currents), then ‘new’ water flowing into the Bay will have the opportunity of being carried towards the southern and eastern shores and to mix with ‘old’ water in those localities. Wind stress on the water surface is the most likely driving force to induce ‘new’ water to flow from near the entrance into the further reaches of Okawa Bay.

The numerical H-D model (see description in Section 2.3.3) provides a useful tool to estimate how much mixing occurs within Okawa Bay, and the amount that through-channel exchange flows are interchanging with the entire water body in the bay. The model can also be used to illustrate the effect of an additional 1 $m^3 s^{-1}$ inflow from the Ohau Channel.

Currents predicted by the HD numerical model for the ADP deployment period are shown in Figure 3.16 for comparison with measured currents (Figure 3.12). The model includes the near-surface layer that the ADP measurements missed (upper plots in Figure 3.16 are centred at 0.5 m depth).

The major discrepancy between the measured and modelled data is that modelled speeds are over-predicted. The main reason for this is that wind-forcing (from Rotorua Airport) was applied evenly over the model grid, even though Okawa Bay is sheltered by high hills on its southern end. Therefore energy inputs are higher to the model than would be experienced in reality. Also, the 1 m layering in the model may have enhanced horizontal shear between layers, resulting in faster bottom-return-flows. The predicted current magnitudes could have been improved by calibration, but this was not undertaken due to time constraints.

There is close similarity between predicted and measured current directions. This shows that the wind stress is being transformed by the model into realistic flow patterns that increase our understanding of mixing and exchange in Okawa Bay. The model confirms that near-surface currents did largely flow in the wind direction during the ADP deployment and that current measured by the ADP were mostly wind induced return-flows. The shear flow is seen by comparing the upper 0.5 m and lower 3.5 m direction plots in Figure 3.16, they are generally 180^o out of phase, flowing in opposite directions.

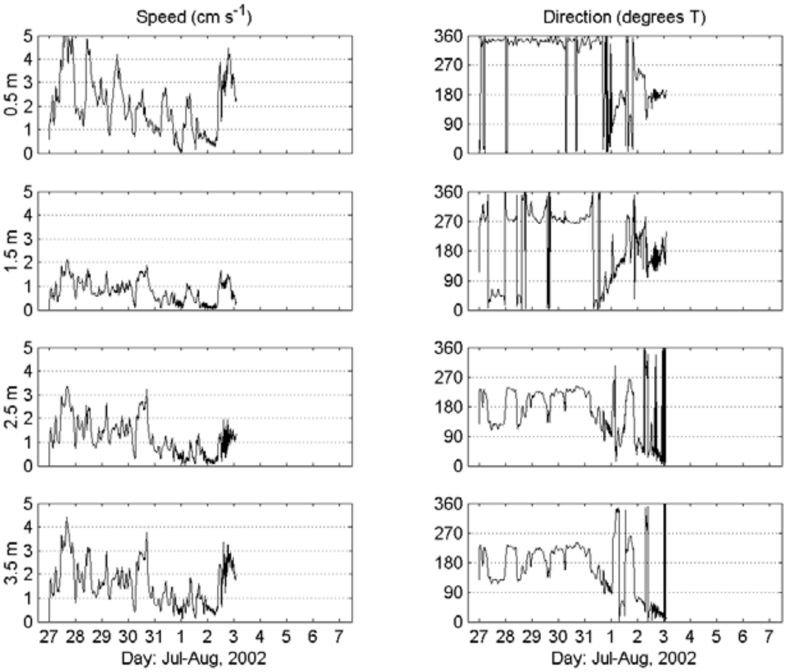


Figure 3.16: Currents at the ADP deployment site predicted by the numerical model. Depths on the y-axis refer to the mid-depths of 1 m vertical layers in the model. Current directions are in true-vectors (“going-to”) convention.

Figure 3.16 shows currents from an unstratified (uniform temperature) model run. Stratification enhanced the shear between the near-surface and lower layers, resulting in faster near-surface wind-driven flows and near-bed return-flows. Flow directions remained similar. Stratification thus served to increase the exchange flow through the channel.

Figure 3.17 shows an example of the patterns of flow from the numerical model. Plot A shows currents and temperature in the surface layer, centred at 0.5 m below the water surface, while plot B shows a near-bed layer centred at 3.5 m depth. At the time (12:00, 28 July) the wind was blowing from the southeast, forcing a northwest-directed surface current of about 5 cm s^{-1} and a southeast-directed bottom-return-flow of 7-8 cm $s^{-1.}$ These current speeds are likely to be over-predicted, but the circulation pattern and relative strength of the currents will be similar to reality. The model shows that there is significant mixing in the bay. Note that after 1.5 days the temperature is similar in both the top and bottom of the water column, despite being initially set at 21°C in the surface layer and 19°C below, i.e. the wind-induced currents have vertically mixed the bay.

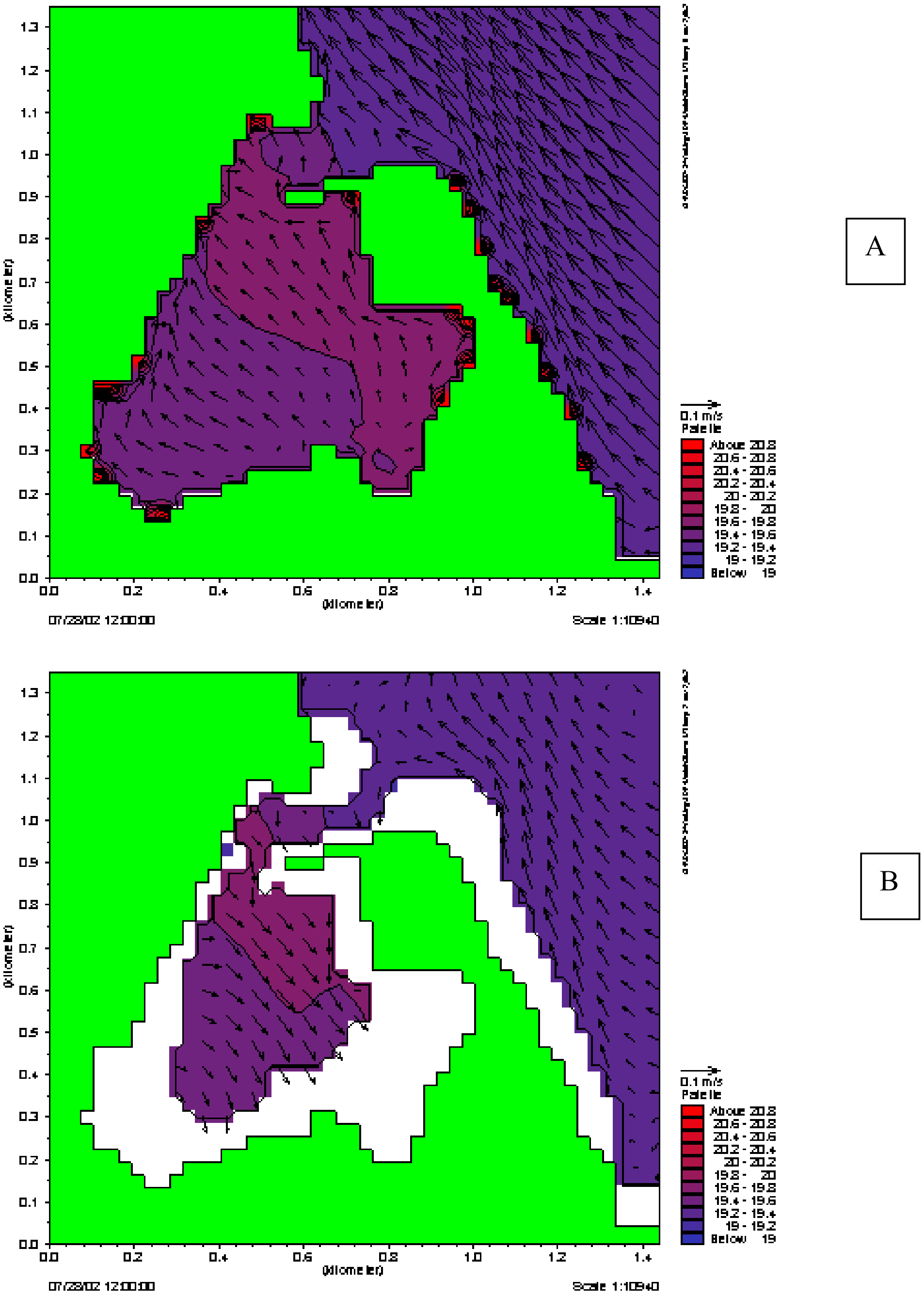


Figure 3.17: Velocity and temperature in Okawa Bay, predicted by the numerical model: A) In the near-surface layer centred 0.5 m below the water surface, B) in a near-bed layer centred at 3.5 m below the water surface. The predictions shown are for at 12:00 on 28 July 2002. The simulation started at 00:00 on 27 July, when the surface layer temperature was set at 21°C and the lower layers at 19°C.

A model simulation was also run incorporating a 1 $m^3 s^{-1}$ inflow to simulate the proposed diversion of Ohau Channel flow through Okawa Bay. Other than raising water levels inside Okawa Bay a small amount with time, the extra inflow had an unidentifiable effect on water flow i.e. it was completely masked by the dominant wind-induced circulation.

There is further evidence to suggest that Okawa Bay is horizontally well-mixed during periods of moderate winds. During the February field work we collected depth-averaged water samples from three different sites in Okawa Bay over a period of four days (Sites 1, 2 and 3 – refer to Section 2.4.3 and Appendix 2). If the Bay was poorly mixed we might expect to see higher nutrient and chla concentrations in the southern and eastern parts of the Bay (i.e., Sites 2 and 3). The nutrient and chla measurements are compared in Figure 3.18. There is no obvious consistent difference in nutrient or chla concentrations at any of the sites. This suggests that, during the period of 19-22 February, the Bay was reasonably well mixed horizontally.

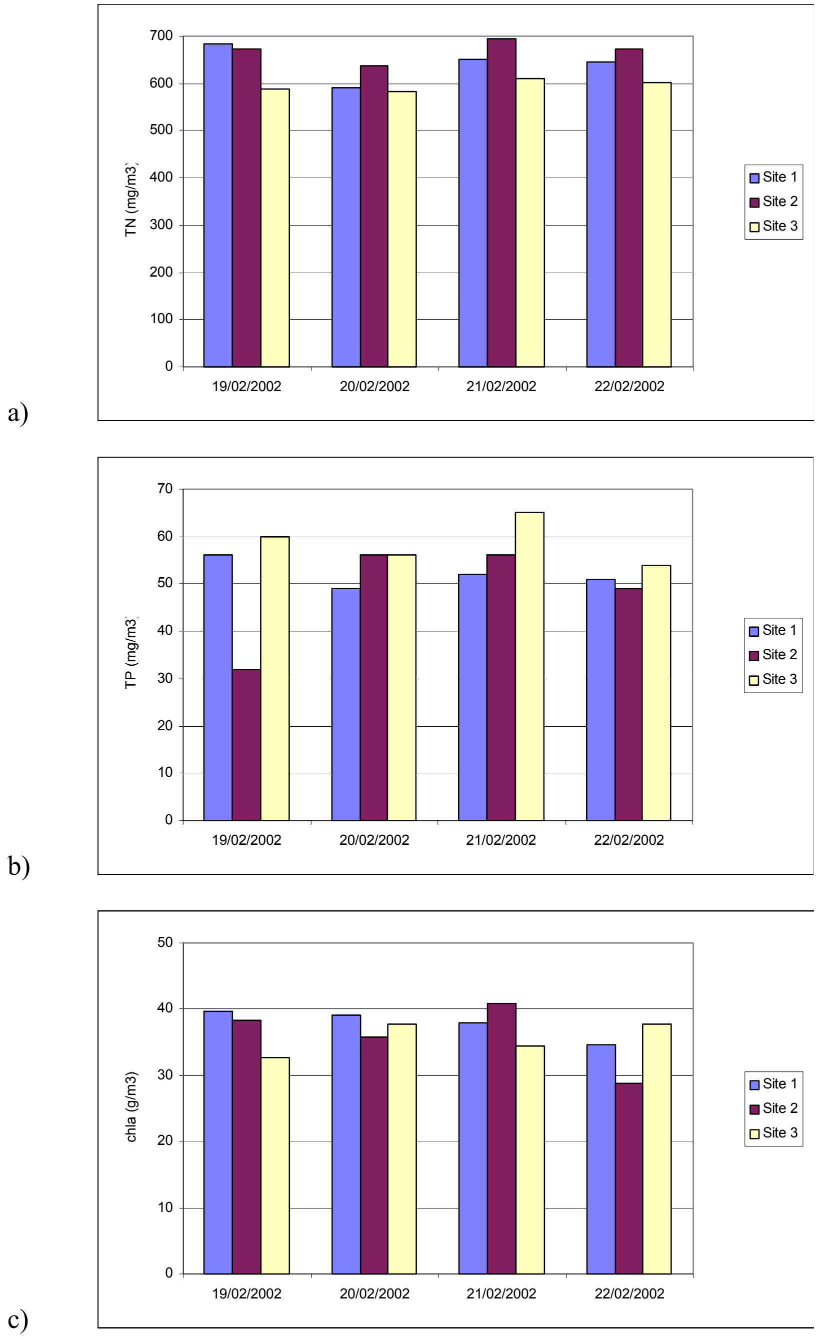


Figure 3.18: Depth-averaged concentrations at Sites 1, 2 and 3 between 19 and 22 February 2002 for: a) TN; b) TP; c) chla.

3.4.6 Estimation of residence time

In Section 3.1.2, we estimated the theoretical residence time of Okawa Bay *without* the influence of exchange flow between Okawa Bay and the Western Basin. Table 3.4 shows how the exchange flow influences the residence time, with and without the Ohau Channel diversion flow (refer to Section 3.1.2 for data on rainfall, Okawa Bay area and volume, etc).

Table 3.4: Estimates of residence time for Okawa Bay.

	Residence time with no Ohau Channel diversion flow	**Residence time with Ohau Channel diversion flow = 1 $m^3 s^{-1}$**
Exchange flow = zero	712 days	18 days
Exchange flow = 5 $m^3 s^{-1}$	3.7 days	3.1 days
Exchange flow = 10 $m^3 s^{-1}$	1.8 days	1.7 days

Table 3.4 shows that the influence of a diversion flow on residence time is greatly reduced if there is an exchange flow between Okawa Bay and the Western Basin of 5 $m^3 s^{-1}$ or more.

3.5 Water quality measurements

Water quality measurements by Environment B·O·P (December to February) and NIWA (19-22 February) are presented in Appendices 1 and 2, respectively. The data are summarised in Table 3.5.

Table 3.5: Summary of water quality results. Mean concentration (minima and maxima shown in brackets). All in mg m^{-3}. ND = not determined. Detailed results in Appendices 1 and 2.

	Okawa Bay			**Okawa Bay inlet**	**Western Basin**			**Ohau Channel**	
	NIWA	**Environment B·O·P**		**NIWA**	**NIWA**	**Environment B·O·P**		**NIWA**	**EBoP**
Sample depth	Depth-averaged	1 m	4 m	Depth-averaged	Depth-averaged	1 m	9 m	Depth-averaged	0.5 m
Sampling period	19-22/2/02	4/12/01 – 22/2/02	24/1/01 – 22/2/02	19-22/2/02	19-22/2/02	8/1/02 – 22/2/02	8/1/02 – 22/2/02	19-22/2/02	Dec-Mar, 1995-2002
NH_4-N	3.6 (2-6)	16 (1-120)	233 (5-588)	4 (1-7)	4 (3-5)	6 (2-16)	59 (4-198)	8 (3-15)	20 (2-95)
NO_3-N	3.4 (0.6-7.6)	2 (1-11)	5 (1-24)	3 (1-6.1)	1.3 (0.5-2)	1 (1-1)	5 (1-18)	27 (4.4-84)	23 (1-132)
TN	636 (582-695)	859 (639-1051)	757 (663-912)	570 (533-613)	396 (352-453)	412 (382-439)	561 (388-1043)	348 (268-403)	412 (257-658)
DRP	2.1 (1-3)	4 (1-12)	37 (2-112)	2.2 (1.5-3.3)	1.4 (1-2)	6 (1-34)	6 (1-18)	15 (13-19)	9 (1-44)
TP	53 (32-65)	50 (24-61)	84 (44-155)	44 (41-47)	29 (27-34)	22 (18-24)	46 (26-89)	48 (38-56)	36 (10-72)
Chl a	36 (29-41)	72 (6-136)	ND	33 (26-40)	19 (17-24)	19.5 (19-20)	ND	14.4 (13-18)	ND

On 19-22 February, NIWA measured low total ammoniacal nitrogen (NH_4-N), nitrate-nitrogen (NO_3-N) and dissolved reactive phosphorus (DRP) concentrations in all water samples. Total nitrogen (TN) and total phosphorus (TP) concentrations were high, due to the organic N and P in the phytoplankton. We used averaged NIWA data in the phytoplankton model.

Environment B·O·P data indicate occasional high NH_4-N, NO_3-N and DRP in the bottom waters of the Bay and the Western Basin. These high values are likely to have occurred when the waters were stratified and the bed sediments reduced. Under such conditions significant amounts of nutrient can be released from the sediments (White 1977; Fish et al. 1980).

3.6 Phytoplankton growth experiment

The results of the phytoplankton growth experiment are presented in Table 3.7, and are given as the ratio of final to initial chlorophyll *a* concentrations in the control and nitrate-spiked incubations. The control result shows a loss of phytoplankton biomass during the incubation period, while the nitrate-spiked result shows the phytoplankton biomass remained essentially unchanged. The ratio of final nitrate-spiked to final control shows a maximum difference of +20%. This relatively small difference indicates that the phytoplankton in Okawa Bay were not nitrogen-limited for growth.

Table 3.7: Phytoplankton growth experiment results. Results are the ratio of final to initial chl a concentrations.

Control incubation	Nitrate-spiked incubation	Spike:control
0.85	1.03	1.20

3.7 Lake bed nutrient release experiments

3.7.1 February 2002 experiments

As discussed in Section 2.4.1, the objective of the use of the benthic chambers was to investigate how quickly nutrients are released from the sediments, especially when the water above the sediments turns anoxic. Nitrogen and phosphorus bound in the sediments is usually released into the water column more rapidly when the water above the sediments approaches anaerobic conditions (i.e., when dissolved oxygen concentrations fall below c. 1 g m^{-3}).

The dissolved oxygen and nutrient concentration measurements for the benthic chambers at the three sites in Okawa Bay are presented in Figures 3.19 to 3.24. The results were somewhat unexpected. Typically, dissolved oxygen (DO) concentration in the dark chambers should fall more quickly than in the light chambers, since the dark chambers prevent the plants (phytoplankton and trapped macrophytes) inside the chambers photosynthesising and hence producing oxygen. However, Figures 3.19 to 3.24 show the opposite effect; the DO fell more sharply in two of the three light chambers than in their paired dark chambers. The reason for this is not clear.

Furthermore, when the water in the chambers turns anaerobic there is usually a very pronounced increase in both NH_4-N and DRP concentrations in the chambers. This was not experienced in this experiment. Instead, both NH_4-N and DRP concentrations showed a gradually reducing rate of increase over the whole incubation period, apparently unrelated to DO concentrations. The release of nutrients from sediments into a benthic chamber typically shows an initial linear release rate from which the aerobic diffusive flux may be calculated. As DO levels approach zero, those rates should increase until the nutrient concentrations inside the chamber begins to influence the rate of diffusion.

One possible explanation for this is that the chambers were not properly sealed against the lake bed, allowing water to flow into and out of the chambers. This is possible in the dark chambers at Sites 1 and 2, and the results for those chambers have been discarded (Figures 3.20 and 3.22). However, we feel confident that the other four chambers were correctly sealed, because they were difficult to dislodge from the lake bed at the end of the experiment, indicating a good seal with the lake bed. Furthermore, the nutrient concentrations in those chambers were much higher than those in the surrounding water.

Another possibility is that there was a continual flow of groundwater with high nutrient concentrations into the chambers, to an extent that this groundwater inflow dominated the nutrient and DO concentrations during the experiment. This possibility could explain the shape of the concentration curves for NH_4-N (i.e., dilution curves). Using a dilution model, we estimated for each chamber the groundwater flux and nutrient concentrations that would be required to 'fit' the observed nutrient concentration measurements. We then averaged these flows and concentrations to assess an average groundwater flow and concentration for the whole Bay. The results of this analysis give an estimated flow rate of about 0.7 $m^3\ s^{-1}$ for the whole Bay, with DIN and DRP concentrations of 375-2500 and 35-300 mg m^{-3}, respectively. This range of nutrient concentrations is plausible, but the estimated groundwater flow of c. 0.7 $m^3\ s^{-1}$ was far greater (c. 27 times) than the assessed catchment water yield for Okawa Bay (0.026 $m^3\ s^{-1}$ – refer to Section 3.1.2). One possibility for this large groundwater inflow was cold water springs, but we had no direct evidence to support this theory. We therefore decided to repeat the experiments in July, simultaneously measuring nutrient concentrations and groundwater inflows to the chambers.

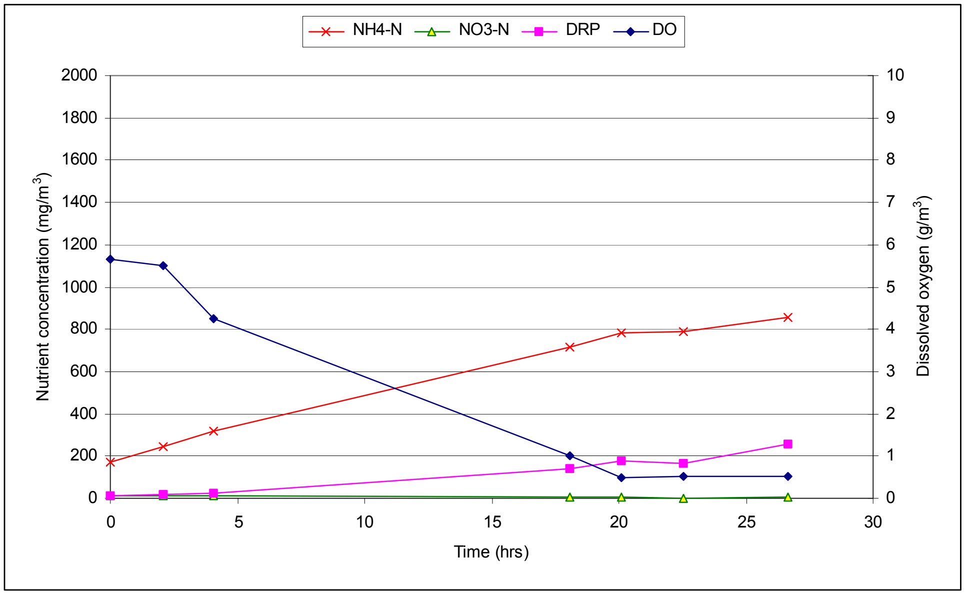


Figure 3.19: Nutrient and dissolved oxygen concentrations during benthic chamber experiment, light chamber, Site 1, February 2002.

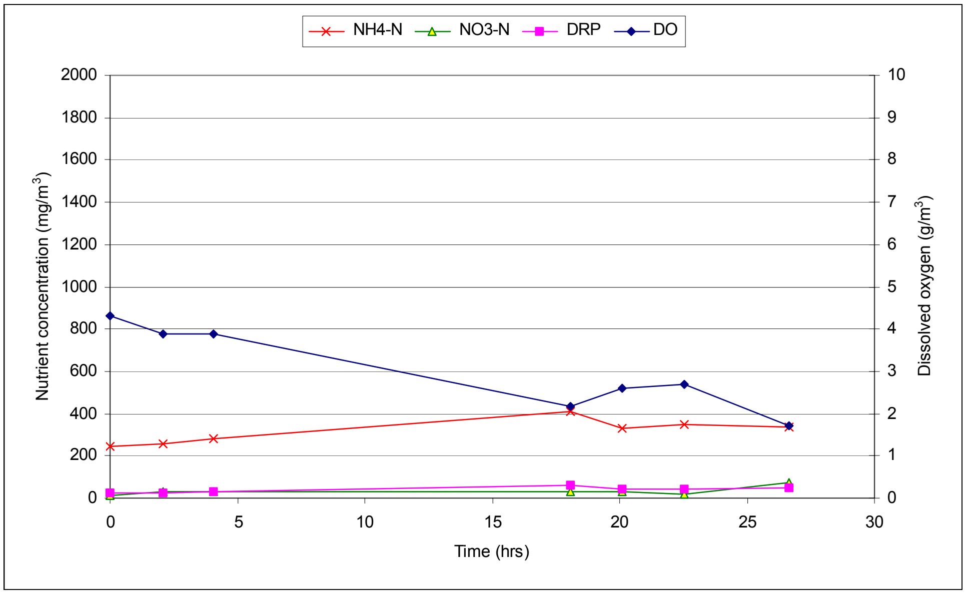


Figure 3.20: Nutrient and dissolved oxygen concentrations during benthic chamber experiment, dark chamber, Site 1, February 2002. This chamber may not have sealed (note that DO concentrations were higher than in the corresponding light chamber, Figure 3.9). Consequently the results have not been used.

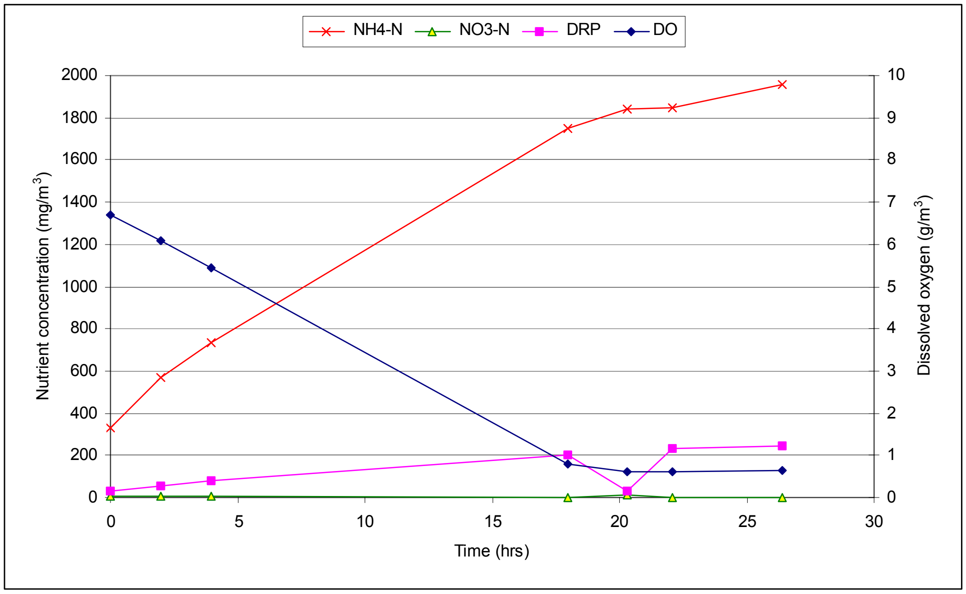


Figure 3.21: Nutrient and dissolved oxygen concentrations during benthic chamber experiment, light chamber, Site 2, February 2002.

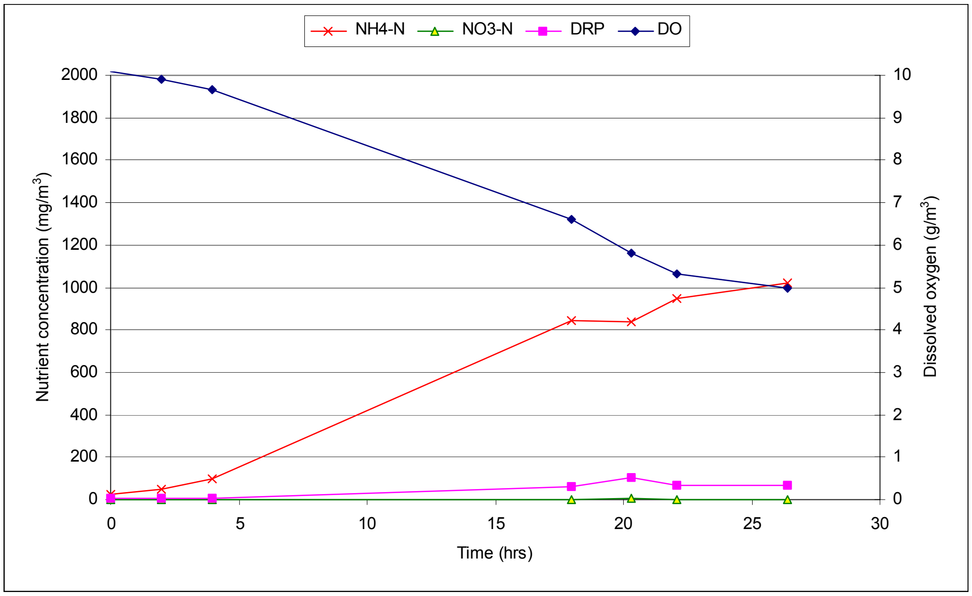


Figure 3.22: Nutrient and dissolved oxygen concentrations during benthic chamber experiment, dark chamber, Site 2, February 2002. This chamber may not have sealed (note that DO concentrations were higher than in the corresponding light chamber, Figure 3.11). Consequently the results have not been used.

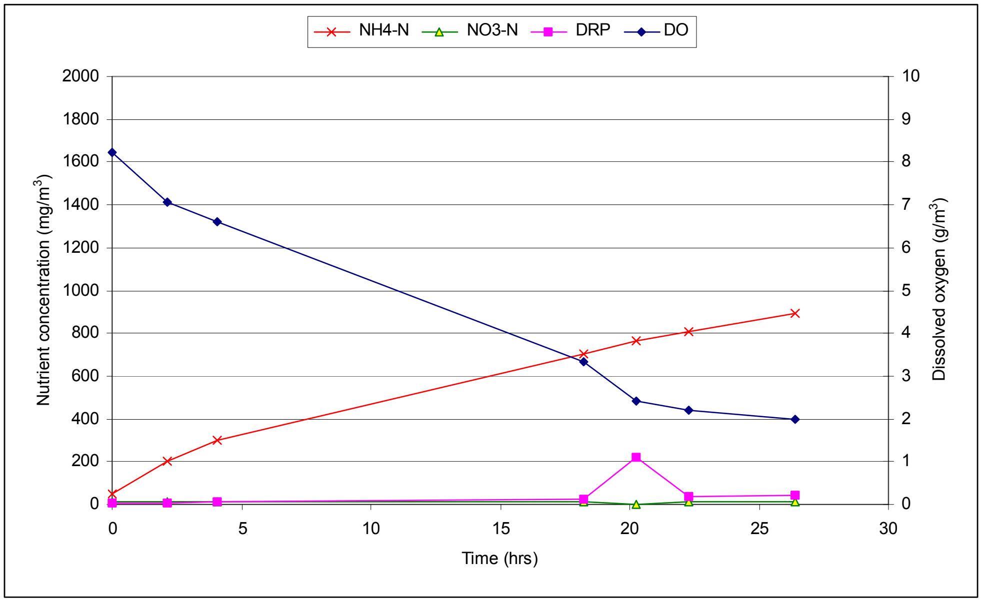


Figure 3.23: Nutrient and dissolved oxygen concentrations during benthic chamber experiment, light chamber, Site 3, February 2002.

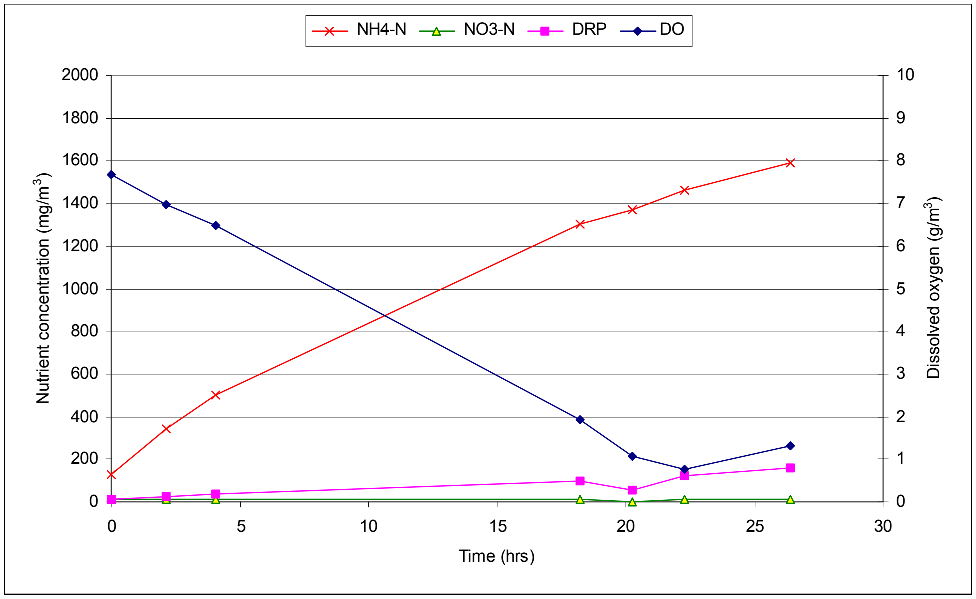


Figure 3.24: Nutrient and dissolved oxygen concentrations during benthic chamber experiment, dark chamber, Site 3, February 2002.

The mass inflow of DIN and DRP from groundwater inferred from our February experiments is 9.7-45 t N yr^{-1} which is equivalent to 26.5-123 kg N day^{-1} and 0.4-5.0 t P yr^{-1} or 1.1-13.7 kg P day^{-1}. This compares with the assessed DIN and DRP inputs from septic tanks of 1.48 t N yr^{-1} (4 kg N day^{-1}) and 0.14 t P yr^{-1} (0.38 kg P day^{-1}), and total catchment inputs (including septic tanks) of 2.18 t N yr^{-1} (6 kg N day^{-1}) and 0.21 t P yr^{-1} (0.57 kg P day^{-1}) (Tables 3.2 and 3.3). This implies that there is a much greater nutrient input to the Bay from groundwater than from septic tanks or other Okawa Bay catchment sources. However, we must ascribe a large uncertainty to our groundwater flow estimate, which is inferred from chamber measurements made over small areas of the bed at only three points in the Bay.

3.7.2 July 2002 experiments

The July 2002 benthic flux chambers experiments were undertaken to measure groundwater inflow through the bed of Okawa Bay and to assess the magnitude of nutrient release from the sediments in winter. Measurements were made at the same sites used in summer so that direct comparisons could be made with the earlier data. The results are shown in Figures 3.25 to 3.30. From duplicate measurements from each chamber at the beginning of the incubation period, it was determined that there was a groundwater flow ranging from 0.4 to 30 L m^{-2} h^{-1}, giving an average inflow of 7.9 L m^{-2} h^{-1} across the 3 sites. This compared favourably with the February estimate of c. 6 L m^{-2} h^{-1}. However, the flow measurements at the end of the 4 day experiment were all around 0.4 L m^{-2} h^{-1}. Unless the benthic chambers could influence the advection of water through the bed of Okawa Bay (unlikely), this indicates that the initial flows were probably an artefact of the chambers settling into the very soft sediments. The measured flow rate of 0.4 l m^{-2} hr^{-1} equates to a bay-wide groundwater inflow of about 0.05 m^3 s^{-1}, which is in the same order of magnitude as the inflow assessed from the difference between rainfall and evapotranspiration (0.026 m^3 s^{-1} – see Section 3.1.2). We therefore conclude that the nutrient inflow to the chambers was a diffusive inflow from the sediments rather than a nutrient-rich groundwater inflow.

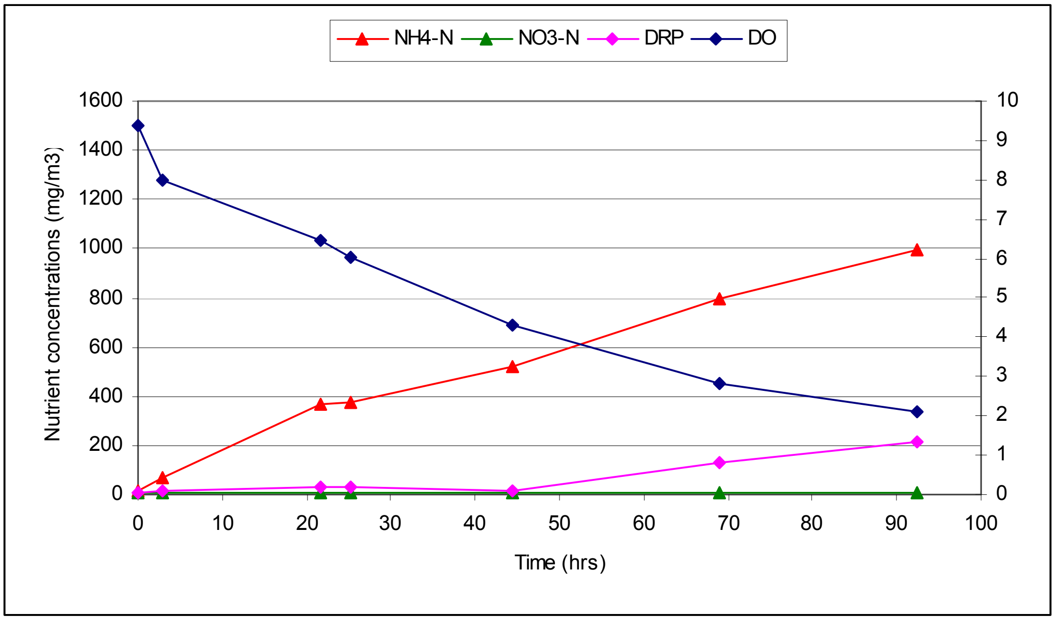


Figure 3.25: Nutrient and dissolved oxygen concentrations during benthic chamber experiment, light chamber, Site 1, July 2002.

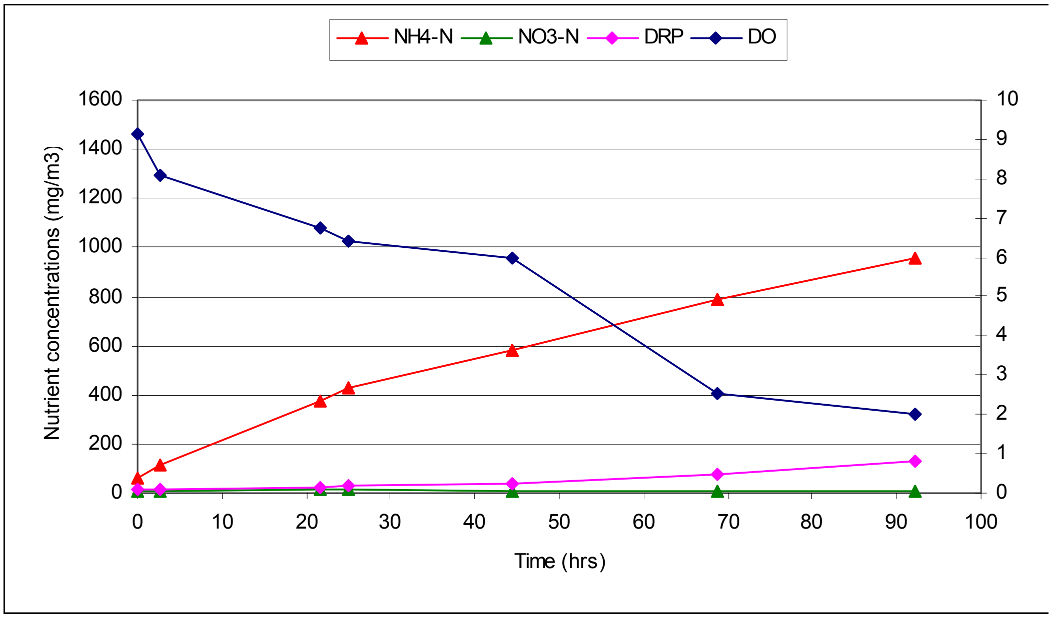


Figure 3.26: Nutrient and dissolved oxygen concentrations during benthic chamber experiment, dark chamber, Site 1, July 2002.

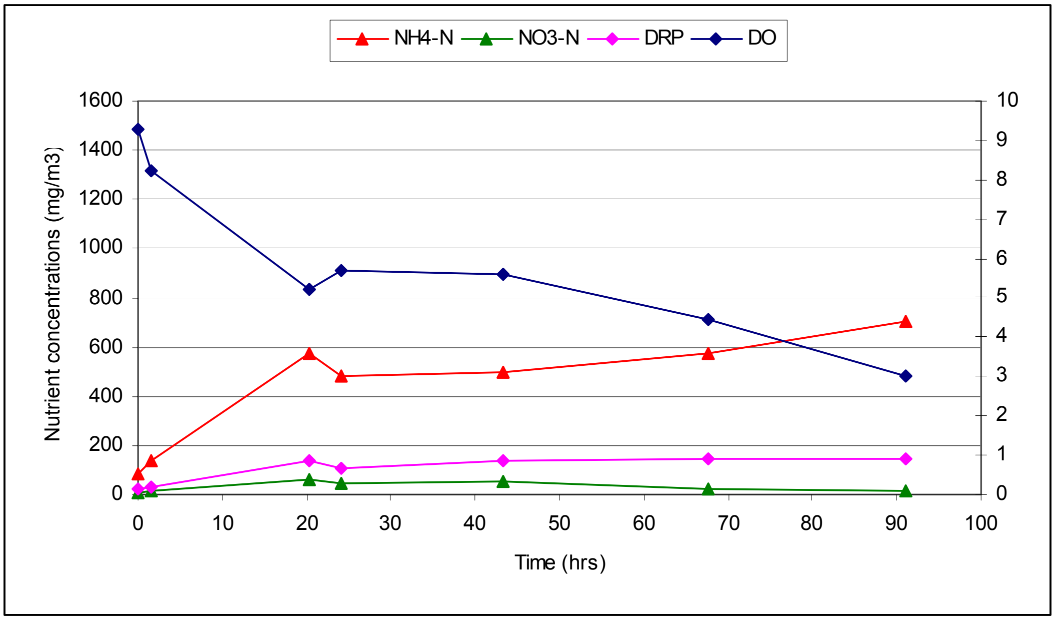


Figure 3.27: Nutrient and dissolved oxygen concentrations during benthic chamber experiment, light chamber, Site 2, July 2002.

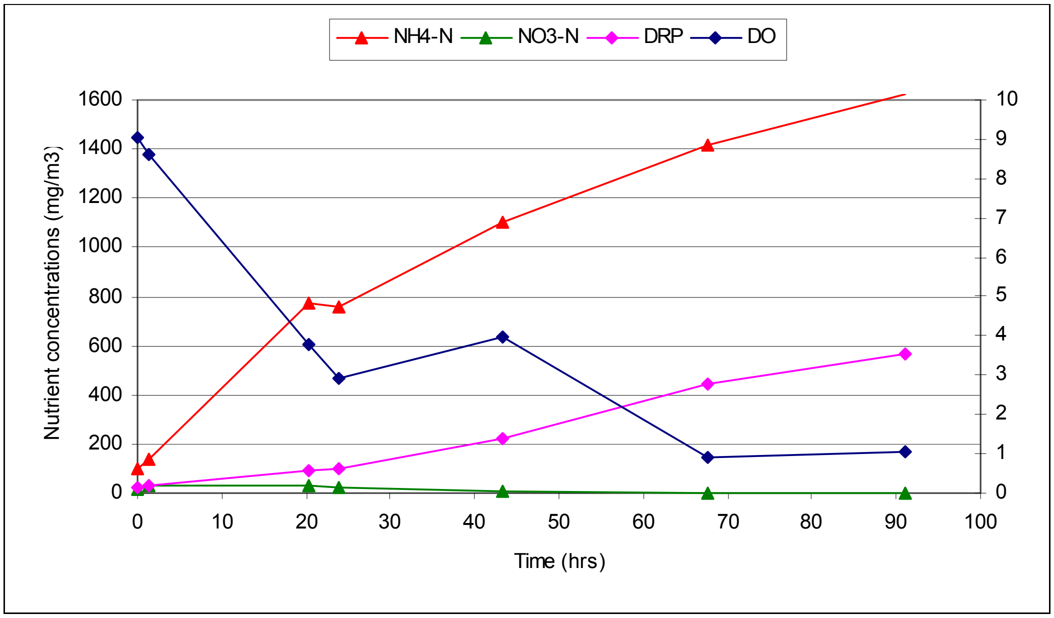


Figure 3.28: Nutrient and dissolved oxygen concentrations during benthic chamber experiment, dark chamber, Site 2, July 2002.

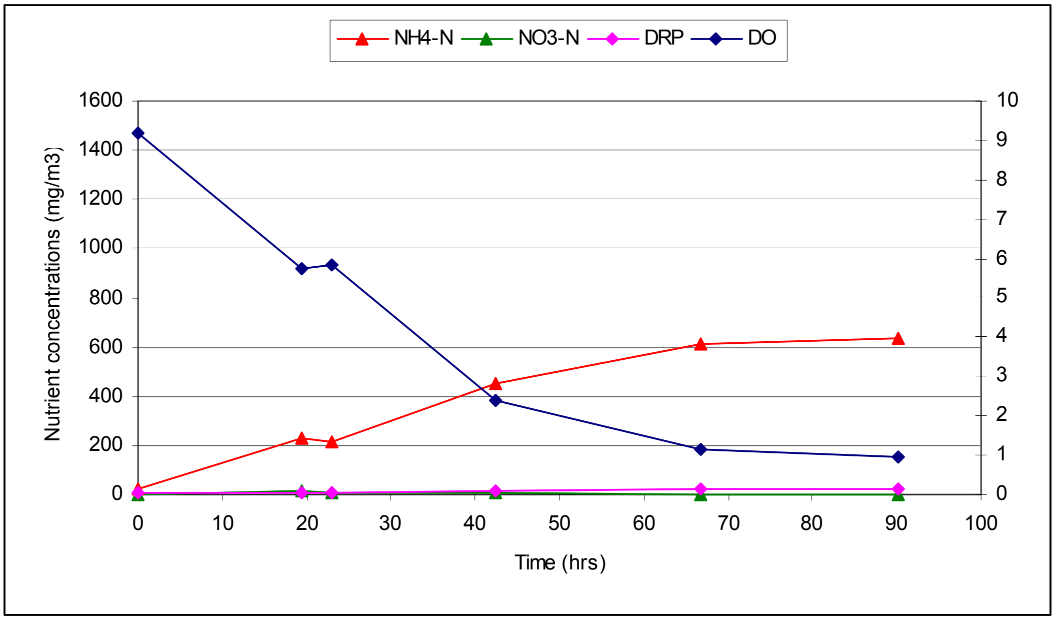


Figure 3.29: Nutrient and dissolved oxygen concentrations during benthic chamber experiment, light chamber, Site 3, July 2002.

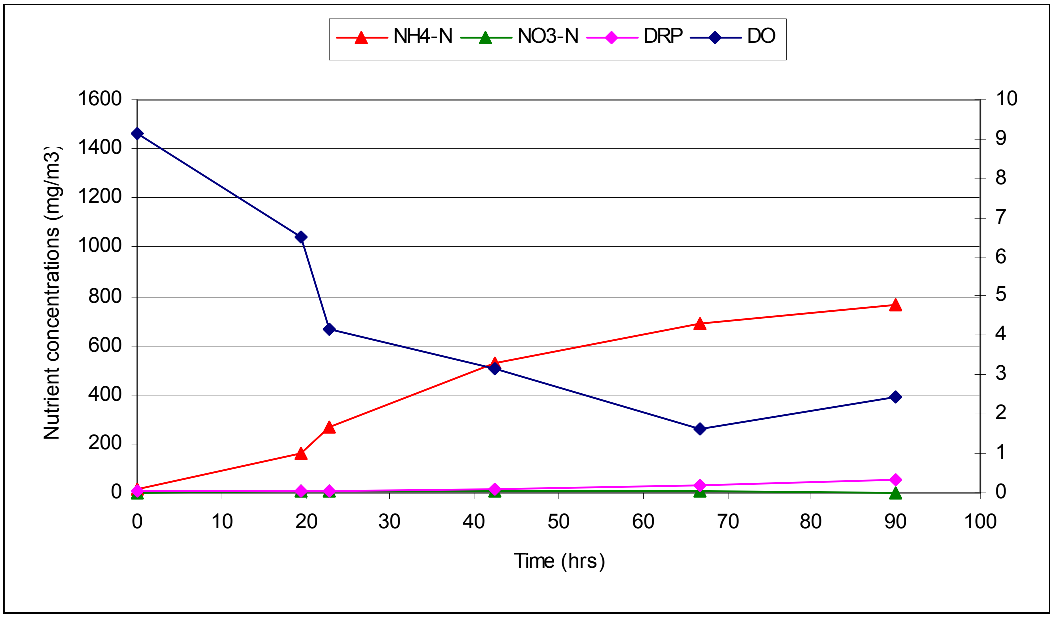


Figure 3.30: Nutrient and dissolved oxygen concentrations during benthic chamber experiment, dark chamber, Site 3, July 2002.

3.7.3 Estimate of nutrient release from lake bed

Having concluded from our July field work that the results of our February chamber experiments were not influenced by large groundwater inflows, we have estimated the nutrient input from the sediments as a diffusive flux. We calculated the diffusive flux for both the February and July deployments from the initial linear rise in nutrient concentration within the benthic chambers (i.e., the slope of the curves in Figures 3.19 to 3.30). For the February experiments, this gave summertime bay-wide efflux estimates of 23-124 kg N day^{-1} (8.3-46 t N yr^{-1}) and 1.2-15 kg P day^{-1} (0.43-5.6 t P yr^{-1}).

The increase in nutrient concentration in each chamber in July was about four times slower than in summer, which is consistent with the temperature difference of 19ºC (summer) to 11ºC (winter) and the effect of temperature on biological processes. The July chamber results give bay-wide efflux estimates of 11-30 kg N day^{-1} (4-10.8 t N yr^{-1}) and 0.2-3.6 kg P day^{-1} (0.07-1.3 t P yr^{-1}).

The February and July results are at the seasonal extremes, and the annual mean efflux rates will probably lie somewhere between them. The mean annual nutrient efflux might therefore be about 17-77 kg N day^{-1} (6-28 t N yr^{-1}) and 0.7-9.3 kg P day^{-1} (0.3-3.5 t P yr^{-1}). By comparison the expected nitrogen inflow (excluding septic tanks) from the catchment, given the catchment area and land use, is c. 2 kg day^{-1} (0.7 t yr^{-1}), while the inflow from sewage is estimated to be c. 4 kg day^{-1} (1.5 t yr^{-1}). Therefore our estimates of nutrient releases from the bed are much larger (4 to 19-fold) than inputs to the lake from the septic tanks. We postulate that the sediment nutrient ‘pool’ has built up over many years, as algae and macrophytes die and sink onto the lake bed. This nutrient pool is likely to be continually recycling between the water column and the sediments. We have measured only the release of nutrients from the sediments to the water column; there is likely a similarly large deposition occurring each year, particularly in autumn when the macrophytes die back and decompose on the lake bed.

The estimated input of nutrients to Okawa Bay from the lake bed is summarised in Table 3.8. We have used the summertime estimates of groundwater nutrient inputs in the nutrient-phytoplankton model simulations (Section 3.8).

Table 3.8 Summary of estimated nutrient inputs to Okawa Bay from the bed

	Summer (from February results)	Winter (from July results)	Annual average
NH_4-N	23-124 kg N day^{-1}	11-30 kg N day^{-1}	17-77 kg N day^{-1} (6-28 t N yr^{-1})
DRP	1.2-15 kg P day^{-1}	0.2-3.6 kg P day^{-1}	0.7-9.3 kg P day^{-1} (0.3-3.5 t P yr^{-1})

Conversion of NH_4 to NO_3 (i.e., nitrification) and subsequent conversion of NO_3 to nitrogen gas (i.e., denitrification) can occur at the sediment-water interface of lakes. There is some evidence in the July benthic chamber results to suggest this nitrification-denitrification process is occurring in Okawa Bay. At Sites 1 and 2, there was initially an increase in NO_3-N concentrations, followed by a decline (Figure 3.31). It is probable that the initial increase in NO_3-N was due to nitrification of the NH_4-N released from the sediments. The subsequent fall in NO_3-N concentrations would have been due to denitrification (the initial lag in denitrification may have been due to there being insufficient numbers of denitrifying bacteria). We did not observe any significant NO_3-N concentrations during the February experiments; this may have been due to the warmer temperatures and hence very rapid denitrification rates (i.e., the nitrate was probably denitrified as soon as it was produced). Such a nitrification-denitrification process could be a significant mechanism by which nitrogen is removed from the Bay.

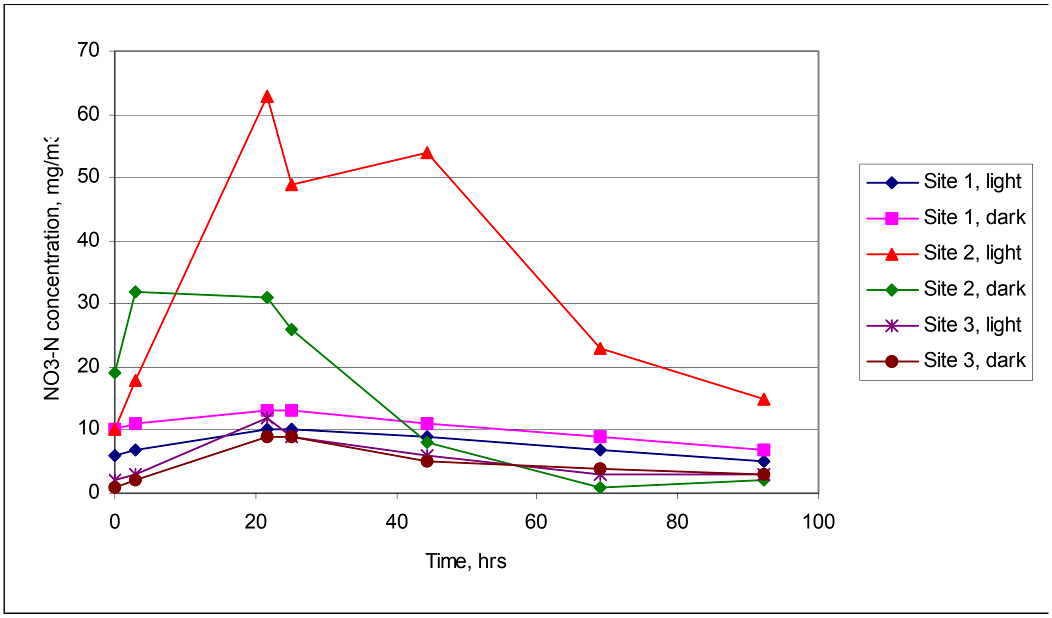


Figure 3.31: NO_3-N results for benthic chamber experiments, all sites, July 2002.

3.8 Nutrient/phytoplankton modelling results

3.8.1 Model calibration

Figure 3.32 illustrates the performance of the calibrated model. Simulations were run for 100 days assuming constant summer meteorology and constant exchange flow rate at the entrance of 3 $m^3 s^{-1}$. Groundwater inflows were 0.026 $m^3 s^{-1}$, and nutrient release from the bed was taken as 75 kg N day^{-1} and 5.3 kg P day^{-1} (the average results from the February benthic chamber experiments – see Table 3.8 in previous section).

The starting values of DIN, DRP, detritus and Chla in the Bay, and the boundary conditions in the Western Basin, were those measured by NIWA on 19-22 February. Predicted DIN, DRP and chlorophyll concentrations remain very close to those observed (the initial conditions of the model) throughout the simulation. Predicted detrital concentrations fall from the initial value over the first 10 – 15 d of the simulation but remain approximately constant thereafter. We have no direct measurements of detrital concentration within the bay and so do not regard this deviation between the predicted, ultimate detrital concentration and the (indirectly inferred) field concentration (initial value) as strong evidence of an error in the model's calibration. Rather, we believe that the close correspondence between predicted and observed concentrations of DIN, DRP and chlorophyll as strong indications of a good calibration. The calibrated model suggests that the phytoplankton were a little more strongly limited by available inorganic nitrogen than by available inorganic phosphorus (limitation factors of ~0.14 and 0.16 respectively). The nitrogen limitation is in agreement with both earlier bioassay studies (White &

Payne 1977) that consistently showed Lake Rotorua and Rotoiti water to be nitrogen limited. The comparable N and P limitation factors are consistent with our own phytoplankton incubation experiments, which showed that phytoplankton near the lake bed did not respond to artificial increases in nitrate concentrations, and hence that light- or phosphorus must have been at least as limiting to phytoplankton growth (Section 3.6). Microscopic inspection also revealed that most of the phytoplankton cells in the Okawa Bay water samples were capable of utilising dissolved nitrogen gas sourced from the atmosphere, rather than requiring nitrate or ammonium – i.e., they have the potential to fix N_2.

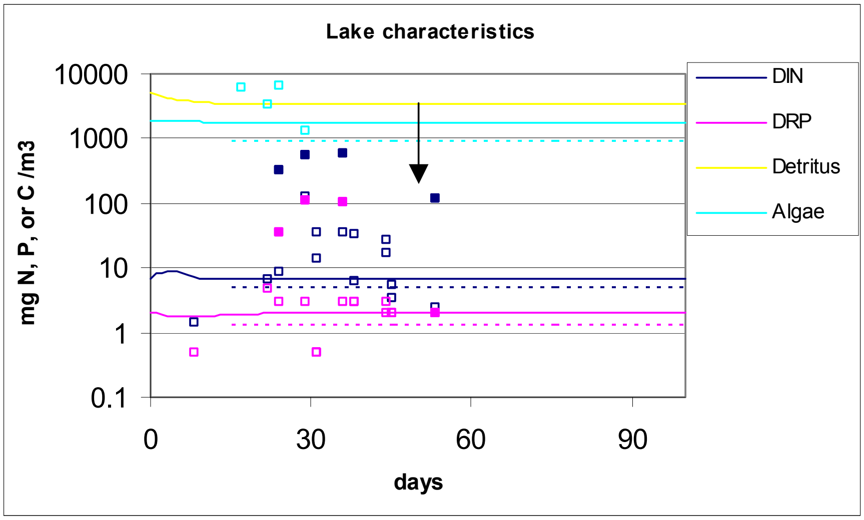
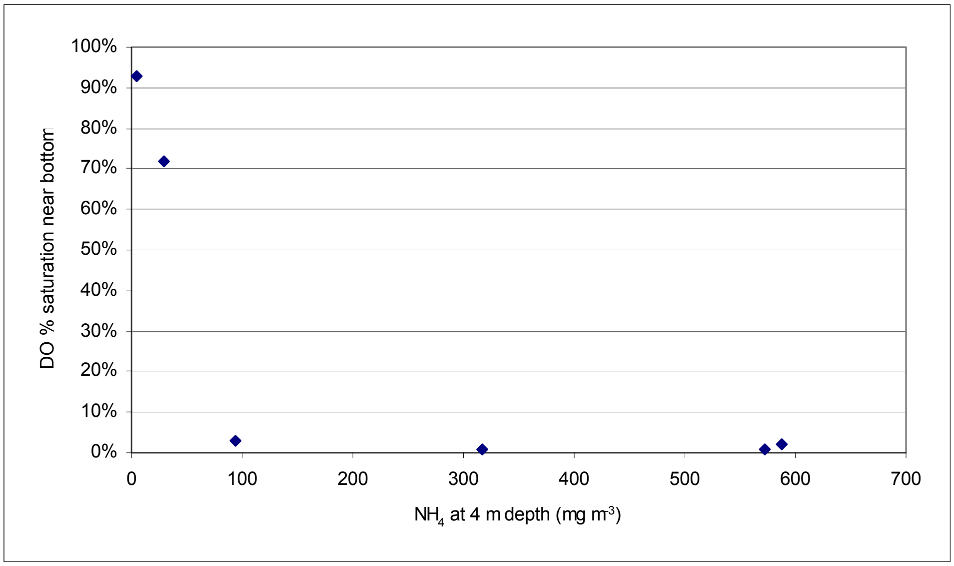


Figure 3.32: Simulation results (solid curves) from the calibrated model, overlaid on data gathered by Environment B·O·P and NIWA. Concentrations of phytoplankton and detritus are mg C m^{-3}, concentrations of nutrient are mg N m^{-3} (DIN) or mg P m^{-3} (DRP). Squares are Environment B·O·P data (solid squares denote bottom-water samples collected at times when bottom water is known to have had DO<10% of saturation). Dashed lines indicate average concentration in the Western Basin of Rotoiti as measured by NIWA over the period February 19-22, 2002. The initial conditions for the simulation (concentrations for the simulation results on day 0) were the concentrations measured within Okawa Bay by NIWA over February 19-22, 2002 (approx. period of the NIWA measurements is denoted by the vertical arrow).

The phytoplankton component of the model includes several parameters governing cell physiology and rate processes etc. In reality, many of these parameters vary not only between species, but also between individuals or over time in a single individual. We have chosen to treat all of the parameters as constants, and adopted typical literature values for most (Table A3.1). We have treated the phytoplankton N:C, P:C and the half-saturation constant for phytoplankton DIN-uptake as calibration parameters. It is pleasing to note that the calibrated values for each of these parameters falls inside published values (*e.g.* EPA 1985). The calibrated N:C and P:C ratios are towards the lower end of published values. This is to be expected given that the ambient nutrient concentrations were substantially less than the half-saturation concentrations for uptake of DIN or DRP.

The Environment B·O·P water quality monitoring data for Okawa Bay are also shown in Figure 3.32, and can be compared with the model simulations to independently assess the reliability of the model calibration. The model accurately matches Environment B·O·P surface concentrations (Table 3.6). This fit can be regarded as providing evidence that the calibrated model provides reasonable predictions of averaged water quality in the Bay. The model does not predict any of the variations present in the Environment B·O·P data because it assumes that environmental conditions (e.g., irradiance, water temperature, rates of exchange between Rotoiti and Okawa Bay) remain constant throughout the 100-day simulation. In reality, there would have been day-to-day changes in all these characteristics.

One feature of the Environment B·O·P data deserves special note. On occasion, nutrient concentrations within the Bay were very high, especially near the lake bed. Comparison of the Environment B·O·P bottom water oxygen concentration and bottom water nutrient concentrations (Figure 3.33) indicate that the high nutrient concentrations are associated with periods of low bottom-water oxygen concentration. High rates of nutrient release when bottom water dissolved oxygen concentrations are low have been observed in many lakes including Rotorua and Rotoiti (Fish and Andrew 1980; White 1977). However, our February benthic chamber experiments provided no evidence that rates of nutrient release from the sediment increased when oxygen concentrations fell. Rather, they were high at all times. During our July/August experiments chamber DO concentrations remained >2 g m^{-3}. One possibility is that, within Okawa Bay, the accumulation of nutrients in bottom waters during periods of low benthic oxygen does not reflect increased efflux from the sediments, but rather, poor mixing within the water-column. Stratification is the result of poor mixing between surface and bottom waters. Consequently, it is possible that that when the lake is stratified (as indicated by low bottom water DO concentrations), nutrient-rich water rising out of the lake bed accumulates near the lake floor rather than being rapidly mixed throughout the water-column.



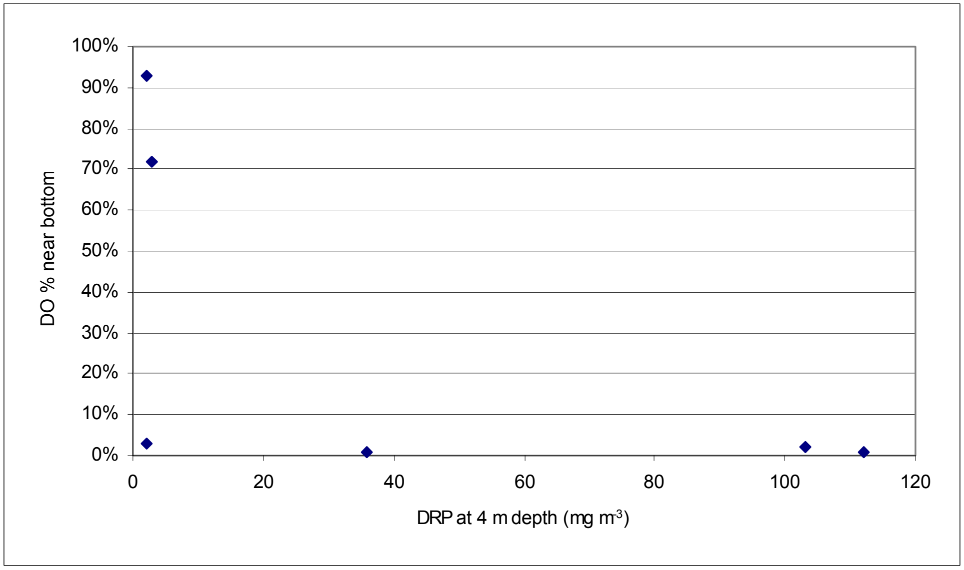


Figure 3.33: Environment B·O·P-measured NH_4-N (upper plot) and DRP (lower plot) concentrations plotted against DO concentrations (% of saturation) for the bottom waters of Okawa Bay. Note high nutrient concentrations during periods of low DO concentrations, which may be caused by groundwater inflow being trapped near the lake bottom during periods of stratification.

3.8.2 Model Predictions

Table 3.9 illustrates the model predictions of the consequences of (a) removing the septic tank inputs to Okawa Bay, (b) adding a diversion flow from the Ohau Channel of 1 m^3 s^{-1}, and (c) adding the diversion flow as well as removing the septic tank inputs.

It is important to note that the model is not intended to predict *absolute* phytoplankton concentrations; rather, it is intended to provide an indication of *change* in phytoplankton concentrations likely for each lake management scenario. These predictions of change are intended to provide guidance on the likely improvement in water quality that would result from removing septic tanks and/or adding the diversion flow.

Table 3.9: Predicted summer-time concentrations of phytoplankton within Okawa Bay under existing and proposed management scenarios. Simulations assume the exchange flow with Rotoiti to be 3 $m^3 s^{-1}$, and use the NIWA-measured mean concentrations of nutrient and phytoplankton in the Western Basin of Lake Rotoiti (DIN=5.3 mg N m^{-3}, DRP=1.4 mg P m^{-3}, Chl a=19.3 mg m^{-3}) and the Ohau Channel (DIN=34.8 mg N m^{-3}, DRP=14.8 mg P m^{-3}, Chl a=14.4 mg m^{-3}) as 'boundary conditions'. Assumed nutrient release from bed of Okawa Bay = 75 kg N day^{-1} and 5.3 kg P day^{-1}.

Scenario	Chla (mg m^{-3})
Existing (NIWA field measurements)	36.5
Existing (calibrated model simulation)	34.0
Septic tanks removed	31.2
Addition of 1m^3 s^{-1} diversion flow	31.1
Septic tanks removed, addition of diversion flow	29.3

Removing the septic tank inputs is predicted to reduce the abundance of phytoplankton by ~ 3 mg Chl a m^{-3} (10%). Adding the diversion flow (without also removing the septic tank inputs) is also predicted to reduce the phytoplankton concentration by ~ 3 mg chl a m^{-3} (10%). This is in spite of nutrient concentrations in the Ohau Channel water being slightly higher than in the Bay. Two factors contribute to the slight decline in the Bay's phytoplankton population: (a) increased export of resident phytoplankton from the Bay, as a result of additional 'flushing' by the diversion flow, and (b) dilution of the resident population (during the period of our study, the phytoplankton concentration within the Ohau Channel was ~ 50% of that within the Bay). Removing the septic tanks *and* adding a diversion flow from the Ohau Channel is predicted to decrease the concentration of chlorophyll within the Bay by ~ 5 mg m^{-3} (15%).

Addendum:

On 9 September 2002 RDC asked NIWA to also consider the option of adding a larger diversion flow of 3 m^3 s^{-1}, both with and without septic tanks removal. The model predictions for these two additional scenarios are as follows:

Scenario	**Chla** **(mg m^{-3})**
Existing (calibrated model simulation)	34.0
Addition of 3 m^3 s^{-1} diversion flow	27.8
Septic tanks removed, addition of 3 m^3 s^{-1} diversion flow	26.5

3.8.3 Influence of exchange flow between Okawa Bay and Lake Rotoiti

Our current meter measurements suggest that the largest individual source of water for Okawa Bay is the exchange with the Western Basin of Lake Rotoiti. This exchange flow is variable, as are the nutrient and phytoplankton characteristics of the waters of the Western Basin of Rotoiti. We examined the effect of differences in the exchange flow on the efficacy of the proposed management interventions (i.e., addition of diversion flow and removal of septic tanks) by assuming the exchange flow to be 10 m^3 s^{-1} rather than 3 m^3 s^{-1} (Table 3.10). When the exchange flow is increased to 10 m^3 s^{-1}, the phytoplankton population are predicted to fall by ~ 30% (see second row of Table 3.10).

Table 3.10: Simulated characteristics in Okawa Bay for a variety of scenarios concerning the nature of the exchange between Okawa Bay and Lake Rotoiti, and the nature of the water entering Okawa Bay from the proposed Ohau Channel diversion. Unless otherwise noted, the exchange flow between Okawa Bay and Rotoiti is assumed to be 3 $m^3 s^{-1}$. These simulations assume the presence of the proposed diversion flow (1 $m^3 s^{-1}$) and the removal of septic tank inputs. All units mg m^{-3}.

Scenario	Western Basin boundary conditions			Okawa Bay (simulated)
	DIN	DRP	Chla	Chla
Exchange flow = 3 $m^3 s^{-1}$	5.3	1.4	19.3	29.3
Exchange flow = 10 $m^3 s^{-1}$	5.3	1.4	19.3	23.5
Ohau Channel water sinks in Lake Rotoiti	22.4	4.3	3.9	23.8
Ohau Channel water floats in Lake Rotoiti	163	44	30	49.3
Diversion flow free of nutrient and phytoplankton	5.3	1.4	19.3	23.3

Even when the exchange flow remains constant, the consequences of the exchange can change as a result of differences in the characteristics of the water of the Western Basin of Lake Rotoiti. We surmise that much of the variability in the characteristics of the Western Basin waters is driven by the fate of water entering from the Ohau Channel (which tends to have higher nutrient and phytoplankton concentrations than does the water of Lake Rotoiti). When the Ohau Channel water is colder than the Rotoiti water (summer: late night/early morning, wintertime, and frequently during spring and autumn), it will tend to sink below the Rotoiti water as it leaves the Ohau Channel. Conversely, when warmer, it will tend to float over the Rotoiti water (Vincent et al. 1991).

We examined the influence of this variability by making two further simulations. In the first (corresponding to a situation in which the Ohau Channel inflow is likely to have been sinking), we apply the lowest known summertime measurement of average surface water (0-15 m) Western Basin phytoplankton abundance together with the nutrient concentrations measured on this date (22 mg N m^{-3}, 4.3 mg P m^{-3}, 3.9 mg Chl a m^{-3}, 6 January 1982; M. Gibbs unpublished data). In the second (corresponding to a situation in which the Ohau Channel water is floating), we apply the highest known nutrient concentrations measured by Environment B·O·P in the Ohau Channel during summer months (December-March, 1995-2002; DIN 163 mg N m^{-3}; DRP 44 mg P m^{-3}; there are no corresponding measures of phytoplankton concentration, so we assume a concentration of phytoplankton 30 mg Chl a m^{-3}). The results of these simulations are presented in rows 4 and 5 of Table 3.10.

We note that water entering Okawa Bay via the proposed diversion from the Ohau Channel will also bring nutrient and phytoplankton. As we have already seen, if the diverted water is richer in nutrient or phytoplankton than is Okawa Bay, this diversion will serve only to worsen the situation within Okawa Bay. A more interesting question is: "what is the maximum benefit which could be attained by introducing the diversion flow?" We address this by running the model under the extreme assumption that the Ohau Channel water diverted into Okawa Bay is devoid of both nutrient and phytoplankton. Thus, it serves both to dilute the nutrients and phytoplankton within the Bay, and flush these from the Bay without also adding new phytoplankton or nutrient. Even under this 'ideal' (and unrealisable) scenario, it is predicted that the phytoplankton concentration within Okawa Bay will be reduced by only ~ 20% (bottom row of Table 3.10).

In summary, Table 3.10 shows that the phytoplankton content of Okawa Bay is strongly influenced by exchanges with the Western Basin of Lake Rotoiti (and, by implication, water entering this area from the Ohau Channel).

4. Conclusions

We used our computer model to predict the effects of removing sewage and/or diverting 1 m^3 s^{-1} from the Ohau Channel into Okawa Bay. These model predictions use the summertime lake bed nutrient load estimated during our study (measured during typical summer conditions rather than severe bloom conditions), and assume that this is unaffected by sewage removal or flow diversion. Modelling indicates that, in the short term (i.e., <10 years), removing sewage and introducing a 1 m^3 s^{-1} diversion flow into Okawa Bay from the Ohau Channel will reduce algal concentrations in the Bay by only about 15%. There are two main reasons for this finding. Firstly, the high lake bed nutrient inputs appear to dominate nutrient loads to the Bay, being 4 to 19 times larger than the sewage load. Secondly, the high exchange flow between the Bay and the Western Basin (average flow about 5 m^3 s^{-1}) limits the effectiveness of local initiatives such as sewage removal and the Ohau Channel diversion.

In nearby Lakes Rotorua and Rotoiti (and in many other lakes), high nutrient concentrations are periodically measured near the bed during summer stratification, as a result of sediment anoxia and accelerated sediment nutrient release. We did not observe this phenomenon during our study. Nor did we measure accelerated release rates in the benthic chambers when the DO concentration dropped to low levels. However, Environment B·O·P has occasionally measured high nutrient concentrations in near-bottom water at times when DO concentrations there were low. Thus, although it did not occur during our study, accelerated sediment release of nutrients has been documented in the Bay. Nutrients released at such times are likely to enhance algal productivity and aggravate algal blooms.

We have not modelled the situation when blooms occur because there is insufficient information about the release of nutrients from the lake bed or exchange flow during blooms. However, in our opinion removal of sewage will not affect blooms in the short term because of the large nutrient releases from the bed. We also believe that, even if there is little exchange flow during bloom conditions, the diversion flow of 1 m^3 s^{-1} will not affect blooms because it will not reduce the residence time of the Bay sufficiently. With a diversion flow of 1 m^3 s^{-1} and no exchange flow, the residence time of the Bay would be approximately 18 days, while the algae population can double in one or two days.

It has been shown in other lakes that there is a link between sewage inputs and sediment nutrient release. For example, in Lake Rotorua sewage diversion in the early 1990s resulted in an immediate reduction in lake nutrient and phytoplankton concentrations. However, a substantial mass of nutrient remains in the lake bed sediments. Occasionally the lake stratifies, the bed goes anoxic, sediment nutrients are released and there may be an algal bloom. Modelling of Lake Rotorua indicates that over time it can be expected that the frequency of anoxia will decrease, sediment nutrient concentration will decrease, and less nutrient will be released during stratification (Rutherford et al. 1996). In Lake Rotorua this improvement is unlikely to be detectable for 10-20 years and is not expected to return to pre-1970s levels for c. 100 years. The same processes may operate in Okawa Bay on a similar time frame, but it was not possible to quantify them in this study.

Water quality in Okawa Bay is strongly affected by water quality in the Western Basin because of the exchange flow through the entrance channel. For example, if water quality is low in the Western Basin (e.g., because Ohau Channel water accumulates on the surface) this will adversely affect water quality in Okawa Bay. The converse also applies and high quality water at the surface of the Western Basin (e.g., when Ohau Channel water plunges) may benefit Okawa Bay. Sewage diversion away from Lake Rotorua has resulted in improved water quality in the Ohau Channel and this trend can be expected to continue slowly over time as bed sediment nutrients decline in Rotorua. As water quality gradually improves in the Western Basin, we would expect benefits in Okawa Bay.

An obvious question is: why are algal blooms in Okawa Bay more serious than in the Western Basin of Lake Rotoiti? There are at least three likely contributing factors, other than the possible influence of septic tank nutrient inputs. All three factors relate to the shallow, sheltered nature of the Bay. Firstly, because the Bay is relatively shallow, the full depth of the water column receives enough light for phytoplankton growth, whereas this occurs in only the upper half of the Western Basin (thus the phytoplankton are ‘diluted’, and can sink below the illuminated zone, where they will no longer grow). Secondly, because the Bay is shallow any nutrient release from the bed results in greater water-column-average concentrations within the Bay than in the Western Basin. As a result, phytoplankton growth rates may be higher. Thirdly, because of its sheltered nature, particulate material is more likely to settle onto the bed of Okawa Bay than in the more exposed Western Basin. If this happens then particulate nutrient transported into the Bay from the Western Basin by the exchange flow through the entrance may accumulate in the Bay. It is also possible that soluble nutrients may accumulate in the Bay by being taken up by macrophytes which, when they decay, will contribute particulate nutrient to the bed. Macrophytes can grow over a large portion of the bed of the Bay because of its shallowness, unlike the Western Basin. Nutrients in the bed contribute to nutrient releases from the bed, and hence to algal blooms.

In conclusion:

1. In the short-term (i.e., <10 years) the removal of sewage and/or a diversion flow of 1 $m^3 s^{-1}$ from the Ohau Channel are unlikely to substantially reduce algal blooms in the Bay.

2. The reasons are that: (a) nutrient release from the lake bed currently dominates the nutrient load; (b) the high exchange flow between the Bay and the Western Basin limits the effectiveness of the proposed management options; and (c) even when exchange flows are small, a 1 $m^3 s^{-1}$ diversion flow would not sufficiently reduce the residence time of the Bay.

3. In the long term: (a) improvements in water quality in Lake Rotorua and the Western Basin, and (b) removal of sewage inputs to Okawa Bay (which should reduce nutrient releases from the lake bed) are likely to benefit Okawa Bay, although these improvements have not been quantified.

5. Acknowledgements

Environment B·O·P provided substantial funding assistance for this project.

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7. Appendix 1: Environment B·O·P monitoring results

For location of sampling sites, refer to Figure 2.1. All in mg m^{-3}.

Station Name	Date	Depth From	Sample ID	NO_3-N	NH_4-N	TN	DRP	TP	Chla
Okawa Bay	26/04/2001	0	011795					27.0	13.9
Okawa Bay	13/06/2001	0	012253	1.0	7.0	284.0	3.0		12.8
Okawa Bay	10/07/2001	0	012521					16.0	9.4
Okawa Bay	8/08/2001	0	012830					23.0	7.4
Okawa Bay	18/09/2001	0	013264					37.0	5.5
Okawa Bay	15/10/2001	0	013482	8.0	3.0	238	10.0	24	6.2
Okawa Bay	6/11/2001	0	013759					22.0	
Okawa Bay	13/12/2001	0	014334	0.5	12.0		7.0		
Okawa Bay	13/12/2001	0.2	014337						6.4
Okawa Bay	8/01/2002	0	020061	0.5	1.0		0.5		
Okawa Bay	17/01/2002	1	020198	3.0				61	127.0
Okawa Bay	17/01/2002	4	020201	0.5					
Okawa Bay	22/01/2002	1	020427	1	6	1051	5	46	70.0
Okawa Bay	24/01/2002	1	020502	3	6		3	53	136.0
Okawa Bay	24/01/2002	4	020503	3	317	775	36	80	
Okawa Bay	29/01/2002	1	020536	11	120	946	3	24	27.0
Okawa Bay	29/01/2002	4	020537	1	572	912	112	155	
Okawa Bay	31/01/2002	1	020622	0.5	14	469.5	0.5	25	1.6
Okawa Bay	31/01/2002	4	020623	0.5	36	451.5	0.5	26	
Okawa Bay	5/02/2002	1	020694	0.5	36		3		
Okawa Bay	5/02/2002	4	020695	2	588		103		
Okawa Bay	7/02/2002	1	020735	0.5	6		3		
Okawa Bay	7/02/2002	4	020736	4	30		3		
Okawa Bay	13/02/2002	1	020943	0.5	17		2		
Okawa Bay	13/02/2002	4	020944	0.5	28		3		
Okawa Bay	13/02/2002	0	020952	0.5					
Okawa Bay	14/02/2002	1	020992	0.5	3	639.5	2	56	
Okawa Bay	14/02/2002	4	020993	0.5	5	676.5	2	57	
Okawa Bay	22/02/2002	1	021104	0.5	2	782.5	2	49	
Okawa Bay	22/02/2002	4	021105	24	94	663	2	44	
Western Basin	13/12/2001	0	014335	0.5					
Western Basin	8/01/2002	0	020062	0.5	2.0		0.5		
Western Basin	17/01/2002	1	020200						
Western Basin	17/01/2002	9	020202	3		1043		57	
Western Basin	22/01/2002	1	020428	0.5	4	392.5	2	18	
Western Basin	24/01/2002	1	020500	0.5	3	439.5	2	22	20.0
Western Basin	24/01/2002	9	020501	0.5	6	397.5	2	26	19.4
Western Basin	29/01/2002	1	020534		280		129	27	
Western Basin	29/01/2002	9	020535	1	689	1061	4	177	24.0
Western Basin	31/01/2002	1	020624	0.5	16	434.5	34	24	
Western Basin	31/01/2002	9	020625	2	198	572	18	89	19.1
Western Basin	5/02/2002	1	020692	0.5	2		1		
Western Basin	5/02/2002	9	020693	3	101		8		
Western Basin	7/02/2002	1	020733	0.5	2		0.5		
Western Basin	7/02/2002	9	020734	18	42		5		
Western Basin	13/02/2002	1	020941	0.5					
Western Basin	13/02/2002	9	020942	4					
Western Basin	14/02/2002	1	020990	0.5					
Western Basin	14/02/2002	9	020991	7	4	388	0.5	33	
Western Basin	22/02/2002	1	021106	0.5	10	382.5	0.5	24	
Western Basin	22/02/2002	9	021107	0.5	4	403.5	0.5	27	

Ohau Channel

Date	DRP	TP	NH_4-N	NO_3-N	TN
	g/m^3	g/m^3	g/m^3	g/m^3	g/m^3
18/01/1995	0.012	0.048	0.006	0.002	0.399
15/03/1995	0.020	0.066	0.010	0.032	0.419
30/03/1995	0.030	0.057	0.069	0.009	0.374
12/04/1995	0.030	0.058	0.082	0.017	0.427
17/05/1995	0.017	0.040	0.013	0.039	0.331
22/06/1995	0.016	0.031	0.022	0.061	0.323
27/07/1995	0.014	0.042	0.006	0.165	0.504
17/08/1995	0.010	0.031	0.018	0.153	0.462
18/09/1995	0.007	0.022	0.004	0.021	0.340
16/10/1995	0.006	0.134	0.010	0.077	0.491
16/11/1995	0.007	0.023	0.013	0.047	0.368
15/12/1995	0.003	0.028	0.012	0.008	0.364
17/01/1996	0.002	0.034	0.002	0.002	0.324
19/02/1996	0.012	0.033	0.030	0.005	0.363
19/03/1996	0.010	0.053	0.005	0.006	0.429
17/04/1996	0.007	0.022	0.004	0.007	0.308
16/05/1996	0.010	0.084	0.071	0.340	1.033
18/06/1996	0.003	0.025	0.010	0.039	0.371
25/07/1996	0.010	0.033	0.013	0.121	0.413
22/08/1996	0.003	0.030	0.002	0.023	0.430
16/09/1996	0.005	0.020	0.030	0.057	0.371
16/10/1996	0.008	0.057	0.023	0.172	0.608
13/11/1996	0.002	0.021	0.004	0.022	0.343
11/12/1996	0.005	0.022	0.003	0.083	0.410
16/01/1997	0.002	0.036	0.003	0.006	0.486
12/02/1997	0.005	0.036	0.003		0.464
19/03/1997	0.005	0.050	0.002	0.050	0.507
16/04/1997	0.002	0.048	0.001	0.001	0.524
14/05/1997	0.003	0.099	0.005	0.068	0.587
12/06/1997	0.022	0.055	0.197	0.113	0.699
16/07/1997	0.008	0.031	0.136	0.222	0.981
13/08/1997	0.001	0.020	0.068	0.154	0.407
17/09/1997	0.001	0.027	0.005	0.109	0.509
16/10/1997	0.003	0.030	0.010	0.142	0.514
3/11/1997	0.003	0.035	0.005	0.235	0.688
18/12/1997	0.007	0.022	0.009	0.008	0.257
14/01/1998	0.007	0.022	0.005	0.008	0.387
11/02/1998	0.010	0.026	0.011	0.005	0.326
11/03/1998	0.044	0.072	0.095	0.016	0.431
22/04/1998	0.024	0.061	0.007	0.002	0.353
21/05/1998	0.012	0.044	0.004	0.005	0.401
10/06/1998	0.005	0.036	0.001	0.004	0.309
22/07/1998	0.001	0.022	0.008	0.011	0.369
12/08/1998	0.005	0.019	0.008	0.003	0.386
9/09/1998	0.003	0.063	0.024	0.193	0.863

7/10/1998	0.003	0.029	0.005	0.013	0.389
11/11/1998	0.004	0.030	0.003	0.036	0.363
17/12/1998	0.001	0.013	0.003		
20/01/1999	0.002	0.010	0.006	0.001	0.296
17/02/1999	0.002	0.020	0.010	0.002	0.270
8/03/1999					
17/03/1999	0.003	0.022	0.016	0.009	0.306
22/04/1999	0.002	0.031	0.018	0.019	0.367
19/05/1999	0.004	0.019	0.037	0.126	0.472
18/06/1999	0.003	0.053	0.089	0.208	0.835
15/07/1999	0.001	0.072	0.010	0.030	0.852
19/08/1999	0.002	0.026	0.023	0.169	0.546
16/09/1999					
23/09/1999	0.005	0.030	0.014	0.063	0.376
14/10/1999	0.003	0.043	0.015	0.133	0.496
15/11/1999	0.002	0.036	0.007	0.005	0.403
9/12/1999	0.002	0.021	0.015	0.043	0.304
20/01/2000	0.002	0.025	0.060	0.013	0.440
22/02/2000	0.002	0.028	0.031	0.132	0.633
14/03/2000	0.004	0.042	0.072	0.076	0.658
12/04/2000	0.001	0.044	0.064	0.055	0.677
10/05/2000	0.002	0.041	0.112	0.052	0.577
7/06/2000	0.003	0.044	0.016	0.074	0.519
19/07/2000	0.004	0.031	0.012	0.018	0.421
16/08/2000	0.002	0.028	0.015	0.024	0.393
13/09/2000	0.003	0.034	0.015	0.008	0.370
16/10/2000					
19/10/2000	0.004	0.018	0.018	0.071	0.345
13/11/2000	0.002	0.029	0.010	0.013	0.333
12/12/2000	0.005	0.031	0.038	0.007	0.455
23/01/2001	0.012	0.048	0.006	0.054	0.501
8/02/2001	0.016	0.048	0.006	0.002	0.494
5/03/2001	0.024	0.049	0.008	0.001	0.405
18/04/2001	0.038	0.071	0.022	0.011	0.414
16/05/2001	0.012	0.088	0.029	0.086	0.650
19/06/2001	0.007		0.032	0.098	
25/07/2001	0.006	0.027	0.009	0.080	0.369
18/08/2001	0.011		0.011	0.192	

8. Appendix 2: NIWA water quality results

NIWA ID	*Description*	*Date*	*DRP*	*NO3-N*	*NH4-N*	*TN*	*TP*	*Chla-Av*
			mg/m3	*mg/m3*	*mg/m3*	*mg/m3*	*mg/m3*	*mg/m3*
CD10	Site 0	19/02/02	3.3	1.8	<2	579	43	33.0
CD44	Site 0	20/02/02	1.5	2.9	4	613	47	32.7
CD82	Site 0	21/02/02	1.6	1.0	3	554	43	39.6
CD100	Site 0	22/02/02	2.2	6.1	7	533	41	25.8
CD11	Site 1	19/02/02	2.8	0.9	3	685	56	39.6
CD47	Site 1	20/02/02	1.7	3.4	<2	591	49	39.1
CD81	Site 1	21/02/02	2.0	2.7	3	651	52	37.9
CD101	Site 1	22/02/02	1.8	4.9	6	645	51	34.7
CD12	Site 2	19/02/02	2.9	0.6	<2	673	32	38.3
CD49	Site 2	20/02/02	1.6	2.5	<2	636	56	35.8
CD80	Site 2	21/02/02	2.5	1.2	5	695	56	40.8
CD102	Site 2	22/02/02	1.0	4.2	5	674	49	28.7
CD13	Site 3	19/02/02	3.0	2.6	2	588	60	32.7
CD48	Site 3	20/02/02	1.6	7.6	3	582	56	37.8
CD79	Site 3	21/02/02	2.8	6.0	3	610	65	34.4
CD103	Site 3	22/02/02	1.0	3.6	2	603	54	37.8
CD20	Site 4	19/02/02	2.0	0.8	3	381	34	19.2
CD45	Site 4	20/02/02	1.0	2.0	<2	399	27	16.9
CD83	Site 4	21/02/02	1.3	0.5	<2	352	27	23.8
CD104	Site 4	22/02/02	1.4	2.0	5	453	28	17.4
CD21	Ohau channel (Site 5)	19/02/02	19	5.8	15	403	56	18.2
CD46	Ohau channel (Site 5)	20/02/02	14	84	6	361	43	13.5
CD84	Ohau channel (Site 5)	21/02/02	13	13	8	268	38	12.7
CD105	Ohau channel (Site 5)	22/02/02	13	4.4	3	360	54	13.3

9. Appendix 3: Details of nutrient-phytoplankton model

Table A3.1 Default parameters used in the simulations. Note detrital carbon concentration is approximated as detritus=[Measured total nitrogen – measured chl* Q_A^N / Q_A^{Chl}]/ Q_D^N .

Parameter	Description	Units	Value	Comment
v_{ok}	Volume of Okawa Bay	m^3	1600000	
a_{ok}	Surface area of Okawa Bay (bottom)	m^2	v_{ok}/ z_{ok}	
z_{ok}	Water depth in Okawa Bay (~v_{ok}/a_{ok})	m	3.56	
k_{wa}	Volumetric exchange rate between Rotoiti and Okawa Bay	$m^3 s^{-1}$	3.0	Approx. average from S4 current meter
F_{oh}	Flow in Ohau Channel	$m^3 s^{-1}$	0 (present) 1 (proposed)	
F_{septic}	Inflow from septic tanks	$m^3 s^{-1}$	0.0013	400 people; 275 L $person^{-1}$ d^{-1}
$F_{diffuse}$	Inflow from diffuse sources	$m^3 s^{-1}$	0.85	Average inferred water efflux from benthic chambers
F_{rain}	Inflow from rainfall	$m^3 m^{-2} s^{-1}$	6.3×10^{-8}	Annual rainfall ~ 2 m
N_{wa} $P_{wa,}$ $D_{wa,}$ A_{wa}	DIN / DRP / detritus, algal concentrations in Western Basin of Rotoiti	mg element m^{-3}	5.3, 1.4, 1298, 965	Time-series from Gibbs (unpubl)
$N_{oh,}$ $P_{oh,}$ $D_{oh,}$ A_{oh}	DIN/DRP/detritus C/algal concentrations in Ohau Channel	mg element m^{-3}	14.8, 34.8, 1268, 720	NIWA measurements Feb. 2002
N_{septic}, P_{septic}, D_{septic}	DIN / DRP/detritus concentration in septic tank effluent	mg element m^{-3}	36862 3487	1.48 T N y^{-1}, 0.014 T P y^{-1}
$N_{diffuse}$, $P_{diffuse}$, $D_{diffuse}$	DIN /DRP /detritus concentration in diffuse source water	mg [N,P,C] m^{-3}	1.44×10^3, 139, 0	Average inferred from benthic chambers
$N_{rain,}$ P_{rain}, D_{rain}	DIN /DRP / detritus concentration in rainfall	mg [N,P] m^{-3}	195, 7.7	
d_D	Detrital decay rate	d^{-1}	0.05	Enríquez et al. (1993)
d_A	Algal death rate	d^{-1}	0.0	Assumed
s_D	Detrital sinking rate	$m\ d^{-1}$	0.5	Smayda (1970)
s_A	Algal sinking rate	$m\ d^{-1}$	0	Smayda (1970)
Q_D^N	N:C in detritus	mg N mg^{-1} C	Q_A^N	Assume that all of phytoplankton C & N is transferred to detritus upon death, and that detrital C & N have identical weight-specific decay rates
Q_D^P	P:C in detritus	mg P mg^{-1} C	0.9 x Q_A^P	Assume that 90% of

Parameter	Description	Units	Value	Comment
				phytoplankton P is transferred to Detritus upon death
Q_A^N	N:C in algae	mg N mg^{-1} C	0.09	Calibrated, but see EPA
Q_A^P	P:C in algae	mg P mg^{-1} C	0.006	Calibrated but see EPA
P_m	Phytoplankton max. weight-specific photosynthetic rate	mg C mg^{-1} C d^{-1}	1.5	EPA (1985)
k_I	Shape parameter in algal P-I curve	μE m^{-2} s^{-1}	60	EPA (1985)
k_N	Half saturation DIN constant for DIN-limited algal growth	mg N m^{-3}	40	EPA (1985)
k_P	Half saturation DRP constant for DRP-limited algal growth	mg P m^{-3}	10	EPA (1985)
r_A	Phytoplankton weight-specific respiration rate	mg C mg^{-1}C d^{-1}	0.05	Langdon (1993)
d_A	Phytoplankton weight-specific death rate	mg C mg^{-1}C d^{-1}	0.10	Assumed
s_A	Phytoplankton sinking speed	m d^{-1}	0	Assumed, but observations indicate the population was dominated by that small cells (slow sinking), and by cyanobacteria (which can regulate their buoyancy)
ϕ	Photoperiod fraction	-	14/24 (14 hour day length)	

The equations defining the instantaneous rates of change for DIN, DRP, detritus and lake phytoplankton are listed below.

Lake DIN

$$v_{ok}\frac{dN_{ok}}{dt} = k_{wa}\left[N_{wa} - N_{ok}\right] + F_{oh}\left[N_{oh} - N_{ok}\right] + F_{septic}N_{septic} + F_{diffuse}N_{diffuse} + F_{rain}N_{rain}$$

$$-(F_{septic} + F_{diffuse} + F_{rain})N_{ok} - v_{ok}A_{ok}\,\dot{g}\,Q_A^N + v_{ok}d_D Q_D^N D_{ok}$$

exchange Ohau Channel other inputs volume-conservation exports bottom exchange algal uptake + detrital decay

Lake DRP

$$v_{ok}\frac{dP_{ok}}{dt} = k_{wa}\left[P_{wa} - P_{ok}\right] + F_{oh}\left[P_{oh} - P_{ok}\right] + F_{septic}P_{septic} + F_{diffuse}P_{diffuse} + F_{rain}P_{rain}$$

$$-(F_{septic} + F_{diffuse} + F_{rain})P_{ok} - v_{ok}A_{ok}\,\dot{g}\,Q_A^P + v_{ok}d_D Q_D^P D_{ok}$$

Lake detritus

Assumption: no resuspension

$$v_{ok}\frac{dD_{ok}}{dt} = k_{wa}\left[D_{wa} - D_{ok}\right] + F_{oh}\left[D_{oh} - D_{ok}\right] + F_{septic}D_{septic} + F_{diffuse}D_{diffuse} + F_{rain}D_{rain}$$

$$-(F_{septic} + F_{diffuse} + F_{rain})D_{ok} + v_{ok}\left(d_A A_{ok} - d_D Q_D^P D_{ok} - \frac{s_D}{z_{ok}}D_{ok}\right)$$

Algal growth

$$\begin{aligned} v_{ok}\frac{dA_{ok}}{dt} &= k_{wa}\left[A_{wa}-A_{ok}\right]+F_{oh}\left[A_{oh}-A_{ok}\right] \\ &\quad -(F_{septic}+F_{diffuse}+F_{rain})A_{ok}+v_{ok}A_{ok}\left(\dot{g}-r_A-d_A-\frac{s_A}{z_{ok}}\right) \end{aligned}$$

$$\dot{g} = \frac{f(T)\,p_m}{k_d}MIN\left[\phi\ln\left(1+\frac{2I_{\max}}{\pi k_I}\right),\frac{N}{k_N+N},\frac{P}{k_P+P}\right]$$

These differential equations were solved numerically using the Euler method with a time-step of 0.005 d.

10. Appendix 4: Drogue tracking results

General notes: Blue lines indicate location of shallow drogues (curtain depth 600 mm, except for one drogue with depth of 1100 mm), red lines indicate location of mid-depth drogues (curtain depth 1500 mm, except for one drogue with depth of 3300 mm). Arrows indicate end positions. Green and red triangles show location of permanent channel buoys (red triangles indicate left side of channel for vessels entering the Bay, green triangles indicate right side of channel).

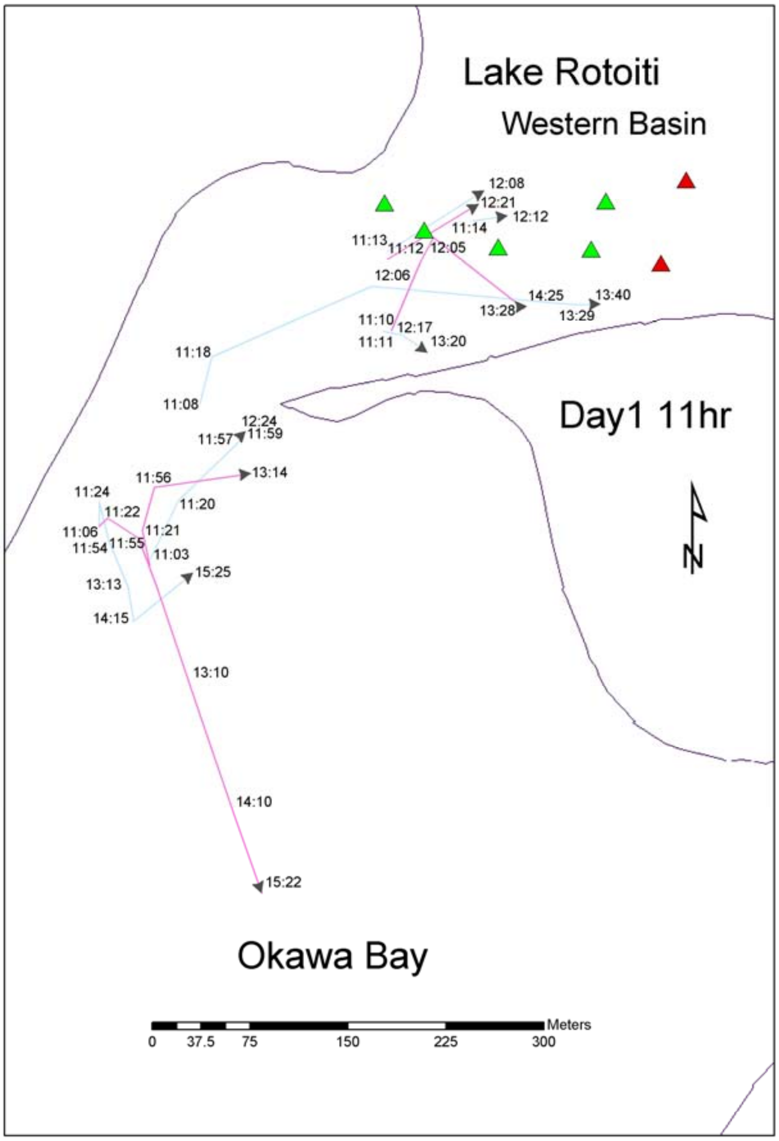

Figure A4.1: Day 1 (19 February 2002), start times between 1100 and 1200 hrs. Wind direction was W, rising from 2 to 5 m s^{-1} (4 to 10 knots).

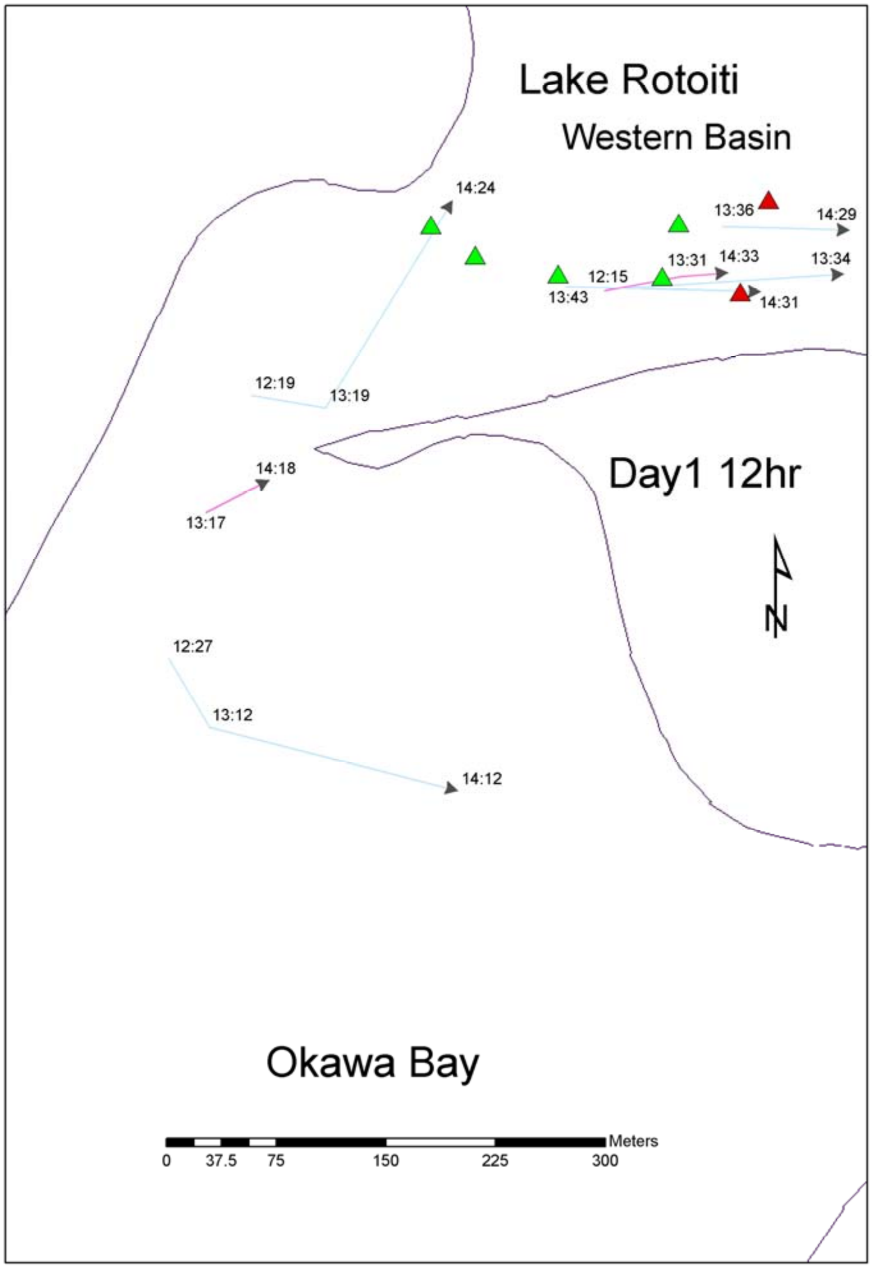

Figure A4.2: Day 1 (19 February 2002), start times between 1200 and 1400 hrs. Wind direction was W, 5 m s^{-1} (10 knots).

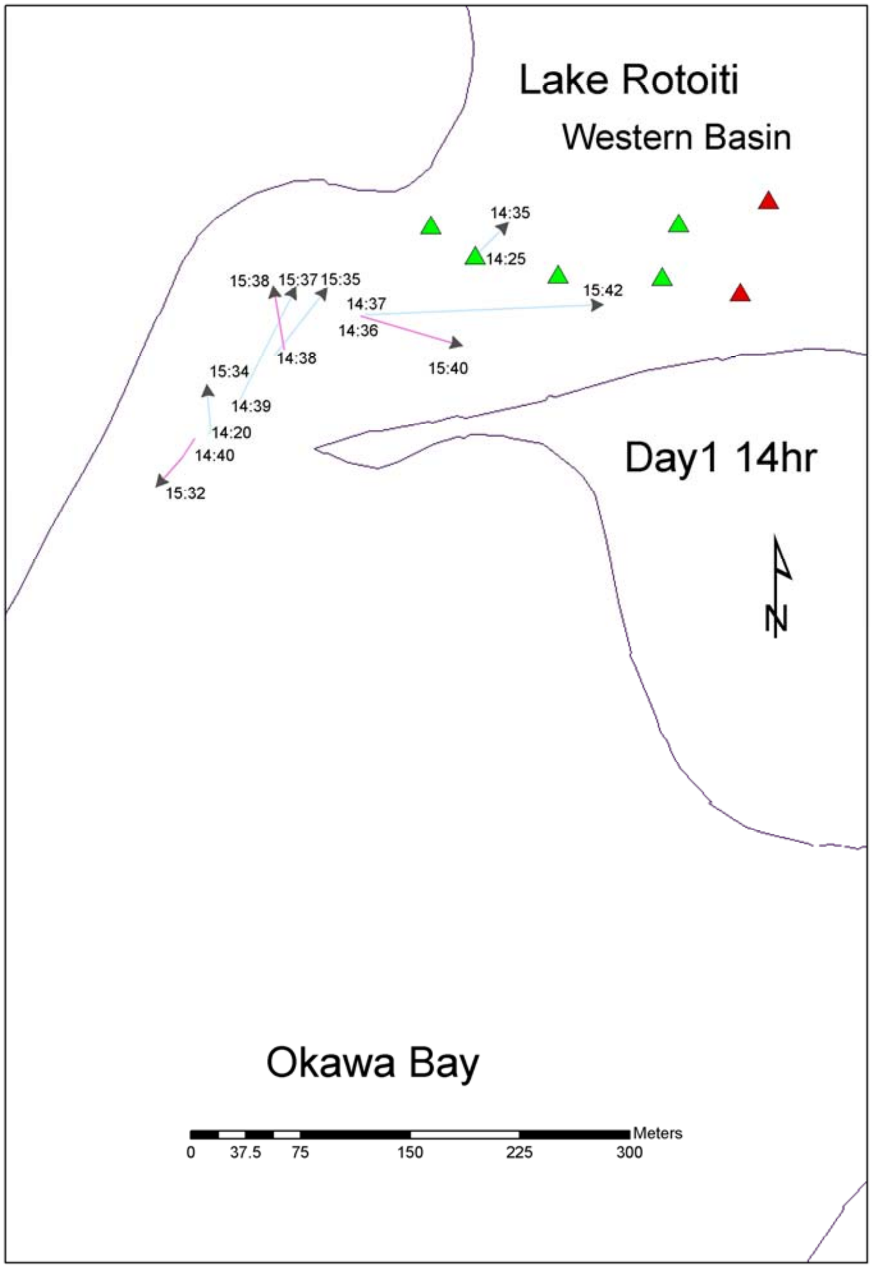

Figure A4.3: Day 1 (19 February 2002), start times between 1400 and 1500 hrs. Wind direction was W, 5 to 6 m s^{-1} (10 to 12 knots).

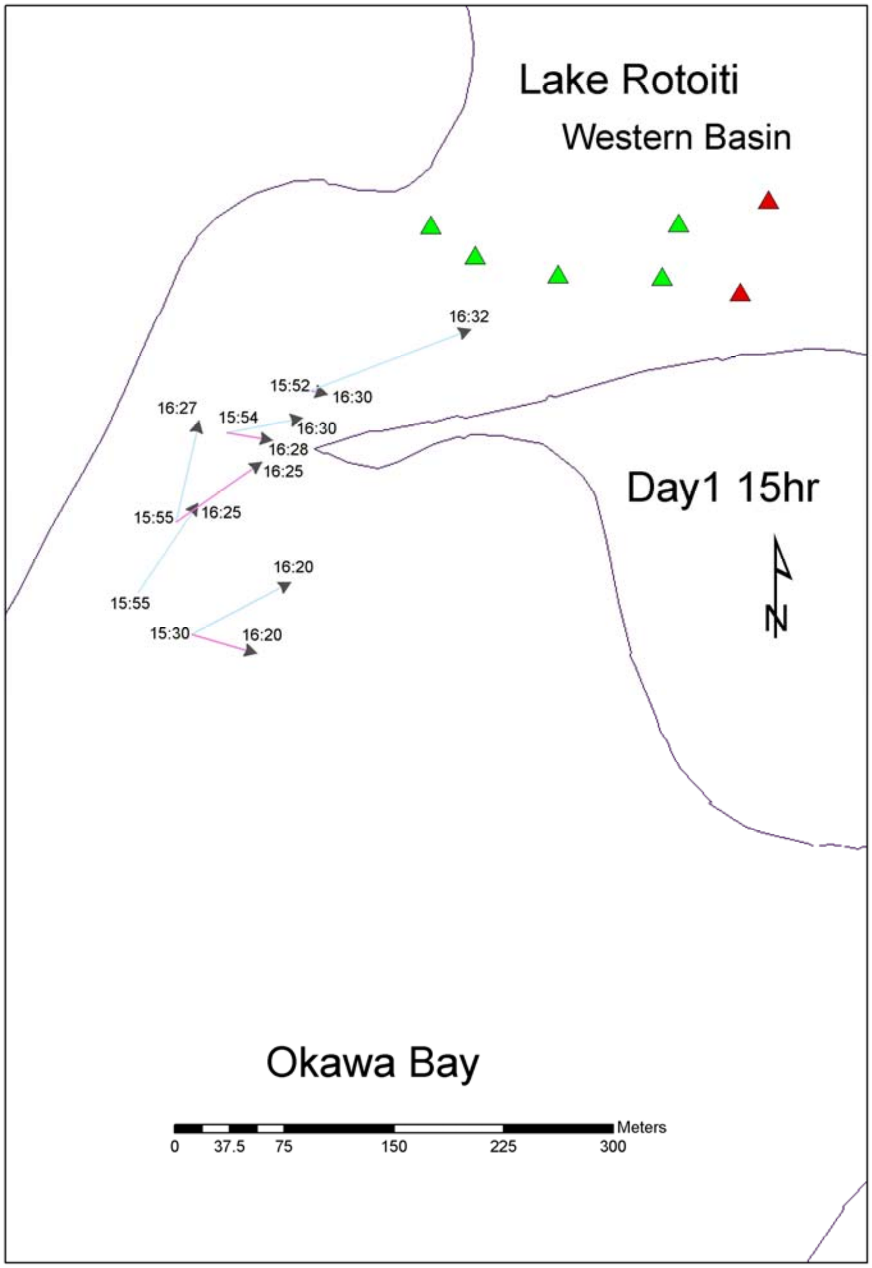

Figure A4.4: Day 1 (19 February 2002), start times between 1500 and 1600 hrs. Wind direction was W, 5 to 6 m s^{-1} (10 to 12 knots).

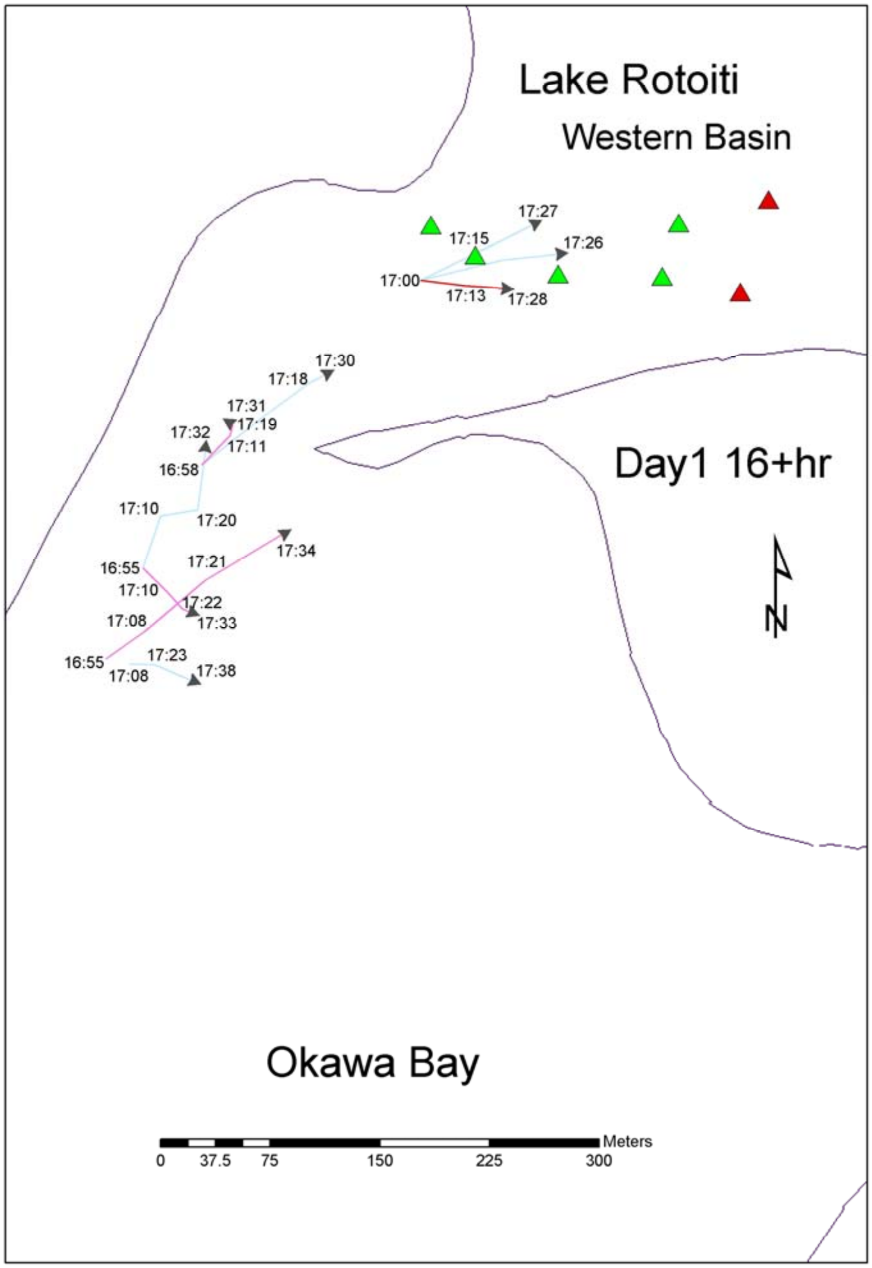

Figure A4.5: Day 1 (19 February 2002), start times after 1600 hrs. Wind direction was W, 5 to 6 m s^{-1} (10 to 12 knots).

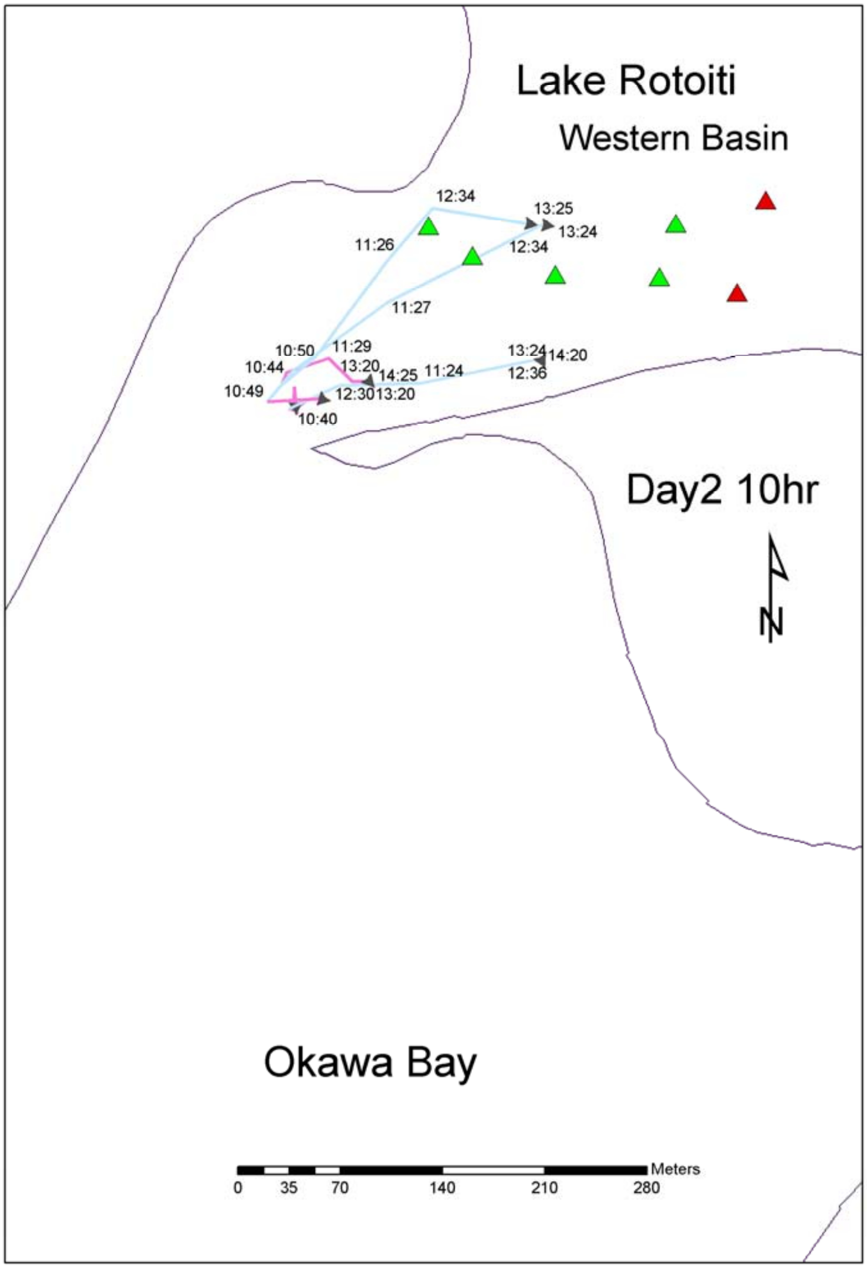

Figure A4.6: Day 2 (20 February 2002), start times between 1000 and 1200 hrs. Wind direction was SW, 2 to 3 m s^{-1} (4 to 6 knots).

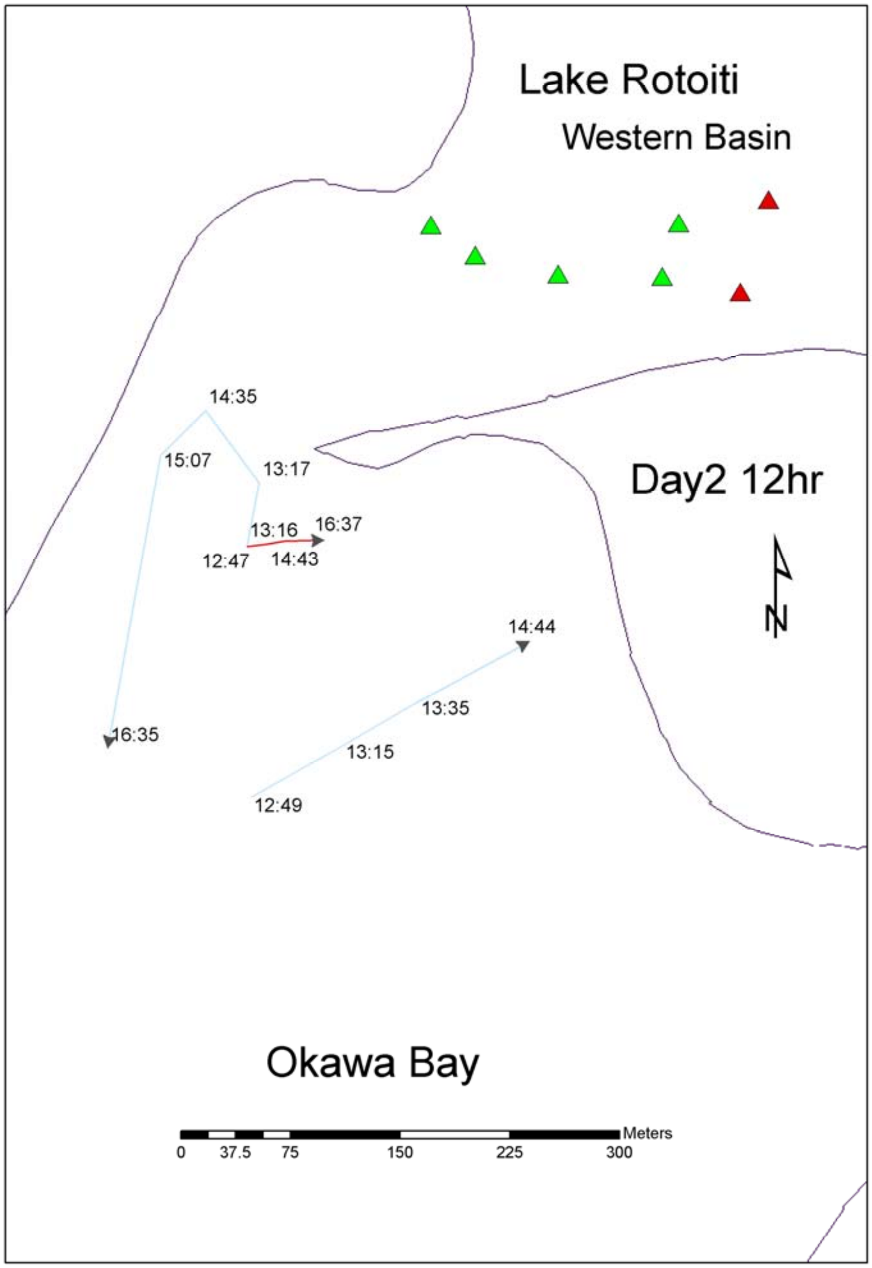

Figure A4.7: Day 2 (20 February 2002), start times between 1200 and 1300 hrs. Wind direction was initially SW, 4 to 5 m s^{-1} (8 to 10 knots), swinging around to NE 2.5 to 3.5 m s^{-1} (5 to 7 knots).

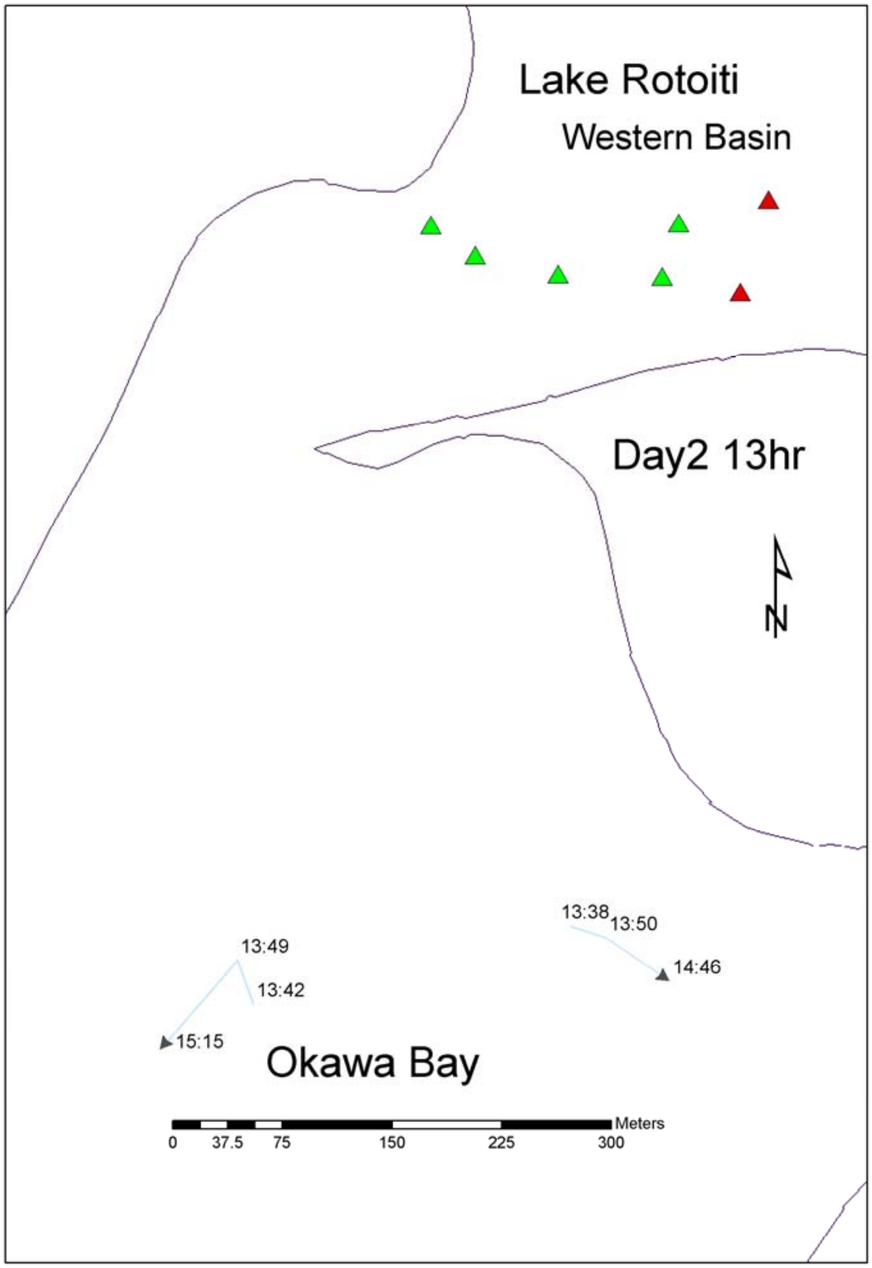

Figure A4.8: Day 2 (20 February 2002), start times between 1300 and 1400 hrs. Wind direction was initially SW, 4 to 5 m s^{-1} (8 to 10 knots), swinging around to NE 2.5 to 3.5 m s^{-1} (5 to 7 knots).

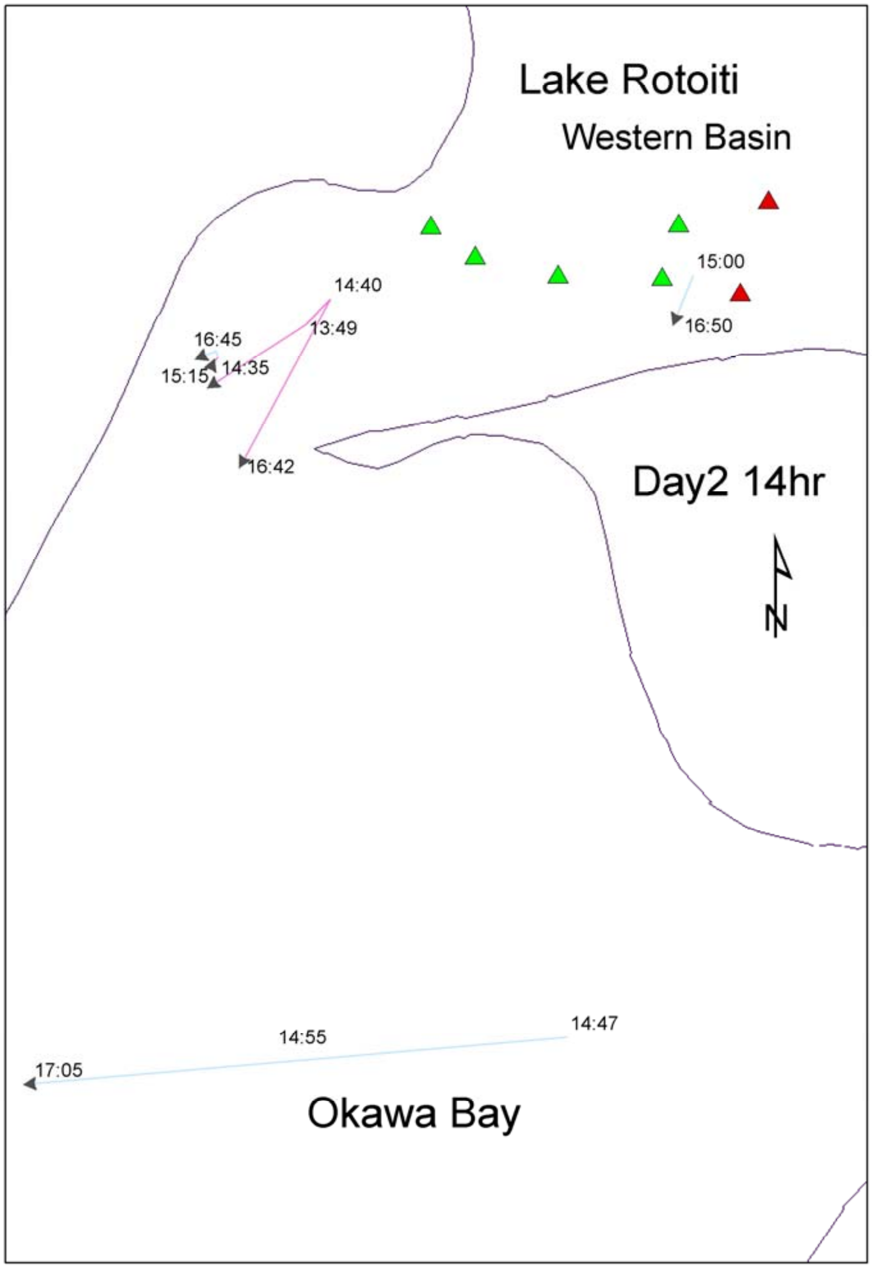

Figure A4.9: Day 2 (20 February 2002), start times after 1400 hrs. Wind direction was NE 3 to 4 m s^{-1} (6 to 8 knots).