Current measurements in Lakes Rotorua and Rotoehu 2010 and 2011

NIWA Client Report: HAM2011-015
February 2011

NIWA Project: BOP11203

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Max Gibbs
Rod Budd
Cliff Hart
Scott Stephens
Aslan Wright-Stow
Scott Edhouse

NIWA contact/Corresponding author

Max Gibbs

Prepared for

Bay of Plenty Regional Council

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

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Reviewed by:

Dr Chris Hickey

Approved for release by:

Ngaire Phillips

Dr Ngaire Phillips

Formatting checked

A. Bartley

Executive Summary

The need to be able to apply sediment capping agents to defined target areas on the lake bed from the surface of the lake, necessitates determining the strength and characteristics of lake currents that will affect their settling. Bay of Plenty Regional Council asked NIWA to measure the lake currents in Lake Rotorua when it was fully mixed and when it was thermally stratified, and to measure the lake currents in Lake Rotoehu in summer when the lake was stratified. This report presents a summary of the current meter data together with the associated wind data to aid interpretation for the three deployment, Lake Rotorua mixed (July/August 2010), Lake Rotorua stratified (November/December 2010) and Lake Rotoehu stratified (January/February 2011).

During fully mixed periods in winter, the whole water column of Lake Rotorua moves in the same direction at the same velocity. Mean water velocity was around 3 cm/s reaching a maximum of 20 cm/s under strong winds. The direction of flow at the current measurement sites was in the opposite direction to the wind direction measured at Rotorua Airport, implying that the water in the lake flows around Mokoia Island as a central axle in the lake. It took about 2 days to establish a current flow from a calm lake, and about 24 hours for the lake currents to reverse when the wind direction reversed. the residual lake currents dissipated after about 3 days when the wind stopped.

During thermally stratified periods, the water column of Lake Rotorua became decoupled at the thermocline with water in the upper layers moving in the opposite direction to the water in the lower layers. In general, water velocities were lower than in winter with mean velocities of around 2 to 3 cm/s reaching a maximum of around 15 cm/s. At low wind velocity, water in the lake appeared to move in slowly rotating gyres. Threshold conditions required to establish the decoupled circulation pattern were a wind velocity of >5 m/s sustained for at least 24 hours.

In Lake Rotoehu, the surface waters flowed with the wind. When the lake was mixed the whole water column moved in the same direction but the current velocity decreased towards the lake bed. When the lake was stratified, the water column became decoupled at the thermocline with water in the upper layers moving with the wind while water in the lower layers moved in the opposite direction. Mean water velocities were 1 to 2 cm/s reaching a maximum of around 18 cm/s during strong winds. Under low wind conditions there was a tendency for the water in the lower layers to move towards the south. Threshold conditions required to establish the decoupled circulation pattern were a wind velocity of >4 m/s sustained for at least 3 hours.

1. Introduction

To manage phosphorus releases from the sediments of Lake Rotorua and improve the water quality of the lake, one strategy is to apply an active barrier to the sediment surface i.e., a sediment cap. Typically sediment capping agents are applied at the lake surface and settle to the lake bed forming the active barrier against phosphorus release. However, preliminary data from earlier hydrology studies on Lake Rotorua indicated that the water column is not stationary and even small lake currents have the potential to move the capping material considerable distances from the point of application as it settles.

To assess the magnitude of this issue, NIWA was asked by Bay of Plenty Regional Council to measure the currents in Lake Rotorua during periods when the lake was mixed and again when the lake was thermally stratified. Current measurements were also required in Lake Rotoehu to assess their likely effect on the use of aeration to manage internal P loads from sediment release.

This report presents a summary of the three current measurement periods with graphical interpretation to provide visual representations of how water moves in these lakes and the role of wind forcing. Data presented in this report is available on CD-ROM with electronic files of the full data set from each period and the associated wind record from Rotorua Airport.

2. Methods

2.1 Current meters

Current measurements were made using bottom mounted Acoustic Doppler Current Profilers (ADCP) which record the water velocity and direction at several depths from about 1.5 m above the sediments to about 1 m below the lake surface. The current is measured by bouncing sound off particles in the water and calculating the velocity from the Doppler shift in the return echo of each "ping". Because the velocity of sound in water is essentially constant, the return echo can be timed to give separate data for selected distances (depths) from the instrument. However, because of the variable distances of particles from the acoustic head, the data is recorded for a depth layer or "bin" of finite thickness – usually 1 or 2 m. Also because it requires a finite time for the ping to stop ringing in the acoustic head, there is a dead zone, close to the acoustic head, in which no data is collected. The data close to the water surface may also be corrupted by wave action. The ADCP has three acoustic heads which allows the calculation of flow direction as well as velocity. The software in the instrument can be set to calculate the velocity and direction at different depths in the water column.

In these deployments each current meter was set to record a burst of data (500 pings each of 0.5 second duration) and produces an average value for these data for each depth bin from the lake bed to the surface – excluding the dead zones. These measurements were repeated at 15 minute intervals for the period of each deployment.

Note: By convention, water flow directions are given as "**going towards**" whereas wind flow directions a given as "**coming from**".

2.2 Lake Rotorua

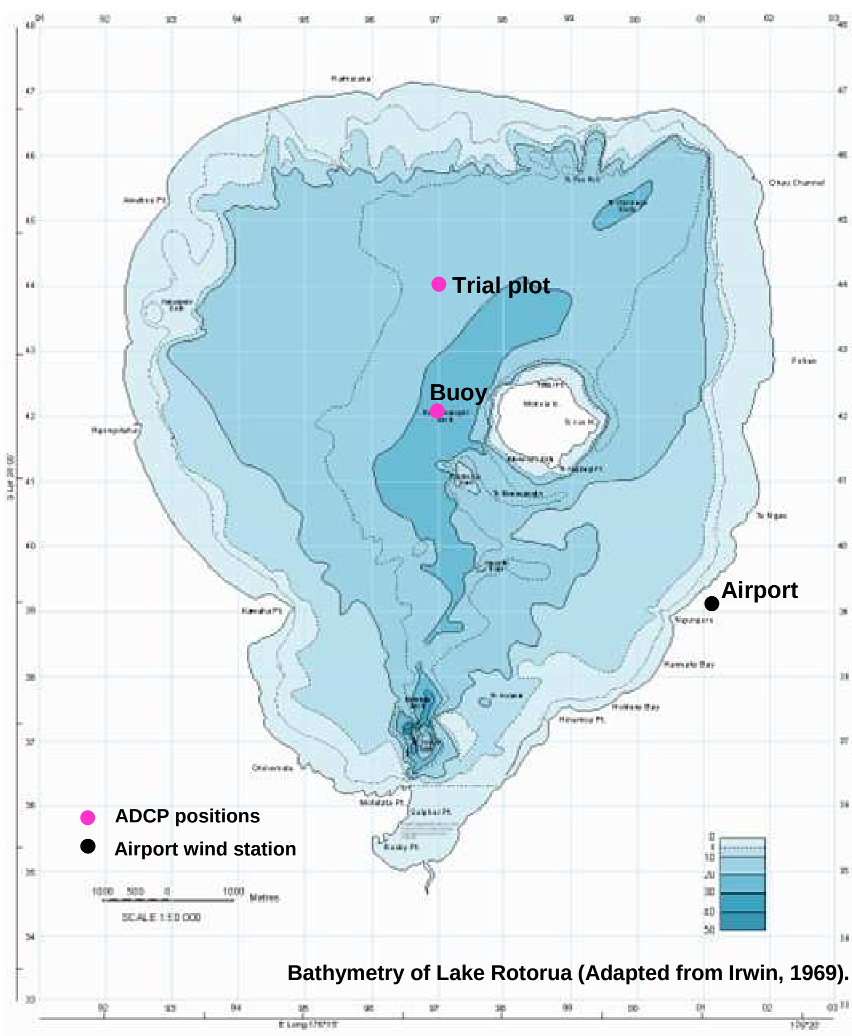

Figure 1: Site map of Lake Rotorua showing the locations of the ADCP current meters beside the monitoring buoy [Buoy] and the proposed sediment capping trial plot [Trial plot] relative to the meteorological station at Rotorua Airport.

Currents in Lake Rotorua were measured for four weeks when the lake was fully mixed in winter [27/07/2010 to 25/08/2010] and when the lake was thermally stratified in spring [5/11/2010 to 8/12/2010]. Two study sites were used in Lake Rotorua in July/August 2010. The first was beside the remote monitoring buoy, in a depth of 21 m, and the second was at the location of a proposed sediment capping trial plot site in a depth of 18 m (Fig. 1). The ADCP site by the buoy was intended to allow direct linkage between water currents and wind forcing using the met station on the monitoring buoy. Unfortunately, the meteorological station on the buoy did not record during the August 2010 period of monitoring. Consequently, all current data interpretation has used the wind data record from Rotorua Airport [meteorological station Agent 1770].

A potential problem using bottom deployment is that the heavy ADCP instruments may sink into the soft sediment. During the July/August deployment, the ADCP at the remote monitoring buoy became buried beneath 5-10 cm of sediment by the end of the measurement period. Review of the July/August data showed a high degree of synchronisation between the two sites such that the data fromone site fully described the other. Consequently, lake currents were only measured at the trial plot site during the November/December 2010 deployment.

2.3 Lake Rotoehu

Lake currents were measured in Lake Rotoehu in summer 2011 [27/01/2011 to 17/02/2011] when the lake was thermally stratified. ADCP current meters were deployed at two sites (Fig.2). The mid-lake site was in the deepest part of the lake at about 13 m depth. The southern site was at a depth of about 8 m on the edge of the shallower plateau. Wind records were from the Rotorua Airport.

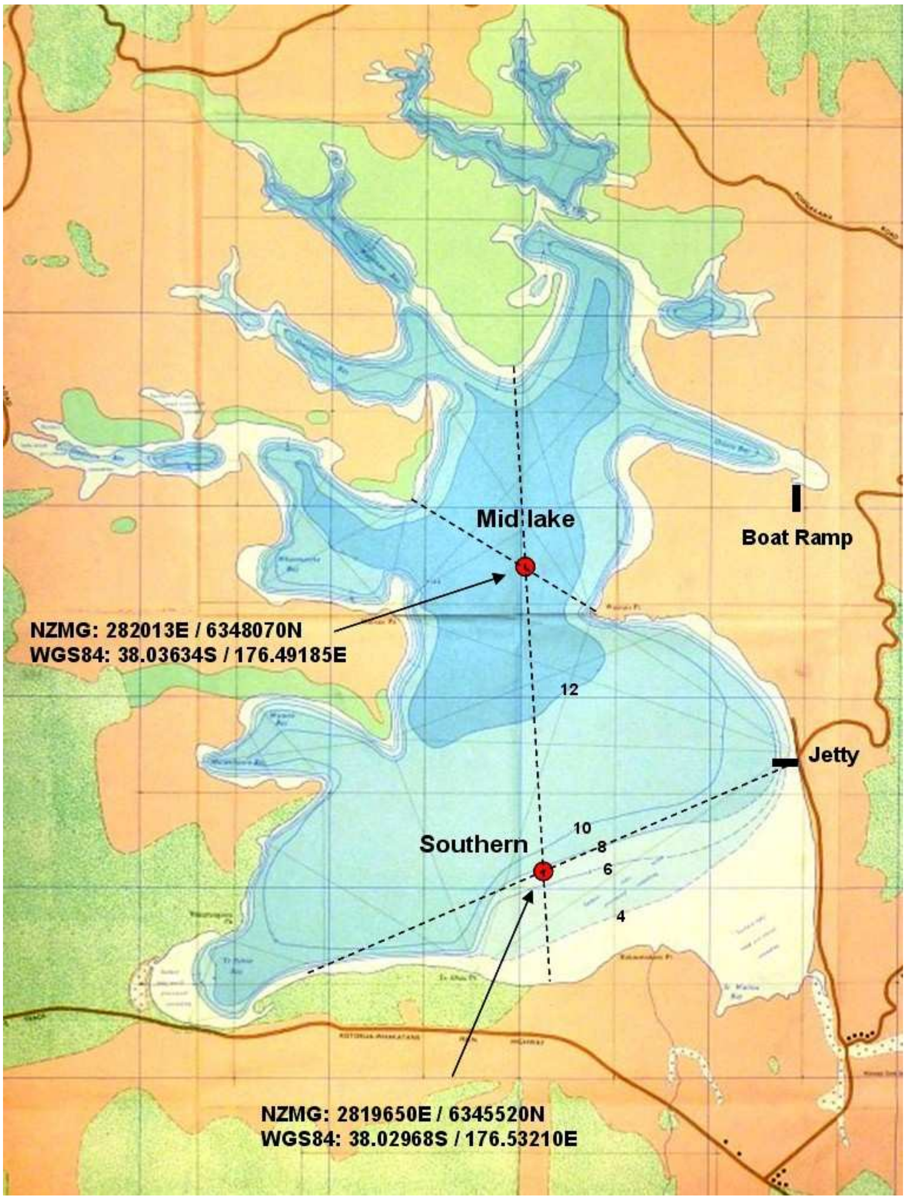

Figure 2: Lake Rotoehu bathymetry with the location of the two ADCP current measurement sites.

3. Results and discussion

3.1 Lake Rotorua July/August 2010

Lake fully mixed.

3.1.1 Current velocity

Current velocity data from selected depth bins (Fig. 3) show that the lake water at the monitoring buoy and the trial plot sites moved at the same velocity at each depth through the water column. Maximum current velocity reached 0.2 m/s at all depths on 14th August 2010. Water velocities of 0.2 m/s are capable of suspending sediment, which may explain why the ADCP at the monitoring buoy was buried. The average water velocity from all data was 3.3 cm/s, with long periods at about 2 cm/s. Minimum velocity was below confidence limit but estimated at <0.5 cm/s.

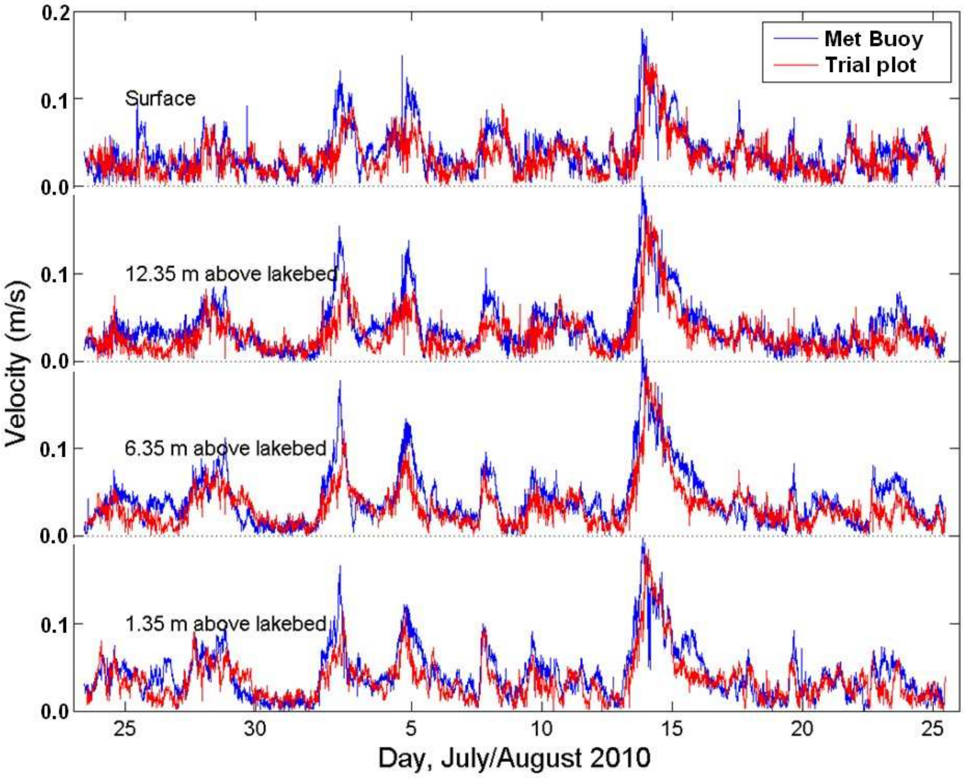

Figure 3: Comparison of lake currents at the remote monitored buoy [Met Buoy] and at the proposed Trial Plot site at selected heights above the lake bed during the July/August ADCP deployments. The graphs for each layer have a vertical scale of 0 to 0.2 m/s and are stacked to show the synchronicity of the currents at these two sites when the lake is well mixed.

3.1.2 Current direction

Current direction data [true north] from selected depth bins (Fig. 4) show that the lake water at the monitoring buoy and the trial plot sites moved in the same direction at each depth through the water column. There was a high degree of "noise" in the plots around true north when the direction switched between slightly above zero to slightly below zero, represented by 360 degrees.

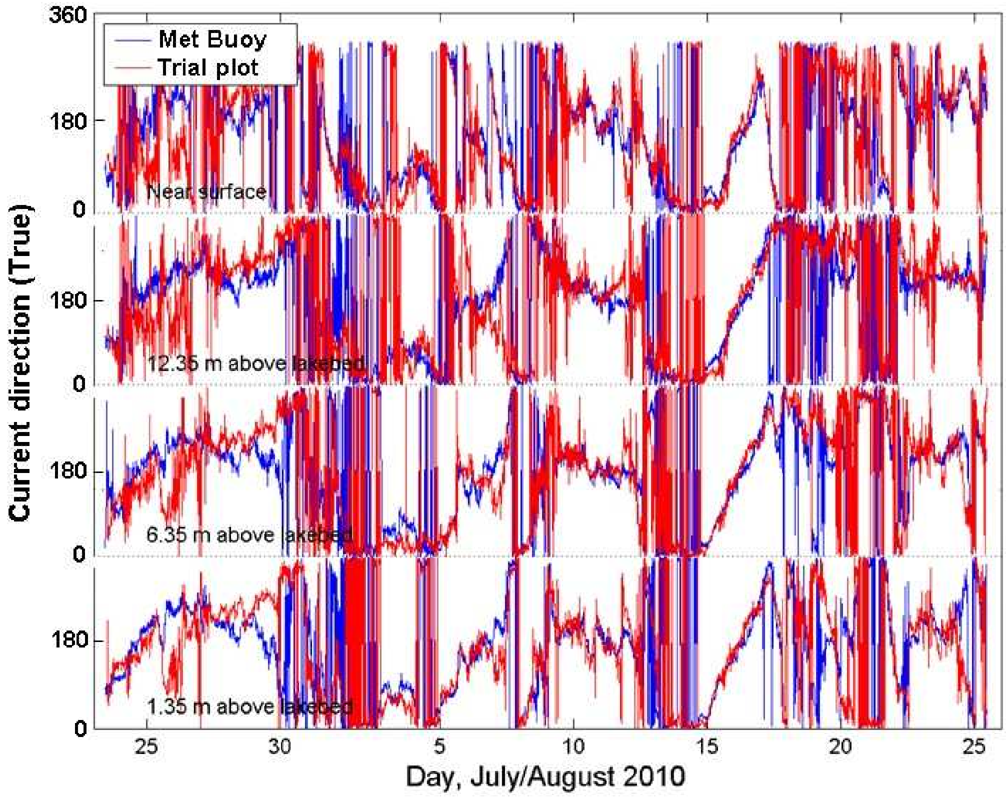

Figure 4: Comparison of current directions at the remote monitored buoy [Met Buoy] and at the proposed trial plot site at selected heights above the lake bed during the July/August ADCP deployments. The graphs for each layer have a vertical scale of 0 to 360 degrees true and are stacked to show the synchronicity of the flow direction at these two sites when the lake is well mixed. Vertical lines indicate a direction change from 0 to 360 around true north.

3.1.3 Wind velocity and direction

Wind records from Rotorua Airport met station [Agent 1770] (Fig. 5) show that Lake Rotorua was subjected to a series of high wind events mostly from the northerly quarters during the period of the ADCP deployments. The most sustained northerly event occurred between the 12th and 15th August before the wind switched to a southerly for about 24 hours (Fig. 6).

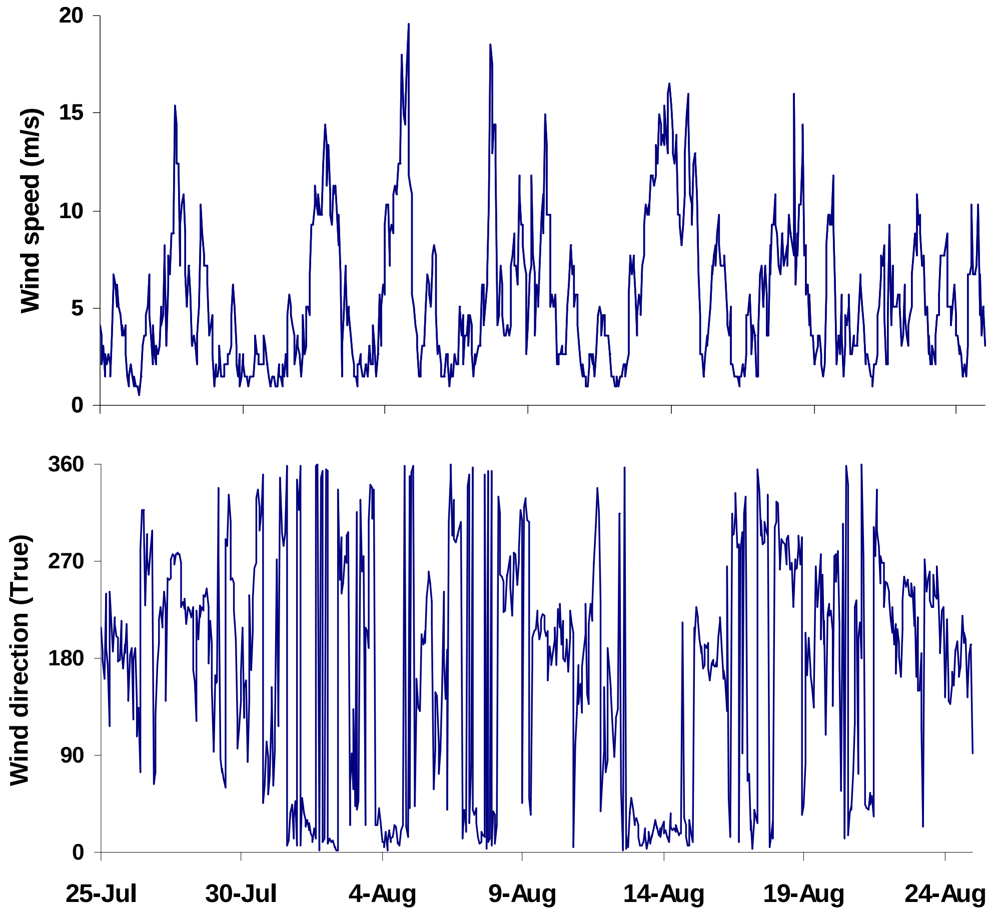

Figure 5: Wind velocity and direction from the Rotorua Airport met station during the July/August period of the ADCP current meter deployments. Note that wind direction is the direction wind is blowing from e.g., the storm event around 14th August was from the north.

3.1.4 Wind-water coupling

Wind forcing was expected to cause the water to move with the wind i.e., a strong wind from the north should cause the water to flow in a southerly direction. However, comparison of the wind and water current direction records between 12th and 17th August (Fig.6) shows that the water at the ADCP sites was moving in the opposite direction to the wind at Rotorua Airport.

This apparent anomalous situation can be explained by examining the locations of the measurement sites relative to the morphometry of Lake Rotorua which is nearly circular and has an island, Mokoia Island, near the centre (Fig. 7). Wind measurements at Rotorua Airport are on the eastern shores of the lake whereas current measurements were made on the western side of the island. When the northerly wind stress was applied to the water on the eastern side of the island, the water would be expected to flow towards the south. This appears to have induced a return flow towards the north on the western side of the island, as seen at the ADCP sites. This implies that the water in Lake Rotorua rotates around the central island.

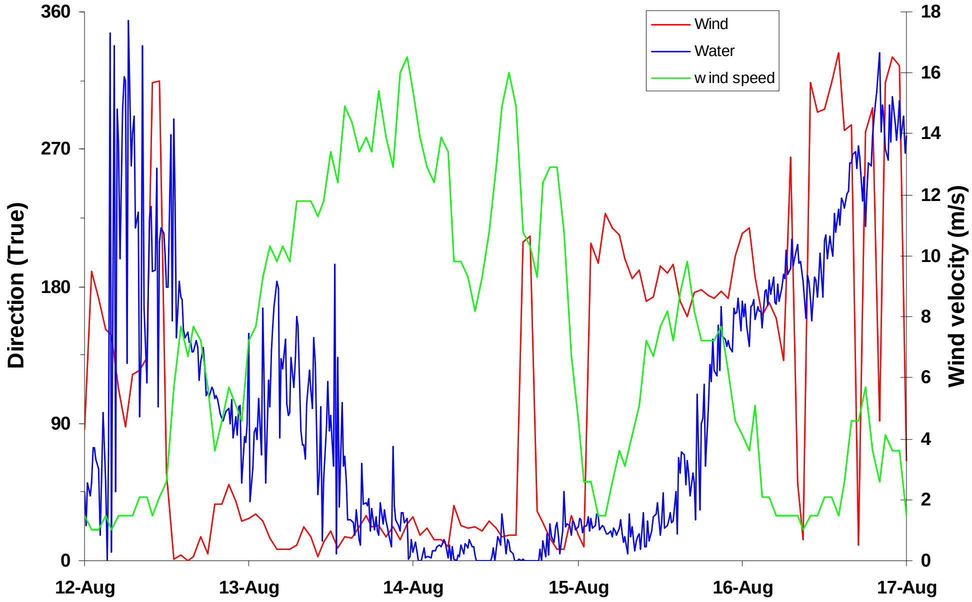

Figure 6: Comparison between wind direction (red) at Rotorua Airport and surface water flow direction (blue) at the trial plot site, relative to wind velocity (green). Note wind is from direction and water is towards direction.

The schematic (Fig. 7) shows conceptual flow directions and includes flow direction rose plots for the wind and the water currents. Further examination of the coupling between wind and water showed that when the wind reversed direction, the water movement also revised direction. The response was remarkably rapid for such a large body of water with a lag of about 24 hours for a change in direction (e.g., Fig. 6; 15th August). It took about two days for lake currents to respond to wind after a calm period (e.g., Fig. 6; 12th to 14th August), and it took more than 3 days for the current velocity to return to low background velocity after a wind event (e.g., Fig. 3; 14th August event).

From the current meter direction data (Fig. 4) and the wind data (Fig. 5), under light winds from the south-westerly quarter, e.g., 24th to 30th July, the expectation would be to have low velocity lake currents moving in an anticlockwise direction around Mokoia Island.

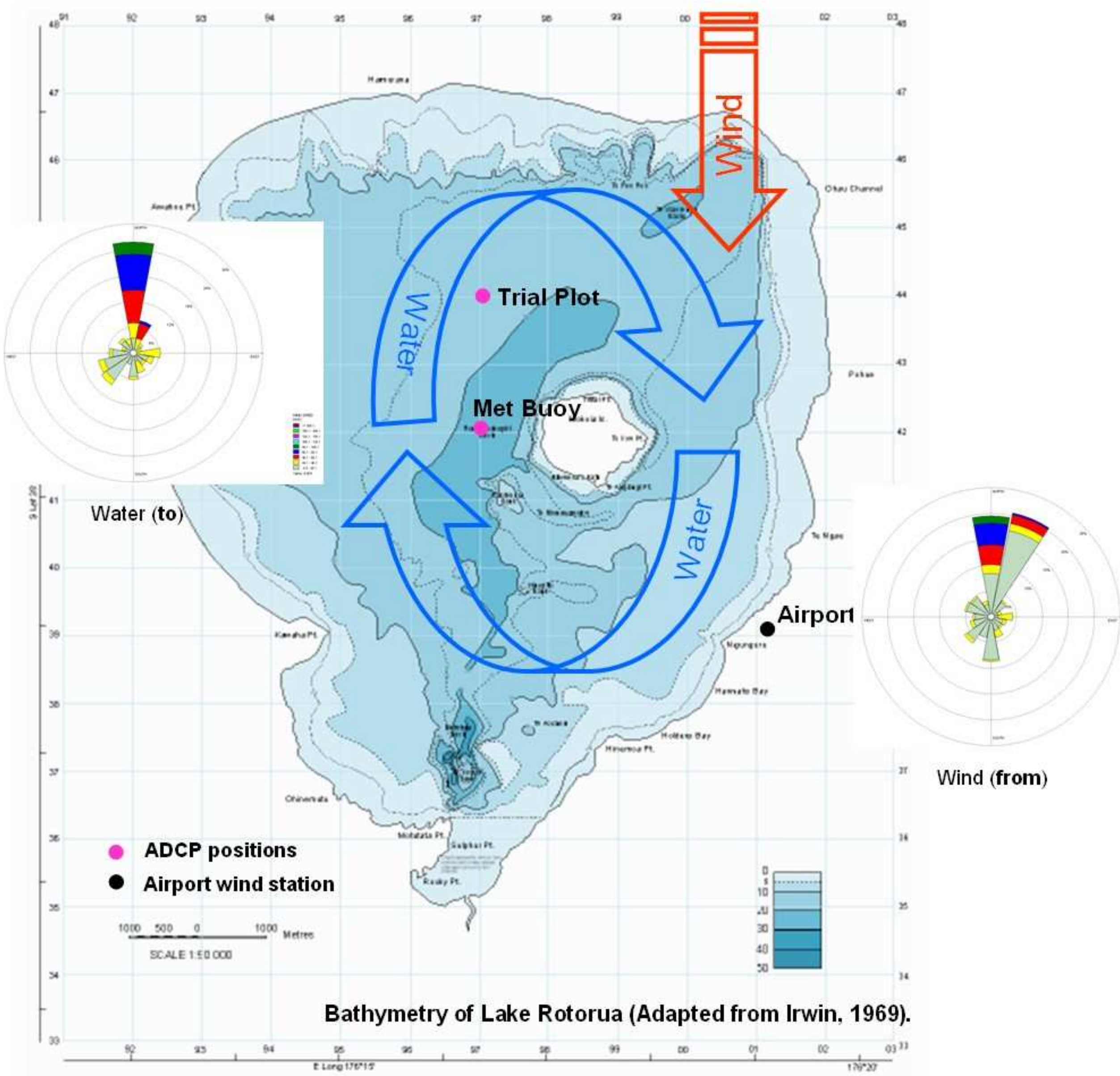

Figure 7: Conceptual water flow directions in Lake Rotorua relative to surface wind stress during a period of strong northerly wind. Directions are based on wind records from Rotorua Airport and the current data recorded by the ADCPs at the Met Buoy and Trial Plot sites. Water and wind direction plots are for the Trial Plot and Rotorua Airport sites, respectively, for the period of 12th to 16th August 2010.

3.2 Lake Rotorua November/December 2010

The lake was thermally stratified with a 1ºC thermocline (Fig. 8), and developed an anoxic hypolimnion during the period of the ADCP current meter deployment (Fig. 9).

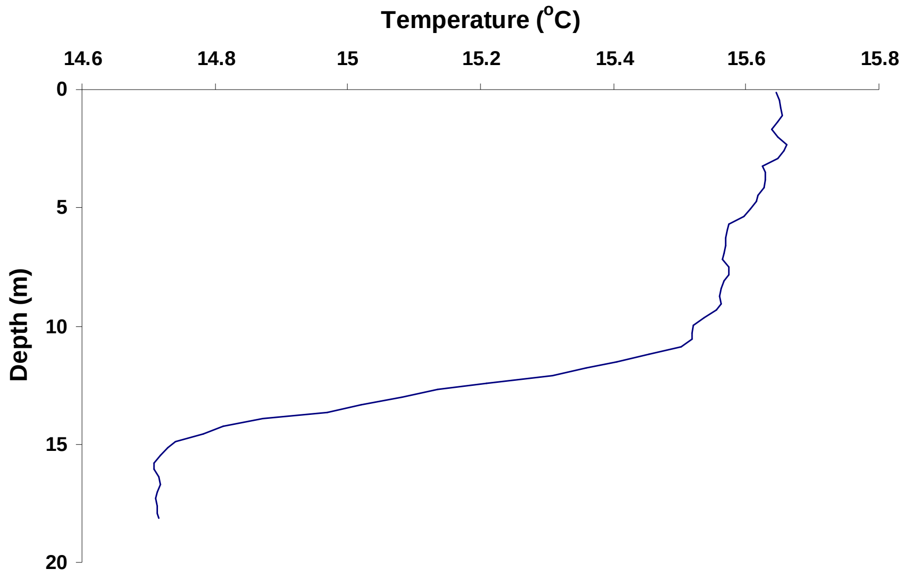

Figure 8: Temperature profile in Lake Rotorua at the Trial Plot site in November 2010 showing a 1°C thermocline below 10 m.

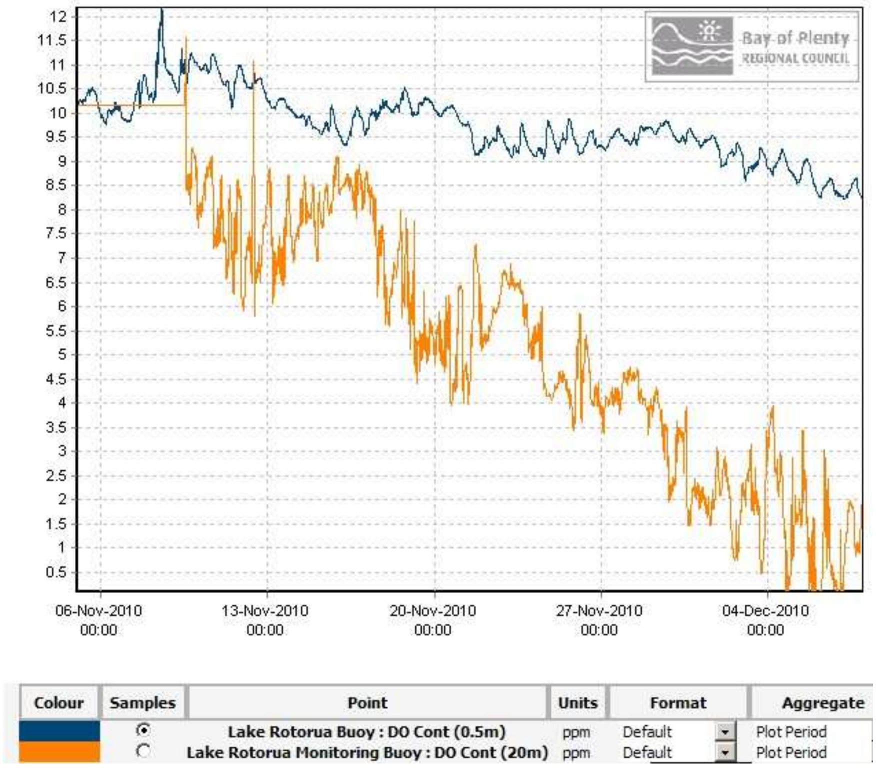

Figure 9: Bottom water oxygen (orange line) showing progressive depletion in Lake Rotorua from saturated to anoxic during the period of the ADCP current meter deployment. Data from the Lake Rotorua Buoy from the Bay of Plenty Regional Council web site.

3.2.1 Current velocity

Current velocity data from selected depth bins (Fig. 10) show that the pattern of lake water movement at the trial plot site was different in the upper water layer (more than 6 m above the lake bed) than in the bottom water layer. Although water velocities were on average around 0.036 m/s throughout the water column, maximum water velocities were higher in the hypolimnion (max 0.198 m/s) than in the epilimnion (max 0.158 m/s). The synchronicity in current velocity timing and amplitude between depths, seen in the July/August deployments (Fig. 3), were no as obvious in the November/December data. Velocities appeared to be lowest just above the thermocline and highest just below the thermocline.

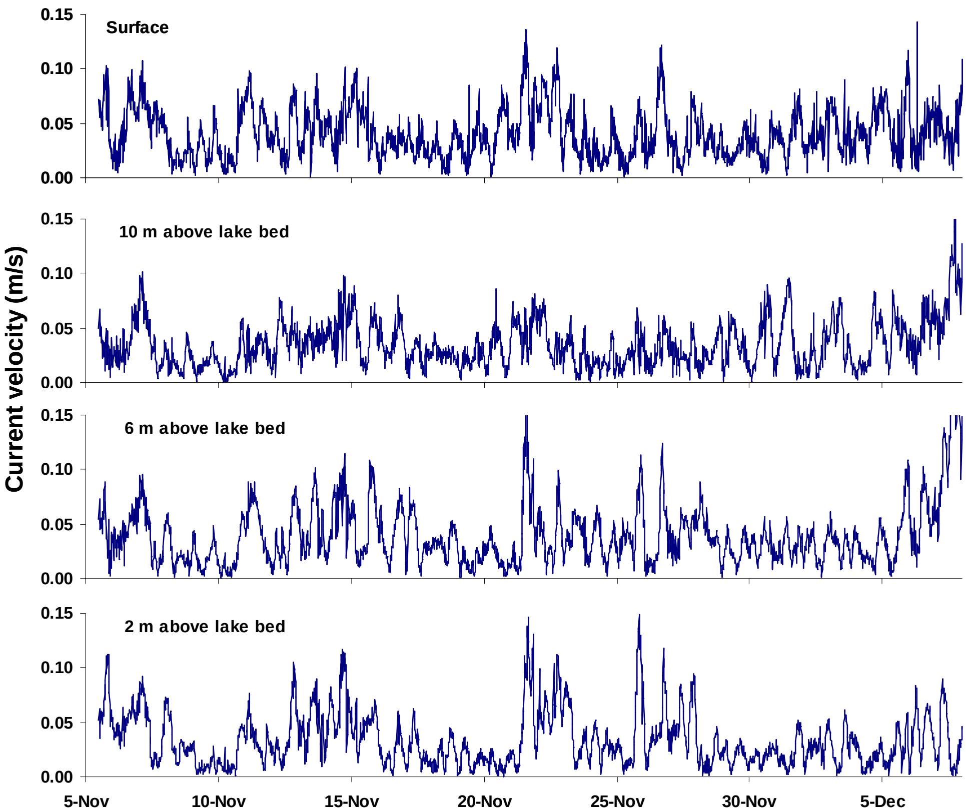

Figure 10: Current velocity data at the proposed Trial Plot site at selected heights above the lake bed during the November/December ADCP deployments. The graphs for each layer have a vertical axis of 0 to 0.15 m/s and are stacked to show the lack of synchronicity of the currents above and below the thermocline when the lake was thermally stratified. The thermocline was just above 6 m above the lake bed (Fig. 8).

3.2.2 Current direction

Current direction data [true north] from same four depth bins (Fig. 11) show that the lake water at the trial plot site often moved in different directions at different depths. On the 15th November, water within 6 m of the lake bed was moving to the east which is in the opposite direction to the water nearer the surface which was moving towards the west. Similar dislocation between upper and lower water layers can be seen through the data set.

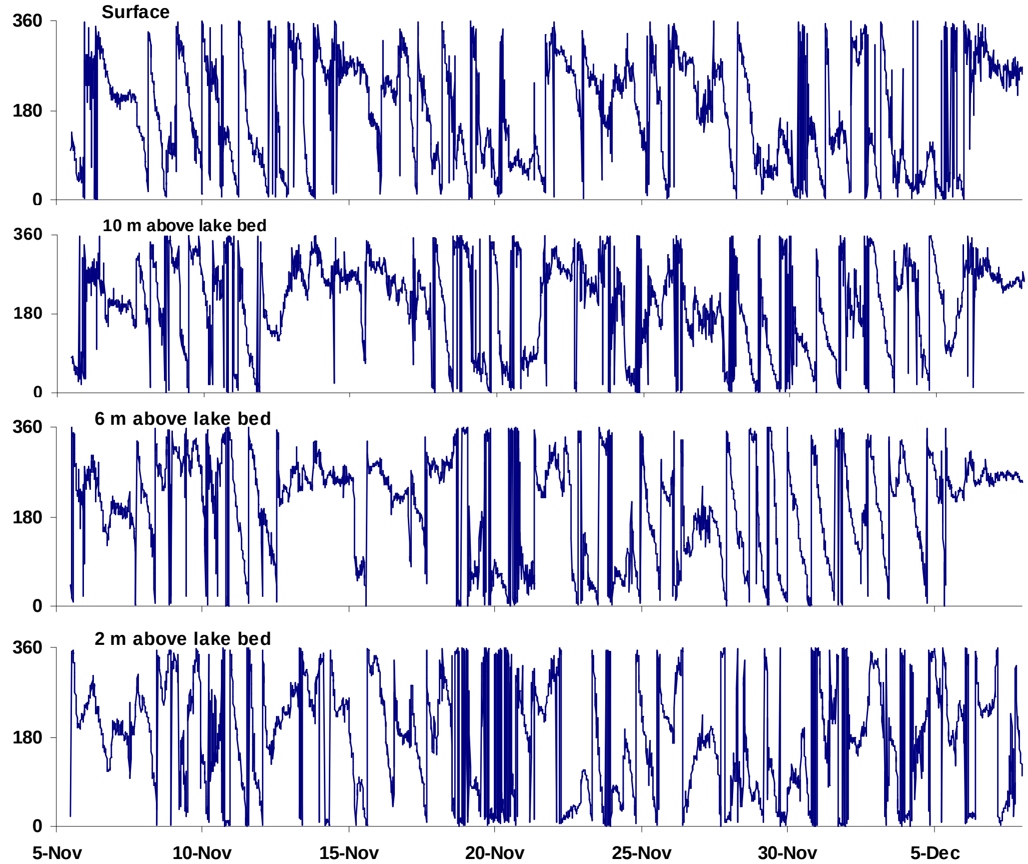

Figure 11: Current direction data from the four depth bins (Fig. 10) showing the lack of synchronicity between water at different depths. Often the bottom water appears to be moving in the opposite direction to the water in the layers above.

3.2.3 Wind velocity and direction

Wind records from Rotorua Airport met station (Fig. 12) show that the winds across Lake Rotorua were light, rarely exceeding 8 m/s, during this monitoring period. That is consistent with the lake being thermally stratified and there being insufficient wind to mix the lake.

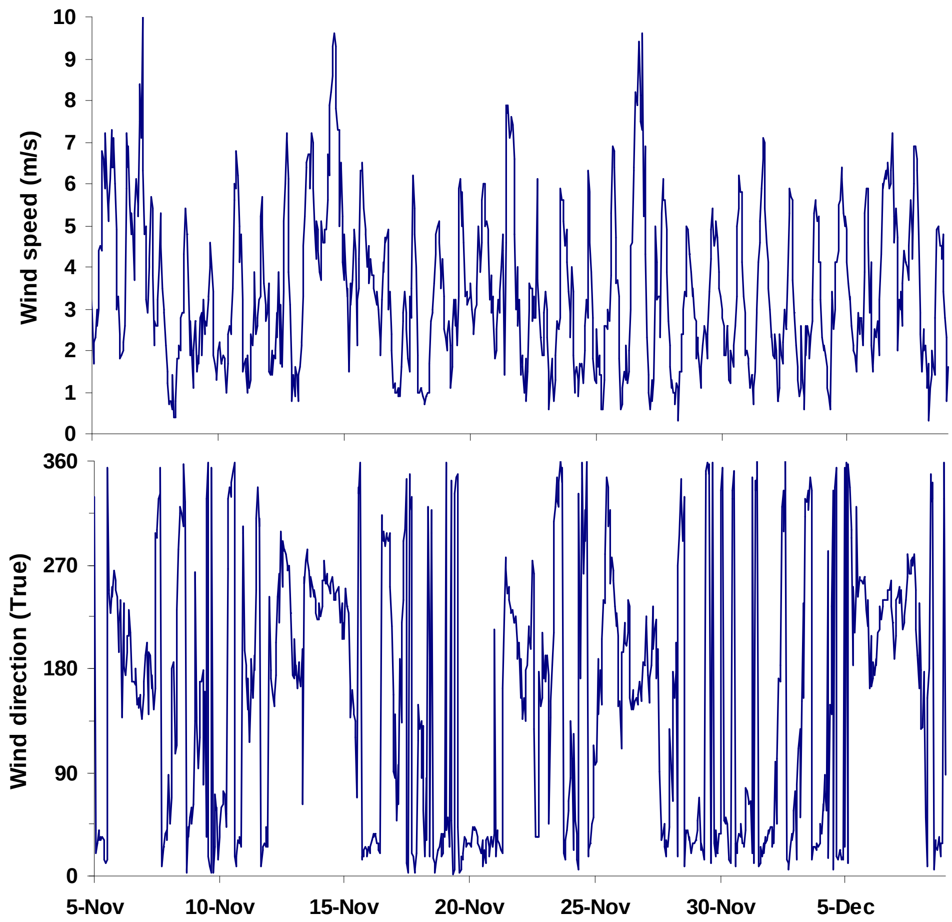

Figure 12: Wind velocity and direction from the Rotorua Airport met station during the November/December period of the ADCP current meter deployments. Note that wind direction is the direction wind is blowing from.

A feature of the wind data during the November/December ADCP deployment was the apparent regular change in direction and velocity on an almost daily basis. As a generalisation, the wind direction switched suddenly from south to North almost daily about 8 am and then switched back again overnight about 1 am (Fig.12). In concert with the wind direction changes, the wind velocity also changed regularly almost on a daily basis. Wind velocity was lowest at about 6 am (<2 m/s) with a low period between 4 am and 8 am, but was highest about 5 pm (>4 m/s) with a high period between 1 pm and 7 pm (Fig.12).

This pattern of regular wind direction and velocity changes is typical of coastal winds where the heating and cooling of the land causes light on and off shore winds on a daily basis.

3.2.4 Wind-water coupling

Wind forcing when the lake was fully mixed in winter resulted in the water at the trial plot site moving in the opposite direction to the wind direction at Rotorua Airport. This pattern was still present during stratification e.g., the wind coming from the west on the 14th November (Fig.13) caused the surface water to flow towards the west. As was found during the mixed period, the response time was about 24 hours.

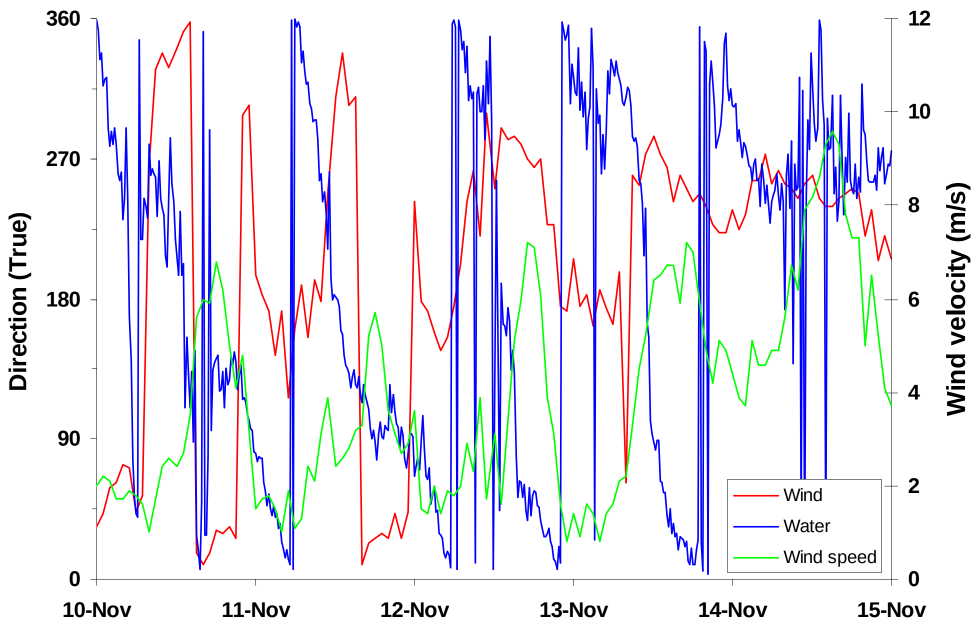

Figure 13: Comparison between wind direction (red) at Rotorua Airport and surface water flow direction (blue) at the trial plot site, relative to wind velocity (green). Note wind is from direction and water is towards direction.

Additional information on the wind velocity threshold and duration is also implied from these data (Fig. 13). A wind velocity of around 5 m/s sustained for at least 24 hours was required to cause the response observed e.g., 13th to 15th November. Wind pulses of more than 5 m/s but of shorter duration e.g., 10th, 11th and 12th November did not set up a flow in the opposite direction. Instead, the flow direction appears to slowly rotate through 360 degrees over the 24 hour period (Fig. 13). Given that the ADCP was at a fixed point on the lake bed, this implies a "local gyre" rotating in an anticlockwise direction with the daily wind pulse keeping it rotating. There are likely to be several of these local gyres spaced across the lake interacting and rotating in opposite directions where they meet.

3.2.5 Water column decoupling

Current direction data for the whole of the November/December ADCP deployment (Fig. 11) indicated that there were periods when the current flow in the upper and lower water columns were in the opposite directions. Examples of this phenomenon occurred on 15th and 22nd November (Fig. 14). In both examples the wind set up conditions exceeded the wind-water coupling thresholds so that the surface water moved in the opposite direction to the wind. The bottom water moved in the opposite direction to the surface waters with the decoupling probably occurring at the thermocline. The water velocity at the thermocline approached zero, consistent with high stability across the thermocline and indicating that these flows were set up over long distances rather than being local circulation patterns.

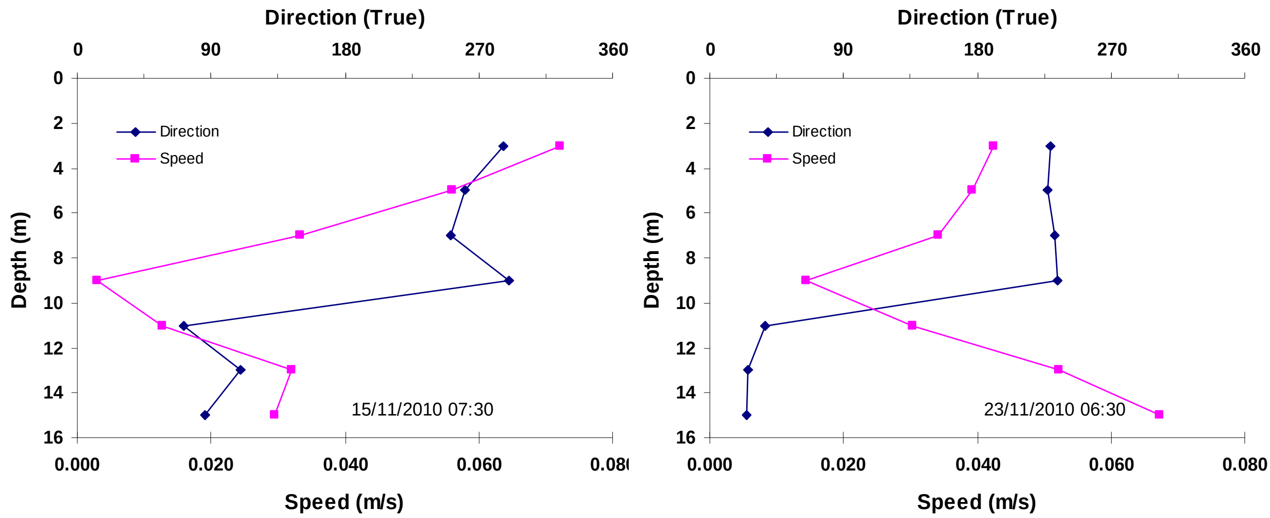

Figure 14: Examples of water column decoupling when wind-water coupling thresholds were exceeded and wind was controlling the surface water flow. Each example is one of many similar profiles from a period of >10 hours on each occasion. The average wind direction and velocity at Rotorua Airport over the previous 24 hours for each occasion was 247° true (SD = ±16.5) at 6.2 m/s (SD = ±1.6) and 232° true (SD = ±28.4) at 6.2 m/s (SD = ±2.0), respectively.

3.3 Lake Rotoehu January/February 2011

The ADCP current meters were deployed in Lake Rotoehu 2 days after a major cyclonic event and before another event with strong winds. Consequently, the lake was well mixed at the time of deployment but reverted to being stratified during the period of the deployments. The cyclonic event included heavy, but warm, rain from the north, which raised the lake level and temperature during the deployments (Fig. 15). The thermocline was at a depth of about 5 m.

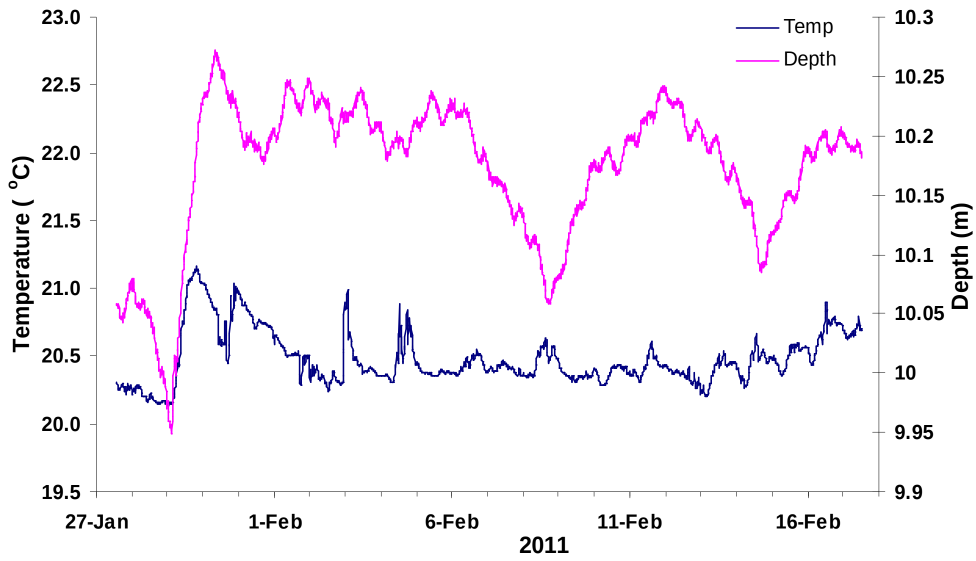

Figure 15: Changes in Lake Rotoehu water level and bottom water temperature accompanied the storm event on 29th January 2011 (mid-lake ADCP data). The warming is an indication of water column mixing during the event while the cooling indicates the return to stratified conditions. Short duration warming indicates strong wind mixing events. Similar depth and temperature patterns were obtained at the southern site at the same time.

As two ADCPs were deployed widely separated spatially i.e., a mid-lake site in 13 m water depth and a southern site in about 8 m water depth, the data for each site are presented separately.

3.3.1 Wind velocity and direction

The wind record from Rotorua Airport was used because there was no wind station close to Lake Rotoehu. The current meters were deployed after an extreme weather event and shortly before another frontal system crossed the region. A consequence of this weather pattern was that the wind sequence was divided into two relatively distinct phases – persistent wind of medium velocity (4 to 10 m/s) from the west before 6th February and then the pulsed diurnal coastal winds (see section 3.2.3) with light winds (<2 m/s) from the south at night switching to stronger winds (>4 m/s) from the north during the day (Fig. 16).

Windrose analysis of the data clearly shows the difference before and after 6th February (Fig. 17A and B) and shows the strength of day (afternoon) northerly wind onto the lake (Fig. 17C).

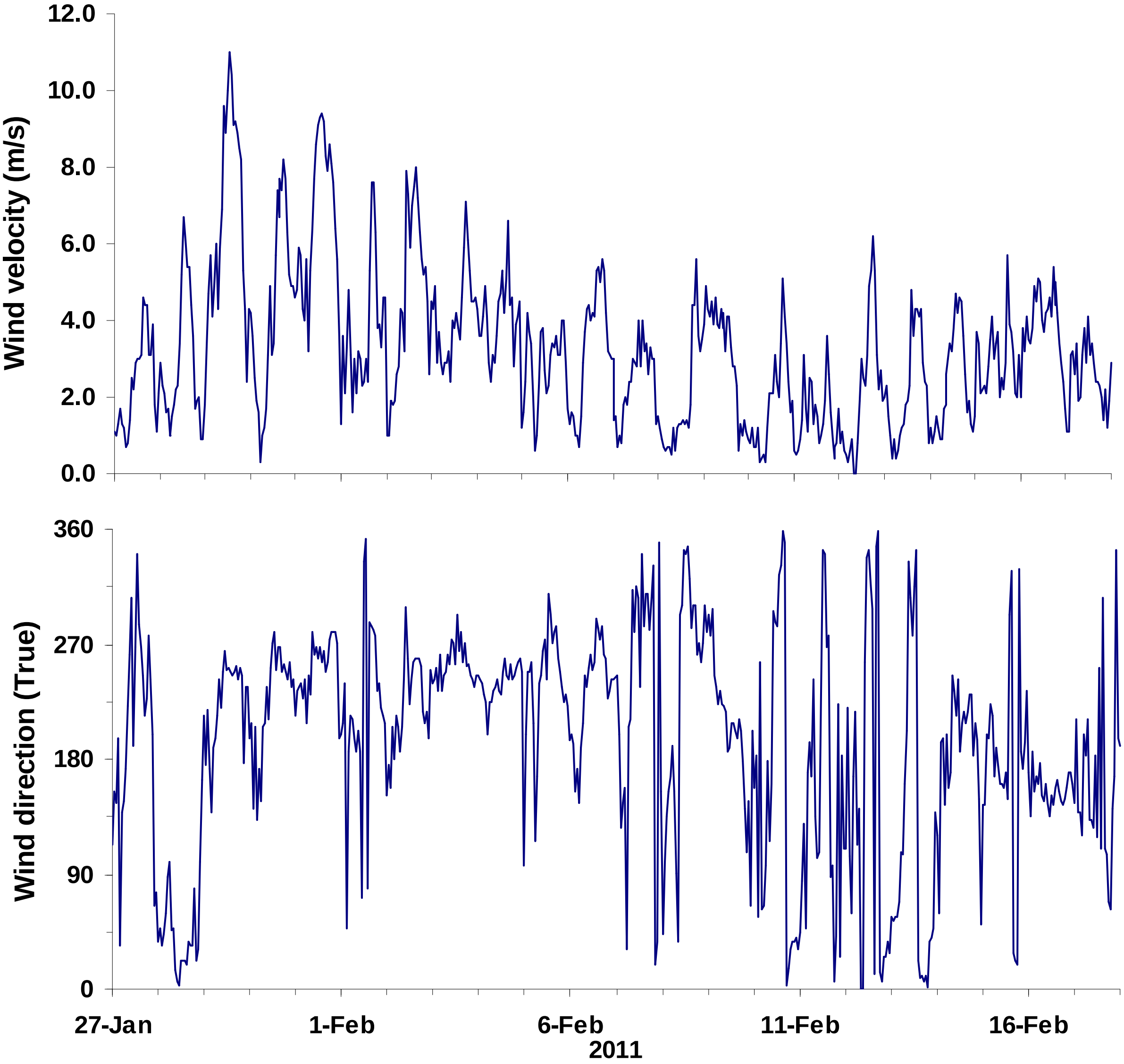

Figure 16: Time series wind record from Rotorua Airport for the duration of the ADCP current meter deployments in Lake Rotoehu in January/February 2011.

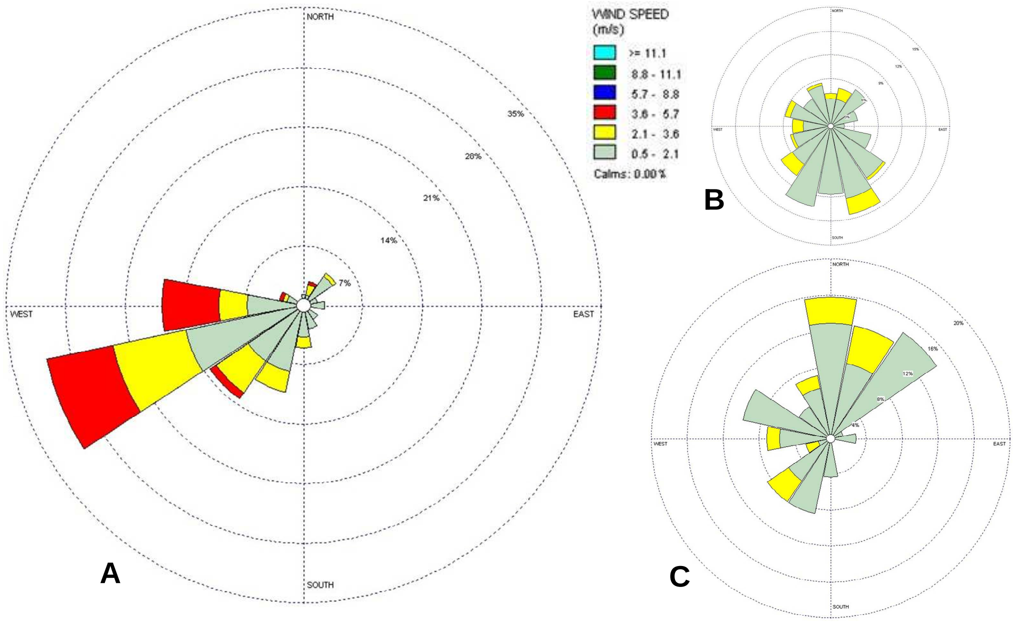

Figure 17: Wind rose analysis of the wind record A) from 27th January to 6th February and B) after the 6th February, at the same proportional scale; (C) the day time winds in the afternoon between 8th and 13th February 2011.

3.3.2 Mid-lake site current velocity and direction

Current velocity data from all depth bins (Fig. 18) show that the pattern of lake water movement was highly synchronous at all depths from 27th January to 6th February after which the water velocity became more variable between depths. This is consistent with the wind forcing being stronger before 6th February than after (Fig. 17). Previous information from Lake Rotorua (see section 3.2.4) showed that below some threshold wind velocity and duration, the lake currents become decoupled from the wind as a driving force. These thresholds may be different for each lake.

In contrast to the Lake Rotorua lake currents, which flowed in the opposite direction to the wind at the ADCP sites, in Lake Rotoehu the current direction in the surface water was with the wind (Fig. 19) i.e., strong winds from the west caused the surface waters to flow towards the east. After the 6th February there is an underlying current direction to the south which could be associated with the diurnal wind cycle with afternoon breezes from the north. If this is the driving force, the threshold for wind velocity may be as little as 4 m/s and the duration may be just a few hours.

Of some interest is the propagation of the diurnal southerly current to the bottom waters (Fig. 19) and that the whole water column moves in the same direction (Fig. 20 C) when the average current velocity is low.

Figure 18: Time series current velocity data at the mid-lake site in Lake Rotoehu. The data is synchronous at all depths until about the 6th February after which current velocities appear to be more variable at different depths, especially below 6 m.

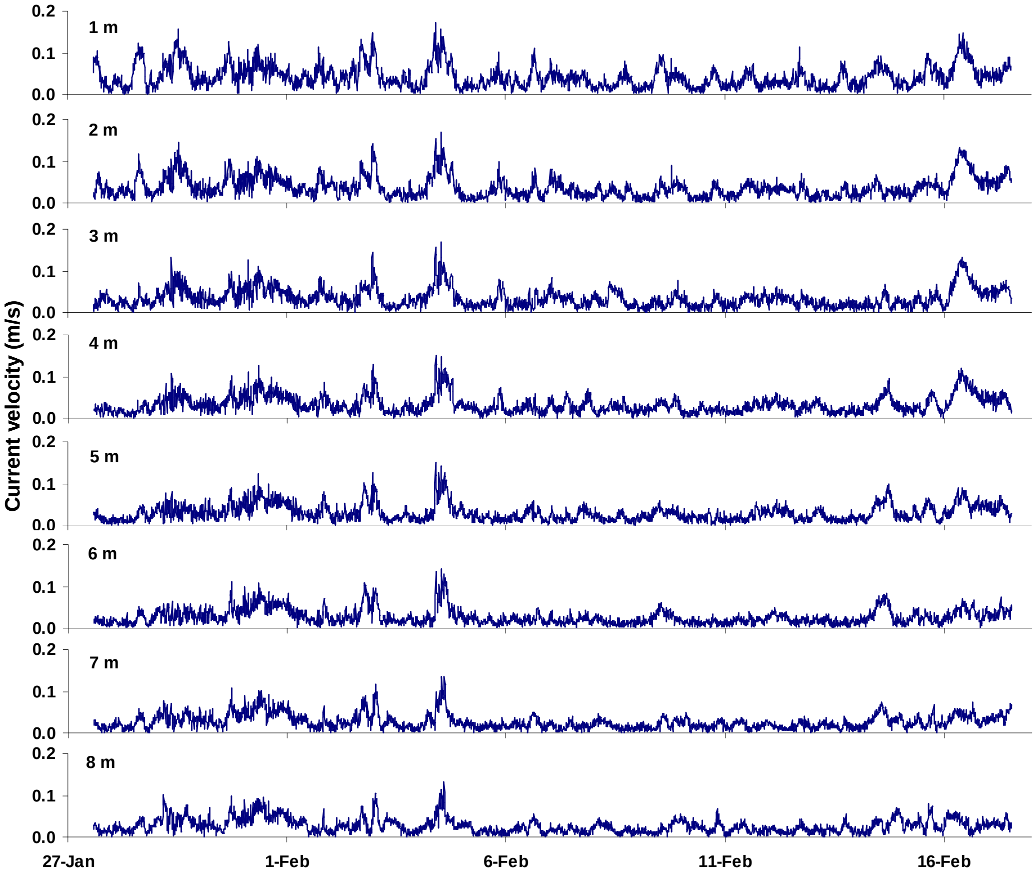

Figure 19: Time-series current direction data from surface and bottom layers at the mid-lake site in Lake Rotoehu. The effect of daily wind pulses is apparent after the 6th February.

Current velocities decreased with depth (Fig. 20). Mean and maximum water velocities before 6th February were on average 1 cm/s and 2 cm/s faster, respectively, than after the 6th February (Fig. 20A, B). Mean current directions changed with depth from easterly to southerly before 6th February but were consistently southerly at all depths after 6th February (Fig. 20C). This pattern of change is clearly seen in the current direction rose plot for the upper water layers (Fig. 20D).

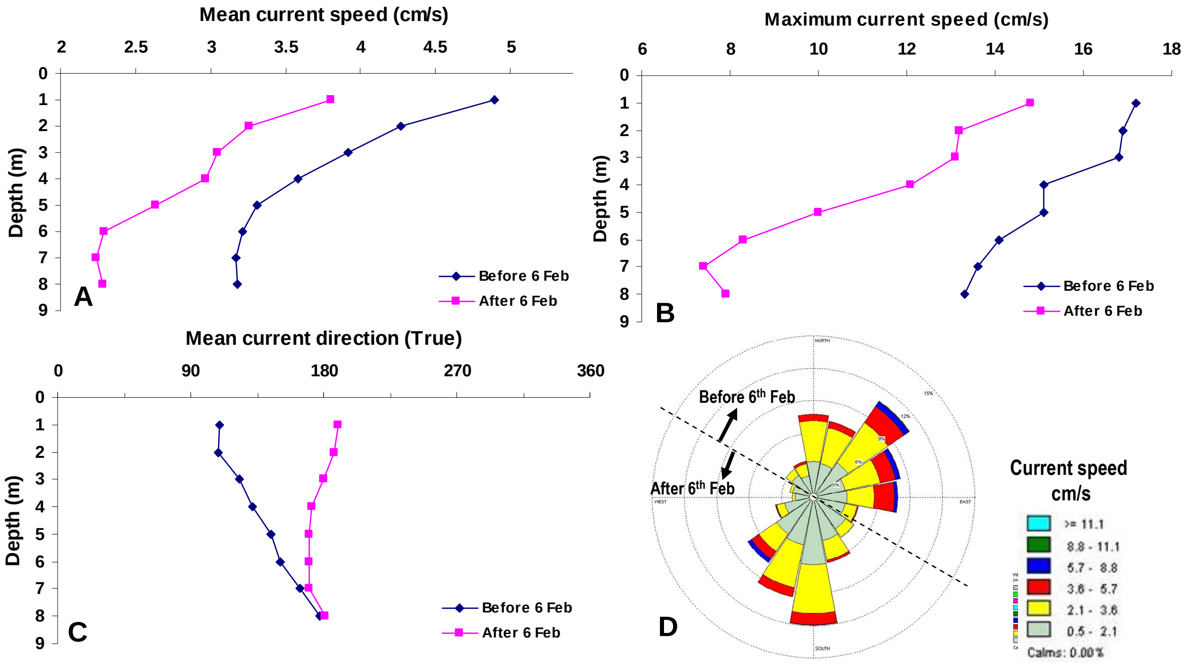

Figure 20: Comparison of (A) mean and (B) maximum current velocity at all depths before and after 6th February 2011 compared with (C) mean current directions for these two periods. D) Rose-plot of current direction in the surface layer shows the direction change after the 6th February 2011.

As occurred in Lake Rotorua, the water column was coupled from top to bottom under strong wind-induced mixing, but rapidly became thermally stratified and decoupled when the wind velocity dropped. (Fig. 21). Essentially the water column was mostly mixed soon after the deployment and in response to the strong winds before the 6th of February (Fig. 21A). After the 6th of February, there were periods when wind forcing was sufficient to control the surface water flow direction but not disrupt the thermal stratification. Under those conditions the water column became decoupled with the bottom water moving in the opposite direction to the surface water (Fig. 21B).

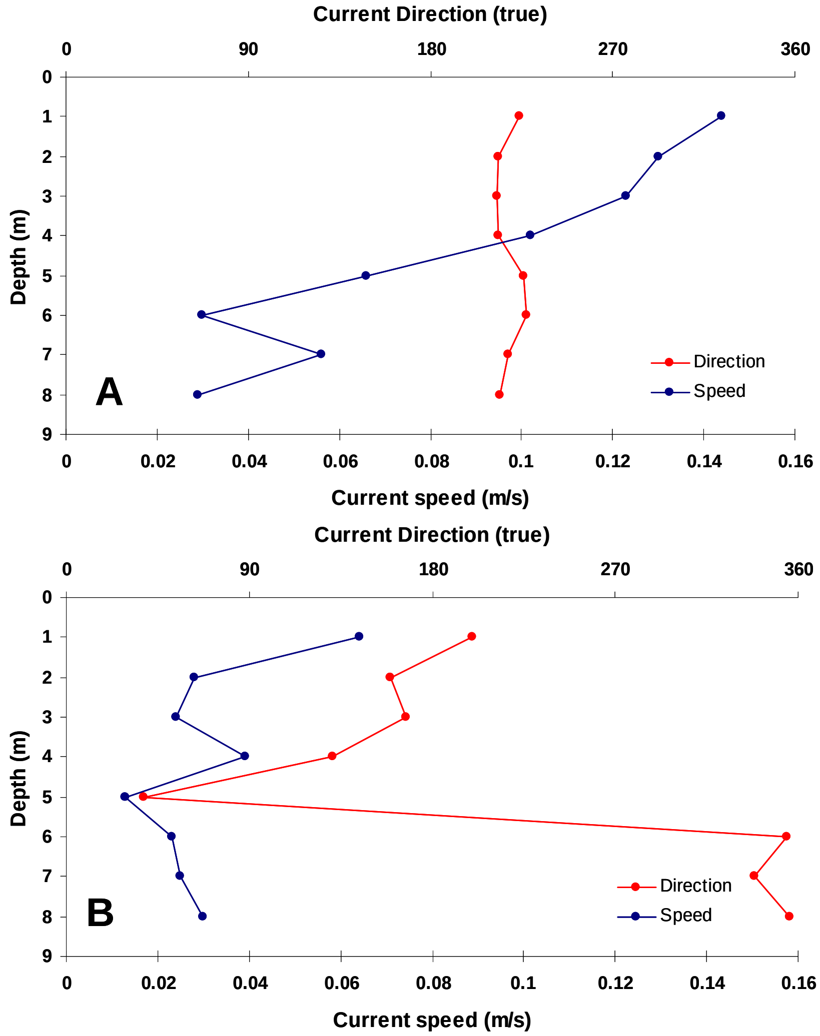

Figure 21: A) Mid lake profile of current velocity and direction showing the water column is fully mixed under strong wind. B) Profile of current velocity and direction showing that the water column decoupled at the depth of the thermocline (about 4 m) with the surface water moving to the south while the bottom water moved to the north.

3.3.3 Southern lake site current velocity and direction

Current velocity data from all depth bins (Fig. 22) show that the pattern of lake water movement was synchronous at all depths from 27th January to 6th February although the velocity decreased with increasing depth. After 6th February the currents became highly variable between depths and short duration wind-induced surface currents did not propagate down below about 4 m.

Current direction data (Fig. 23) show that the water column often became decoupled with the bottom water moving in the opposite direction to the surface layers.

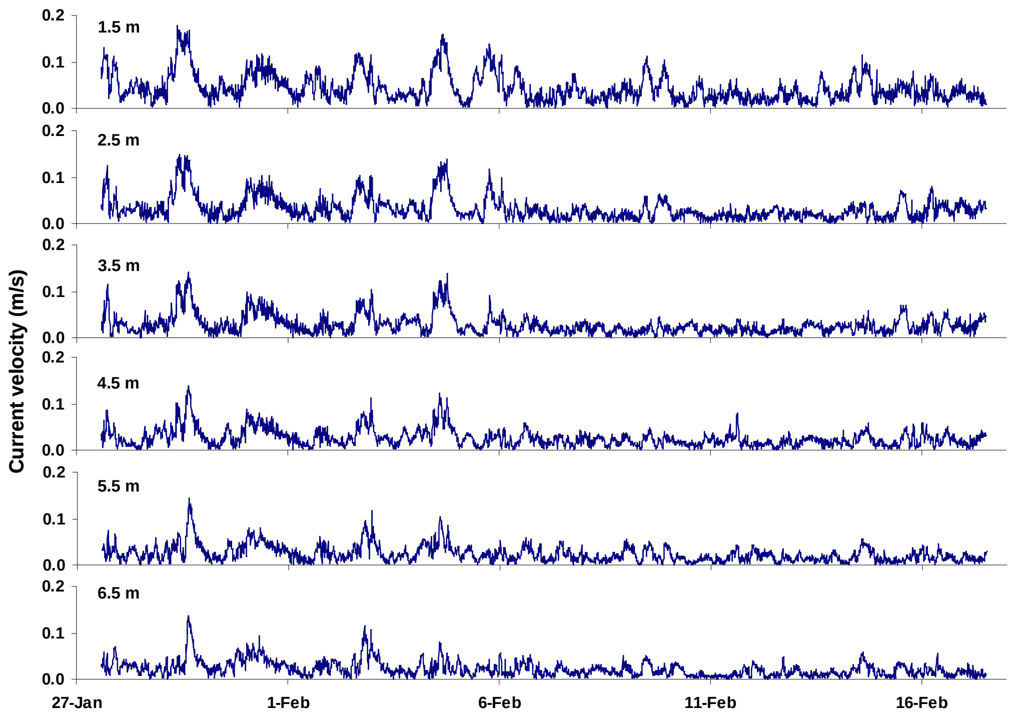

Figure 22: Time-series current velocity data from the southern ADCP site in Lake Rotoehu. The data is synchronous at all depths until about the 6th February after which current velocity became more variable at different depths, especially below about 4 m.

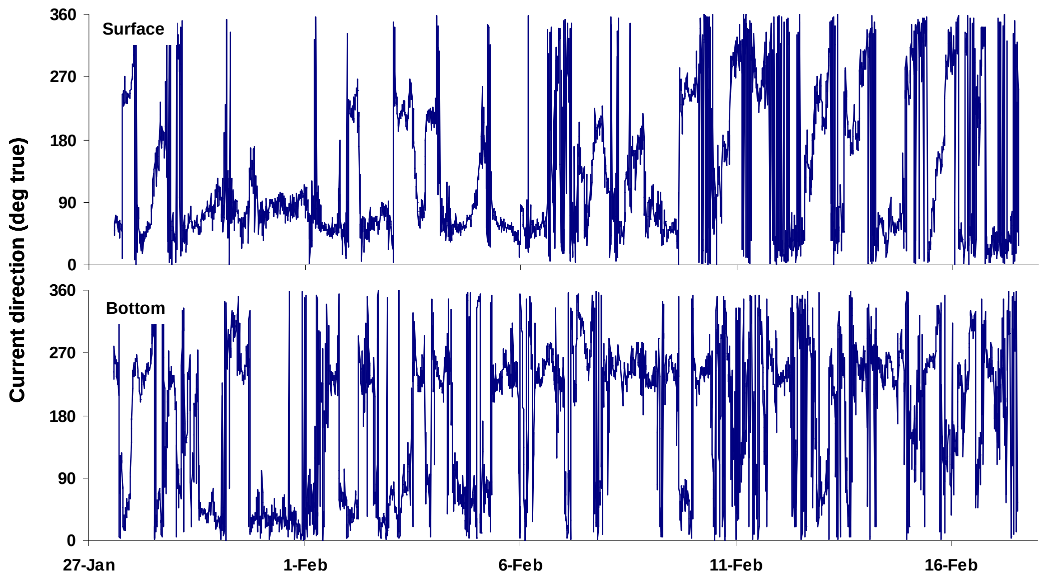

Figure 23: Time-series current direction data from surface and bottom layers at the southern lake site in Lake Rotoehu. The effect of daily wind pulses is apparent after the 6th February. It is also apparent that the water at the bottom is moving in the opposite direction to the water at the surface on many occasions.

The decoupling of the water column is clearly seen in the current direction and velocity profiles (Fig. 24). Currents velocities of up to 11 cm/s at the surface reduced to near zero at the thermocline before increasing to less than half their upper water column velocities. Flow analysis using rose plots show that the flow direction in the upper water column was towards the north-east but was to the south west below the thermocline (Fig. 25).

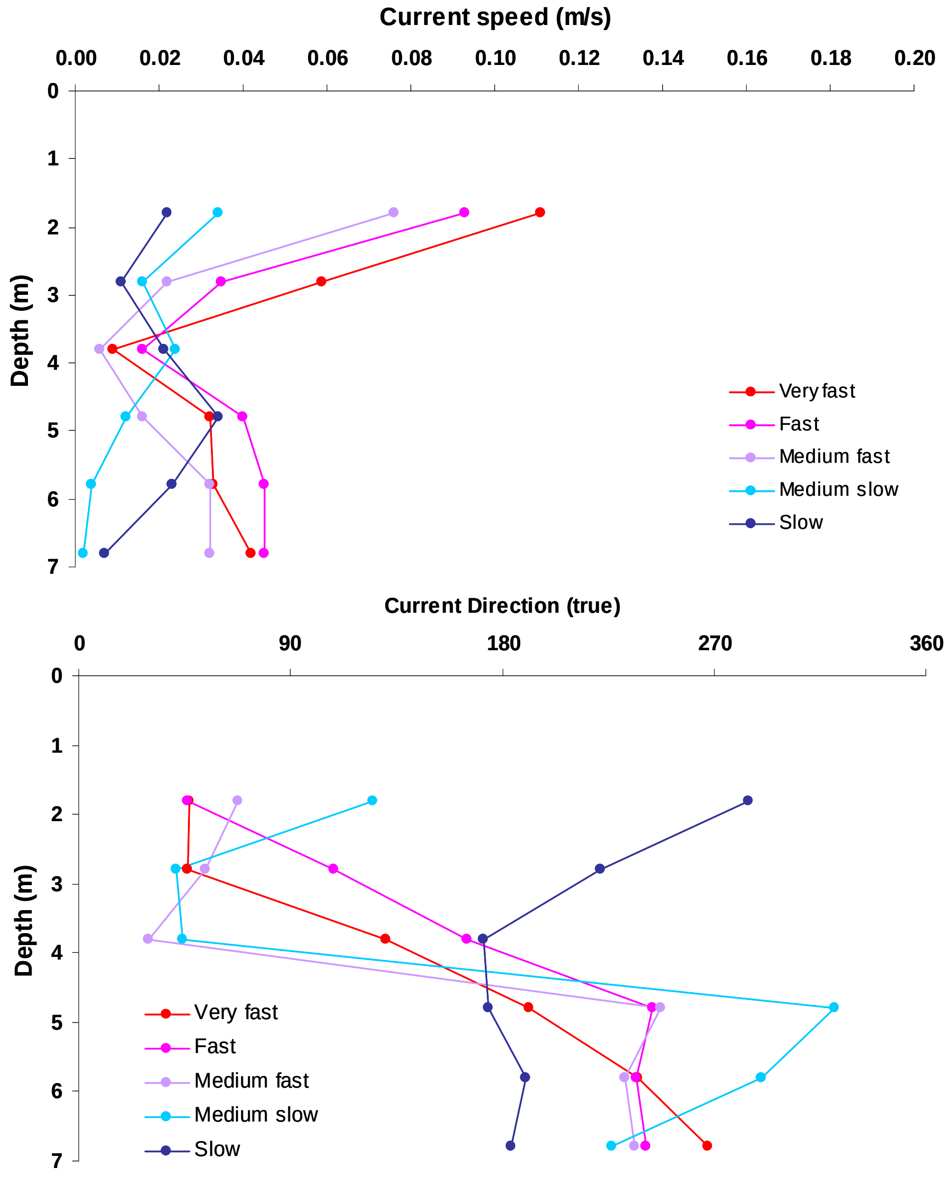

Figure 24: Current velocity and direction profiles for different surface water velocities at the southern lake site. At slow velocities, the linkage between surface water velocity and direction was lost in the upper water column while the flow direction in the bottom water column continued towards the south.

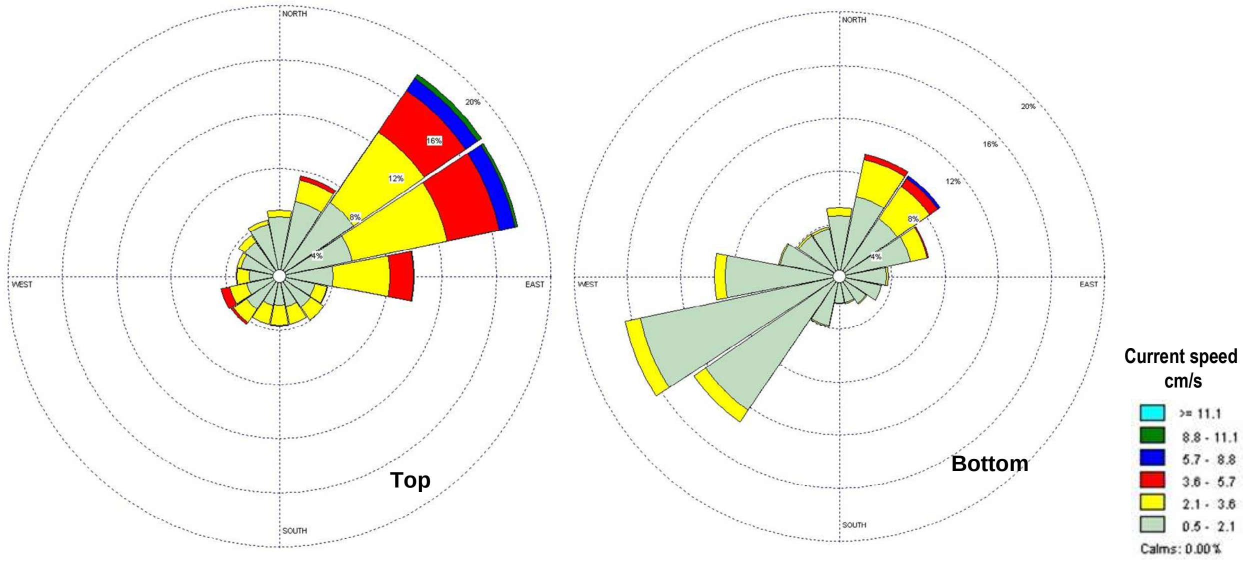

Figure 24: Current data analysis with rose plots at the southern site. Flows in the surface water (Top) were aligned with the wind while, for a large proportion of time, the bottom water was flowing in the opposite direction (Bottom).

3.3.4 Lake Rotoehu current synthesis

Based on the observations from the ADCP current meters coupled with the wind record from the Rotorua Airport meteorological station, it is likely that the light to moderate south-westerly wind stress across the lake surface during the monitoring period caused the surface water to move towards the north-east. When the water encountered the steeply shelving lake shore on the eastern side of the lake, it plunged and formed a bottom counter flow towards the south (mid-lake site) and south-west (southern site). Extrapolating these flows to complete a probable flow path, there must have been a zone of up-welling bottom water in the south-western corner of the lake (Fig. 25).

Light to moderate winds from the north would be expected to cause a reversal of this conceptual flow regime but there was insufficient data to check this hypothesis.

Under strong winds, the surface waters move with the wind but mix deeply causing the whole water column to move with the wind. How the circulation pattern works under these conditions is unknown.

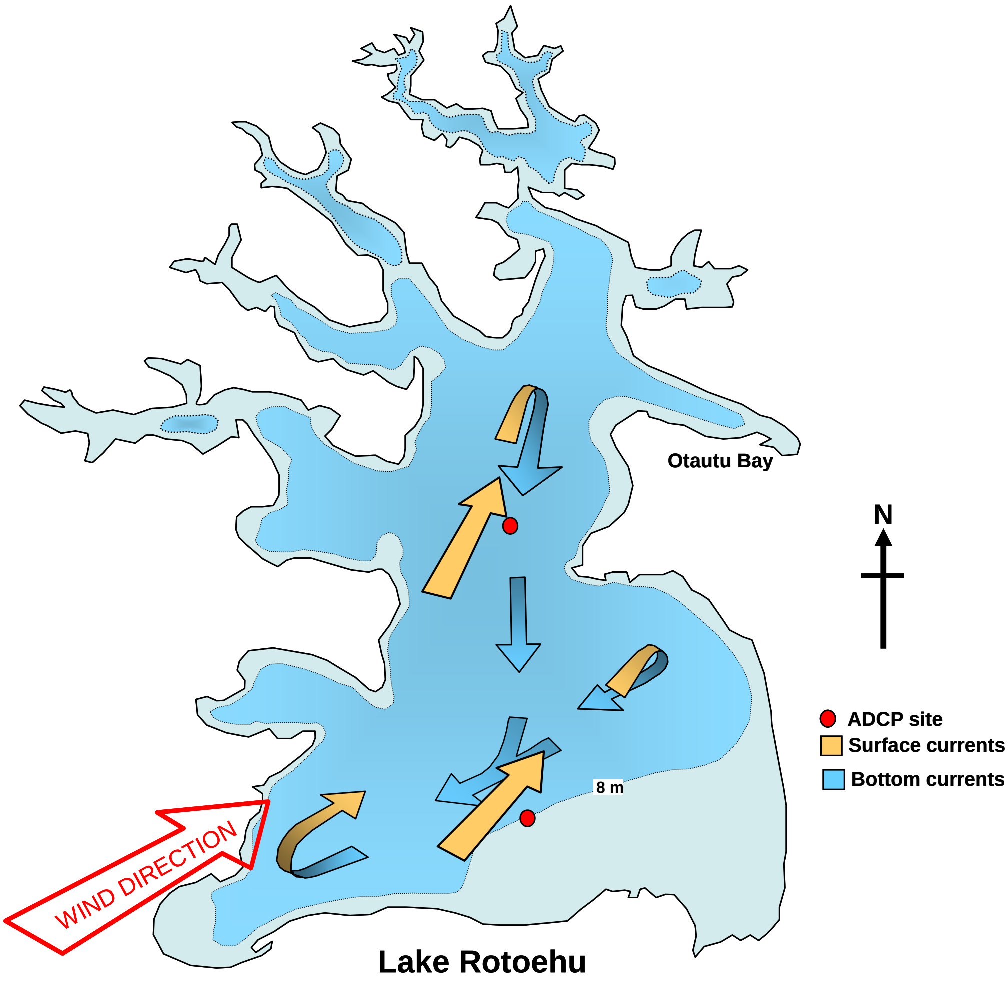

Figure 25: Schematic of the conceptual flow regime that probably operated in Lake Rotoehu in response to the south westerly wind during the deployment of the two ADCP current meters in January/February 2011.

4. Summary

4.1 Lake Rotorua fully mixed

The ADCP data from Lake Rotorua during July/August 2010 was for a period when the lake was fully mixed:

- Current velocity and direction data were synchronous with depth implying that the whole water was moving in the same direction at the same velocity.
- The mean water velocity was around 3 cm/s while the maximum velocity was around 20 cm/s. (20 cm/s is sufficient to suspend fine sediment).
- Water at the two ADCP sites on the western side of Mokoia Island moved in the opposite direction to the wind, as recorded at Rotorua Airport. This implies that the water was moving around the lake with the island as the central hub/axle.
- The circulation pattern reversed when the wind direction reversed. The response time to the change of wind direction was about 24 hours.
- After an extended period of low wind velocity the circulation pattern took 2 days to establish and stabilise when the wind velocity rose.
- When the wind dropped after an extended period of strong wind, the circulation pattern took about 3 days to dissipate and return to low current velocity of 2 to 3 cm/s.

4.2 Lake Rotorua stratified

The ADCP data from Lake Rotorua during November/December 2010 was for a period when the lake was thermally stratified below 10 m:

- The overall circulation patterns remained the same with respect to surface water circulating in the opposite direction to the wind.
- The water column decoupled at the thermocline and the bottom waters moved in the opposite direction to the surface waters.
- Threshold conditions required to establish the decoupled circulation patterns were a wind velocity of >5 m/s sustained for at least 24 hours.

- At low current velocities the water column appeared to be slowly rotating through 360 degrees in an anticlockwise direction.
- Wind data indicated that on and off shore “coastal breezes” occurred on a diurnal basis. Strongest winds were in the afternoon from the north.
- Lake currents were generally lower in early summer than in winter.

4.3 Lake Rotoehu

Lake Rotoehu was initially mixed following a storm event in mid January 2011 but rapidly became stratified at about 5 m depth during the January/February 2011 ADCP deployment:

- Surface water flow direction was aligned with the wind.
- When the water column was mixed, water moved in the same direction although the velocity decreased with increasing depth. It is not certain how the circulation pattern moves around the lake under these conditions.
- When the water column was stratified, the upper and lower layers were decoupled. The upper water layers moved with the wind while the lower water layers moved in the opposite direction, presumably as a return flow.
- Threshold conditions to establish the decoupled flow pattern were for wind velocities of >4 m/s sustained for at least 3 hours.
- There was a persistent southerly bottom water flow direction when wind strength was too low to control the direction of surface water movement.

4.4 Bottom line

In Lake Rotorua, it will take 3 days of calm weather before lake currents are low enough to allow surface application of any slow settling capping agent to reach the lake bed within a predicted target zone.

In Lake Rotoehu, lake currents are rapidly established within a few hours and equally rapidly dissipate in response to wind or the lack of wind. The implications of the stratified circulation pattern identified in this study should be considered when installing aeration equipment.

5. Acknowledgement

Dell Raerino, Te Arawa Lakes Trust, accompanied staff as observer during deployment of the ADCP current meters in Lake Rotoehu.