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# **Hamurana Stream water movement in Lake Rotorua**

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**NIWA Client Report: HAM2007-031  
March 2007**

**NIWA Project: BOP06211**

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# **Hamurana Stream water movement in Lake Rotorua**

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*Prepared for*

**Environment Bay of Plenty**

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## Executive Summary

As part of the studies investigating the feasibility of reducing the phosphorus and nitrogen loads on Lake Rotorua by diverting the Hamurana Stream directly to the Ohau Channel, Environment Bay of Plenty commissioned NIWA to determine (1) the extent of the plume off-shore and any interaction with the thermocline during a period of thermal stratification and (2) whether the size of the cold water refuge habitat for trout changed substantially over the summer period.

The importance of any interaction with the thermocline during stratification is that the Hamurana Stream water forms a cold density current along the lake bed, which has the potential to inject oxygen into the hypolimnion. Injecting oxygen into the hypolimnion would slow down the rate of hypolimnetic oxygen depletion and thus the release of nutrients from the sediment. If oxygen is being injected into the hypolimnion during summer stratification, diversion of the Hamurana Stream would disrupt that transport mechanism and exacerbate the sediment nutrient release process. At other times of year, when the lake is mixed, the effect of the density current is not important as the ambient lake water in contact with the sediments will be fully oxygenated. The contract proposal allowed for 3 dye tracer studies over the summer period.

A previous study in 2005 (Rowe et al. 2005) defined the cold water refuge habitat zone adjacent to the Hamurana Stream Mouth under calm conditions. That study also determined the hydraulic regime and flow path of the stream water, finding that it plunged to form a thermally-induced density current about the mid point across the shallow shelf before flowing as a thin layer across the rest of the shelf and over a drop-off into deeper water. Ambient surface lake water entrained into the density current at the plunge point and across the shelf diluted the stream water component and caused it to warm to near the surface lake water temperature.

The first dye experiment was conducted on 1 March 2007, in fine calm conditions, after an extended warm calm period that was likely to induce thermal stratification in Lake Rotorua.

In this study, the Hamurana Stream water was tracked by an initial injection of Rhodamine dye in the stream to define the cold water refuge habitat on the shelf, and then injection of more dye into the stream plume in the lake at a constant rate over a period of about 1 hour to form a dye ribbon that could be located using fluorometric sensors. These sensors also gave a measure of the dye concentration and thus the amount of dilution, by entrainment, that occurred as the density current moved down the drop-off and out into the lake.

The thermal structure of the lake was determined by temperature profiling and showed the characteristic summer dual thermoclines. The upper thermocline was between 5 and 10 m, impinging on the lake bed about 1.5 km off shore, and the lower thermocline was between 18 and 21 m,

impinging on the lake bed about 3.5 km off shore. The water column above the upper thermocline was 100% saturated with oxygen and the water below the lower thermocline was likely to be close to 0% saturation. Between the two thermoclines oxygen concentrations gradually decreased with increasing depth and the water column was about 70% saturated at 18 m.

The initial mixing of dye in the Hamurana Stream demonstrated that the cold water refuge habitat occupied essentially the same area and position on the shallow shelf as in the 2005 study. From this we concluded that the size of the cold water refuge habitat for trout was unlikely to change substantially over the summer period.

The ribbon of dye followed the same general path as was determined from temperature data in 2005. When overlaid, the centre of the Hamurana Stream plume was in essentially the same location as found in 2005. The rate of dilution of the dye in the plume matched the rate of warming previously found in the temperature study but the dye allowed the stream water plume to be tracked further than was possible by temperature. The change in dye concentration along the centre of the plume indicated that entrainment of ambient lake water into the plume reduced the stream water component to <1% after the density current had flowed down the incline of the drop-off, where it had still not reached the lake thermocline. Assuming the estimated flow velocity of  $6.5 \text{ cm s}^{-1}$  was maintained and not reduced by further entrainment of ambient lake water into the density current, a parcel of stream water would take about 6 hours to reach the upper thermocline and about 14 hours to reach the lower thermocline.

The density current just past the drop-off was >99% ambient lake water and the temperature differential relative to ambient lake water due to the Hamurana Stream water was estimated to be about  $0.05^\circ\text{C}$ . As this was substantially less than the temperature differential of  $0.25^\circ\text{C}$  across the upper thermocline, the density current was unlikely to have sufficient negative buoyancy or inertia to penetrate the thermocline. Consequently, we concluded that the Hamurana Stream water would have minimal interaction with the thermocline or with the biogeochemistry below the thermocline.

Based on these conclusions the 2<sup>nd</sup> and 3<sup>rd</sup> dye studies were not done.

## 1. Introduction

With the need to provide a short term solution to the problem of deteriorating water quality in Lake Rotorua, the diversion of the Hamurana Stream directly to the Ohau Channel outlet from the lake is being investigated. This diversion would reduce the nutrient inputs to the lake by 54.6 t y<sup>-1</sup> (12.3%) of the total nitrogen and 6.4 t y<sup>-1</sup> (18.5%) of the total phosphorus. However, while this diversion would result in a major reduction in nutrients, it could also remove any beneficial effects of the cold, well oxygenated Hamurana Stream water on the biogeochemistry of the lake sediments during periods of thermal stratification in summer and thus exacerbate nutrient release from those sediments. The diversion could also adversely affect the trout fishery at the northern end of Lake Rotorua by removing the summer cold-water refuge habitat at the Hamurana Stream mouth.

The impact on the fishery was investigated by mapping the size of the cold water refuge habitat by temperature (Rowe et al. 2005) and the use of that refuge habitat by trout was considered in that report and a subsequent tagging report (Boubeé et al. 2006). It was found that the cold Hamurana Stream water formed a cold, negatively buoyant, density current which travelled along the lake bed out into the lake. Aspects of the potential impact of this density current on the biogeochemistry were also considered (Rowe et al. 2005) but a ‘proof-of-concept’ study was required to determine whether Hamurana Stream water influenced oxygen concentrations and thus the chemistry in the hypolimnion of Lake Rotorua.

Environment Bay of Plenty commissioned NIWA to determine (1) the extent of the plume off-shore and any interaction with the thermocline during a period of thermal stratification and (2) whether the size of the cold water refuge habitat changed substantially over the summer period.

### 1.1 Background

The importance of the period of thermal stratification is that thermal stratification isolates the upper water column (epilimnion) from the bottom water (hypolimnion) and the boundary between (thermocline) limits the transfer of dissolved oxygen (DO) from the epilimnion to the hypolimnion. In Lake Rotorua the sediments are essentially anoxic to within a few mm from the sediment surface. The oxygen consumed by decomposition processes in the sediment in the hypolimnion exceeds the supply of oxygen diffusing through the thermocline, and the water in the hypolimnion becomes oxygen depleted and eventually anoxic. Under anoxic conditions the biogeochemical

processes associated with nitrogen and phosphorus mineralisation become disrupted as the hypolimnion develops reducing conditions i.e.:-

- For phosphorus, as the oxygen levels fall below  $2 \text{ g m}^{-3}$  ferric iron, which is insoluble, reduces to ferrous iron, which is soluble, and any phosphate bound to the ferric iron is released into the water column as dissolved reactive phosphorus (DRP). A similar effect occurs with manganese at an oxygen threshold of about  $5 \text{ g m}^{-3}$ .
- For nitrogen, mineralisation of organic matter releases ammoniacal nitrogen ( $\text{NH}_4\text{-N}$ ) at the sediment-water interface. Under aerobic conditions,  $\text{NH}_4\text{-N}$  is oxidised to nitrate by nitrifying bacteria and if the nitrate remains in contact with the anoxic sediments it is converted to nitrogen gas ( $\text{N}_2$ ) by denitrifying bacteria and thus some of the inorganic nitrogen is removed from the system. When the hypolimnion becomes anoxic, the nitrification - denitrification process stops and all of the nitrogen released by mineralisation accumulates in the hypolimnion. This change gives the appearance of an accelerated release of  $\text{NH}_4\text{-N}$  from the sediments when anoxia occurs.

Later, when the thermal stratification is destroyed by wind-induced mixing, the accumulated nutrients are dispersed into the upper water column where they can stimulate rapid algal growth which may reach bloom proportions. If the density current was supplying oxygen to the hypolimnion, this oxygen would be slowing the rate of hypolimnetic oxygen depletion and thus reducing the period of no denitrification and accelerated nutrient accumulation in the hypolimnion.

## 1.2 Concerns

The diversion of the Hamurana Stream to the Ohau Channel will remove  $54.6 \text{ t N y}^{-1}$  and  $6.4 \text{ t P y}^{-1}$  from the lake. Without the diversion these annual loads will continue to enter the lake. However, if hypolimnetic re-oxygenation via the density current is substantial, the benefits obtained from the diversion might be outweighed by the increased nutrient load released from the sediments due to the loss of the re-oxygenation under stratified conditions. Objective (1) of this study addresses that concern. Under mixed conditions the concern does not exist as the sediments would be in contact with well oxygenated ambient lake water.

There are two critical factors for reoxygenation of the hypolimnion to occur. These are:-

- 1) The velocity of the density current. This needs to be sufficient to overcome lake mixing currents and establish an inertial flow through the lake. Otherwise the inflow will simply mix into the upper water column without reaching the thermocline.
- 2) The temperature of the density current when it reaches the thermocline. A density current has a buoyancy which is induced by the temperature of the inflow relative to the lake. With a colder inflow the buoyancy is negative and the density current sinks to the lake bed. As the density current flows along the lake bed it entrains ambient lake water into the flow increasing the volume of the flow but decreasing the velocity. It also warms as the entrained lake water is mixed into the flow but will remain on the lake bed while it is still colder, and thus more dense, than the ambient lake water. When the density current reaches a depth where it is just warmer than the ambient lake water, it becomes positively buoyant relative to the ambient lake water and will lift off the bottom as an intrusion layer into the lake at that depth. Consequently, for the density current to penetrate the thermocline it must be colder than the water below the thermocline. Otherwise it will flow across the top of the thermocline as an intrusion layer without penetrating, despite any hydraulic inertia the flow might have.

This study allowed for the use of a tracer dye to follow the Hamurana Stream water on three occasions when Lake Rotorua was thermally stratified in summer. However, after the first dye tracer experiment, it was concluded that Hamurana Stream water was unlikely to reach the thermocline with sufficient temperature differential to penetrate it, and that the cold water refuge habitat was unlikely to change substantially over summer. Consequently, the 2<sup>nd</sup> and 3<sup>rd</sup> dye tracer experiments were not run.

This report presents the results of the first dye tracer experiment and the reasoning which lead to the above conclusions.

## 2. Methods

The size of the cold water plume from the Hamurana Stream and its general flow direction after initial mixing in Lake Rotorua has been determined from temperature studies in summer 2005 (Rowe et al. 2005). That study showed that the cold stream water entrained about an equal volume of ambient lake water on entering the lake (~50% dilution) and tended to pool on the shallow shelf adjacent to the stream mouth before plunging as a cold density current and flowing down the lake bed towards the open lake. While this flow direction and velocity ( $\sim 10 \text{ cm s}^{-1}$ ) indicated that the stream water could potentially reach the thermocline and be a transport mechanism for oxygen as well as other nutrients, the temperature study was not able to confirm the fate of that water.

On 1 March 2007, the cold stream water was marked with low concentration Rhodamine WT, a pink water tracing dye, and the path of the dye was followed using Rhodamine fluorescence sensors. The dye was a 10% solution of stock Rhodamine WT which was injected into the stream flow at the bottom via a narrow bore hard nylon tube, using a constant flow metering pump.

Initially the dye was injected for 10 minutes into the Hamurana Stream just upstream of the mouth (Fig. 1A) where it rapidly mixed and dispersed throughout the cold water trout refuge defined by the temperature study (Rowe et al. 2005). This confirmed that the cold Hamurana Stream water tended to pool on the shallow shelf zone (Fig.1B) before flowing out into the lake as a density current along the lake bed.

To follow the main stream flow, the dye injection point was moved to a position 20 m out in the lake, in the centre of the Hamurana Stream mouth (Fig. 2), and 20-litres was injected over a period of about 1 hour. Dye injected at this point produced a continuous ribbon of dye without substantial lateral dispersion.

The concentration along the dye plume was measured using calibrated Rhodamine WT fluorescence sensors. The starting concentration in the dye plume was around  $40 \text{ mg m}^{-3}$  after the initial dilution. The dye was followed until the concentration in the centre of the dye plume was below confidence level of  $0.5 \text{ mg m}^{-3}$  — the dye was still measurable to  $0.1 \text{ mg m}^{-3}$ . Dye tracking was achieved by profiling using a combination of the profiler used for the original temperature study – a Richard Brancker Research XR420f CTD with chlorophyll fluorescence and dissolved oxygen sensors – and a Sea Point Rhodamine sensor connected to a data logger with direct readout. A Hydrolab data-sonde fitted with a YSI Rhodamine fluorescence sensor was used for deeper profiles and for bottom transects across the dye plume and along its length from shore after the confidence limit had been reached on the Sea Point sensor.



**Figure 1:** A) Dye injection in the Hamurana Stream, B) Dispersion and pooling of the dye in the cold water trout refuge zone on the shallow shelf.



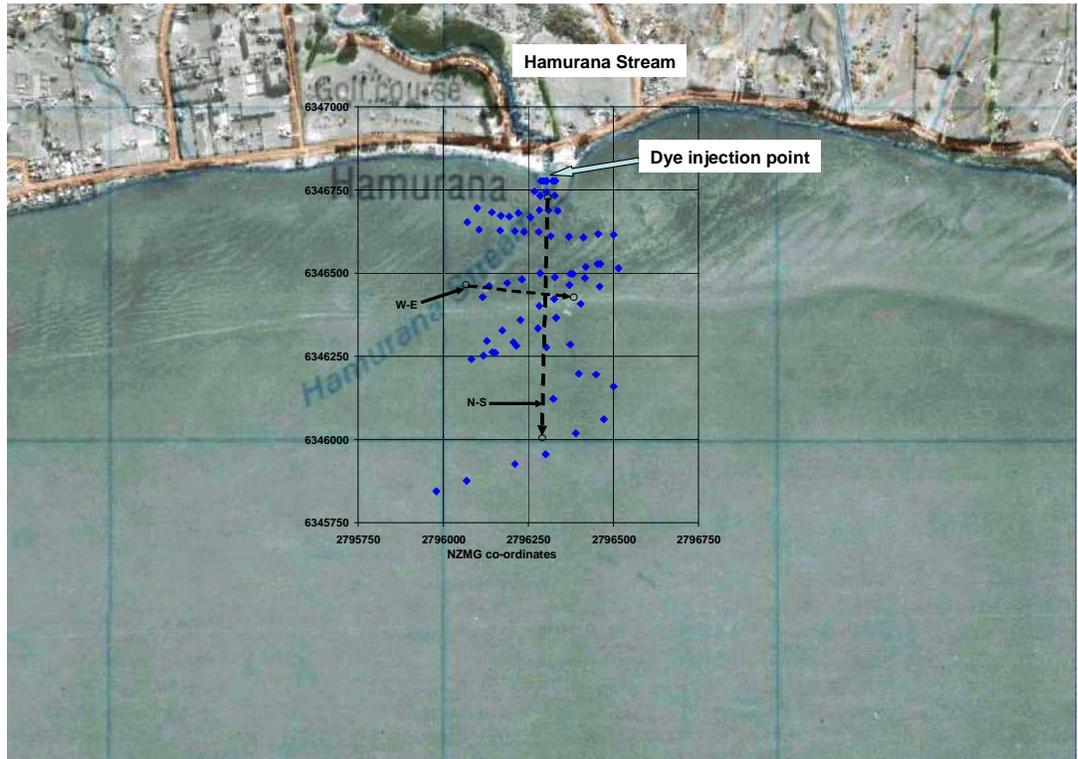
**Figure 2:** Dye injection showing the dye movement as a thin ribbon from the injection point A) looking from shore and B) looking back towards the shore.

Each profiling position was recorded using GPS in WGS84 mode and the latitude and longitudes converted to New Zealand Map Grid (NZMG) coordinates for plotting. The start and end positions of the Hydrolab bottom transects were recorded and relative position was estimated from time of travel between these points assuming a constant boat speed.

The depth of the thermal stratification in Lake Rotorua was determined from a vertical profile with the RBR XR420 and the Hydrolab data-sonde to a depth of 20 m. This profile was taken about 3.5 km off-shore in order to find the appropriate water depth. The position of this profile was also recorded.

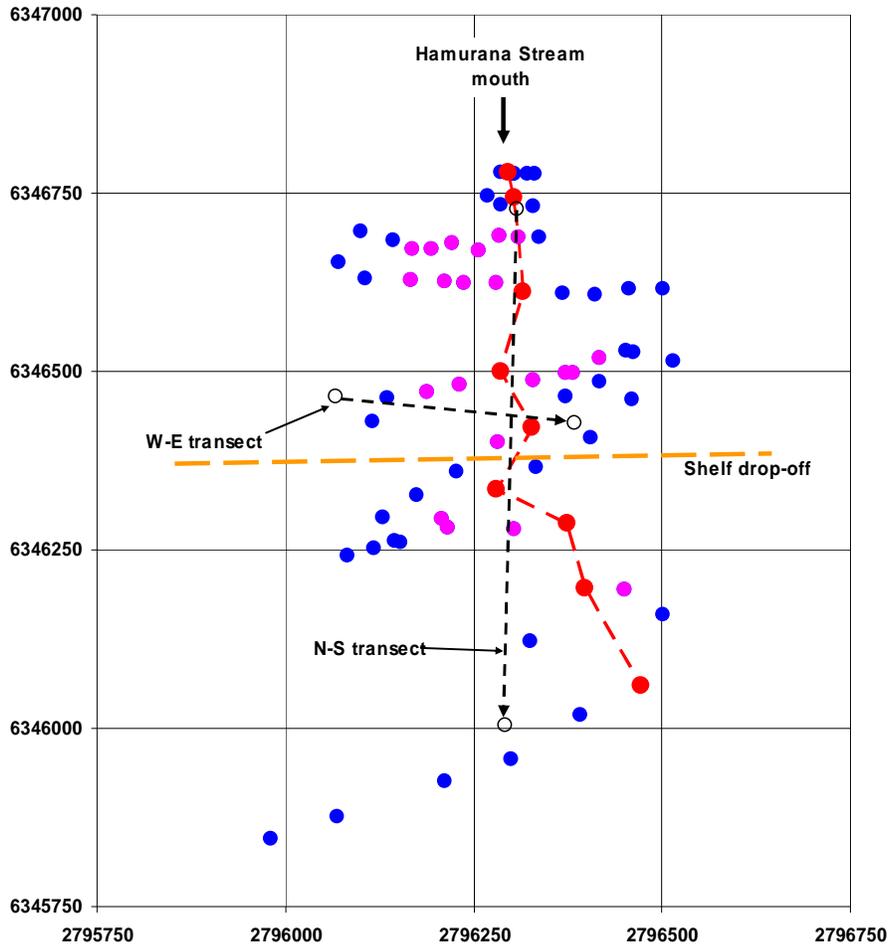
### 3. Results

All positions, except the deep profile, were overlaid on an aerial photo of the Hamurana foreshore where the shallow shelf was visible (Fig. 3).



**Figure 3:** Profiling positions [blue diamonds] and transect lines from the dye tracing on 1 March 2007. Base map U15 1:50,000 with aerial photo at 2.5m by Map Toaster.

Transects were taken across the dye plume from clear water to clear water. The highest concentration of dye measured on each transect was taken as being the centre of the dye plume (Fig. 4).

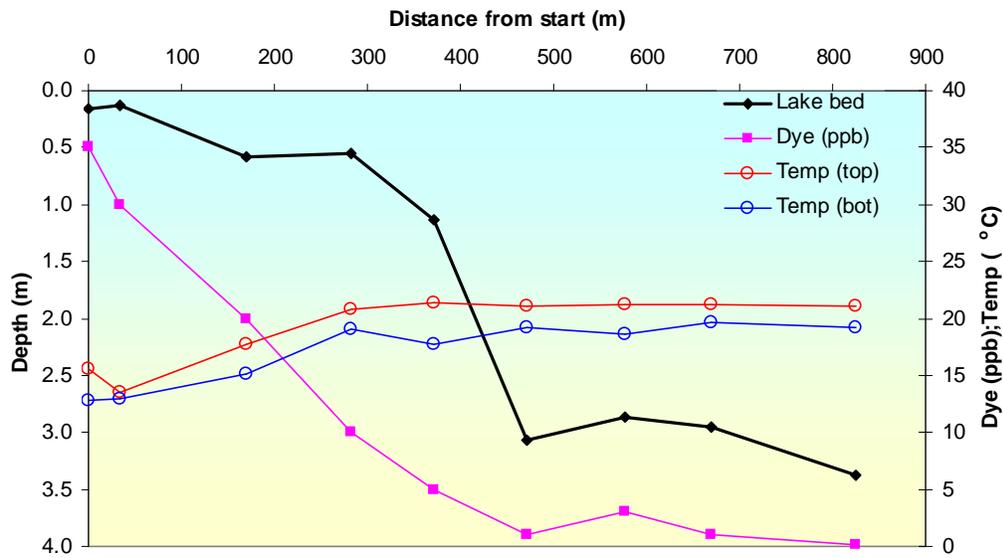


**Figure 4:** Profile points colour coded to show where dye was found. Blue spots had no dye. Pink spots had dye above detection limits ( $0.1 \text{ mg m}^{-3}$ ). Red spots indicate the highest relative dye concentration and the red broken line indicates the centre of the dye plume. Bottom transect lines are indicated in black. Orange broken line indicates the position of the shelf drop-off into deeper water. (Grid scale = 250m, NZMG).

Dye concentrations decreased rapidly downstream from the injection point as the cold water density current flowed across the shallow shelf and down the steep slope into deeper water (Fig.5). The dye concentration was  $20 \text{ mg m}^{-3}$  at the mid point across the shallow shelf i.e., a reduction of 50%, and was  $<0.3 \text{ mg m}^{-3}$  by the time the plume reached the bottom of the shelf drop-off. The reduction in dye concentration was

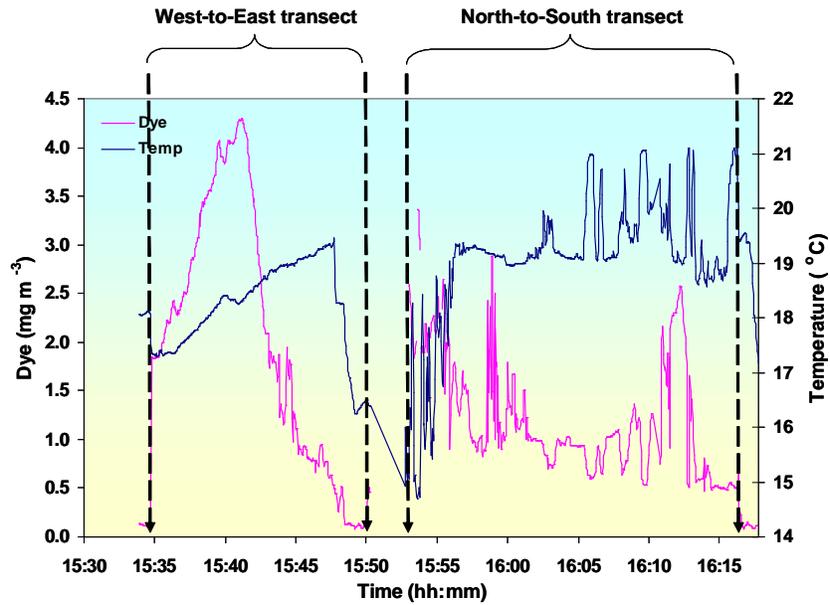
presumably due to entrainment of ambient lake water into the plume as it moved out into the lake. This was more than a 100 fold reduction in dye concentration indicating that there was less than 1% Hamurana Stream water in the density current at this point.

Based on the Hamurana Stream water temperature of 12.6°C and the ambient lake temperature above the lake bed of 20.15°C, the degree of entrainment indicated by the dye data would result in the density current having a temperature around 0.05°C cooler than the ambient lake water impinging on the lake bed at a distance of 1 km from shore.

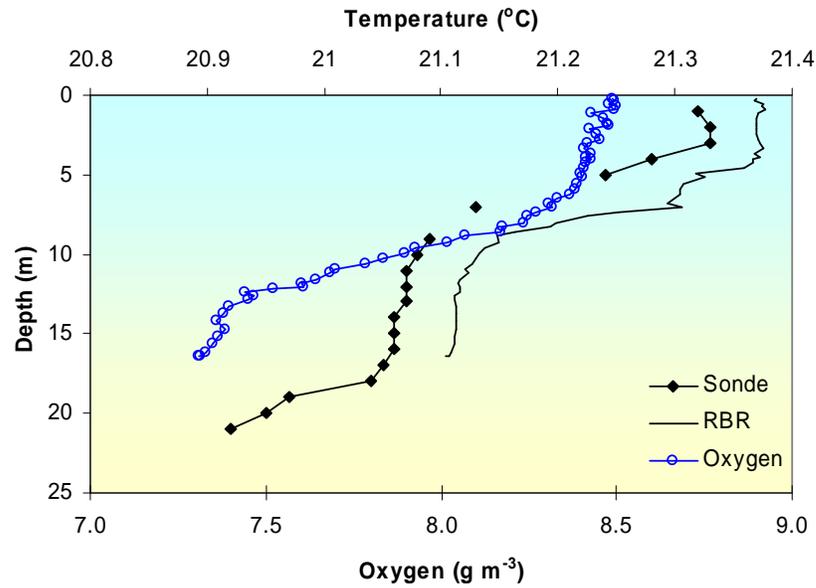


**Figure 5:** Transect data for dye (pink line), temperature (red and blue lines), and water depth (black line) relative to distance from the dye injection point 20 m from the Hamurana Stream Mouth.

The temperature difference between surface and bottom water across the shelf (Fig. 5) was consistent inside and outside the Hamurana Stream plume indicating that this was a function of the thermal structure of the lake on the day rather than being caused by the density current. The bottom water transect data (Fig. 6) showed that the dye was confined to a thin layer on the lake bed. The combination of temperature and dye data show that where the Rhodamine probe was on the lake the temperature was cold but when the probe was lifted a few cm, the data show a sudden drop in dye concentration and an increase in temperature consistent with the probe being above the colder density current on the lake bed.



**Figure 6:** Bottom dye and temperature at the lake bed along a West-to-East and a North-to-South transect through the dye plume 3 hours after the dye injection. Noise in the dye signal due to bottom contact by the Rhodamine sensor has been removed for clarity.



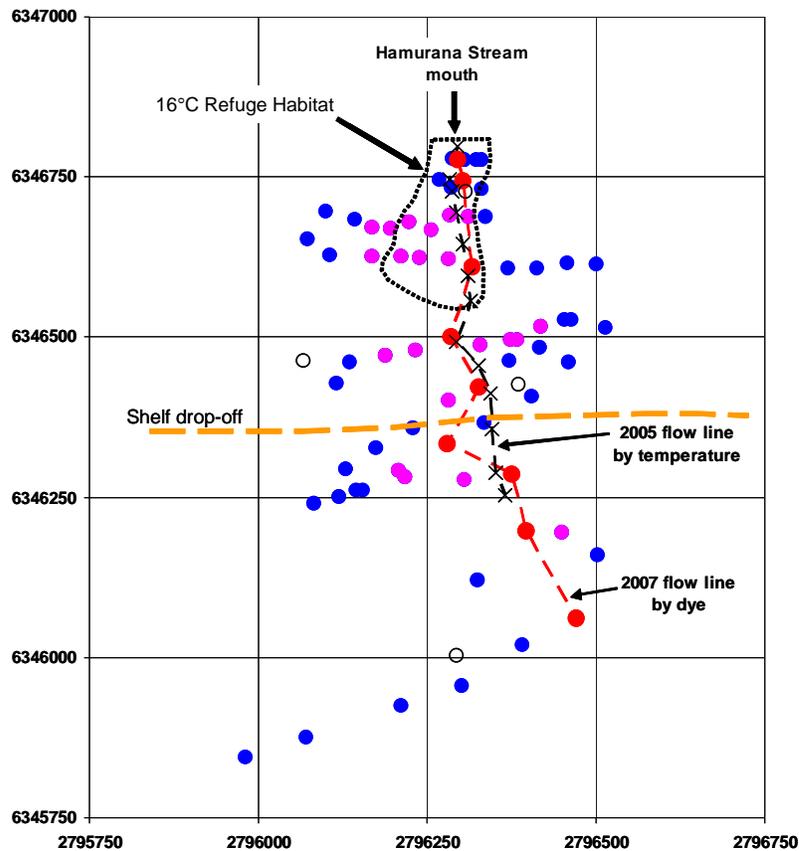
**Figure 7:** Temperature structure of Lake Rotorua to 21m about 3.5 km from shore. The sonde temperature data are off-set by  $-0.05^{\circ}\text{C}$  for clarity.

The temperature profile of Lake Rotorua showed that there was a small temperature gradient of 0.25°C between 5 and 10 m and another similar temperature gradient from below 18 m (Fig. 7). This dual thermocline is a natural feature of Lake Rotorua water column structure in summer, as is oxygen depletion beginning below the upper thermocline (D. Hamilton, UoW, pers. comm.).

The oxygen data obtained with the temperature profile (Fig. 7) indicates that, although oxygen depletion might be expected below the upper thermocline, on this occasion that oxygen depletion was relatively minimal and oxygen concentration had only reduced to around 7.2 g m<sup>-3</sup> at the depth of the second thermocline. Oxygen depletion would be expected to be greater below the deeper thermocline but was not measured on this occasion.

## 4. Discussion

The dye tracer data produced Hamurana Stream water dispersion patterns on the shallow shelf remarkably similar to patterns estimated by the temperature study in March 2005 (Rowe et al. 2005). The dye pooled on the shallows with the high concentrations almost exactly matching the zone of the cold refuge habitat defined by the 16°C contour boundary in 2005 (Fig. 8). The refuge habitat for trout was defined as that zone where the water temperature was <16°C at 20 cm above the lake bed. These data overlaid on the bottom water temperature contour plot (Fig. 9) from the 2005 study show the remarkable similarity between the results of these two studies.

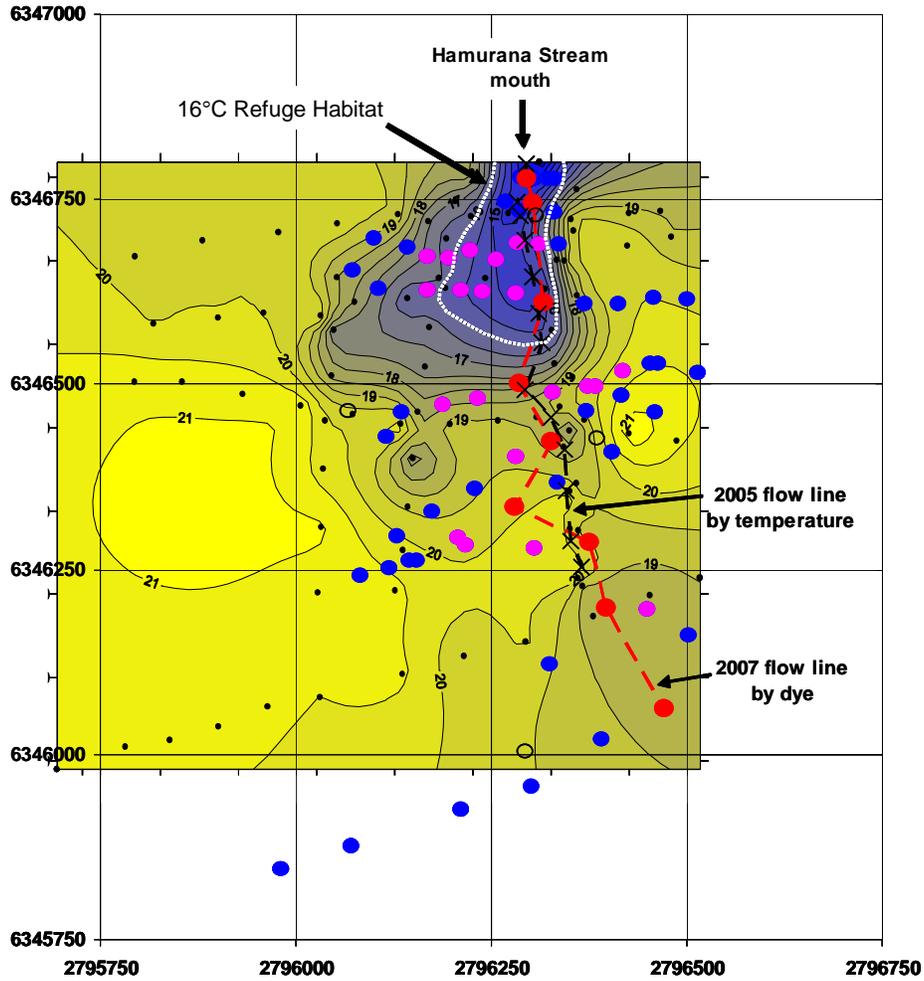


**Figure 8:** Comparison of the dye dispersion patterns and flow path in March 2007 with the cold water dispersion patterns obtained during a temperature study in 2005. The refuge habitat zone identified in 2005 is outlined with a black dotted line. The centre of the dye flow path is marked with red dots and a red broken line compared with the flow path based on temperature in 2005 which is marked with black crosses and a black broken line. Black circles mark the ends of the bottom transect lines for the sonde.

The flow path defined from the dye concentrations is also essentially the same as the flow path defined from the temperature study in 2005 (Fig. 8). Slight differences observed may be due to the resolution of the data and small changes in lake bed morphology in the intervening 2-year period.

Overall, these data indicate that the hydrodynamics associated with the cold water inflow from the Hamurana Stream are relatively constant and that there are unlikely to be major changes in the refuge habitat zone or the flow paths under calm conditions. Under on-shore windy conditions, the cold water from the Hamurana Stream is likely to be rapidly mixed into the lake and dispersed before a cold density current can become established. Consequently, under windy conditions there is unlikely to be a density current moving off the shallow shelf into the deeper waters of the lake.

This dye study has also demonstrated that, under calm conditions in summer when there is a possibility of thermal stratification in Lake Rotorua, the amount of ambient lake water entrained into the density current is so large that the density current effectively becomes moving lake water. Notwithstanding this, the estimated flow velocity of about  $6.5 \text{ cm s}^{-1}$  is more than double the ambient lake circulation currents (Rowe et al. 2005) and thus sufficient to allow the density current to reach the upper thermocline in about 6.5 hours. However, assuming no further entrainment or warming occurred after the density current flowed down the drop-off, the estimated temperature difference of around  $0.05^\circ\text{C}$  less than ambient lake water above the upper thermocline is substantially less than the temperature difference of around  $0.25^\circ\text{C}$  across the upper thermocline. Consequently, the density current will be approximately  $0.2^\circ\text{C}$  warmer and thus more buoyant than the water below the thermocline and is unlikely to penetrate through the thermocline.



**Figure 9:** Data from Figure 8 overlaid on the bottom water temperature contour plot from March 2005 (Rowe et al. 2005) show the similarity between the dye and temperature study results even though they were collected 2 years apart. Base contour plot colours are blue for cold, yellow for warm with a linear colour gradient between the stream temperature of 12.6°C and the surface lake temperature of 21°C. (Grid scale = 250m, NZMG).

## 5. Conclusions

From the data collected in the first dye experiment under conditions of thermal stratification after prolonged calm weather at the hottest period of summer, we conclude that:-

- (1) the extent of the Hamurana Stream plume off-shore was confined to the lake bed above 5 m at which depth the temperature induced density current should lift off the lake bed and become an intrusion layer on top of the upper thermocline. Because of the large amount of entrainment of ambient lake water into the plume and thus substantial warming to within 0.05°C of ambient bottom water temperatures, the density current is unlikely to penetrate the thermocline and thus provide a source of oxygen to the hypolimnion during a period of thermal stratification;
- (2) the size of the cold water refuge habitat under calm conditions was unlikely to change substantially over the summer period.

Consequently, there was no need to conduct the 2<sup>nd</sup> and 3<sup>rd</sup> dye experiments.

## 6. References

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## 7. Acknowledgements

We thank Todd Baldwin for assistance in the field and Dr Bob Spigel for discussions on the buoyancy and inertia of the density current and its ability to penetrate the upper thermocline in Lake Rotorua.