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Further Investigation of Direct Groundwater Seepage to Lake Taupo

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Executive Summary

Environment Waikato commissioned NIWA to undertake further investigations of direct groundwater seepage into Lake Taupo through Whangamata Bay and Whakaipo Bay. This investigation is a follow-up study to a masters degree study by Ross Hector in 2004. The original water balance by Hector indicated that shallow groundwater accounted for only about 5% of the residual water input to these catchments after allowing for stream flow and evaporation. The suggestion was that the remaining groundwater was entering the lake as deep seepages or springs.

This study found that there were areas of deep groundwater inflow within the depth range of 2 m to 6.5 m and that these were as diffuse seepages rather than discrete springs. The size of seepage areas varied on a range of scales. Small patches (cm^2) of seepage were dotted over larger areas (m^2) which were found in zones that covered several hectares of lake bed. Inshore and further offshore from these there were no apparent seepages. Flow estimations indicate deep groundwater inflows totalled about 0.46 m^3 s^{-1} in Whangamata Bay and about 0.24 m^3 s^{-1} in Whakaipo Bay. These inflow estimates have potentially large errors due to the variability of seepage within the groundwater zones and the degree of bay-wide extrapolation, but indicate that almost all of the groundwater unaccounted for in the Hector water balance can be attributed to direct deep groundwater seepage.

It was found that the groundwater inflow was colder than the overlying lake water and thus flowed as a thin layer down the slope of the lake bed, or pooled in depressions. The nutrients in the deep groundwater were being utilised by benthic algae and the lake bed in the areas of inflow was covered with thick algal mats. Nutrient uptake by benthic algae effectively removed a substantial proportion of the dissolved reactive phosphorus and dissolved inorganic nitrogen from the deep groundwater inflows. Because of the temperature-induced density effect initially holding the deep groundwater seepage close to the lake bed and hence protecting it from wave-induced mixing, a high level of nutrient uptake is considered likely throughout the year. However, as this study was conducted in late summer, it is uncertain what the seasonal effects will be on the level of nutrient uptake by the benthic algal mats, especially in winter. If seasonal effects are minimal, the deep groundwater inflow is unlikely to constitute a major direct nutrient source to the lake water column. However, while the nutrient load entering the lake via the deep groundwater is not immediately available to support phytoplankton growth in the lake water column, they will eventually be recycled from the sediments after the algae decay. Other in-lake processes will then determine their fate.

1. Introduction

In a recent University of Waikato Masters thesis, Hector (2004) produced estimates of direct groundwater and nutrient seepage into Lake Taupo through the near-shore sediments to a depth of 1 m in Whakaipo and Whangamata Bays, on the northern shores of Lake Taupo. In the conclusions to his thesis, Hector (2004) notes that

> "*Water budget estimates for Whangamata and Whakaipo Bays catchments indicate that streamflow accounts for 19% of effective rainfall. Direct seepage of groundwater to the lake accounts for only 5% of the non-streamflow residual discharge in the Whangamata and Whakaipo catchments respectively. It is therefore highly likely that the shallow groundwater measured using seepage samplers is not the only source of groundwater entering Lake Taupo from these catchments*."

The water budget provided (Hector 2004) indicates that the total residual groundwater inflow for Whangamata Bay should be 0.846 $m^3 s^{-1}$ of which only 0.051 $m^3 s^{-1}$ was accounted for by the seepage samples along the lake edge. For Whakaipo Bay the total residual groundwater inflow should be 0.328 $m^3 s^{-1}$ of which only 0.021 $m^3 s^{-1}$ was accounted for by the seepage samples along the lake edge.

Hector (2004) also indicated that there were apparent losses of inorganic nitrogen from the groundwater as it moved through the sediment-water interface, although the magnitude of that loss was uncertain.

As a consequence of the water budget presented in this thesis, Environment Waikato commissioned NIWA to determine:

- whether there were other sources of groundwater in these bays, specifically deep seepages or springs, beyond the depth range investigated by Hector (2004);
- an estimate of the hydraulic inflows for each bay;
- an estimate of nutrient mass transport budgets extrapolated according to the hydraulic budgets; and
- the significance of findings for nutrient mass balance estimation and management.

The expectation within the budget provided, was to provide "best estimates" rather than fully quantitative assessments with statistical estimates of error. We note that, as the study was conducted in late summer only, seasonal effects may influence the reliability of extrapolating the results over a whole year. For instance, the temperature difference between groundwater and inshore lake water is not known and that will have implications for the findings in this study.

2. Methods

Groundwater is known to be cooler than near-shore lake water in summer with temperatures of around 12ºC and 20ºC, respectively. However, while slow moving groundwater seepage is likely to warm up towards the overlying lake water temperatures as it approaches the sediment surface, it was considered unlikely that it would reach lake temperature. The faster the flow, the less warming is possible and the colder the inflowing groundwater will be as it enters the lake. Consequently, the survey rationale used was to find potential groundwater inflows by temperature difference. In practice, this was achieved by divers feeling for small temperature differences at the sediment surface with their fingers.

2.1 Whangamata Bay (5 April 2005)

An initial survey was made at the eastern end of Whangamata Bay by divers swimming transects slowly across the bed of the lake parallel to the shore and at right angles to the shore to a maximum depth of 10 m (Block 1, Fig.1). The initial swim phase was replaced with a diver being towed slowly in similar transect patterns by boat to cover a larger area of lake bed (all blocks). On detecting any temperature change, the diver released the tow and conducted a more detailed investigation, including use of a temperature probe inserted into the sediments.

As more cooler water zones were found, visual cues were correlated with the areas of apparent groundwater inflow enabling a larger survey area to be covered by the divers. In this way the whole inshore lake bed adjacent to the foreshore beach from about 1m depth out to a depth of up to 10 m was surveyed in Whangamata Bay (Fig. 1).

The exception was the length of lake bed adjacent to the Kinloch Marina between the marina entrance and the back-flush pump discharge pipe to the east. It was considered that the marina would intercept any groundwater in this area. Discrete springs and groundwater seeps were observed entering the marina during it's construction and some of these can still be seen (personal observations).

Block 3 (Fig. 1) had more consistent cooler interstitial water and was chosen as the area for more detailed study including the installation of benthic flux chambers.

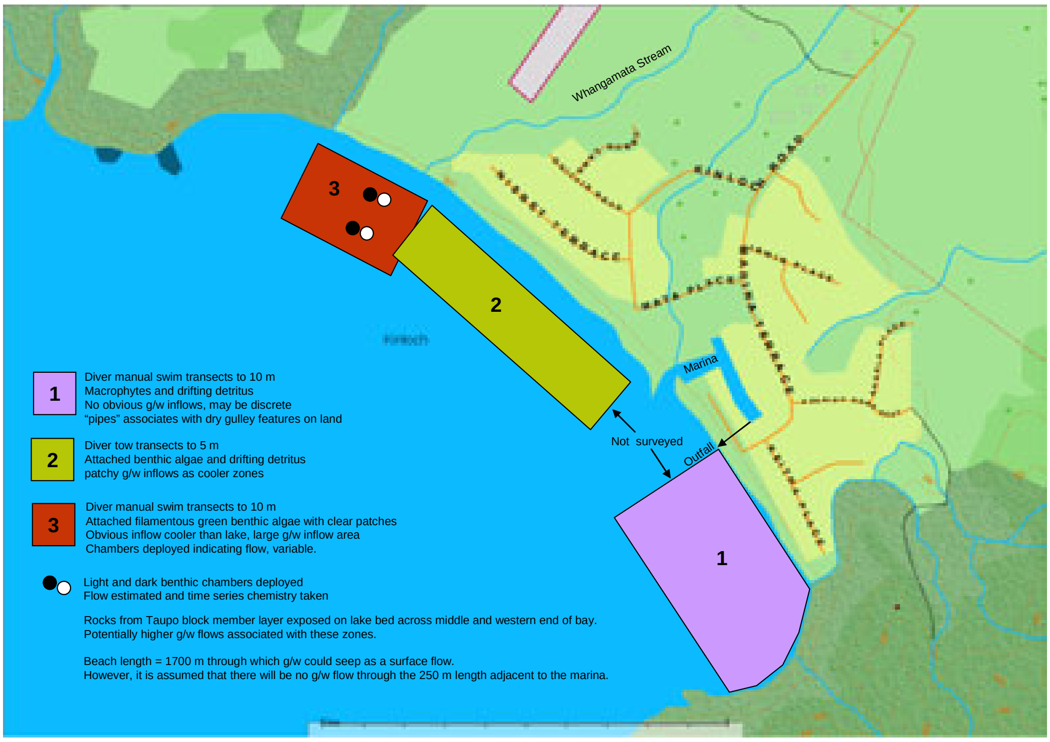

Figure 1: Site map of Whangamata Bay showing the 3 main areas covered by the survey and the locations of the benthic flux chamber deployments. Apart from the Whangamata Stream, the indicated water courses were dry.

2.2 Whakaipo Bay (6 April 2005)

A similar procedure was used for surveying Whakaipo Bay. In this bay the initial diver swim offshore determined that cooler interstitial water associated with potential groundwater inflows did not extend below a depth of around 6m. Consequently, towed diver surveys concentrated on the lake bed between depths of 1 to 6 m across the full width of the bay (Fig. 2). Again, correlation of visual cues with apparent groundwater inflows, as indicated by temperature difference, enabled an extensive survey of the lake bed. Benthic flux chambers were installed at two locations where groundwater inflows were likely.

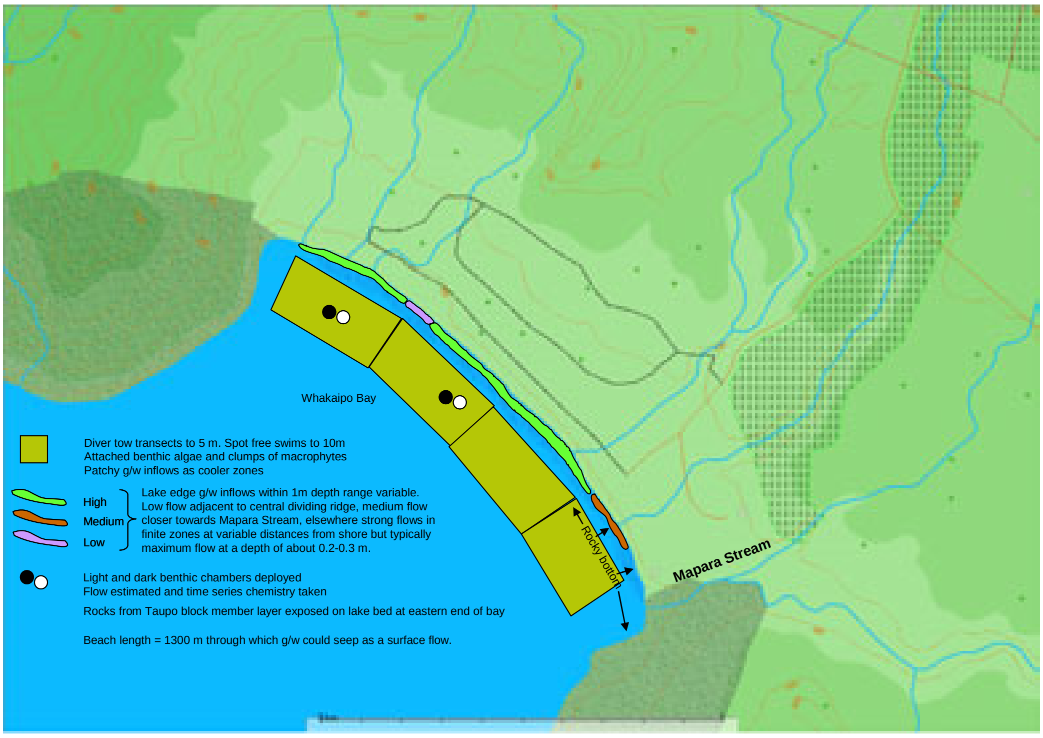

Figure 2: Site map of Whakaipo Bay showing the extent of the diver survey and location of benthic flux chamber deployments. Estimates of lake edge inflow zones are also indicated (see text). Apart from the Mapara Stream, the indicated water courses were dry.

2.3 Groundwater flow estimation

A benthic flux chamber consisted of a 0.5 x 0.5 m square aluminium frame with a clear plastic dome lid sealed via a soft rubber gasket to a flange on the frame and held in place with tight elastic bungis. Dark chambers, simulating night conditions, were covered with heavy duty black plastic sheeting taped to the dome to exclude light.

The assembled flux chamber was pressed into the sediment by divers to the mid-point of the frame. An open vent on the top of the chamber allowed escape of gas bubbles and pressure equalisation during the installation process. A flow measuring head was fitted to this vent to estimate the efflux of groundwater within the chamber. The flow measuring head consisted of a large bore plastic “T” tube inserted through a rubber gasket that completely sealed the chamber vent when fitted so that water displaced from the chamber by the groundwater efflux passed through the “T” tube stem. A plastic tap on each arm of the “T” tube controlled whether the displaced water escaped to the open lake or was diverted into a soft latex collecting balloon (condom). Flow was estimated from the volume of water collected in the collecting balloon in unit time, and the area of sediment enclosed by the chamber (0.25 m^2).

In addition to the flow measuring head, a sensitive recording temperature sensor (resolution 0.001 ºC) was included inside each benthic flux chamber to record the rate of change of temperature and thus provide an alternative estimate of inflow. Flow was estimated using the model equation (from Henry & Heinke 1989):

$$(c_t - c_0)/(c_{in} - c_0) = 1 - \exp(-t/T) \qquad \text{equation 1}$$

where t = time
c_t = temperature inside the chamber at time t
c_0 = temperature inside the chamber at time zero
c_{in} = temperature of the inflow
T = hydraulic residence time of the chamber
= chamber volume / groundwater inflow rate.

It was assumed that the chamber was fully mixed and that the inflowing groundwater displaced an equal volume of chamber water out of the vent or compensation water tube when the vent was closed. The equation has the properties that $c_t = c_0$ at $t = 0$ ($\exp(-t/T) = 1$), and $c_t = c_{in}$ at t = infinity i.e., c_t approaches c_{in} exponentially.

For chemical efflux measurements, the flow measuring head was closed. A stirrer system was not used in study as the expectation was for relatively rapid flushing by groundwater rather than the measurement of a diffusive flux. [Laboratory testing of the chambers with dye tracer has demonstrated that unstirred chambers reached equilibrium concentrations throughout within 10 minutes of dye release.]

For water sampling, a 3 mm-inside diameter hard nylon tube was connected to the chamber and the free end taken to the surface to enable repeat sampling of the chamber water without the use of divers. Sampling was achieved by drawing water from the chamber into a sample bottle in a collection trap under reduced pressure from a vacuum pump. The first volume of water greater than the volume of the sampling tube was discarded as the flushing water and sample bottle rinse. The next volume collected was retained as the sample. A short length of the 3 mm-ID tube was set into the chamber as a pressure equalisation tube to allow ambient lake water to enter the chamber as compensation water. A sample of near-bottom lake water was collected as representing the "compensation water" for correction of nutrient efflux data. A sample of groundwater was drawn into a 60 ml plastic syringe via a stainless steel probe inserted about 5-10 cm into the sediments beside the chamber.

All water samples were analysed for the soluble nutrients, ammoniacal nitrogen (NH_4-N), nitrate plus nitrite nitrogen (NO_3-N), and dissolved reactive phosphorus (DRP) on a Lachat flow injection analyser using NIWA standard methods.

2.4 Dye tracing and flow visualisation

Additional to the main objective of this study, at Whakaipo Bay, waiting time (for the flux chamber experiment) allowed the inflow of groundwater through the lake edge to be investigated in a number of places along the foreshore using a simple dye tracer technique. Small volumes (5 ml) of Rhodamine WT dye (5%) were injected 10cm below the sediment surface in lines out from shore to a depth of around 1m to assess differences in flow with depth. Dye was held in a flexible IV bag attached to an animal drench gun fitted with a 10 cm long stainless steel large bore needle. The drench gun was set to deliver 5 ml per squeeze allowing a precise and rapid inoculation of the area being studied.

The small amount of dye used quickly equilibrated with the groundwater temperature and was flushed from the sediment by the groundwater (Fig. 3), marking the flow path and magnitude of flow.

Figure 3: Dye-stained groundwater flowing from the lake bed above the point of injection.

3. Results

3.1 Whangamata Bay

3.1.1 Diver survey

The diver free swimming survey at the eastern end of Whangamata Bay found no obvious cold water inflows across the lake bed out to a depth of 10 m. This end of Whangamata Bay is adjacent to ephemeral stream channels on land and would be expected to have some level of groundwater inflow. However, as the lake bed consists of coarse sands, these may rapidly disperse a diffusive inflow or discrete springs may be very small making them difficult to detect. Temperature probing showed the groundwater at 150 mm below the sediment surface was not substantially cooler than the overlying lake water in this area (block 1, Fig. 1). The lake bed was also dotted with large clumps of aquatic macrophytes, mostly 1 m tall *Lagarosiphon major*. While such clumps have been associated with groundwater inflows in Acacia Bay, there was no indication of colder water within the clumps tested. Between the macrophyte clumps, the sands were lightly covered with patchy benthic algae and drifts of terrestrial detritus.

The diver tow transects across the centre of the bay (block 2, Fig. 1) found large areas with a thick coating of green benthic algae which formed a mat over much of the lake bed between 2 and 6.5 m depth. The interstitial water beneath these mats was colder (~3 ºC cooler) than lake water indicating a relatively uniform groundwater inflow. We observed random clear patches through the algal mat (Fig. 4) which were associated with soft sand from which the algal mat was easily disturbed. These were apparently linked to groundwater inflow areas and thus the patchy appearance through thick benthic algal mats was used as a visual cue for the rest of the survey.

As with the eastern end of the bay, the lake bed through the mid region of Whangamata Bay had large patches of drifting detritus (mostly terrestrial leaves), presumably material washed out of the Kinloch marina.

The diver tow transects across the western end of the bay (block 3, Fig. 1) found large areas of likely groundwater inflow. A free swimming survey confirmed the presence of cooler temperatures (up to 3 ºC cooler) in the interstitial water over much of this area, with a cut-off depth of around 6.5 m. Below that depth there were no measurable temperature differences to a depth of 10 m. Native aquatic plants, charophytes, covered much of the lake bed below 5 m to the drop off at about 8-10 m.

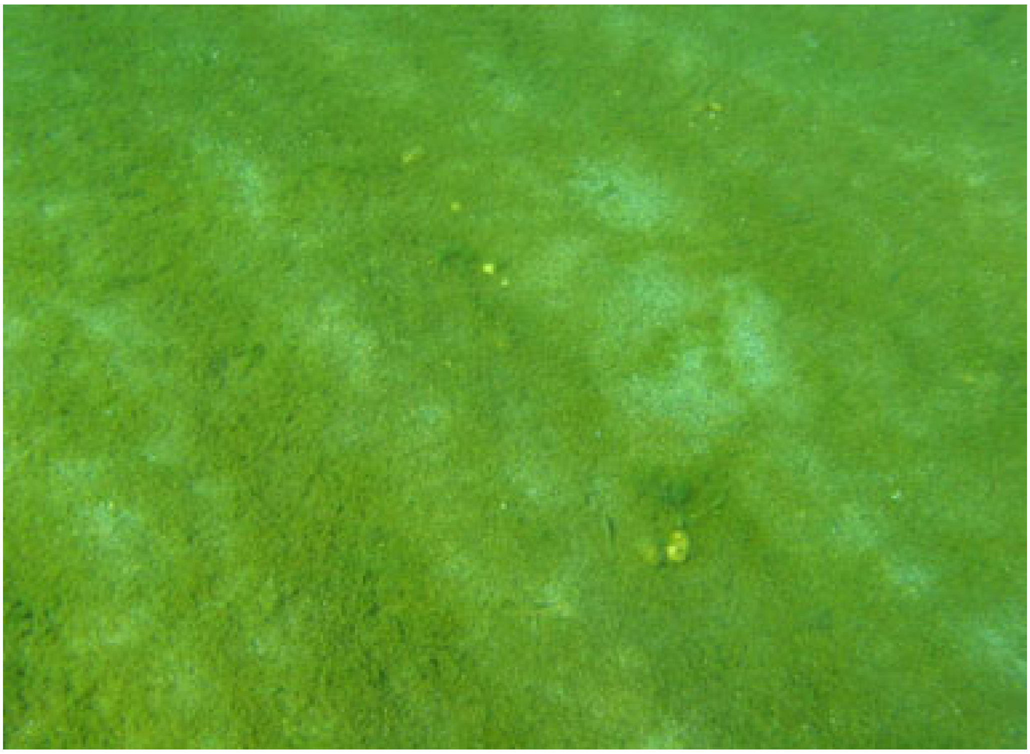

Figure 4: Thick benthic algal mats found across most of Whangamata Bay in the depth range from 2 to 6.5 m. Clear patches provided distinctive patterns in the algal mats where groundwater inflows were found. This lake bed appearance was used as the visual cue for likely groundwater inflows.

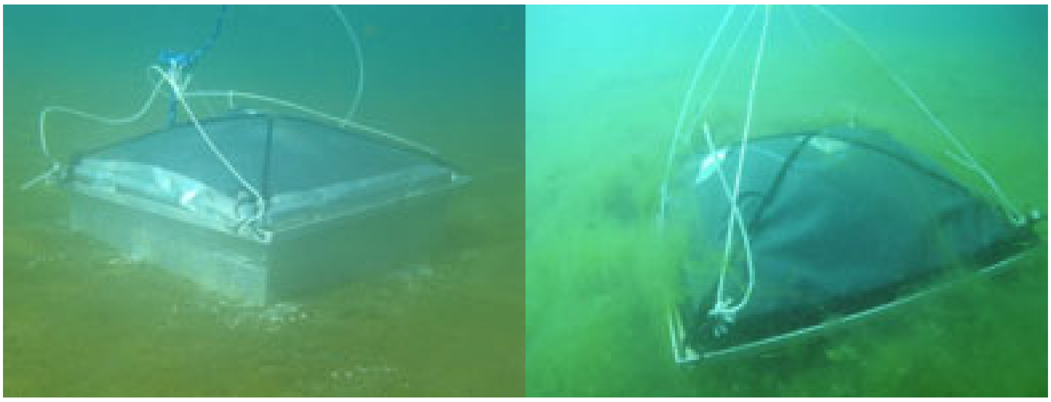

Figure 5: Benthic flux chambers (dark) installed in Whangamata Bay at (left) 3 m and (right) 6 m depths. Note the extensive growth of tall filamentous algae at the deep site not seen at the shallower site.

3.1.2 Groundwater flow estimation

Paired light and dark benthic chambers were deployed at 3 m and at 6 m to estimate flow rates (Fig. 5). The deeper site was covered with an extensive growth of tall filamentous algae not found at the shallower site. This was associated with the zone of cooler interstitial water on the shelf before the drop-off into deeper water beyond 8 m.

The flow measurement head confirmed groundwater inflow through the lake bed but the rate of inflow was variable, potentially up to 40 ml per chamber min^{-1}. There were difficulties sealing the measurement head to the chamber which could affect the flow estimation by this technique. In contrast, the change in water temperature inside each chamber was steady and consistent between pairs (Fig. 6) during the overnight deployment.

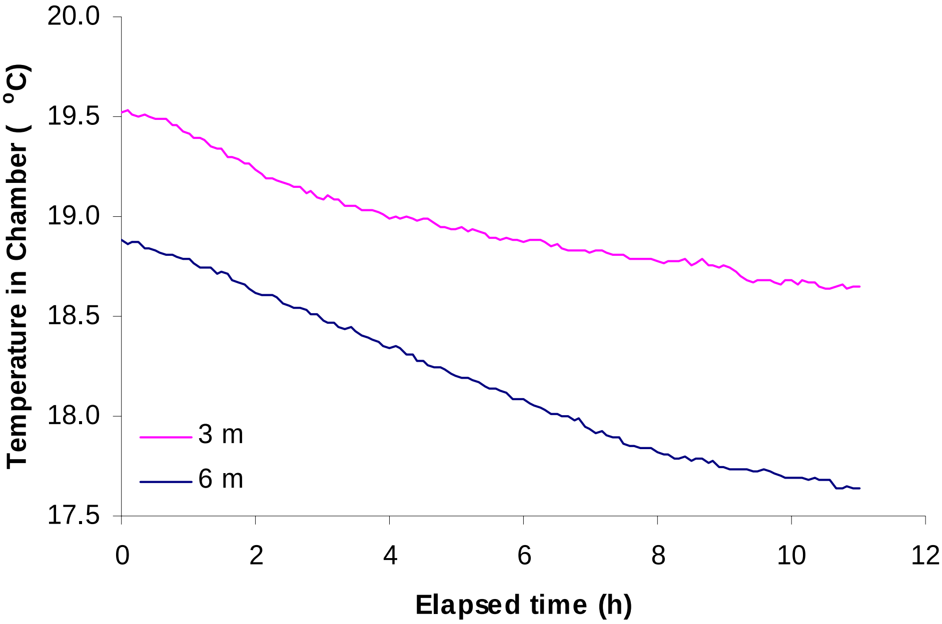

Figure 6: Temperature changes inside the benthic flux chambers at 3m and 6 m sites showing the cooling effect of the groundwater inflow. Cooler temperatures at the 6 m site may reflect the higher groundwater inflow. Groundwater inflow temperature was measured as 16.8 ºC.

Using the temperature modelling equation, the groundwater inflow estimates from both 3 m chambers were around 5.2 litres m^{-2} h^{-1} and from the 6 m chambers inflows were around 10 litres m^{-2} h^{-1}. Extrapolating these inflows for the area of block 3 (Fig.

1) and averaging between the 3 m and 6 m depth rate, gives a groundwater inflow of around 0.19 m^3 s^{-1} for this area.

If it is assumed that similar groundwater inflow occurs across the rest of the bay, excluding the lake bed adjacent to the Kinloch marina, then the total direct groundwater inflow through the lake bed along the whole foreshore could be in the order of 0.78 m^3s^{-1}. Combined with the 0.051 m^3 s^{-1} estimated for the edge water (Hector 2004), this would give a total groundwater inflow of around 0.83 m^3 s^{-1} which represents 98% of the expected groundwater inflow. This is clearly an overestimate because it ignores the known but unmeasured groundwater inflow through the bed of the Kinloch Marina and the observations of the initial diver survey of the eastern end of the bay, suggesting that there was little groundwater inflow at that end of the bay.

If the middle and western surveyed areas (blocks 2 & 3, Fig. 1) only are used to estimate the deep groundwater inflows, the groundwater inflow estimate is around 0.46 m^3 s^{-1} giving a total groundwater inflow of around 0.51 m^3 s^{-1}, which represents about 60% of the expected groundwater inflow. This is more in keeping with the long dry period before the survey and the need to account for the groundwater inflow through the Kinloch marina and the lake bed at the eastern end of the bay.

Note that there are potentially large errors in the this groundwater estimation due to extrapolation from just 4 measurements of 0.25 m^2 to a lake bed area approaching 200,000 m^2. However, this study has demonstrated that there are potentially large areas of direct groundwater seepage through the bed of the lake beyond the reach of the lake edge survey of Hector (2004).

3.1.3 Groundwater nutrient efflux

Water samples collected from the lake bed sediments at the 3 m and 6 m sites had generally low nutrient concentrations (Table 1) which were comparable with those measured by Hector (2004) at adjacent lake-edge groundwater sites.

The nutrient efflux estimation from the time series samples taken from the chambers showed little increase in nutrient concentration within the chambers, despite there being measurable groundwater flows. Estimated as a % loss relative to the expected concentration using the flow model equation (equation 1) suggests that up to 95% of NO_3-N and 75% of DRP was removed from the groundwater as it entered the lake. Although there is also a substantial NH_4-N component in this groundwater, none was detected in the benthic flux chamber at the end of the deployment, indicating 100% removal.

Table 1: Groundwater nutrient concentrations (mg m^{-3}) in the lake bed at Whangamata Bay and Whakaipo Bays, taken from the syringe samples.

	Whangamata Bay		Whakaipo Bay	
Nutrient	**3 m site**	**6 m site**	**Western**	**Mid bay**
DRP	30	84	167	176
NH_4-N	64	18	1	4
NO_3-N	99	564	515	426

There are several assumptions made with the benthic chamber efflux results. These include:

1. That the nutrients in the groundwater equilibrated with the overlying water within 10 minutes, as found in the laboratory tests. The chambers were deployed for at least 3 hours and up to 19 hours in Whangamata Bay, thus equilibration is unlikely to be a problem.

2. That the confinement of those nutrients over the biomass on the lake bed did not enhance uptake of nutrients which would otherwise be dispersed by lake currents. With a continuous groundwater efflux into the chamber and rapid equilibration, there should have been a progressive increase in nutrient concentrations in the chamber unless they were removed by uptake at the sediment-water interface. Thus it is unlikely that the high removal rates observed were an artifact of the chamber presence.

3. That the dark chamber results truly reflect night conditions and that the benthic algal uptake continued during the short incubations because the uptake mechanism is slow to respond to the dark or switches to a microbial response. This is possible with dark uptake of nutrients being reported in other studies (e.g., Anderson et al. 2003) and would explain why there was no nutrient accumulation in the dark chambers even though one set were run over a full night cycle.

Further work would be required to confirm these effects, but may not be necessary if the objective of this study is to assess whether there is a potential nutrient removal effect across the sediment-water interface.

3.2 Whakaipo Bay

3.2.1 Diver survey

Based on the visual cues found in Whangamata Bay, a rapid survey of the lake bed out to about 5 m depth was made using a viewer before towed diver transects were made. This preliminary survey showed similar benthic algal mats covering much of the lake bed along most of the length of the bay (Fig. 7) as were found in Whangamata Bay.

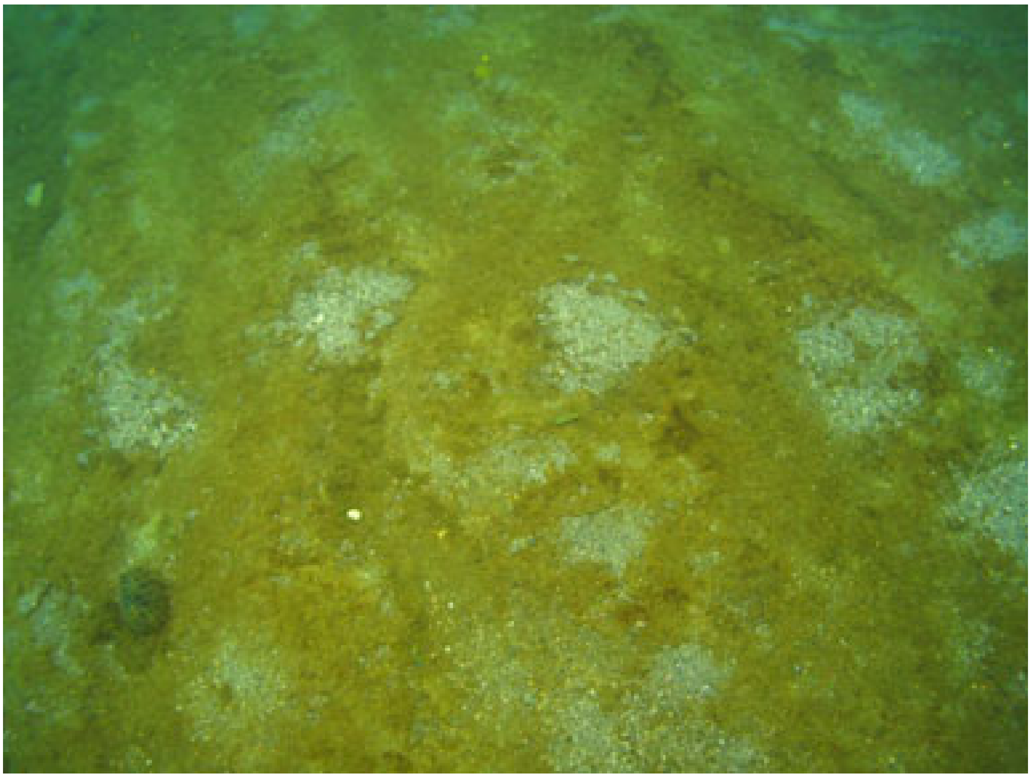

Figure 7: Whakaipo Bay lake bed between 2 and 5 m depth showing the benthic algal mats. Clear patches through the mats were found to be cold water inflows.

The divers suggest that, despite the patchy appearance, the groundwater inflow was probably quite uniform beneath the algal mats with the exception of one area where the patches were associated with physically pock-marked depressions that may have been due to differential groundwater inflow rates.

Free swimming diver surveys determined that the algal mats and the cool groundwater zones extended from about the 2 m depth to about 5.5 m depth range and that the temperature difference between the interstitial water and overlying lake water was variable from 1 to 3 ºC.

At both ends of the bay, there were large clumps of aquatic macrophytes. At the western end, the macrophytes were mostly *Lagarosiphon major* with *Myriophyllum triphyllum* and there were small drifts of terrestrial detritus in some areas. From the middle of the bay towards the east, there were clumps of other native and exotic aquatic macrophytes (Fig 8), increasing in frequency of occurrence towards the east.

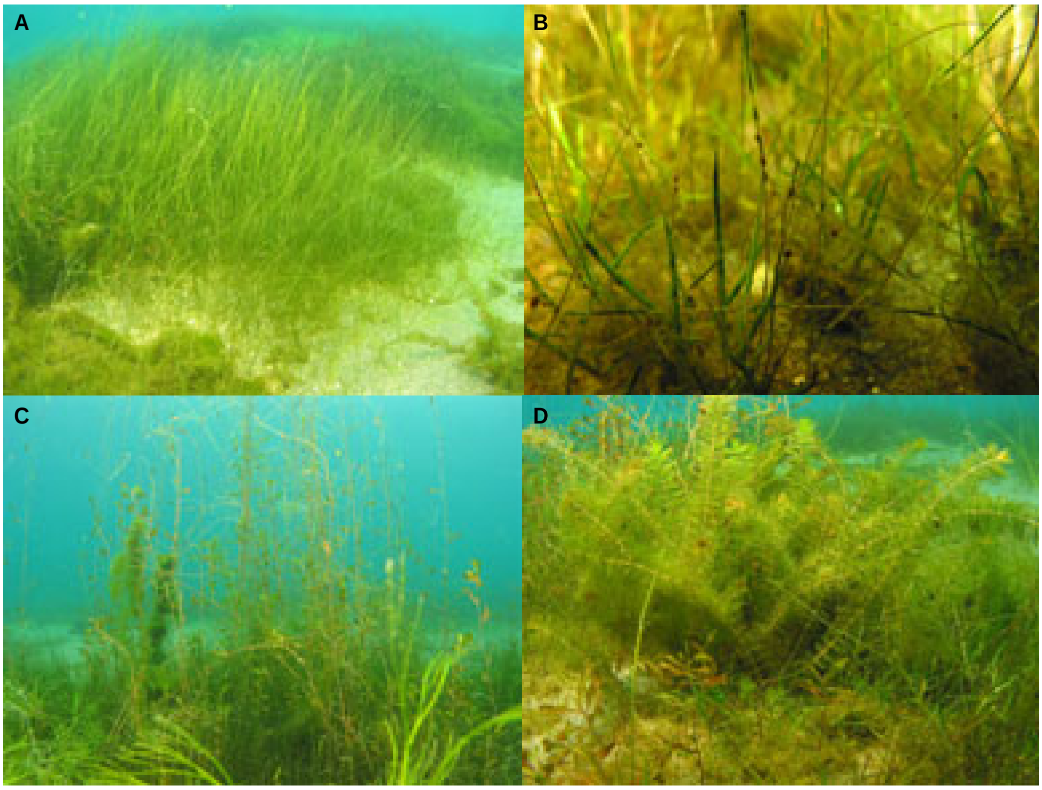

Figure 8: Native aquatic macrophytes found across the eastern end of Whakaipo Bay. **A**) *Ruppia sp*; **B**) a turf community (*Lilaeopsis ruthiana*); **C**) tall growing native species dominated by *Potomogeton cheesemanii* with some exotic *Ranunculus trichophyllus* (foreground); and **D**) mixed communities including *Myriophyllum triphyllum*, *Potomogeton cheesemanii*, and various turf communities.

The tall *Potomogeton* plants almost reached the lake surface through 4 – 5 m water depth in places. Temperature differences were not found in these clumps indicating that the groundwater may be confined to the areas with algal mats. This is different to the groundwater inflow pattern observed in the weed beds in Acacia Bay (M. Gibbs, pers. comm.) and may reflect a build up of sediment in the mounds beneath the macrophytes deflecting local groundwater away.

Towards the eastern end of the bay, the lake bed was stony due to exposed rocks from the Taupo lapilli block member. The rocks were thickly coated with attached brown algae (Fig. 9).

Figure 9: Rocks coated with brown algae towards the eastern end of Whakaipo Bay. The rocky areas extended from the lake edge for up 100 m out into the lake and to depths of >3 m.

3.2.2 Groundwater flow estimates

Paired light and dark benthic flux chambers at the western end and in the middle of Whakaipo Bay confirmed the presence of groundwater inflow via collection in the groundwater flow head (Fig. 10) and the fall in temperature within the chambers.

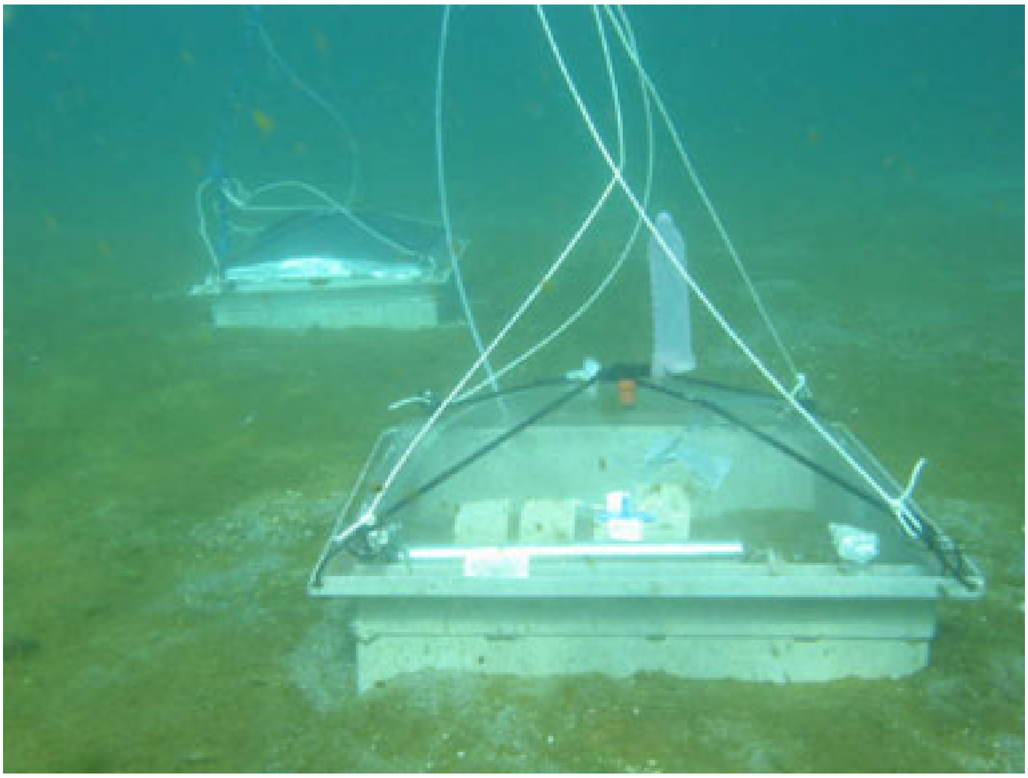

Figure 10: Benthic flux chambers installed at the mid bay site in Whakaipo Bay. The inflation of the flow measuring head balloon confirms groundwater flow through the lake bed into the chamber. Light chamber in foreground, dark chamber behind.

Based on the temperature data, the estimated groundwater inflow was in the order of 5 litres m^{-2} h^{-1} at both sites. Unlike Whangamata Bay, where there were areas with no apparent inflow, Whakaipo Bay appeared to have some level of groundwater flow across nearly all of the bay. Consequently, extrapolating from the benthic chamber data for the whole bay is reasonable and gives an estimate of around 0.24 m^3 s^{-1} for the deep groundwater inflows. Combined with the lake edge estimate of 0.021 m^3 s^{-1} (Hector 2004), this gives a total potential groundwater inflow of around 0.26 m^3 s^{-1}, which is about 70% of the expected groundwater inflow.

Note that there are potentially large errors in the this groundwater estimation due to extrapolation from just 4 measurements of 0.25 m^2 to a lake bed area approaching 180,000 m^2. However, this study has demonstrated that there are potentially large areas of direct groundwater seepage through the bed of the lake beyond the reach of the lake edge survey of Hector (2004).

3.2.3 Groundwater Nutrient efflux

As with groundwater chemistry from Whangamata Bay, nutrient concentrations in the groundwater emerging through the lake bed (Table 1) were much lower than those measured in the lake edge groundwater (Hector 2004).

The nutrient efflux estimation from the time series samples taken from the chambers showed a higher increase in nutrient concentration within the chambers than at Whangamata Bay but still did not reach the concentrations expected without nutrient loss at the sediment-water interface. Estimated as a % loss relative to the expected concentration using the flow model equation (equation 1), suggests that up to 75 % of NO_3-N and 54% of DRP was being removed. These removal rates may be underestimates due to disturbance of the algal mat during deployment of the chambers. Although the NH_4-N concentrations in the deep groundwater were lower than those in Whangamata Bay, none was measured in the benthic flux chambers indicating 100% removal.

3.3 Lake edge dye tracer

After installing the benthic flux chambers and completing the diver survey of Whakaipo Bay, the lake was flat calm and the opportunity was taken to investigate the variability of the lake edge groundwater inflows along the foreshore using the dye tracer technique. Dye was injected in a grid pattern across the near-shore lake bed out to a depth of about 1 m at a number of locations across the bay (Fig. 11).

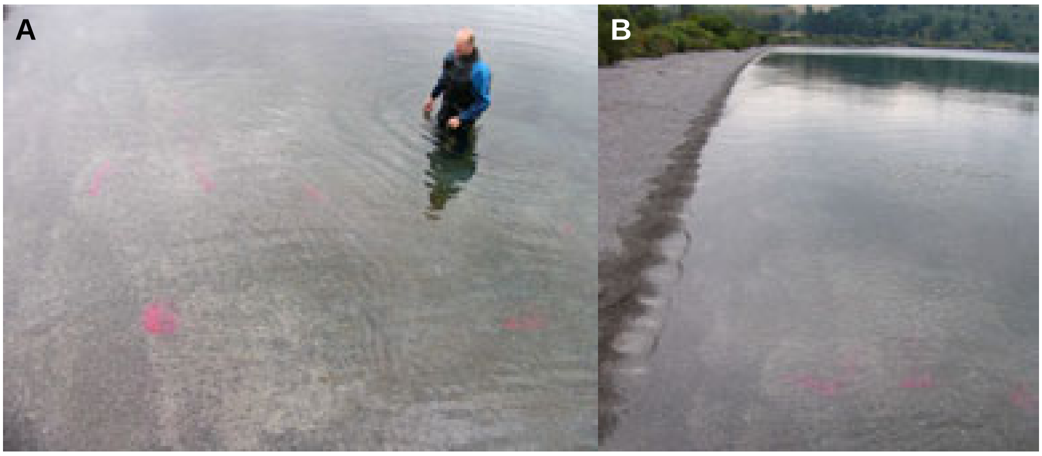

Figure 11: (**A**) Injection of dye into the lake bed in a grid pattern from the lake edge (left hand side) out to a depth of 1 m (right hand side); (**B**) View east along Whakaipo Bay showing the lack of wave action on the beach.

In almost all locations there was an obvious flow of groundwater through the beach with maximum flows in the depth range between 0.2 – 0.3 m. Although quantification of the groundwater inflow was not attempted, it was apparent that the flow varied spatially (Fig. 2), both with water depth and along the shore over relatively short distances i.e., perhaps within a 2-fold range over 10 m of beach. The beach area adjacent to the central ridge in the catchment (Fig. 12) had little apparent groundwater inflow through the lake edge in line with that ridge. In contrast, areas adjacent to dry ephemeral stream channels either side of the ridge appeared to have relatively high groundwater inflows.

Figure 12: View of Whakaipo Bay looking north showing the central ridge which divides the catchment.

While it is normally assumed that groundwater entering a lake will rapidly disperse into the open water, this was not true in Lake Taupo under the study conditions of a hot calm day. Under these conditions, the cold groundwater (coloured with dye) stayed as a thin (~5 mm) layer on the lake bed and flowed down the slope of the bed as a discrete flow (Fig. 13). The groundwater moved over patches of attached brown benthic algae as it moved deeper into the lake. The presence of these algal mats may be directly related to the movement of nutrient rich water as a confined layer across the sediment surface.

While the dye tracer allows us to see the groundwater inflow at the points of injection, groundwater was entering across the whole area of each test site. Consequently, dye in the colder groundwater flowing down the slope of the lake bed does not disperse laterally because it is being confined into laminar flow by the unmarked groundwater beside it.

As Whakaipo Bay beach faces south, it is exposed to vigorous wave action associated with a long fetch under the dominant south-westerly winds and should stir up the beach sands and dislodging any algal growth under windy conditions. However, contrary to these expectations, there was a proliferation of brown algal mats on the lake bed along the foreshore indicating the presence of groundwater inflows. The presence of these algal mats in the wave zone implies minimal wave action over the summer of 2004/05 to disrupt them or very rapid growth when the lake is calm for a few days.

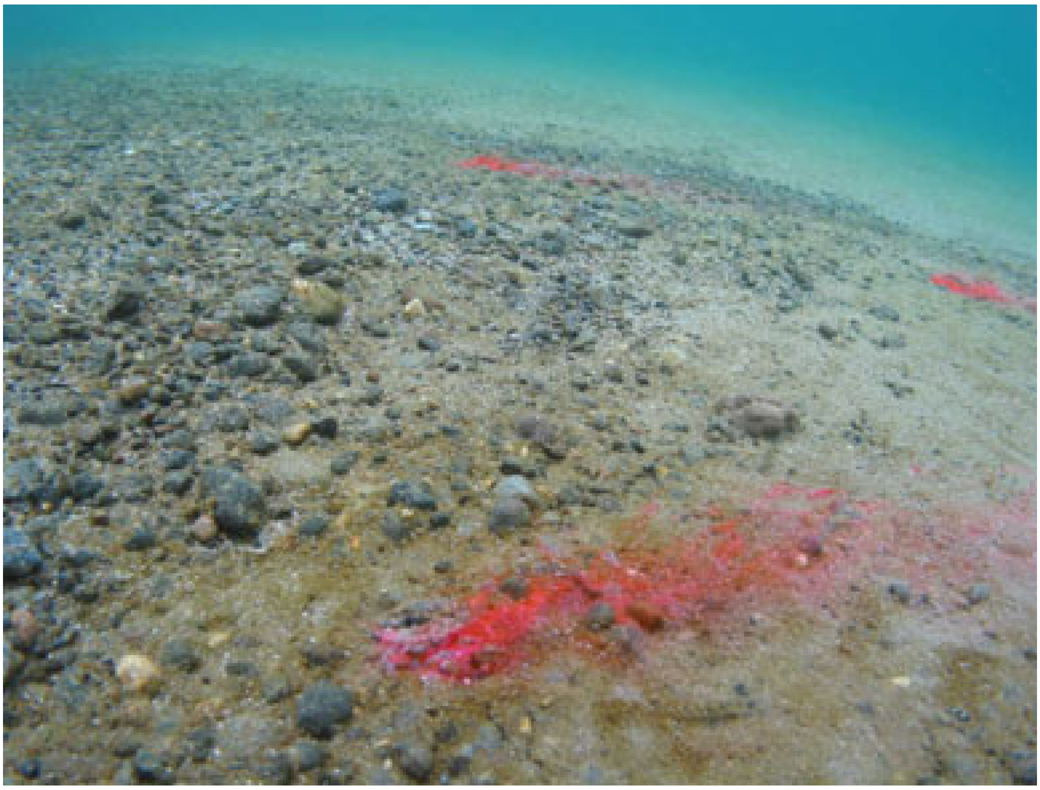

Figure 13: Dye tracing of groundwater demonstrating that the colder groundwater flows in a thin layer over the lake bed. Note the proliferation of brown benthic algae around the inflow in the foreground. The dye is allowing the inflow to be seen at the points of injection, but groundwater is flowing out of the lake bed across the whole area of the photo.

It became apparent in the mid afternoon that the groundwater inflows were being deflected by local lake currents. The dye plumes moved towards the west at the western end of the beach, they moved south (straight out into the lake) in the middle of the bay, and they moved towards the east at the eastern end of the bay (Fig. 14). Despite this movement, the dye tracks from individual injections remained as discrete plumes along the lake bed for considerable distances. Dye tracer from the mid bay tests (Fig. 14B) was observed to have travelled more than 20 m from the injection point without adjacent plumes merging or dispersing.

Amongst the rocks of the Taupo block member at the eastern end of the bay, the groundwater pooled and flowed around rather than over them (Fig. 14D). This pattern was attributed to the temperature-induced density difference between the cooler groundwater and warmer overlying lake water.

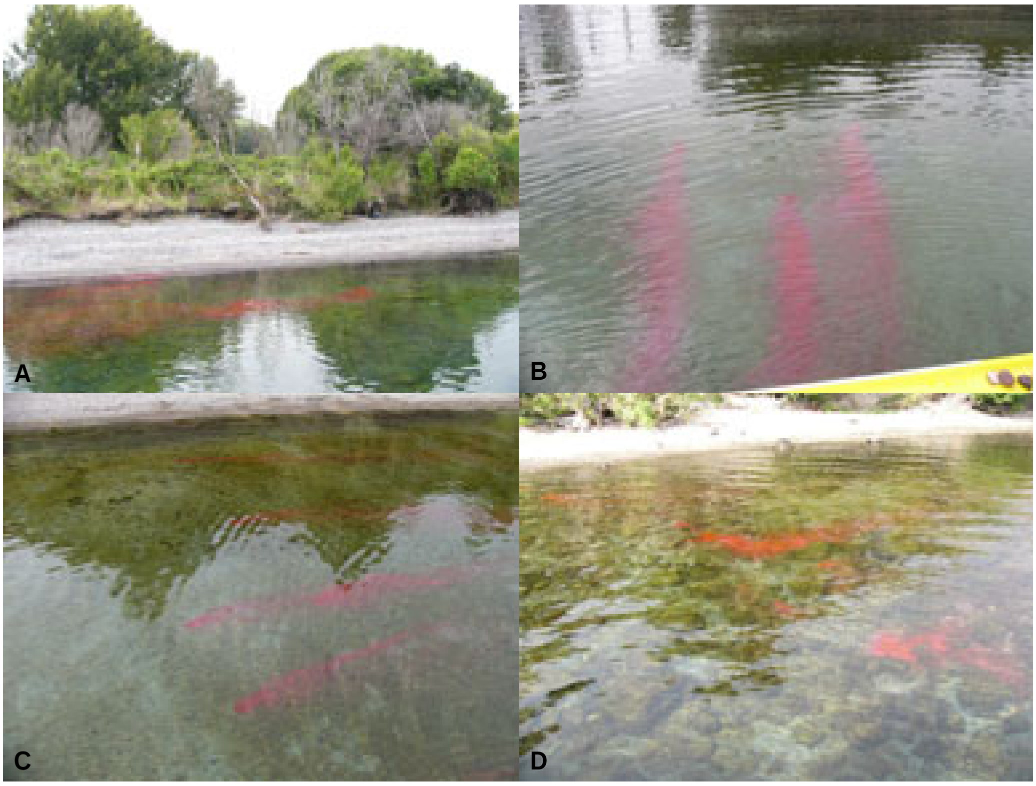

Figure 14: Dye-marked groundwater moving as discrete flows along the lake bed (**A**) to the west at the western end of the beach, (**B**) straight out into the lake in the middle of the bay, (**C**) to the east at the eastern end of the bay, and (**D**) pooling between the rocks in the rocky area near the eastern end of the bay.

4. Discussion

4.1 Groundwater inflow

The results of this study confirm the hypothesis that groundwater enters Lake Taupo through the bed of the lake down to a depth of at least 6.5 m, rather than just through the lake edge. The lack of obvious groundwater inflow between depths of 1 m and 2 m and below 6.5 m implies at least 2 aquicludes confining the groundwater in one or more discrete aquifers. The difference in groundwater inflow and chemistry at 3 m and 6 m in Whangamata Bay may indicate further confining layers within the greater aquifer between 2 m and 6.5 m.

The estimates of deep groundwater inflow in Whangamata Bay and Whakaipo Bay are generally in the order of magnitude suggested by the water balance estimates for these bays (Hector 2004; Table 4.2 page 59) suggesting they are likely to be correct. Our groundwater inflow estimates of around 0.5 $m^3 s^{-1}$ and 0.25 $m^3 s^{-1}$, respectively, in these two bays combined with the estimates of Hector (2004), account for 60% and 70% of the net residual groundwater as calculated from the annual water budget for these bays. A lower than average groundwater inflow would be expected following an extended dry period. Also, the confirmation of an apparent diffusive deep groundwater inflow across both bays does not preclude the existence of larger more defined inflows that could be associated with natural groundwater "pipes", as suggested by Hector (2004; Chapter 4.8 page 44).

A more detailed study of the deep groundwater inflows would be needed to refine this estimate further, but may not be necessary if it is sufficient to know that a large component of the groundwater inflow does enter Lake Taupo through the bed of the lake beyond the near-shore influence of the shallow groundwater aquifer.

4.2 Nutrients

The nutrient efflux results, which suggested high removal rates of both NO_3-N and DRP, were surprising until the larger picture is considered. The nutrient concentrations measured in the deep groundwater (Table 1), although high relative to the overlying lake water, are low compared with nutrient concentrations typically found in surface aquifer groundwater. This means that uptake by benthic algae, plants, and removal by microbial activity could be very efficient if the biomass was high, which it was at the time of this study. Diver observations confirmed that across most of the areas associated with the deep groundwater inflow, algal biomass was very high

(Figs. 4 & 7). Outside the benthic flux chambers, the clumps of aquatic macrophytes and algae mats covering the stones and rocks on the lake bed (Figs. 8 & 9) uptake could remove even more of the groundwater nutrients entering the lake.

Further consideration of the likely limnology associated with these deep groundwater inflows suggests that the expectation should be for almost no nutrient enrichment of the overlying lake water in summer. The dye tracer investigation of the near-shore groundwater inflows demonstrated that the groundwater was colder than the overlying lake water and thus did not mix up into the lake but flowed along the lake bed for considerable distances or pooled in depressions. This means that the highest possible nutrient concentrations were available to the benthic algae and the algae growing on the rocks on the lake bed. Elsewhere, the cooler groundwater could pool around the root mounds of the aquatic macrophytes, sheltered from dispersion by lake currents, even in rough weather.

These affects are directly related to the temperature-induced density difference between the groundwater and the overlying lake water. In this study, in late summer, the temperature of the lake water was around 18 – 19 ºC while the groundwater at the point of inflow measurement was 16.8 ºC. This difference is sufficient to ensure that the slow moving groundwater inflow remains on the lake bed in contact with the benthic algal mats or within the root zone of the aquatic macrophyte clumps, if present.

This situation, with cooler groundwater than lake water, is likely to continue for most of the year except in winter when cold nights may chill the near-shore lake waters below 10 ºC. This is generally considered to be the nominal lowest temperature of groundwater around Lake Taupo. Except in extreme stormy conditions, orbital velocities associated with wave action are unlikely to disturb the deep groundwater inflows below 2 m while near-shore surface groundwater inflows will be rapidly mixed into the overlying waters along the foreshore. This means that nutrients in deep groundwater are likely to be in close contact with algal mats and aquatic plants which can use them all year round. This assumes that the algal mats remain as found in this study all year round.

While uptake by benthic algae of nutrients (DRP and DIN) from the deep groundwater inflows prevents these nutrients mixing up into the water column where they can support water column primary production, it does not remove the nutrients from the lake. Rather it binds these nutrients into organic layer on the lake bed until the algae decay and they are released back into the water column or uptaken by benthic algae once more. Consequently, there is a "biological lag" between the inflow of nutrients in the deep groundwater and their availability to the phytoplankton community in the water column of the lake. The extent of this biological lag may be determined by a range of in-lake processes associated with nutrient cycling and the presence of viable algal mats on the lake bed that can utilize the nutrients as they are released from the sediments.

4.3 Management considerations

These findings have significance for nutrient mass balance estimation and management. Table 2 presents estimates of the potential nutrient load entering the lake via the deep groundwater and the likely net annual loads immediately available for primary production in the water column assuming the % losses, as estimated from the benthic flux chambers, were applied all year. Clearly this is an oversimplification but illustrates the effect of benthic processes on nutrient inflows from deep groundwater sources.

Table 2: Groundwater nutrient budgets (t yr^{-1}) for Whangamata Bay and Whakaipo Bay from this study. (* net load assumes the % nutrient losses estimated from the benthic chamber results occur at that rate over the whole year)

	Whangamata Bay		**Whakaipo Bay**	
	Potential load	**Net load***	**Potential load**	**Net load***
DRP	0.96	0.24	1.3	0.6
NH_4-N	0.5	0.0	0.02	0.0
NO_3-N	5.9	0.3	3.6	0.9

In these calculations it is assumed that a similar rate of nutrient uptake occurs throughout the year. Seasonal affects on nutrient uptake rates and changes in groundwater nutrient concentration (e.g., Hector 2004), probably due to fluctuations in groundwater flow between wet and dry seasons, would need to be modelled to provide a more reliable "best estimate". The potential loads estimated (Table 2) are the total nutrient load on the lake from the deep groundwater inflows to these bays.

The presence of a deep groundwater layer implies a groundwater recharge zone further back in the catchment. This is consistent with the very high DRP concentrations in the deep groundwater, indicating dissolution of pumice soil over a long period of time before reaching the lake (Timperley 1983). This further implies that the deep groundwater is older than the shallow groundwater entering at the lake edge, which is likely to have much lower DRP concentrations (John et al. 1978). That the inorganic nitrogen concentrations in the deeper groundwater are generally lower than would be expected from shallow groundwater (John et al. 1978, Hector 2004), suggests that any nutrient enrichment that has occurred within the catchment of these bays has yet to reach the lake.

The nutrient uptake rate indicated for the benthic communities appears to be coping with the present level of deep groundwater nutrient input but this may well change with an increase in inflowing nutrient concentrations over time.

The apparent nutrient uptake rates estimated in this study suggest that the deep groundwater inflows in these bays may not add a substantial nutrient load to the lake water column. However, nutrient uptake by benthic algae does not remove the nutrients from the lake and these may become available for water column primary production after a period.

5. Conclusions

1 There is evidence of deep groundwater inflow into both Whangamata Bay and Whakaipo Bay.

2 Deep groundwater inflows appear to be mostly confined to the depth layers between 2 m and 6.5 m, and there may be more than one aquifer within this depth range.

3 The magnitude of these deep groundwater inflows is likely to account for all the residual catchment drainage not included in stream flow or measured by the shallow groundwater investigation by Hector (2004).

4 The potential nutrient loads in the deep groundwater inflow appear to be largely removed through uptake by benthic algae and aquatic macrophytes across the bay and thus are unlikely to constitute a large nutrient source to the lake water column in summer.

5 Nutrient uptake does not remove the nutrients from the lake and these may become available after a period. Consequently, the potential nutrient loads should be used in the estimation of an annual nutrient budget for the lake.

6 Seasonal effects on the deep groundwater nutrient loads and their uptake by benthic algal mats and microbial activity at the sediment-water interface are unknown and may alter conclusion 4 for other times of the year, with more or less nutrients being immediately available for water column primary production.

7 The recharge zone for the deep groundwater is likely to be towards the back in the catchment and hence any enrichment due to past land use changes may have yet to reach the lake.

8 Similar deep groundwater inflows are likely to occur in other areas with large catchments and small surface water inflows.

6. Where to from here?

Information presented in this report provides a new understanding of transfer processes across the sediment-water interface into Lake Taupo. It also raises a number of management focused questions including:

- Does the hydrodynamic regime change seasonally?
- Does the nutrient uptake rate by the benthic algal mats change seasonally?
- Is the level of nutrient uptake sustainable in the long term? With the expectation of increasing nutrient concentrations in the groundwater as historic enrichment reaches the lake, is there a “burst through” level above which the benthic algal mats cannot strip the DIN and DRP from the inflowing groundwater?
- What is the recovery / recolonisation time for the benthic algal mats following disturbance or clearance?

Scientific questions include:

- What is the species composition of the benthic algal mats and are they the same in each embayment? Green and brown mats in Whangamata and Whakaipo Bays, respectively – is there a difference in uptake efficiency?
- If the benthic algal mats take up DIN and DRP from the groundwater in roughly Redfield ratio proportions (i.e., 15:1) they can remove all of the DIN but only part of the DRP load. Does this alter the concentration of DRP in the inshore water column in a way which could favour cyanobacteria growth?

7. References

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