Using fibre-optic distributed temperature sensing and heat modelling to characterize groundwater- surface water interaction in Whakaipo Bay, Lake Taupo, New Zealand

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ABSTRACT

The water quality of Lake Taupo is under threat. Agricultural development in the catchment has led to an excess of nutrients in the water systems. Groundwater is the primary link for the transport of nutrients between land and lake. The spatial distribution and groundwater seepages rates in Lake Taupo are still unknown.

This study used horizontal and vertical fibre optic distributed temperature sensing to characterize the groundwater inflow areas in Whakaipo Bay, Lake Taupo. During the summer the temperature of the lake water is warmer than the groundwater, 17 and 12 °C respectively. Horizontal temperature profiles of the lakebed were acquired to study the spatial differences of groundwater inflow zones. Lower lake bottom temperature is an indication for groundwater inflow.

Vertical temperature profiles with a spatial resolution ranging from 1 metre to 1 millimetre where acquired to get a general idea of the vertical temperature differences in the lake. The high resolution temperature profiles where combined with a numerical conduction-convection heat transport model resulting in a temperature based seepage meter. The seepage meter was used in three different temperature areas in the bay, a cold, a medium warm and a warm area in order to verify the differences in groundwater inflow rates.

The horizontal temperature profiles indicated spatial differences in temperature ranging from 13.7 to 18.5 °C. The three high resolution profiles were in agreement with the horizontal profile. The colder the temperature measured in the horizontal profile, the larger the groundwater seepage rate calculated with the numerical heat transport model.

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1 INTRODUCTION

The problem of eutrophication of aquatic ecosystems caused by the addition of artificial and natural substances like nitrogen is of worldwide concern. In New Zealand, intensification of farming and increased fertiliser use has resulted in deterioration of water quality by increased levels of nitrogen (Morgenstern & Doughney, 2012) (Wilcock, Nagels, Rodda, O'Conner, Thorrold, & Barnett, 1999) (Quinn & Stroud, 2002). Lake Taupo, New Zealand's largest lake, is also under the threat of eutrophication. Historically the lake had extremely low levels of nitrogen, which has limited the growth of nuisance plants, and helped maintain excellent water quality (Wildland Consultants Ltd., 2013). To date, the health of the lake is slowly but surely being compromised as a result of human activity (Environment Waikato, 2003). The nitrogen load in the lake has more than doubled since prehistoric times (Silvester & White, 2006). The most important pathway for nutrients generated from land use to the lake is via groundwater-fed streams and direct groundwater seepage through the lakebed. Groundwater in the Lake Taupo catchment has a mean residence time between 20 and 180 years (Morgenstern, 2007). The current deterioration in the quality of the lake water, might just be the tip of the iceberg, as due to the long residence times and the importance of groundwater inflow, one can expect a considerable delay between land use changes designed to improve lake water quality and any observed improvement.

Better characterisation of groundwater seepage in Lake Taupo is needed to better understand the likely effects of past, present and future land use changes. Rough estimations on the quantity of groundwater seepage into Lake Taupo have been made in several studies. Most of these estimates are based on water budgets (Hector, 2004) or point measurements (Gibbs, Clayton, & Wells, 2005). Methods focussing on spatial variability of seepage have been labour intensive and expensive (Klug, Daughney, Verhagen, Westerhoff, & Dudley Ward, 2011). In 2011 a team of European and New Zealand research partners started a project called SMART (Save Money and Reduce Time). The overall aim of this project is to develop a suite of highly innovative methods for characterising New Zealand's groundwater systems. The SMART project will place emphasis on techniques that use passive data sources. That is, they rely on existing data sources, or on new measurements that can be made over large areas with little effort and minimal costs.

The research presented in this thesis focuses on one of the methods included in the SMART project: Fibre Optics Distributed Temperature Sensing (FO-DTS). This method uses fibre optic cables that measure the temperature approximately every meter with a theoretical resolution of 0.01 °C. The temperature difference between the groundwater and the lake water is used to detect groundwater inflow areas. Heat has been used as a groundwater tracer for over 50 years (Anderson, 2005). However, many of the previous temperature based methods have the same limitations as mentioned before. They are too time consuming and too expensive for wide scale application. FO-DTS allows for a fine spatial resolution but also gives the opportunity to cover a large area. Aside from the high spatial resolution FO-DTS also allows for a higher temporal resolution than former methods. With a high temporal resolution the stability of the condition can already be analysed within a short period of time.

A research project of Gibbs et al. (2005) focussed on groundwater seepage in Whakaipo and Whangamata Bay, Lake Taupo. They used the principle of temperature difference between groundwater and lake water. Divers felt with their hands for colder areas to detect seepage locations. Seepage meters were installed at two points in each bay at locations where the diver had felt a cold zone. The measured flux was then extrapolated over the entire bay/assumed seepage area, not taking spatial variability into account.

Horizontal deployment of FO-DTS enables to get more inside in the spatial differences within an area. Fibre optic cable is deployed on the lakebed in Whakaipo Bay over an approximated area of 0.25 km^2. The cable is able to take measurement approximately every meter of cable. Vertical temperature measurements, with temperature loggers and FO-DTS, are used to verify the horizontal measurement interpretations and quantify groundwater inflow with the help of a numerical model. The main research questions of this study are:

- To what extent are seepage areas in Whakaipo Bay detectable by horizontal deployment of FO-DTS?
- To what extent are vertical deployments of FO-DTS in combination with a numerical model able to quantify the groundwater flux in different areas?

Furthermore, this study serves as a test to assess the suitability of FO-DTS in locating groundwater seepage areas in lakes.

This thesis starts with an introduction to the study area of Lake Taupo and Whaikapo Bay. Then the theoretical background of this study is presented in chapter 3. Chapter 4 will explain the details of the methodology of this research. Chapter 5 gives the main findings of the research. The discussion in chapter 6 will combine the results and relate them to previous research. The reliability of the results and the limitations of the method are also outlined in this chapter leading to recommendations for further research. The conclusion will give answers to the above mentioned research questions.

2 SETTING

2.1 Lake Taupo

Lake Taupo is situated in the centre of the Northern Island of New Zealand. The lake fills the Taupo caldera which formed approximately 22,600 years ago by an enormous volcanic eruption (Peltier, Hurst, Scott, & Cayol, 2009). The lake measures approximately 30 km wide by 40 km long and has a surface area of 622 km^2 (Wildland Consultants Ltd., 2013) with a greater catchment size of 3,487 km^2 (Environment Waikato, 2003). The main tributaries are the Waitahanui River and the Tongariro River with the Waikato River being the sole river to which the lake is drained (de Jong, 2011). Waikato River flow rates are controlled for hydropower generation through a series of dams. There are a number of small towns and villages around the lake of which the largest is the township of Taupo located at the Northern lake shore.

2.2 Geology catchment

This study focuses on the interface between the subsurface and the lake. The geology of the area is not taken into consideration with measurements and interpretations. However to get a general idea of the area a short paragraph is taken from the summary of “Hydrogeology Of Lake Taupo Catchment – Phase 1” (Hadfield, Nicole, Rosen, Wilson, & Morgenstern, 2001):

“Geology is dominated by young (< 0.4 Ma), locally derived, rhyolitic pyroclastics. The sequence in the western catchment is relatively simple with surficial Oruanui ignimbrite overlying a large thickness of Whakamaru ignimbrite. The latter is sufficiently welded in places to have moderate vertical fracture development and to form impressive cliffs along the lake-front. East of Kawakawa Bay faulting is common and there is a more complex sequence of ignimbrites, fall deposits, localised lava extrusions and lacustrine sediments. Of most hydrogeologic relevance are the Oruanui ignimbrite and the underlying grouping of rhyolite pyroclastics. Although not fractured, they are likely to have moderate permeability. Occasional paleosols, which punctuate these formations, are expected to act as localised aquitards and to sometimes induce perching.”

The geology of the area is visualized in figure 2.1.

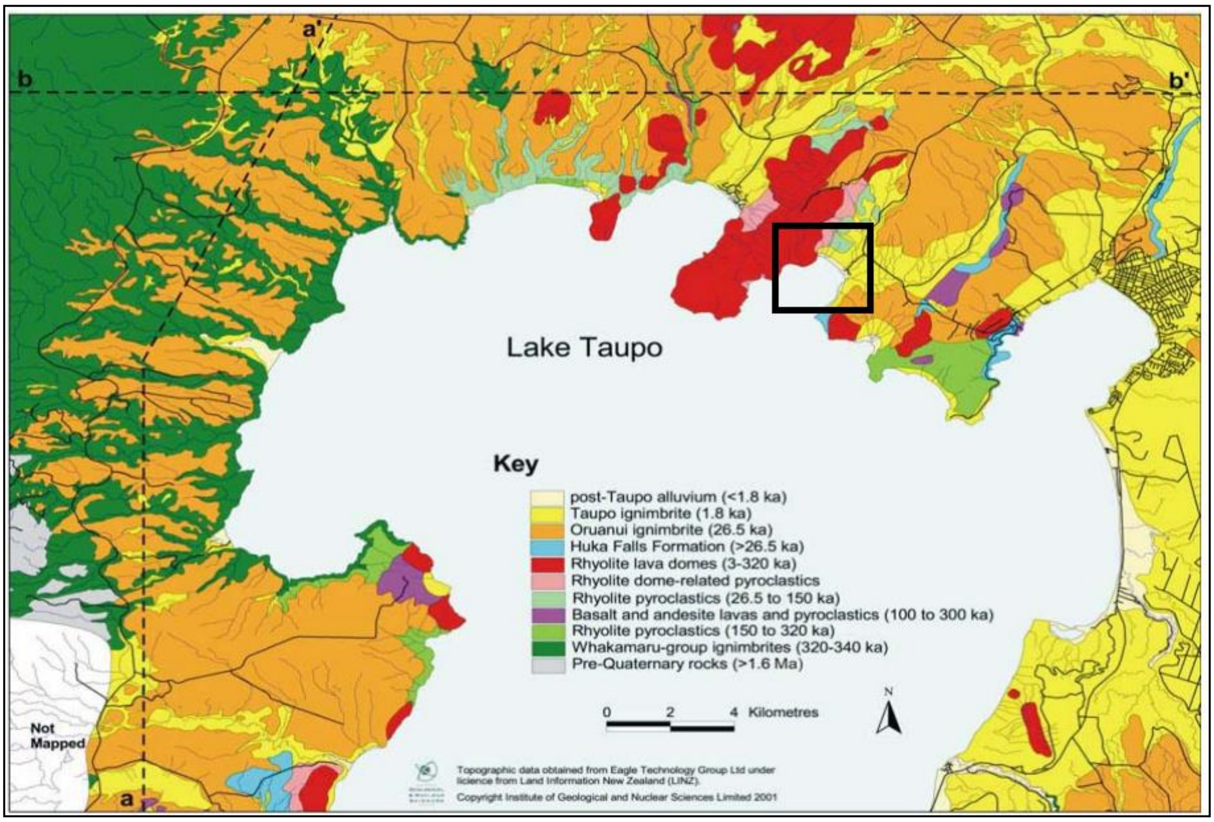


Figure 2.1: Geological map of Lake Taupo. Black square indicates study area Whakaipo Bay (Hadfield et al., 2001)

2.3 Hydrogeology

Groundwater primarily occurs in pyroclastic sediments (e.g. ignimbrite) and alluvial aquifers (Hadfield, 2001). Groundwater flows into the lake in the northern catchment with unwelded ignimbrites is mostly via lake bed seepage with long time delay in the groundwater system (Morgenstern, 2007).

Streams in the northern catchments are characterized by low flow and runoff estimates. This reflects the occurrence of the unwelded ignimbrites, allowing most rainwater to infiltrate to deep groundwater systems (Morgenstern, 2007). A relative large groundwater storage reservoir with large mean residence time is supported by measured old water ages in the area.

2.4 Water quality

The chemical character of groundwater in the area is influenced by a large number of factors. These include rainwater chemistry, aquifer geology, soil type and geothermal influences and modifying factors such as climate and geomorphology. Human activities can have an important influence on the composition of water. Agricultural land use activities is the most pronounced anthropogenic influence in the catchment, introducing excess input of nitrate to the system.

The groundwater quality in the catchment is generally high, although there is clear evidence of land-use impacts. The impacts are greatest in younger waters, as nitrate sulphate and chloride concentrations are higher at shallow locations compared to deeper locations. The nitrogen load from groundwater entering the lake is expected to increase with time.

3 THEORETICAL BACKGROUND

This chapter will provide the theoretical background on the system studied and the methods used. First, the general processes of surface water groundwater interaction is outlined. Thereafter, the concept of heat as a tracer and the method of distributed temperature sensing is explained.

3.1 Surface water groundwater interaction

Lakes can interact with groundwater in different ways: some either receive or lose groundwater throughout their entire bed; but most lakes receive groundwater inflow through part of their bed and have seepage lost to groundwater through part of their bed (Winter, Harvey, Lehn Franke, & Alley, 1998). The slow through flow rate in lakes often result in accumulation of low permeable sediments in the lake floor which can affect the distribution of seepage. The rate of seepage is therefore often highest around the lake margin where wave action may restrict the deposition of finer sediments (Canterbury Regional Council, Pattle Delamore Partners, 2000).

Water in the subsurface moves from areas with high to areas low hydraulic heads. Hydraulic head is the sum of the elevation head and the pressure head. The pressure head is zero at the lake surface, with respect to the atmospheric pressure. Hydraulic head is used to describe the potential energy in groundwater flow systems. Figure 3.1 shows a generalized vertical section of subsurface water flow. Water that infiltrates at higher elevations moves downward to become groundwater and then also moves laterally from point of higher to lower hydraulic head (USGS, 2013).

Surface water bodies (e.g. lakes, rivers, and streams) are generally located at lower elevations than surrounding groundwater in mountainous areas, and therefore generally gain water from groundwater systems.

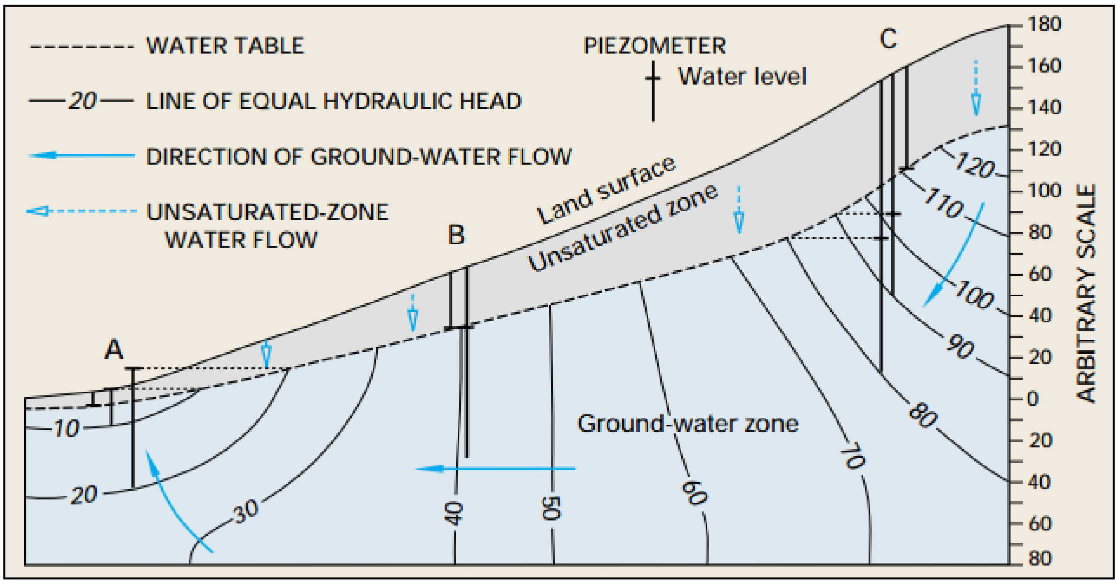


Figure 3.1: **Generalized vertical section of subsurface water flow (Winter, Harvey, Lehn Franke, & Alley, 1998)**

3.2 Temperature as a tracer & DTS

Using temperature as a natural tracer in groundwater surface water interaction has several advantages. The signal will arrive naturally and will continue to arrive naturally as long as the groundwater and surface water are connected, there is no contamination by introducing chemicals to the local environment and measurement of temperature is robust and relatively inexpensive (Stonestrom & Constantz, 2003).

Commonly, temperature is measured at multiple depths at a single location. The flux can then be calculated using an analytical solution, time series analysis, and/or a groundwater flow and heat transport model (Lowry, Walker, Randall, & Anderson, 2007). A reasonable new method that uses temperature as a hydrological tracer is Distributed Temperature Sensing (DTS). The general concept of DTS is to observe temperature variations at a particular distances along a fibre optic cable (Selker, et al., 2006). These temperature sensing methods were first developed in the 1980s for industrial applications like pipeline and fire monitoring. Nowadays, DTS is also widely used in hydrologic applications and can be used for monitoring of streams, catchments, lakes, the atmosphere and the oceans (Tyler, et al., 2009).

To measure temperature with DTS the instrument sends a laser pulse down the length of the fibre-optic cable. Variations in temperature cause differences in backscatter, changing the wavelength and intensity of the light. The scattered light travels back up the fibre as a higher (Stokes) and lower (anti-Stokes) wavelength. The temperature does not affect the Stokes, but only the anti-Stokes. The ratio of the two intensities can be used to calculate the temperatures at different sections of the cable (Lowry et al., 2007).

Briggs et al. (2012) compares DTS technology with three of the most widely used techniques namely: differential gauging, dilution gauging and geochemical mixing. They conclude that DTS heat tracing can be used in a comparable manner to the more conventional methods, while it describes the inflow distribution at a higher spatial resolution.

The exact extent of the seepage areas in lakes may be hard to determine with DTS. The density differences between the cold groundwater and the warmer lake water causes the inflowing groundwater to flow downwards on the lakebed following the topography. This means that cold water can also be present at locations where there is no groundwater seepage; rather this water originates from upper regions of the lake. This process is visualized in figure 3.2. At location A, cold water indicating groundwater, can be present but this does not mean that this is a groundwater seepage area.

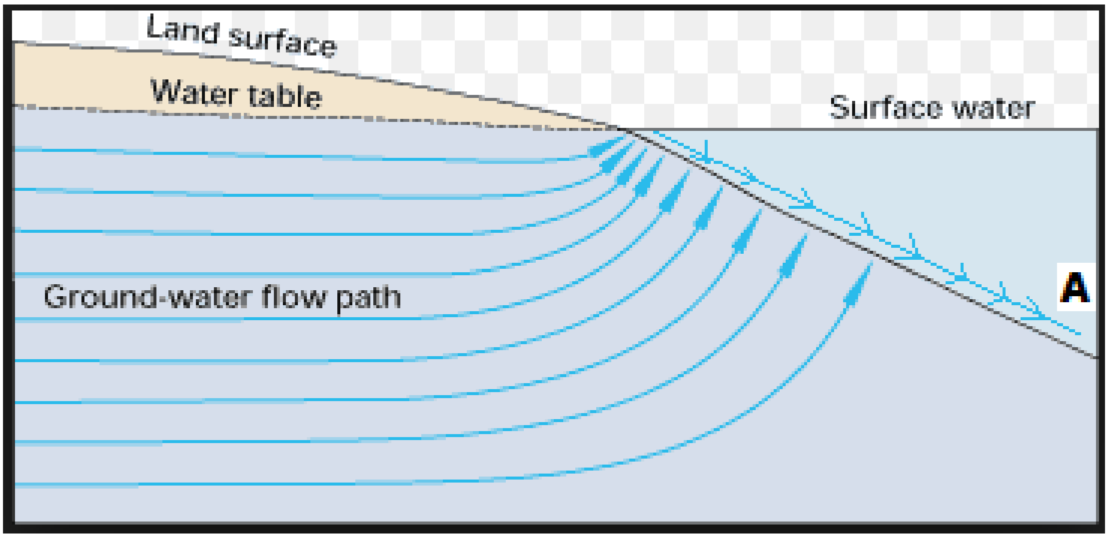


Figure 3.2: Groundwater flow paths in subsurface and lake

3.3 Groundwater in Whakaipo Bay

Previous research in Whakaipo Bay by Gibbs et al. (2005) showed that the groundwater during the summer in Whakaipo Bay is colder than the lake water. Although the exact temperature of the groundwater in Whakaipo Bay is not known, in general groundwater temperature is around 12 °C. Lake water in summer at water depth range of 2-9 meters is around 18-20 degrees; therefore high-discharge zones should show relative colder areas at sediment water interface (SWI) in the summer. Furthermore, if discharge is stable then the changes in temperature at the SWI are reduced by constant input of cold water. In other words, the diurnal amplitude (difference between daily minimum and maximum) or diurnal standard deviation of temperature should be lower in these areas (Sebok et al., 2013).

4 METHODS

This chapter will give an outline of the methods used in this research. Briefly, horizontal Fibre Optic Distributed Temperature Sensing (FO-DTS) profiling is used to locate possible groundwater seepage areas in Whakaipo Bay. Then, vertical profiles at several locations using FO-DTS and temperature loggers are used to verify the groundwater inflow in located cold areas. A detailed outline of the fieldwork days is given in the appendices.

4.1 Fibre Optic Distributed Temperature Sensing

A consistent method was used during all FO-DTS measurements in order to have the most reliable data possible. The settings of the software, the installation of the hardware, the calibration methods and all other factors that could have influenced the data were kept the same as much as possible over all measurements. Small deviations were only made when circumstances forced this. This will be mentioned in the particular sections and the possible influence of the deviation will be considered in the data analyses.

A four-channel Oryx Distributed Temperature Sensing (DTS) remote unit (Sensornet LLC.) was used for all deployments. This device has an along cable resolution up to 1.03 meter. The installation was placed inside a car with air-condition which was used occasionally to keep the air temperature relatively stable. A data collection computer was connected to the Oryx allowing for onsite dynamic calibration. This calibration method results in absolute temperature measurements. The temperature readings obtained by the Oryx are calibrated with two temperature sections along the cable. Chilly bins are installed at both ends of the cable with a 20-30 meter coil cable submerged in a 0 °C ice-slush mixture. The temperature of the water in the calibration baths was kept uniform by an aquarium bubbler and independently monitored with two temperature probes connected to the Oryx. The general setup of the measurement system is visualized in figure 4.1. Depending on the type of measurement the instrument collected a temperature reading along the cable every 15-60 seconds. The Oryx, data collection computer and aquarium bubbler were powered using a 24V battery system.

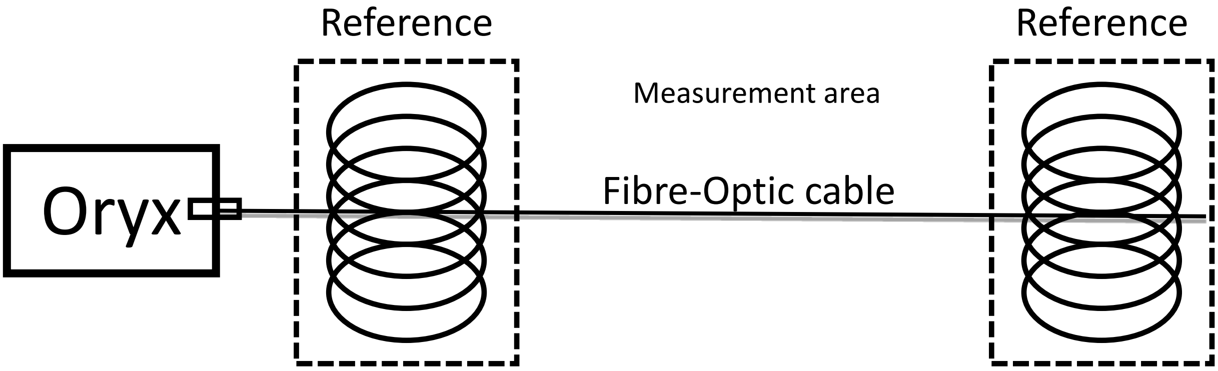


Figure 4.1: General setup of FO-DTS measurements. Temperatures in the reference sections is kept at 0°C

FO-DTS was used to make horizontal and vertical temperature profiles in Whakaipo Bay. Two types of FO cables were used, a black OCC (Optical Cable Corporation) Military Grade Fibre Optic Cable with a core/cladding diameter of 50/125 µm and a protection armour making the total diameter of the cable 5 mm. The cable has inscribed cable length markings every meter. The second used cable is a 900 µm unarmoured fibre.

4.2 Horizontal FO-DTS profiling

Two horizontal temperature data sets were gathered in Whakaipo Bay. In order to get a general overview of the water temperature variations on the lakebed near shore a 2.3 km cable was deployed close to shore. In the next phase a 5 km cable was deployed further offshore in deeper water. With both deployments the measurement repetition time is kept short to provide onsite data checking and flexibility in post-collection data analysis. The basic details of the horizontal FO-DTS measurements are listed in table 4.1.

Table 4.1: Basic details on the horizontal FO-DTS measurements in Whakaipo Bay

Length cable	Date	Measurement time	Repetition time	First measurement	Last measurement	Total time
2.3 km	18 Feb ‘14	15 sec	15 sec	14:09:54	14:16:09	7m
5.0 km	10/11 Mar ‘14	15 sec	60 sec	13:30:27	8:41:27	19h 12m

4.2.1 Near shore deployment

To investigate groundwater discharge in the shallow, near-shore zone a 2.3 km cable was deployed at 18.02.14 in the bay. The cable was laid by wading and use of a cable and reel system mounted onto a kayak. The cable deployment in the bay is visualized in figure 4.2. The DTS unit was located on shore in the centre of the bay. The first 20-30 meter of cable was coiled up in the first calibration bath. Then, the cable was laid to the north-west side of the bay where it was secured (a), and laid back to the middle of the bay where approximately 15 meter cable was removed from the water to provide a reference point of air temperature (b). Then the cable was laid to the opposite, south east side of the bay (c) where it was secured and again laid back to the middle of the bay where the last part of the cable was reserved for the second calibration bath. A minimum distance of 1 m was maintained between the parallel sections of the cable.

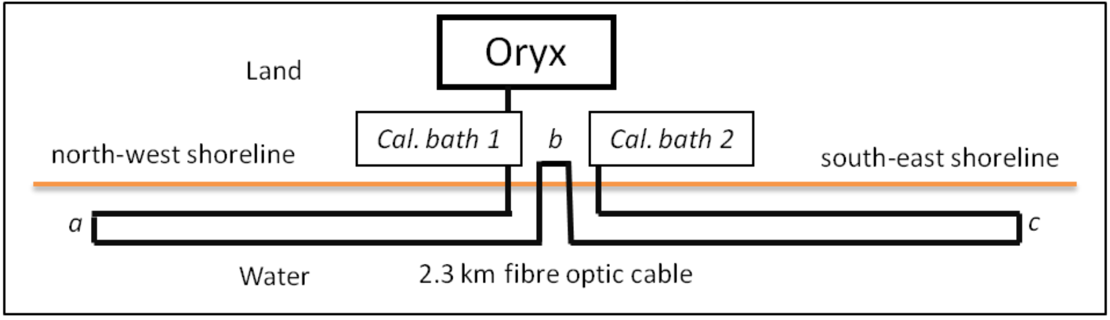


Figure 4.2: Scheme of the layout for the 2.3 km cable deployment. Order of deployment: calibration bath 1 → a → b → c → calibration bath 2

4.2.2 Off shore deployment

To get a more detailed inside in the groundwater discharge further away from shore a 5 km cable was deployed using a cable reel system transported by a barge operated by the Lake Taupo Harbourmaster. The cable deployment is visualized in figure 4.4. The DTS unit was located in the north western corner of the bay where 20-30 meter of the begin section of the cable was put in the first calibration bath. From here, the cable was deployed approximately 80 meter from shore to the south eastern corner of the bay, where it was secured on land to provide a reference point of air temperature (a). From here, the cable was deployed roughly parallel to the first stretch approximately 160 m from shore to the north-west shoreline where it was secured on land to stabilise the cable and provide a reference point with the air temperature (b). Approximately 500 m was doubled over by an extra loop to the centre of the bay and back to the start area (c). From here, the cable was deployed in an offshore direction for approximately 400 meter before it returned to the north western corner of the bay where the last 20-30 m of cable was put in the second calibration bath (d). The cable was deployed in water up to a depth of 8 m and sunk to the lakebed due to the negative buoyancy of the cable. On crucial points extra weight was added with pegs to stabilize the cable.

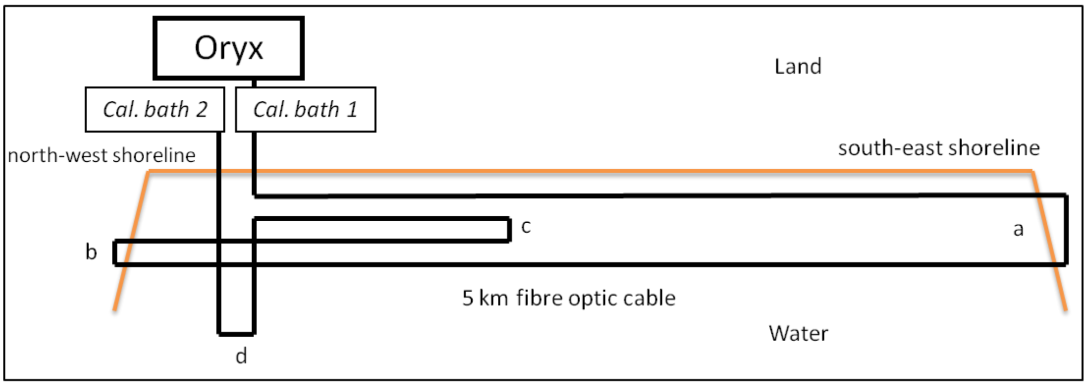


Figure 4.3: Schematic visualization of the layout for the 5 km cable deployment. Order of deployment: calibration bath 1 → a → b → c → d → calibration bath 2

A handheld Global Positioning Unit (Garmin Inc.) tracked the boat during deployment and hereby provided an indication of the cable location. 4 extra reference waypoints were made during deployment at the location where red tape was secured on the cable.

When the cable was retrieved on the next day, 4 new waypoints were made on the moment the red tape appeared from the water. Comparison of these points gave an indication of the location and movement of the cable during the time it was deployed in the bay. Three temperature loggers (HOBO Stainless Temperature Data Logger U12-015) were attached to the cable to provide additional temperature calibration points.

4.3 Vertical temperature measurements

Vertical temperature measurements were taken at 18 locations in Whakaipo Bay. Initially vertical temperature measurements were made at low resolution using a vertical array of temperature loggers and a FO-DTS device with wrapped 5 mm diameter cable. Later, vertical measurements were taken at higher resolution using 900 µm diameter FO-DTS cable on another construction.

4.3.1 Low resolution vertical profiling

Initially a general overview of the vertical temperature profile at different locations and depths in the lake was obtained by temperature loggers. Ten loggers were used for a device which was able to measure the temperature at different depths. In total 8 loggers where attached to a 9 meter rope at different intervals (see table 4.1 and figure 4.4). A weighted anchor at the base of the rope ensured the device did not drift. Two loggers were attached to the anchor to get higher spatial resolution temperature measurements near the lake bed. The deepest logger was located on the lake bed. A floating buoy was secured at the water surface to keep the rope in a vertical position. Eight measurements were taken with the logger device.

Table 4.2: Logger distance to lakebed

Depth from lake bed (m)	**0**	**0.3**	**0.5**	**0.75**	**1**	**2**	**3**	**4**	**5**	**6**
Logger number	116	113	112	109	118	114	117	115	111	110

A vertical temperature profiling FO-DTS device was constructed for a higher spatial temperature resolution. This device was able to measure the temperature every 0.4 cm. In total 144 meter cable was wrapped around a 38 cm diameter PVC pipe. The rest of the cable, 66 meter, was used for the calibration baths and to overpass the length from the device to the measuring location. Besides the higher spatial and temporal resolution, the DTS device allows for real time visualization of the temperature profile. Vertical measurements were taken at 7 locations in the Whaikapo Bay using this DTS device.

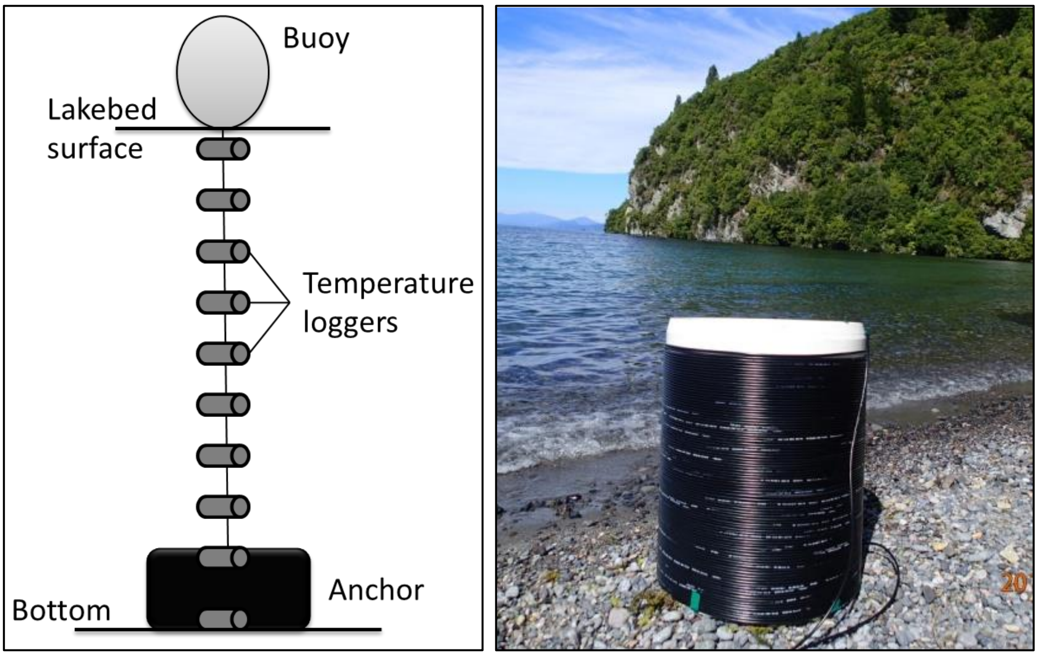


Figure 4.4: Left: schematic of logger setup, right: medium resolution DTS device.

4.3.2 High resolution vertical profiling

In order to detect the smallest temperature changes near the lakebed a modified DTS setup was used that (1) had a high vertical spatial resolution, (2) captured inflowing groundwater ensuring an evolution of groundwater over time, (3) minimized turbulence and (4) minimized the effect of heating by radiation on the construction by surroundings.

A 900 µm diameter DTS cable was wound around a 0.3 m diameter specially fabricated metal/bamboo frame. In total 350 m cable was wrapped around the frame to form a vertical column with a height of 0.32 m (figure 4.6). This resulted in a vertical spatial resolution of ~0.94 mm. The device was lowered in a 38 cm diameter PVC pipe of a height of 52 cm (figure 4.6). The PVC pipe was inserted 40-50 mm into the lakebed allowing groundwater to flow from the lakebed through the vertical DTS device without horizontal dispersion. Furthermore a white narrow meshed sized grid net was used to cover the PVC pipe. The cover reduced the turbulence in the pipe but allowed water to flow freely from the pipe to the lake. The device was left for a minimum duration of two hours and was deployed at three locations along the lakeshore.

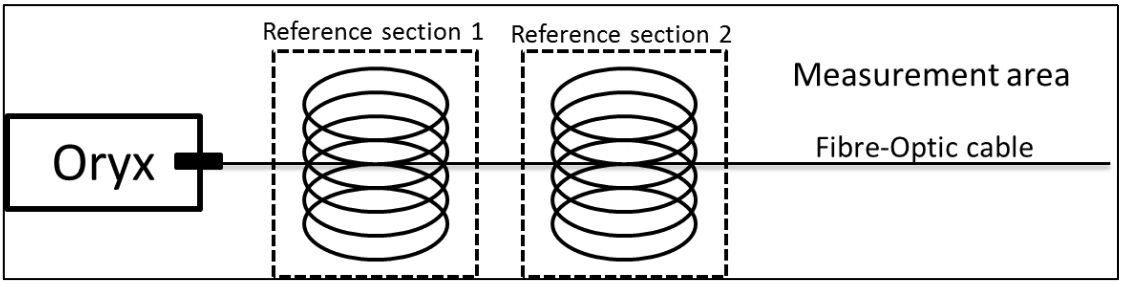


Figure 4.5: DTS setup high resolution vertical measurements

Figure 4.6: Vertical FO-DTS device created from unarmored fibre optic cable and bamboo in lab (left) and installed inside a PVC cylinder during deployment in Whakaipo Bay

4.4 Flux determination model

With little mixing of water by turbulence the temperature change in time in the PVC pipe is determined by convection and diffusion. Assuming no horizontal heat exchange through the plastic PVC cylinder, the process is simplified to a 1-dimensional situation. The temperature change in the water by convection and diffusion can be described by the equation (Majchrzak & Turchan, 2012):

$$\rho c\left[\frac{\partial T(z,t)}{\partial t}+\epsilon u\frac{\partial T(z,t)}{\partial z}\right]=\lambda\frac{\partial^2 T(z,t)}{\partial z^2}$$

In which *z* is the vertical coordinate [m] , *c* is specific heat capacity of water [J $^{o}K^{-1}$ kg^{-1}] , ρ is mass density of water [kg m^{-3}], λ thermal conductivity [J s^{-1} m^{-1} K^{-1}], ϵ is porosity (the ratio of liquid volume to the total volume), *u* is vertical seepage velocity of groundwater entering the lake [m s^{-1}] , *T* denotes temperature [K] and *t* is a time (s). The equation can be written as:

$$\frac{\partial T}{\partial t}=a\frac{\partial^2 T}{\partial z^2}-\epsilon u\frac{\partial T}{\partial z}$$

Where $a=\frac{\lambda}{c\rho}$ is the diffusion coefficient.

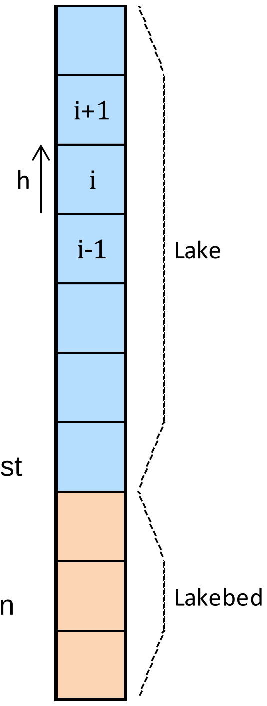
Using the explicit scheme of the finite difference method the following approximation for the internal node can be made:

$$T_i^f = \left(1 - \frac{2a\Delta t}{h^2}\right) T_i^{f-1} + \left(\frac{a\Delta t}{h^2} + \frac{\epsilon u \Delta t}{2h}\right) T_{i-1}^{f-1} + \left(\frac{a\Delta t}{h^2} - \frac{\epsilon u \Delta t}{2h}\right) T_{i+1}^{f-1}$$

Where h is the mesh step, the lower index *i* indicates position and the higher index *f* indicates time. The criteria of stability are the following:

$h < \frac{2a}{\epsilon u}, \quad \Delta t < \frac{h^2}{2a}.$

A numerical model is developed using the basic convection-diffusion equation introduced above. The model is split into two parts. When the column is placed on the lakebed there is also a change in heat exchange within the soil. Therefore the bottom part of the model describes the 10 cm saturated soil below the lakebed. The top part of the model describes the first 30 cm of the lake above the lakebed. The initial condition assumes no cold water on the lakebed because initially turbulence is large. When the pipe is deployed (t=0 in the model), turbulence decreases and cold water can develop on the lakebed without wave disturbance. Initially the temperature in the soil equals the groundwater temperature of 12 °C. The two parts of the model, lake and lakebed, have different thermal properties, which are listed in table 4.2.



The 17 °C isotherms of the measured high resolution temperature profiles are analysed; the slope and the z-intercepts of these isotherms are determined. The groundwater outflow *u* in the model is varied until a good fit of the 17 °C isotherm is found.

Table 4.3: Values of the physical parameters used in the model

Property	Units	Symbol	Value
Porosity	Dimensionless	ϵ	0.22 [a]
Specific heat water	J g^{-1} °C^{-1}	c_w	4.1855 [b]
Specific heat sediment	J g^{-1} °C^{-1}	c_s	2.5253 [c]
Mass density water	g m^{-3}	ρ_w	0.99 x 10^6 [d]
Mass density sediment	g m^{-3}	ρ_s	2 x 10^6 [e]
Thermal conductivity water	J min^{-1} m^{-1} °C^{-1}	λ_w	34.8 [f]
Thermal conductivity sediment	J min^{-1} m^{-1} °C^{-1}	λ_s	132 [g]

[a] Estimated for Whakaipo Bay

[b] The International Committee for Weights and Measures, Paris, 1950, accepted W. J. de Haas's recommended value of 4.1855 Jg−1 °C−1 for the specific heat capacity of water at 15 °C

[c] Based on typical value for saturated medium coarse to medium fine sand sediment (Nederlandse organisatie voor energie en milieu, 2003)

[d] Value at 15 °C

[e] (Sekellick, Banks, & Myers, 2013)

[f] Value at 15 °C

[g] based on typical value for saturated medium coarse to medium fine sand sediment (Nederlandse organisatie voor energie en milieu, 2003)

5 RESULTS

The results of the various temperature measurements are described in this chapter. The chapter will start with the results of two horizontal profiles made in Whakaipo Bay. Then the key findings of the vertical measurements are presented. The chapter will end with the results of the numerical model; the modelled temperature profiles and the corresponding groundwater fluxes of the modelled locations.

5.1 Horizontal temperature profiling

The acquired temperature data sets of the two horizontal deployments are analysed and modified with the help of Matlab. Data sets are created and imported in ArcMap so it can be visualized on a map of Whakaipo Bay with the locations of the cold spots.

5.1.1 Near shore deployment

Due to software problems in the field during cable deployment, useful data was acquired for 7 minutes. The water temperature over the study period ranged between 17.9 to 21.3 °C. The DTS profile shows relatively homogenous temperatures over the study area with slightly lower temperatures along a stretch of approximately 30 meters on the south east side of the bay. The visualised data in figure 5.1 are the average temperatures over the 7 minutes. Visual inspection of the colder area showed pock marked depressions in the lakebed ranging in diameter from 1 to 10 cm (figure 5.2). This area also showed remarkable algae growth on the lakebed, in contrast to similar areas in the proximity.

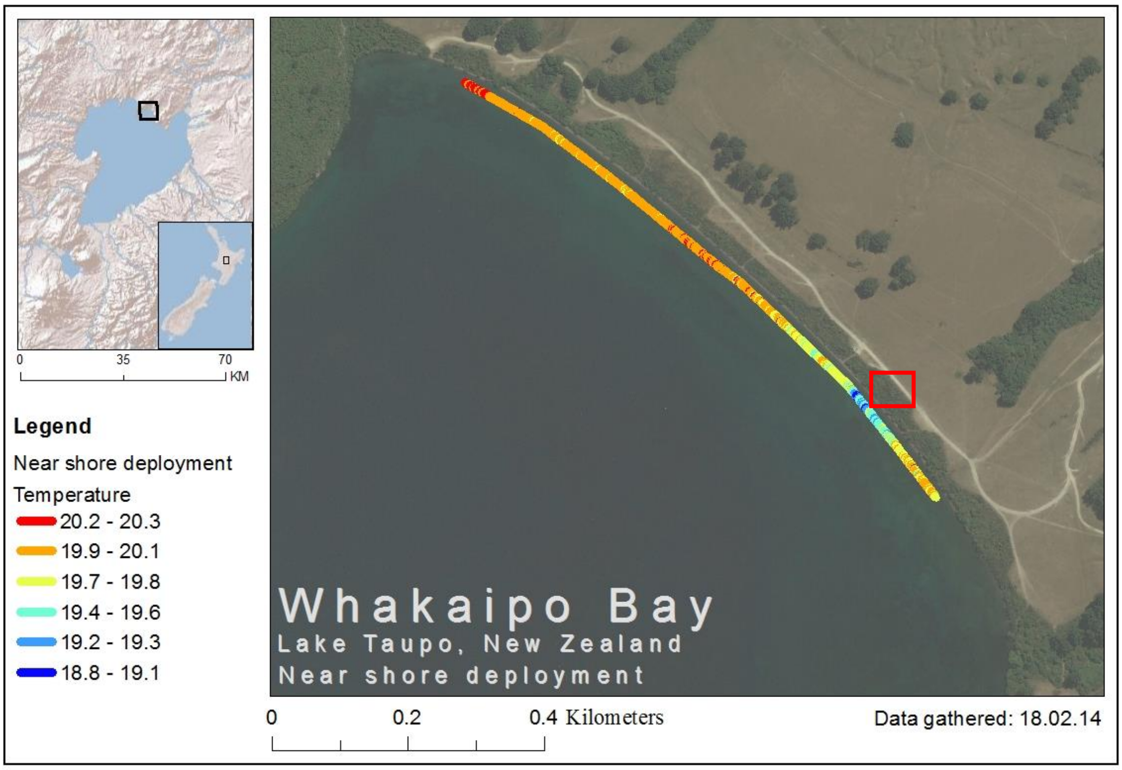


Figure 5.1: Average measured temperature (°C) of near shore FO-DTS deployment in Whakaipo Bay. Red square is location of picture 5.2

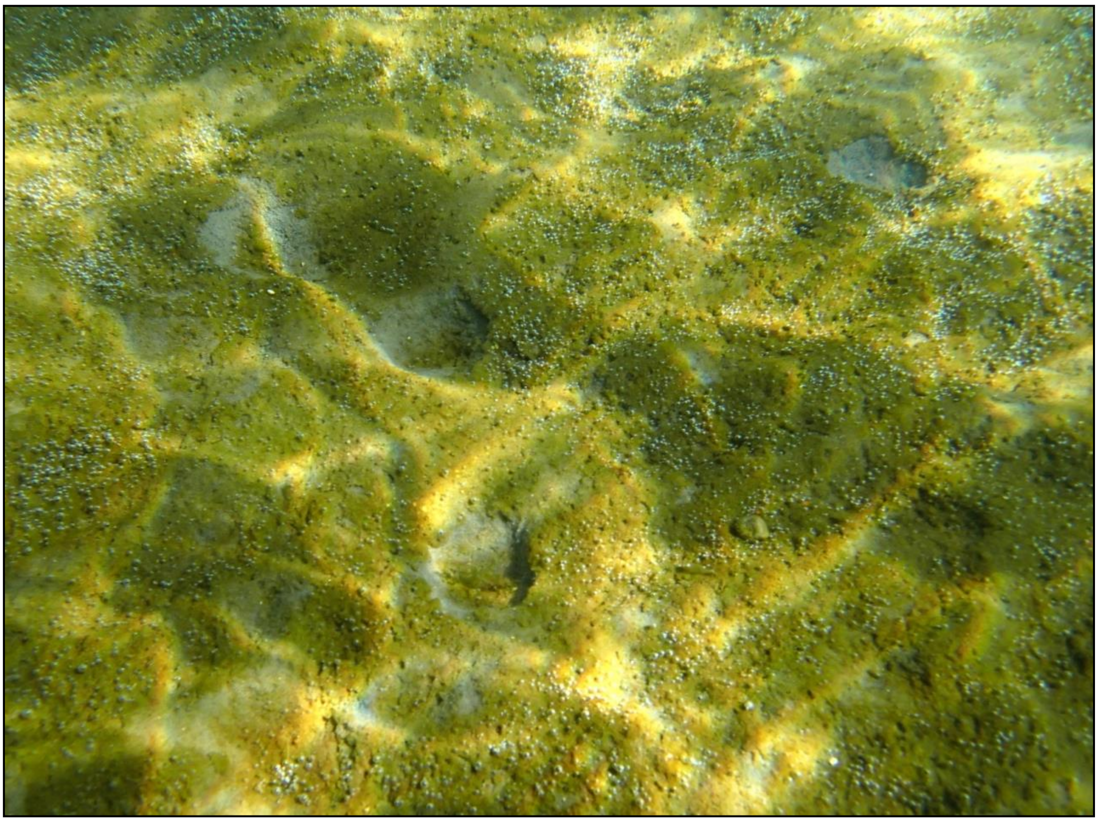


Figure 5.2: Picture of pockmarked depressions and algae growth in lakebed at cold area near shore in Whakaipo Bay

5.1.2 Offshore DTS deployment

The temperature results visualize the night time data because turbulence was smallest in this time span (figure 5.3). The average water temperature at the lakebed during the night ranged between 13.7 and 18.5 °C. Three areas of cooler temperatures (<16.5 °C) are visible; one in the centre of the bay approximately 160 m offshore, the second near the north western corner of the bay and the third approximately 80 meter offshore in between the other two cooler areas. The predominant temperature along the cable is 17 to 18 °C. This temperature is defined in this research as “medium warm”. An area of warmer temperatures (>18.0 °C) is present close to shore near the north eastern corner of the bay.

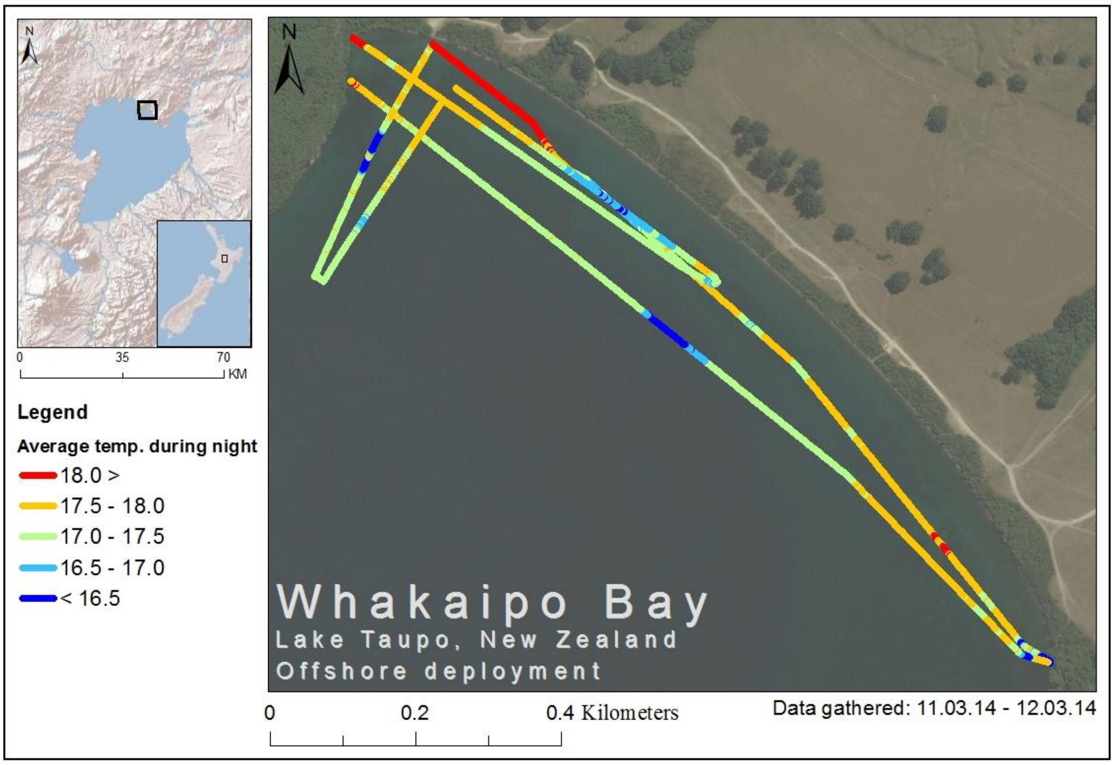


Figure 5.3: Average measured temperature (°C) at the lakebed during the night by FO-DTS deployment in Whakaipo Bay

5.2 Vertical temperature profiling

Figure 5.4 shows the locations of all the vertical measurements made in Whakaipo Bay deployed in the time frame between February 12th 2014 and April 19th 2014. Tables 5.1 to 5.3 contain the basic information of the measurements. The logger device was easy moveable because it was not restricted to an onshore located device. Therefore measurements could be taken at a broad range of depths and distances from shore. The FO-DTS measurements are more clustered close to the Oryx location; in the vehicle on the road at one of the entrances to the shore. These measurements are therefore more clustered in groups.

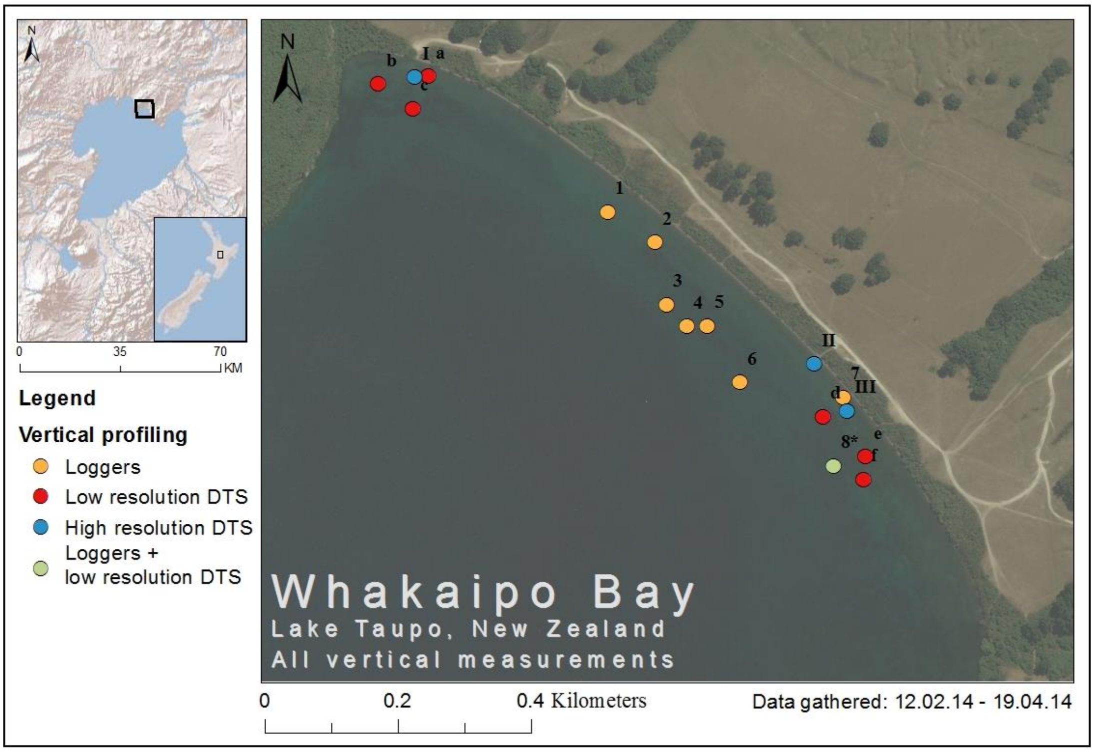


Figure 5.4: All vertical temperature deployments Whakaipo Bay

Table 5.1: Basic details of the vertical temperature logger measurements in Whakaipo Bay

Label	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8***
Date	18/2	18/2	18/2	18/2	18/2	26/2	26/2	24/2
Measurement time (min)	11	8	61.5	16	44	30.7	37.3	22.5
Depth (m)	3.8	3.8	5.8	5.8	4.3	7.0	1.1	5.1
Average temp (°C)	19.25	19.55	18.72	18.71	18.76	19.64	19.58	20.20

Table 5.2: Basic details of the low resolution FO-DTS measurements in Whakaipo Bay

Label	**a**	**b**	**c**	**d**	**e**	**f**	**8***
Date	12/2	12/2	12/2	24/2	24/2	24/2	24/2
Measurement time (min)	30	22	29	25	19	18	53
Depth (m)	1.7	2.4	4.5	3.5	2.5	3.4	5.1
Average temp (°C)	19.27	18.86	17.97	19.15	17.94	18.09	19.03

Table 5.3: Basic details of the high resolution FO-DTS measurements in Whakaipo Bay

Label	**I**	**II**	**III**
Date	10/4	02/4	10/4
Measurement time (min)	152	144	139
Depth (m)	1.2	1.1	1.2
Average temp (°C)	18.03	17.81	18.48

5.2.1 Loggers

The average temperature of the 7 logger deployments is between 18.71 and 20.20 °C. Most logger measurements show a relative homogeneous temperature within the measured vertical profile. However, the logger data at location 7 (figure 5.5) shows a 1 degree temperature difference between the logger at the lakebed and the three loggers at respectively 0.3, 0.5 and 0.75 meter above the lakebed. The temperature data of the other 7 locations in Whakaipo Bay did not show a significant temperature difference between the lakebed and the overlying water. This can either mean that there is no groundwater inflow at these locations, or the resolution of the device is not high enough to detect the groundwater layer.

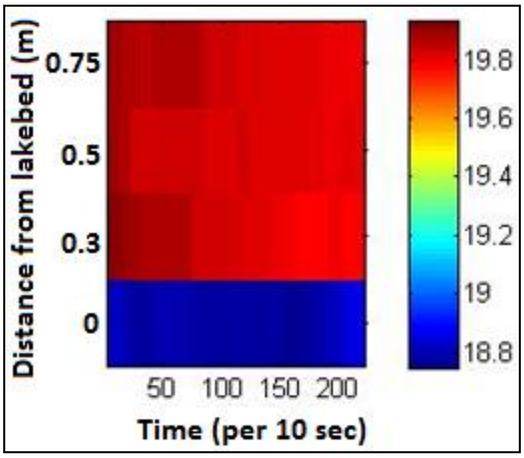


Figure 5.5: Vertical logger temperature (°C) profile in time of location 7 (figure 5.4). Total measurement time of 37.3 min with 10 sec time steps

5.2.2 DTS low resolution

The average temperatures measured with the low resolution DTS device at the 7 locations range between 17.94 and 19.29 °C. The temperature profiles are visualized in appendix #. At location 8* (figure 5.4) two measurements were taken with the vertical low resolution DTS device. Initially the device was placed in the vegetation. After 30 minutes the device was moved 1 meter away from the initial location out of the vegetated area. The data shows a colder layer at the lakebed when the device was located at a location surrounded by plants. This cold layer disappears almost completely, and does not return, when the device was taken out of the vegetated area and repositioned at a non-vegetated area (figure 5.6).

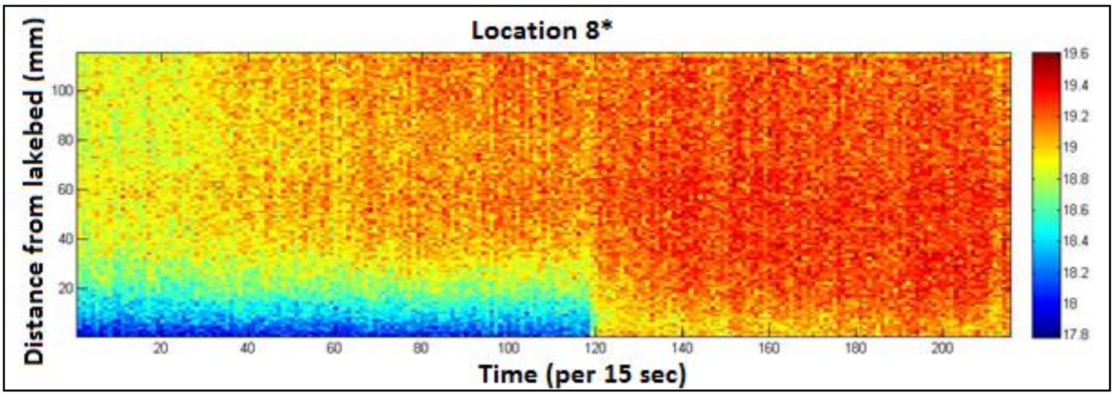


Figure 5.6: Measured temperatures of the vertical low resolution FO-DTS (°C) profile at location 8* as a function of vertical distance from lakebed (0-120mm) and time (0-53 min). Device was moved from vegetated area to non-vegetated lakebed at time step 120 (minute 30)

5.2.3 DTS high resolution

Results of the three vertical FO-DTS deployments in Whakaipo Bay are presented as graphs which show the temperature changes over time. The datasets of location I and II have slightly been corrected for the measuring anomalies caused by the devices. The uncorrected data are visualized in appendix VI.

Location I:
During the deployment at location I part of the cable was coiled and submerged in the lake. This caused abnormal and unrealistic temperature data. Initially the temperature measured at the lakebed was approximately 16.5 °C decreasing to the top of the column to approximately 14.5 °C. At minute 136 the coiled part of the cable was straightened and the data rapidly shifted to realistic temperatures. The temperature profile of this period showed a relative homogenous temperature of approximately 18 °C throughout the column. The measurements data after the cable was uncoiled, at minute 136, are assumed to be reliable. The data before this time was corrected using the difference between the moment before and after minute 136.

The corrected temperature data set of location I (figure 5.7) shows a period of 16 minutes with significantly warmer temperatures. It is assumed that this is caused by a sudden change in the calibration of the DTS unit. The temperatures before and after this warmer period are assumed to be a better approximation of the absolute temperatures in the lake. The period before the warm period (minutes 0 to 65) shows a gradual cooling from the lakebed upwards. This might be caused by overcorrection of the data. No conclusions are drawn for this period because of the uncertainty on the reliability of the temperatures of this period. The period after the warmer period shows little temperature changes within the water column. These temperatures are assumed to be the most reliable. No colder layer at the lakebed becomes visible, therefore it is assumed that there is no groundwater inflow at this location.

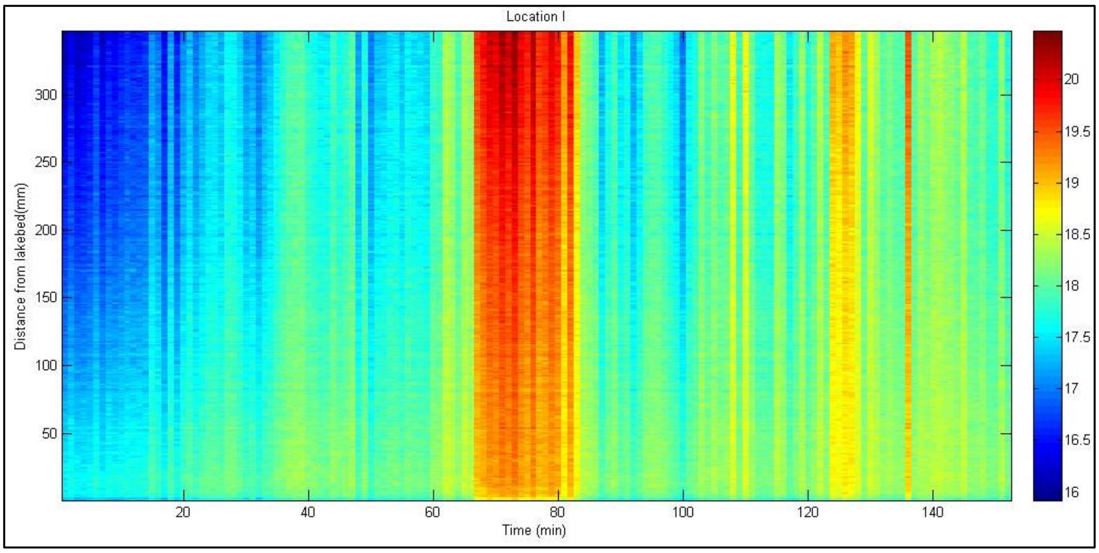


Figure 5.7: Measured corrected temperatures (°C) as a function of vertical distance (0 to 350 mm) and time (0 to 152 min) at location I (see figure 5.4)

Location II:

The dataset of location II shows two sudden jumps in temperature, at minute 58 a relative small jump and at minute 73 a bigger jump (see appendix VI for the uncorrected data). At minute 73 the temperature along the entire cable decreases approximately 1 degree Celsius. It is assumed that this jump is caused by a sudden change in calibration by the DTS unit and does not represent the true temperatures of the lake. The data set is therefore corrected for this sudden jump using the difference of a short period (7 minutes) before and after the jump. This correction increases the jump at minute 58. The data set shows higher temperatures in the first few minutes for a large part of the column. It is assumed that the cable was still adapting from the sudden change in temperature from air to water and these values are not considered to be reliable representation of the water temperature. Throughout the deployment at location II, the water column consistently has colder temperatures at the lakebed compared to the top of the water column (figure 5.8). In time a growing layer of lower temperature arises at the lakebed. Temperatures at the lakebed at the start of the measurement are 17.3 °C and slowly decrease in time to approximately 15.1 °C (decrease of 2.2 °C). Temperatures at the top of the column become stable after approximately 20 minutes. The thin layer of cold water developing at the base of the column slowly increases in thickness over time to approximately 100 mm. This colder layer is assumed to be cold inflowing groundwater.

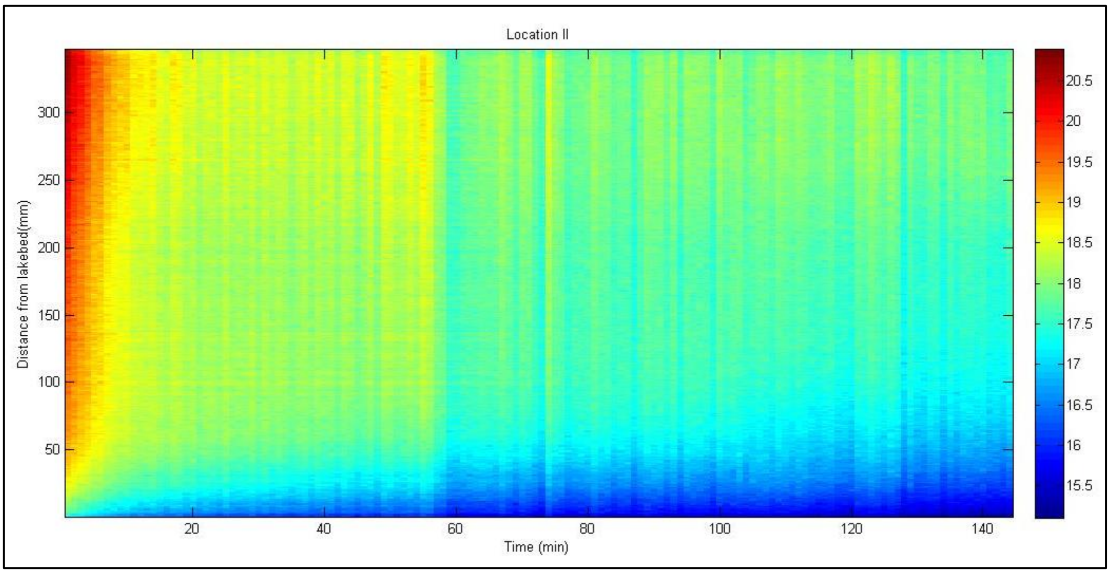


Figure 5.8: Measured corrected temperature (°C) as a function of vertical distance (0 to 350 mm) and time (0 to 144 min) at location II (see figure 5.4)

Location III:
The data of location III did not show any sudden changes by calibration or deployment errors and did therefore not need any correction. The data set of location III (figure 5.9) shows increasing temperatures from the lakebed to the top of the water column. The temperature at the lakebed at the beginning of deployment is 18.3 °C and slowly decreases in time to 15.3 °C (a decrease of 3.0°C). The thin layer of cold water at the base of the column increases to a thickness of approximately 110 mm after 144 minutes. Temperatures at the top of the water column stay relatively stable. The layer of colder temperatures is assumed to be inflowing groundwater through the lakebed.

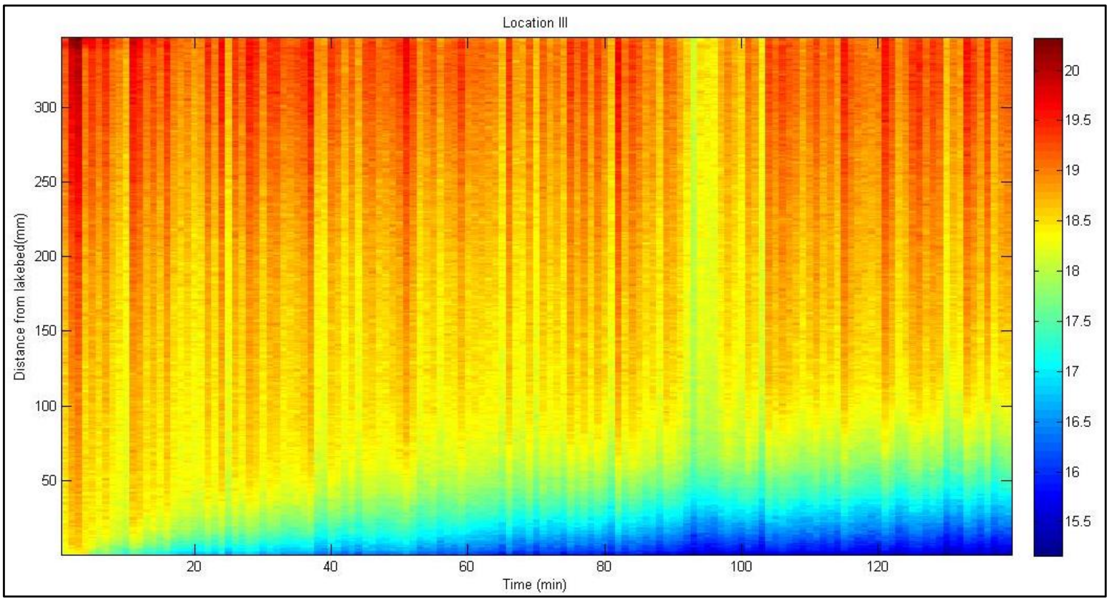


Figure 5.9: Measured temperature (°C) as a function of vertical distance (0 to 350 mm) and time (0 to 139 min) at location III (see figure 5.4)

5.3 Flux modelling

The high resolution FO-DTS profile of location II and III show groundwater inflow from the lakebed. The temperature profiles of these two locations are modelled with the numerical model in order to find the corresponding groundwater fluxes of the two locations. Results of the heat transfer model derived in Matlab are visualized in a similar way as the measured high resolution FO-DTS profiles. The figures show the temperature change in time and distance from the lakebed.

The corrected temperature profile of location II shows a small jump in temperature at minute 60. This small jump is caused by a change in the calibration by the DTS unit. The period after this moment is used for the model (min 60 to 140). The isotherm of 17 °C is drawn in the temperature profile of location II (figure 5.10). The slope of this isotherm is 0.38. The average temperature of the lake water that is used in the model is 17.6 °C. This is the average temperature of the overlying lake water. The modelled temperature profile for location II can be seen in figure 5.11. The slope of the 17 °C isotherm of this profile is 0.39. The corresponding groundwater flux is 1.3 cm h^{-1} also 0.013 m^3 m^{-2} h^{-1}.

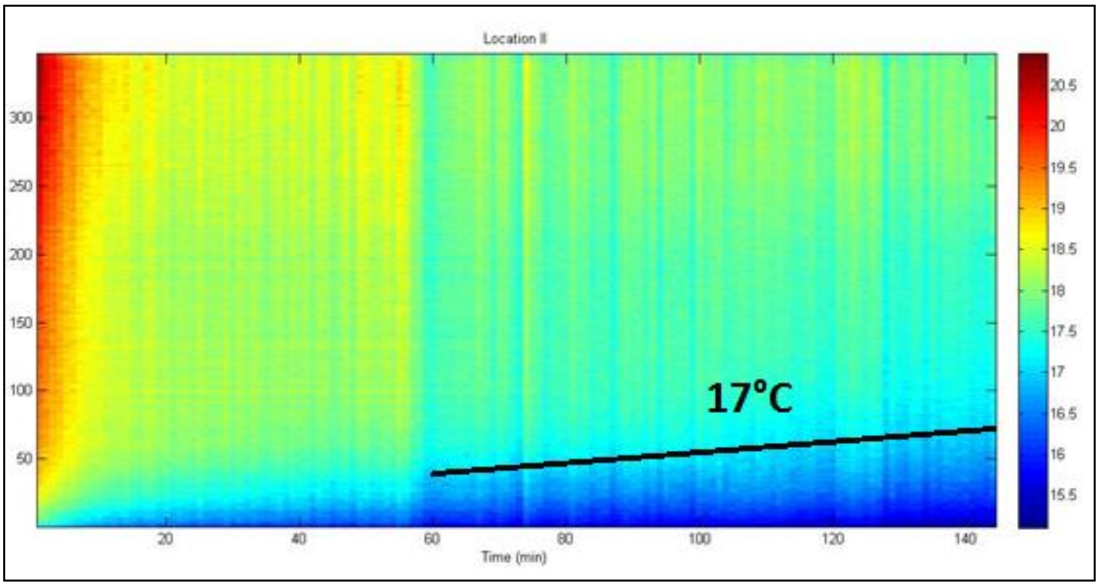


Figure 5.10: Measured temperatures and 17 °C isotherm of location II

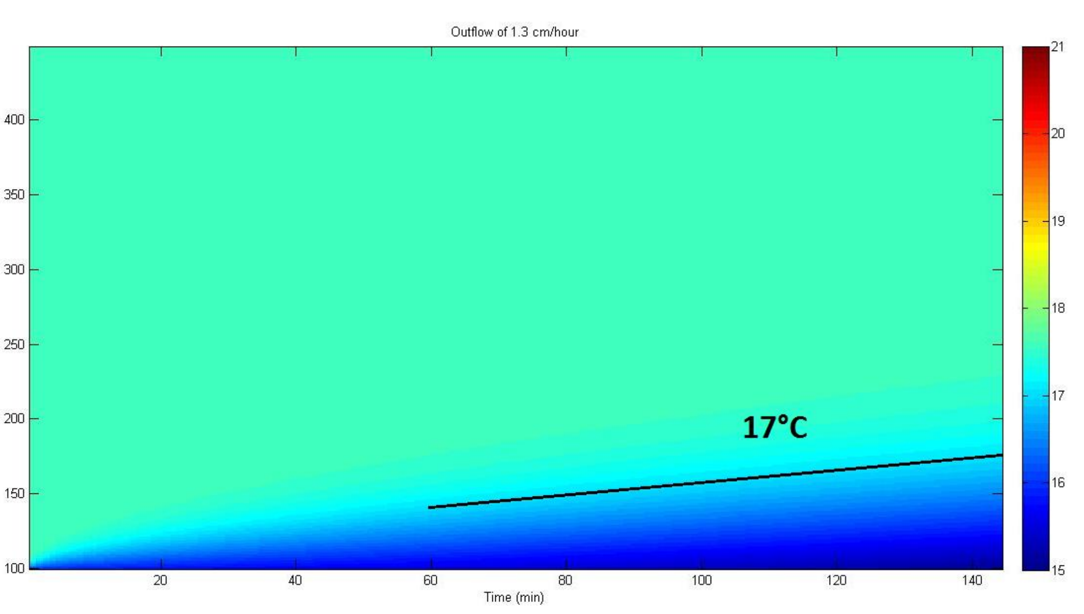


Figure 5.11: Modelled temperatures (°C) and 17 °C isotherm for location II

The 17 °C isotherm of the measured temperature profile of location III is drawn in figure 5.12. The slope of this isotherm is 0.32. The average temperature of the lake water that is used in the model is 19 °C, which is the temperature of the water of the lower half of the profile. This part has the most effect on the temperature exchange with the inflowing groundwater layer. The modelled temperature profile can be seen in figure 5.13. The slope of the 17 °C isotherm of this profile is 0.31. The corresponding groundwater flux is 1.8 cm h^{-1} also 0.018 m^3 m^{-2} h^{-1}.

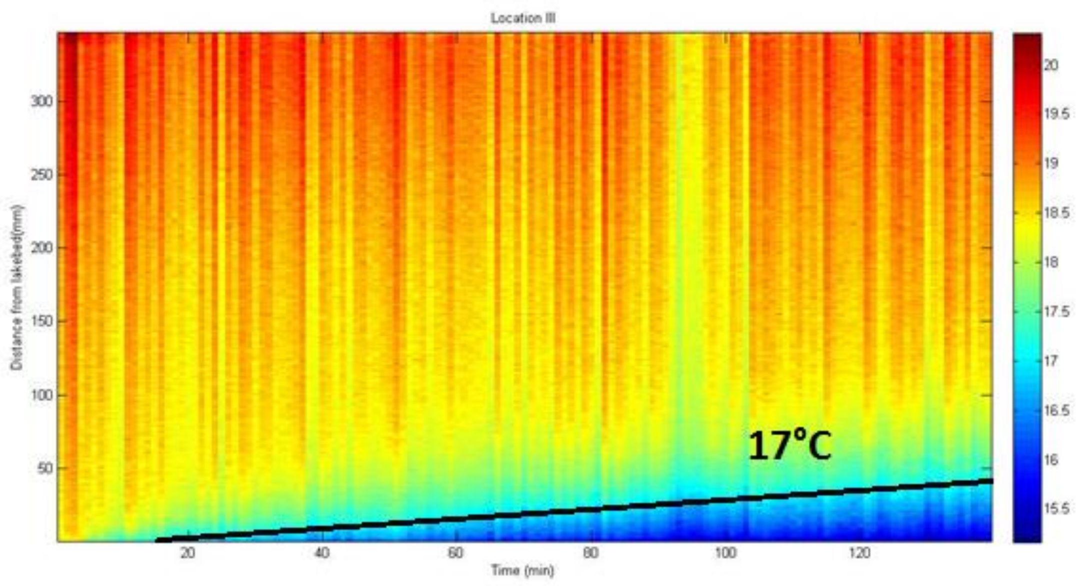


Figure 5.12: Measured temperatures and 17 °C isotherm of location III

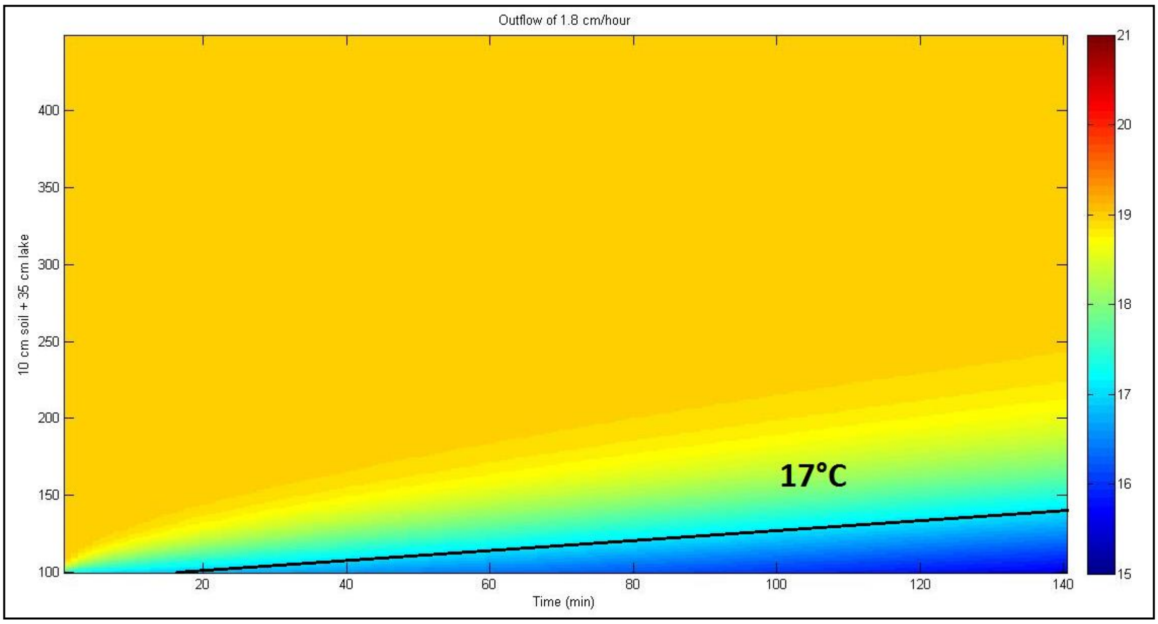


Figure 5.13: Modelled temperatures (°C) and 17 °C isotherm for location III (Fig 4.4)

According to the numerical model the groundwater flux on location III is higher than the flux on location II, 0.018 m^3 m^{-2} h^{-1} and 0.013 m^3 m^{-2} h^{-1} respectively. Location III is also distinguished as a cold zone by the near shore horizontal deployment.

6 DISCUSSION

The previous chapter illustrates the main findings of the temperature measurements made in Whaikapo Bay and shows the outcomes of the numerical model for location II and III. This chapter will attempt to verify the outcomes of the model by comparing the values with other data. Also, this chapter will consider the accuracy and reliability of the method and the acquired datasets. A focus on the limitation of this research will lead to recommendations for future research.

6.1 Reality check

By horizontal profiling different temperature zones are detected in Whakaipo Bay. The hypothesis that different temperatures indicate different groundwater inflow rates is proved with three vertical temperature profiles. These profiles are combined with a 1D convection diffusion model. The model used in this research is a simplification of the real world with several assumptions. Before going into these assumptions and the uncertainties of the model a quick reality check is done to check if the results of the model are close to realistic values. The most reliable method to do this is measuring the groundwater flux in Whakaipo Bay with another method, like a benthic flux chamber. It is recommended to deploy this device at the same moment and location as the deployment of the vertical high resolution FO-DTS device. Because this was not done during this research, we compare the model results with a previous study and the *displacement calculation* that also uses the acquired temperature profiles. Gibbs et al. (2005) measured the groundwater flux in 2005 at two locations in Whakaipo Bay with a benthic flux chamber at a rate 5 litres m^{-2} h^{-1} (equals 5 mm h^{-1}) at both locations. The displacement calculation calculates the volume of displaced lake water by the inflowing groundwater. It assumes no heat conduction between the inflowing cold water and the overlying lake water. The thickness of the cold layer at the end of the measuring period is measured and with the measurement time the groundwater flux is calculated. Location II had a cold layer of approximately 0.0592 meter thick which formed in 144 minutes. This is 0.0592*(60/144) = 0.0247 m h^{-1} (24.7 mm h^{-1}). At location III a cold water layer formed of 0.0376 meter in 140 minutes. This is 0.0376*(60/140) = 0.0161 m h^{-1} (16.1 mm) The results of these two quick scans and the model outcome for both analysed locations in this research are listed in table 6.1.

Table 6.1: Derived groundwater inflow in this study at three locations near shore compared with the derived ground water inflow at two locations further off shore (by Gibbs et al. (2005))

Method	Location I	Location II	Location III	Two locations off shore
DTS and displacement calculation	**0 mm h^{-1}**	**24.7 mm h^{-1}**	**16.1 mm h^{-1}**	
DTS and convection-diffusion model	**0 mm h^{-1}**	**13 mm h^{-1}**	**18 mm h^{-1}**	
Benthic chamber and temperature residence time model by Gibbs et al. (2005)				**5.0 mm h^{-1}**

An interesting result from this comparison is that the simple method results in a higher inflow rate at location II while the model results in a higher discharge for location III. This arises from the fact the simple method does not take the heat conduction between the layers into account which is important for location III where there is a large temperature difference between the layers. The temperature difference at location II is 17.6 - 12 = 5.6 °C, while the temperature difference at location III is 19 – 12 = 7 °C. The larger the temperature difference the more important the conduction factor is in the process of heat transfer, assuming the same turbulence during both measurements.

Gibbs et al. (2005) measured with a benthic chamber a flux of 5 mm h^{-1} at two different locations. This is a factor 2.5 - 3.5 difference between the measured fluxes at location II and III. The measurements of Gibbs et al. (2005) were made at deeper locations further off shore compared to location II and III. This might explain the different groundwater fluxes. It is known that the seepage rate is often largest around the lake margins where wave action restrict the deposition of fine sediments.

6.2 Vegetation as groundwater inflow indicator

At two measurement sites in Whakaipo bay a possible connection between vegetation growth and groundwater inflow is detected. The first is at location 8* where temperature is measured with the vertical low resolution DTS device. Initially the device is placed in a vegetated area and a small layer of cold water becomes visible at the lakebed. When the device is taken out of the vegetated area and placed 1 meter away from the initial location, the cold layer is not present. The cold layer at the lakebed in the vegetated area can either mean that cold water is trapped in the vegetation because there is less mixing with warmer water. It can also mean that the plants are growing at this location because there is nutrient rich cold groundwater inflow creating favourable conditions for vegetation.

The second location where groundwater inflow might be related with vegetation is at location III. At this location groundwater flux is highest and algae patches and pockmarked depression were present. The algae growth might imply more favourable conditions for vegetation growth caused by nutrient rich inflowing groundwater.
Algae growth can be influenced by many factors like temperature, nutrients, salinity, pH and light. Therefore, only speculations can be made on the causal relation between groundwater inflow and vegetation present in Whakaipo bay. However, this research shows that vegetation might be a useful indicator for groundwater inflow.

6.3 Assumptions and uncertainties

This research combined three vertical high resolution temperature measurements with horizontal temperature measurements. The vertical measurements are in agreement with the horizontal profile; no groundwater inflow was measured in the warm zone (location I), moderate inflow in the medium warm (location II) and the highest inflow in the coldest zone (location III). More vertical measurements need to be done before conclusions can be drawn about the usability of the horizontal FO-DTS in detecting groundwater inflow zones.

The thermal properties and sediment parameters, like porosity and specific heat, in the model are now based on literature and estimated values. Using the location specific thermal properties, such as the local heat conductivity of the sediment and local groundwater temperature, would improve the reliability of the outcome of the model. Although the model is not very sensitive for changes in porosity. Calibrating the method and model by measuring the flux with another proven method would enable one to make the theoretically based model more location specific.

The model uses an explicit scheme, the temperature is totally dependent on the temperature of the previous time step. The explicit scheme is not unconditionally stable and it is important to comply with the stability criteria. An implicit scheme is more robust and unconditionally stable, however this method involves more involved numerical schemes and programming.

The two high resolution vertical temperature profiles were both acquired in shallow water of approximately 1.5 meter deep. The groundwater fluxes calculated with the model are location specific and do not represent the inflow over the entire bay. The horizontal profile can be used as an indicator for the spatial variability in the bay. However, more vertical measurements are needed to get a clear understanding of the spatial variability of the groundwater inflow.

Because temperature is used as a tracer a difference in temperature between the groundwater and lake water is needed. Therefore the method is restricted to the months when there is a difference in temperature. This study was done during summer months, when the lake water was warmer than the groundwater. The groundwater outflow in summer probably differs from the outflow in other periods by factors such as lake level. The calculated flow is therefore not representative for the entire year.

6.4 Recommendations

To give more inside in the relation between the horizontal and vertical temperature profiles, and to reduce the uncertainties, the following actions are recommended:

1. More vertical measurements need to done in order to establish a reliable relation between the vertical and horizontal temperature profiles. If a relation can be found with little uncertainty, horizontal measurements might be useful to estimate the groundwater flux in a large area without doing the vertical point measurements.
2. Observations in deeper areas of the lake need to be done in order to determine the difference between shallow and deep groundwater inflow into Whakaipo Bay. If a relationship can be determined between water depth and inflow, an estimation of total groundwater inflow into Whakaipo Bay can be made.
3. The sensitivity of site specific thermal properties and parameters in the Matlab model need to be investigated.

The method currently uses the temperature difference of the lake water and groundwater in the summer months. However, there is also a temperature difference present in the winter months. In contrast with the summer, the lake water during these months is colder than the groundwater. It can be investigated if the used method is also applicable in the winter months, extending the period in which the method could be used.

7 CONCLUSIONS

This thesis presents a new combination of methods for characterizing groundwater surface water interaction. High-resolution spatial and temporal temperature measurements were combined with a numerical convection-diffusion heat transport model to quantify the groundwater inflow in Whakaipo Bay. This chapter lists the main conclusions that can be drawn from the results in chapter 4 and the analyses of the results in 5. The conclusions will be based on the research questions described in chapter 1.

> *To what extend are seepage areas in Whakaipo Bay detectable by horizontal* deployment of FO-DTS?

The horizontal temperature profile of the water at the lakebed showed clear temperature zones both off- and near shore. The three high resolution profiles acquired in Whakaipo Bay were in agreement with the hypothesis that colder areas are a result of groundwater seepage at that location. Although more verification of the method is needed, the results of combining horizontal and vertical FO-DTS profiles indicate high potential to characterize the variability of groundwater seepage.

> *To what extend are vertical deployment of FO-DTS in combination with a numerical model able to quantify the groundwater flux in different areas?*

For this study a new innovative FO-DTS device was constructed to acquire high resolution vertical temperature profiles. These profiles were input for a numerical model to calculate the flux of seepage water through the lakebed. With the model the groundwater inflow flux can be calculated. The method shows great potential as an easy to deploy, accurate seepage meter.

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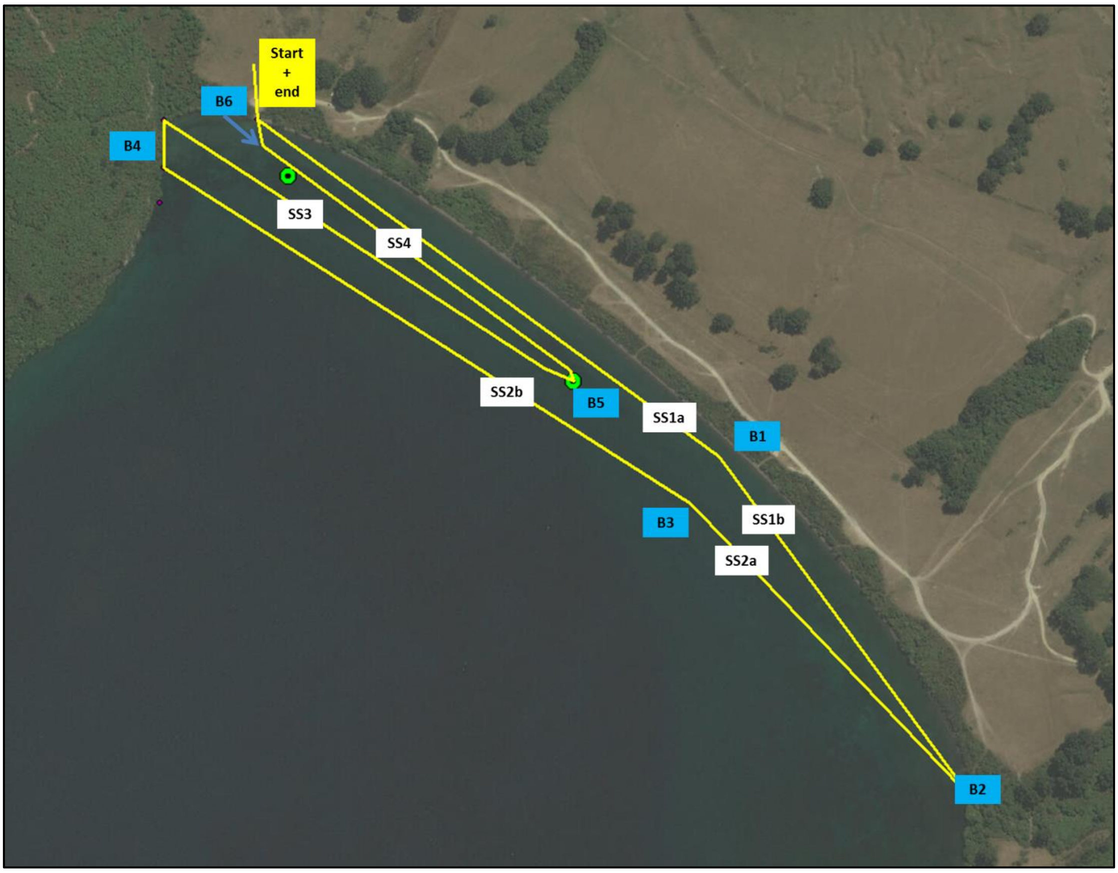
Annex I
Near shore horizontal deployment February 18th 2014

Date : 18-2-2014
Location : Whakaipo Bay, Lake Taupo
People : E.C. Meijer, F. Verhagen, S.Cameron, R. Westerhof
Garmin Waypoints : 185
Cable length : 2,300 meters

I.I: GPS track of cable deployment

Annex II
Offshore horizontal deployment April 11th + 12th 2014

Date : 11-4-2014 and 12-4-2014
Location : Whakaipo Bay, Lake Taupo
People : Heath Cairns : boat navigation
Johno : Assistant on boat
Abigail Lovett : Land/kayak man 1
Floris Verhagen : Land/kayak man 2
Elisabeth Meijer : boatman 1
Maryam Moridnejad : boatman 2
Stewart Cameron : boatman 3
Rogier Westerhof : boatman 4
Garmin Waypoints : 221 - 243
Cable length : 5,000 meters



II.I: Planning cable deployment March 11

II.II: GPS coordinates March 11 and 12

III.III: GPS track of cable deployment March 11

Working schedule:

Monday morning		
9:00	go/no go decision for Tuesday depending on the weather forecasts	All
	If no go, the data in this file all shifts by the number of days the fieldwork is postponed.	
Monday		
9:00-17:00	Packing equipment and canoe at trailer and in car	Floris and Lizzy
	Make sure everything is fully charged *1	Lizzy
	Find out how the radio's work	Lizzy and Floris
	Print all maps and schedules	
	Prepare extensive fieldwork forms	Floris and Lizzy
17:00	Take chilly bins home for next day	Lizzy & Floris
Tuesday		
6:00	Floris picks up Lizzy with own car	Floris and Lizzy
6:10	Buy ice at garage	Lizzy and Floris
6:30	Pick up car and trailer at GNS	Lizzy & Floris
7:00	Meeting at the harbour, load cable onto boat	Lizzy, Floris, Heath, Maryam, Abi
7:30	Leave with boat (& DTS Cable) to Whakaipo Bay	Heath, Maryam
7:30	Drive with own cars to bay	Floris, Stew, Abi
7:30	Drive GNS car with kayak and Oryx to bay	Lizzy
8:00	Boat meets Stew + Abi + Floris + Lizzy on North end of the bay (coordinates start/end see table)	All
8:05	Floris drives with car + equipment (see appendix) to southern end of bay (use car of Abi of Stew)	Floris
8:05	Get the first meter of the cable on the land (see marking in table for details)	Lizzy, Stew, Maryam
8:10	Start deployment of cable	All (except Floris)
10:30	Stew leaves but Land/kayak person 1 is now on the boat so no enough people	
13:00	Start measurements	All
13:00	Lunch break	Oryx & laptop
From 13:00	Keep check output data every half an hour	Maryam, Lizzy, Floris
18:00	Bring Maryam back to Taupo and get dinner	Lizzy
21:00	Go to bed?	Lizzy and Floris
Wednesday		
8:55	Rogier drives to B2 to release cable from pole and take mini piece of pipe with him	Rogier
9:00	Rogier arrives with car at the bay with breakfast for Floris and Lizzy	Rogier
10:00	Heath arrives with boat at the bay to retrieve the cable	Rogier, Floris, Heath, Lizzy and
13:00?	Finished retrieving the cable	
14:30	Car has to be back at GNS	Rogier or Lizzy or Floris

Detailed working scheme for deployment of the cable:

Heath will slowly (2.5-5 km/hour) navigate the boat along the planned lines. This can't be too fast, because it is very important to ensure that there is no pressure/tension on the cable. Every once in a while the marking on the cable needs to be checked to make sure that every 500 meter a GPS waypoint is taken and that the planning of the cable still matches (see tables for details). Also at each curve on the outer sides of the bay GPS waypoints need to be taken.

Position	**Length**	**Planned marking**	**Real marking**	**Notes**
Cable start		5250		
Slack + CB 1	30	5250 – 5220		
Car to water	30	5220 – 5190		
SS1a	900	5190 – 4290		
SS1b	670	4290 – 3620		
B2	5	3620 – 3615		
SS2a	645	3615 – 2970		
SS2b	985	2970 – 1985		
B4	80	1985 – 1905		
SS3	770	1905 – 1135		
SS4	620	1135 – 515		
B6	40	515 – 475		
Water to car	30	474 – 445		
Slack + CB 2	30	445 – 415		
Extra	165	415 – 250		
Total	5000			

CB = calibration bath

SS = straight stretch

B = Bend

Nr.	**Marking**	**Location**	**GPS**
1	5000	SS1a	
2	4500	SS1a	
3	4000	SS1b	
4		B1	
5	3500	SS2a	
6	3000	SS2a	
7		B3	
8	2500	SS2b	
9	2000	SS2b	
10	1500	SS3	
11		B5	
12	1000	SS4	
13		B6	

Start of deployment: The start of the deployment is on the northern end of the bay where the car with the Oryx and calibration baths will be located. At this point 30 meter cable is released from the reel for the calibration baths and for some extra slack. Another 30 meter of cable is calculated to run from the car to the water.

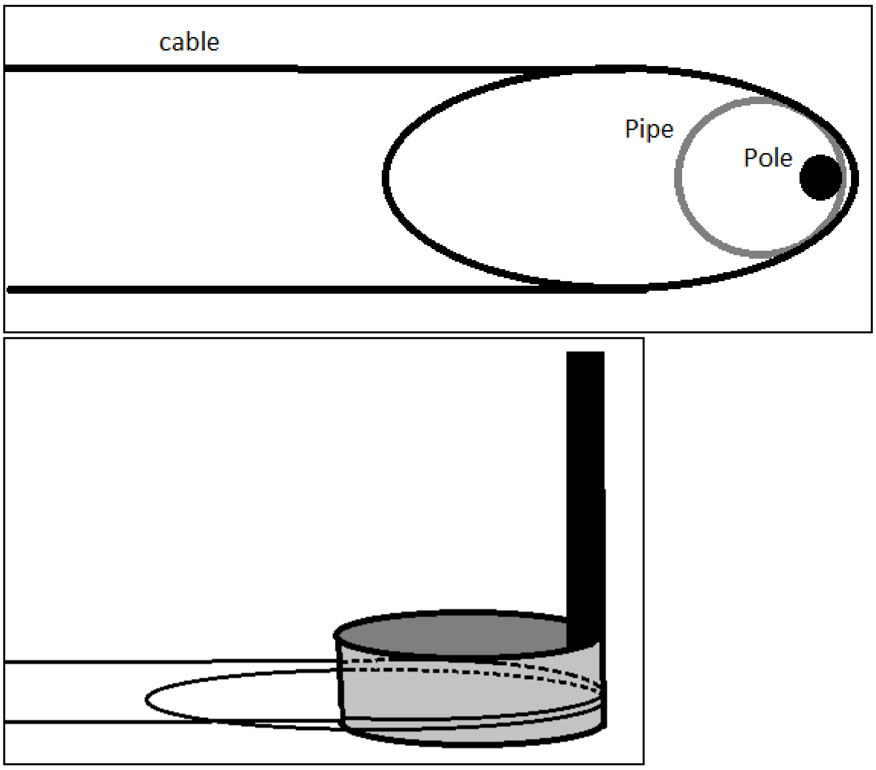
Land/kayak man 1 will hold the cable in place from the beach, or wading a few meters in the water. The first straight stretch to the southern end of the bay is made. Land/kayak man 1 holds the cable until all force/tension is off the cable. Only then he can let the cable go. For extra weight 4/5 pegs, each at a distance of aproximatly a meter is taped to the cable by Land/Kayak man 1.

Straight stretch 1a: Heath will navigate the boat to coordinate number 2. Here a small bend is made to direct the boat to B2 (the pole). In this straight stretch 2 GPS locations at markings 5000 and 4500 have to be made.

Bend 1: When this small bend is made the cable needs to be weighted down by 4/5 pegs which have to be taped to the cable.

Straight stretch 1b: After B1, Heath will navigate the boat to coordinate number 3. It is now very important that the persons on the boat ensure that there is no tension on the cable because at this point there is no man standing in B1 to hold the cable in place. In this straight stretch 1 GPS location at marking 4000 has to be made. Red tape is wrapped around the cable. Later, this part of the cable will be easier to relocate with snorkel and mask. With new GPS measurements it can be checked if the cable has moved from its deployment location.

Bend 2: At this location a long pole (for measuring the height of the water in the lake) is present on the beach. A small piece of pipe has to be put over this pole. Here the cable has to go out of the water and wrapped around the pole. Preferably twice in order to get a few meters of cable out of the water. It is unsure if the boat can navigate in shallow waters. Therefore **land**/kayak person 1 needs to be in waiders or swimming clothes to receive the cable from the people on the boat. When the boat heads north again for SS2 this person will hold the cable in order to keep the pressure of it. When the actions of the boat do not influence this part of the cable this person can release is and drive back to the start/end point of the cable.



II.IV: Cable deployment at B2

Straight stretch 2a: Heath will navigate the boat to coordinate number 4. Here is again a small bend in the cable which need 4/5 pegs to give the cable extra weight and stability.

Bend 3: When this small bend is made the cable needs to be weighted down by 4/5 pegs which have to be taped to the cable.

Straight stretch 2b: After B3, Heath will navigate the boat to coordinate number 5. It is now very important that the persons on the boat ensure that there is no tension on the cable because at this point there is no man standing in B1 to hold the cable in place.

Bend 4: (It is possible that a red flag is attached above this rock, but it is probably blown from the tree by the wind) The start of this bend is located at a rock in the water. It is possible to stand on this rock (however, watch out you don’t slip on the bird droppings). The boat will arrive here after SS2. The cable can either (1) go around this rock, (2) be coiled for a few meters and then hang in the three or (3) be coiled for a few meters and then laid down on the rock.

From this rock the cable will run through the water to the start of the beach. At the beach the bend toward the southern end of the bay is mad so here it is again important to hold the cable in place until all pressure is of it (probably after B5).

Straight stretch 3: Heith will navigate to coordinate number 6, which is an underwater well.

Bend 5: this bend is located at an underwater well. A small piece of pipe can be lowered with ropes so that is falls around this well. This pipe will protect the well and ensure that the cable will make a nice bend.

Straight stretch 4: This is the last straight stretch of the cable. Heath will navigate the boat to coordinate number 7.

Bend 6: This is the last bend of the cable. After this bend the cable will run the last 40 meters through the water before coming on land again. It is important that the cable is pressured down with some extra weight of 4/5 pegs. This might be possible from the boat but assistance from the kayak will be useful.

Equipment per location:

Land/kayak man 1:
- Kayak
- Pegs (2 x 5)
- Tape
- Scissors
- Tie-wraps

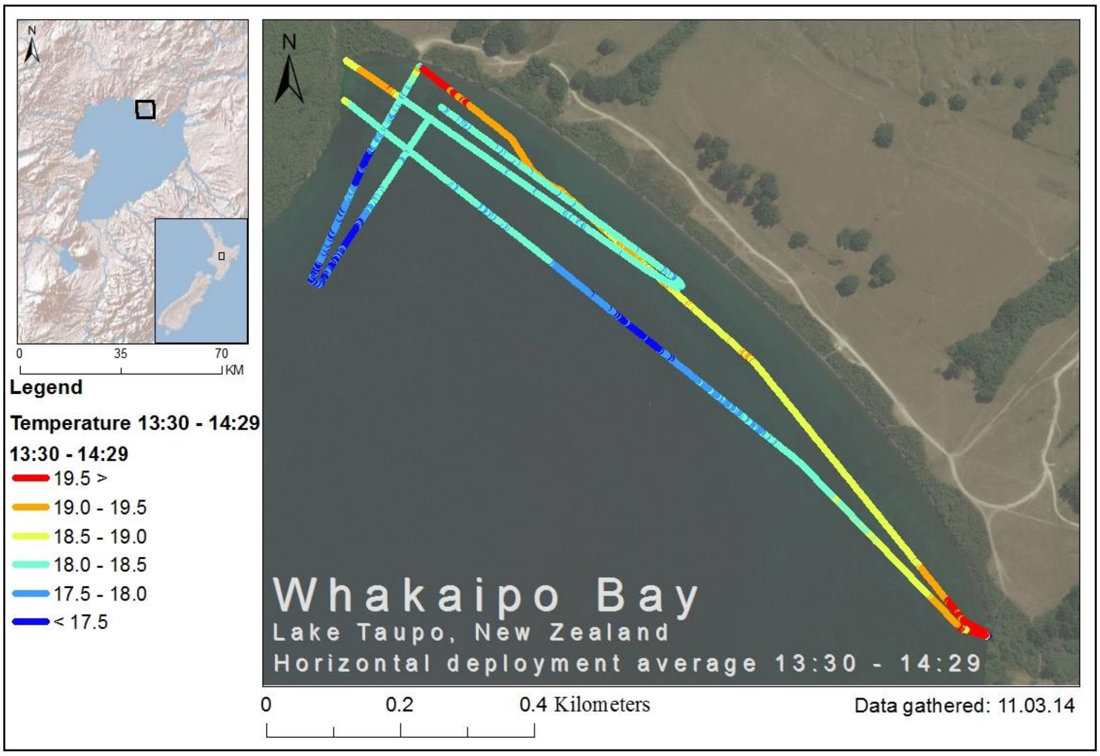
Land/kayak man 2:
- Waiders/swimming clothes
- Tape
- Scissors
- Mini piece of pipe for around poll
- Radio 1

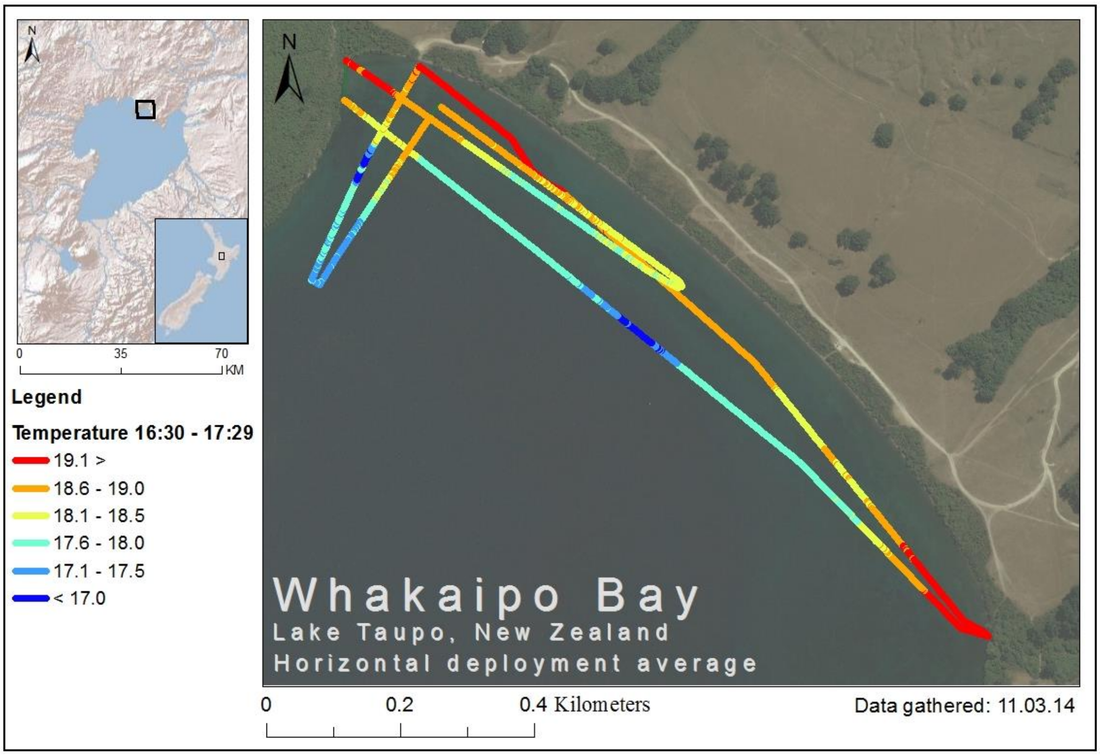
Boat:
- Red tape for the three SS1 markings
- Piece of pipe with rope to lower over the well.
- Pegs (2 x 5)
- Reel for left over cable (2x? maybe for in tree?)
- Radio 2

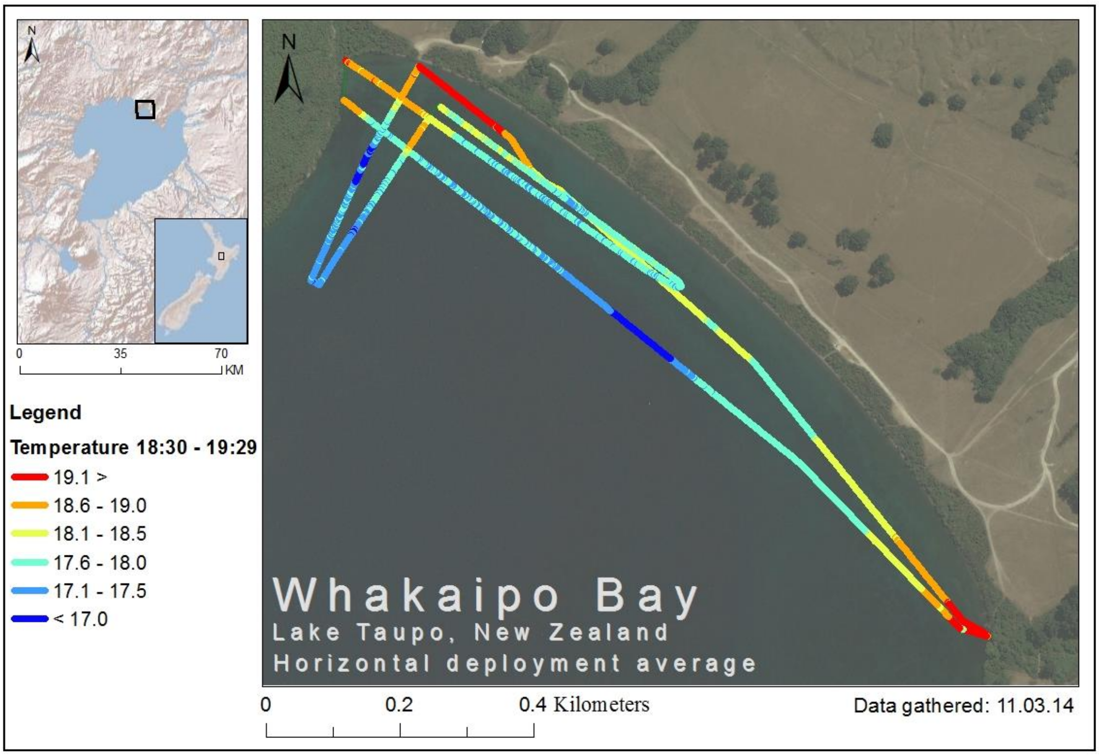
Bend	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**
Way of anchoring	Pegs	Figure II.IV	-	Three	Well	Pegs

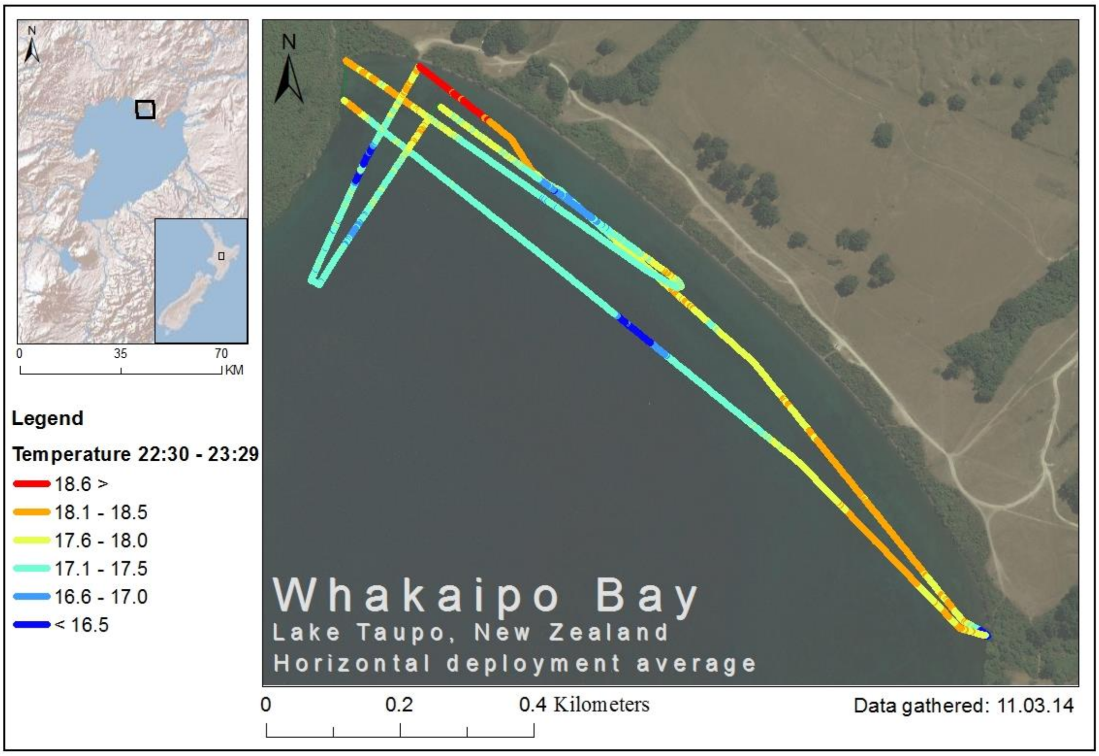
Notation on cable	**Metre cable from start**	**What**
550	0	Start cable
555-565	5-15	Cold bath
565-586	15-36	Clear
586-700	36-150	Wrapped
700-725	150-175	Clear
725-745	175-195	Hot bath
745-750	195-200	Clear

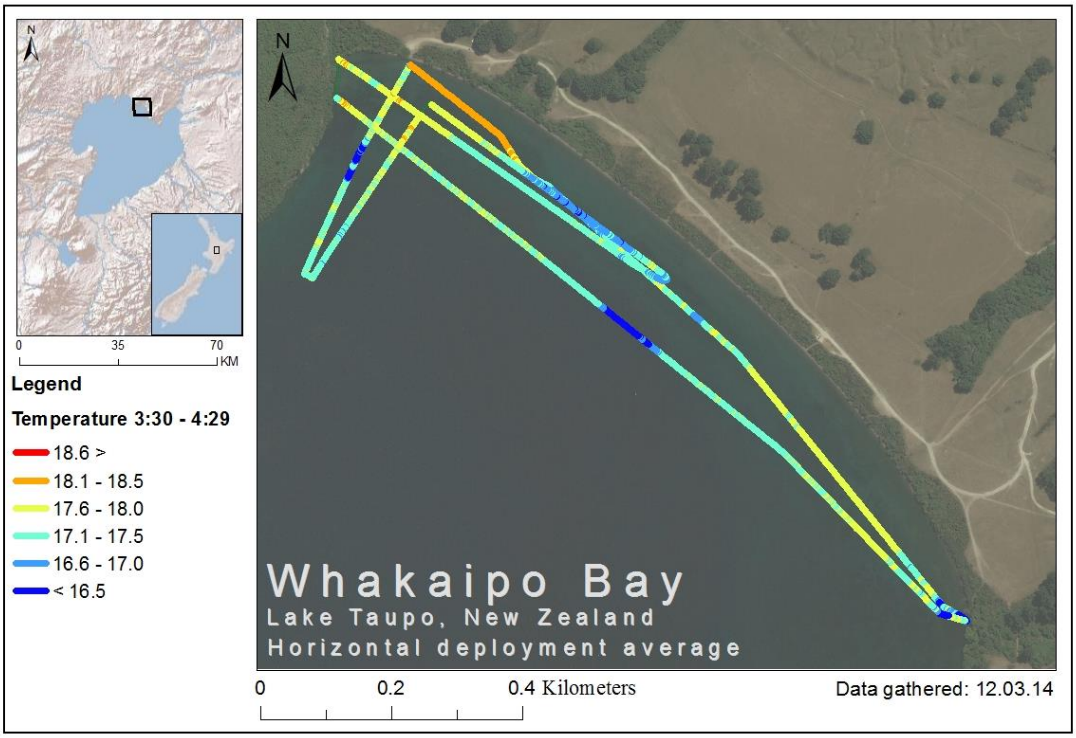
Annex III
Horizontal long cable results


N
0
35
70
KM
Legend
Temperature 13:30 - 14:29
13:30 - 14:29
19.5 >
19.0 - 19.5
18.5 - 19.0
18.0 - 18.5
17.5 - 18.0
< 17.5
N
Whakaipo Bay
Lake Taupo, New Zealand
Horizontal deployment average 13:30 - 14:29
0
0.2
0.4 Kilometers
Data gathered: 11.03.14


N
0
35
70
KM
Legend
Temperature 16:30 - 17:29
19.1 >
18.6 - 19.0
18.1 - 18.5
17.6 - 18.0
17.1 - 17.5
< 17.0
N
Whakaipo Bay
Lake Taupo, New Zealand
Horizontal deployment average
0
0.2
0.4 Kilometers
Data gathered: 11.03.14

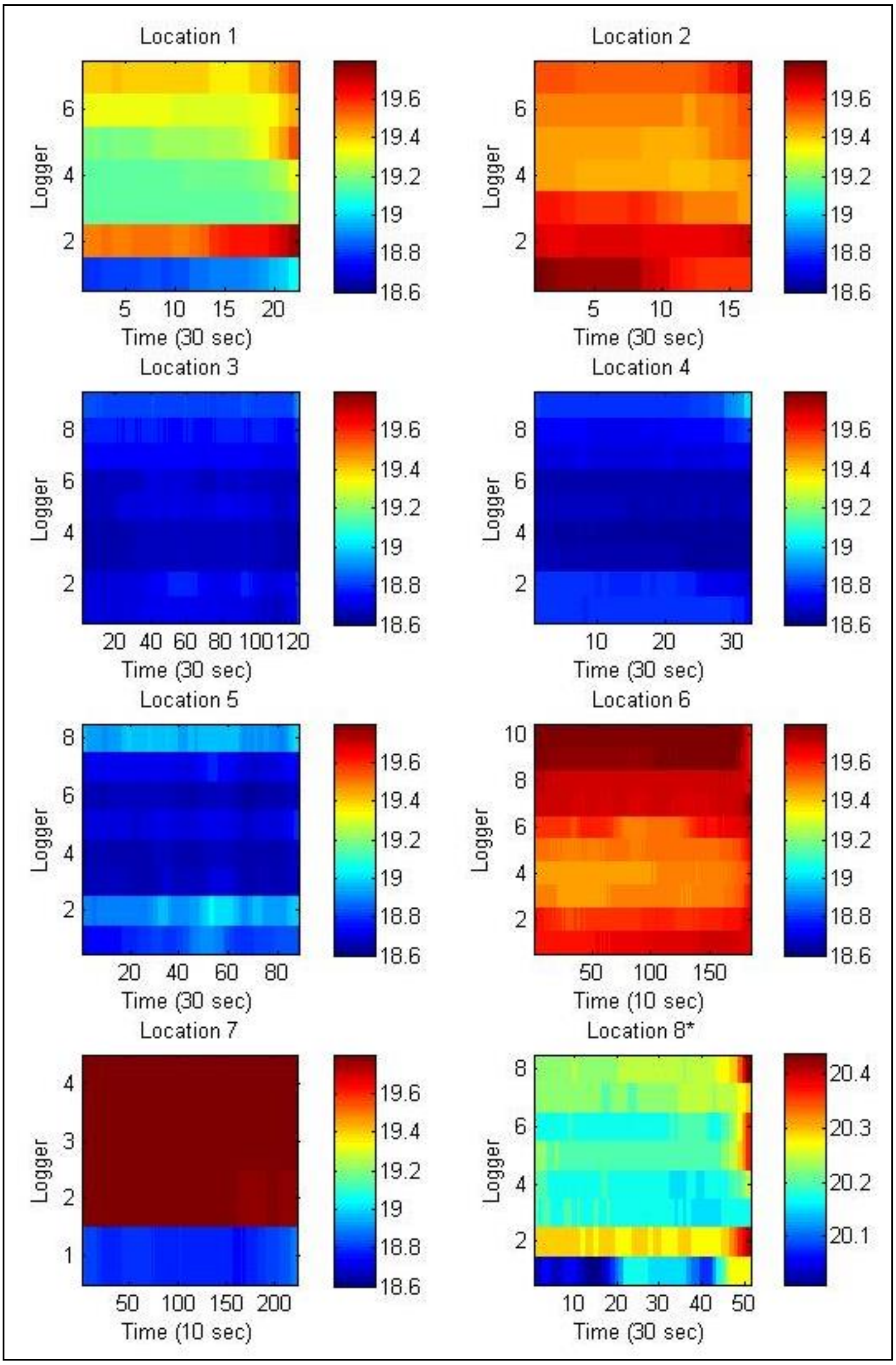

N
0
35
70
KM
Legend
Temperature 18:30 - 19:29
19.1 >
18.6 - 19.0
18.1 - 18.5
17.6 - 18.0
17.1 - 17.5
< 17.0
N
Whakaipo Bay
Lake Taupo, New Zealand
Horizontal deployment average
0
0.2
0.4 Kilometers
Data gathered: 11.03.14


N
0
35
70
KM
Legend
Temperature 22:30 - 23:29
18.6 >
18.1 - 18.5
17.6 - 18.0
17.1 - 17.5
16.6 - 17.0
< 16.5
N
Whakaipo Bay
Lake Taupo, New Zealand
Horizontal deployment average
0
0.2
0.4 Kilometers
Data gathered: 11.03.14


N
0
35
70
KM
Legend
Temperature 3:30 - 4:29
18.6 >
18.1 - 18.5
17.6 - 18.0
17.1 - 17.5
16.6 - 17.0
< 16.5
N
Whakaipo Bay
Lake Taupo, New Zealand
Horizontal deployment average
0
0.2
0.4 Kilometers
Data gathered: 12.03.14

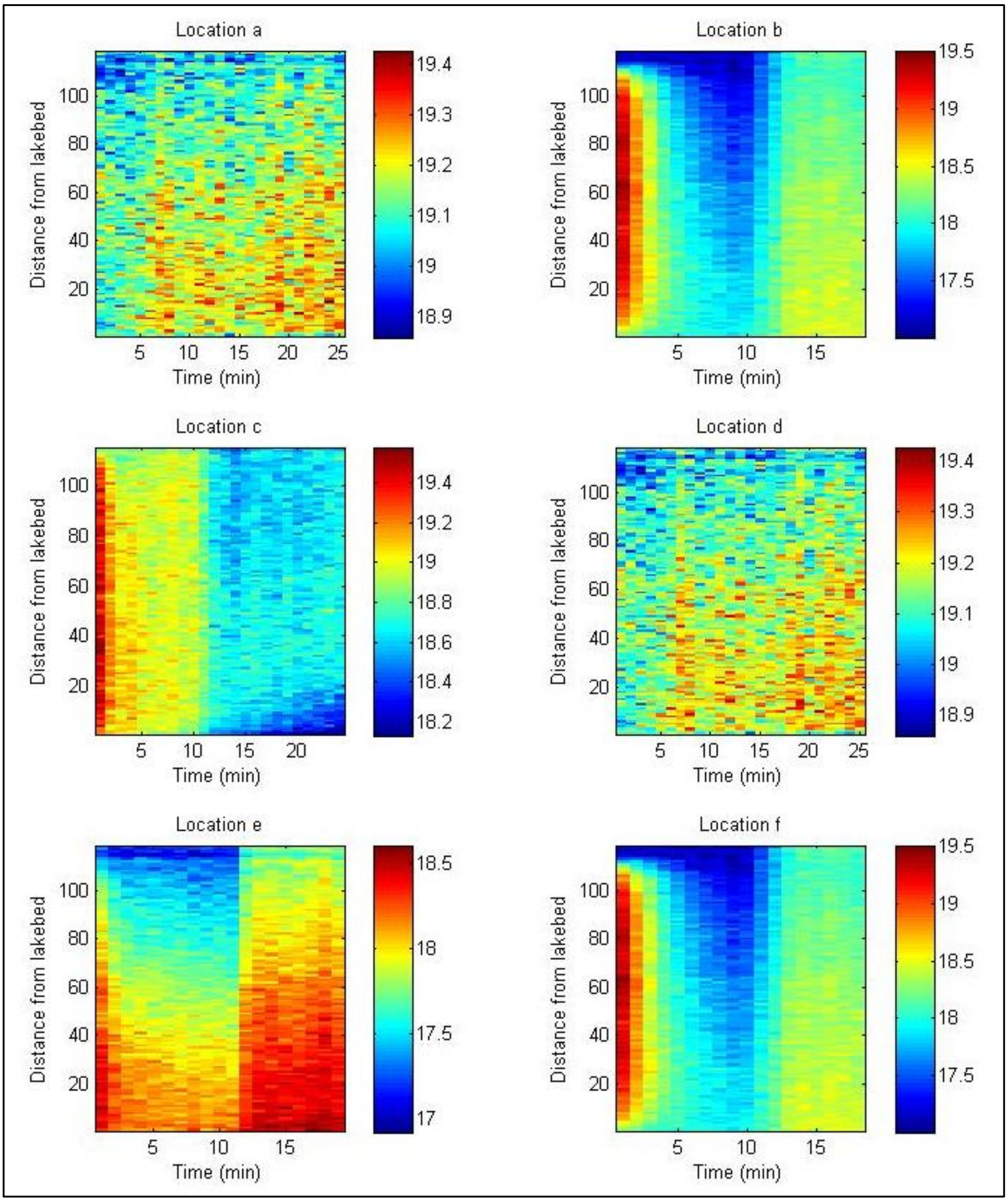
Annex IV
Results vertical profile temperature loggers

Label	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8***
Date	18/02	18/02	18/02	18/02	18/02	26/02	26/02	24/02
Depth (m)	3.8	3.8	5.8	5.8	4.3	7.0	1.1	5.1

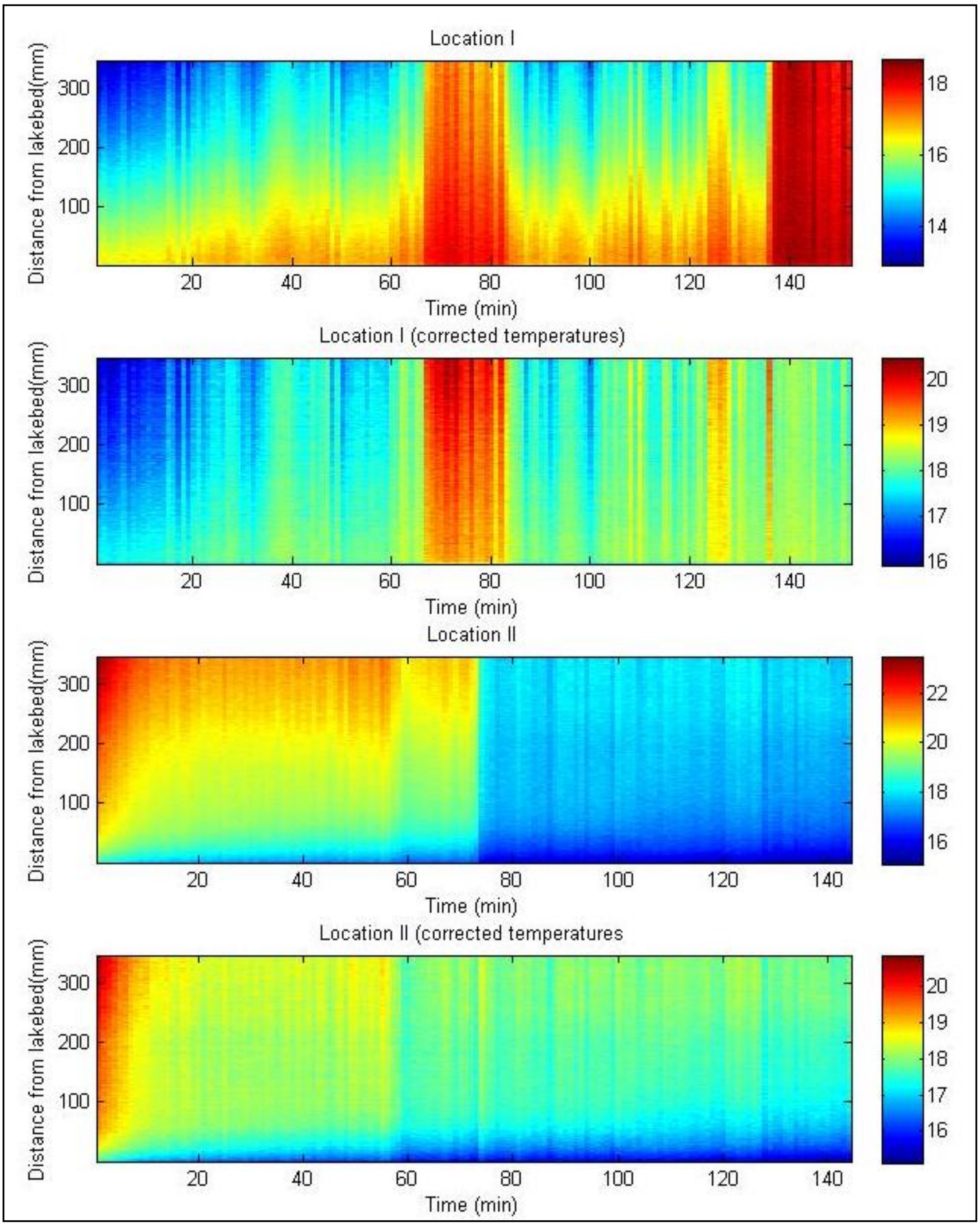


Annex V
Results vertical profile low resolution DTS

Label	**a**	**b**	**c**	**d**	**e**	**f**	**8***
Date	12/02	12/02	12/02	24/02	24/02	24/02	24/02
Depth (m)	1.7	2.4	4.5	3.5	2.5	3.4	5.1



Annex VI
Results vertical profile high resolution DTS


Location I
Distance from lakebed(mm)
300
200
100
20
40
60
80
100
120
140
Time (min)
18
16
14
Location I (corrected temperatures)
Distance from lakebed(mm)
300
200
100
20
40
60
80
100
120
140
Time (min)
20
19
18
17
16
Location II
Distance from lakebed(mm)
300
200
100
20
40
60
80
100
120
140
Time (min)
22
20
18
16
Location II (corrected temperatures
Distance from lakebed(mm)
300
200
100
20
40
60
80
100
120
140
Time (min)
20
19
18
17
16