MONITORING AND HYDRODYNAMIC MODELLING OF GROUNDWATER INFLOWS INTO LAKE ROTOKAKAHI, NEW ZEALND

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KO TE TANGATA

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WAIKATO
Te Whare Wānanga o Waikato

Abstract

Lake Rotokakahi is located 10 km south of Rotorua and is of immense cultural importance to the local iwi. The lake also has significant historical and recreational values, which prompted iwi to make the lake private in 1996. Lake Rotokakahi is one of several Rotorua/ Te Arawa lakes. Several of these lakes have become eutrophic and some have declining water quality. This study was prompted by declining water quality of Lake Rotokakahi and the need to identify potential sources of nutrients to the lake, particularly groundwater inflows.

The interaction between groundwater and surface water has a major influence on the trophic status of lakes, particularly those that are predominantly or solely groundwater fed systems. Lake Rotokakahi has one small spring-fed surface water inflow and one outflow, the Te Wairoa stream. Thus the lake is predominantly groundwater fed. The main objective of this thesis was to quantify the contribution of groundwater and surface water to Lake Rotokakahi and to examine interactions of the groundwater system with the lake, in order to provide a basis to improve lake management practices. Multiple monitoring sites were established around the perimeter of the lake to determine the spatial and temporal variation of groundwater inputs, as well as the groundwater nutrient dynamics. A three-dimensional hydrodynamic lake model was set up and simulations were used to examine how groundwater and surface water inflows were dispersed within the lake upon entry.

Monitoring of the shallow groundwater system took place from 1 January to 1 July 2016. Three separate storm events were monitored at high frequency within this monitoring period. The monitoring results showed the groundwater system varied significantly both spatially and temporally and also contributed a high proportion of the total nutrient load to the lake. Groundwater discharge and nutrient concentrations generally increased in association with or immediately following high rainfall events.

The three-dimensional model ELCOM was set up using hydrological data for the catchment, meteorological data from a nearby station and bathymetry of the lake. Simulations were based upon different methods of calculating groundwater inflows. Simulation 1 was based upon the common water balance equation method. Simulation 2 used constant groundwater inflow and outflow volumes as determined by a groundwater flow model, MODFLOW, which had been applied to the catchment by White et al., (2015). Simulation 3 combined MODLFOW values and measured groundwater levels to create a varying inflow volume based on water level. The three simulations accurately captured surface and bottom temperatures and had varying lake water levels. Only simulation 3 accurately captured the presence of the groundwater spring near the lake shore and was concluded the more accurate method of groundwater inflow calculation.

Acknowledgements

First and foremost I would like to thank my supervisor David Hamilton for the support, guidance and patience given to me throughout this project and for making this research project a reality.

I also thank the Rotokakahi Board of Control for allowing access to Lake Rotokakahi to undertake research in this amazing area. I am extremely grateful for the funding provided by Bay of Plenty Regional Council for the External Study Award which made this research possible. A huge thank you is due to Joe Butterworth for not only providing access but also for providing assistance in the field and extensive knowledge of the lake and the surrounding area. Also, thanks to Grant Tempero for providing technical advice and support throughout the entirety of this project. To the LERNZ group, particularly Chris McBride, Richard Lamont, Ronald Ram, Theo Kopondu, Eunju Cho, Simon Stewart, Mat Allan and especially Kohji Muraoka, thank you for getting me through the tough times of modelling. To Lena Schallenberg thank you for being my modelling buddy and keeping me sane throughout the process.

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1 Introduction

1.1 Groundwater-surface water interaction

New Zealand's rivers, streams, lakes, estuaries, and aquifers are associated with its national identity (Wright 2015). Both surface and subsurface water quality in New Zealand is an issue causing immense public concern. The focus of attention has recently shifted to determining the sources of pollution and ways to effectively manage water resources and prevent further decline.

Groundwater is an integral part of the hydrological cycle, however it is the least-understood component (Rosen & White, 2001). The interaction of groundwater with surface water systems is a topic gaining increasing attention (Kludge *et al.*, 2007) and is considered extremely complex and interconnected (Shaw *et al.*, 2013). In regard to lake ecosystems, the exchanges between the surface water and groundwater components play a major role in the ecological status of lake (Shaw *et al.*, 2013). In spite of the importance of this interaction, groundwater resources have generally not been well quantified or estimated, largely due to the difficulty of locating and quantifying groundwater flows. Due to interaction of surface and groundwater systems the management of the two must be integrated (White *et al.*, 2001).

Groundwater flows provide pathways for the transport of pollutants that can in turn impact sensitive aquatic receiving environments, particularly surface water systems that are predominantly groundwater fed. However groundwater discharge into surface water systems is not generally considered in quantifying biogeochemical fluxes in surface waters (Burnett *et al.*, 2006). This is largely due to difficulties with quantifying and understanding groundwater discharges, as they tend to be patchy, rapidly diffused and show significant spatial and temporal variations, and there may also be multiple aquifers (Burnett *et al.*, 2006).

Combined, groundwater and surface water inflows largely control lake water chemistry, water quality, aquatic habitat and biodiversity (Shaw *et al.*, 2013). In groundwater-dominated catchments, water quality decline and eutrophication have sometimes been linked to groundwater composition, including in the Lake Rotorua catchment (White & Moreau-Fournier, 2012a).

1.2 Rotorua Lakes Region

The Rotorua Lakes region is located in the Central North Island of New Zealand and contains 12 lakes of varying size and depth. The region and lakes are relatively young, in geological terms, formed by volcanic events and tectonic plate subsidence. The lakes have many economic, historical, cultural, ecological and recreational values. Historically, lake catchments of this region were predominantly native forest. As settlements established and populations increased, widespread changes occurred to land use in the surrounding catchments. Significant areas of land have been cleared for farmland, exotic forest plantations and urban development.

The Rotorua Lakes are of immense cultural importance to the local Te Arawa Iwi. Freshwater systems have always been considered tāonga (treasure) and of immense spiritual and cultural importance to Māori. This relationship begins from whakapapa, a genealogical association linking Māori with all natural resources. Freshwater plays a central role in tribal and personal identity, with each iwi having a special relationship with certain water bodies. With European settlement, which began in the 1800s, conflicts occurred between the new settlers and Te Arawa. In 1922 the Crown took ownership of the Rotorua Lakes area and paid an annuity to Te Arawa, except for Lake Rotokakahi which remained in ownership of the local iwi (Butterworth, 2008). Lake Rotokakahi is located within the Rotorua Lakes region and is owned by the Lake Rotokakahi Board of Control who are descendants of Ngati Tumatawera and Tuhorangi hapu, subtribes of Te Arawa (Butterworth 2008). The lake is administered by the Lake Rotokakahi Board of Control and is privately owned by iwi, with no public access permitted. Despite this, lake water quality has declined considerably in recent years (Jones *et al.*, 2014).

Water quality issues first arose in the Rotorua region in the 1950s and 1960s when the exotic weed species *Lagarosiphon major* and *Egeria sp.* first became prevalent in Lake Rotorua before spreading to surrounding lakes (Miller, 2003). As human populations and urban development in the area increased, increased nutrient loads to the lakes occurred from wastewater discharges, including input of treated sewage to Lake Rotorua from the city of Rotorua. Algal blooms began to occur in the 1960s together with eutrophication (Miller 2003).

A measure of water quality used for Rotorua and New Zealand lakes is the Trophic Level Index (TLI). The TLI was established by (Burns *et al.*, 2005) and is a number calculated from four different water quality parameters: total nitrogen, total phosphorus, water clarity and chlorophyll-a. The TLI numbers provide information on the trophic status category: super trophic, eutrophic, mesotrophic, oligotrophic and micro trophic. For the majority of lakes in the region, target TLIs have been set and Action Plans to achieve these targets have been put in place by the Bay of Plenty Regional Council, together with the Te Arawa Lakes Trust and the Rotorua Lakes Council. Lake Rotokakahi does not have an Action Plan and its TLI have increased over recent years (Scholes, 2011) (Butterworth, 2012a).

As a result of declining TLI in Lake Rotokakahi, evaluation is required of the dynamics of the catchment and lake, to understand the dynamics of the lake and implement effective management actions. Groundwater is the main pathway for water and nutrients entering the lake (Butterworth 2012). The Rotokakahi Board of Control has encouraged research to assess the groundwater system and its impacts on the lake. Research on groundwater-lake interactions is relatively new and is relevant to Rotorua Lakes, which have a large relative volume of input from this source.

1.3 Aquatic Ecosystem Modelling

Coupled hydrodynamic-ecological models are computer models developed for studies of aquatic ecosystems. These models have been widely applied to evaluate the ecology of lakes (Trolle *et al.*, 2012). These models can then be used as a tool for decision makers to improve lake management.

ELCOM (Estuary and Lake Computer Model) is a numerical model developed by the University of Western Australia. It applies hydrodynamic and thermodynamic models to simulate the temporal behaviour of stratified water bodies with environmental forcing (Hodges & Dallimore., 2008). The model simulates advection and diffusion in three dimensions and includes surface thermal forcing, inflows, outflows and wind stresses (Zhang, 2010). It is based on thermodynamic transfers in the water column and includes physical transport equations of Reynolds-averaged Navier-Stokes, scalar transport and Boussinesq approximation (Hodges and Dallimore. 2008). Combining hydrodynamic model simulations and field measurements enables an in depth understanding of processes that occur within lake ecosystems. These simulations can be used for evaluation of groundwater-lake interactions.

Modelled data output from a Geological and Nuclear Sciences (GNS) research project from White, *et al*. (2015) has been used in this study for the purpose of calculating groundwater inflows. This research involved creating a groundwater flow model for the greater Tarawera catchment which included eight lakes, one of which was Lake Rotokakahi. These eight lakes are hydraulically linked through the groundwater system and lake zones were created for each lake. Output from a groundwater flow model MODFLOW – 2005 was used as a means of groundwater flow calculation for inflows and outflows from Lake Rotokakahi.

In this study, a combination of high frequency monitoring data and field data have been combined with simulations from the hydrodynamic model ELCOM. Modelled data output from a Geological and Nuclear Sciences (GNS) research project from White, *et al*, (2015) has been used in this study for the purpose of calculating groundwater inflows. This has allowed for analysis of groundwater interactions with the lake itself. This information is essential for understanding lake ecosystem processes.

1.4 Research aims and objectives

The overarching aim of this thesis is to determine the interactions between groundwater and surface water in Lake Rotokakahi and the impacts these interactions have on lake ecosystem health.

To address this aim, the following objectives were set out:

1) To gain an understanding of the groundwater system and quantify groundwater inflows through field surveys.

2) To compare field groundwater observations with calculations derived from water balance equations and modelled values from a groundwater model.

3) To set up a three–dimensional hydrodynamic model of Lake Rotokakahi to assist with evaluating groundwater inflows.

4) To use the model developed in (3) to test the sensitivity of different methods for quantifying groundwater inputs to the lake.

2 Hydrogeological setting

2.1 Study area

Lake Rotokakahi (Green Lake) is located in the Rotorua Lakes Region of New Zealand and is 10 km south of Lake Rotorua and within the greater Tarawera catchment (Fig. 1). The hydrogeological components of the wider Lake Rotokakahi catchment area are relevant to groundwater investigations. Knowledge of the geology, soils, land use and hydrology are important as each affects groundwater movement and quality in different ways. These components are described separately below, together with the setting of Lake Rotokakahi and the history of the water quality and ecosystem health of the lake.

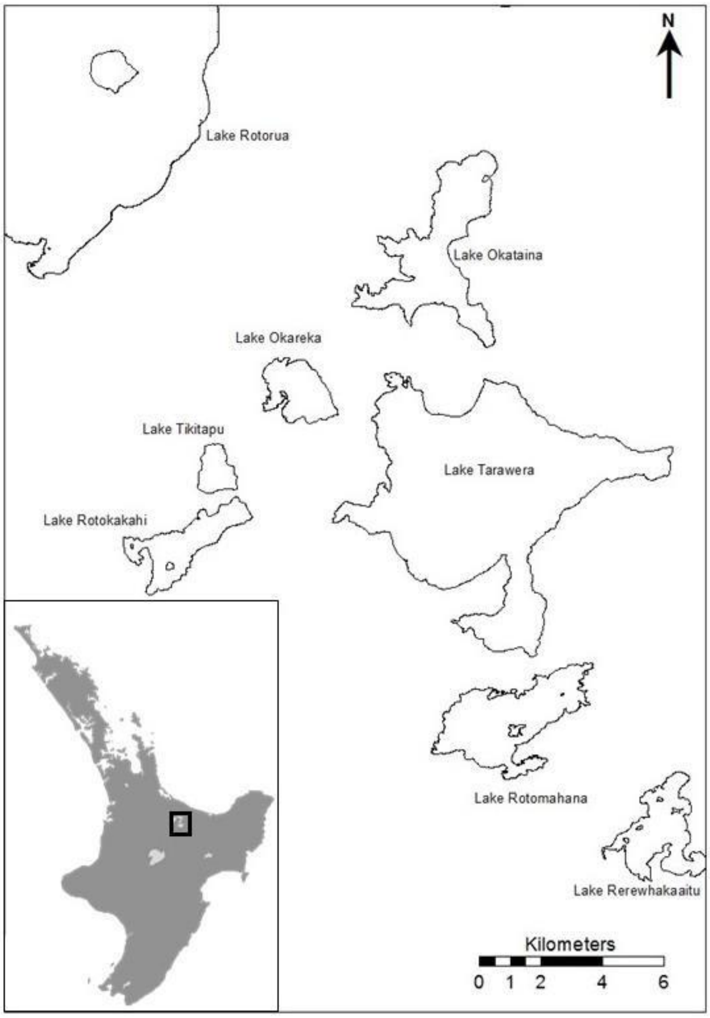

Figure 1: Map of the North Island, New Zealand and the Rotorua Lakes region.

2.2 Geologic Setting

The Rotorua Lakes Region lies in a geologically unique area in New Zealand. New Zealand lies upon the boundary of the Australasian and Pacific Plates. The collision of these two plates has resulted in the Pacific Plate sub ducting under the Australasian Plate, which has caused uplift, subsidence, volcanism, geothermal activity, erosion and deposition. This unique tectonic and geologic setting has resulted in aquifers with a range of lithologies within New Zealand.

Lake Rotokakahi is within the Rotorua Volcanic Centre which is located in the central part of the larger Taupo Volcanic Zone (TVZ). The TVZ is a North-East striking zone of volcanic and geothermal activity which extends from Mt Ruapehu to beyond White Island, just off the Bay of Plenty coastline and is, on average, 50 km wide (Wilson *et al.*, 1995). The TVZ was formed due to the Pacific Plate subducting under the Australasian Plate, which began approximately 2 million years ago and resulted in a rift zone being created (Wilson *et al.*, 2007). The TVZ includes a NE-trending zone of active rifting within the continental lithosphere that extends NW-SE at a rate ranging from ~15 mm y^{-1} at the Bay of Plenty coast to < 5 mm y^{-1} south of Lake Taupo, with extension of ~ 12 mm y^{-1} within the Rotorua Volcanic Centre (Cole *et al.*, 2010). The study area contains several rhyolitc calderas and caldera complexes with associated rhyolite lavas and lava domes. The edges of the TVZ differ as they are characterised by andesitic to dacitic effusive volcanism with no rhyolitic calderas (Nairn & Kohn, 1973). The oldest geologic units or basement rocks in this area are referred to as greywacke, which contains sandstones, argilites and conglomerates (Wilson *et al.*, 2007). The younger units that overlay the basement are described below (Fig. 2).

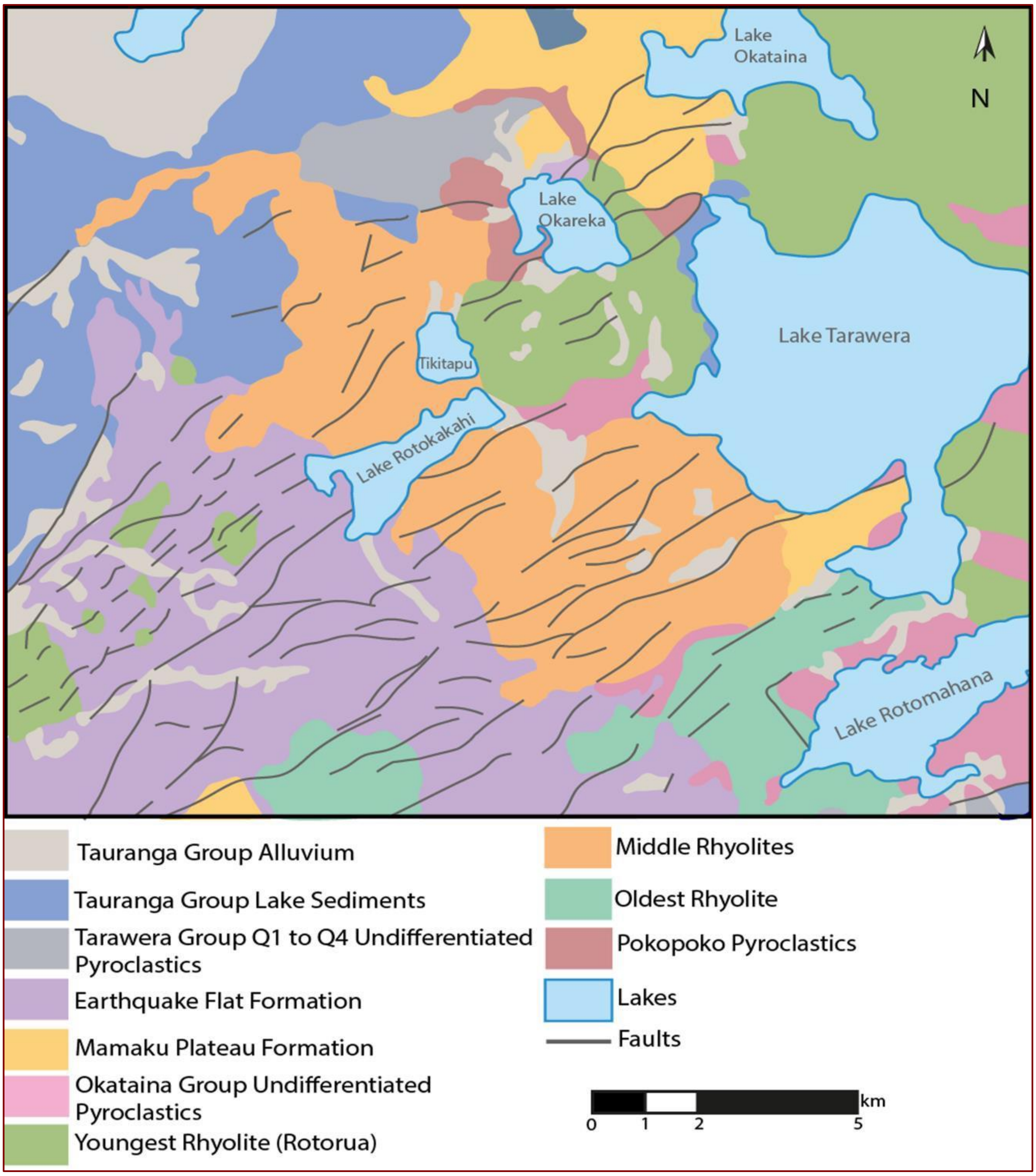

Figure 2: Simplified geologic map of greater Rotokakahi zone. Adapted from Leonard *et al*. (2010).

2.2.1 Geologic Units

The major geologic units of the Lake Rotokakahi area are described below. The geological categorization of these units is based on the quarter million mapping programme (QMAP), 1:250 000 scale, series for the Rotorua geological map from Leonard *et al*,. (2010).

2.2.2 Rhyolites

Rhyolitic units have been grouped together as Okataina Rhyolites as they are sourced from the Okataina Volcanic Centre (OVC) which is the most recently active rhyolitic caldera complex located south of Lake Rotorua. The most recent volcanism in the OVC was the 1886 Mt Tarawera Eruption. The oldest unit is dated at 550 ka (Cole *et al.*, 2010). The Okataina Rhyolites are grouped into youngest, middle and oldest rhyolites. The youngest rhyolites are post 61 ka, the middle rhyolites are between 61 and 180 ka and the oldest rhyolites are 180-322 ka and older (Leonard *et al.*, 2010). Rhyolite is known to be almost impermeable, thus groundwater flow is fracture dominated, with the size and number of fractures affecting the flow, as well as the linkages between them. The spring that flows into Lake Rotokakahi is located within the middle rhyolite unit near the east to west fault line (Fig. 2), indicating that the groundwater flow is controlled through a fault line within the rhyolitic unit.

2.2.3 Earthquake Flat Formation

The Earthquake Flat Formation is the other unit that dominates the geological catchment of Lake Rotokakahi. It is a thick, biotite-rich, rhyolitic ash and pumice deposit that covers 110 km^2 (Nairn & Kohn, 1973). The unit extends from Waiotapu in the south to the Hemo Gorge, just south of Rotorua, in the north. The formation consists of many pyroclastic flow units with interbedded and mantling air fall pyroclastic units (Nairn & Kohn, 1973) and is sourced from a line of eruption craters to the west of Lake Tarawera (Cole *et al.*, 2010). The Earthquake flat deposits have been considerably faulted, undergone erosion and have been described as highly permeable (Nairn, 1981) with a maximum thickness of 120 m (Leonard *et al*., 2010). The magma (biotite-bearing, crystal-rich) seems to be closely related to the Kapenga rhyolite lavas which was erupted earlier in the

Kapenga caldera to the northwest of Earthquake Flat (Cole *et al.*, 2010). The NW trend of the Earthquake Flat formation vents suggests that the magma was produced by melting of a previously cooled and largely crystallised silicic pluton. The melting was induced by basalt under plating during a widespread episode of basalt intrusion that also affected the Rotoiti magma body (Cole *et al.*, 2010). This is the unit that contains the majority of groundwater flow that enters Lake Rotokakahi. Due to the large pumice component and its permeable nature, this unit can contain a large aquifer that can have relatively fast groundwater flows. It is important to consider the land use practices that occur within the boundaries of the earthquake flat formation, as all areas within this zone, contribute to one aquifer. This area may extend out of Lake Rotokakahi's topographical catchment as groundwater catchments differ from those of surface water. This is due to surface water catchments being dominated by topography and groundwater catchments being controlled by geological formations, hence a sound understanding of hydrogeology of a lakes catchment is important to derive groundwater inflows into lakes.

2.2.4 Tauranga Group Alluvium

This group comprises Pliocene to Holocene alluvial sediments (sands and gravels), non-welded ignimbrite and tephra layers (Leonard *et al.*, 2010). These units are typically located in valleys around the lakes and are mostly saturated, indicating drainage of water to the groundwater system. However the unit is heterogeneous vertically and laterally which can result in varying hydraulic characteristics (White *et al.*, 2015a). In the Rotokakahi catchment the lower lying valleys of the earthquake flat formation are covered with Tauranga Group alluvium, indicating areas of groundwater recharge and flow.

2.2.5 Geologic Summary

The geology of the Lake Rotokakahi area consists of a combination of ignimbrite sheets, pyroclastics materials, rhyolite and dacite lava domes and alluvial sediments. The alluvial sediments are constricted to valleys which are volcanic deposits from erosion, as observed in the Rotokakahi catchment. There are three rift fault zones within the study area that strike northeast to southwest, the

Ongahoro faults and the Tumunui fault (Leonard *et al.*, 2010). There is a large degree of fracturing and interconnected fractures that control groundwater flow in rhyolite and welded ignimbrite units (Cole *et al.*, 2010) whereas in the unconsolidated sediments and un-welded ignimbrites the groundwater flow is controlled by the grain size of the material. Deposits coarser in composition, such as the sands and gravels of the Tauranga Group, allow high permeability whereas fine-grained layers such as tephra's and paleosols may act as aquitards that prevent groundwater flow between units.

2.3 Soils

The soils that dominate an area are dependent on different soil forming factors. These factors include climate, parent material, vegetation, time and topography and have given the soils of the Rotorua region unique characteristics. The parent material in the Rotorua region is dominated by volcanic deposits and includes tephra and peat deposits (Rijkse, 1979). The topography, particularly within the Rotokakahi catchment, is moderately steep with materials eroded and deposited in the lower lying valleys around the lake. There are three main soils that immediately surround the lake and several others higher up in the catchment.

2.3.1 Okareka steep land soils

Okareka steep land soils make up the majority of the soil surrounding Lake Rotokakahi (Fig. 3). These soils are defined as well drained and have high permeability (Rijkse & Guinto, 2010). They are described as recent tephric soils with the parent material being a thin layer of Rotomahana mud on rhyolitic tephra upon ignimbrite (Rijkse, 1979). The rhylotic tephra layer ranges in thickness from 0 to 200 cm (Rijkse, 1979). The steep land soils have variable soil profiles and are largely modified by erosion. Many outcrops of ignimbrite or rhyolite occur and the steep slopes restrict land use due to the erosion potential (Rijkse, 1979). The south eastern area is in native forest and dry stock grazing, however on the northern side the area is exotic forest subject to frequent harvest. This results in large amounts of sediment and soil runoff entering the lake during harvesting, due to the high erosion potential of the Okareka Steep land soils.

2.3.2 Haparangi sandy loam and Haparangi hill soils

Haparangi sandy loam and Haparangi hill soils occur to the western area of the Lake Rotokakahi catchment. These soils are described as being well drained with a loamy texture and rapid permeability (Rijkse & Guinto, 2010). They are very friable with very weakly developed structure (Rijkse & Guinto, 2010). The parent material for these units is Taupo Pumice < 50 cm thick, on weathered rhyolitic tephra (Rijkse & Guinto, 2010). Characteristics of this soil include low nutrient levels, high phosphate retention in the subsoil, and poor topsoil structure (Rijkse & Guinto, 2010). The majority of this area is in forest with a small area to the south being in dry stock farming.

2.3.3 Whakarewarewa sandy loam and Whakarewarewa hill soils

The Whakarewarewa sandy loam and Whakarewarewa hill soils dominate the western basin and western shores of Lake Rotokakahi, where it is forested. They are similar to the Haparangi sandy loam and hill soils and are differentiated by their different parent material. They are hill soils with parent materials being shallow patchy Rotomahana Mud, on 10 to 30 cm Taupo Pumice on weathered rhyolitic tephra, on ignimbrite (Rijkse, 1979). The Whakarewarewa soils have an unstable soil structure, erosion potential and low nutrient levels (Rijkse, 1979).

2.3.4 Soil Summary

The soils that are present in the Lake Rotokakahi catchment are all sourced from volcanic deposits. These deposits are rhyolitic, resulting in the soils having similar chemical composition. The soils on the western side of the lake are characterised by low moisture due to the large sand component and free-draining material. The majority of water does not reside on the surface, rather percolating through the soil layers to the groundwater table. The soils on the northern and southern ends of the lake have high erosion potential and should be managed in accordance. The soils that surround Lake Rotokakahi are largely sandy loams which can impact the hydrology of the area, particularly in regard to storm flows where, due to the nature of the soils, surface ephemeral streams do not form. The water instead drains down into the soil until it reaches the water table then enters the groundwater system.

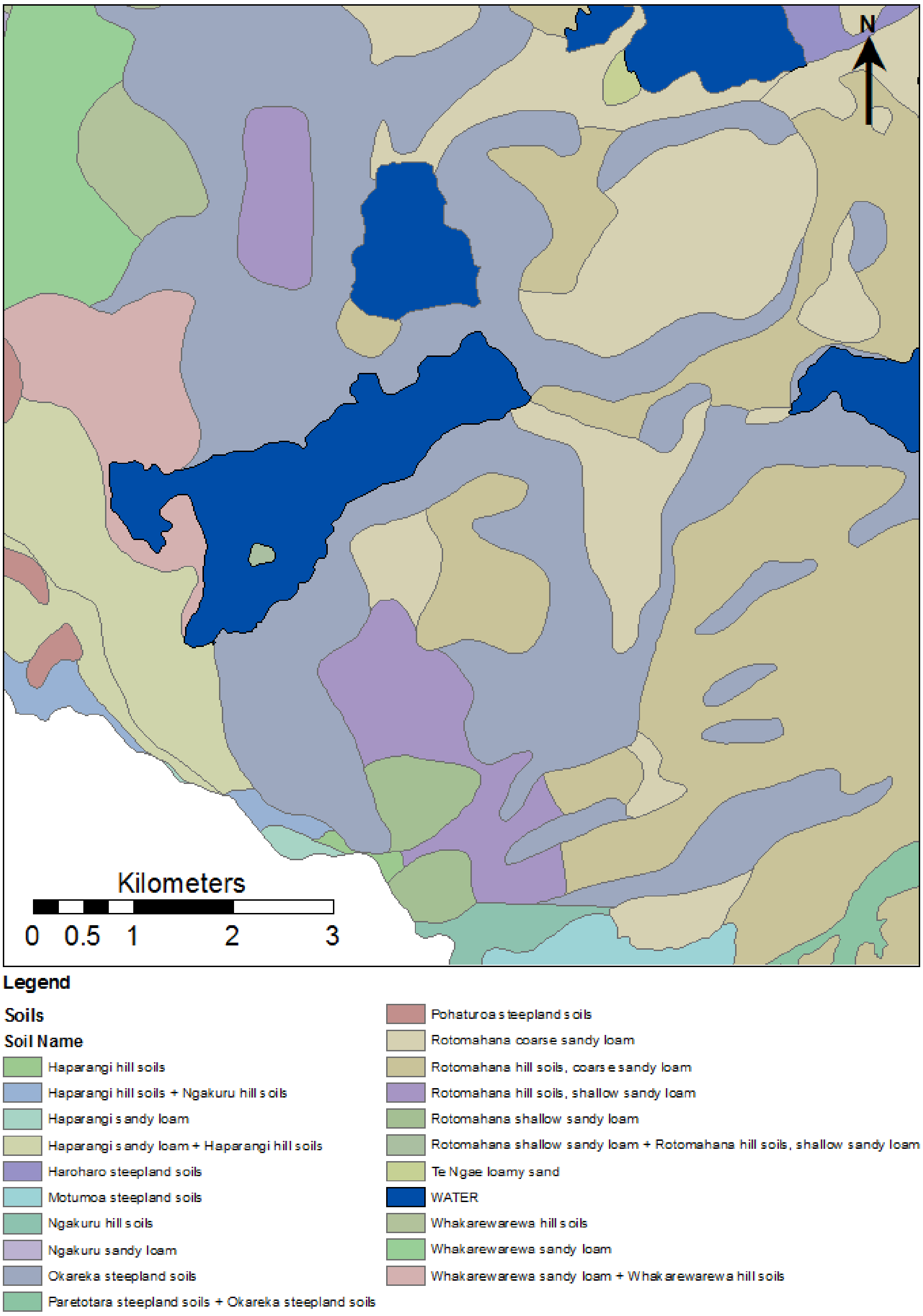

Figure 3: Soil map of the Lake Rotokakahi Catchment and surrounding area. Adapted from Bay of Plenty Regional Council GIS database.

2.4 Hydrology

The hydrological characteristics of the Lake Rotokakahi catchment are unique and distinct. The lake has no surface water stream inflows and only one small surface outflow. There is a small spring located on the lake edge that is recognised as the only inflow. Due to the lack of surface water inflows the lake is assumed to be predominantly groundwater fed.

The catchment, particularly in the southern end which is currently farmed, used to have several surface water streams. These streams reportedly flowed down the catchment from the higher elevations in the southern end down to the lower elevations of the lake surface and, at some points disappeared below the ground (Foster, 2015) and appeared further down the catchment and flowed into the lake. However it has been observed by locals in the area that these groundwater fed, intermittent streams have now dried up and no surface water flows occur (Foster, 2015). The old dried-up stream channels have also been dammed along the lake edge which also prevents ephemeral streams from forming and flowing into the lake during periods of high rainfall.

The only recorded inflow to the lake is a small spring located on the southern end of the catchment. The spring is covered by native bush and was only found through site exploration. The spring is routinely tested for water quality by Bay of Plenty Regional Council and was gauged during this study period. The average flow for the spring was recorded as 0.15 $m^3 s^{-1}$ during the study period

Lake Rotokakahi also has only one surface water outflow, the Te Wairoa Stream. The Te Wairoa stream flows east into Lake Tarawera, with additions from several small tributaries along the way. The stream is located in the eastern most corner of the lake and has been used historically as a proxy for lake water quality. The stream was gauged during the field period and gave average discharge values between 0.15 $m^3 s^{-1}$ and 0.57 $m^3 s^{-1}$.

Due to the distinctive surface water setting, the lake is dominated by water entering from groundwater inflows. This has also been observed through the large areas of groundwater seepage around the lake shore during site visits.

2.5 Land Use

Historically, land use within the catchment was largely indigenous forest. The total catchment area is 19.7 km^2 (Jones *et al.*, 2014) and is now largely in exotic forest (Douglas fir and pine; (Butterworth, 2008) with little remaining native forest left (Fig. 4). The northern part of the catchment is the Whakarewarewa forest which is exotic and has been harvested right up to the lake margin and then re-planted. The south-west part of the catchment is in pasture for sheep and beef farming and covers the lake margin around Kaiteriria Bay and extends up to the southern end of the catchment. This is known as Highlands station and is administered by Tumunui, a Māori trust. The surrounding areas in the south east are in regenerating native forest.

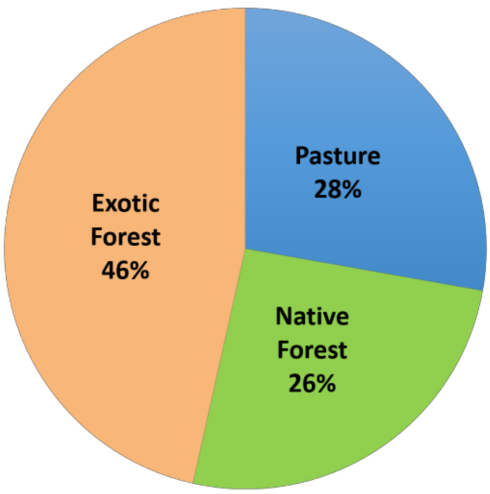

Figure 4: Lake Rotokakahi catchment land use. Data from (Jones *et al.*, 2014).

2.6 Water Quality

Lake Rotokakahi was monitored monthly by Bay of Plenty Regional Council (BOPRC) up until permission to the lake was no longer granted by the owners from 1996. BOPRC began monitoring the lake outlet, Te Wairoa stream, in 2006 and used it as a proxy for water quality of the lake. During the period 2006 – 2007 water quality sampling in the lake was re-established due to an iwi member's Master of Science research project (Butterworth, 2008) and monitoring has been carried out monthly from 2009 to present (Butterworth, 2012b).

The quality of Lake Rotokakahi has recently declined and has shifted from a mesotrophic to a eutrophic state over time. The target TLI is set at 3.6 but is currently 4 (Fig. 5). It ranged from 3 to 3.5 between 1990 and 1996, but had increased to 4.5 by 2010 (Butterworth, 2012a). This decline has been due mostly to a decline in water clarity, with Secchi depth measurements declining from 6.6 m in the 1990s to between 2 and 4 m between 2009 and 2012 (Butterworth, 2012a). There was an algal bloom recorded in May 2011, which was of a potentially toxic cyanobacterial species (*Anabaena lemmermannii*) (Jones *et al.*, 2014). It was likely linked to a fish kill in Te Wairoa Stream. Nutrient concentrations (total nitrogen and total phosphorus) have also shown an increasing trend from 1990 to the present. There is some indication that lake phytoplankton are more likely to have become nitrogen limited more recently due to large increases in phosphorus concentrations (Butterworth, 2012a).

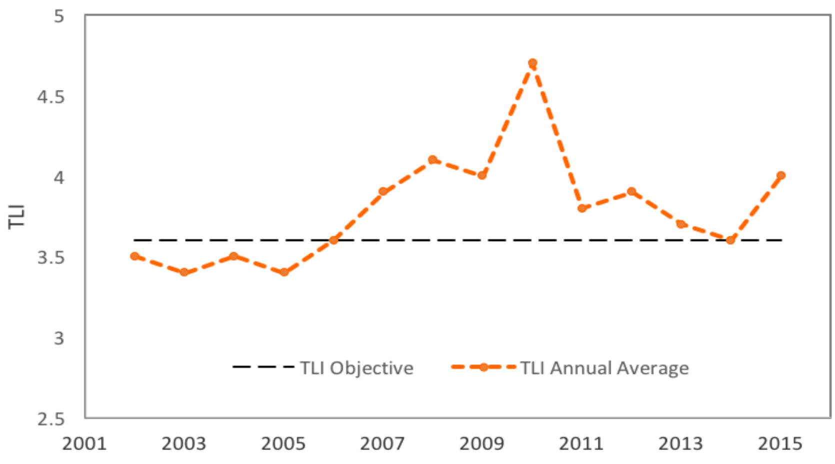

Figure 5: Trophic Level Index values in Lake Rotokakahi from 2002 to 2015 from Bay of Plenty Regional Council regular monitoring data.

The cause of decline on water quality of Lake Rotokakahi is unclear as catchment land use is predominantly forest and little land use change has occurred. There is only one sheep and beef farm in the southern catchment bordering Kaiteriria Bay (Highlands Station). It is administered by Tumunui, a Māori trust. Forestry operations have occurred in the northern catchment right up to the lake shore, which has possibly caused increased phosphorus and sediment loads to the lake through surface runoff. Harvesting of the plantation forest occurred in 2007 and 2008, with 44% of the lake margin harvested (Butterworth, 2012a). This was done through conservative harvesting methods and included selective thinning, with trees harvested by helicopter to minimise the disturbance on the ground and in an attempt to minimise sediment run-off into the lake (Butterworth, 2012a). This water quality decline has also impacted the lake ecology, especially in regard to population numbers of freshwater mussel/kākahi (*Echyridella menziesii*) which has been studied through a Master of Science thesis (Butterworth, 2008).

2.7 Groundwater

Lake Rotokakahi has been identified as a groundwater dominated system. There has been limited research and monitoring done on groundwater inflows to the lake. In regard to nutrient budgets, groundwater inputs are generally neglected, although they can contribute a high proportion of nutrient loads. Shallow groundwater can provide 50% of nitrogen inputs to a lake and can reach a lake within months or years (White *et al.*, 2015a) compared to deeper groundwater which may take decades to reach a lake. The lakes in the greater Tarawera region are all linked through the groundwater system.

The northern part of the Rotokakahi catchment, the Whakarewarea forest, is an area where the Rotorua district’s treated sewage and wastewater is irrigated. A study undertaken by White and Moreau-Fournier (2012) showed that there is likely to be a groundwater divide, which is similar to the topographic divide, in the area, which prevents groundwater flow from the Whakarewarewa forest discharging to Lakes Rotokakahi and Tikitapu. All of the base flow within the Puarenga Stream catchment that flows from the forest to Rotorua is accounted for through irrigation (White & Moreau-Fournier, 2012b) and groundwater water levels measured in monitoring wells through the Whakarewarewa forest are shown to be lower than the topographic contour of the lake level of Rotokakahi (White & Moreau-Fournier, 2012b), further indicating that groundwater flow into the lake from this area is unlikely.

In an investigation undertaken by the Institute of Geological and Nuclear Sciences Limited (GNS) and commissioned through the Bay of Plenty Regional Council, a three-phase report was completed including a drilling programme, leading to the monitoring and development of geologic and groundwater flow models. The report stated that insufficient piezometric levels were obtained from the Earthquake flat area to confirm groundwater flow directions as there could be some flow into the Waikato Region to the west of the Lake Rotokakahi zone which is not included in this report. The modelled output showed that a significant amount of groundwater was flowing into Lake Rotokakahi. The largest amount occurs at the lake edge and also groundwater outflow to Tarawera (White *et al.*, 2015a). The calculated outputs from GNS research have given inflow and outflow volumes which are used in the hydrodynamic modelling section.

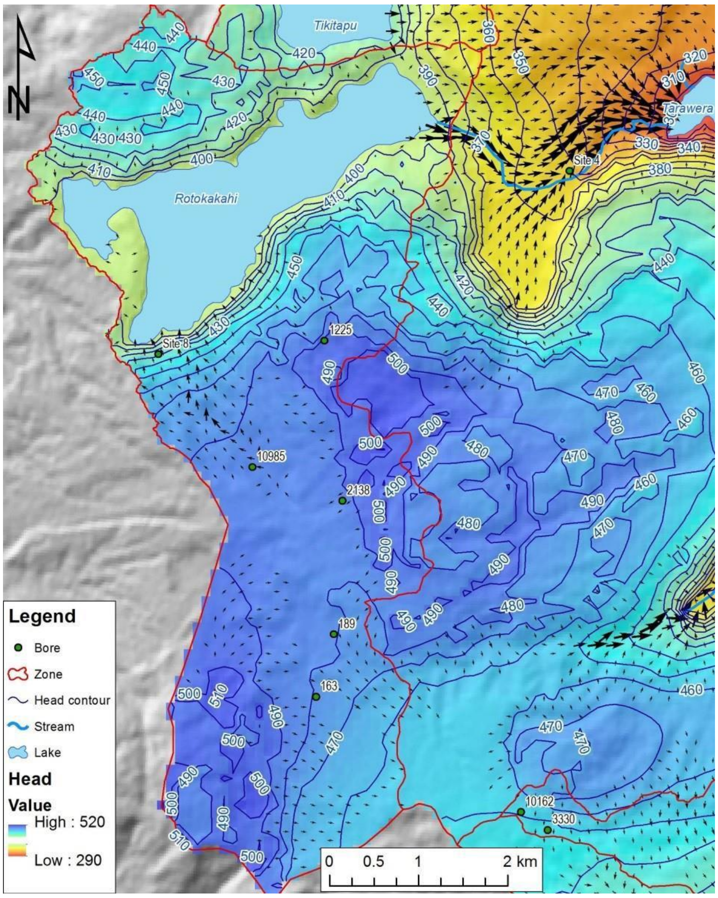

Figure 6: Groundwater flow diagram and extent of Rotokakahi zone from (White et al., 2015a).

3 Methodology

3.1 Field Methods

Lake Rotokakahi and its catchment were monitored between January 2016 and July 2016. Monitoring included monthly sampling of piezometers for water quality and water level, event-specific sampling of water quality during high rainfall events and high frequency (30 min intervals) of water level and temperature from loggers in the piezometers. Also, intermittent stream gauging, thermistor chain data from three deployments and meteorological data were measured and recorded during the sampling period

3.1.1 Installation of piezometers

Eight groundwater sampling sites were selected around the lake catchment (see Fig. 7, table1). The site locations were selected based on the different land use zones, ease of access and proximity to the water table, to ensure piezometers would not go dry during sampling period. Location of each of the sites was recorded by GPS and was able to be accessed by boat.

The piezometers were installed manually using a hand auger. The auger head consists of a sharp, rounded, metal corer. The auger was driven into the ground by repeatedly turning and pushing down on the auger handle, driving the corer into the soil. The auger was then lifted up and some of soil was removed and the process is repeated until there was sufficient water depth in the piezometer. The piezometers were installed in 18 December 2015 during summer when the water table was assumed to be its lowest. They were installed up to 1 m below the water level at the time.

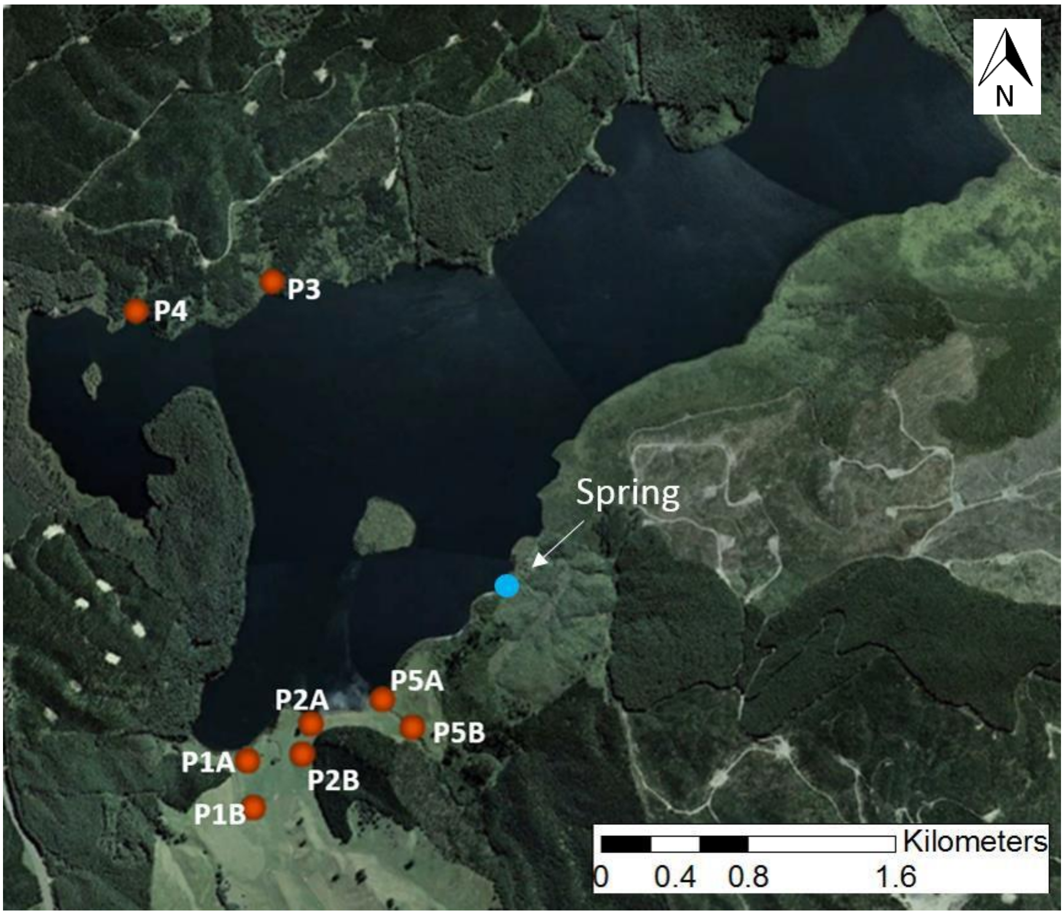

Figure 7: Map showing piezometer locations around Lake Rotokakahi.

Table 1: Groundwater sampling sites and locations

Site	GPS Co-ordinates	Land Use	Piezometer depth (m)	Logger
P1A	E1889800 N5763281	Farmland	0.95	Yes
P1B	E1889826 N5763263	Farmland	1.67	No
P2A	E1889908 N5763393	Farmland	0.3	Yes
P2B	E18889916 N5763345	Farmland	1.57	No
P3	E1889750 N5765194	Exotic Forest	1.02	Yes
P4	E1888881 N5765703	Exotic Forest	0.84	No
P5A	E1890229 N5763457	Farmland/Native Forest	1.62	No
P5B	E1890274 N5763408	Farmland/Native Forest	1.85	No

Figure 8: Equipment used for piezometer installation. Metal hand auger (top), plastic tubing (middle), and screen and soil log taken from drilling (bottom).

The piezometers were made with 32-mm diameter PVC pipes with a screen. The screen consisted of 2 mm incisions that were drilled into the plastic material around the perimeter of the piezometer. The screen was 40 cm in length. These pipes were placed into the holes and filled in with bentonite sands, until the area of the screen was covered, and then was filled in with soil. The piezometers were all capped.

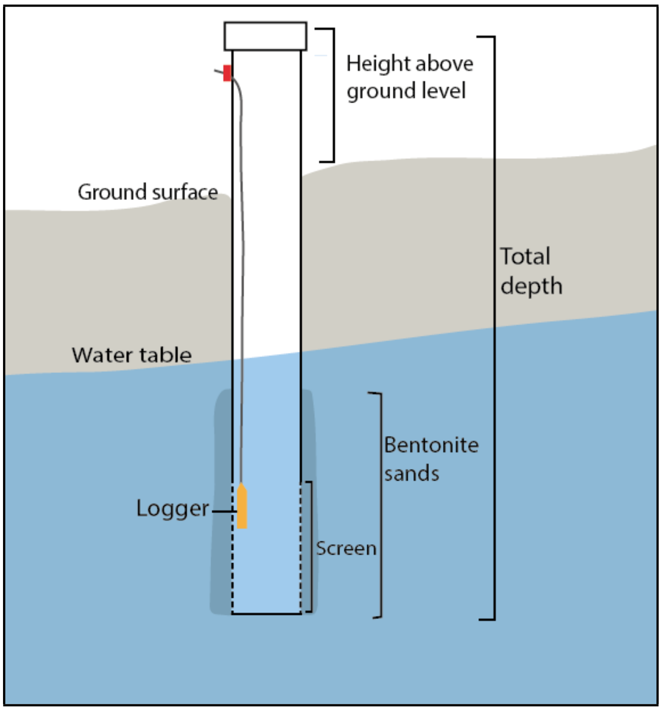

Figure 9: Diagram showing piezometer components and installation.

3.1.2 High frequency temperature and level measurements

Solinist Level loggers, model 3001 (Canada), were installed in a selection of the piezometers and at the spring. The loggers were attached to a wire down the piezometer, the wire was fed through a small hole drilled at the top of the casing and a metal crimp was used to prevent the movement of the logger (Fig. 9). At the spring a logger was cable tied to a waratah that was inserted into the ground surface at a depth that prevented any movement. A barometric logger was installed on a fence post near P2 location to provide an atmospheric correction of water level.

The Solinist loggers recorded water level and temperature every 30 minutes. The data were downloaded using the Solinist software and converted to text documents for analysis.

3.1.3 Monthly groundwater monitoring

Monthly monitoring was undertaken at the piezometer sites. The water level was measured by removing the logger (if present) and the level meter. Water level was measured to the top of the casing.

The water from the piezometers was extracted using a GeoPump (ThermoFisher Scientific, Australia) powered by a 12W battery. The piezometer was purged three times before sampling and the purge volume (V) was calculated as:

$$V = 3.14 \times \textit{(well depth – depth to water)} \times \textit{(well radius)}^2 \times 1000 \quad (1)$$

where the units of volume are in litres, depth in metres and radius in metres. After the piezometer was purged the water was pumped into a bucket for field parameter measurements. Dissolved oxygen (DO) and temperature were measured using a hand-held Hach DO meter (model HQ 30d, New Zealand). Conductivity was measured using a Hach conductivity meter (Hach Pacific, New Zealand). pH was also measured, using a H-Series H160 pH meter (Hach Pacific, New Zealand).

Water quality samples for groundwater quality were collected using the GeoPump. Samples for total nutrient analysis were taken by transferring water into a 50 mL Falcon tube. Samples were then frozen at the laboratory.

3.1.4 Flow gauging

The flow of the spring and Te Wairoa stream was measured during the study period using a FLO-MATE, model 2000 portable flow meter (Marsh-McBirney Inc., Maryland). The FLO-MATE uses an electromagnetic sensor to measure the velocity (m s^{-1}) in water, which is conductive.

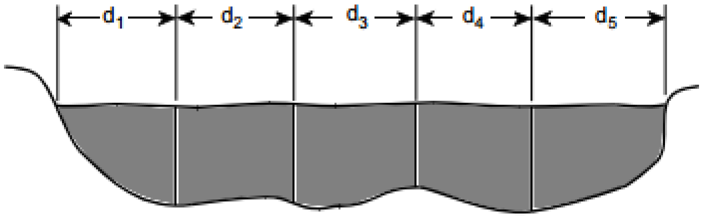

Figure 10: Cross -section of stream verticals along the width of a stream (image FLO-MATE manual, Marsh McBriney 1990), verticals were spaced 10 cm apart due to size of waterways.

The FLO-MATE consists of a sensor attached to an adjustable wading rod and attached to a power box. The total wetted width of the stream was measured and divided into verticals at 10 cm intervals with recordings taken at each interval along the width of the stream (Fig. 10). Due to both the stream and the spring being too shallow to do recordings at 20, 60 and 80 % of the total depth, the sensor was placed at 50% of total depth across the segments. Velocity was measured in m s^{-1} at each vertical section. The area between vertical measurements was calculated as the width between each vertical and the water depth. Discharge was calculated at each section and the sum of all verticals gave total discharge. Total discharge was calculated by:

$$Q = V * A \quad (2)$$

Where Q is discharge in (m^3 s^{-1}), V is velocity and A is area (m^2).

3.1.5 High frequency temperature data

A 20-m thermistor chain was used to determine temperature changes along the lake shore. It consisted of 20 Dallas Instruments DS18B temperature sensors spaced at 1 m intervals. The cable was powered by a 12 Volt battery and solar panels. The thermistors were programmed to record data every 1 minute by an Arduino micro-controller. The factory accuracy was noted at 0.5 °C, however laboratory calibration experiments gave accuracy within 0.2 °C.

The cable was placed at three different locations around the lake shore. The battery box was placed on the bank of the lake in a secure, open location for receiving sunlight. The cable was then moved by boat until it was in a tight, straight line perpendicular to the shore, and was carefully dropped to the lake bed. Fishing weights (1 kg) were attached to the cable every 3 m to ensure the cable would rest on the lake bed. The data were downloaded in the field after each deployment. It is important to note the data from the first two deployments was not corrected.

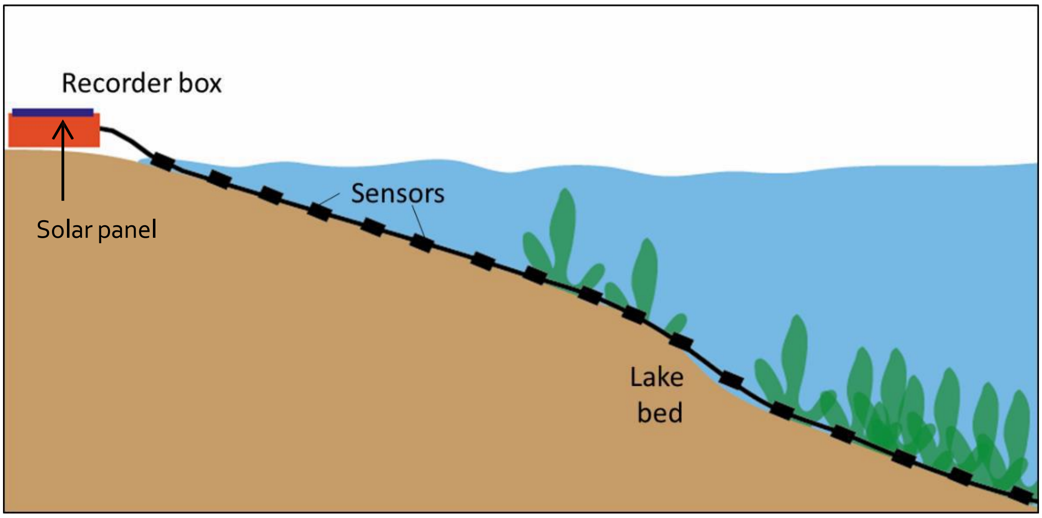

Figure 11: Diagram showing how thermistor chain was placed on lake bed. Each sensor was 1 meter apart and a total of 20 sensors were on the chain which was connected to power box with a solar panel.

3.1.6 Storm Sampling

During periods of high rainfall, water samples were taken at 2.5 h intervals using a Manning Environmental Inc. Portable Vacuum Sampler (model VST-7750, United States of America). A total of three storm events were sampled at five sites around the lake.

For the spring site (Fig. 7), the auto sampler was placed on a flat surface on the spring bank and the tubing was attached to a waratah in the middle of the flow, using cable ties. For the piezometer samples the auto sampler was placed directly beside the piezometers and the tubing was placed down the pipe until it was just above the base of the piezometer, to ensure it would always be submerged. The tubing was then taped to the top of the piezometer to prevent movement and avoid water entering the piezometer from above the ground surface.

The sampler runs off a 12 V battery and uses an air compressor with associated valves to produce vacuum in a chamber to draw water in to be sampled. It also produces pressure to purge the chamber and intake tube. After purging the line water is drawn up the sample tube to the chamber. The volume in the chamber was set at 500 mL and the above process was repeated until 500 mL was in the chamber. The sample was then deposited into one of the 24 bottles and the process repeated every 2.5 hours so that the total duration of sampling was 36 hours (i.e., 24 samples). This time value was set in order to capture the groundwater lag time from the increase in rainfall and subsequent infiltration to the water table resulting in subsurface quick flow. Samples were stored in plastic bottles on ice until they were taken to the laboratory for further analysis.

3.2 Laboratory Analysis

3.2.1 Nutrient samples

Samples were filtered in the laboratory for dissolved nutrient analysis using a 50 mL syringe and Whatman glass microfiber (GF/C) filter papers. Samples were then transferred into acid washed 50 mL Falcon tubes and frozen until analysis.

All nutrients were analysed using a Lachat QuickChem Flow Injection Analyser (FIA+8000 series, Zellweger Analytics, Inc.). Total nitrogen (TN) and total phosphorus (TP) samples were simultaneously determined using a persulphate - hydroxide digestion. The digested solution then underwent an ascorbic acid colorimetry (APHA 4500-P) and Discreet Analyser. The detection limit for total phosphorus was 0.004 mg/L. For total nitrogen the digested solution was analysed for nitrate using cadmium column reduction to nitrite and colorimetric analysis (APHA 4500-N C) with a default detection limit of 0.004 mg/L.

Dissolved nutrients were determined by analysing the filtered samples. Phosphate (PO_4-P) was analysed by molybdenum blue colorimetry and discreet analyser (APHA 4500-P-E). Ammonium (NH_4-N) analysis involved reaction with hypochlorite ions to form monochloramine, which reacts with salicylate ions in the presence of sodium nitroprusside to form a blue compound. Nitrite (NO_2-N) was analysed by the flow injection analyser. Nitrate (NO_3-N) was determined through subtracting NO2-N values from NO_X-N (NO_3-N + NO_2-N) values. All reagents were prepared fresh daily. Milli-Q water was used in preparing all standards and reagents. Calibration standards were prepared by diluting stock standards with Milli-Q water.

3.3 Hydrodynamic Modelling

3.3.1 ELCOM Model Description

ELCOM (Estuary and Lake Computer Model) is a three-dimensional hydrodynamic model developed by the Centre for Water Research at the University of Western Australia. This model is based on the Navier-Stokes equation which describes the unsteady and viscous behaviour of flow and simulates the temporal behaviour of water bodies with environmental forcing. ELCOM was used in this study to simulate temperature, water levels and water transport in Lake Rotokakahi. ELCOM can also be coupled with an aquatic ecological model.

3.3.2 ELCOM Model Inputs

Input files for the ELCOM model included inflows, outflows, lake and meteorological data. They were prepared in a specific format for the requirements of ELCOM. Three–dimensional model run times are notably long and greater than one- dimensional models. Therefore, the model simulation period was set for 6 months from 1 January 2016 to 1 June 2016. For this period ELCOM was run at 90 second time intervals, i.e., 145,920 time steps.

3.3.3 Surface Inflow data

The inflow data was given in daily values for discharge and temperature. There was only one surface inflow identified for Lake Rotokakahi and this was the spring (Fig. 7). Spring inflow was set as a constant value of 0.15 m^3 s^{-1}. This value was set as there were rare and sporadic discharge measurements which were averaged to provide this value. Temperature of the spring was also set to a constant of 10.5 °C. This value was the average of data recorded by the Solinist logger which recorded spring water temperature every 30 minutes. The temperature data were averaged over the measured time period and showed little variation.

3.3.4 Outflow Data

Outflow data was derived through using interpolation of observed field data. Due to few stream gaugings being undertaken during the study period, historical data was used to show seasonal variation and daily values were obtained through interpolation.

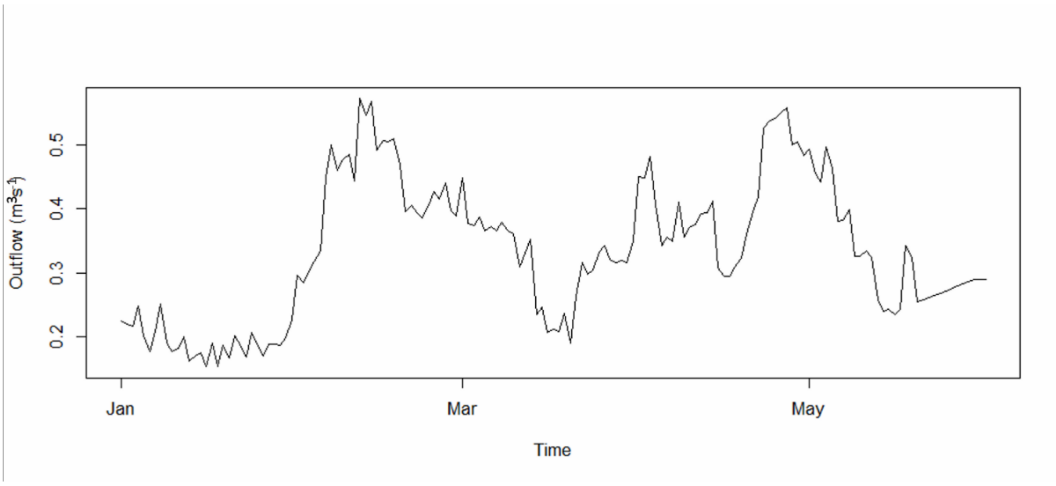

Figure 12: Derived outflow data calculated for the 6-month study period from 1 Jan 2016 to 1 Jul 2016.

Outflow temperature was measured sporadically, thus to obtain daily values the stream temperature was modelled using air temperature using the method described in Mohseni *et al.* (1998):

$$T_S = \frac{\alpha}{1 + e^{\gamma(\beta - T_a)}} \quad (3)$$

where: T_s is the estimated stream temperature, T_a is the measured air temperature, α is the coefficient for the estimated maximum stream temperature, γ is a measure of the steepest slope of the function and β represents the air temperature at the inflection point.

3.3.5 ELCOM Bathymetry

The bathymetry of Lake Rotokakahi was taken from a high resolution hydrographic survey, undertaken by Discovery Marine Ltd (DML) on 20 April 2016. For model input the bathymetry data was averaged to a 30 m x 30 m resolution. A hypsographic curve was also created using the bathymetry data.

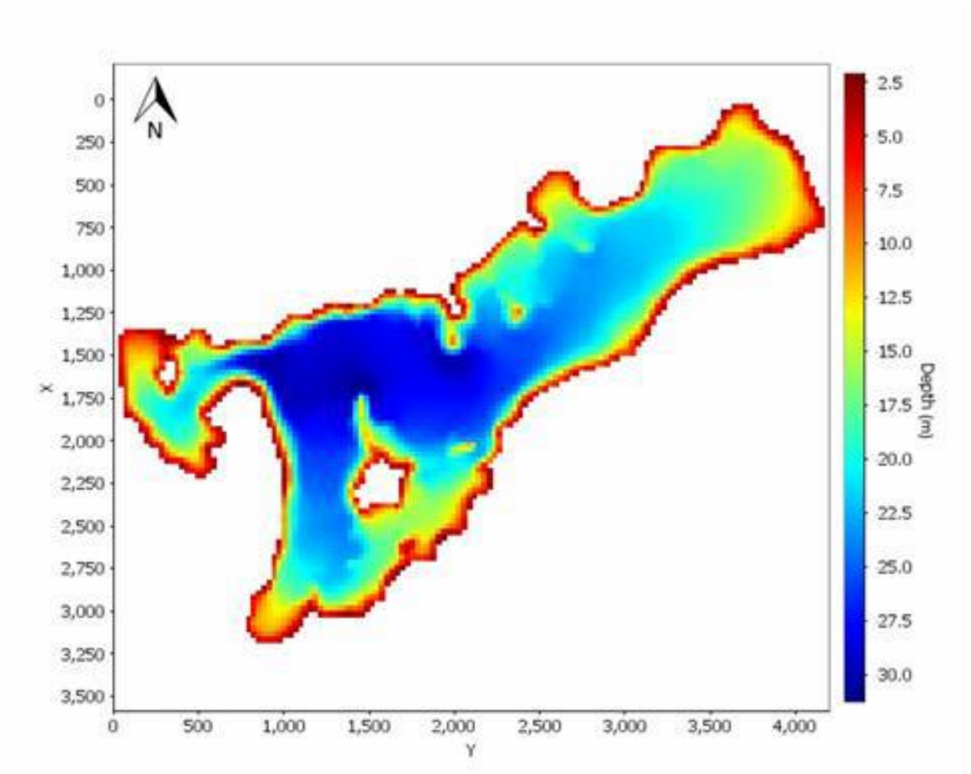

Figure 14: Bathymetry from 2016 used for ELCOM inputs. Bathymetry data sourced from Discovery Marine Ltd.

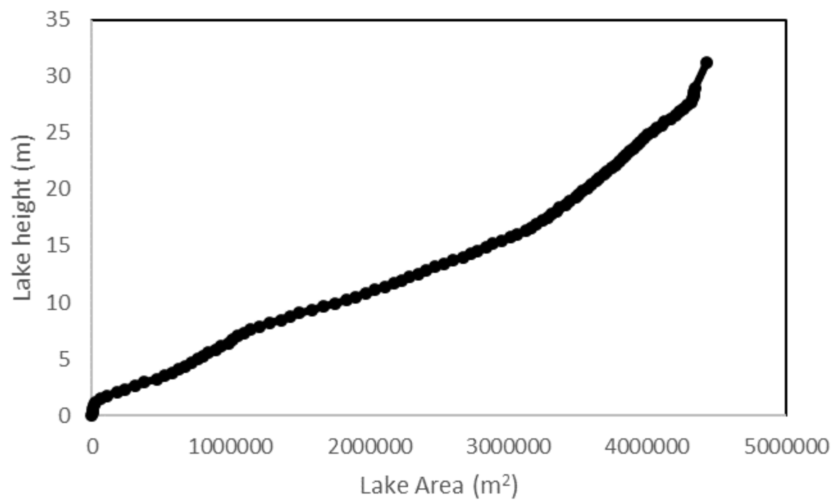

Figure 13: Hypsographic curve for Lake Rotokakahi showing depth (m) versus area (m-2) calculated from x,y,z data points from Discovery Marine Ltd. bathymetry data.

3.3.6 Meteorological Data Input

Meteorological data were obtained from the National Climate Data Base for the Rotorua Airport Climate Station. The climate station is located 10 km from Lake Rotokakahi. The data collected from that station included rainfall (mm), air temperature (°C), wind speed (km h^{-1}) and direction (°), relative humidity (% of saturation) and solar radiation (MJ m^{-2}). Variables were measured at different time intervals and averaged to give hourly values. Wind direction and speed are measured at 10 minute intervals, temperature, atmospheric pressure and relative humidity are measured every minute, and rainfall and solar radiation are one-hour accumulated values.

For the purpose of ELCOM configuration rainfall was converted to metres, relative humidity was converted from percentage to fraction of saturation (0-1) and solar radiation was converted from MJm^{-2} to Wm^{-2} for the 10-minute time step used in ELCOM.

Cloud cover was calculated using historical data. A sinusoidal curve was fitted to shortwave radiation data from the Rotorua Airport climate station for from 2001 to 2012. From this equation, coefficients were produced for 100% cloud cover and 0% cloud cover.

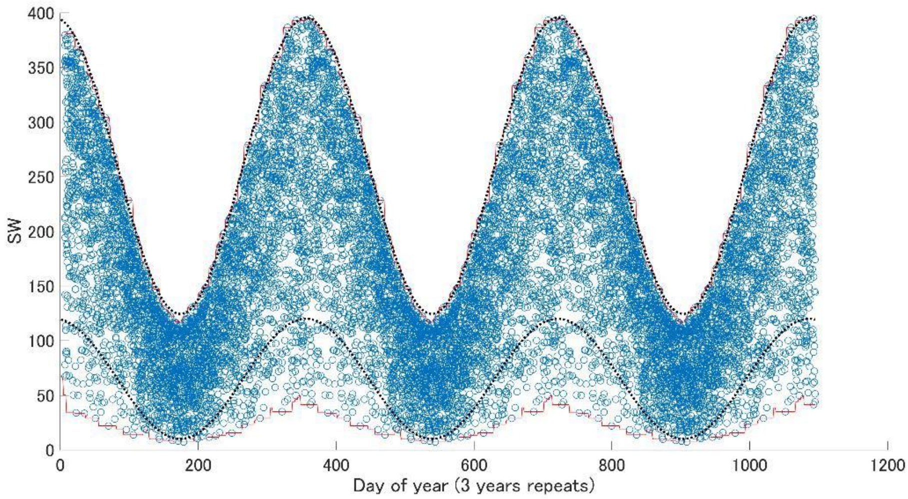

Figure 15: Eleven years of historical solar radiation (MJm-2) data with sinusoidal curve fitted (black dotted line).

Component equations of Fig. 15 include:

$$Daily\ SW(\mathrm{Wm^{-2}}) = a * \sin\left(2\pi\left(\frac{x}{b}+\frac{1}{c}\right)\right) + d \tag{4}$$

where: *a*,*b*, *c* and *d* are co-efficients with *a* is 54.976, *b* is 365.33, *c* is -1.375, *d* is 65.024 and *x* is the day of the year.

$$Daily\ clear\ sky\ SW(\mathrm{Wm^{-2}}) = a * \sin\left(2\pi\left(\frac{x}{b}+\frac{1}{c}\right)\right) + d \tag{5}$$

where: *a*,*b*, *c* and *d* are co-efficients with *a* is 135.5362, *b* is 365.33, *c* is -1.375, *d* is 260.014 and *x* is the day of the year and:

$$Cloud\ cover = 1 - \frac{SW - Cloudy\ sky\ SW}{Clear\ sky\ SW - Cloudy\ sky\ SW} \tag{6}$$

3.3.1 Groundwater inflow data

Groundwater inflows were calculated by three different methods and run in separate ELCOM model simulations in order to test model sensitivity to the three methods. The first method was based on a mass balance, with groundwater inflow calculated from surface inflow (spring observations), outflow (interpolated observations), catchment rainfall, evaporation and rainfall directly to the lake. The second simulation had groundwater inflows calculated by MODFLOW, a groundwater flow model set up by the Institute of Geological and Nuclear Science (GNS) and based on a flow model for the greater Tarawera region (White *et al.*, 2015b)The groundwater inflows in this scenario were given as constant values. The third simulation also used MODFLOW output, however it was compared with field level measurements and extrapolated to give a variable groundwater flow. The details behind these methods are outlined below.

3.3.2 Water balance calculations

A water balance was calculated for Lake Rotokakahi using data that was available for the catchment. This data included meteorology and inflow hydrological data. The water balance equation was:

$$\Delta S = \sum(surface\ inflows) + groundwater + rainfall - E_L - Outflow \quad (7)$$

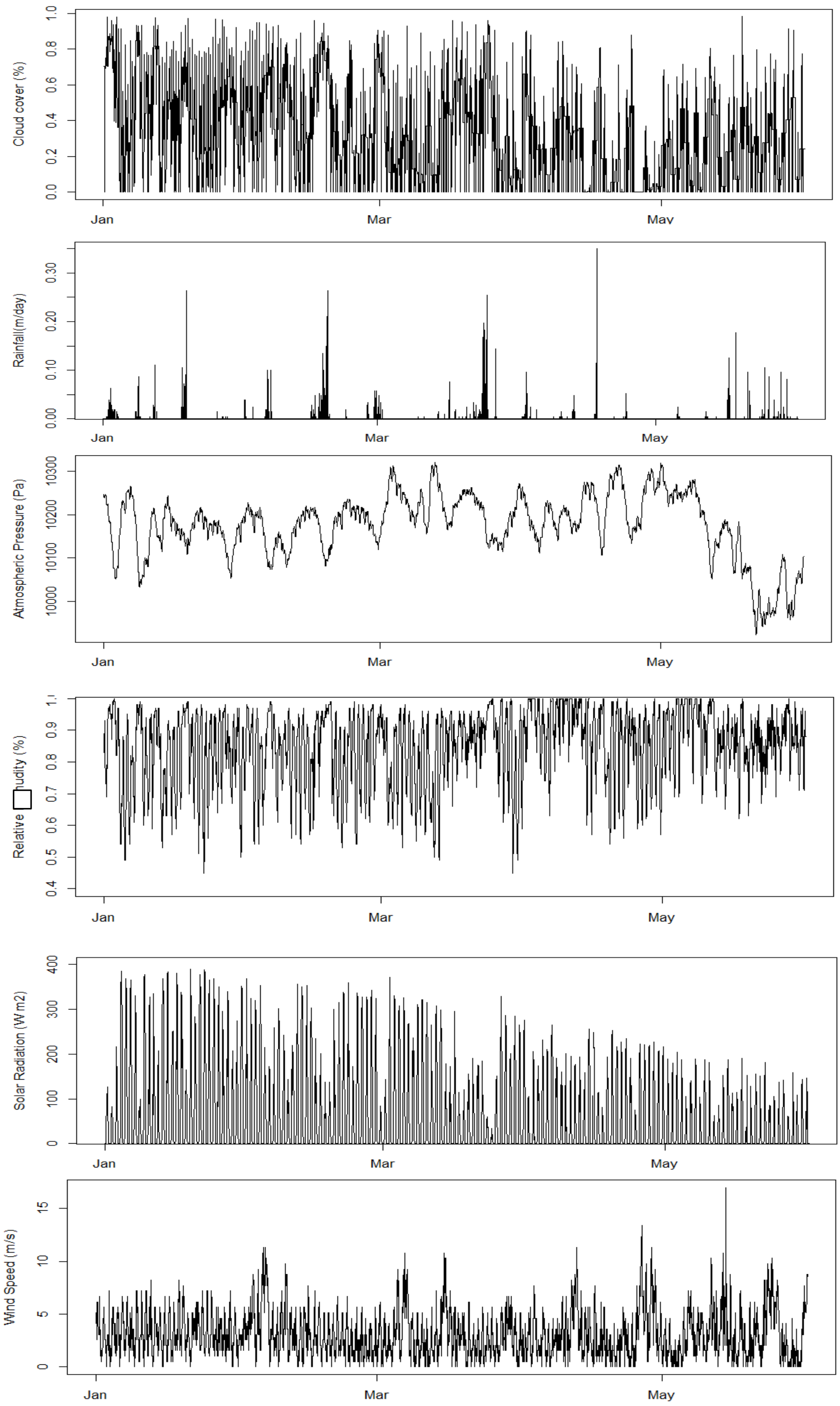

Figure 16: Meteorological data used as input into the ELCOM model (01/01/2016 to 01/06/ 2016). From top: Cloud cover, rainfall, Atmospheric Pressure, Relative Humidity, Solar radiation and wind speed.

Where E_L is evaporation in m^3 d^{-1} and ΔS is change in storage. Evaporation from the lake was calculated using wind speed and air vapour pressure from the daily evaporative heat flux, from Fischer et al. (1979, equation 6.20).

$$Q_{lh} = minimum\left(0 \geq \frac{0.622}{P} C_L P_A L_E U_A\left(e_A - e_A(T_s)\right)\Delta t\right) \quad (8)$$

where Q_{lh} is evaporative heat flux (m3 d-1), P is atmospheric pressure (hPa), C_L is latent heat transfer co-efficient for wind speed at a height of 10 m (1.2 x 10-3), P_A density of air (kg m-3), L_E is latent heat of evaporation of water 2.453 x 106 J kg-1, U_A is wind speed (m s-1) at 10m height above ground level, T_s is water surface temperature derived from ELCOM output (°C), $e_A(T_s)$ is saturation vapour pressure at the water surface temperature (hPa) and e_A is vapour pressure of the air (hPa).

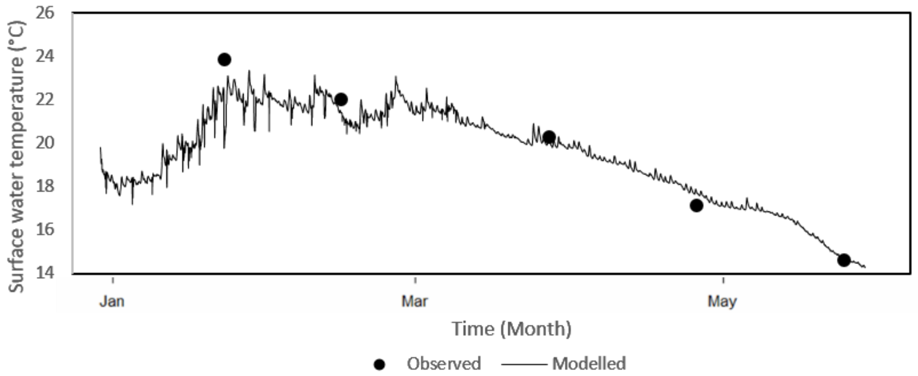

Figure 17: Lake surface water temperature (°C) as derived output from ELCOM from 01/01/2016 to 01/06/2016 compared with observed surface water temperatures (°C) from monthly monitoring from Bay of Plenty Regional Council.

A catchment water balance was carried out. Catchment land use data is useful for evaporation and run-off purposes. Data was obtained through the Bay of Plenty Regional Council GIS database and are shown in Table 2.

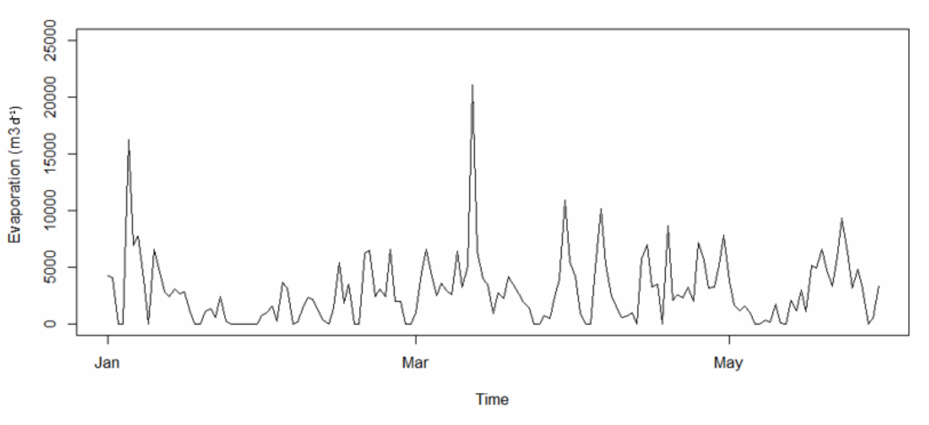

Figure 18: Daily evaporation (m-3day-1) calculated for Lake Rotokakahi from 01/01/2016 to 01/06/2016 calculated from equation 8 above.

Table 2: Catchment land use types used for calculating the water balance for Lake Rotokakahi.

Land use	**Area (km^2)**
Farmland/ Pasture	5.48
Exotic forest	9.17
Native forest	5.07
Total	19.72

Overland flow occurred during storm events. Total daily rainfall > 20 mm was considered a storm event. For these cases it was estimated that 10% of the rainfall that fell on pasture in the catchment went into overland flow and flowed into the lake as surface inflow.

Catchment evaporation rates were assumed to be similar to the values stated by Scotter and Kelliher (2004) of 800 mm yr^{-1} for pasture and 1000 mm yr^{-1} for forestry from an average annual rainfall of 1850 mm yr^{-1} based on the Rotorua catchment. Based on values given in Scotter and Kelliher (2004), annual catchment evapotranspiration rate was calculated as 53.4% of rainfall with seasonal variation with a peak of 73.4% for summer and a minimum of 33.4% for winter (McBride *et al.*, 2014).

Using Eq. 1, groundwater inflow was calculated for Lake Rotokakahi using inflow, storage change, measured rainfall and estimated evaporation and outflow. Inflow from the spring was set as a constant due to limited measurements, and daily outflow values were calculated through interpolation of outflow discharge measurements collected from field gauging.

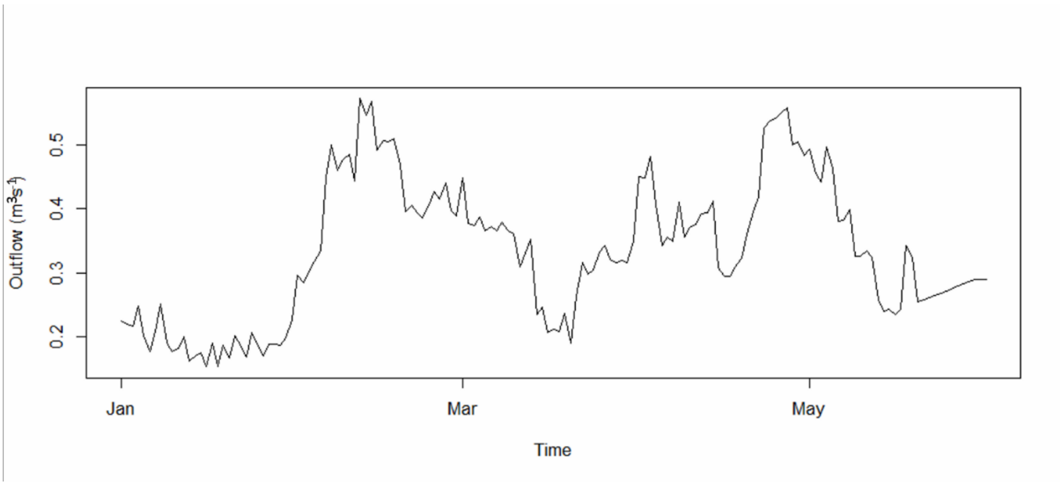

Figure 19: Interpolated outflow volumes (m-3s-1) from the Te Wairoa stream during the 6-month sampling period from 01/01/2016 to 01/06/2016.

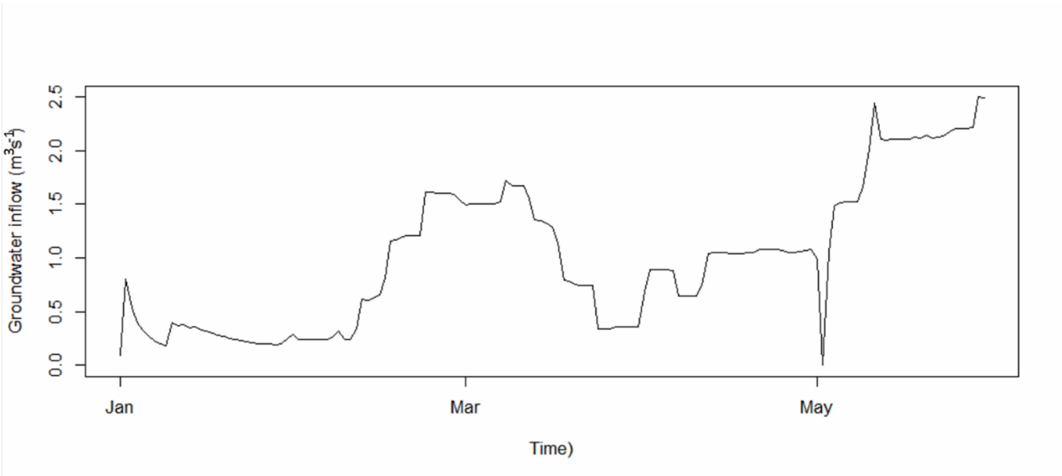

Figure 20: Estimated groundwater inflow (m-3 s-1) calculated from the water balance equation during the 6-month sampling period from 01/01/2016 to 01/06/2016.

3.3.3 Groundwater flow model (MODFLOW)

Modelled output data from the groundwater flow model in White *et al*. (2015) was used for calculating groundwater inflow and outflows for the hydrodynamic model. Groundwater flow values, based on hydraulic heads, were taken from Table 4.7 of White *et al* (2015). The values were given as 87 L s^{-1} flow from the lake to the aquifer (groundwater outflow) and 176 L s^{-1} for flow from the aquifer to the lake (groundwater inflow). These values were set as constant values for ELCOM inputs for one of the simulations.

The third simulation used the constant MOFLOW values from White *et al*. (2015) above and the observed groundwater level data. Groundwater level data measured in piezometers showed distinct variation over the sampling period. Following the assumption that groundwater level corresponds with groundwater flow the groundwater flow was calculated using the observed variation in groundwater level. The mean groundwater level was considered equal to the 0.176 $m^{-3}s^{-1}$ as outlined from White *et al*,.(2015). The groundwater levels (in 30 minute intervals) were divided by the mean groundwater level and multiplied by 0.176 $m^{-3}s^{-1}$ giving the groundwater flow volume for that specified water level in $m^{-3}s^{-1}$. The results were then averaged to give daily values (Fig. 21).

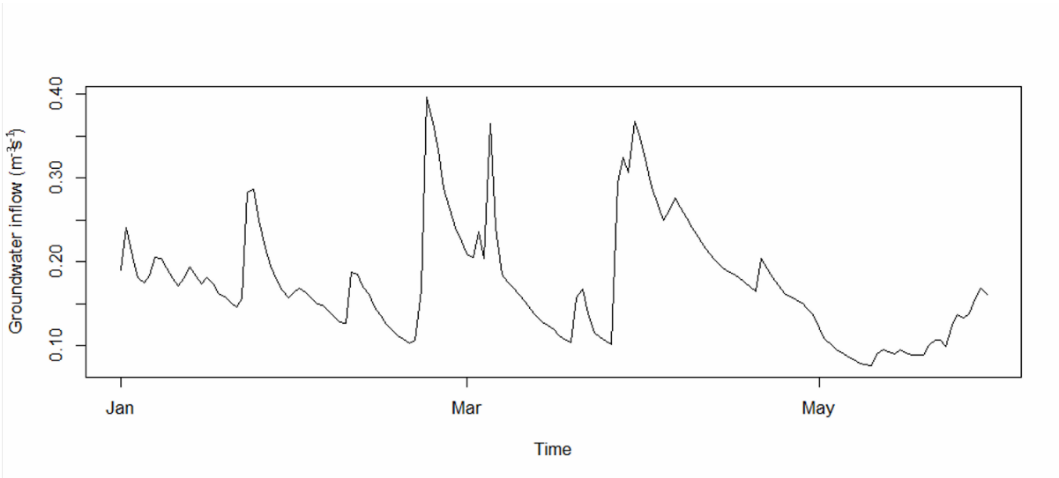

Figure 21: Groundwater inflow ($m^{-3}s^{-1}$) based on measured groundwater levels and MODFLOW output from (White et al., 2015a).

4 Results

4.1 Meteorology

During the sampling period from 1 January to 1 June 2016, the daily mean air temperature was 16.2 °C, with the highest temperature 22.2 °C on 28 February and the lowest 5.4 °C on 1 June (Fig. 22). The total rainfall over the sampling period was 595.8 mm and there were three significant high rainfall/storm events (Fig. 22). Significant rainfall events were considered to be more than 20 mm a day.

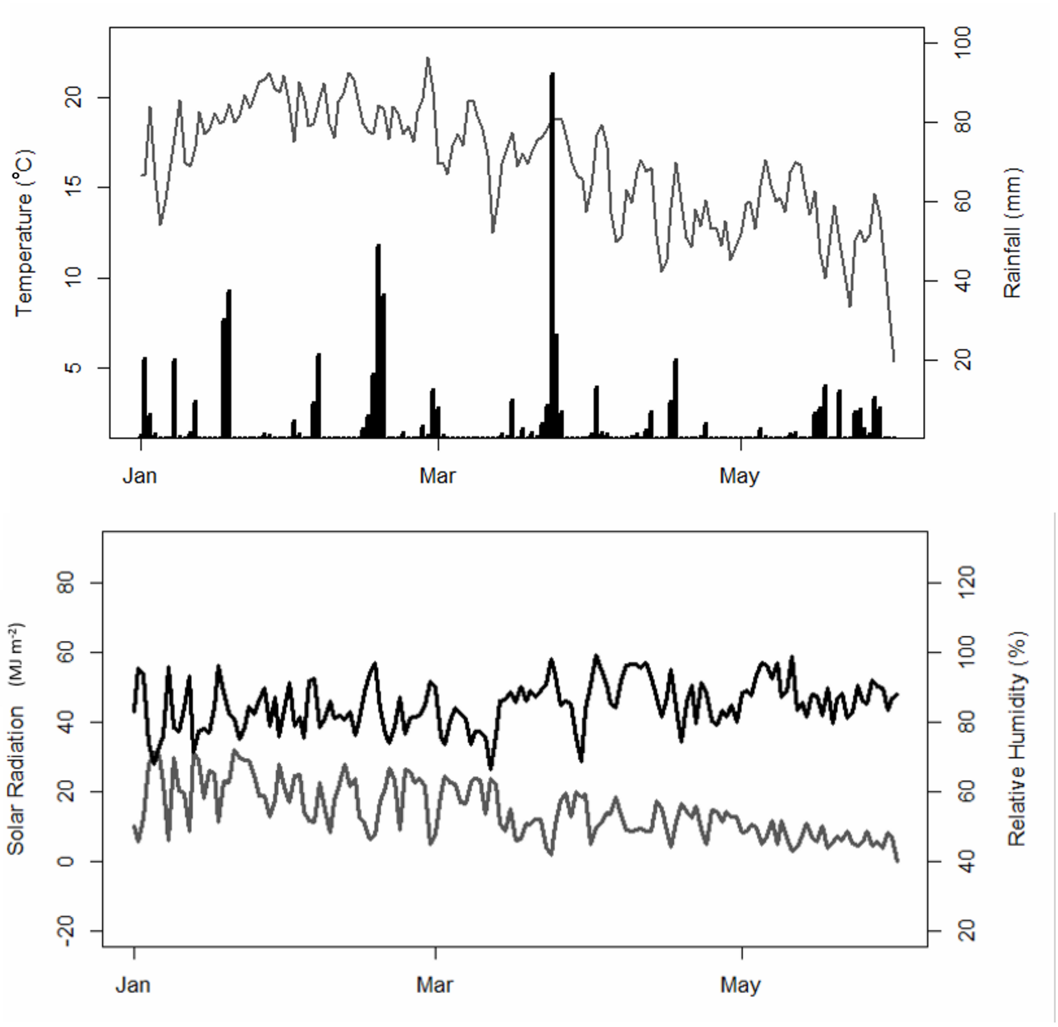

Figure 22: Temperature and rainfall (upper panel) and solar radiation and relative humidity over the sample period 01/01/2016 to 01/06/2016.

4.2 Groundwater

The nutrient concentrations of the spring and the piezometer sites were measured monthly. The results for each component have been averaged over the sampling period and compared to the average concentration of both the lake and the spring inflow. Three of the eight piezometers were destroyed during the sampling period by either stock or human interference, thus the results from the five piezometers which remained intact are shown. For the dissolved nutrients, the farm sampling site P1 showed the highest concentration of nitrate (NO_3–N) concentration over the sample period. Ammonium (NH_4-N) concentrations were highest at P2, the swampy area within the farm land, and the lowest at P3, the forested site. Concentrations of phosphate (PO_4–P) were highest at P5, another farm site, and lowest at P4, the site located by the boat ramp in the forested area.

For NO_3-N both the spring and lake levels were only 0.001 and the groundwater was considerably higher. Ammonium levels in the groundwater across all piezometer sites were well below those of the spring, which were significantly higher at 0.2 mg L^{-1}. The ammonium concentration in the lake was 0.08 mg L^{-1} which was higher than all of the piezometer sites except P2. For phosphate (PO_4-P) the spring had highly elevated levels (0.225 mg L^{-1}) and the lake had very low levels (<0.001 mg L^{-1}) (Fig. 23).

Concentrations of total nutrients for the piezometer sites are shown in Fig. 24. Total nitrogen (TN) was highest at the farm site P1, the lowest at P2. For total phosphorus (TP), site P5 on farm land had the highest concentrations and P3, the forested site, the lowest. Compared to the spring and lake concentrations, total nitrogen in groundwater was considerably higher than levels in both the lake and the spring

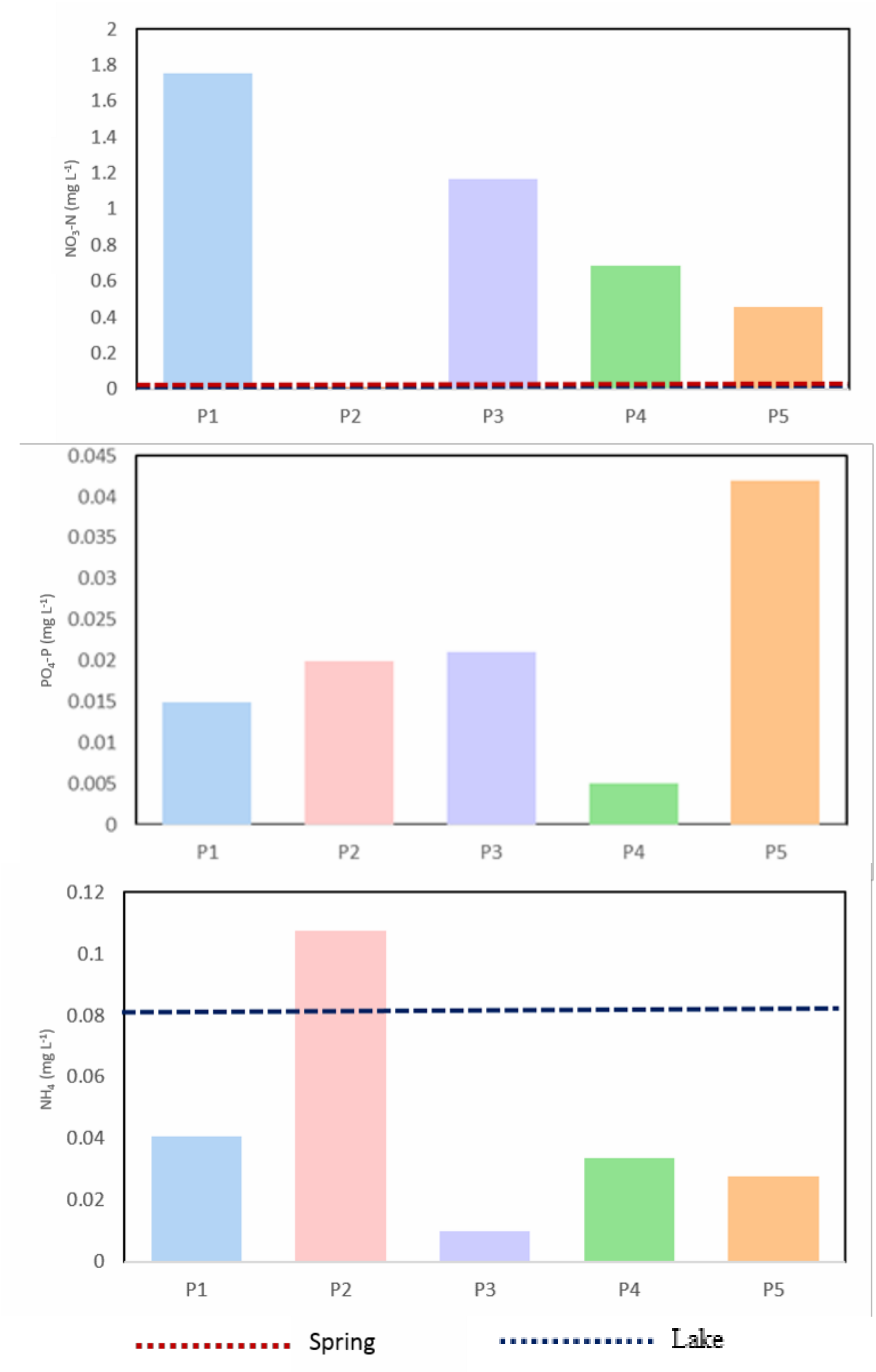

Figure 23: From top: Nitrate (NO3-N), phosphate (PO4–P) and ammonium (NH_4) averaged concentrations for groundwater sampling sites within the Lake Rotokakahi catchment, an in-lake site and a spring inflow site. Measurements are from the sampling period 01/01/2016 to 01/06. NH_4 concentrations (0.2 mg L^{-1}) were too high to show on plot.

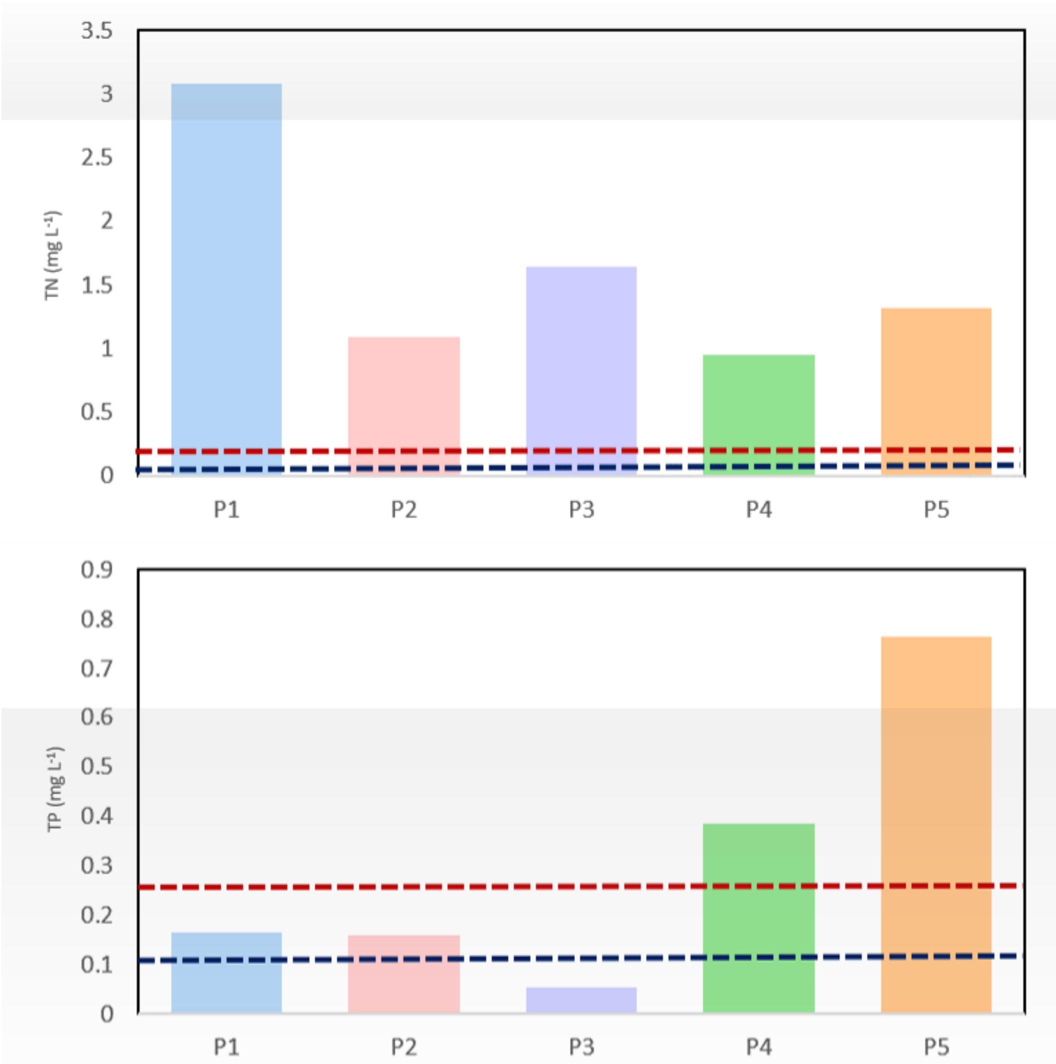

Figure 24: From top: Total nitrogen (TN) and total phosphorus (TP) across the five groundwater sampling sites compared to in-lake and spring inflow concentrations. Piezometer concentrations were averaged over the sample period from 1/01/2016 to 1/06/2016.

4.3 Groundwater responses to high rainfall events

4.3.1 Storm event one: 5/2/2016-7/2/2016

A total of three storm or high rainfall events were sampled over the study period of 1 January to 1 July 2016. For the first storm event a total of 28 mm fell over the storm period of 5/2/2016 to 7/2/2016. The sampling period for this storm event was 60 hours, with samples taken every 2.5 h. The majority of the rain that fell in the first storm event was within the first 24 h, with a small burst of rain occurring later in the sampling period. The sites sampled for the first storm event were P2 and the spring. P2 showed distinct increases in NO_3-N, PO_4-P, NH_4-N, TN and TP with increased rainfall. compared with the spring site where NH_4, PO_4-P, TN and TP concentrations were nearly constant. There were variations in NO_3-N measurements during the storm period and concentrations of NO_3-N in the spring were much higher than the piezometer site, however there was no relationship with rainfall.

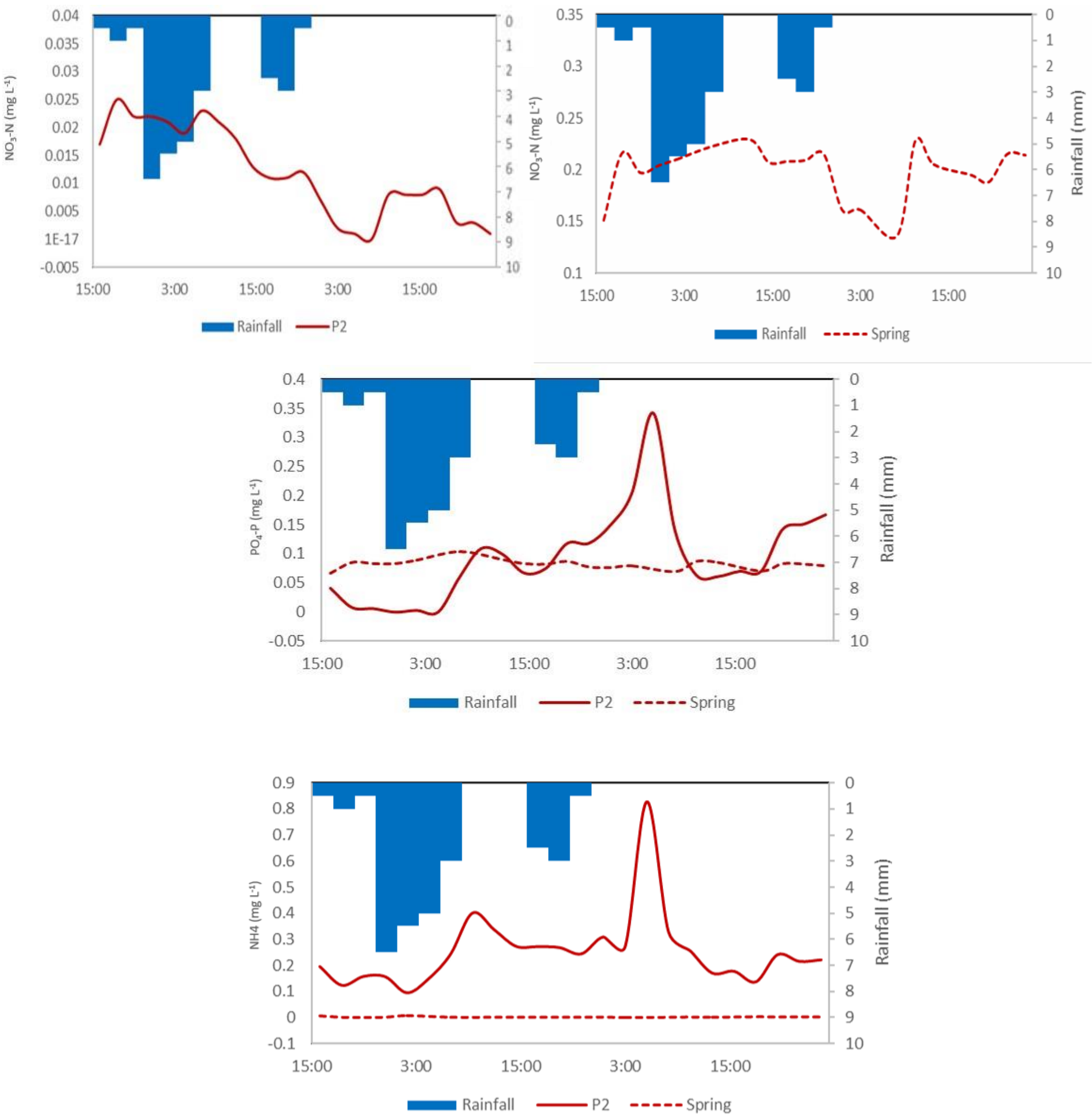

Figure 25: From top: NO3-N at P2 (left and the spring (right), PO4-P and NH4 concentrations in both the spring and P2 sites during storm event 1 from 5/02/2016-7/02/2016.

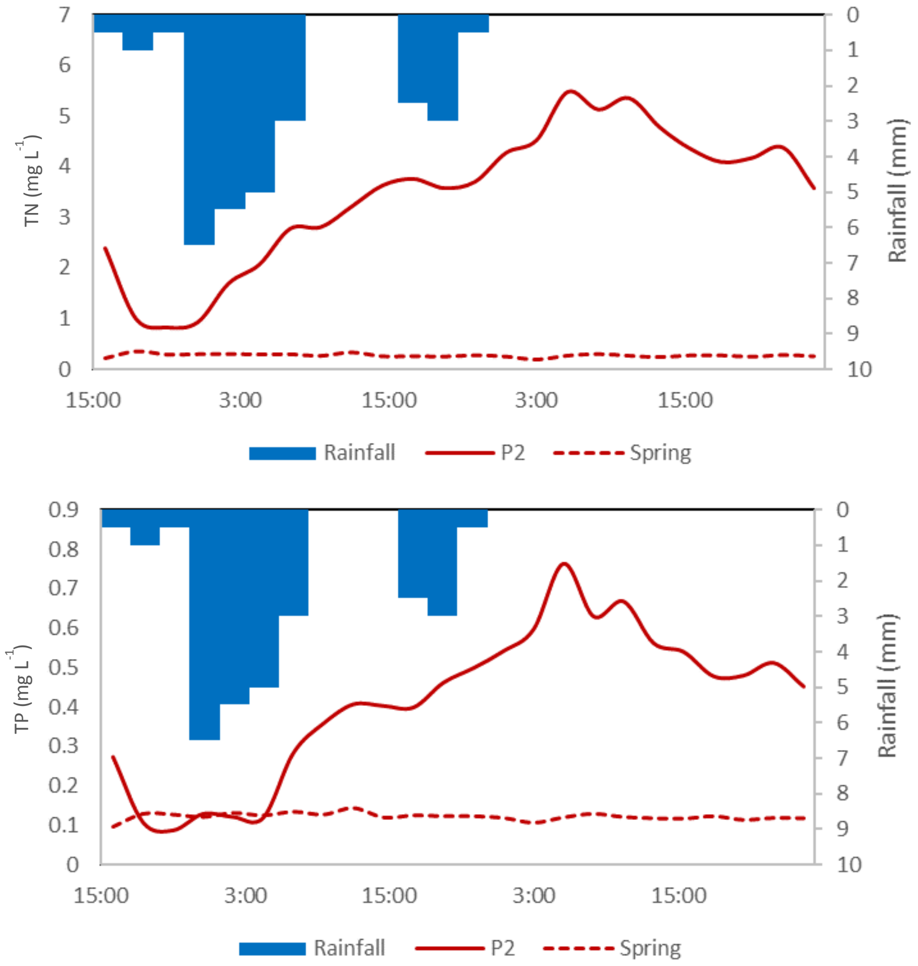

Figure 26: Total nitrogen (TN) and total phosphorus concentrations in both the spring and P2 sites during storm event 1 from 5/02/2016-7/02/2016 against rainfall (mm).

4.3.2 Storm event two: 17/2/2016 to 19/2/2016:

The second storm sampling occurred was 17 February to 19 February 2016. The total rainfall for this period was 94 mm, considerably larger than the first storm event. During site visits before and after the storm, no surface water flows or ponding had occurred. The majority of the rain fell towards the end of the sampling period. The sites sampled during this storm were P2 and P4, the farm and the boat ramp site. The farm site showed higher concentrations of all nutrient species except for nitrate. Nitrate and phosphate at the boat ramp site remained stable and a slight increase in ammonium was observed after the large downpour of rain whereas a large peak was observed at P2 at the beginning if the rain event.

Total nitrogen increased with rainfall at both P2 and P4 sites with P4 showing a more rapid response. Total phosphorus also increased with rainfall, with an immediate increase at P2 and remaining high throughout the sampling period. P4 showed more variable responses to rainfall, with a longer lag time but also a large increase after sustained heavy rainfall.

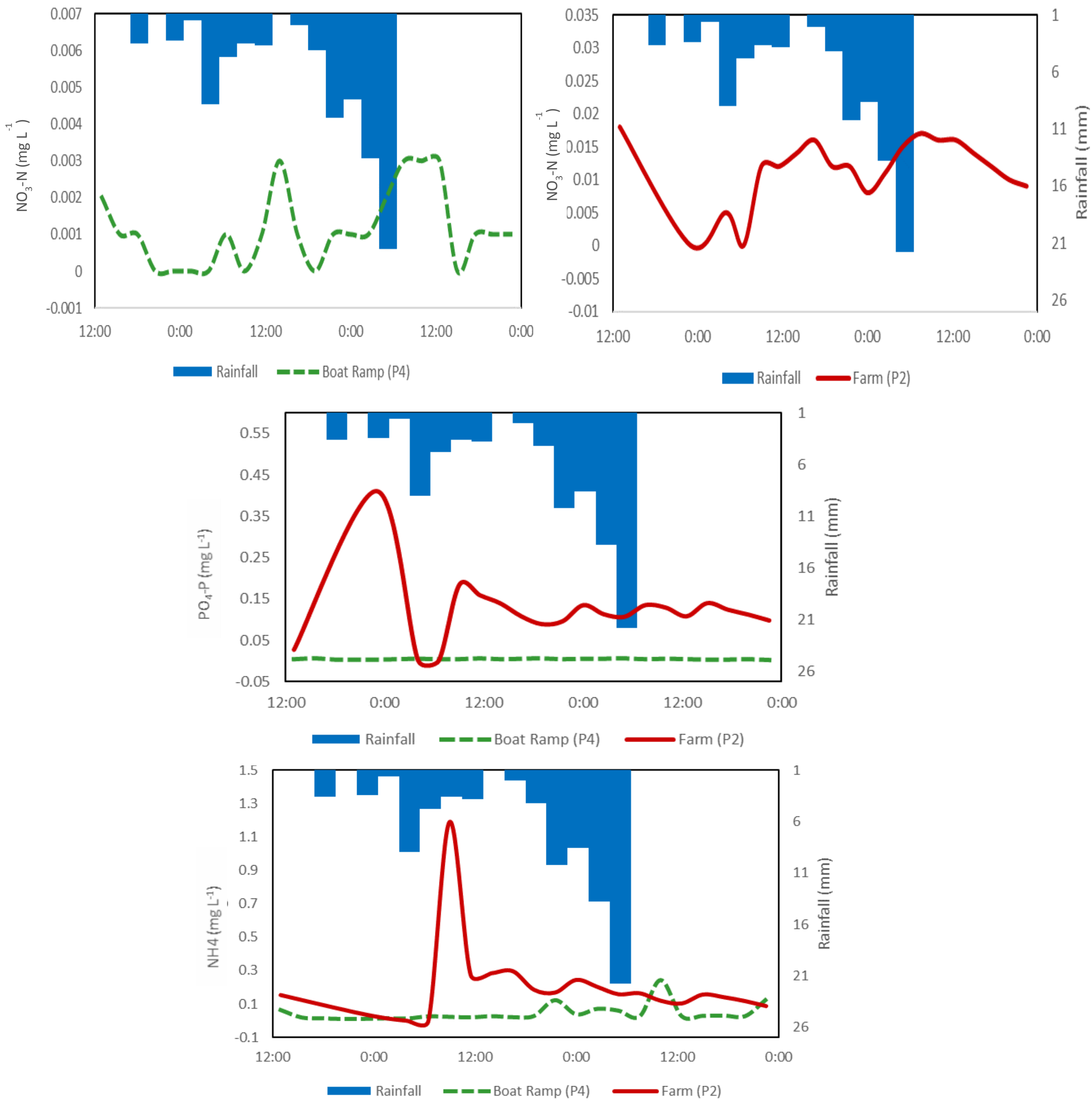

Figure 27: From top: NO_3-N at boat ramp (P4) (left) and P2 (right) and PO_4-P and NH4 across both sites during storm period during storm event 2 17/02/2016 to 19/02/2016

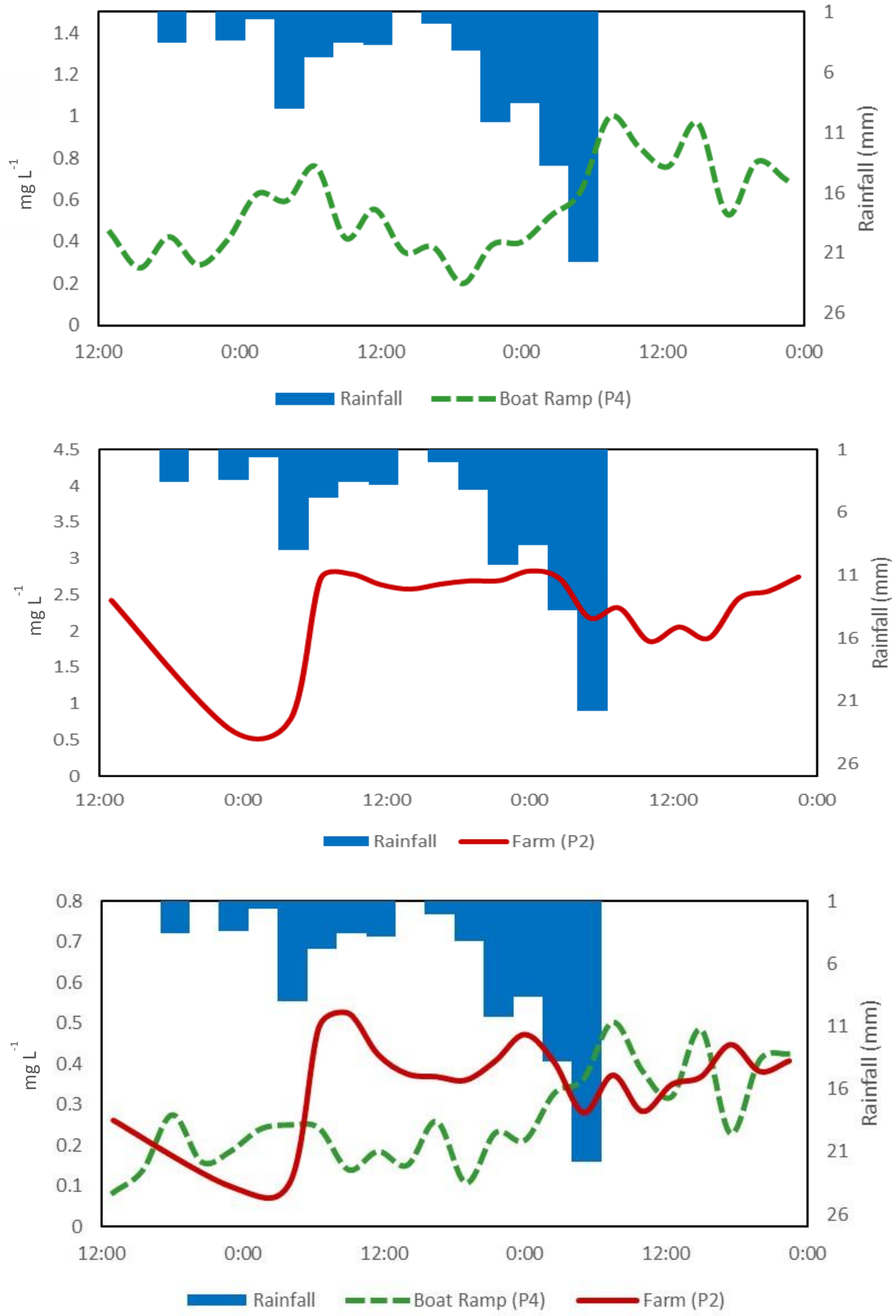

Figure 28: From top: Total nitrogen (TN) concentrations at P4 (top) and P2 (second down) and total phosphorus (TP) (bottom) during storm event 2 17/02/2016 to 19/02/2016.

4.3.3 Storm event three: 25/03/2016

On 25 March 2016 only one site was sampled, P3, the forest site. A paired site was set up at P2 however technical difficulties with the auto-sampler resulted in mechanical failure and no samples being taken during the storm event. For this period rain had begun falling before the sample station was set up,so concentrations may have already been affected by the rainfall. The majority of the rainfall during storm period was captured during the sampling period, however some rain had occurred before sampling began. Nitrate and ammonium showed distinct increases after heavy rainfall. Phosphate showed to decrease after heavy rain, similar to previous sample sites.

4.3.4 Storm Event Summary

For the storm sampling data, regression relationships were used to examine correlations between rainfall and nutrient concentration. Due to the groundwater system being sampled, it is important to consider the lag time that occurs. Regression relationships were established for each site and each nutrient species, with concentrations lagged from rainfall by 0,2.5, 5 and 7.5 h. (Table 3).

Table 3: R^2 values from nutrient concentrations versus rainfall with increasing lag times as averaged across all storm events

	P2	*P3*	*P4*	*Spring*
Normal time	0.05	0.05	0.03	0.11
+2.5 hours	0.08	0.03	0.05	0.11
+5 hours	0.07	0.07	0.13	0.08
+7.5 hours	0.11	0.07	0.13	0.02

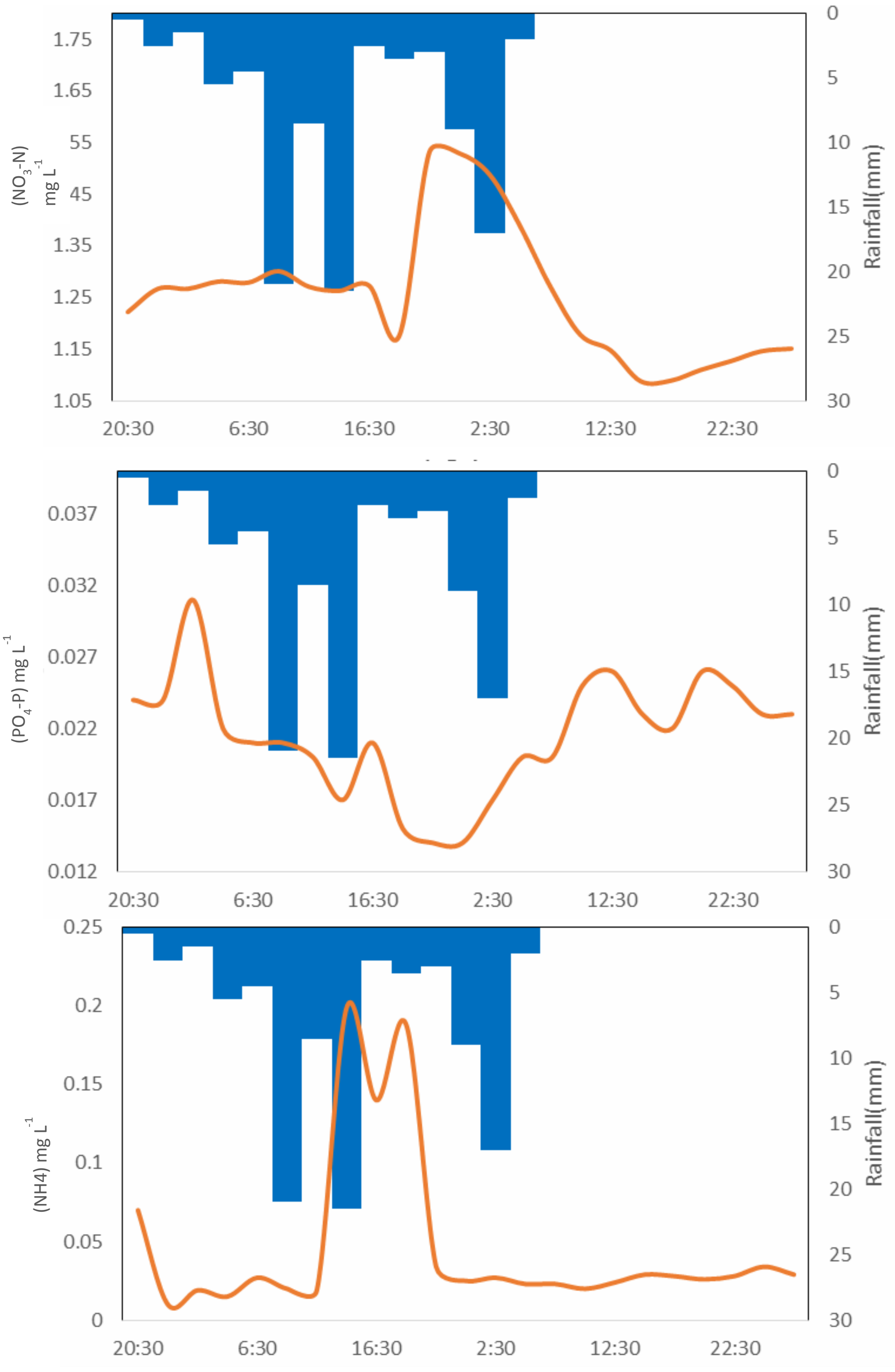

Figure 29: From top: NO3-N, PO4-P and NH4 concentrations at P3 during storm event 3 25/03/2016.

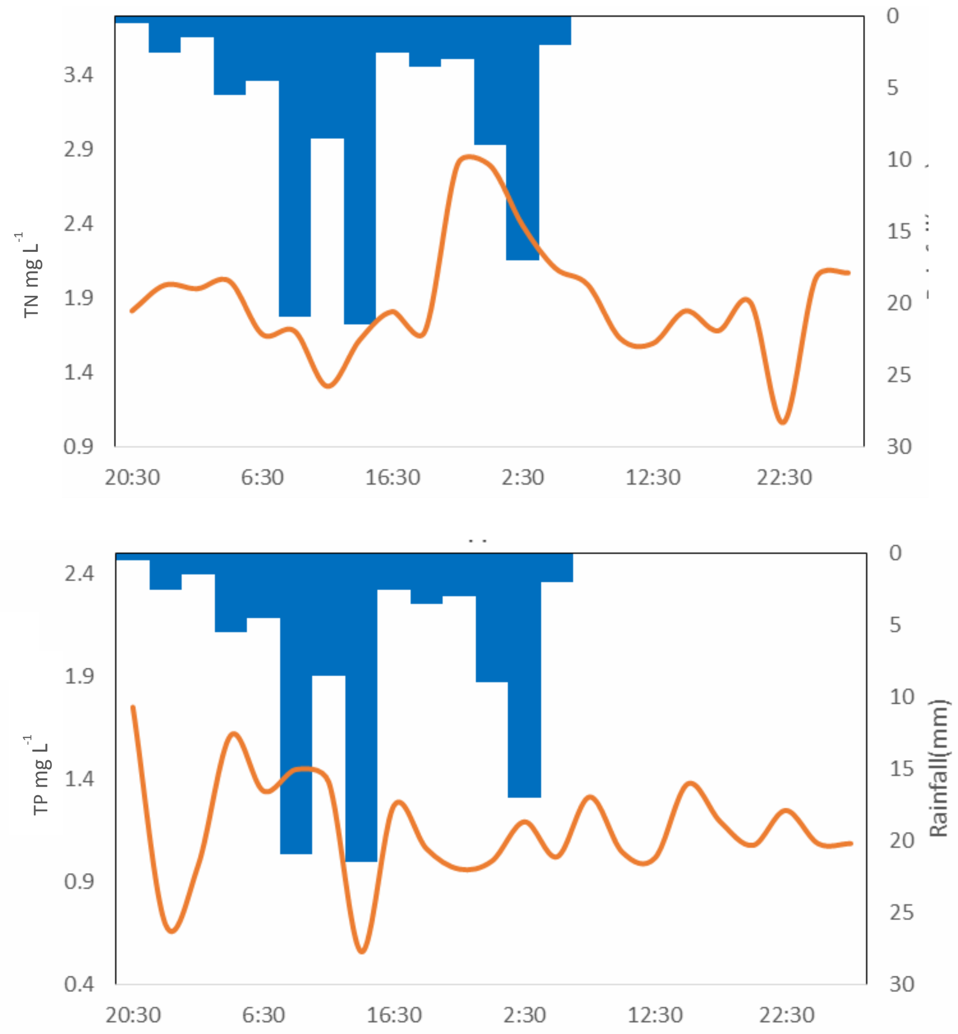

Figure 30: Total nitrogen (TN) (top) and total phosphorus (TP) (bottom) concentrations at P3 during storm event 3 25/03/2016.

The R^2 values differ for each site, suggesting the sites have different lag times between them. For P2 the lag time of 7.5 h produced the highest R^2 value (0.11) . P3 showed generally low R^2 values overall with the highest being at 5 and 7.5 h after rainfall initially fell. Nitrate (NO_3-N) had the same R^2 (0.2) at 5 and 7.5 h lag time.

P4 had the highest R^2 values at 5 and 7.5 hours after rain. A significant relationship between nitrate (NO^3) (r^2 of 0.4) was observed at this 7.5 hours lag time. The spring followed a different trend to that of the piezometer data and had the higher correlation values with no, or a small lag time (2.5 hours). These values are generally too low to be significant in this instance however it is important to note that phosphate had a high R^2 of 0.3 at 0 and 2.5 hours after. The spring results indicate the effect on the nutrients in the water are going to be relatively instant compared to the piezometer sites which suggested significant lag times.

4.4 Groundwater level variations

There was a strong relationship between daily rainfall and daily groundwater levels showing a large degree of variation. During storm event sampling the logger was removed from the piezometer, the data friom these time periods have been removed

Water levels at P1 showed an immediate level of range during rainfall (Fig. 31). Out of a sample size of 3,787 recorded measurements it produced a P value of less than 0.01 meaning that it is a significant relationship and an r value of 0.12. The P2 site also showed a strong relationship with rainfall (Fig.31), with 3747 recorded measurements it also produced a significant P value of less than 0.1 and showed a higher coefficient of correlation than P1 with an r value of 0.31. P3 was the forested site and indicated a longer recovery time (Fig. 31), P2 responded rapidly to high rainfall and large peak in levels were observed before returning back to the base level relatively quickly where as P3 showed increases with rainfall but a slower, more gradual return to base flow level. P3 also showed a significant P value being less than 0.01 however a weak r value of 0.05 and 3830 recorded measurements.

The spring site showed a different relationship from the piezometer sites (Fig. 32). There was significantly less variation in water level and a smaller response to the larger rainfall events, indicating the spring may not be connected to any surface water system. The spring not responding to rainfall also indicates that the recharge zone is not located in close proximity and long travel times could be involved before the water is discharged at the spring. The largest variation in level was around then 26/2/2016 when there was relatively little rainfall recorded but a distinct increase in water level at the spring was observed from the data.

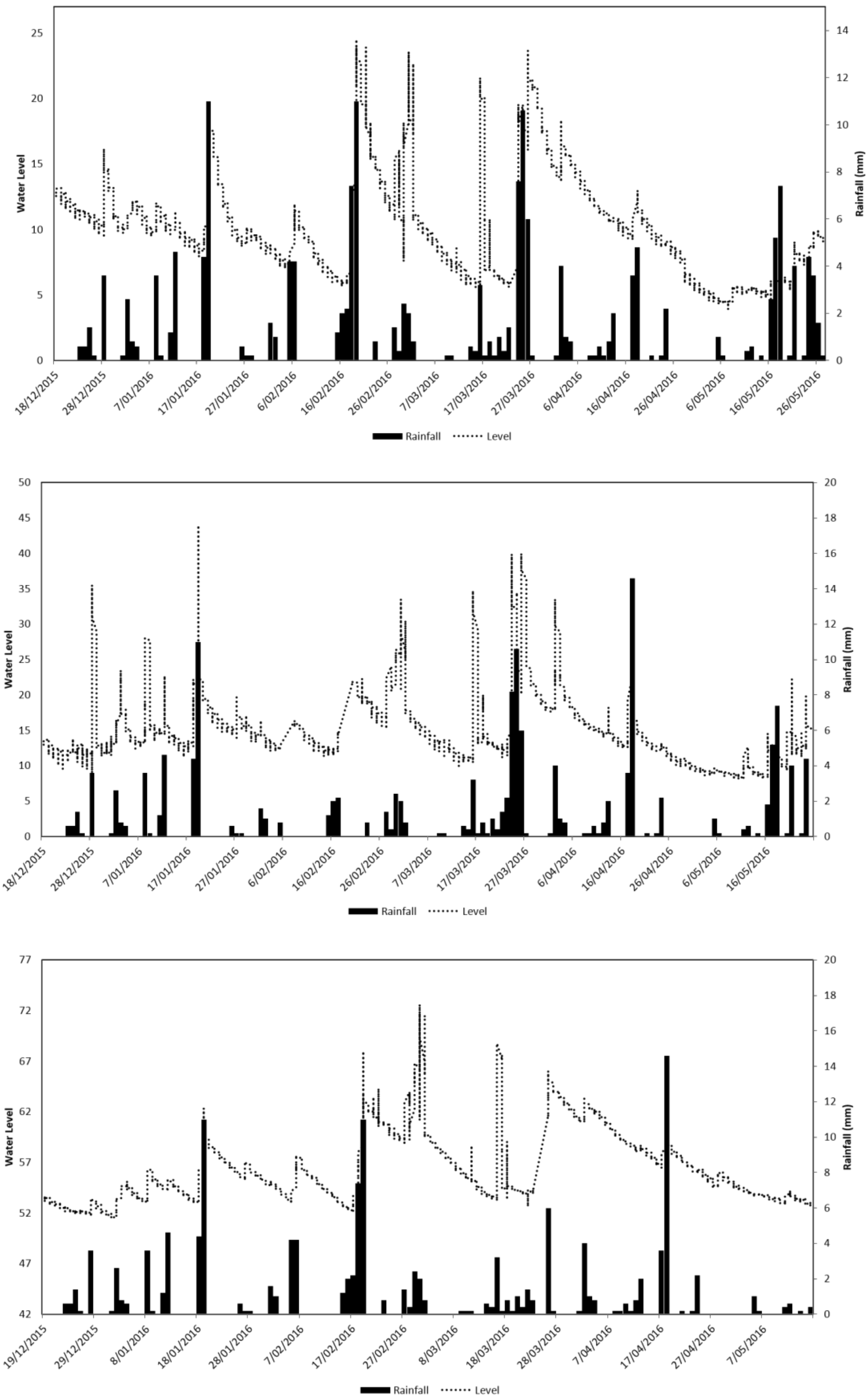

Figure 31: Groundwater levels and rainfall at P1 (top), P2 (second) and P3 (bottom) during study period 01/01/2016 to 01/06/2016.

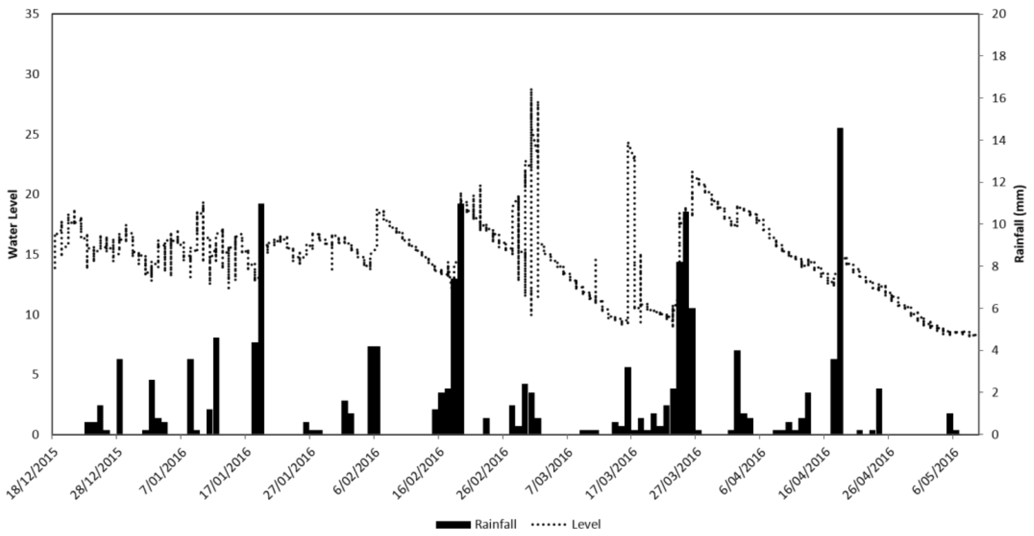

Figure 32: Water levels at the spring versus rainfall (mm) during study period 01/01/2016 to 01/06/2016 from water level loggers.

4.5 Shore bed temperature profiles

The thermistor chain was deployed at 3 locations within the lake. First deployment was at the spring out to the lake bed, the second deployment was on the eastern side of P5 (Fig. 7) and the third deployment was between P1 and P2 (Fig. 7). The data from the thermistor chain showed temperature variations of the lake bed at high frequency. The first site was at the spring as the cable was placed from the base of the spring and ran outwards into the lake along the bed. The contour plot shows the cooler water coming from the spring from 0-2 m and does not plunge to the cooler deeper layers but rather spreads across the surface layer of the lake (Fig. 34).

The second deployment had no rainfall during the recording (Fig. 35). It showed diurnal variation, with cooler temperatures at night and warming during the day. At around 4 metres along the lake bed a there was a colder section than at other depths. It is important to note that this does not represent vertical depth but mostly horizontal distance from the lake shore; the thermistor at 20 m was in 9 m depth of water. The third deployment there was rainfall was encountered during this period, however it did not appear to have been reflected in the temperature plot.

This site showed strong diurnal temperature variation in the first 10 thermistors (to depth ~ 4 m), but little temperature fluctuation in the remaining 10 thermistors.

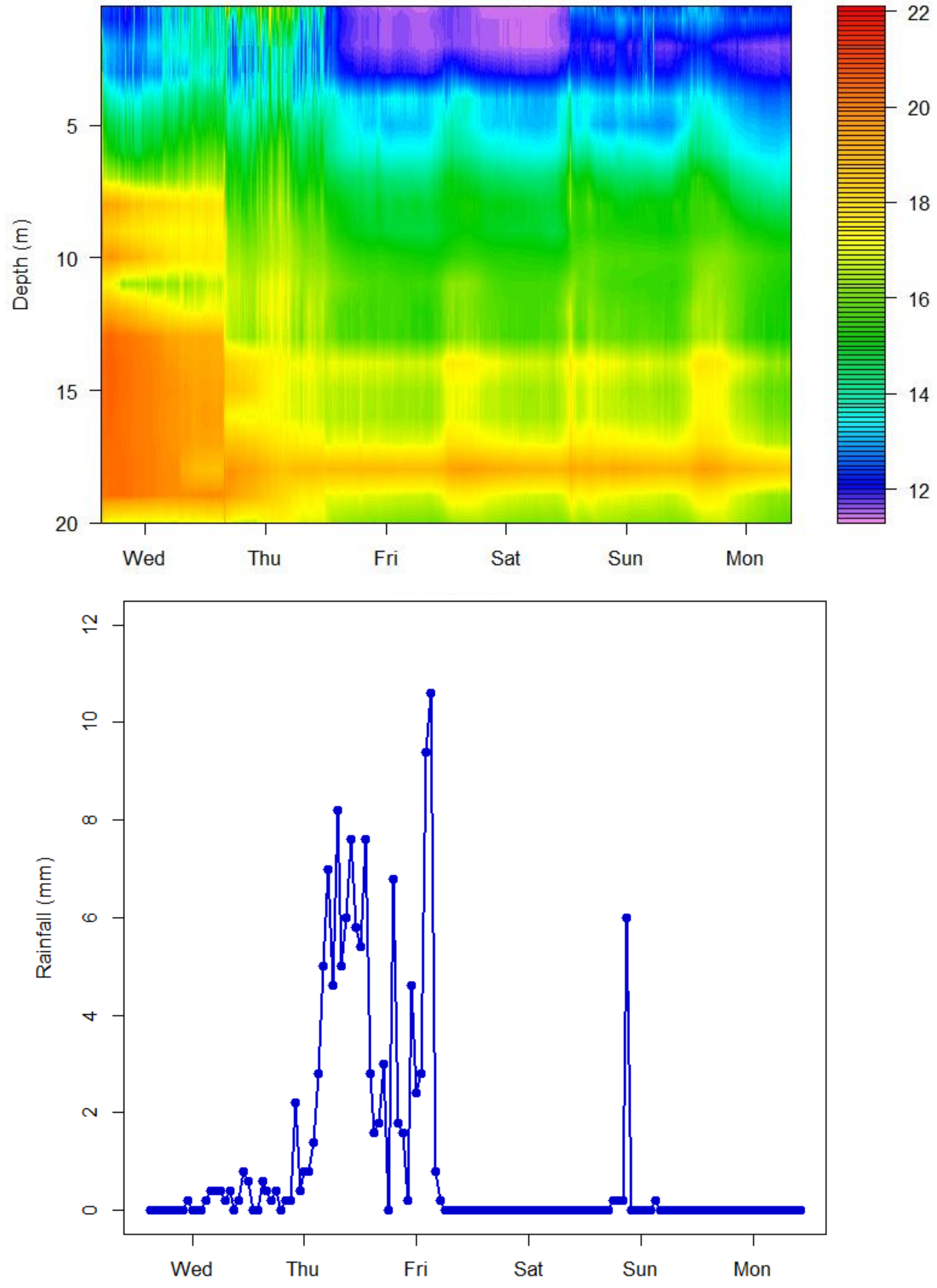

Figure 34: Contour plot of temperature (°C) with depth during the time of the first deployment at the spring location and rainfall (mm) during the same time period.

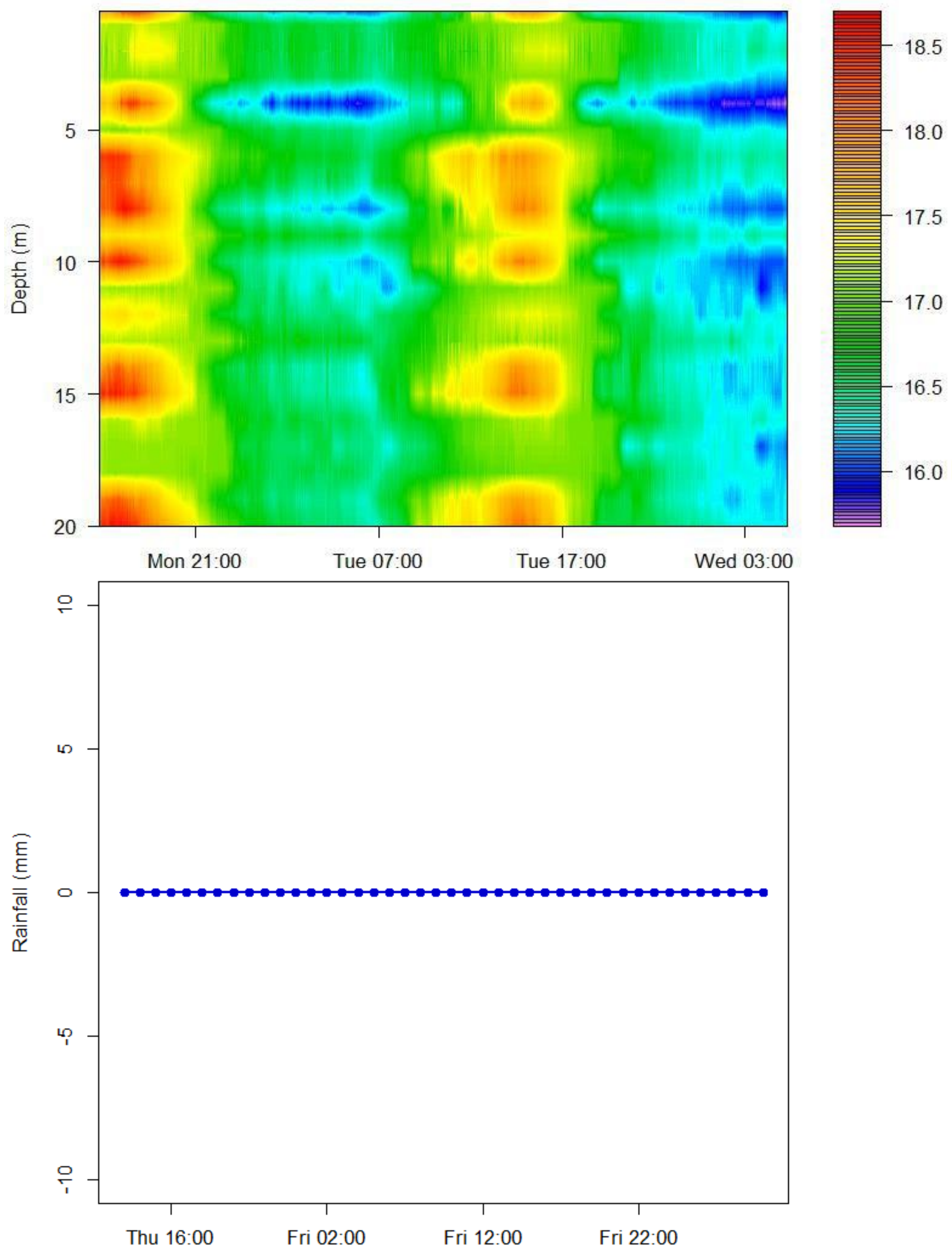

Figure 35: Contour plot of temperature (°C) with depth over time against rainfall (mm) during the second deployment.

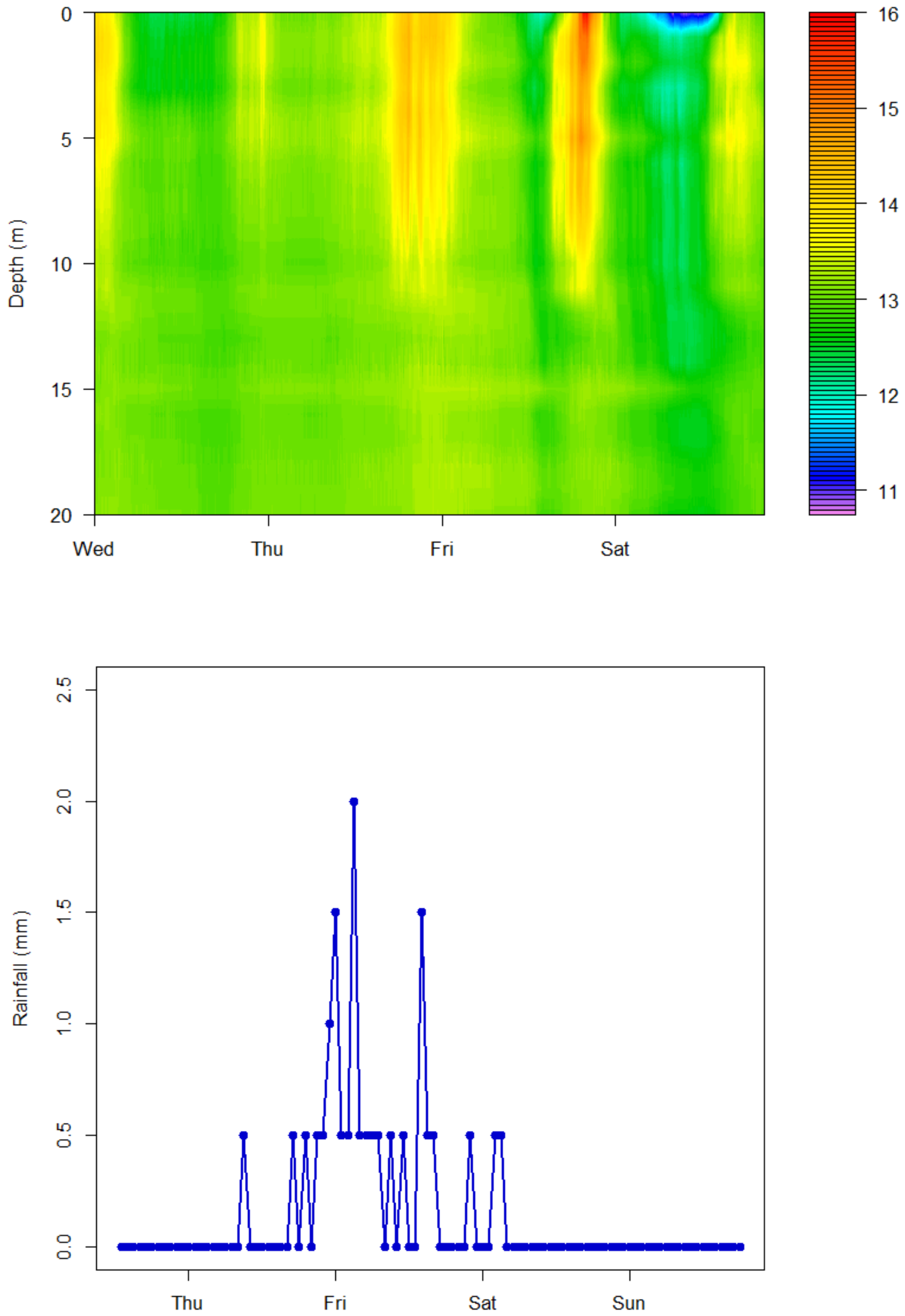

Figure 36: Temperature contour plot (°C) from site 3 from 08/06/2016 to 12/06/2016 and rainfall (mm) during the same period.

4.6 Hydrodynamic modelling

The three different model simulations showed variation in regard to water level over the simulation period with water levels within 2.5 meters (Fig. 37). For simulation 1 which had groundwater inflows calculated through water balance equations, the water levels remained relatively constant but increased towards the end of the simulation period. The second simulation with the constant groundwater inflow and outflow values showed a slight decrease in water level over time and the third simulation showed the most variability, decreasing the most over the simulation period. There was limited observed data for the lake water level with only three observed measurements.

There was little variation in modelled temperature among the three simulations (Fig. 38 and 39). The model accurately simulated temperature profiles (Fig. 38 and 39). The lake was stratified for the entirety of the simulation and this was accurately simulated by the model simulations by having the thermocline depth the same as the observed data (Fig. 39). Simulation one and three were similar in regard to temperature and remain heated at the surface, however simulation two began mixing earlier, which matched the observed data. The third simulation also showed the location of the cooler spring water entering at the spring location constantly throughout the simulation period where as simulations 1 and 2 only recognised the spring for shorter time periods (Fig. 40-44).

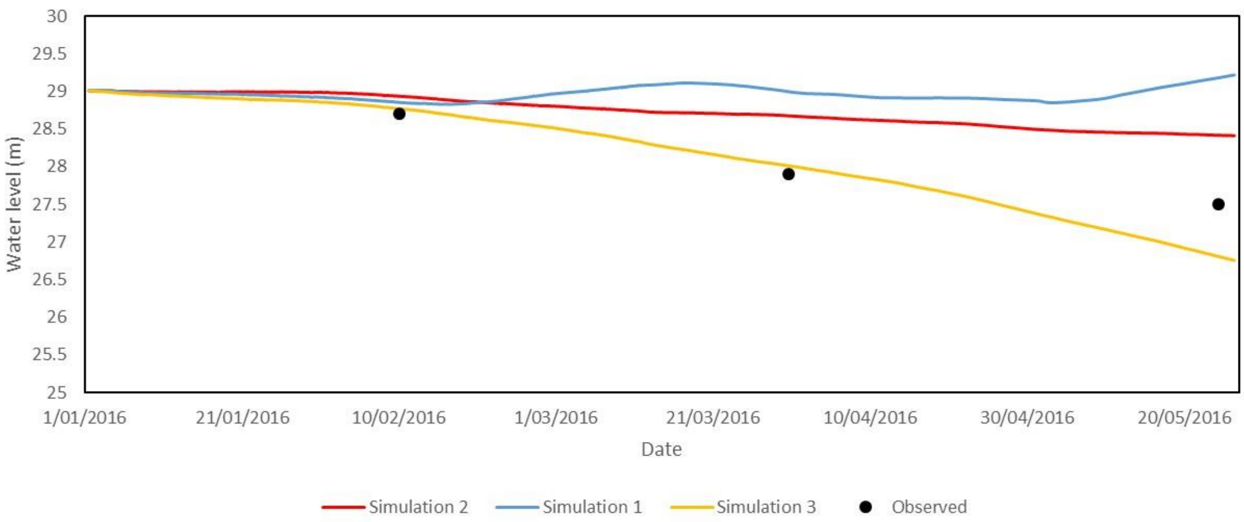

Figure 37: Modelled water levels (m) from three simulations against observed water levels during the simulation period 01/01/2016 to 01/06/2016.

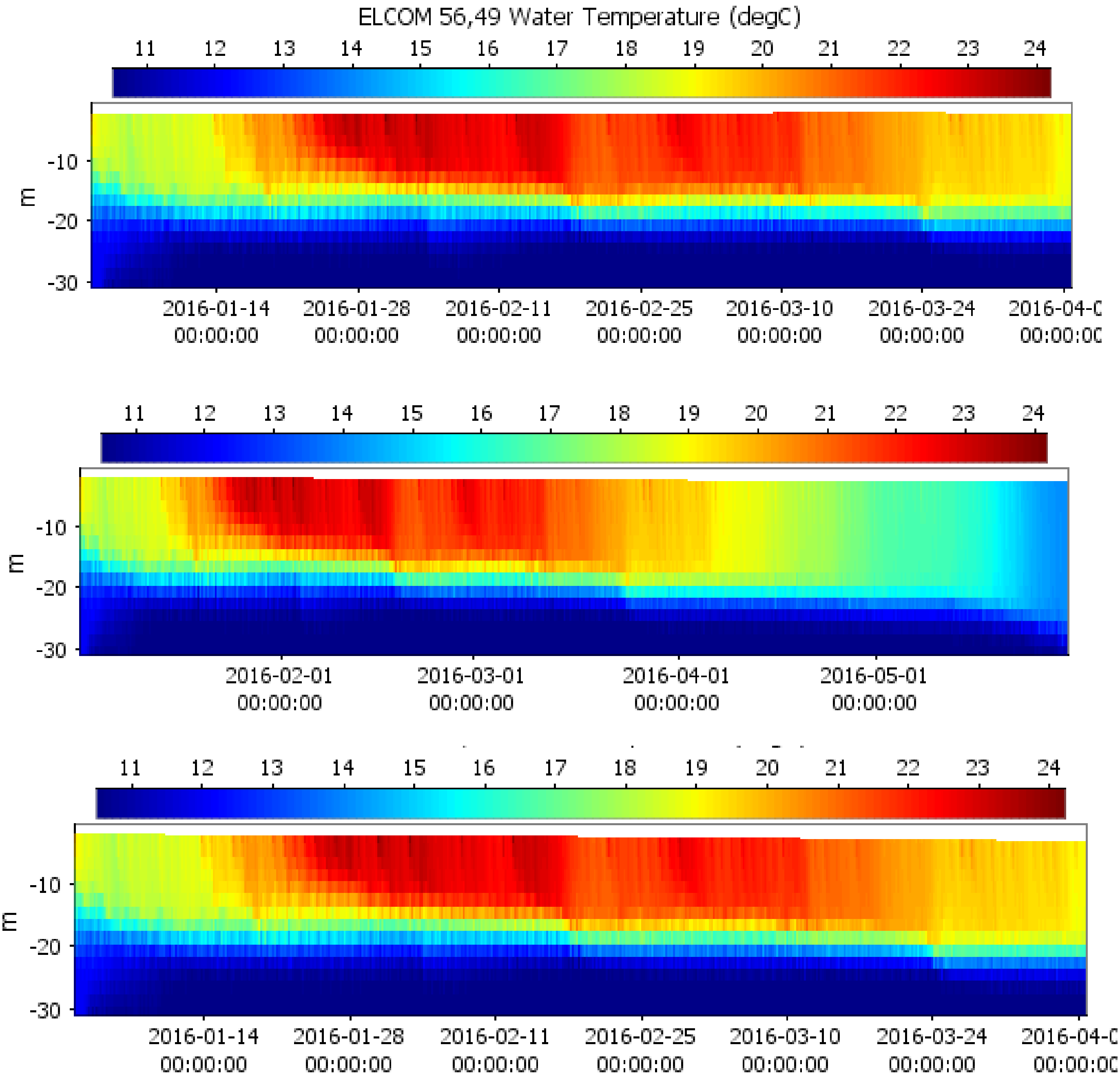

Figure 38: Modelled temperature (°C) throughout the simulation period 01/01/2016 to 01/06/2016. Top to bottom, simulation 1, simulation 2 and simulation 3.

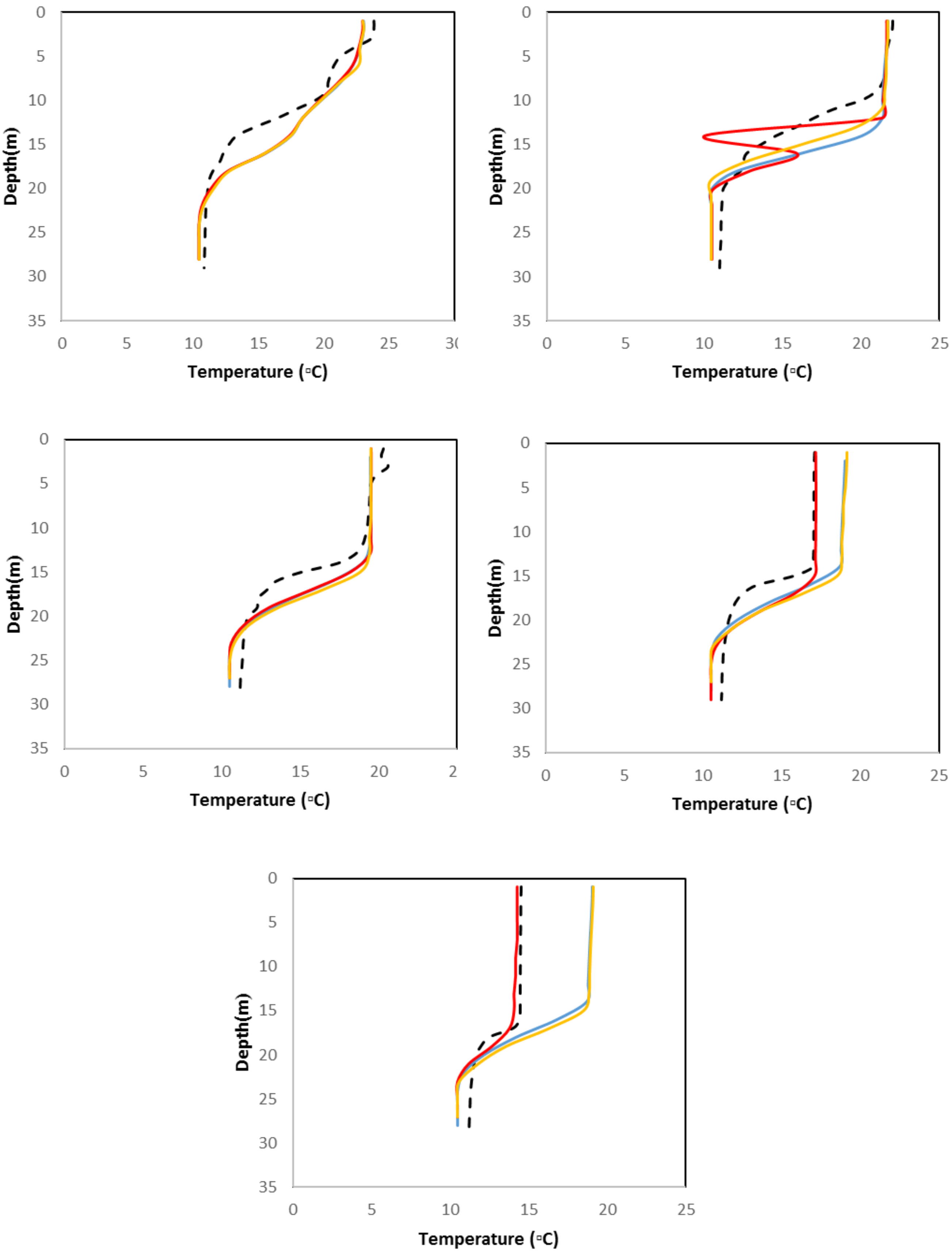

Figure 39: Temperature profiles (°C) of Lake Rotokakahi showing observed and modelled temperatures from all simulations. From left to right, top to bottom 26/01/2016, 18/02/2016, 30/03/2016, 25/04/2016, 25/05/2016

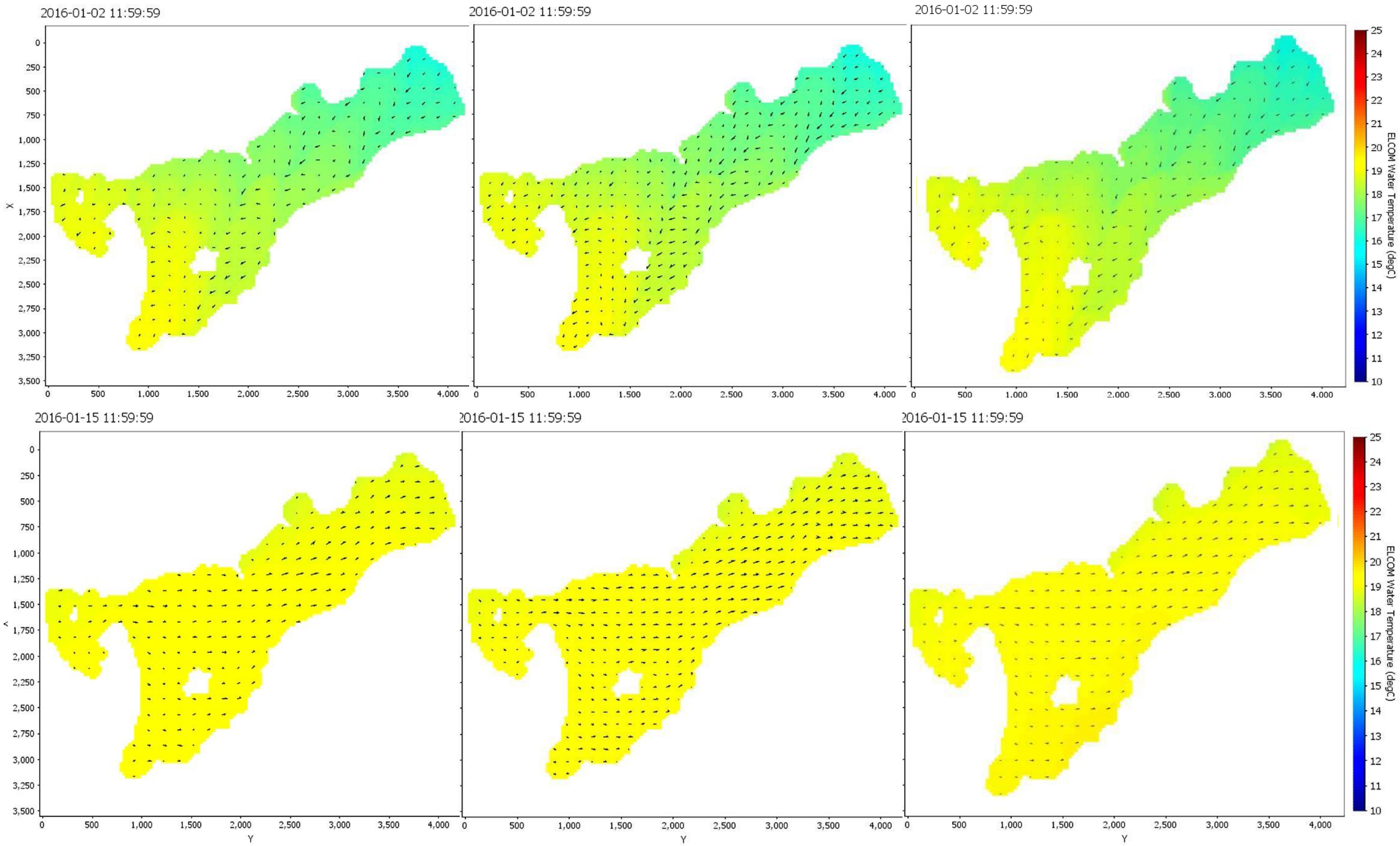

Figure 40: Modelled surface temperatures (°C) and velocity arrows on 02/01/2016 (top) and 15/01/2016 (bottom) from all simulations, left to right: simulation 1, 2 and 3.

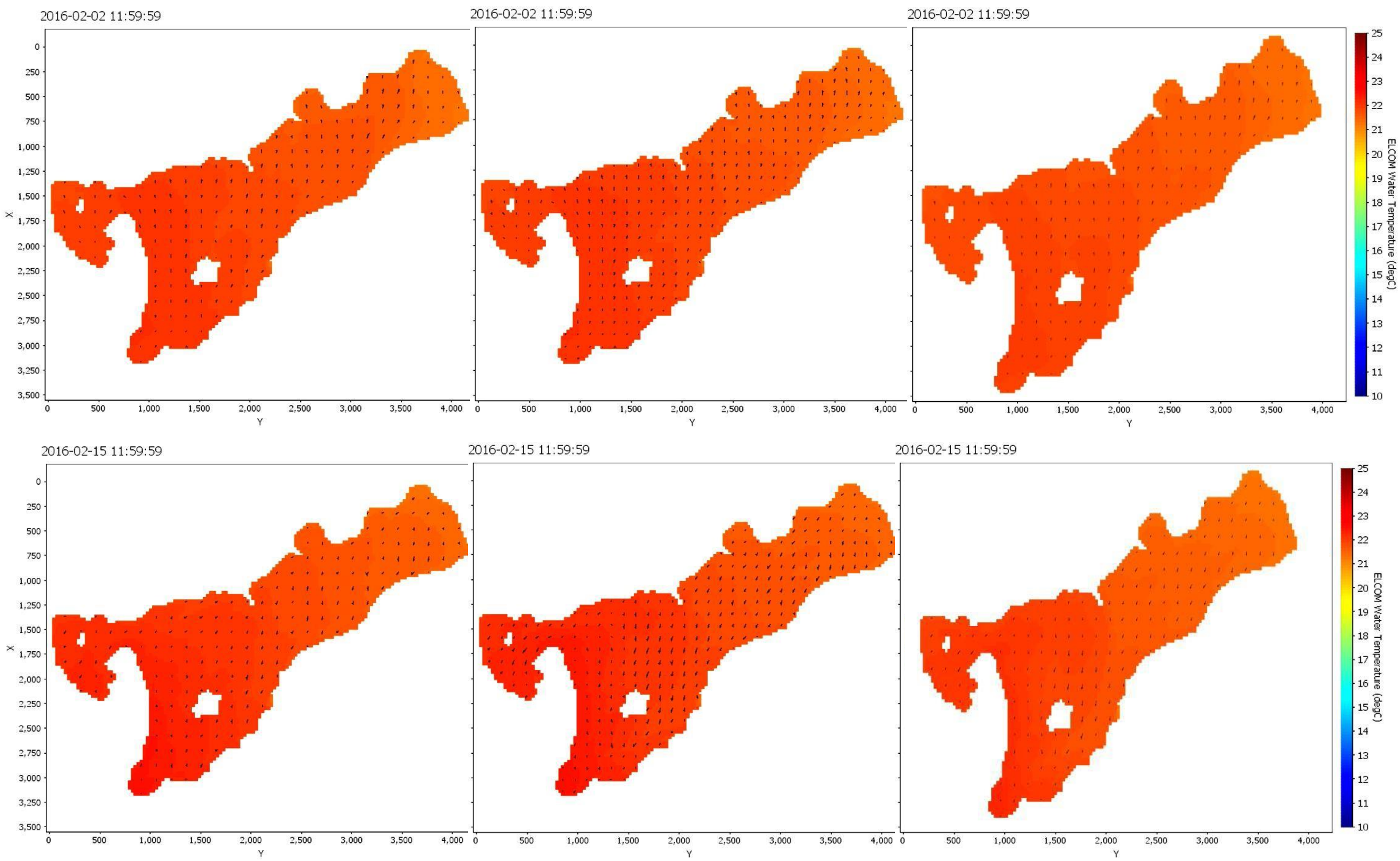

Figure 41: Modelled surface temperatures (°C) and velocity arrows on 02/02/2016 (top) and 15/0/2016 (bottom) from all simulations, left to right: simulation 1, 2 and 3.

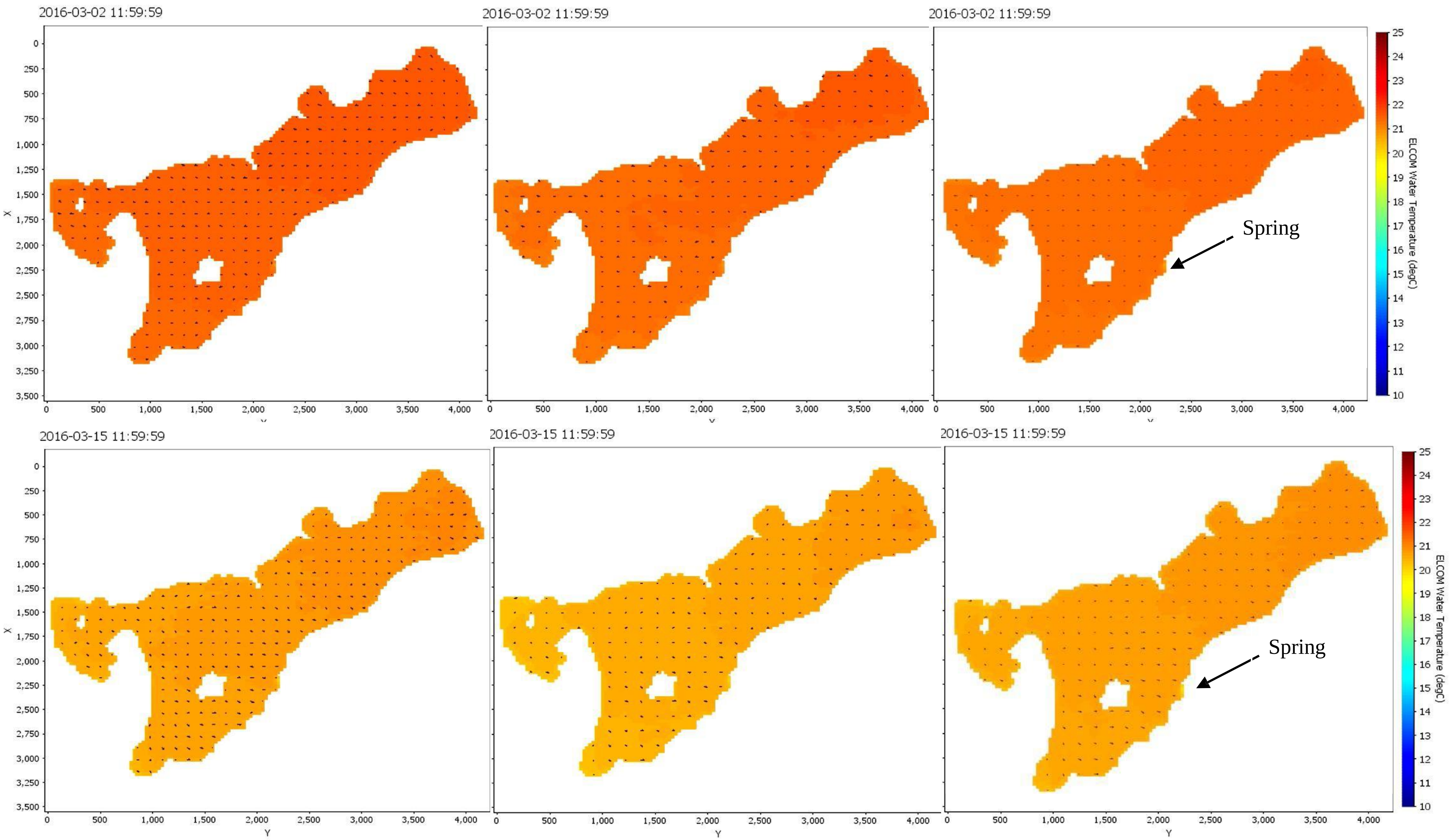

Figure 42: Modelled surface temperatures (°C) and velocity arrows on 02/03/2016 (top) and 15/03/2016 (bottom) from all simulations, left to right: simulation 1, 2 and 3.

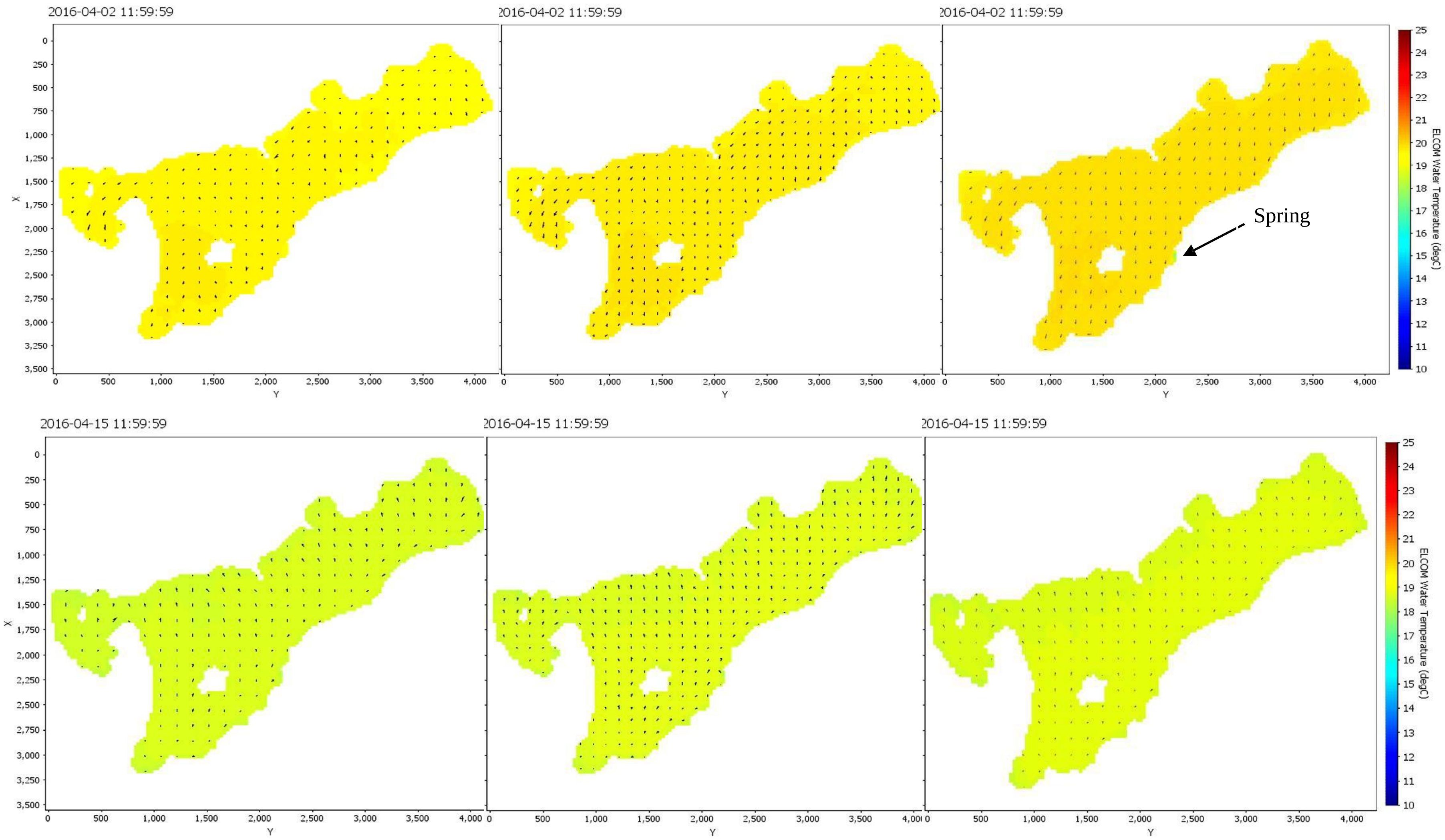

Figure 43: Modelled surface temperatures (°C) and velocity arrows on 02/04/2016 (top) and 15/04/2016 (bottom) from all simulations, left to right: simulation 1, 2 and 3.

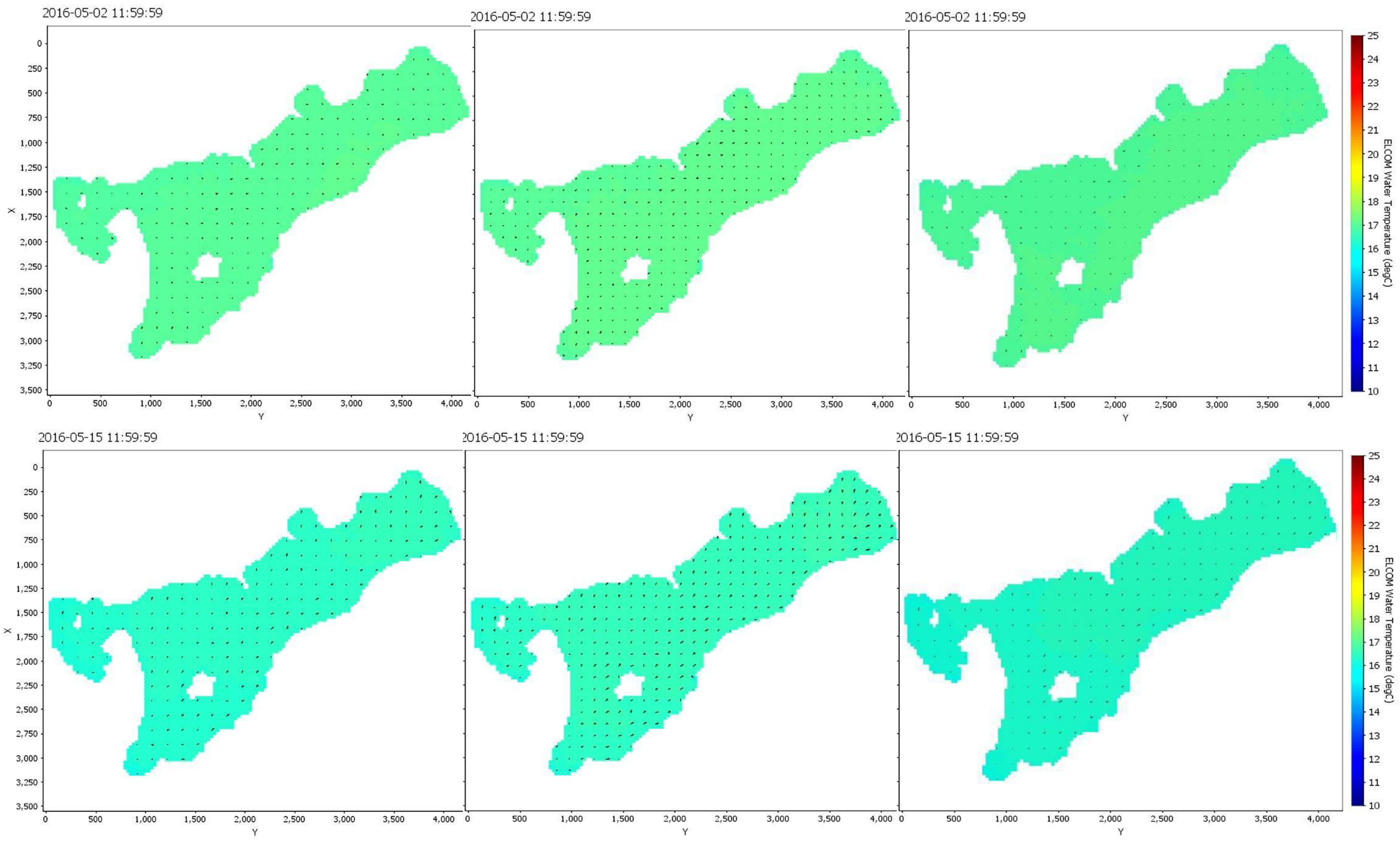

Figure 44: Modelled surface temperatures (°C) and velocity arrows on 02/05/2016 (top) and 15/05/2016 (bottom) from all simulations, left to right: simulation 1, 2 and 3.

5 Discussion

In this study the interaction between groundwater and surface water has been analysed in Lake Rotokakahi through observing the groundwater system, examining measurements of temperature where surface and groundwater flows enter the lake, and carrying out three-dimensional modelling of the lake. The three – dimensional hydrodynamic modelling was used to investigate the differences between three methods of groundwater volume calculation, each of which was entered as input to separate model simulations.

5.1 Groundwater quality

Sampling of the shallow groundwater system was undertaken during the study period and compared to nutrient concentrations of the lake and the spring inflow. Nutrient concentrations in general were higher in groundwater than in the receiving lake.

Nitrite and nitrate are natural occurring ions that are abundant in the environment (Jahed Khaniki *et al.*, 2008). Water quality monitoring shows that nitrite is present in the groundwaters surrounding Lake Rotokakahi, though in relatively low numbers in regard to drinking water standards (*Drinking-water standards for New Zealand 2005 (Revised 2008)*, 2008) which has limit of 0.2 mg L^{-1}. The dominant nitrogen compound found in the groundwaters in this area are in the form of nitrates (NO_3-N). Nitrates in the groundwaters were highest in one of the farmland sites (P1) however the other farmland sites (P2 and P5) showed the lowest. All of the piezometer sites were higher in nitrates than the lake and the spring which showed extremely low nitrate values. The forested sites showed relatively high values which is common for harvested forestry area, however. The lower values at farm site (P2) can largely be attributed to the fact that the area is often highly saturated, near wetland conditions and P5 is located in a valley which is largely forested in the higher catchment but farmed on the immediate lake shore.

Concentrations were shown to be lower in the groundwaters than the receiving lake, with the exception of the spring and one piezometer site. P2, located in the saturated wetland area of the farmland showed the highest ammonium concentrations of the shallow groundwater system. The spring showed extremely elevated levels of ammonium (0.2 mg L^{-1}) and was higher than the other groundwater sites. High ammonium concentrations are a common indicator of anthropogenic activity (Lingle, 2013) but can also occur through the decay of natural organic material (Lingle, 2013). In regards to the spring, the source of the high ammonium levels is most likely through the in situ decaying of organic material due to the native forest location, rather than from anthropogenic sources however isotopic analysis of the spring should be undertaken to determine recharge location and potential sources of nutrients. However, these ammonium concentrations are below 0.2 mg L^{-1} which is the upper limit for naturally occurring ammonium.

In regards to total nitrogen, groundwater was shown to contribute the majority of nitrogen to the lake system. The lake had the lowest nitrogen concentration and the spring also had low concentrations. Groundwaters in the agricultursl area had the highest in nitrogen concentrations. One of the forested sites also showed relatively high nitrogen concentrations also. The nitrogen concentrations were below the national drinking water guidelines (Drinking-water standards for New Zealand 2005 (Revised 2008), 2008) indicating that they are still of good quality.

Phosphorus can be a highly important in eutrophication of surface water systems. Excess phosphorus can cause an imbalance in nutrient cycling process (Ricklefs & Schluter, 1993). Phosphorous in groundwaters is largely sourced from overlying soils, dissolution of minerals from aquifer sediments, fertilisers and waste waters (Welch *et al.*, 2010). Geologic sources generally have a greater influence on phosphorous concentrations than anthropogenic sources, however it is common for P to be immobile in groundwater systems (Meinikmann *et al.*, 2015) however the results have shown significant contribution of P from the groundwater system.

The concentrations of phosphate in the piezometer sites were well below the standard value of 0.09mg L^{-1} for surface waters considered to be 'enriched' (Scott & Wong, 2016), this value is used as there are currently no groundwater standards for phosphorus. There was one site P5, in the farmland which had values higher than 0.03 mg L^{-1} which in the limit for excessive levels (Scott & Wong, 2016). The spring showed highly elevated levels of phosphate (0.225 mg L^{-1}) which is also largely unexpected. This exceeds the 'enriched' standard as outlined above. In regard to phosphorus levels the groundwater sites including the spring were higher than the lake, with the exception of the forested site P3. The farm site (P5) showed the highest concentration across all sites. Phosphate monitoring of the groundwater has been important in determining that phosphate is entering the lake through the groundwater system which can have implications for overall lake ecology if these levels continue to rise and contribute higher concentrations to the lake.

Sources of phosphorus are largely through wastewater contamination from urban sources (Meinikmann *et al.*, 2015) however, this source is unlikely in the Rotokakahi catchment. The source of phosphorus in this catchment can be largely identified as coming from the local soil and geology structure. P5 showed the highest levels of phosphorus. This area where the piezometer was located was not commonly used by stock however had a very coarse, sandy substrate compared to the other farm sites which were dominated by smaller grained sand.

5.2 Temporal variations in nutrients during high rainfall events

From analysing the three storm events that were sampled during the study period a distinct insight was gained into how the shallow groundwater systems responds to high rainfall events. It is known that the majority of the nutrient loading into a lake is caused from storm events however due to the soil structure and geologic units within the Lake Rotokakahi catchment all water that would otherwise go into overland flow, infiltrates through the sandy soil layer and into the groundwater table. The shallow groundwater system is an area which is often ignored in terms of nutrients into the receiving water bodies. By observing the general nutrient concentrations between sites as above, the temporal variability of these flows and how they respond to high rainfall events was analysed.

It is generally expected that higher rainfall will result in higher dilution and lower concentrations however the opposite has occurred (Abell, 2013). The relationships between nutrient concentrations and rainfall were similar between the different piezometer sites and showed a general increase during periods of high rainfall. Nitrite levels across all sampled sites showed a distinct increase with rainfall, however the peak wasn't observed for up to 12 hours after a period of heavy rainfall. Nitrate (NO_3) generally increased with rainfall, apart from the first storm event when a decrease in concentration occurred. The first storm event was only 28 mm of rain throughout the 60 our sampling period compared to the others which were 94 mm and 97 mm respectively. Light rain would have minor effects on nutrient concentrations. The events with higher rainfall had a small calculated lag time for nitrate delivery. Ammonium showed distinct peaks that corresponded closely with peaks in rainfall, particularly in the sites that were located in the farm land. Forest sites showed smaller, more delayed peaks in concentrations. This was expected due to the buffer that was provided by the vegetation in this area. By contrast rainfall on farmland would have infiltrated rapidly into the sandy soil layers until it reached the groundwater table.

Phosphate showed to increase during light rainfall but decreased during heavy rainfall. The coarse volcanic soils in the catchment are high in allophanic clays (Rijkse & Guinto, 2010) and have a high capacity to absorb phosphorus (Abell et al., 2013) therefore the soils in which the shallow groundwater systems interacts with have the ability to buffer phosphate through either absorption or desorption processes (Abell *et al.*, 2013). This means that increases in phosphate are likely to occur outside of storm events or with light rain, as observed during the first storm event. Total phosphorus however showed a distinct increase across the majority of the sites except for P4 where no relationship was observed.

Total phosphorus concentrations increased substantially with rainfall, and remain elevated long after rainfall has ceased. Similar to nitrogen, the response was near instantaneous in the farm land sites however a considerable lag time was noticed in the forested sites. Higher TP concentrations are largely attributed to higher suspended sediments as phosphorus binds to particles. This was observed particularly when analysing and filtering the samples that contained large amounts of suspended sediments. As heavy rainfall infiltrates the surface layers, soil particle can be dislodged through the infiltration process, carrying phosphorus.

Whether the inflow spreads across the surface of the lake or whether it plunges to the deeper layers is dependent on buoyancy which is associated with temperature. Plunging of relatively cool stream inflows on entry to a lake is well recognised (Abell,. 2013) however figure 34 shows the cooler water of the spring inflow spreading across the surface of the lake during a period of rainfall. The nutrients transported during high rainfall events, based on this data, will spread across the surface of the lake rather than plunging into the deeper, cooler layers of the water column. This can have implications as these nutrients are likely to be accessible to phytoplankton within the shallow euphotic zone of the lake.

5.3 Temporal variation of groundwater levels over study period

It is generally assumed that groundwater systems are in a steady state. Steady state means groundwater flows remain constant over time however from high frequency groundwater level data obtained during the study period, immense variation has been observed. All sites showed significant relationships (P values <0.01) with rainfall. At most of the sites, distinct increases in groundwater level were observed almost simultaneously with rainfall. The groundwater levels peaked relatively quickly after rainfall and remained elevated for a period of time before slowly returning to base level conditions. This data indicates that the shallow groundwater system within the Lake Rotokakahi catchment is responsive to rainfall and highly variable over time and connected to the surface water system. Assuming groundwater levels correspond to groundwater flow, the groundwater flow can also be variable over time, similar to surface water systems.

The exception to the above was the spring. Some large rainfall events had no impact on the water level of the spring where as some small events produced a slight increase in water level. This further emphasises the fact that the spring is most likely sources elsewhere, possibly out of the catchment where it may be sourced from a different groundwater system.

5.4 Hydrodynamic modelling

In this study ELCOM was set up and applied to Lake Rotokakahi to investigate the hydrodynamic differences when alternate methods of groundwater volume were used as major lake inflows. All modelled simulations accurately modelled lake thermodynamics with modelled temperatures showing the lake was stratified during the simulation period which was observed from the monitoring data. The depth and extent of the thermocline was accurately modelled along with the depths of the hypolimnion. The eplimnion was accurately modelled up until the end of May 2016 where modelled temperatures showed to remain heated (simulations 1 and 2). The model was able to accurately simulate the hydrodynamics of Lake Rotokakahi as shown by the good fit with the observed temperature data. This also indicates that the location of the cooler groundwater inflows were placed in the correct position within the lake model grid as large inflows of cooler temperatures, if not in the correct locations or depths would drastically alter the temperature profile of the lake.

It is important to consider that groundwater does not follow usual seasonal trends that would be expected for flowing surface water bodies. Due to the time delay rates of groundwater inflow are often reversed from surface water inflows with higher groundwater levels in the summer rather than winter. This could be the case for Rotokakahi with the third simulation having decreasing groundwater inflow values with the onset of winter due to the delayed effects of the summer drought.

The different methods groundwater inflow calculation gave different volumes of water inflow however testing the accuracy of these different methods was largely impacted by the lack of observations for Rotokakahi. Of the observed values that were available simulation 3, which used the constant, steady state value generated through MODFLOW from White *et al*, (2015) combined with observed water level measurements, provided the most accurate form of groundwater volume calculation. More information particularly around lake levels as well as outflow volumes is required to accurately calibrate a water balance model.

6 Conclusions

The aim of this study was to gain an understanding of how the groundwater system interacts with the surface water system and the potential impacts on lake water quality. The three-dimensional lake hydrodynamic model ELCOM was used as a tool to explore these impacts.

Groundwater contributes a high proportion of the total nutrient load to the lake, especially during high rainfall events. During these events a slight time lag was observed between rainfall and nutrient concentration. The shallow groundwater system also varied considerably over time, largely in response to rainfall. ELCOM was used to demonstrate differences in the use of alternate methods of groundwater flow calculation and to reproduce hydrodynamic conditions in the lake during the sampling period.

Quantifying groundwater – surface water interactions requires accurate models and , regular measured data to gain a comprehensive understanding of their dynamics. This study provided valuable information for the shallow groundwater system, however monitoring of the deeper system will provide insight into the long term responses and homogeneity through the aquifer. In particular, isotopic analysis of groundwaters will provide age and chemical structure which will aid in determining lag times on a catchment scale and of possible sources of the groundwater. Isotopic sampling within the lake itself can also be undertaken to accurately quantify groundwater inflow volumes and whether these inflows are constant throughout the entire lake or whether groundwater discharges are occurring in ‘hot spots’ or localised zones. Frequent monitoring of the lake and groundwater system is essential for providing information on the condition of the two systems. This could be done by the installation of a monitoring buoy and regular monitoring of the groundwater system.

The addition of the model CAEDYM could also be considered as part of the lake modelling strategy. CAEDYM is an ecological model also developed by the University of Western Australia which is used to simulate three-dimensional water quality and can be coupled with ELCOM . This is challenging computationally and was not undertaken in this study due to time constraints, however is an area of future research.

The management of Lake Rotokakahi requires attention at a catchment scale that should include consideration of both surface and groundwater systems. Land use in this catchment has impacts on the lake water quality and thus applying better land management practices in the headlands of the catchment, even though further way from the lake, could still be effective where it was in close proximity to the groundwater aquifer. It is important to consider that even though groundwater cannot be seen and is less obvious than surface water systems, the need to manage the groundwater system and prevent further increases in nutrients levels is of utmost importance. More specifically, in this catchment groundwater inflows dominate the inflows to Lake Rotokakahi. Significant planting of the lower lying, swampy areas on the southern shore of the catchment and exclusion of stock from particularly damp areas should help reduce the nutrient infiltration to the shallow groundwater system., Areas that have a high water table, as observed in the southern shore of the Rotokakahi catchment, provide minimal if any buffer zone for land use impacts to the aquifer. protecting these areas could decrease the impacts on the shallow groundwater system.

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