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Nitrogen discharge from the groundwater system to lakes and streams in the greater Lake Tarawera catchment

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EXECUTIVE SUMMARY

Bay of Plenty Regional Council commissioned GNS Science to assess groundwater resources and groundwater quality in the greater Lake Tarawera catchment. A three-phase programme of hydrogeological investigations was developed to assist policies that aim to reduce the discharge of nutrients (nitrogen and phosphorus) to lakes in the catchment. Eight lakes (Tarawera, Okaro, Rotomahana, Rerewhakaaitu, Okataina, Okareka, Tikitapu and Rotokakahi) are within this catchment, and the groundwater system is a key component of the hydrology of the study area. The study area includes the estimated outer catchment boundary of the greater Tarawera lakes; eight zones represent topographic boundaries of lake catchments within the study area.

Surface geology of the greater Lake Tarawera catchment is dominated by volcanic units including ignimbrites and other pyroclastic deposits, as well as rhyolite lava domes and flows. Most of these deposits are sourced from the Okataina Volcanic Centre (OVC). Two major OVC eruptions (the 61 ka Rotoiti Formation pyroclastics and 322 ka Matahina Formation ignimbrites) produced deposits that are widespread throughout the study area and resulted in a large complex basin structure (caldera) that includes most of the greater Lake Tarawera catchment. These units are relatively permeable; however, finer-grained layers (air fall layers) may act as aquicludes (i.e., layers that have a low permeability).

Characterisation of surface flows in streams and rivers in the study area was completed, and water budgets were developed to improve the understanding of water inflows to lakes and outflows from lakes. This information was used to inform the development of a groundwater flow model based on MODFLOW-2005. For example, the catchment of Lake Tarawera includes cold springs, hot springs and streams. Natural streams flowing into Lake Tarawera from the west include: Wairoa Stream, sourced from Lake Rotokakahi; Te Puroku Stream and Wairua Stream that are sourced from cold springs and seeps; and Waitangi Stream that is primarily sourced from Lake Okareka. In addition, springs predominantly located in Kotukutuku Bay and the southeast of Lake Tarawera, provide significant inflow to the lake.

Interaction between surface water and groundwater was demonstrated with characterisation of the hydrogeological system and with a groundwater flow model. The model shows that groundwater flows into lakes and streams in the greater Tarawera catchment and that water from some lakes discharges into groundwater. In addition, groundwater flow between zones was identified. The model mostly indicates that lakes are recharged by groundwater because model-calculated groundwater levels are typically higher than lake elevation. Commonly, groundwater flows into lakes, streams and springs around, or near, the lake edges. However, the model calculated that groundwater in the topographic catchment of Lake Rerewhakaaitu is recharged by the lake, i.e., the lake is perched relative to sub-regional groundwater levels.

The groundwater flow model was used to estimate nitrogen inflows to lakes and streams associated with five land use scenarios, in order of increasing land use intensity:

- forested land use;
- low-intensity agricultural land use;
- current land use;
- foreseeable intensification; and
- large-scale intensification.

The model calculated that current land use has a large effect on nitrogen concentrations in groundwater in the west and the south of the catchment, including Earthquake Flat and parts of the Rotomahana and Rerewhakaaitu zones. Intensification beyond current land use was calculated to generally increase nitrogen concentration in the west. The model also calculated nitrogen discharge to lakes and streams. An increase in nitrogen loading to all lakes, except Lake Rerewhakaaitu because it is perched, was calculated with the more intense land uses.

Generally, the groundwater catchment boundaries are represented by zone boundaries. However, groundwater catchment boundaries do not always match zone boundaries, e.g., in the vicinities of: Te Whekau crater, Okareka Loop Road, Highlands Road, Tumunui, Earthquake Flat, the headwaters of the Lake Tarawera and Okaro zones, and Brett Road. Therefore, the report recommends that groundwater catchment boundaries could be defined in these areas using the following information: zone boundaries; model calculations of groundwater flow directions; zone budgets; the Digital Terrain Model; and additional measurements of groundwater level.

Other recommendations include consideration of denitrification by lakes and streams. For example, relatively high nitrogen concentrations were calculated in groundwater between Lake Tarawera and Lake Rotomahana. However, these concentrations are probably an over-estimate because nitrogen attenuation (e.g., by sediments) and in-lake denitrification by Lake Rotomahana were not considered by the model.

1.0 INTRODUCTION

Restoration of water quality in the Rotorua lakes by Bay of Plenty Regional Council (BOPRC) and the local community requires specific policies that aim to reduce the discharge of nutrients (nitrogen and phosphorus) to lakes (e.g., BOPRC policies WL3B and WL6B; Bay of Plenty Regional Council, 2014a). BOPRC and research providers, including the Institute of Geological and Nuclear Sciences (GNS Science), are currently working across a range of lakes and lake catchments in the Rotorua area with aims to protect, or restore, the water quality of these lakes.

Water quality in the Rotorua lakes is summarised using the Trophic Level Index (TLI). This index includes four indicators of water quality: i.e., concentrations of phosphorus and nitrogen, visual clarity and algal biomass (Verburg *et al*., 2010). A target TLI has been calculated in each of the Rotorua lakes and BOPRC has developed action plans for the lakes (and their catchments); Bay of Plenty Regional Council (2010 and 2014b). Consideration of options for groundwater assessment associated with lakes in the greater Lake Tarawera catchment, i.e., within the Okataina Volcanic Centre (OVC; Leonard *et al*., 2010), identified the Lake Tarawera catchment as the top priority for investigation (White, 2008 and 2009) and a restoration plan was developed for Lake Tarawera (Bay of Plenty Regional Council, 2014c).

The greater Lake Tarawera catchment includes eight lakes (Tarawera, Okaro, Rotomahana, Rerewhakaaitu, Okataina, Okareka, Tikitapu and Rotokakahi; Figure 1.1) that eventually drain partly or wholly to the Tarawera River. Commonly, these lakes are hydraulically linked through the groundwater system. For example, water budgets and spring flows indicate that groundwater outflow from Lake Rotomahana travels to Lake Tarawera (Gillon, 2008; Gillon *et al*., 2008); and Lake Rerewhakaaitu discharges through springs that provide baseflow for streams that flow into Lake Rotomahana (White *et al*., 2003; Reeves *et al*., 2008; White and Tschritter, 2015).

Groundwater in the greater Lake Tarawera catchment is important to consider in the assessment of the effects of land use on lake water quality. This is because the majority of the water and nutrients that reach the lakes does so through the groundwater system, i.e., via spring-fed streams and via direct groundwater discharge to the lake. The Lake Rotorua catchment provides an example of the importance of groundwater flow to lake inflows as flow into the lake is in the approximate proportions: 76% with surface baseflow that is generally spring-fed and 24% with direct groundwater discharge to the lake (White *et al*., 2007).

BOPRC commissioned GNS Science to assess groundwater, including nitrogen and land use, in the greater Lake Tarawera catchment in a three-phase programme:

- Phase 1: a drilling programme that measured key aquifer properties including aquifer hydraulic conductivity, groundwater quality and groundwater age was completed (Thorstad *et al*., 2011; Rose *et al*., 2012; and Lovett *et al*., 2012);
- Phase 2: a geological model of the greater Lake Tarawera catchment that identified key aquifers relevant to groundwater flows towards lakes and between lake catchments which included lithologies identified by Phase 1 was developed (Tschritter and White, 2014), Figure 1.2;
- Phase 3: which is described in this report, developed a groundwater flow model of the greater Lake Tarawera catchment. This model was applied to an assessment of land use and nitrogen discharge to surface water relevant to surface water quality in lakes and streams.

This report describes this groundwater flow model, based on the model layers identified by the geological model, to represent steady-state groundwater and surface water flows in the greater Lake Tarawera catchment area. Therefore, steady-state water budgets are described for each catchment and each lake, which required characterisation of water budget components including rainfall, evaporation and stream flows. Water inflows and water outflows in each catchment and lake were then used in the flow model to establish groundwater flows in the study area including groundwater outflow to surface water and lakes.

Then, the land use model, which includes five land use scenarios, was used with the groundwater flow model to calculate nitrogen loadings to lakes and streams. These scenarios include land use intensities that range from low (i.e., all catchments forested) to high (i.e., large-scale intensification); current land use was one of the scenarios.

A discussion includes issues that have been highlighted by the three models, including: catchment boundaries; groundwater interaction with lakes; and groundwater flow between catchments. This discussion also considers implications of nitrogen loading to lakes and streams on surface water quality and the implications of groundwater residence time on the response of lakes and streams to land use change. Lastly, recommendations include further work in the greater Lake Tarawera catchment to improve our understanding of nitrogen transport to the lakes in groundwater and streams.

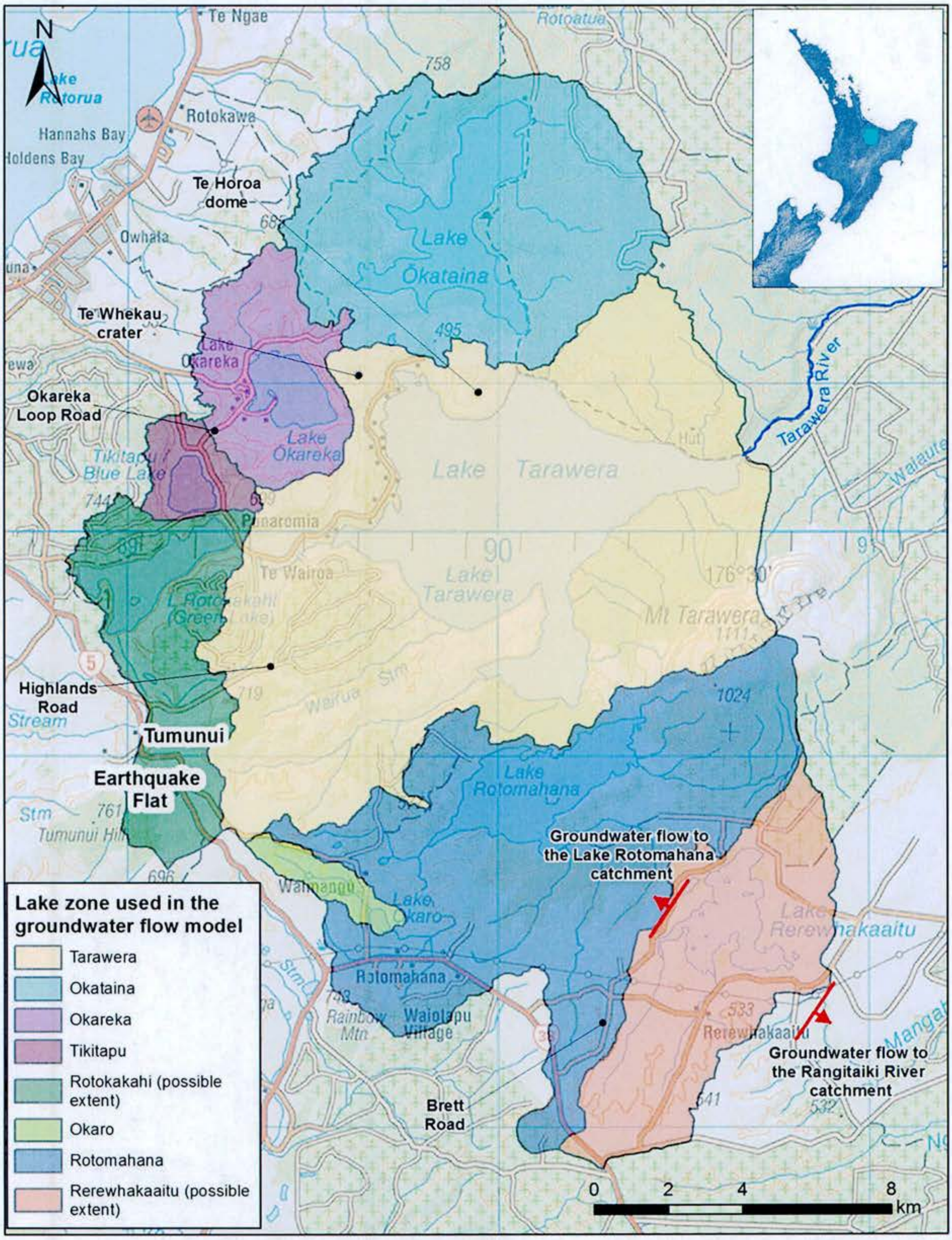

Figure 1.1 Lakes in the greater Lake Tarawera catchment and associated zones used in the groundwater flow model.

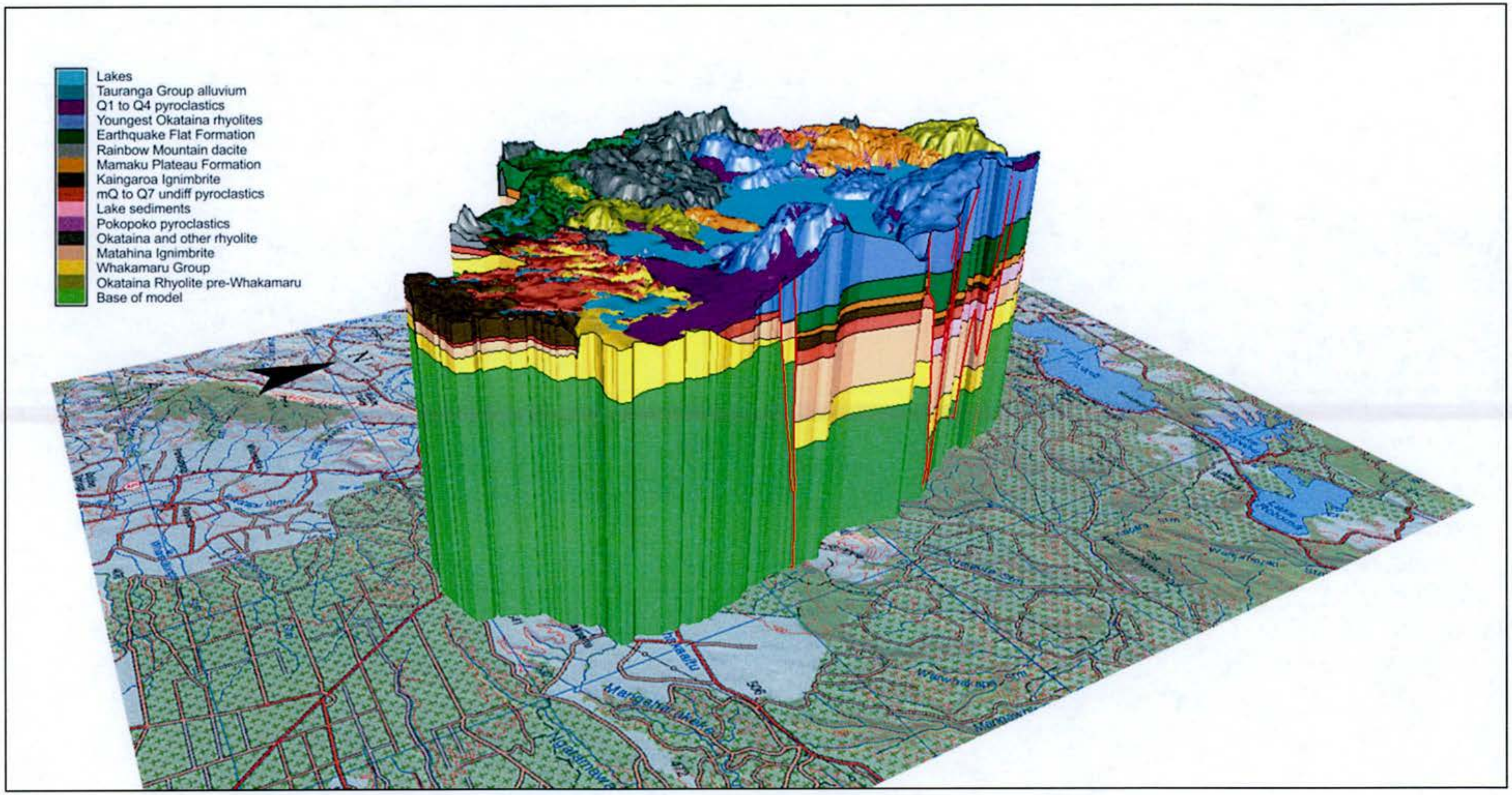

Figure 1.2 Geological model of the greater Lake Tarawera catchment (Tschritter and White, 2014).

2.0 REVIEW

2.1 LAKES IN THE GREATER LAKE TARAWERA CATCHMENT: TROPHIC LEVEL INDEX AND WATER QUALITY

Water quality has recently been improving (i.e., TLI is decreasing) in two lakes and typically declining in two others (Table 2.1).

Table 2.1 TLI in greater Tarawera catchment lakes (Bay of Plenty Regional Council, 2014b).

TLI	Lake							
	Okareka	Okaro	Okataina	Rerewhakaaitu	Rotokakahi	Rotomahana	Tarawera	Tikitapu
Trend in 3-year average[1]	Stable	Not clear	Stable	Improve	Decline	Stable	Decline	Improve
2014	3.3	4.5	2.7	3.4	3.6	3.8	3.0	2.8
Target	3.0	5.0	2.6	3.6	3.1	3.9	2.6	2.7

[1] 2011-2014.

Water quality indicators show that lake water quality in Lake Okaro is the poorest in the area (Tables 2.1 and 2.2). TLI and median total nitrogen (TN) are highest in Lake Okaro, with median total phosphorus (TP) in this lake less than only Lake Rotomahana. In comparison, median TN concentration in Lake Tarawera was the lowest, which is consistent with observations of good water quality in this lake. However, a decline in lake water quality in Lake Tarawera (Table 2.1) indicates that water quality in this lake may be impacted by land use.

Table 2.2 Median estimates of TLI variables (Bay of Plenty Regional Council, 2014b).

Variable	Lake						
	Okareka	Okaro	Okataina	Rerewhakaaitu	Rotomahana	Tarawera	Tikitapu
Chlorophyll a (µg/l)	3.4	9.9	2.0	3.4	3.9	1.6	1.9
Secchi (m)	7.8	2.7	10.4	5.3	5.0	8.6	7.1
TN (µg/l)	182	757	90	361	191	88	159
TP (µg/l)	9.0	38.0	11.0	10.0	47.0	19.0	4.0

2.2 STUDY AREA

The study area boundary generally follows the topographic catchment of the greater Tarawera lakes (Figure 1.1). In addition, the study area included possible groundwater catchment areas of the greater Lake Tarawera catchment in the vicinity of: Tumunui and Earthquake Flat, located within the Waikato Regional Council boundary; and the topographic catchment of the Lake Rerewhakaaitu catchment located in the Rangitaiki River catchment within the BOPRC boundary.

There were two reasons for including the Tumunui area in the greater Tarawera lakes catchment. Firstly, Rotoiti Formation non-welded ignimbrite forms an extensive deposit between Tumunui and Lake Rotokakahi. Therefore, this formation may provide a pathway for groundwater to flow from the Tumunui area to Lake Rotokakahi. Secondly, the Tumunui area was located in the groundwater catchment of Lake Rotokakahi by a map of the piezometric surface (Jones and Hughes, 2007). However, the catchment of Lake Rotokakahi probably does not include the Whakarewarewa Forest in the Waipa Stream catchment, which drains to Lake Rotorua (White and Moreau-Fournier, 2012).

The Earthquake Flat area was included within the study area because of the continuity of the Rotoiti Formation, and the relatively large piezometric gradients, towards Lake Rotokakahi (Jones and Hughes, 2007). However, this map has Earthquake Flat located within the groundwater catchment of Lake Tarawera. The map has few measurements of groundwater level in the Earthquake Flat area, which means that that there is generally a poor control on estimated piezometric elevations and on estimated groundwater flow directions.

The topographic catchment of Lake Rerewhakaaitu is included in the study area to assess evidence that the lake is generally perched relative to the groundwater system, e.g.:

- groundwater elevation is generally lower than lake elevation, with the exception of a relatively small area of the topographic catchment located on the north-eastern side of the lake (White *et al*., 2003). Therefore, groundwater recharge from the land in the topographic catchment will generally not travel to the lake;
- a water budget indicates that the lake itself is losing water to groundwater;
- groundwater generally does not drain to streams because of the low rate of stream flow into the lake (Section 4); and
- groundwater could drain from the topographic catchment towards the west (i.e., to the Lake Rotomahana catchment) and to the east (i.e., to the Rangitaiki River catchment) (White *et al*., 2003; Reeves *et al*., 2008; White and Tschritter, 2015).

Therefore, the actual groundwater catchment of Lake Rerewhakaaitu is probably smaller than the topographic catchment.

2.2.1 Model zones and lake catchments

The study area was separated into zones (Figure 1.1). The purpose of these zone boundaries was to assess groundwater model calculations, e.g., groundwater budgets and groundwater flow directions (Section 3). These zones generally represent the topographic catchments of lakes. Zone boundaries were derived from various sources. The western boundaries of four zones (i.e., Okataina, Okareka, Tikitapu and Rotokakahi) were identified with a topographic analysis of the Lake Rotorua catchment boundary (White *et al*., 2014). Other zone boundaries, except for the outer boundaries of Lake Rotokakahi and Lake

Rerewhakaaitu, were derived from a topographic analysis of data that was developed from 20 m contours on the 1:50,000 topographic map.

Topographic boundaries of catchments may not represent the hydrogeological boundaries of the lake catchments. This is because topographic boundaries may not identify groundwater divides, particularly on relatively flat-lying plateaus, as described in a report on the Lake Rotorua groundwater catchment (White *et al.*, 2014). However, the location of zone boundaries is a guidline to the location of the catchment boundaries of lakes. The groundwater flow model developed in this report can be used to calculate groundwater flow directions which will allow mapping of groundwater catchment boundaries (Section 5 and Section 6).

2.3 GEOLOGY IN THE GREATER LAKE TARAWERA CATCHMENT

Geology in the greater Lake Tarawera catchment, summarised here from Tschritter and White (2014), is dominated by volcanic units including pyroclastics, rhyolites and ignimbrites (Figure 2.1). Most of these deposits are sourced from the OVC. The OVC is the most recently-active rhyolitic caldera complex in the Taupo Volcanic Zone. Two major OVC eruptions (the 61 ka Rotoiti Formation pyroclastics and 322 ka Matahina Formation ignimbrites resulted in a large subsiding basin structure (Figures 2.2 and 2.3). The following text summarises the geology and hydrogeological properties in the greater Lake Tarawera catchment, from the youngest to oldest units.

Tauranga Group comprises Pliocene to Holocene alluvial sediments (in particular, sands and gravels), non-welded ignimbrite and tephra layers. Generally these deposits are mostly saturated and provide good opportunities for groundwater supply. However, due to their mixed composition, Tauranga Group deposits are very heterogeneous laterally and vertically, which results in highly varying hydraulic characteristics over short distances.

Q1 to Q4 pyroclastics, Earthquake Flat Formation and Rotoiti Formation comprise air fall and ignimbrite components, primarily sourced from the OVC. Rotoiti Formation is widespread throughout the study area and reaches its maximum thickness within the Rotoiti Caldera, whereas deposits of the other units are less widely distributed. These pyroclastics are relatively permeable; however, finer grained zones (air fall layers) may act as aquicludes.

The youngest (post-61 ka) Okataina rhyolites are associated with the Q1 to Q4 pyroclastics (e.g., Mangaone-, Haroharo-, and Mt Tarawera subgroups) and are exposed at the surface in areas inside, and outside, the caldera boundaries. Groundwater flow in these rhyolites is fracture-controlled, and therefore, depends on the size, amount and conductivity of the fractures.

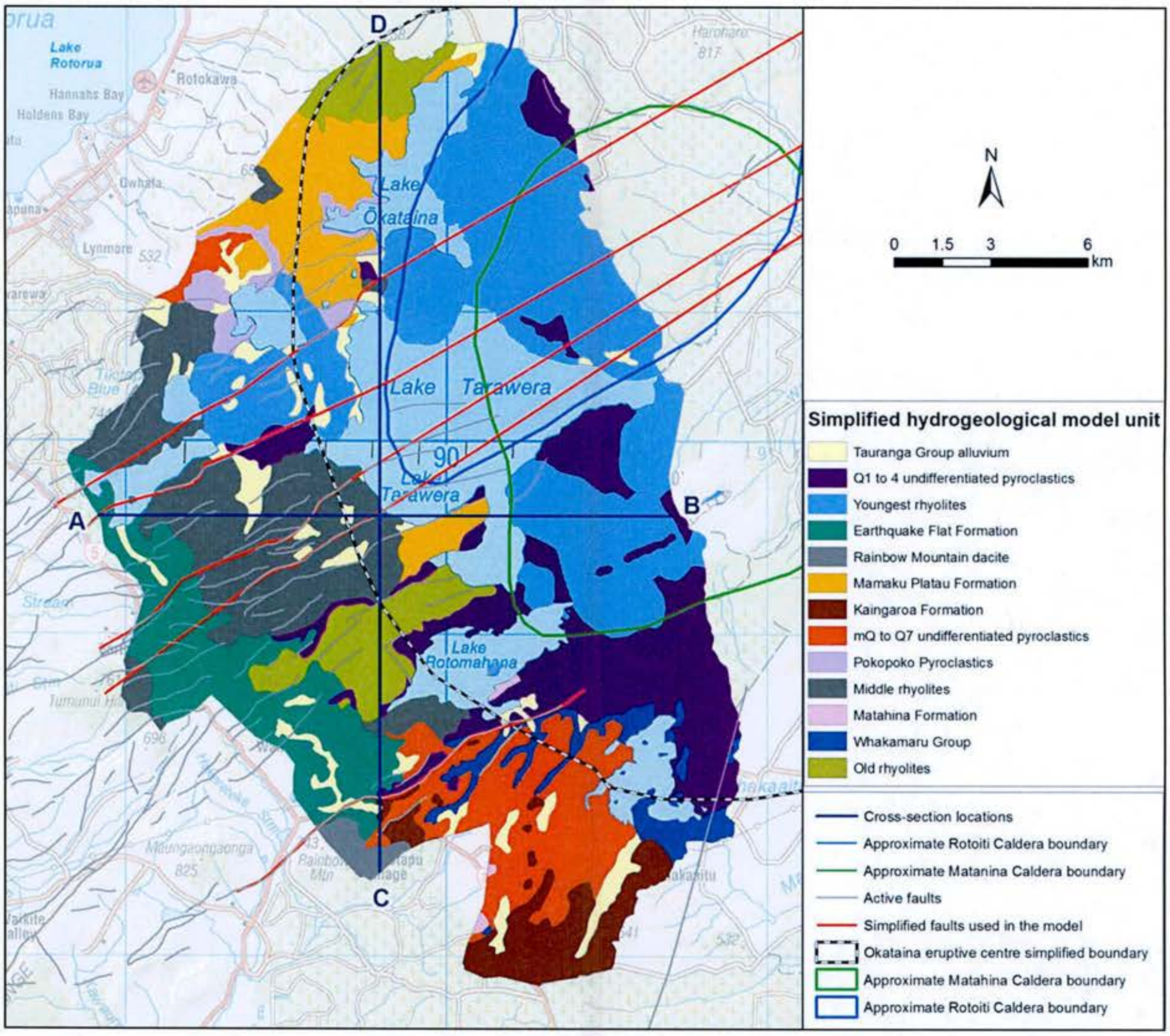

Figure 2.1 Surface geology of the greater Lake Tarawera catchment simplified from Leonard *et al.* (2010).

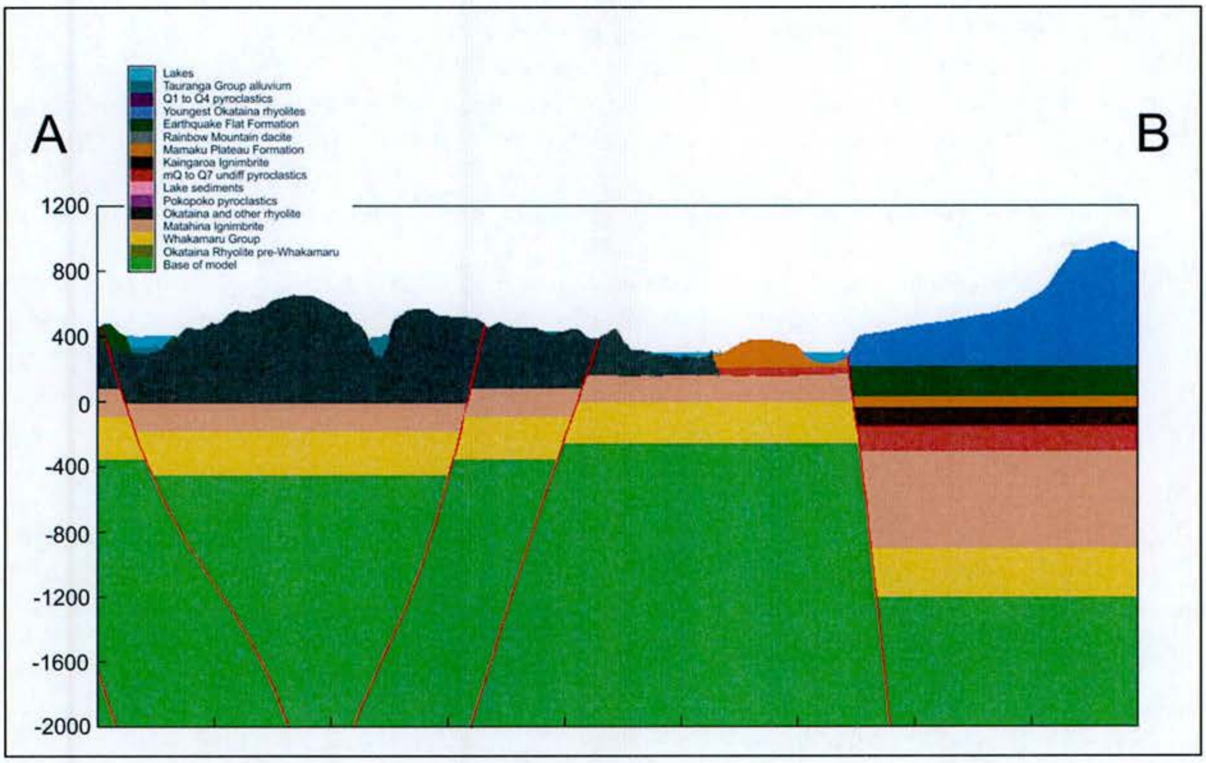

Figure 2.2 West – East cross section of the greater Lake Tarawera catchment. The location of the section is shown on Figure 2.1.

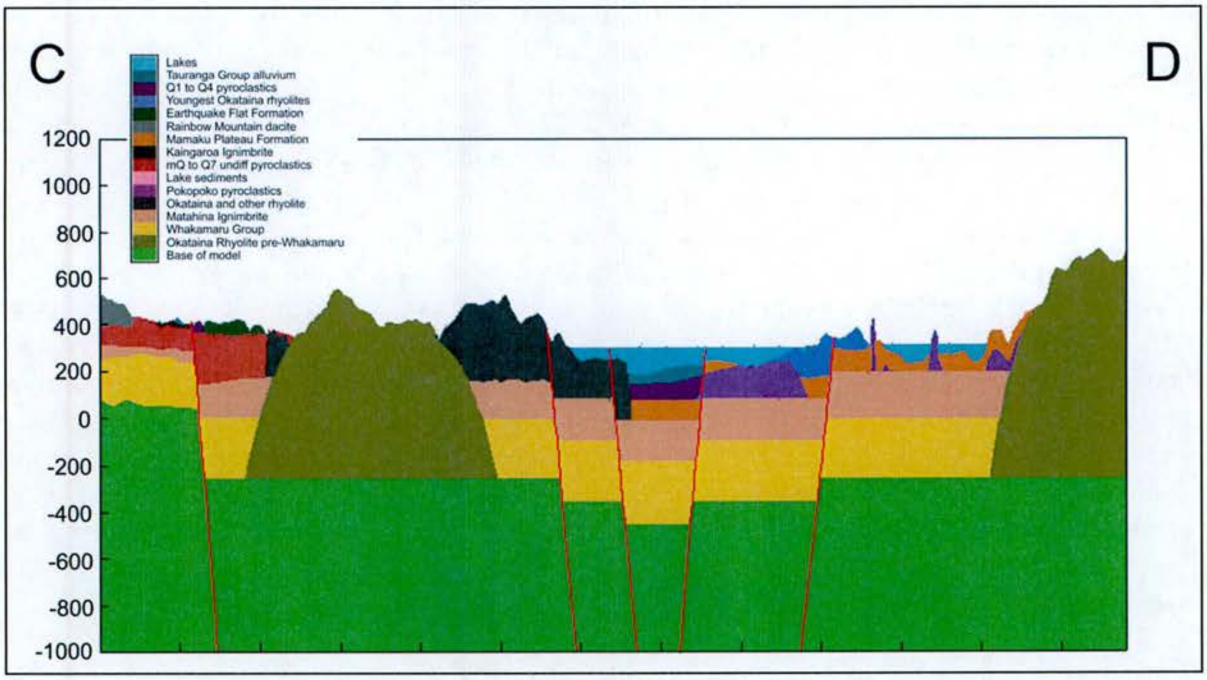

Figure 2.3 South – North cross section of the greater Lake Tarawera catchment. The location of the section is shown on Figure 2.1.

Mamaku Plateau Formation and Kaingaroa Formation are widespread ignimbrite deposits that erupted from the Rotorua Caldera and the Reporoa Caldera, respectively, at approximately 240 ka. Both formations comprise basal tephra (air fall) layers that are overlain by three ignimbrite units with a varying degree of welding. The basal air fall deposits generally act as aquicludes, whereas the ignimbrite units exhibit differing hydraulic properties, depending on the pore space and the degree of welding and jointing.

Pokopoko Pyroclastics and mQ to Q7 undifferentiated pyroclastics (e.g., Onuku) consist of pumiceous fall and flow deposits with different degrees of compaction and welding. Finer-grained layers likely act as aquicludes whereas the ignimbrite units may be aquifers, depending on the pore space and the degree of welding and jointing. Lake sediments have been assumed, but not drilled, within the Rotoiti and Matahina calderas (Nairn, 2002).

Rhyolites (180-61 ka) are sourced from the Okataina and Rotorua Volcanic Centres. These rhyolites are partly buried or eroded and may be down-faulted in the caldera boundaries. Groundwater flow in these rhyolites is fracture-controlled depending on the size, amount and conductivity of the fractures. The hydraulic behaviour of the Rainbow Mountain dacite is expected to be similar. Okataina Rhyolites include rhyolites older than 322 ka.

Matahina Formation (322 ka) and Whakamaru Group (340-350 ka) are voluminous, older ignimbrite sheets that cover large parts of the study area and are down-faulted within the caldera boundaries. The Pre-Whakamaru rhyolites are the oldest unit mapped at the ground surface outside of the calderas, but down-faulting or erosion are likely to have buried or removed these deposits within the caldera boundaries. Groundwater flow in these units is fracture-controlled and may vary over short distances, depending on the size, amount and conductivity of the fractures.

2.4 WATER BUDGETS, GROUNDWATER FLOW MODELS AND NITROGEN DISCHARGE TO LAKES

An assessment of current and future nitrogen loads in groundwater to Lake Tarawera has been completed by Gillon (2008). This assessment included water budgets of the lakes in the greater Lake Tarawera catchment. The water budget model aimed to define the water balance for the lakes, and each lake catchment, to assess the groundwater flows between lake catchments. The lake water budgets were calculated with an equation that related the rate of change of storage in each lake to rainfall input, evaporation output, stream flow input/output and groundwater input/output for each lake catchment (Table 2.3). Groundwater flows between lakes were calculated with Darcy's law and the lake water budgets (Table 2.3). For example, groundwater outflow from Lake Tarawera was an estimated 918 l/s. In addition, the Lake Tarawera water balance shows that surface inflows (stream flows and rainfall on the lake) contribute 42% of the lake inflows, i.e., groundwater comprises the largest inflow to Lake Tarawera. Groundwater outflow from Lake Tarawera was calculated with various scenarios of water budget components (Table 2.4). These estimates demonstrate the importance of rainfall to the groundwater budget and show the sensitivity of groundwater outflow to rainfall estimates. For example, groundwater outflow from the Lake Tarawera catchment (3,848 l/s; Scenario 2) is calculated to approximately halve with a 10% reduction in average rainfall.

Table 2.3 Groundwater flows between lake catchments (Gillon, 2008). Also noted are adjacent catchments that are possibly hydraulically linked to the lake catchment, i.e., the Okareka catchment is possibly linked to the Tarawera and Rotorua catchments (Gillon, 2008).

Lake catchment	Groundwater inflow from other catchments (l/s)	Groundwater outflow to other catchments (l/s)	Catchments that are possibly linked
Okataina	0	2,319	Tarawera/Rotorua/Rotoiti
Okareka	0	544	Tarawera/Rotorua
Tikitapu	0	215	Rotorua/Rotokakahi
Rotokakahi	85	420	Tarawera/Waikato
Okaro	0	67	Rotomahana
Rerewhakaaitu	0	1,021	Rotomahana/Rangitaiki
Rotomahana	767	3,018	Tarawera
Tarawera	3823	918	Tarawera River

Table 2.4 Groundwater outflow from Lake Tarawera with nine scenarios of groundwater outflow and catchment rainfall (Gillon, 2008).

Scenario		Lake Tarawera groundwater outflow (l/s)
1	Groundwater outflow as per Table 2.3	918
2	Groundwater discharge from the greater Tarawera catchment is solely from the Lake Tarawera catchment	3,848
3	Groundwater discharge from the greater Tarawera catchment is from the Tarawera and Okataina catchments[1]	1,993
4	Scenario 1, but with 10% more rainfall	2,153
5	Scenario 1, but with 10% less rainfall	-286[2]
6	Scenario 2, but with 10% more rainfall	5,570
7	Scenario 2, but with 10% less rainfall	2,151
8	Scenario 3, but with 10% more rainfall	3,417
9	Scenario 3, but with 10% less rainfall	593

[1] Groundwater outflow from the Tarawera catchment (Scenario 2) is split between the Tarawera and Okataina catchments and so outflow to the Tarawera catchment in Scenario 3 is less than Scenario 2.

[2] Rainfall that is 10% less than Scenario 1 results in a Tarawera groundwater outflow that is less than zero, i.e., a net inflow of groundwater to the catchment is required to maintain surface flow at the Lake Tarawera outflow (Tarawera River).

These budgets contributed a groundwater flow model that used FEFLOW software (Gillon, 2008). This model calculated nitrogen discharge to Lake Tarawera based on a variety of land uses (Table 2.5). For example, conversion of all pasture to dairy farming is estimated to result in a 43% increase in the nitrogen load to Lake Tarawera, compared with current loading. The FEFLOW model was also used to estimate the relationship between the timing of land use change and the response of nitrogen loading to Lake Tarawera, i.e., nitrogen loads take approximately 150 years to equilibrate to land use change (Gillon, 2008).

Table 2.5 Nitrogen loading to Lake Tarawera with various land use scenarios (Gillon, 2008).

Land use	Nitrogen load to Lake Tarawera (tonnes N/year)
Prehistoric, i.e., indigenous forest	66
Current	92
Extension of beef farming	108
Extension of dairy farming	136
Tourist development	103

Groundwater flow models have also been used in similar applications in other lake catchments, including a groundwater transport model of the western Lake Taupo catchment. This model was calibrated with measured tritium concentrations in five streams and rivers, after the associated flow model (which used a layer distribution that was defined by a geological model) was calibrated to groundwater levels and stream baseflow observations (Gusyev *et al*., 2013). Then, groundwater age distributions and mean residence times (MRTs) were simulated with the transport model. Cross-sections of groundwater age demonstrated the hydrogeological complexity of the area. For example, groundwater in the Waihaha River catchment near the water table was less than five years old and older groundwater in the deeper Whakamaru Group ignimbrite was likely to flow upwards into the river under artesian pressure.

Future nitrate-nitrogen discharge to Lake Rotorua was calculated to increase by approximately 50% above current discharge and 90% of this increase will have occurred in the next 200 years (Morgenstern *et al*., 2004). This increase, calculated from the 'young fraction' and MRT in springs and groundwater-fed streams, is likely to come as future water quality in spring-fed streams equilibrates with current land use. For example, future nitrogen discharge from spring-fed Hamurana Stream would increase from approximately 50 tonnes/year at present to about 120 tonnes/year by about 2350 should land use stay the same over the period (Morgenstern *et al*., 2015). The long duration of this increase was due to the large MRT (125 years) of water in Hamurana Stream. An assessment of options to reduce nitrogen discharge into Lake Rotorua to the target level of 435 tonnes N/year used the ROTAN model (including MRTs of Morgenstern and Gordon, 2006) to estimate the response, over time, of catchments to land use (Rutherford *et al*., 2011). Nitrogen discharge approached the target within 35 years after a step reduction in nitrogen export from the soil. This was because shallow groundwater, which provides about 50% of the nitrogen to the lake, reaches the lake within months, or years. In contrast, deep groundwater reaches the lake within ten-to-hundreds of years.

3.0 METHODS

In this report, a groundwater flow model was developed and was used to estimate nitrogen inflows to lakes associated with different land uses. The following text describes the methods that were used to develop this model. Steady-state water budgets for lakes and their catchments were developed to estimate rainfall and evaporation in the lake catchments. These budgets included characterisation of surface flows in streams and rivers in the greater Tarawera lakes area to improve the understanding of water inflows to lakes and outflows from lakes.

Together, these flows (i.e., surface water, rainfall and evaporation) are summarised in water budgets of the lakes and catchments that provide the water flux data for the groundwater flow model. Development and calibration of the groundwater flow model is described in this section. The calibrated groundwater flow model was then used to assess nitrogen discharge to surface water (i.e., lakes and streams) associated with five land use scenarios. These scenarios, also described in this section, aim to represent nitrogen discharge from current land use and from land uses that are less intensive, and more intensive, than current land use.

3.1 WATER BUDGETS

A general water budget equation describes the relationships between water inflow, water outflow and water storage within a defined area of a catchment (Scanlon *et al.*, 2002; Scanlon, 2012).

$$\text{water inflow} = \text{water outflow} \quad (1)$$

i.e., $$P + Q_{IN} = ET + Q_{OUT} + \Delta S \quad (2)$$

Water inflows include:

P precipitation,

$$Q_{IN} = Q^{SW}{}_{IN} + Q^{GW}{}_{IN} \quad (3)$$

$Q^{SW}{}_{IN}$ is quick flow + base flow

$Q^{GW}{}_{IN}$ is groundwater inflow

Water outflows include:

ET (evapotranspiration), including ET_G (evapotranspiration from the ground surface) and ET_L (evaporation from the lake surface)

Q_{OUT} water flow out from the area

ΔS change in water storage.

With:

$$Q_{OUT} = Q^{SW}{}_{OUT} + U^{SW} + Q^{GW}{}_{OUT} \quad (4)$$

$$Q^{GW}{}_{OUT} = U^{GW} + Q^{GW}{}_{AOUT} \quad (5)$$

$Q^{SW}{}_{OUT}$ surface water outflow, i.e., surface water inflow plus surface water flow generated in the area

U^{SW} consumptive use of surface water

$Q^{GW}{}_{OUT}$ is groundwater outflow, including consumptive groundwater use (U^{GW}) and groundwater discharge across the area boundary ($Q^{GW}{}_{AOUT}$).

Expanding Equation 2 for surface water and groundwater terms, with the assumption that ΔS is zero, meaning that all flows are the same over time, has:

$$P + Q^{SW}_{IN} + Q^{GW}_{IN} = ET + Q^{SW}_{OUT} + U^{SW} + U^{GW} + Q^{GW}_{AOUT} \tag{6}$$

With the convention that inflows are recorded with positive numbers and outflows are recorded with negative numbers, then the equation used to calculate water budgets for lake catchments (Figure 3.1) has:

$$P + Q^{SW}_{IN} + Q^{GW}_{IN} + ET + Q^{SW}_{OUT} + U^{SW} + U^{GW} + Q^{GW}_{AOUT} = 0 \tag{7}$$

A variant of this equation is used to calculate water budgets for lakes (Figure 3.2), i.e.:

$$P + Q^{SW}_{IN} + Q^{GW}_{LIN} + ET + Q^{SW}_{OUT} + Q^{GW}_{LOUT} = 0 \tag{8}$$

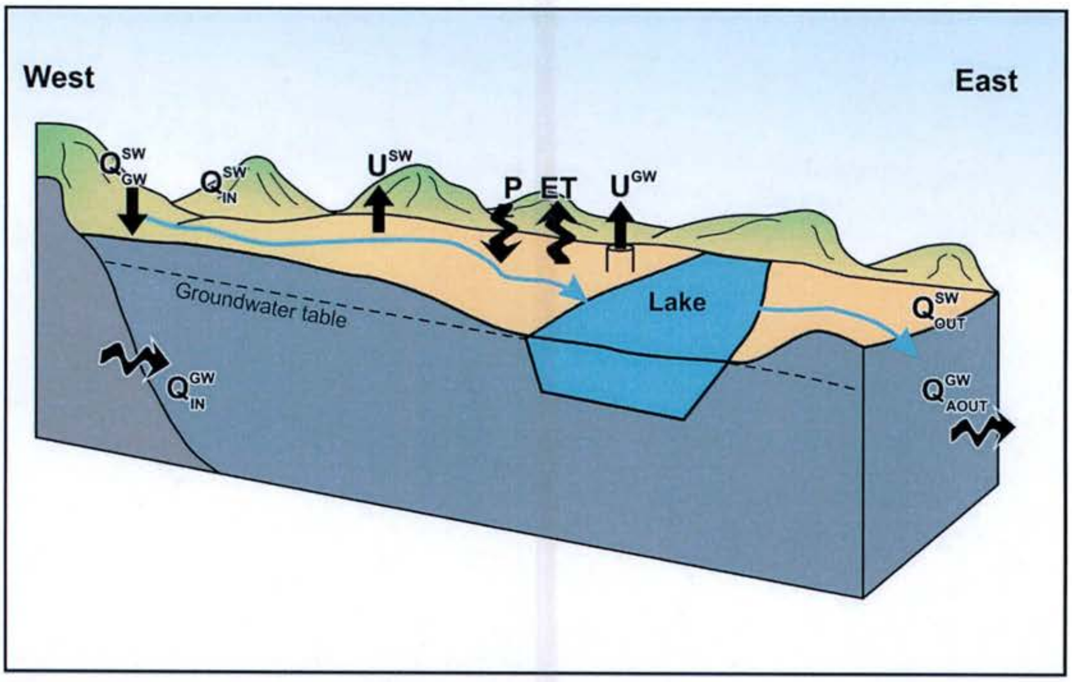

Figure 3.1 Water budget schematic for lake catchments.

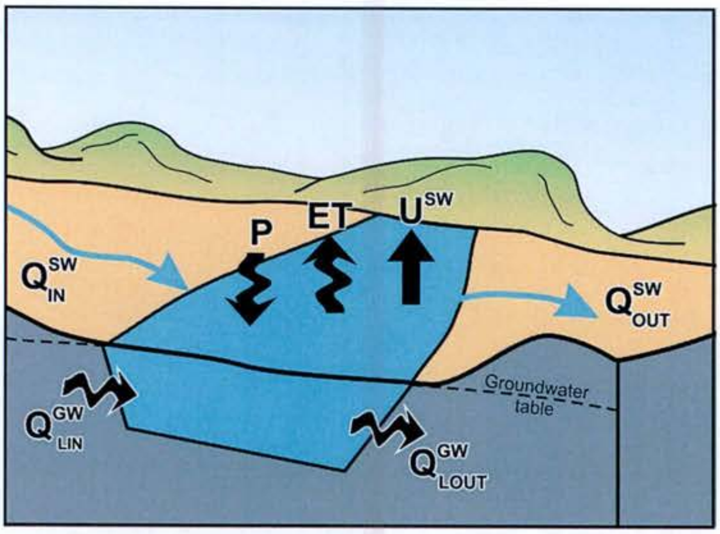

Figure 3.2 Water budget schematic for lakes.

The following text discusses each of the components in this equation in the greater Tarawera catchment.

3.1.1 Rainfall and evapotranspiration

Median annual rainfall (P) was estimated by GIS using the nationwide National Institute of Water and Atmospheric Research (NIWA) dataset based on the rainfall measurements at individual climate stations (Tait *et al.*, 2006). This dataset was interpolated throughout New Zealand by NIWA and averaged for the period 1960-2006 (Tait *et al.*, 2006). Median annual evapotranspiration (ET) was estimated over lake catchments by GIS as actual (AET) values from the land surface derived from a national-scale map developed by NIWA for the period 1960-2006 without specific consideration of land use, land cover, soil type or groundwater recharge (Woods *et al.*, 2006).

Two methods to calculate evaporation from lakes were assessed: evaporation was 41% of rainfall, as was estimated for Lake Rotorua (Rutherford and Palliser, 2014); and measurements of vapour pressure, surface water temperature and wind speed recorded at Rotorua Airport between January 1 1991 and December 31 2005 were used to calculate evaporation in all lakes (Gillon, 2008). On average, the evaporation estimates of the two methods are similar, i.e., within 11% (Table 3.1). The first method was preferred because this has evaporation as a fraction of P and is therefore more consistent with water budget calculations.

Table 3.1 Comparison to two estimates of ET from lakes in the study area.

Lake	P (l/s)	Evaporation (41% of rainfall on the lake) l/s	Evaporation (Gillon, 2008) l/s	Difference in ET estimates (%)
Lake Tarawera	2,458	1,008	887	-12
Lake Okataina	677	278	214	-23
Lake Okareka	168	69	59	-14
Lake Tikitapu	68	28	24	-14
Lake Rotokakahi	208	85	56	-34
Lake Okaro	14	6	6	0
Lake Rotomahana	409	168	213	27
Lake Rerewhakaaitu	232	95	93	-2
Total	4,234	1,737	1,552	-11

3.1.2 Surface water flow

An aim of this report was to assemble all flow measurements in the greater Tarawera catchment that were relevant to water budgets of catchments and lakes. These flows were measured in streams, rivers and springs. Data sources included measurements reported in BOPRC reports, including:

- stream flow measurements in the Rangitaiki River catchment that were relevant to the water budget of Lake Rerewhakaaitu (Section 2.2; White and Tschritter, 2015);
- Tarawera River inflow from Lake Tarawera relevant to the estimate of groundwater outflow from Lake Tarawera into the Tarawera River (White *et al.*, 2010);
- stream flow measurements in the Paengaroa-Matata area that were relevant to the water budgets of the lakes north of Lake Okataina (i.e., Lake Rotoiti, Lake Rotoehu and Lake Okaro), White *et al.* (2008);
- flows in the Puarenga catchment as described in an assessment of the groundwater catchment of Waipa Stream (White and Moreau-Fournier, 2012);
- flows in the middle reaches of Wairua Stream in the Lake Tarawera catchment (Jones and Hughes, 2007);
- surface flows in the Lake Rerewhakaaitu catchment (McIntosh, 2012); and
- Lake Okaro inflows and outflows (Hamilton, 2015).

University of Waikato reports that summarise stream gauging measurements in the greater Lake Tarawera catchment, include:

- all catchments in the study area (Gillon, 2008); and
- Lake Tarawera (Hamilton *et al.*, 2006).

In addition, gauging measurements made by BOPRC include:

- Tarawera River gaugings outside the study area relevant to the estimate of groundwater outflow from Lake Tarawera into the Tarawera River (Putt, 2012);
- the Lake Okareka drain and inflows to Lake Tarawera from Lake Okareka (Putt, 2015);
- Lake Rotomahana catchment measurements relevant to catchment flows and lake inflows from Haumi Stream, and others (Scott, 1991; Putt, 2014); and
- Lake Okaro inflows and outflows (Hamilton, 2015).

Spring and stream features, including cold and hot water, were mapped around the shores of two lakes, including:

- Lake Tarawera features were identified from a survey by boat in January 2014. This survey aimed to locate features including those that are monitored by Terry Beckett for University of Waikato (Hamilton *et al.*, 2006);
- one spring flowing into Lake Rotokaakhi (Noakes, 2016);
- Lake Rotomahana geothermal features (Scott, 2015).

3.1.3 Groundwater-surface water interaction

Groundwater-surface water interaction, i.e., Q^{SW}_{GW} (discharge of stream flow to groundwater) and Q^{GW}_{BF} (groundwater discharge to streams), was assessed with available gauging data and water budgets. Surface water discharge to groundwater in the greater Lake Tarawera catchment includes outflow of lake water to groundwater. For example, Lake Rerewhakaaitu is mostly perched relative to groundwater and therefore probably discharges water to the groundwater system (Section 2.2). Groundwater discharge to surface water provides the base flow in streams. Flowing streams are typically located near the bottom of catchments and near lakes. These locations indicate where the stream bed is at, or below, the groundwater table. In contrast, some streams receive inflow from lakes. These streams may increase in flow to the point of discharge; these increases may indicate where groundwater is flowing into the stream channel. However, many stream beds are dry in the greater Tarawera catchment as stream beds are commonly located vertically above the groundwater table.

3.1.4 Water use

Consumptive uses of groundwater and surface water in the greater Lake Tarawera catchment include: irrigation, drinking water and commercial applications (Lambert, 2015). In addition, non-consumptive water uses include diversions to control lake levels. Consumptive water allocation is recorded by only three consents, for the following uses:

- groundwater use for pasture irrigation, including domestic, with a maximum rate of take of 18 l/s;
- groundwater use for dairy shed and stock with a maximum rate of take of 2.5 l/s; and
- surface water for commercial use (accommodation) with a maximum rate of take of 0.76 l/s.

The rate of water use, which will be less than allocation, is very low in the greater Lake Tarawera catchment. Therefore, the water budgets assume that the rate of consented use is zero. Groundwater is also used by "permitted" users. These users may take relatively low volumes (i.e., up to 35 m^3/day/property; White *et al.*, 2012) of groundwater to supply drinking water to humans and animals. However, this use is also assumed as zero as statistics on household wells and permitted use rates are not available in the greater Lake Tarawera catchment

3.1.5 Water budget calculations

Water budgets were developed in the greater Tarawera area to provide boundary conditions (BCs) (i.e., inflows and outflows) for the groundwater flow model. Two sets of water budgets were calculated. Firstly, water budgets were estimated for each lake and then for each lake and catchment (i.e., "lake + catchment") using Equation 8. Each lake water budget has a calculation of "net groundwater outflow" (i.e., $Q^{GW\ LNET}_{OUT} = Q^{GW}_{LIN} + Q^{GW}_{LOUT}$, Figure 3.2). This is set to balance the water budget. A negative number indicates net groundwater outflow from the lake whereas a positive number indicates net groundwater inflow to the lake. Q^{GW}_{LIN} and Q^{GW}_{LOUT} are not resolved in the water budgets but are identified in the groundwater flow model. Likewise, "net groundwater outflow" is calculated for "lake + catchment" water budgets, i.e., $Q^{GW\ CNET}_{OUT} = Q^{GW}_{IN} + Q^{GW}_{AOUT}$, Figure 3.1.

Some catchments in the greater Lake Tarawera catchment are linked through the groundwater system, i.e., groundwater inflow to one catchment is provided by an adjacent catchment or catchments (Figure 3.3). Water budgets were used to estimate inflows from adjacent catchments. For example, stream flow in a catchment may be larger than rainfall recharge on the catchment that was calculated with a water budget. In this case, groundwater inflow to the catchment may explain the difference between stream flow and rainfall recharge.

Three surface water channels were engineered to maintain lake levels. These include Waitangi Stream (where a drain is used to maintain the level of Lake Okareka) and channels at lakes Rotomahana and Rerewhakaaitu that flow, rarely, during periods of high lake level. Water discharge from the greater Lake Tarawera catchment area to the east includes surface water flow, and may include groundwater flow, in the Tarawera River valley. Groundwater flow from the Rerewhakaaitu catchment flows to the Rangitaiki River catchment. The water budgets aim to represent natural flows. Therefore, water use was assumed as equal to zero. Note that water allocation is zero, or close to zero in catchments (Section 3.1.4).

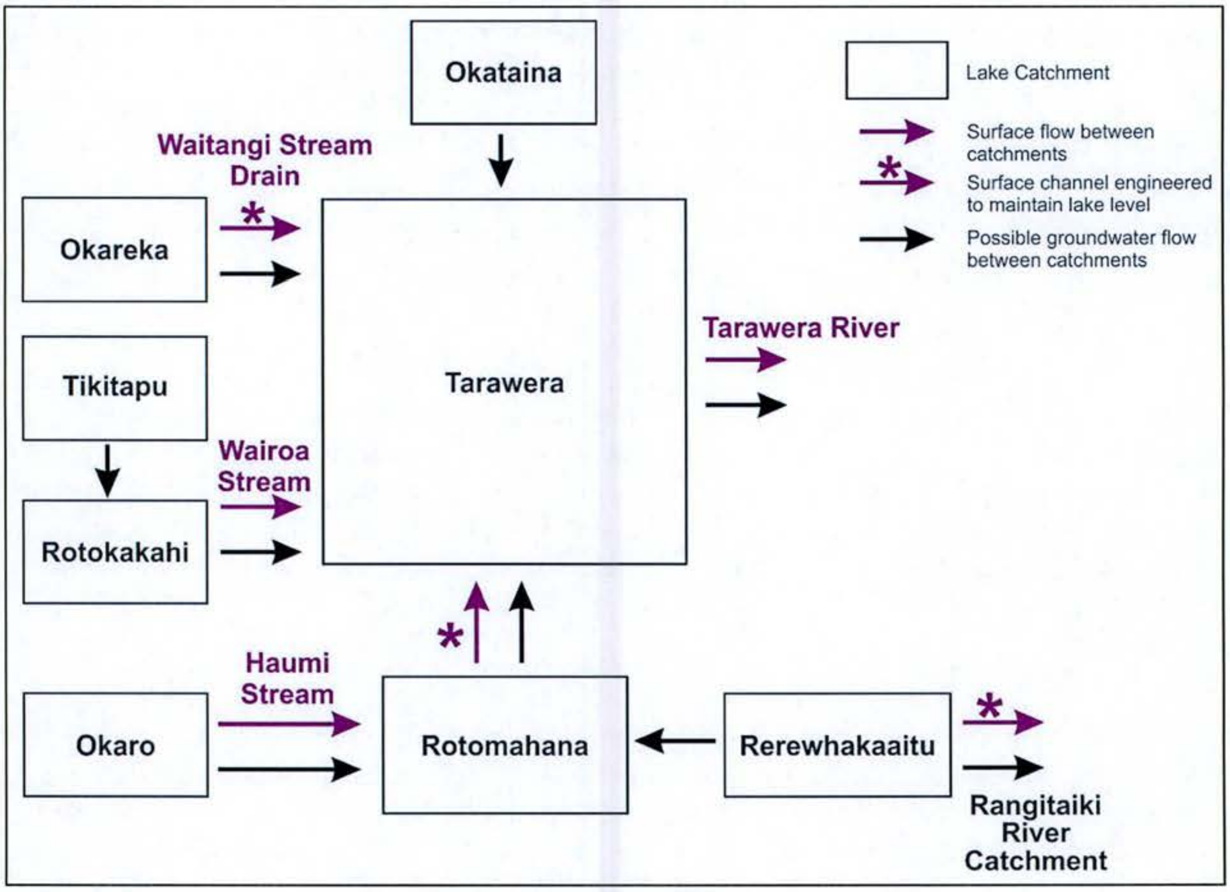

Figure 3.3 Water budget schematic for the greater Lake Tarawera catchments.

3.2 GROUNDWATER FLOW MODEL

3.2.1 Groundwater modelling software

The software GMS 10.0 (Aquaveo, 2014) was primarily used to build and run the groundwater flow and transport models of the greater Lake Tarawera catchment. GMS uses a conceptual model approach to build finite difference MODFLOW and MT3DMS models from vector-based solid geologic models and GIS data.

MODFLOW-2005 (Harbaugh, 2005) was used in conjunction with MT3DMS v5.3 (Zheng and Wang, 1999; Zheng, 2010) to simulate groundwater flow and nutrient transport. Additionally, MODFLOW-NWT (Niswonger *et al.*, 2011) was used to simulate groundwater flow for calibration, as it converges more reliably on hilly topography where many dry cells are anticipated, but cannot be used with the mass transport model, which requires MODFLOW-2005 (Bedekar and Tonkin, 2011). Groundwater flow simulations from the two versions of MODFLOW were compared to ensure they produced similar groundwater flows.

3.2.2 Model grid

The coordinate references system used for the groundwater model was the New Zealand Transverse Mercator 2000 (NZTM2000). Other spatial data, such as the geological model, use New Zealand Map Grid 1949 (NZMG1949), which was superseded by NZTM2000 in 2001. Coordinate transformations were properly performed using the NTv2 grid-based transformation method, which are widely available using online tools or specialised GIS software.

Two finite element grid designs were used in parallel, having fine and coarse resolutions. A coarse resolution model has a smaller number of active cells which allows it to simulate much faster than a fine-resolution model, and is well suited for calibration. However, the fine-resolution model better represents small-scale geology and hydrological features, and was used to simulate groundwater flow and nutrient transport. Dimensions and resolutions for coarse- and fine-resolution models are compared in Table 3.2. The modelled region in NZTM2000 is between eastings 1888200 and 1909200 and between northings 5749000 and 5778500 (i.e., the model domain has the dimensions of 21 km by 29.5 km). About 62% of the finite-difference cells are defined in the IBOUND array as active, while the remainder are outside the groundwater model boundary and marked as inactive. The fine-resolution model has about 9.4 times more cells than the coarse grid, and can be used as a proxy to scale the relative file storage size and simulation time differences.

Table 3.2 Comparison of coarse- and fine-resolution finite difference model grids.

Parameter	Coarse	Fine
Horizontal resolution	250 m × 250 m	100 m × 100 m
Dimensions	84 columns, 118 rows, 16 layers	210 columns, 295 rows, 24 layers
Approximate vertical resolution	75 m	50 m
Total number of cells (active cells)	158,592 (97,712)	1,486,800 (915,672)
Area	381.7 km^2	381.5 km^2
Volume	458.1 km^3	458.0 km^3

3.2.3 Translation of geological model to groundwater model

The 3D geological model developed in EarthVision (Tschritter and White, 2014) was translated into a 3D finite-difference grid for MODFLOW. This was primarily accomplished using GMS 10.0 (Aquaveo, 2014). Gridded horizon elevation data with an 80 m resolution were exported from the 15 EarthVision geological horizons into cartesian XYZ text files. These 15 files were further converted to conventional GeoTIFF raster formats for processing in GIS environments.

The geological model was reconstructed as solids using wedge polyhedrons that are based on triangulated irregular network (TIN) meshes. First, the groundwater catchment was imported as a polygon, and vertices of the perimeter were redistributed to 250 m and 100 m spacings for the coarse and fine models, respectively. Each polygon was then used to generate uniformly-spaced 250 m and 100 m TINs for building solids. The TINs were also used to define the top of the model, from the uppermost gridded value from the EarthVision horizons, and the bottom of the model, which is approximately 1,200 m below the top.

The bottom horizon of the groundwater model was determined using a Gaussian smoothed representation of the top surface with a kernel radius of 40 km, and 1,200 m was subtracted from the smoothed horizon. The Gaussian smoothing algorithm was implemented in NumPy and GDAL for raster file formats. The purpose of using a semi-uniform thickness of 1200 m was to create a 3D cell-centred mesh where most of the grid cells had similar thicknesses, which is intended to yield stable simulations using the finite difference grids with MODFLOW and MT3DMS. A thickness of 1,200 m was chosen as it contains all 15 geological horizons and materials. The purpose of using a smoothed representation of the top surface as the bottom surface is a compromise between using a constant, flat, cut-off horizon and using a strict 1,200 m vertical offset. If a flat horizon was used, then cell thicknesses would vary across the domain (i.e., cells are thinner at lower elevations and thicker at higher elevations). If a constant 1,200 m vertical offset were used, each topographic irregularity from the top surface would be repeated for all layers at depth. A smoothed mesh bottom minimises the spatial variation of elevations.

A combination of a raster catalogue and a horizon conceptual model was used to generate solids in GMS 10.0. The raster catalogue was assembled using the 15 geological horizon rasters, where each row was identified by both a horizon ID (1 to 15, from bottom to top) and a unique name (Table 3.3). All rows were specified as "fill" horizons. The horizon conceptual model consists of 15 polygon coverages, which represent the spatial extent of each horizon. These polygon extents were first generated by polygonising valid data portions of each horizon raster; then, the resulting shapefiles were "cleaned up" as necessary in a GIS environment, and imported into GMS.

The horizons-to-solids conversion was completed using an inverse distance weighted interpolation with a constant nodal function. Neither the "intersect horizon surfaces" nor "minimum solid thickness" options were used. Each of the 250 m coarse-resolution and 100 m fine-resolution solids were re-projected from NZMG1949 to NZTM2000 using the NTVv2 grid transform method. Solids were mapped to uniform cell-centred 3D grids using a "grid overlay" option with a minimum thickness of 10 m and a maximum of 50 smoothing iterations. The process of converting the solid geological representation to a finite element mesh is shown in Figure 3.4 for the coarse mesh.

After conversions, both geological solids and MODFLOW finite element meshes were carefully compared to their equivalents in EarthVision to ensure that they were properly translated across different software.

Table 3.3 Summary of horizon data from surface to base.

ID	Name
15	Tauranga Group alluvium
14	Q1 to Q4 undifferentiated pyroclastics
13	Young Okataina rhyolites
12	Earthquake Flat Formation
11	Rainbow Mountain dacite
10	Mamaku Plateau Formation
9	Kaingaroa Formation
8	mQ to Q7 undifferentiated pyroclastics
7	Lake sediments
6	Pokopoko pyroclastics
5	Okataina and other rhyolites
4	Matahina Formation
3	Whakamaru Group
2	Okataina Rhyolite pre-Whakamaru
1	Base of model

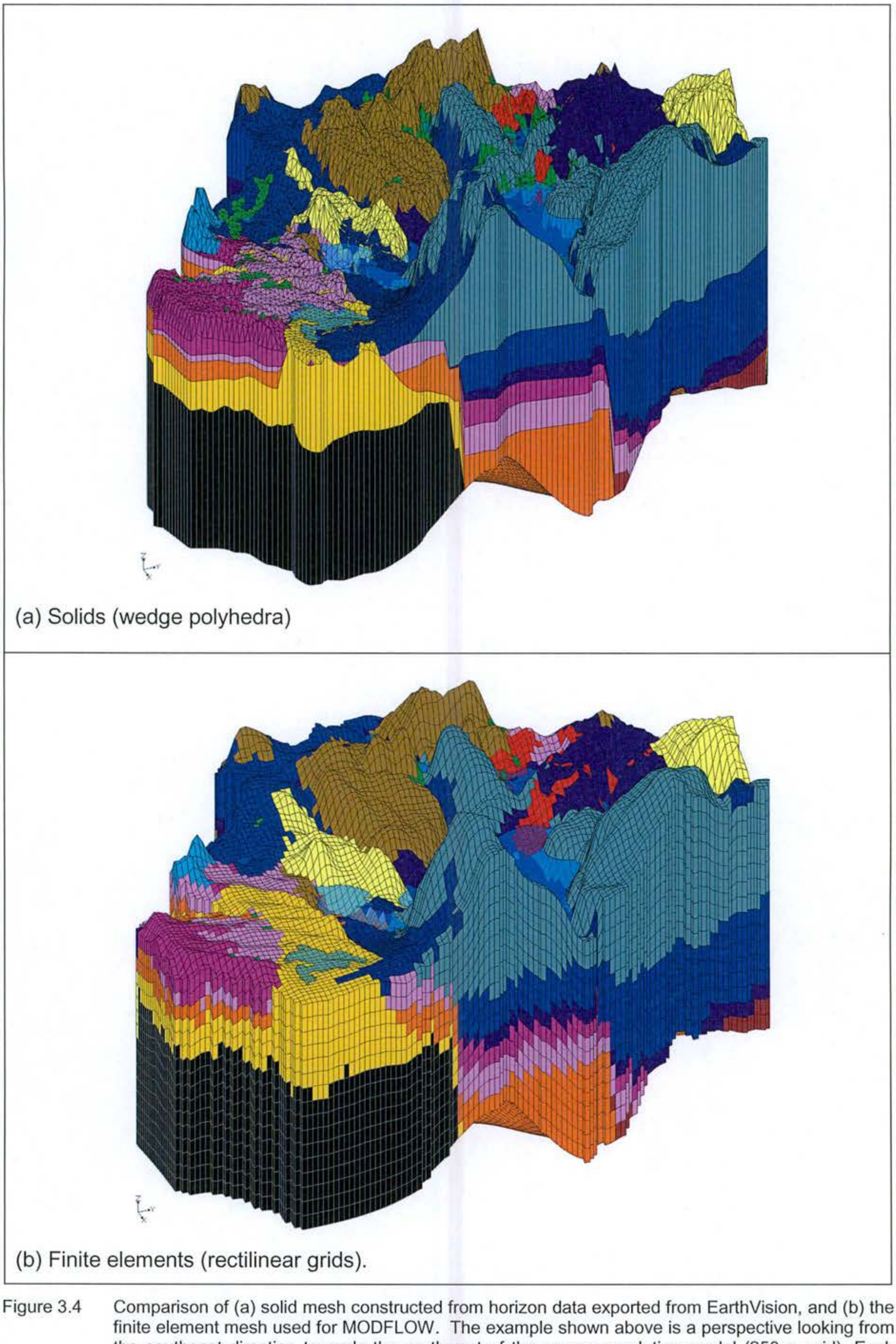

Figure 3.4 Comparison of (a) solid mesh constructed from horizon data exported from EarthVision, and (b) the finite element mesh used for MODFLOW. The example shown above is a perspective looking from the southeast direction towards the northwest of the coarse resolution model (250 m grid). Each colour represents one of fifteen geological materials.

3.2.4 Boundary conditions

The numerical models are controlled by the assignment of BCs, which represent the flow (or lack of flow) along the outer boundary, flow in and out of lakes, flow to streams, groundwater recharge and nitrate loading. In MODFLOW, BCs are implemented using a modular concept of packages. MT3DMS has a similar concept, although more simplified in a single "Sink and Source Mixing" package.

Groundwater recharge was simulated using the recharge (RCH) package, applied on the uppermost active cells (Figure 3.5). Variable recharge rates across the region were derived from the difference of gridded national precipitation rates between 1960-2006 (Tait *et al.*, 2006) and AET estimates (Woods *et al.*, 2006), Section 3.1. The gridded 500 m resolution dataset was interpolated to the MODFLOW model using an inverse distance weighted method, and a scaling factor of 2.7379093×10^{-6} was applied to convert from units of mm/year to m/d.

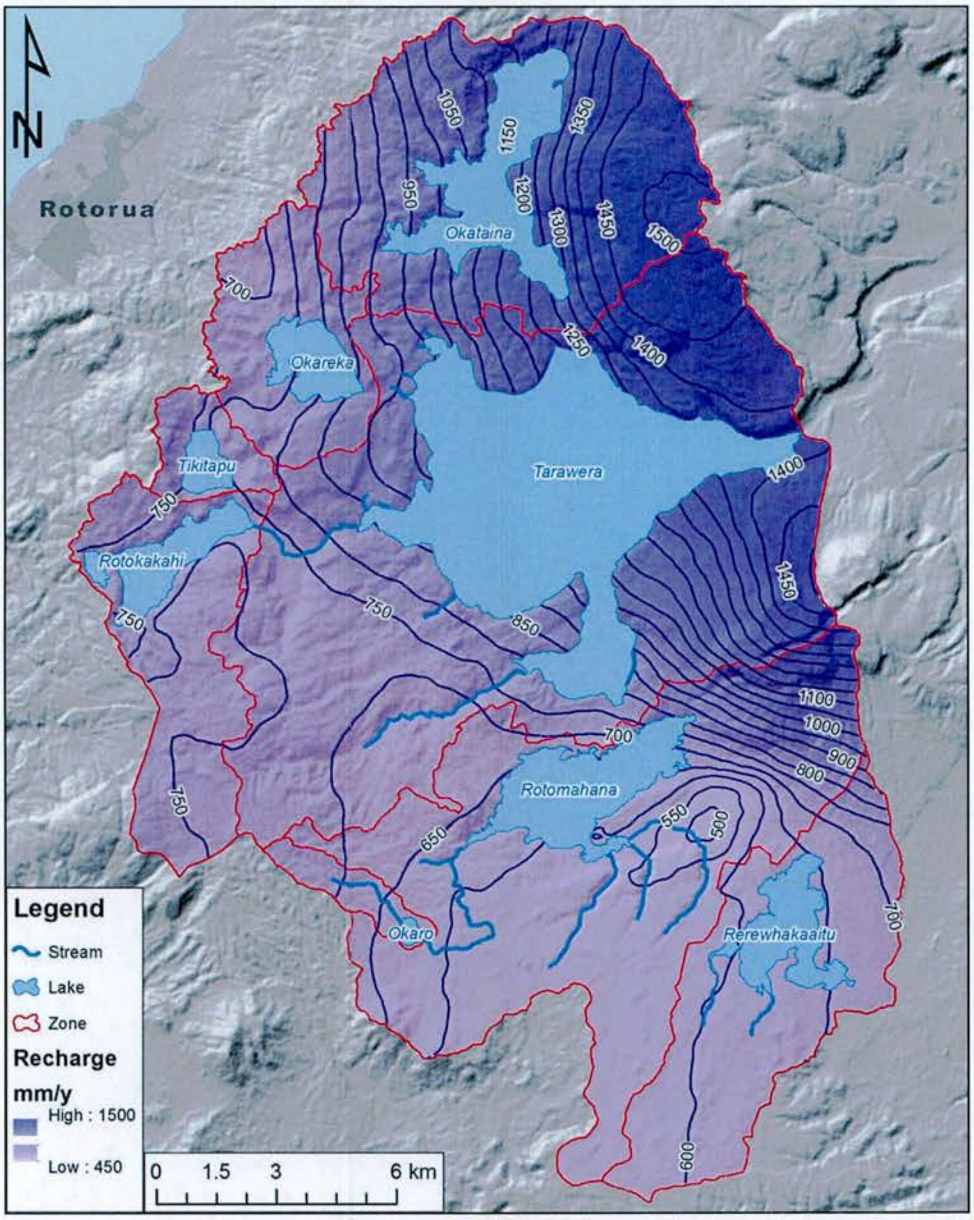

Figure 3.5 Groundwater recharge applied to the top surface of the model, which varies between 483 mm/y to 1,513 mm/y on a 100 m regular grid for the model.

Most of the outer perimeter of the model is a no-flow boundary, since the outer boundaries are based on groundwater catchment boundaries. However, non-zero flow exceptions were permitted along two parts, based on the conceptual flow model. Constant-flux boundaries were implemented along the edge of the model near Tarawera River and near Lake Rerewhakaaitu. These specified fluxes were enabled using the Well (WEL) package, for selected cells on the perimeter, along the upper four layers.

The eight lakes were represented using the General Head Boundary (GHB) package, which is a head-dependent boundary (Table 3.4). Average autumn lake stage levels (Environment Bay of Plenty, 2007) were used to represent the lake levels for the steady-state models. Rates of fluid exchanges with the underlying aquifer were controlled using conductance values assigned for each lake during calibration.

Table 3.4 Summary of lake stage data (Environment Bay of Plenty, 2007). IDs are assigned from lowest to highest stage.

ID	Lake name	Gauge location	Site No.	Data capture		Mean autumn stage (m)
				From	To	
1	Tarawera	Te Wairoa	15301	Jan-26	Dec-05	298.0
2	Okataina	Tauranganui Bay	15309	Jan-53	Dec-05	309.1
3	Rotomahana	Crater Bay	15338	Jan-25	Dec-05	338.7
4	Okareka	Acacia Bay	15307	Jan-66	Dec-05	353.6
5	Rotokakahi	Te Wairoa	15344	Jan-72	Dec-05	394.9
6	Okaro	Reserve	1015325	Jan-90	Dec-05	411.8
7	Tikitapu	Tarawera Rd	15347	Jan-72	Dec-05	417.3
8	Rerewhakaaitu	Homestead Arm	1015310	Apr-83	Dec-05	434.9

Streams and some springs were represented using the MODFLOW Drain (DRN) package, which is a head-dependent boundary that only allows flow out of the aquifer. This type of package is commonly used to represent smaller stream flows in numerical groundwater models, since the streams are typically gaining flows from aquifers without losing flow back to the ground. The package can only simulate net flow gains, so flow accumulated in the upper reaches of streams cannot be routed downstream to re-enter the aquifer in the lower reaches. This approach is reasonable for the catchments in the study area because losing streams (i.e., streams that lose water to groundwater) are not observed in the study area. Streams were conceptualised by vector lines, with elevations for the top and bottom (Table 3.5).

Table 3.5 Streams and springs implemented as DRN boundaries. Net flow is used as an observation target only, and does not influence numerical simulations. Elevations, determined from LiDAR data, are used for the drain BCs, and are linearly interpolated along stream lines from the top node to the bottom node. The two spring groups implemented have only one elevation.

ID	Abbreviation (8 characters)	Site	Description	Flow (l/s)			Elevation (m)	
				Start	End	Net	Top node	Bottom node
Flows to Lake Tarawera								
18	SpencFrd	NSN1983	Spencer Road Ford	0	1.5	1.5	306.400	298.001
15	TeWhekau	15390	Te Whekau	0	19.5	19.5	308.100	298.001
19	Waitngui	1015336	Waitangui Spring	0	3.9	3.9	305.812	298.001
4	Waitangi		Waitangi Stream	0	164	164	326.380	298.001
16	TeToroa	1015306	Te Toroa	0	91	91	303.001	
17	Orchard	15387	Orchard Stream	0	16	16	341.160	298.001
5	Wairoa	15385	Wairoa Stream	310.6	347	36.4	394.888	298.001
11	TePurku	15382 15383	Te Puroku No. 1 and 2 (Twin Creeks)	0	507	507	397.793	298.001
13	Wairua	15380	Wairua Stream	0	208	208	357.047	298.001
14	WatfalCS	15332 15377	Waterfall and Camp Site	0	238	238	303.001	
Flows to Lake Okaro								
61	OkaroSt		Okaro Stream	0	35	35	442.957	411.760
Flows to Lake Rotomahana								
32	Waimangu	15322	Waimangu Stream	0	30	30	364.230	340.540
6	Haumi1	15396	Haumi Stream 1	30	110	80	411.760	340.540
33	Haumi2		Haumi Stream 2	140	140	0	340.540	338.657
34	TeKauae	15378	Te Kauae at Ash Pit Rd	0	166	166	404.570	338.657
35	Putunoa	NSN2069	Putunoa at Farm Track Culvert (Ash Pit Rd #2)	0	26	26	382.059	338.657
36	RotomhSt	15399	Rotomahana Stream	0	56	56	412.060	338.657
Flows to Lake Rerewhakaaitu								
81	Mangakno		Mangakino Stream	0	27.8	27.8	438.361	434.863
82	Awaroa		Awaroa Stream	0	9.8	9.8	441.320	434.863

Spatial discretisation and attributes of lakes and streams were stored as vector shapefiles, and translated to GHB and DRN BCs for MODFLOW using the conceptual model building approach built into GMS 10.0. River and lake boundaries are restricted to only the top layer of the MODFLOW model, and care was taken to ensure that boundary elevations are within each cell's top and bottom elevations. Some cell elevations were adjusted using a Python script to ensure that the elevations used for head-dependant GHB and DRN BCs were within 0.001 m of the top layer elevation range. The discretized BCs for coarse and fine models are shown in Figures 3.6 and 3.7.

Zone boundaries are shown in the coarse and fine models (Figures 3.6 and 3.7, respectively).

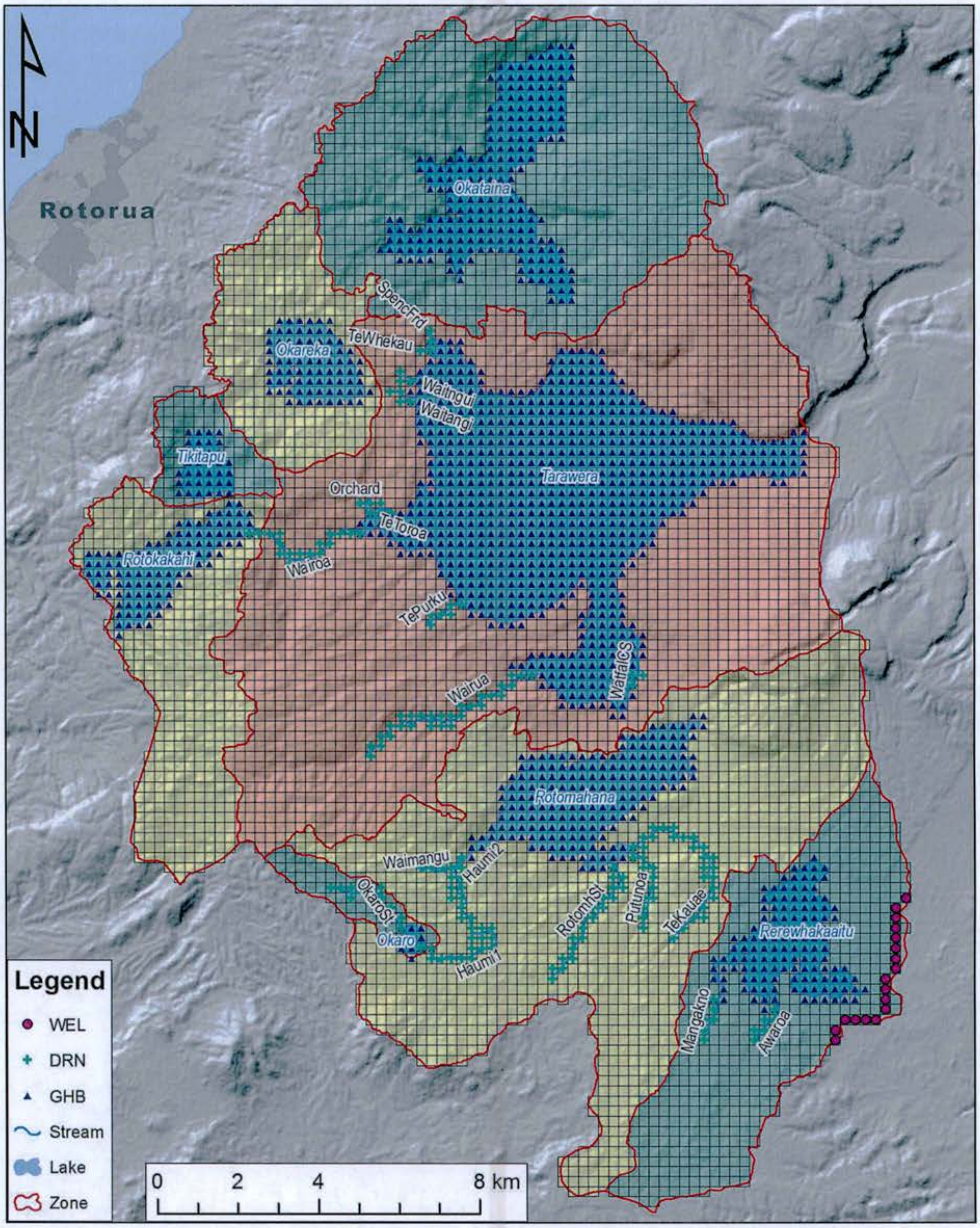

Figure 3.6 MODFLOW BCs on the coarse 250 m resolution grid. Abbreviated stream names are listed in Table 3.5.

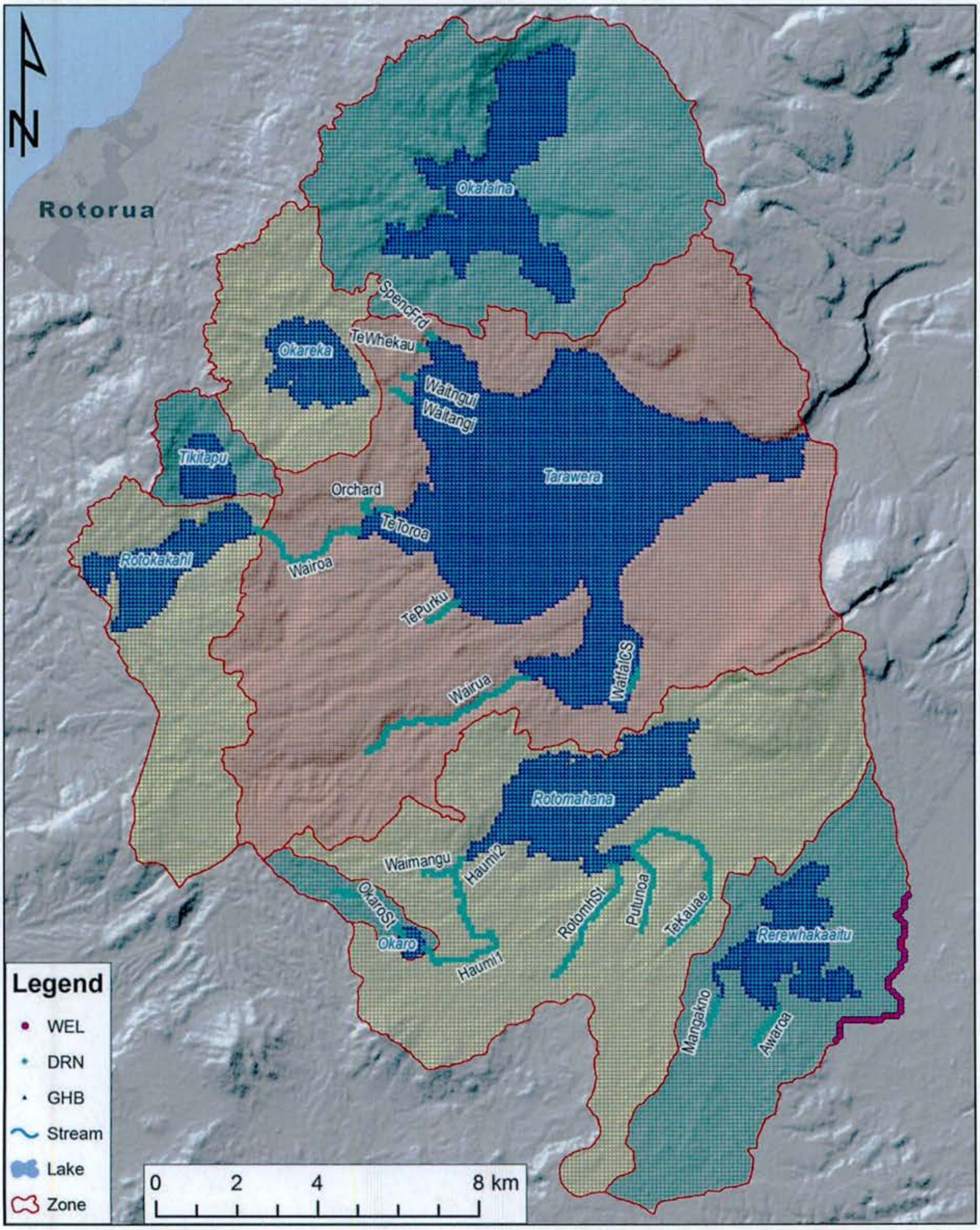

Figure 3.7 MODFLOW BCs on the fine 100 m resolution grid. Abbreviated stream names are listed in Table 3.5.

3.2.5 Model calibration

Static water levels from 40 wells were used to calibrate hydraulic heads (Table 3.6). Surface elevations were obtained from bilinear interpolation of a digital terrain dataset that was derived by BOPRC and includes LiDAR measurements. The observation point is defined vertically by the screen elevation, which is the difference of surface elevation and screen depth. The observed value is the static water level.

Table 3.6 Observation wells used to represent static water levels.

ID	Reference	Name	NZTM2000		Surface elevation (m)	Screen depth (m)	Screen elevation (m)	Static water level (m)
			X (m)	Y (m)				
1	Thorstad *et al.* (2011)	Te Miro	1896550.1	5769003.0	320.59	10	310.59	298.20
2		Dollimore	1897767.0	5770595.0	315.67	10	305.67	299.50
3		Lake T. outlet	1906630.1	5768031.5	297.99	10	287.99	282.10
4	Rose *et al.* (2012)	Site 4	1894431.5	5765182.1	382.34	10	372.34	370.50
5		Site 5	1907536.9	5755671.4	442.69	4	438.69	438.20
6		Site 6	1904400.6	5758441.0	358.04	1	357.04[a]	358.46
7		Site 7	1901559.2	5753618.2	447.80	10	437.80	398.60
8	Lovett *et al.* (2012)	Site 8	1889811.4	5763120.4	403.42	5	398.42	396.85
9		Site 10	1891409.0	5768196.6	428.15	10	418.15	418.10
10		Site 11	1893815.0	5771192.2	357.76	1	356.76[b]	357.90
11	Bay of Plenty Regional Council (2010)	10486	1903704.6	5749876.5	504.09	10	494.09	424.11
12		10730	1901702.3	5750374.6	481.94	10	471.94	397.08
13		10728	1901500.9	5751375.2	467.58	10	457.58	391.60
14		3585	1902301.1	5751776.5	474.49	10	464.49	408.54
15		10601	1905203.1	5752180.4	460.89	10	450.89	431.78
16		10625	1905403.2	5752280.7	465.13	10	455.13	433.18
17		10604	1905192.0	5753081.2	455.44	10	445.44	428.48
18		11081	1904731.5	5753130.7	465.04	10	455.04	432.09
19		3505	1905502.1	5753181.7	446.99	10	436.99	435.28
20		10602	1902699.2	5753578.6	476.95	10	466.95	452.92

ID	Reference	Name	NZTM2000		Surface elevation (m)	Screen depth (m)	Screen elevation (m)	Static water level (m)
			X (m)	Y (m)				
21		11513	1899796.2	5753975.4	429.75	10	419.75	410.65
22		1595	1903259.0	5754139.8	456.32	10	446.32	430.41
23		10157	1898614.6	5754474.4	421.40	10	411.40	411.25
24		1075	1898174.2	5754483.8	415.38	10	405.38	403.13
25		2048	1896993.1	5754572.4	413.69	10	403.69	389.28
26		2144	1903098.0	5754780.1	451.61	10	441.61	409.18
27		11102	1903338.2	5754810.5	444.65	10	434.65	407.55
28		10612	1903998.6	5754981.4	444.67	10	434.67	423.71
29		10608	1904498.0	5755782.8	462.07	10	452.07	431.49
30		10605	1908501.5	5755887.8	445.39	10	435.39	429.52
31		10606	1908000.8	5756087.4	448.30	10	438.30	433.31
32		11080	1906097.5	5757356.2	467.61	10	457.61	442.37
33		3330	1894186.8	5757771.6	510.60	10	500.60	451.24
34		11100	1906176.9	5757866.7	413.73	4	409.73	409.70
35		10162	1893886.3	5757971.4	543.28	10	533.28	519.34
36		163	1891582.8	5759269.6	521.80	10	511.80	480.59
37		189	1891782.0	5759970.4	514.20	10	504.20	475.18
38		2138	1891880.2	5761471.7	540.66	7	533.66	533.02
39		10985	1890868.9	5761850.8	431.85	1	430.85	430.01
40		1225	1891677.7	5763272.9	538.76	10	528.76	506.72

(a) For 250 m grid model, this was adjusted to 356.26 m to fit within domain.

(b) For 100 m grid model, this was adjusted to 353.77 m to fit within domain.

3.3 LAND USE SCENARIOS AND NITROGEN LOADING

Nitrogen loadings to lakes and streams were calculated with the aim of contributing to the assessments of the impacts of land use on water quality. Firstly, five land use scenarios were developed for the greater Lake Tarawera catchment with the aim to derive maps of land use intensity and nitrogen loading, from low to high, including current land use. Then, maps of specific nitrogen discharge were calculated using published nitrogen discharge estimates from the various land uses in each scenario and nitrogen loadings to zones were calculated. Lastly, the groundwater flow model was used to calculate nitrogen loadings to lakes and streams.

3.3.1 Land use scenarios

Land use scenarios aim to represent a range of land use intensity, from low to high, with ArcGIS maps. Five scenarios were developed with the assistance of BOPRC in meetings and discussions:

- identification of current land use;
- two scenarios where land use is less intensive than current land use;
- two scenarios where land use is more intensive than current land use.

The land use scenarios are numbered 1 to 5, with current land use as Scenario 3, in order of increasing intensity of land use (Table 3.7), i.e.:

1. Forested land use (Figure 3.8).
2. Low-intensity agricultural land use (Figure 3.9).
3. Current land use (Figure 3.10).
4. Foreseeable intensification (Figure 3.11).
5. Large-scale intensification (Figure 3.12).

The map of current land use (Scenario 3; Figure 3.10) formed the basis on which the other four scenarios were developed. Current land use was estimated by simplifying the Land Use Classifications of the Ministry for the Environment (2014), including:

a) amalgamation of *Grassland – low producing* and *Grassland – with woody biomass* into Grassland – low producing or with woody biomass;

b) amalgamation of *settlements* and *other* (e.g., bare rock, quarry) into "Settlements and other";

c) amalgamation of *Planted forest – Pre 1990* with *Post 1989 Forest* into "Planted Forest"; and

d) amalgamation of *wetlands* and *lakes* into "Wetlands and lakes".

Scenario 3 was modified to derive scenarios 1, 2, 4 and 5 (Table 3.7). Scenario 4 aims to represent foreseeable intensification of land use in the catchment. Scenario 4 does not replace forested land uses with grassland land use. However, some small areas of forested land uses are replaced with grassland land use, based on the land use capability map, in Scenario 5.

Table 3.7 Description of the five land-use scenarios, including modifications to the land use classification base map with the land use capability map.

Scenario	Method
1) Forested land use	Natural forest, planted forest, lakes and wetlands, and urban/other polygons as per current land use. Grassland (high and low producing) and cropland polygons were changed to planted forest.
2) Low-intensity agriculture	Natural forest, planted forest, lakes and wetlands, and urban/other polygons as per current land use. High-producing grassland was changed to low producing grassland.
3) Current land use	Based on the current land use classification map with a simplified legend (see amalgamations above) and estimated area of current dairy land use that was obtained from discussions with BOPRC (MacCormick, 2015).
4) Foreseeable intensification	Natural forest, planted forest, lakes and wetlands, and urban/other polygons as per current land use. Dairy land use occupies all high-producing grassland.
5) Large-scale intensification	Natural forest, planted forest, lakes and wetlands, and urban/other polygons as per current land use. Dairy land use occupies all high- and low-producing grassland and woody-biomass, except land on the top of Mount Tarawera and Te Horoa dome. The land use classification base map was overlain with a land use capability map (Landcare Research, 2015). All areas with land use capability classes 1-5 were changed to high producing grassland; land use capability classes 6-8 were kept as is.

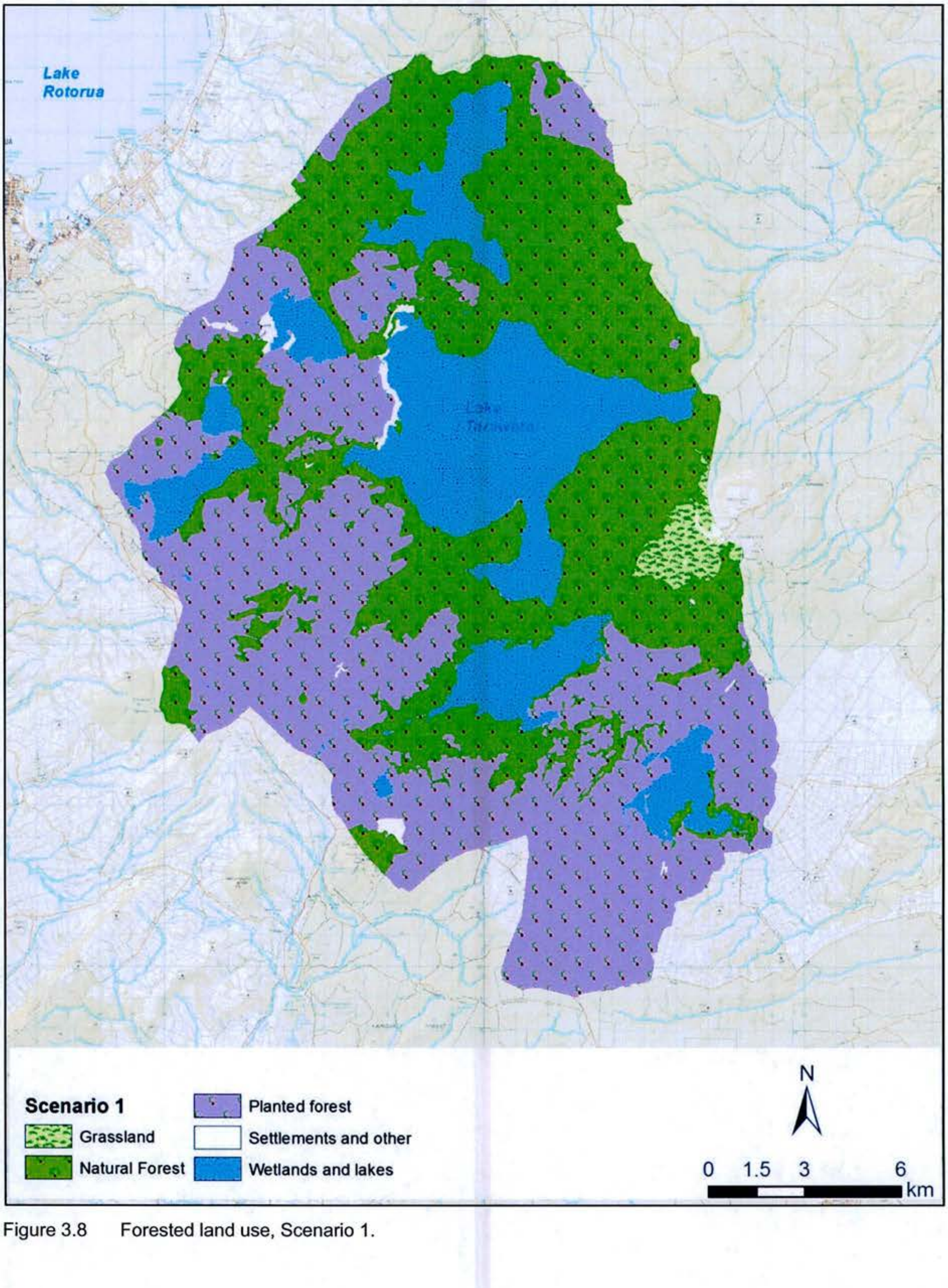

Figure 3.8 Forested land use, Scenario 1.

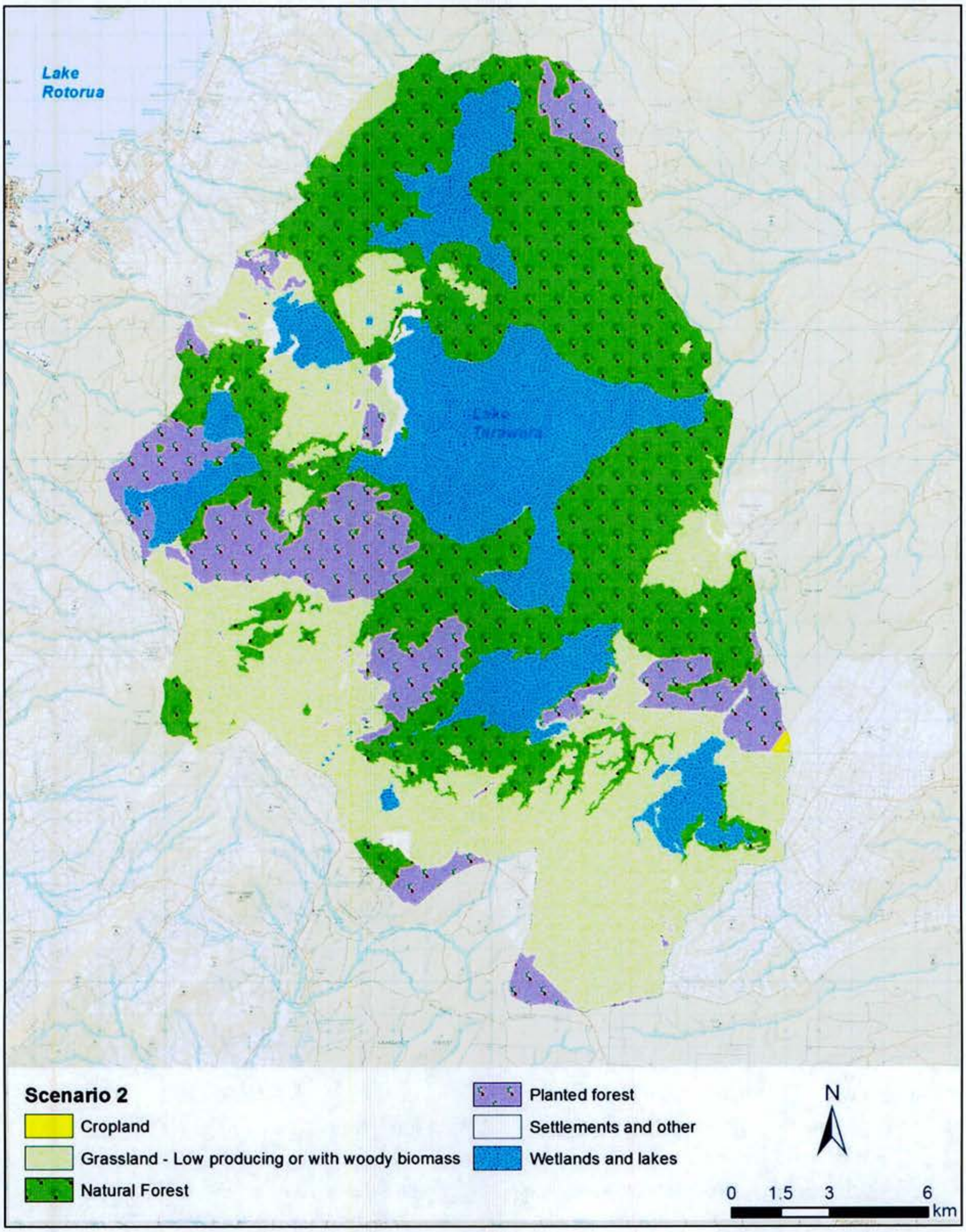

Figure 3.9 Low-intensity agricultural land use, Scenario 2.

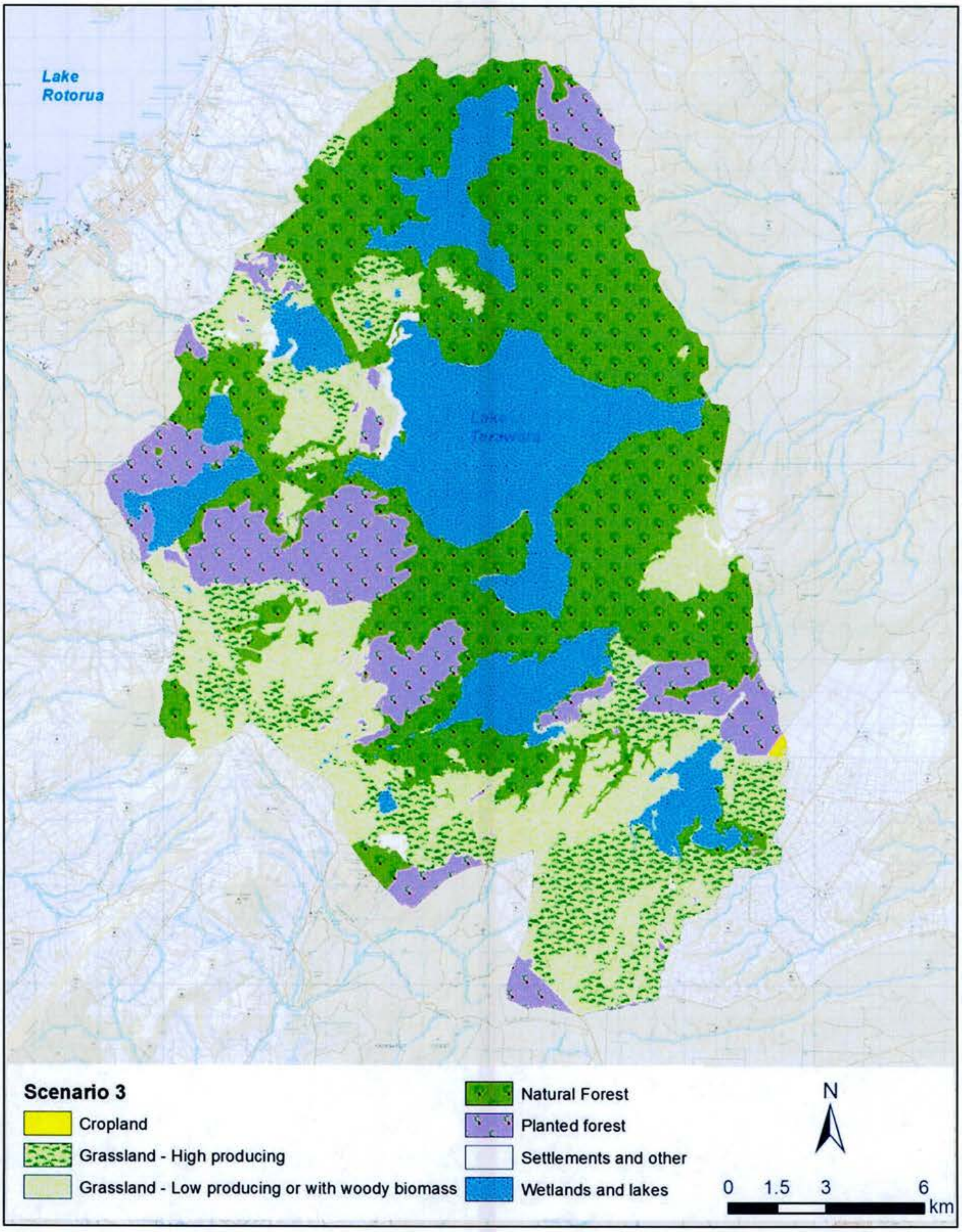

Figure 3.10 Current land use, Scenario 3 which represents current land use and is therefore the baseline for other scenarios.

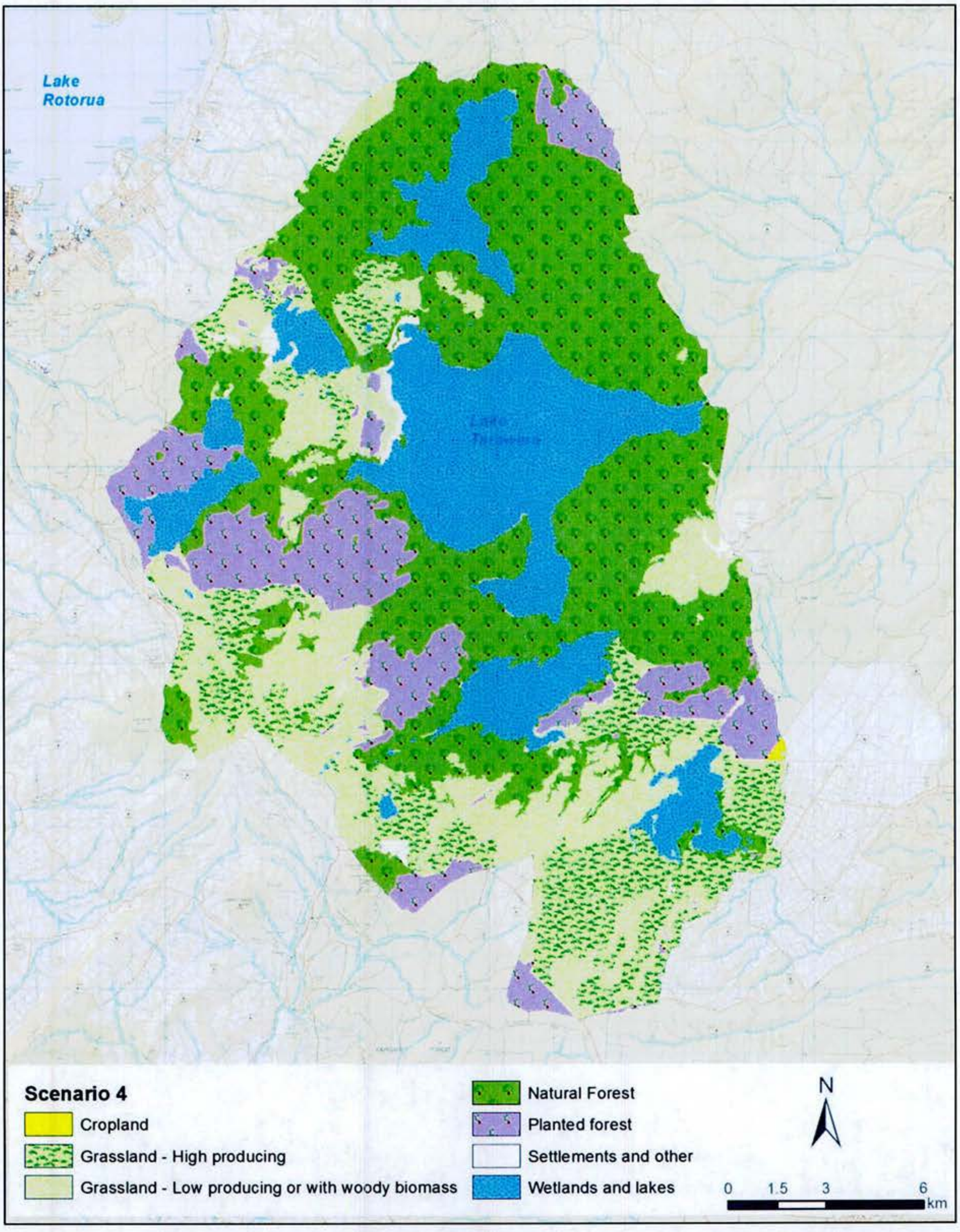

Figure 3.11 Foreseeable intensification, Scenario 4. Note that land use classifications are similar to current land use and that foreseeable intensification occurs within the two 'grassland' land use categories.

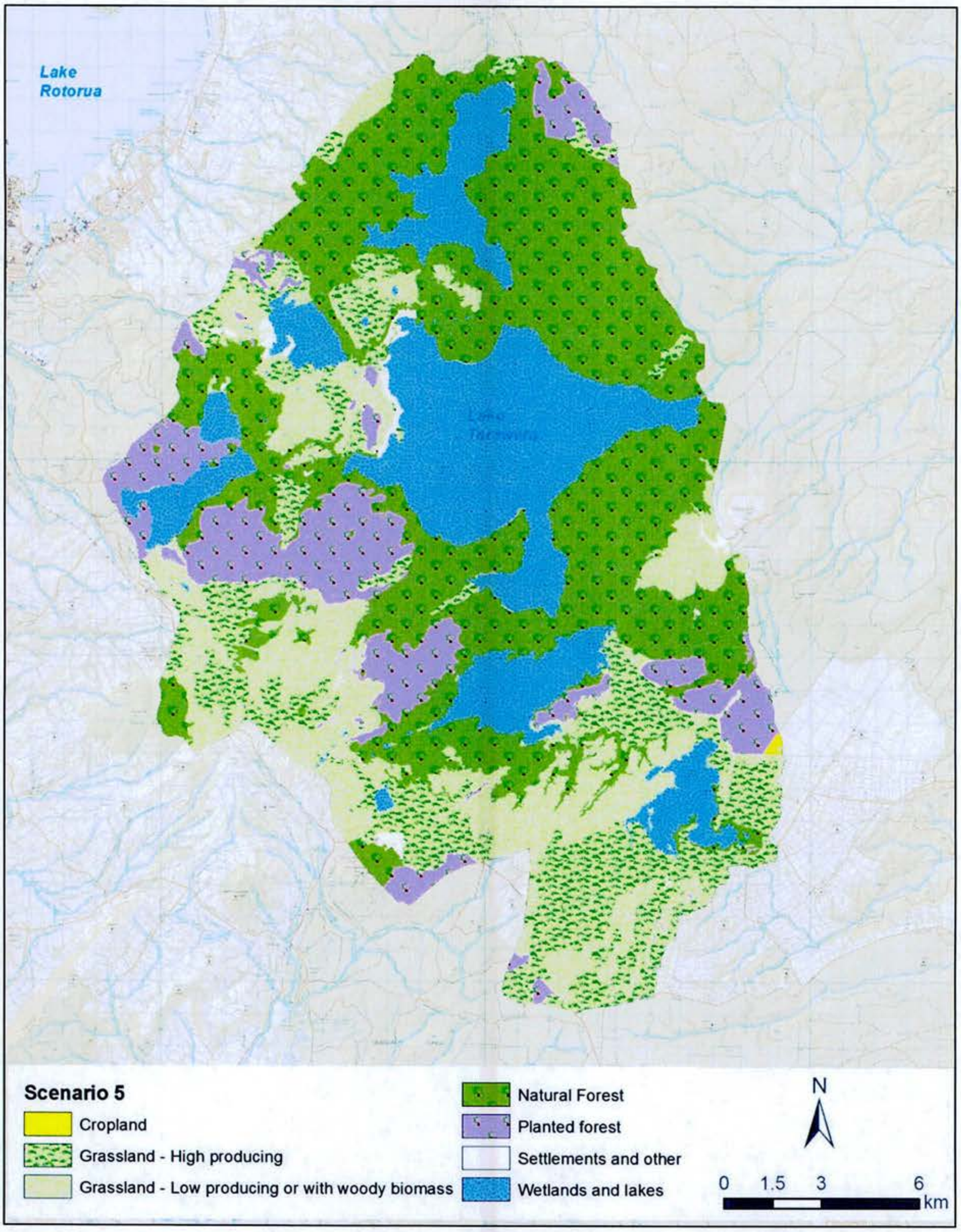

Figure 3.12 Large-scale intensification, Scenario 5. Note that land use classifications are similar to current land use and that large-scale intensification occurs within the two 'grassland' land use categories.

3.3.2 Nitrogen loading

Nitrogen loadings to zones within the study area were developed for the five land use scenarios. Nitrogen loadings were assigned to polygons using loading estimates for each land use type, including lakes and wetlands, calculated for the Lake Rerewhakaaitu catchment (Table 3.8); McIntosh (2012) and Hamilton (2014). These loadings may be appropriate for the study area as most of pasture suitable for potential development is in the south of the greater Tarawera catchment.

Nitrogen loadings for scenarios 1 to 5 represent a progressive increase in land intensification (Figure 3.13 and Table 3.9). Note that low-producing grassland and woody-biomass on the top of Mount Tarawera and the Te Horoa dome were assigned a nitrogen loading of indigenous forest and scrub.

Table 3.8 Land use and nitrogen loading calculated for the Lake Rerewhakaaitu catchment.

Land use	Nitrogen loading (kg N/ha/yr)
Cropping	32[1]
Exotic forest	3[2]
Indigenous forest and scrub	4[2]
Dairy and dairy grazing	31[1]
Sheep, beef and deer	10[2]
Urban	8[1]
Lake and wetland	4[1,2]

1 Source of loading estimate: McIntosh (2012).

2 Source of loading estimate: Hamilton (2014). Note that a large uncertainty is associated with this estimate (Hamilton, 2016).

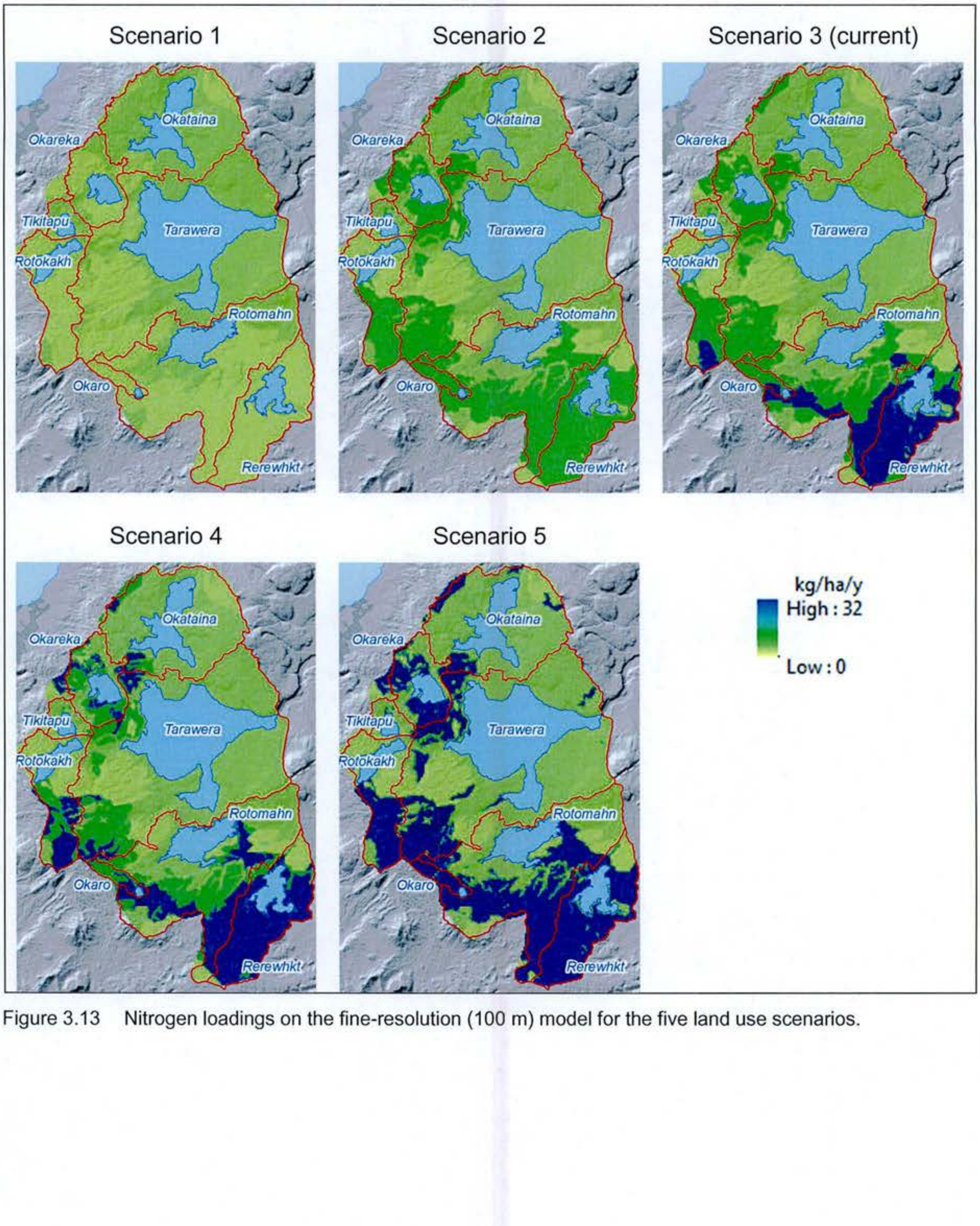

Figure 3.13 Nitrogen loadings on the fine-resolution (100 m) model for the five land use scenarios.

Table 3.9 Nitrogen loading to each zone, including lake surfaces.[1]

Zone	Nitrogen loading (kg N/year)				
	Land use scenario				
	1	2	3	4	5
Tarawera	54083	68111	68111	77926	117688
Okataina	23175	25940	25940	29207	36999
Rotomahana	28633	51863	78505	91247	128548
Okareka	6778	12758	12758	18853	31273
Rotokakahi	9049	16634	21419	30908	39679
Okaro	1198	3673	5194	6272	11099
Tikitapu	2354	2518	2518	2518	3010
Rerewhakaaitu	11836	29842	74780	84770	86054

1 Note that the land use GIS polygons cover an area that is slightly larger than the groundwater model area. Therefore, that TN loading that is calculated with the land use model is slightly larger than the totals of the figures in this table.

3.3.3 Nitrogen loading to the groundwater flow model

The "Source/Sink Mixing" package in MT3DMS was used to simulate an aerially distributed source from recharge flux. The spatially variable nutrient flux was derived from the GIS data of nitrogen loading scenarios (Figure 3.13). Gridded nitrogen loadings were prepared by rasterising the vector polygons to 10 m resolution, then deriving the average of 250 m or 100 m resolution grids. This technique of rasterising conserves mass more appropriately than directly rasterising each grid from the vector data. Rasters of nitrogen loading expressed in units of kg/ha/year were converted to a recharge nitrogen flux boundary expressed as a concentration (i.e., kg/m^3) by dividing the loading by recharge rates (in units of m/d).

4.0 RESULTS

4.1 CHARACTERISATION OF LAKE INFLOWS AND OUTFLOWS

4.1.1 Lake Tarawera

Surface water features relevant to Lake Tarawera inflows include cold springs, hot springs and streams (Figure 4.1). Natural streams flow into Lake Tarawera from the west. Wairoa Stream, sourced from Lake Rotokakahi, flows into Kotukutuku Bay (Figure 4.2 and Table 4.1). In addition, Te Puroku Stream and Wairua Stream are sourced from springs and seeps. Waitangi Stream, which flows into Waitangi Bay, is sourced from the Lake Okareka drain.

Cold-water springs are most common in two areas: Kotukutuku Bay and the southeast of Lake Tarawera (Figures 4.2 and 4.3, respectively). Most springs in Kotukutuku Bay are located below Spencer Road and possibly drain the Okareka Rhyolite Complex located above the road (Nairn, 2002). Inflows were mapped from eight spring-sourced features in Kotukutuku Bay. Flows have been measured at four of these sites (Te Toroa, Orchard Stream, The Landing drain 1 and Wairoa Stream) by BOPRC (Naysmith, 2013). Flows at the other five sites have not been measured by BOPRC. These sites include: Pohutukawa Stream with three inflows to the lake, i.e., a, b and c; site "37"; and Rewarewa Stream; and The Landing drain 2. Estimated flow at these five sites totalled 10 l/s (Table 4.1); flow from The Landing drain 2 was zero at a site visit in January 2014. This report recommends that BOPRC measures flows and improves its site records for spring-fed features in Kotukutuku Bay (Section 6).

Springs located in the southeast of Lake Tarawera are associated with the Ngawhiro Rhyolite Dome; this feature was mapped, but not named as such, by Nairn (2002). Flow is recorded from two springs by BOPRC at sites 15377 and 15332 (Table 4.1). In addition, five other flowing streams were observed during a survey of the area by boat in January 2014: Dancing Sands, The Cut, Rock Slide, Wattle Stream and Flax Stream (Figure 4.3). Estimated flow at these five sites totalled 10 l/s (Table 4.1). This report recommends that BOPRC measures flows and improves its site records for spring-fed features in the area of these spring-fed features (Section 6).

Ngawhiro Rhyolite Dome was mapped on the shores of Lake Tarawera and Lake Rotomahana and is a possible pathway for groundwater to flow from Lake Rotomahana to Lake Tarawera. This suggestion is reinforced by gauged flows and rainfall recharge estimates for Ngawhiro Rhyolite Dome. The sum of gauged flows in springs along the Lake Tarawera shoreline (i.e., gauging sites 15331, 15332 and 15377) is approximately 0.2 m^3/s. However, rainfall recharge is less than 0.1 m^3/s in the area of the 0.5 km^2 area of Ngawhiro Rhyolite Dome in the Lake Tarawera catchment.

Streams that are sourced from springs or seeps include Te Puroku Stream, located at a rock face approximately 500 m from the lake edge (Scott, 2015) and gauged near the lake in two channels (Table 4.1). Flow in Wairua Stream begins approximately 4 km from the lake where groundwater seeps to the stream (Figure 4.1; Jones and Hughes, 2007). Surface features of Lake Tarawera related to geothermal activity include hot springs, seeps and iron staining of lake-side sediments (Figures 4.1 and 4.3). Brown staining is commonly associated with gas bubbles that may indicate geothermal inflows to the lake (Scott, 2015) or redox features associated with reduced iron complexes of the intruding groundwater (Hamilton, 2016).

The Tarawera River is the sole surface outflow from Lake Tarawera (Figure 4.1 and Table 4.2). Groundwater may flow out of Lake Tarawera down the Tarawera River valley. Two pieces of evidence indicate this possibility: Tarawera River gaugings that show a significant increase in river flow between Lake Tarawera and below Tarawera Falls (Figure 4.4); and the discovery of permeable, fractured rhyolite in a drill hole at the Lake Tarawera outlet (Thorstad *et al.*, 2011).

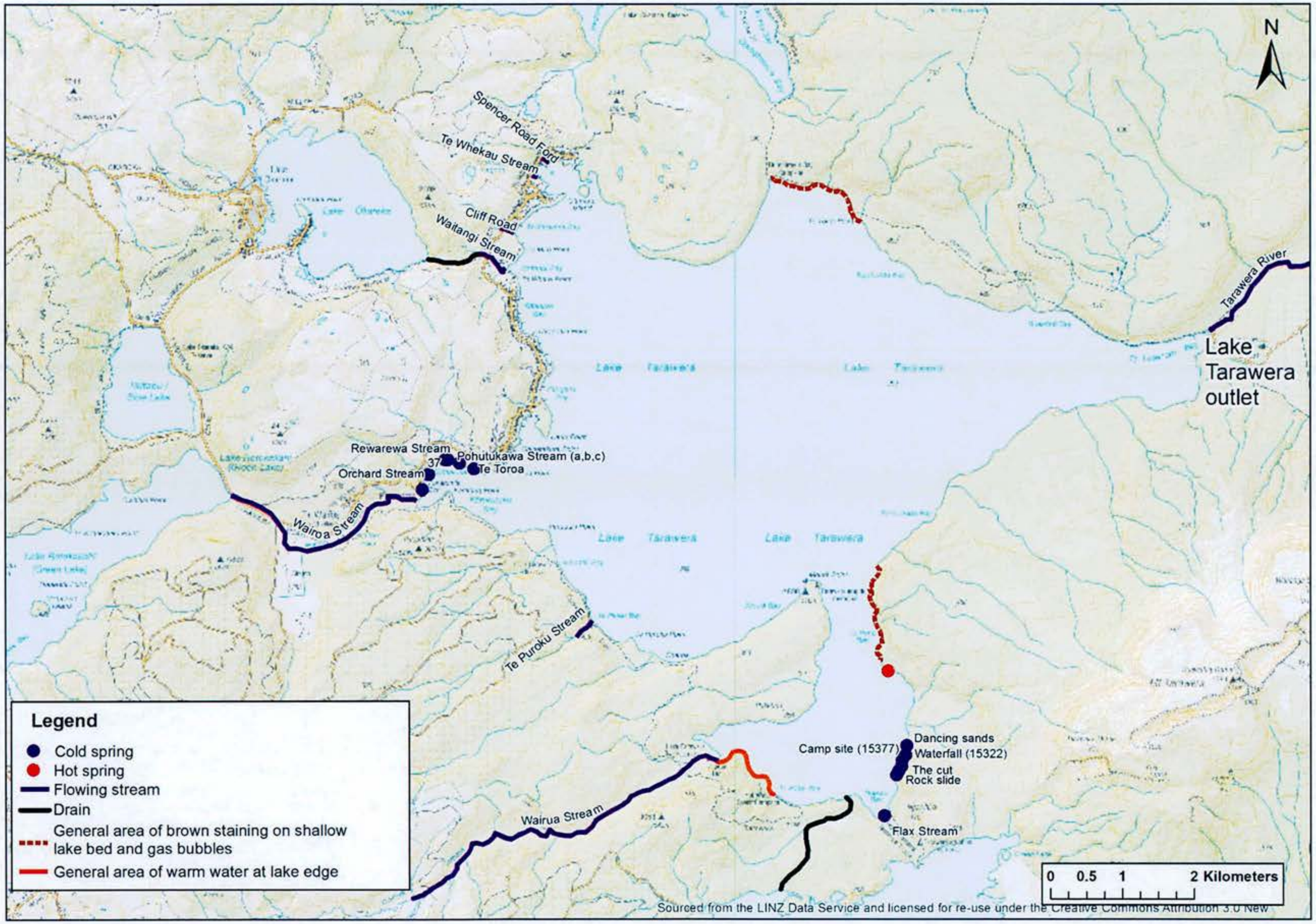

Figure 4.1 Lake Tarawera: location of surface hydrological features associated with inflows to, and outflows from, the lake. The thin blue lines on the background map are watercourses (Department of Lands and Survey, 1982 and 1987). These watercourses are generally dry, except as noted by the features described in the legend.

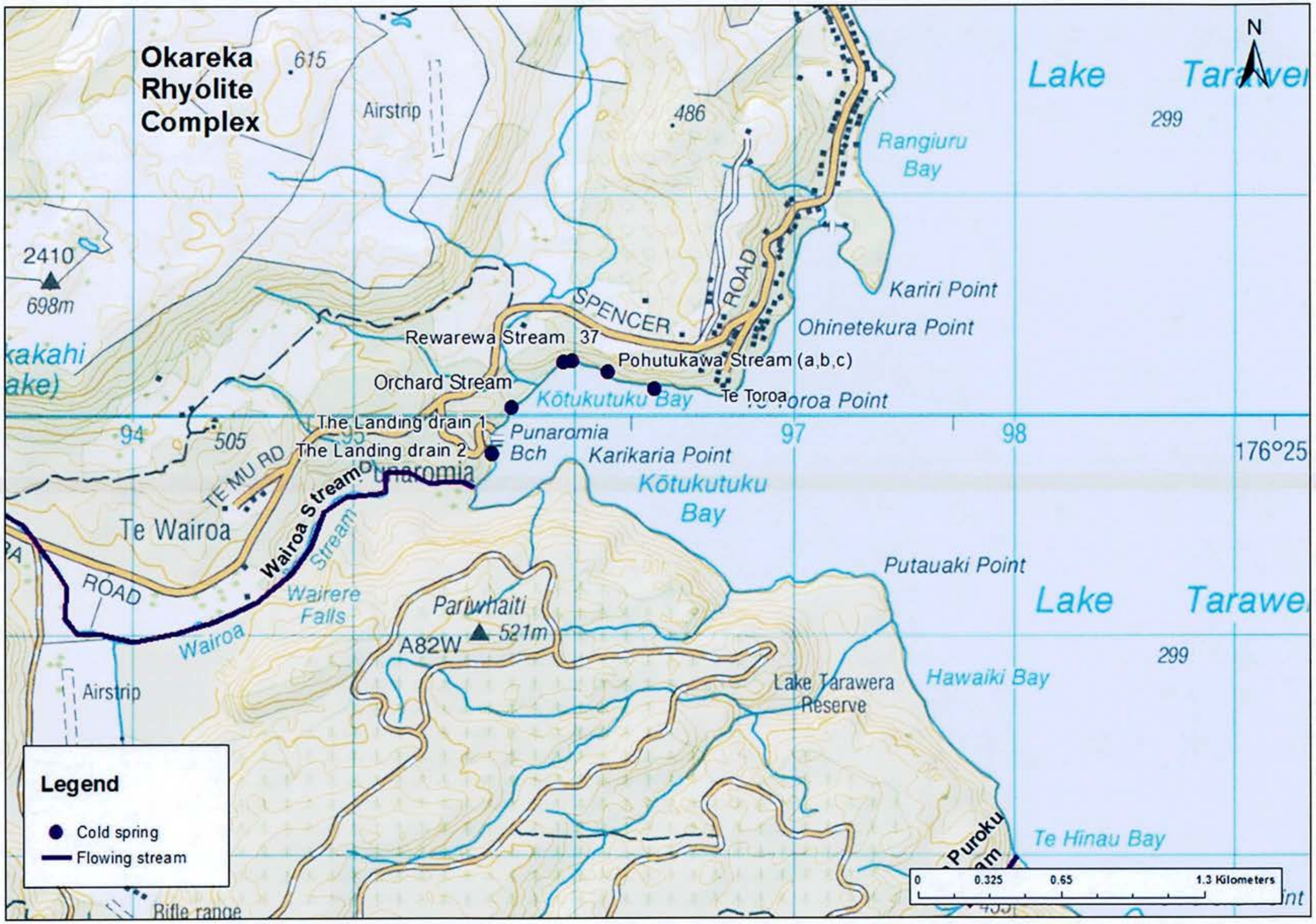

Figure 4.2 Lake Tarawera: surface hydrological features in Kotukutuku Bay. The thin blue lines on the background map are watercourses (Department of Lands and Survey, 1982). These watercourses are generally dry, except as noted by the features described in the legend.

Table 4.1 Surface inflows to lakes in the study area, rounded to the nearest 1 l/s.

Lake	Surface inflow to lake (l/s)	Location x (NZMG)	Location y (NZMG)	Site	BOPRC site	Reference
Lake Tarawera	65	2812510	6324080	Camp Site	15377	Gillon (2008)
Lake Tarawera	174	2812490	6323530	Waterfall	15332	Gillon (2008)
Lake Tarawera	208	2809840	6323520	Wairua Stream	15380	Gillon (2008)
Lake Tarawera	123	2808070	6325490	Te Puroku No. 1 (Twin Creeks)	15382	Gillon (2008)
Lake Tarawera	384	2808070	6325490	Te Puroku No. 2 (Twin Creeks)	15383	Gillon (2008)
Lake Tarawera	347	2805660	6327220	Wairoa Stream	15385	Gillon (2008)
Lake Tarawera	32	2805840	6327380	The Landing drain 1	15386	Putt (2015)
Lake Tarawera	16	2805840	6327560	Orchard Stream	15387	Putt (2015)
Lake Tarawera	91	2806480	6327640	Te Toroa	1015306	Putt (2015)
Lake Tarawera	10	various	various	Ungauged sites in Kotukutuku Bay	na	Site visit January 2014
Lake Tarawera	164	2806627	6330640	Waitangi Stream	NSN1751	Putt (2015)
Lake Tarawera	4	2807100	6330900	Waitangui Spring	1015336	Gillon (2008)
Lake Tarawera	20	2807420	6331730	Te Whekau Stream	15390	Gillon (2008)
Lake Tarawera	1.5	2807405	6332011	Spencer Rd Ford Stream	NSN 1983	Gillon (2008)

Lake	Surface inflow to lake (l/s)	Location x (NZMG)	Location y (NZMG)	Site	BOPRC site	Reference
Lake Tarawera	10	various	various	Ungauged sites in SE of lake	na	Site visit January 2014
Lake Okaro	35	2806700	6317400	Lake Okaro Stream baseflow		Environment Bay of Plenty (2006)
Lake Rotomahana	110	2808030	6318850	Haumi Stream (above Waimangu Stream confluence)	15396	Putt (2014)
Lake Rotomahana	58	2808000	6318900	Waimangu Stream (above Haumi Stream confluence)	15322	Putt (2014)
Lake Rotomahana	166	2813750	6319700	Te Kauae Stream at Ash Pit Rd Ford (Ash Pit Rd #1)	15378	Putt (2014)
Lake Rotomahana	26	2812800	6319000	Putunoa Stream at Farm Track Culvert (Ash Pit Rd #2)	NSN2069	Putt (2014)
Lake Rotomahana	56	2812000	6319000	Rotomahana Stream at Swamp	15399	Putt (2014)
Lake Rerewhakaaitu	16	2814600	6315600	Mangakino Stream base flow		McIntosh (2012)
Lake Rerewhakaaitu	12	2814600	6315600	Mangakino Stream quick flow		McIntosh (2012)
Lake Rerewhakaaitu	10	2816000	6315500	Awaroa Stream quick flow		McIntosh (2012)
Lake Rerewhakaaitu	7	2815750	6318400	Brett Rd quick flow		McIntosh (2012)
Lake Rerewhakaaitu	6	unknown	unknown	Ash Pit Rd 1 quick flow		McIntosh (2012)
Lake Rerewhakaaitu	4	unknown	unknown	Ash Pit Rd 2 quick flow		McIntosh (2012)

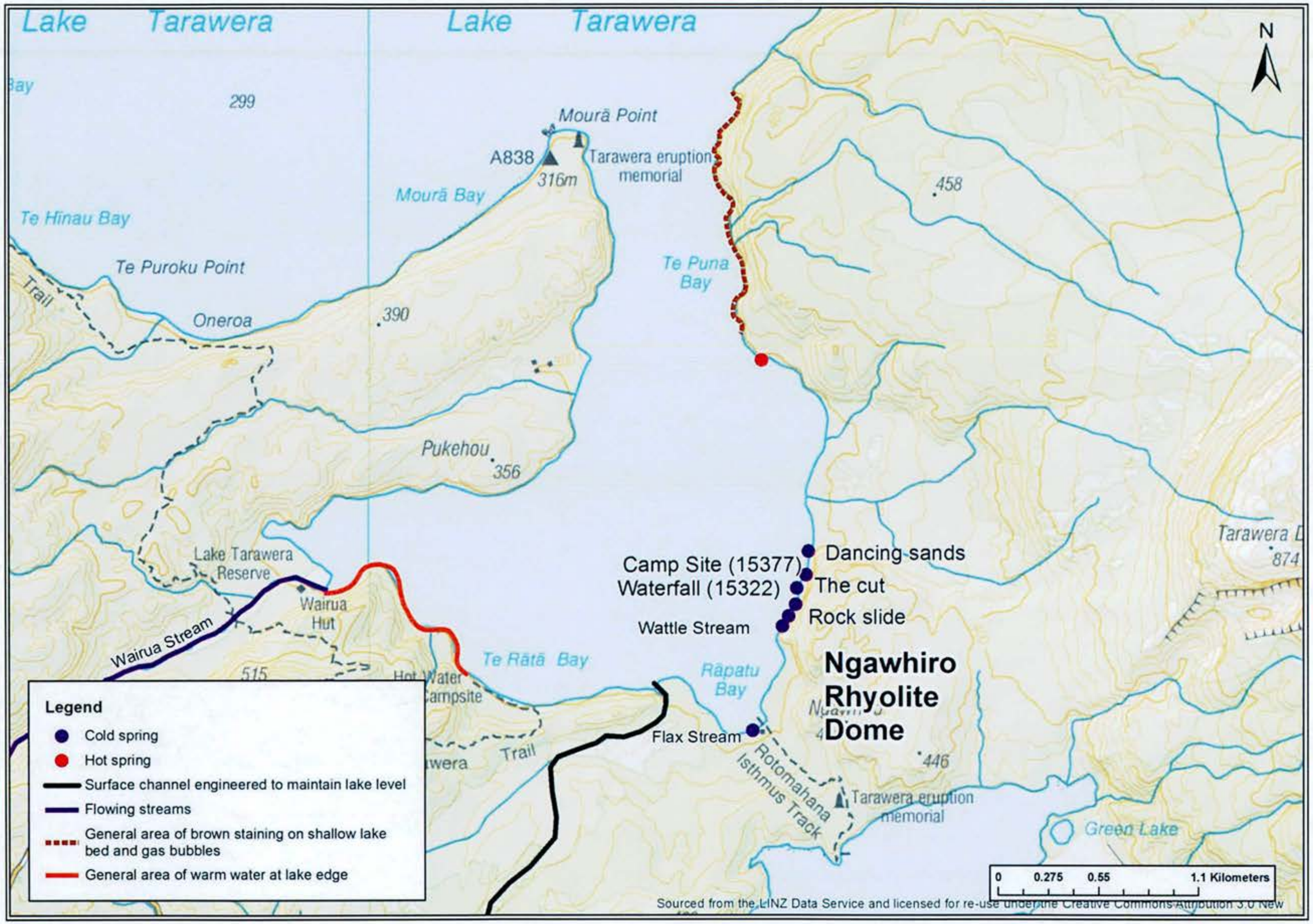

Figure 4.3 Lake Tarawera: surface hydrological features in the southeast area. The thin blue lines on the background map are watercourses (Department of Lands and Survey, 1982 and 1987). These watercourses are generally dry, except as noted by the features described in the legend.

Table 4.2 Surface outflows from lakes in the study area.

Lake	Surface outflow from lake (l/s)	Location x (NZMG)	Location y (NZMG)	BOPRC site	Notes
Lake Tarawera	6738	2816750	6329550	15341	Mean flow 1972 to 2000 (Environment Bay of Plenty, 2001)
Lake Okareka	164	2806627	6330640	NSN1751	Mean flow, Waitangi Stream (u/s of Spencer Rd)
Lake Rotokakahi	311	2803100	6327250	15385	Wairoa Stream
Lake Okaro	30	2807400	6316900	Haumi Stream: approximate average of estimated outflow (2004-2005); Hamilton (2015)	

Figure 4.4 Tarawera Falls (Putt, 2012).

Fractured rhyolite was found at Tarawera outlet in a drill hole (the "deep well", BOPRC bore number 1000134 located between the lake and the Department of Conservation camp ground) at a depth of 80 to 95 m (Figure 4.1). Fractures in a three metre-long core of rhyolite were predominantly horizontal and vertical. The elevation of the top of this rhyolite was approximately 220 m above mean sea level, which is similar to the elevation of the lava flow at the top of the Tarawera Falls. Therefore, the rhyolite may be the same Lower Pokohu lava identified by Nairn (2002) at the Tarawera Falls. This rhyolite has a reasonable permeability; transmissivity, derived from a pump test, was 660 m^2/day.

Synoptic gaugings in the Tarawera River show that the river gains approximately 2 m^3/s of flow between Lake Tarawera outlet and the base of Tarawera Falls (Table 4.3). This flow gain is from groundwater, which is potentially sourced from Lake Tarawera and lava flows from Mt Tarawera and the Haroharo complex north of Lake Tarawera. Pokohu lava was sourced from Wahanga dome on Mt Tarawera (Nairn, 2002). The Lower Pokohu lava occupies the area between the dome and the Tarawera Falls on the true right bank of the Tarawera River. The Tapahoro lava flows are on the true left of the river bank between Tarawera River and Makatiti dome. Both lava flows are generally devoid of surface water.

Groundwater recharge to the estimated area of these lavas above Tarawera Falls totals 0.5 m^3/s (Table 4.4). Therefore, groundwater discharge of approximately 1.5 m^3/s is required from Lake Tarawera to make the observed 2 m^3/s flow gain between Lake Tarawera and the Tarawera Falls. This discharge is similar to the groundwater flow loss from Lake Tarawera estimated by flow budgets (0.9 m^3/s; Table 2.3).

Gaugings indicate gain in flow of Wairoa Stream between Lake Rotokakahi and Lake Tarawera. This gain is an estimated 36 l/s, i.e., the difference between estimated flow in this stream at Lake Rotokakahi (311 l/s) and flow at Lake Tarawera (347 l/s). This gain may be due to groundwater entering the stream on its path between the two lakes.

Table 4.3 Gaugings measured in the Tarawera River and tributaries to assess groundwater inflow above Edwards Road bridge (Figure 4.5).

Site name	Site number	Easting	Northing	Comments	Flow, rounded at 28 June 2012 (m^3/s)
Lake Tarawera Outlet at Footbridge	15304	2816740	6329560	Gauged at footbridge	7.6
Tarawera R. at outlet recorder (NIWA)	15341	2817350	6330350	Gauged at NIWA slack line	8.1
Tarawera R. at Below Tarawera Falls	1015318	2818490	6332140	Gauged as close to base of falls, as possible – 300 m below falls	9.6
Tarawera at Waterfall Road End	NSN2327	2818540	6332410	Gauged 300 m above Waterfall Rd end, or 80 m above left bank tributary (which was ~ 2 l/sec)	9.9
Tarawera R. at Waterfall Road Bridge	1015319	2821200	6333750	Gauged 150 m below bridge (lower end of large pool)	9.7
Mangakotuku Stream at Pukemaire Road Bridge	15376	2820970	6334360	Gauged at bridge	1.2
Kaipara Stream at Fenton Road Bridge	15375	2822330	6334780	Gauged at bridge	1.2
Tarawera R. at Edwards Road	15373	2825950	6333670	Gauged from bridge	14.3

Table 4.4 Rainfall recharge to groundwater in the catchment of Tarawera Falls below Lake Tarawera.

Lava unit	Area (km^2)	P (m^3/s)	AET (m^3/s)	Rainfall recharge (m^3/s)
Pokohu lava	4.2	0.3	0.1	0.2
Tapahoro lava	7.1	0.5	0.2	0.3
Total	11.3	0.8	0.3	0.5

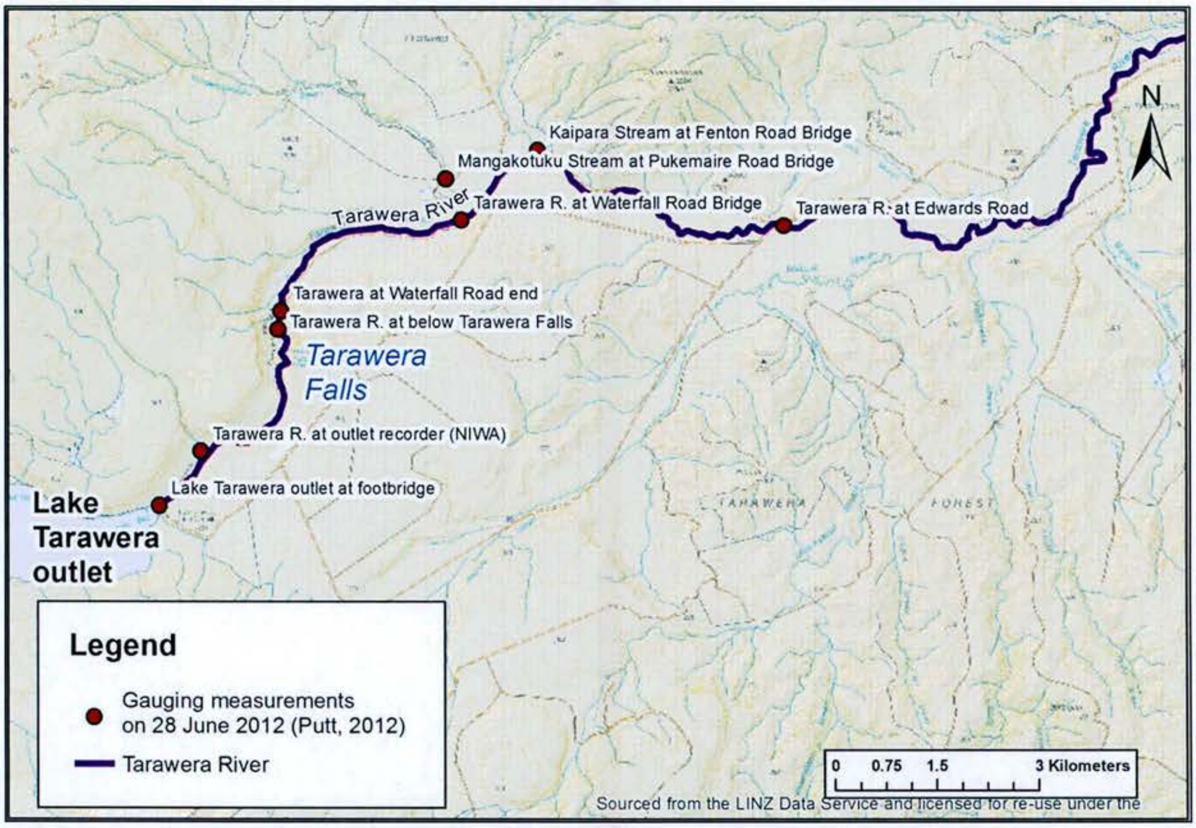

Figure 4.5 Location of synoptic gaugings between Lake Tarawera and Edwards Road (Putt, 2012).

4.1.2 Other lakes and catchments

A lake-edge survey was not undertaken in Lake Okataina. Although flow in stream beds on the western side of the lake is usually present (Scott, 2015), flow rates in these streams have not been measured (Figure 4.6). An area of thermal inflows to Lake Okataina is present in the southeast where near-shore sediments are stained brown (Figure 4.6).

Lake Okareka has no known permanent inflows from streams or springs (Figure 4.7), however some streams may flow during flood events (e.g., Boyes Beach). Permanent surface outflow from the lake occurs through a drain that aims to maintain lake level by discharge of Lake Okareka water to Waitangi Stream which flows to Lake Tarawera. The drain inlet is located approximately 300 m downstream of the lake at the end of an open channel and the outlet is on Waitangi Stream just above Spencer Road. Outflow from Lake Okareka may also occur from a small spring located in Waitangi Stream between the eastern end of the drain and the Spencer Rd culvert. The flow in this was measured at 1 l/s on the 9/6/2015 (Putt, 2015).

No permanent surface inflows or outflows occur to, or from, Lake Tikitapu; however a seep, identified by Scott (2015) may be a permanent flow feature (Figure 4.8). One small spring is located near to the shore of Lake Rotokakahi (Noakes, 2016; Figure 4.8). The permanent outlet of Lake Rotokakahi is Wairoa Stream, which flows into Lake Tarawera (Figure 4.1).

Okaro Stream is the sole surface inflow into Lake Okaro and no springs are mapped around the shore of this lake (Figure 4.9). Outflow from this lake (Haumi Stream) flows to Lake Rotomahana after merging with Waimangu Stream, which drains the Waimangu thermal area (Figure 4.9). In addition, hot springs flow into Haumi Stream above the confluence with Waimangu Stream (Nairn, 2002). Other permanent streams flow into Lake Rotomahana from the south (Putt, 2014). Thermal features, including hot springs, are located on the shores of Lake Rotomahana (Scott, 2015).

Mangakino Stream is the sole permanent inflow to Lake Rerewhakaaitu (Figure 4.10). Flows associated with other Lake Rerewhakaaitu catchment stream beds are noted in Table 4.1, e.g., Awaroa Stream. No springs are observed around Lake Rerewhakaaitu.

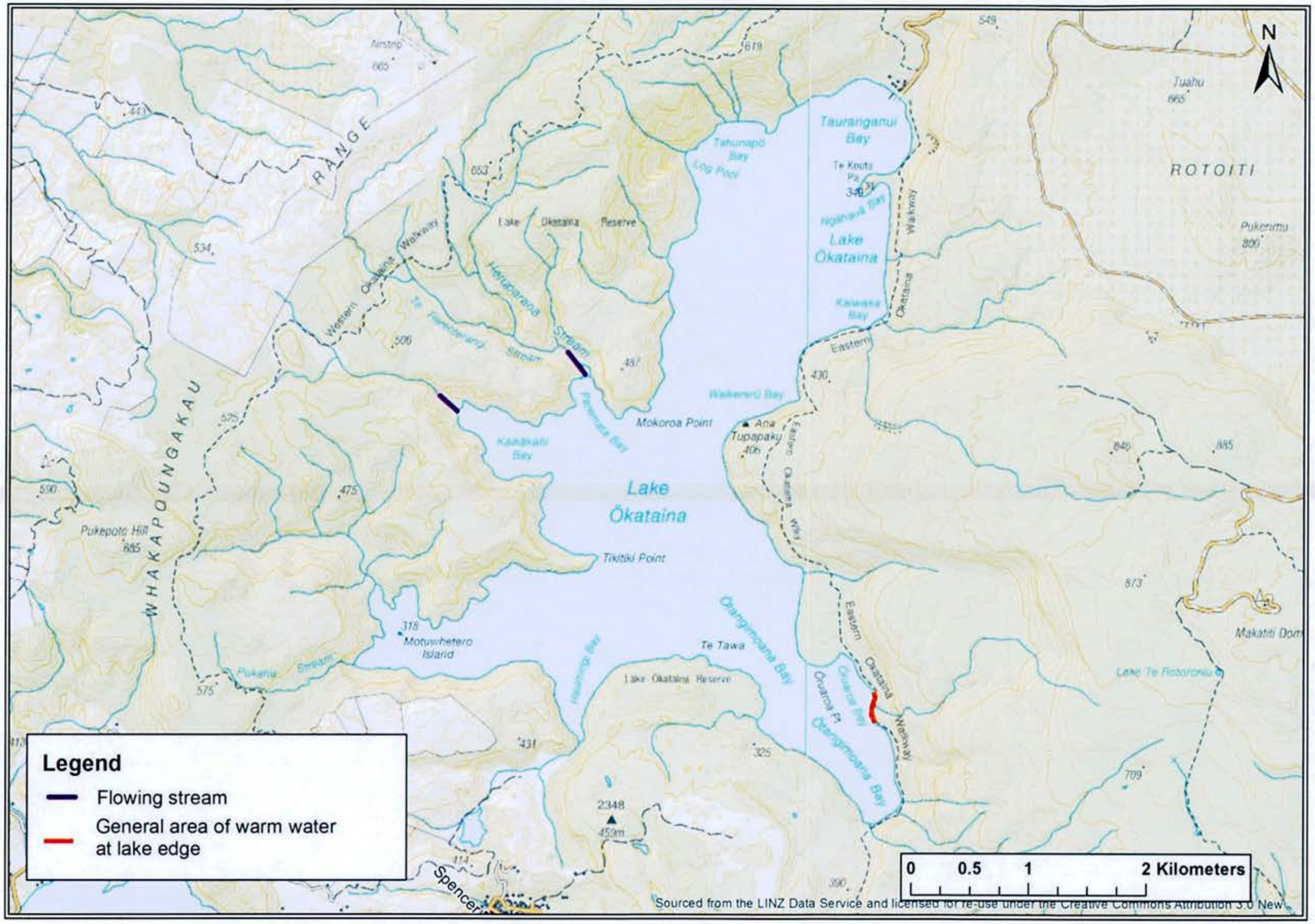

Figure 4.6 Lake Okataina: location of surface hydrological features associated with inflows to, and outflows from, the lake. The thin blue lines on the background map are watercourses (Department of Lands and Survey, 1982 and 1987). These watercourses are generally dry, except as noted by the features described in the legend.

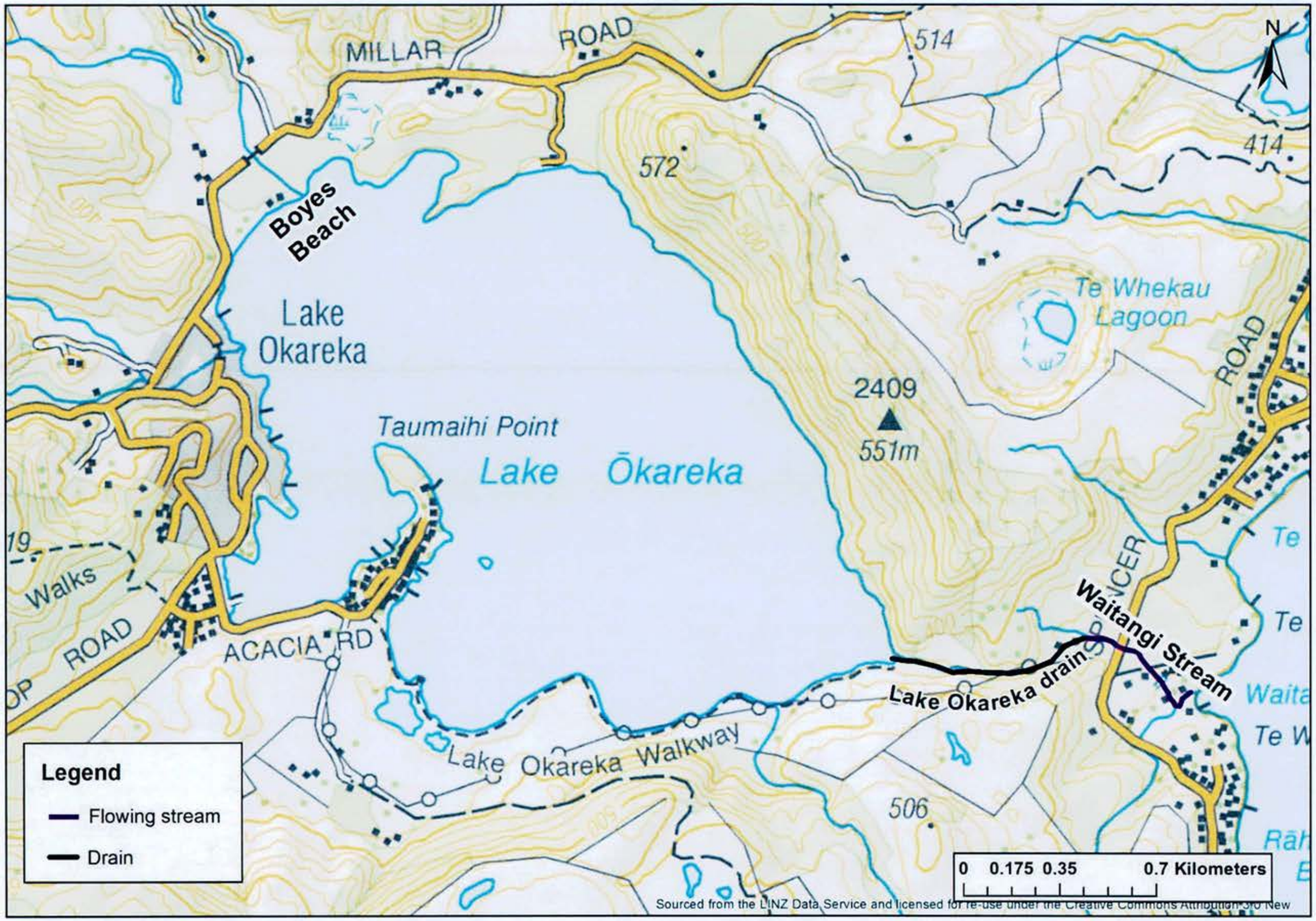

Figure 4.7 Lake Okareka: location of surface hydrological features associated with inflows to, and outflows from, the lake. The thin blue lines on the background map are watercourses (Department of Lands and Survey, 1982). These watercourses are generally dry, except as noted by the features described in the legend.

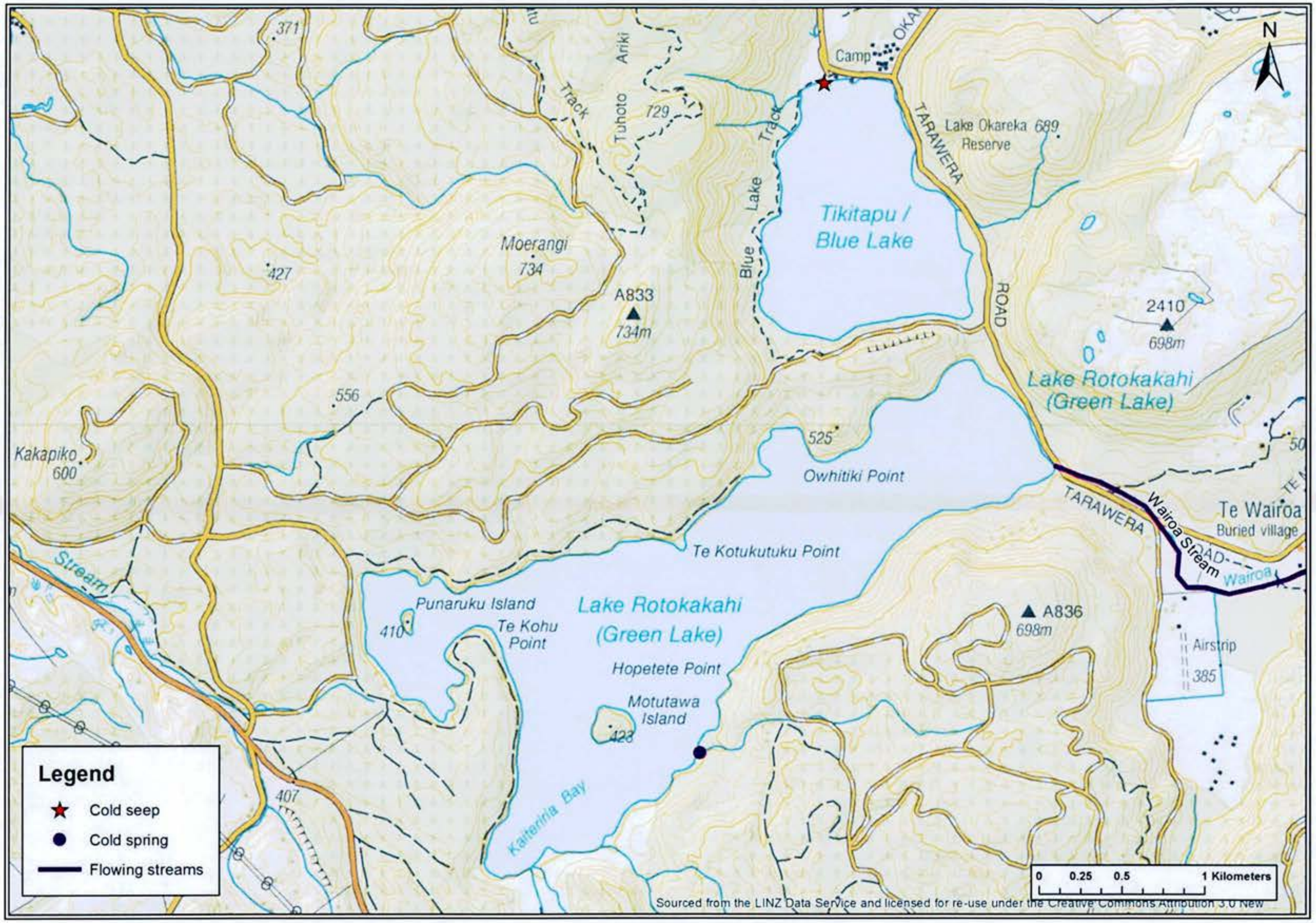

Figure 4.8 Lake Tikitapu and Lake Rotokakahi: location of surface hydrological features associated with inflows to, and outflows from, the lake. The thin blue lines on the background map are watercourses (Department of Lands and Survey, 1982). These watercourses are generally dry, except as noted by the features described in the legend.

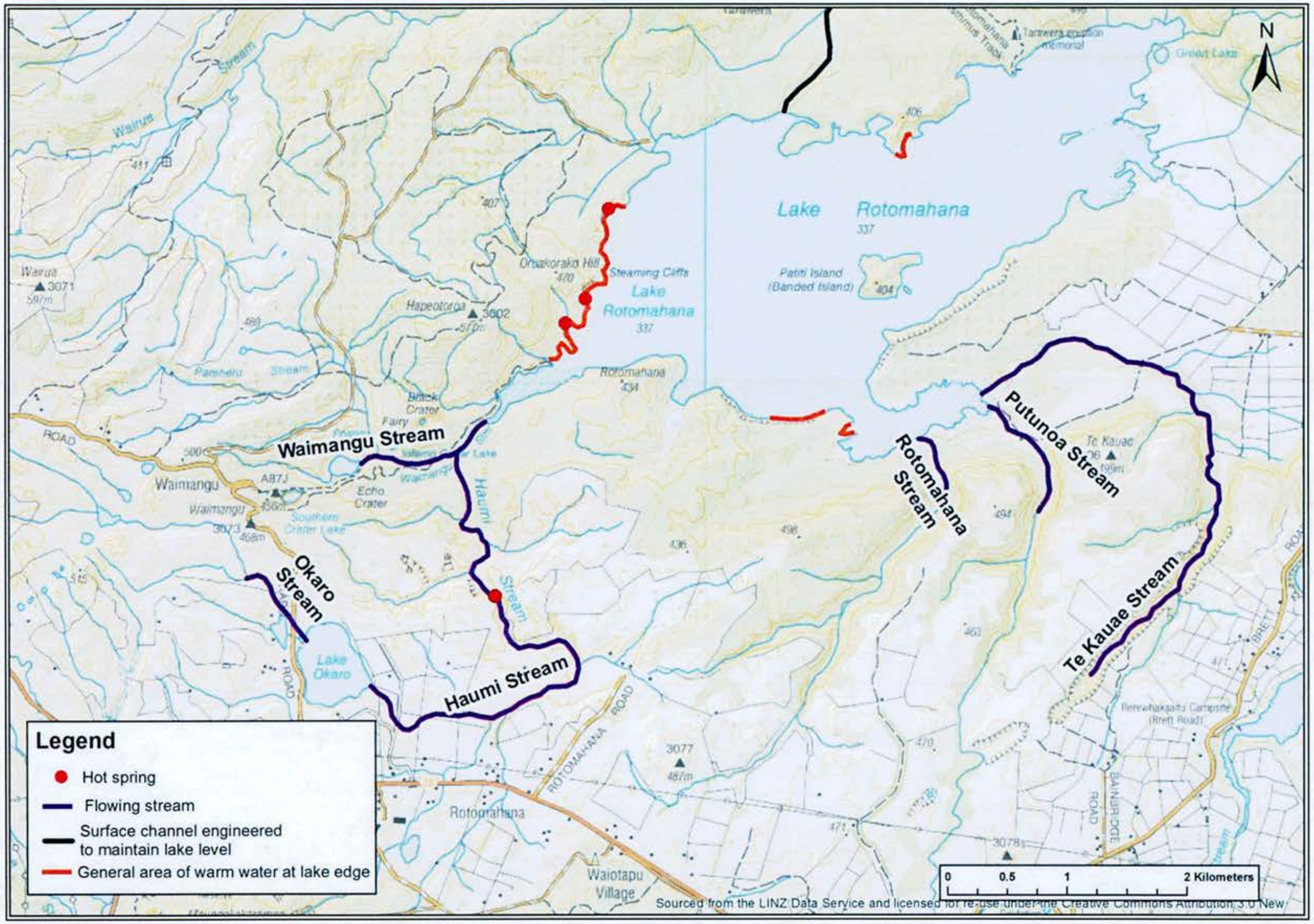

Figure 4.9 Lake Okaro and Lake Rotomahana: location of surface hydrological features associated with inflows to, and outflows from, the lake. The thin blue lines on the background map are watercourses (Department of Lands and Survey, 1982 and 1987). These watercourses are generally dry, except as noted by the features described in the legend.

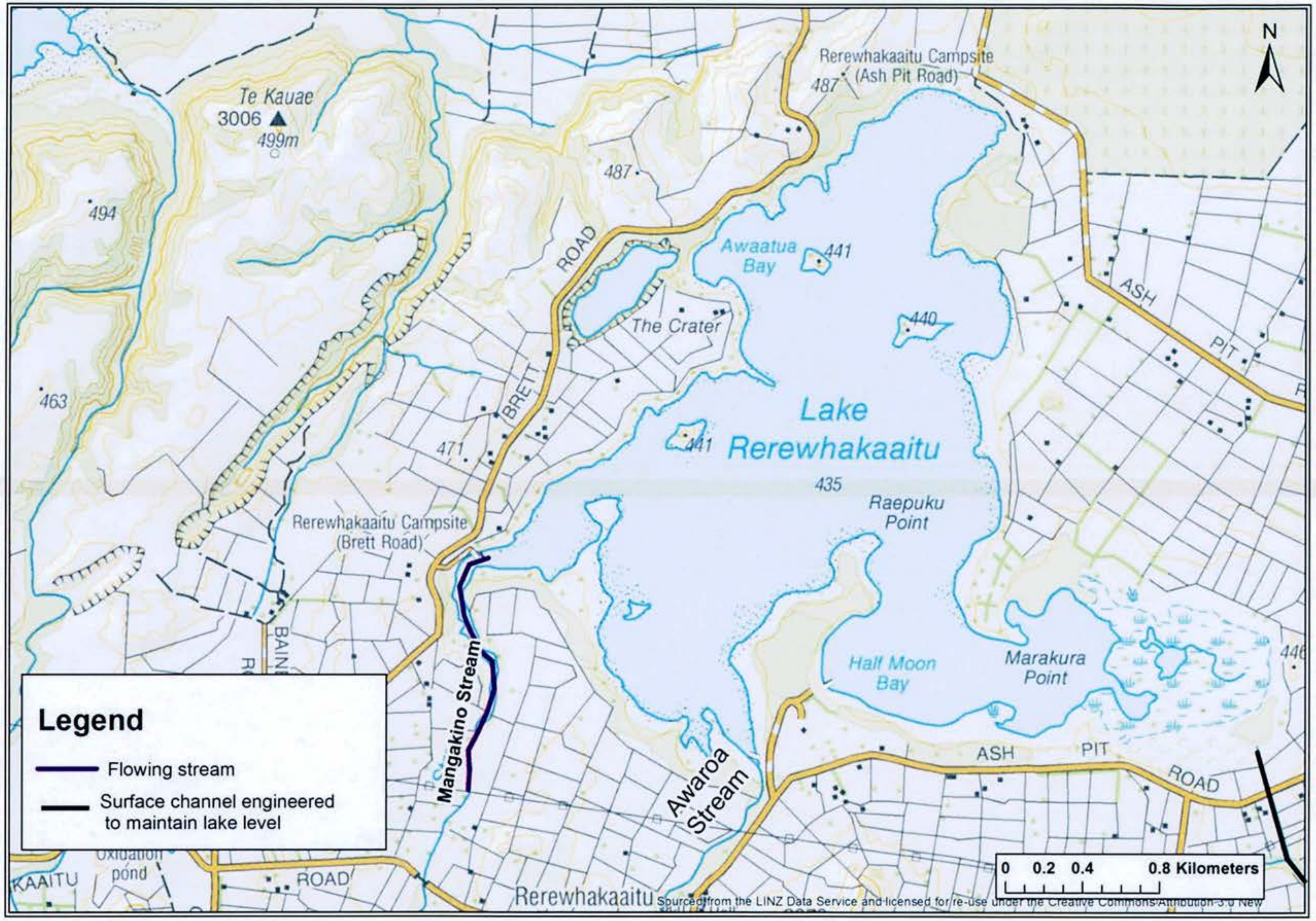

Figure 4.10 Lake Rerewhakaaitu: location of surface hydrological features associated with inflows to, and outflows from, the lake. The thin blue lines on the background map are watercourses (Department of Lands and Survey, 1987). These watercourses are generally dry, except as noted by the features described in the legend.

4.1.3 Water budgets

Water budgets were developed with Equation 8 (Figure 3.2) with a calculation of net groundwater inflow, or outflow, for each lake ($Q^{GW\ LNET}_{OUT}$), Table 4.5. These budgets indicate a net gain of groundwater for three lakes (Lake Tarawera, Lake Okareka and Lake Rotokakahi), Table 4.5. This gain is required to balance total inflows from rainfall and surface water against surface outflows. Water budgets for other lakes typically show a net loss of groundwater, i.e., groundwater outflows are larger than groundwater inflows. Net groundwater outflows are small, i.e., the absolute value of outflow is less than 100 l/s and so is possibly less than the uncertainty in water budget components, for three lakes (i.e., Lake Okareka, Lake Tikitapu and Lake Okaro). Therefore, groundwater inflows to these lakes may equal groundwater outflows, or inflows and outflows may equal zero.

Table 4.5 Water budgets for greater Tarawera lakes based on equation 8 (Figure 3.2). A positive value of $Q^{GW\ LNET}_{OUT}$ indicates that a lake gains flow from groundwater.

Lake	Lake area (km^2)	Inflow (l/s)		Outflow (l/s)		
		P	Q^{SW}_{IN}	Evaporation	Q^{SW}_{OUT}	$Q^{GW\ LNET}_{OUT}$
Lake Tarawera	41	2,458	1,750	-1,008	-6,738	3,538
Lake Okataina	10.7	677	0	-278	0	-399
Lake Okareka	3.3	168	0	-69	-164	65
Lake Tikitapu	1.4	68	0	-28	0	-40
Lake Rotokakahi	4.3	208	0	-85	-311	188
Lake Okaro	0.3	14	90	-6	-30	-68
Lake Rotomahana	8.9	409	326	-168	0	-567
Lake Rerewhakaaitu	5.1	232	55	-95	0	-192
Total	75	4,234	2,221	-1,737	-7,243	2,525

Water budgets of Tarawera zones, developed with Equation 7, including the water budgets of lakes (Table 4.5) with a calculation of net groundwater outflow from each catchment ($Q^{GW\ CNET}_{OUT}$ indicate that most catchments lose groundwater to adjacent zones (Table 4.6). Lake Tarawera is the exception which probably has a net gain of groundwater. The locations of groundwater gains and losses (i.e., by lakes and catchments) is summarised from results of the calibrated groundwater flow model (Section 4.1.3).

Table 4.6 Water budgets for greater Tarawera zones, including lakes based on Equation 7 (Figure 3.1). A positive value of $Q^{GW\ CNET}_{OUT}$ indicates that a catchment gains flow from groundwater.

Zone and lake	Zone and lake area (km^2)	Inflow (l/s)		Outflow (l/s)		
		P	Q^{SW}_{IN}	AET	Q^{SW}_{OUT}	$Q^{GW\ CNET}_{OUT}$
Lake Tarawera	143.8	8,019	475	-3626	-6,738	1,870
Lake Okataina	59.8	3,841	0	-1,542	0	-2,299
Lake Okareka	19.6	970	0	-486	-164	-320
Lake Tikitapu	6.2	302	0	-146	0	-156
Lake Rotokakahi	27.3	1,314	0	-641	-311	-362
Lake Okaro	3.9	183	0	-96	-30	-57
Lake Rotomahana	83.3	3,714	30	-2,044	0	-1,700
Lake Rerewhakaaitu	37	1,658	0	-900	0	-758
Total	380.9	20,001	505	-9,481	-7,243	-3,782

4.2 GROUNDWATER FLOW MODEL: WATER FLOWS

Simulated groundwater levels (or hydraulic heads) from the fine-resolution MODFLOW-NWT model are shown in Figures 4.11 to 4.15. All groundwater flow results shown were selected from the uppermost flowing layer of the 3D grid, which is defined by MODFLOW-NWT as cells that have a hydraulic head above the cell bottom. In previous versions of MODFLOW (including 2005) dry cells did not have head values. The uppermost flowing layer is the top layer where the groundwater is shallow, but may extend down several layers where it is deep.

Directions and relative magnitudes of groundwater flux (also called Darcy flux) are represented in Figures 4.12 and 4.14 as arrows. These were determined from the cell-by-cell flow budget data for flow through the right and front faces of grid cells of the uppermost flowing layer. The horizontal cell face budgets were converted to horizontal Darcy flux components along *x* and *y* directions by dividing by the cell-by-cell vertical areas, as given by the product of cell thickness and grid resolution. Darcy flux magnitudes were determined by the Euclidian length of *x* and *y* components, and flow direction was determined using the arctan2 function on the two horizontal components. Only Darcy flows greater than 0.002 m/day are shown for display purposes.

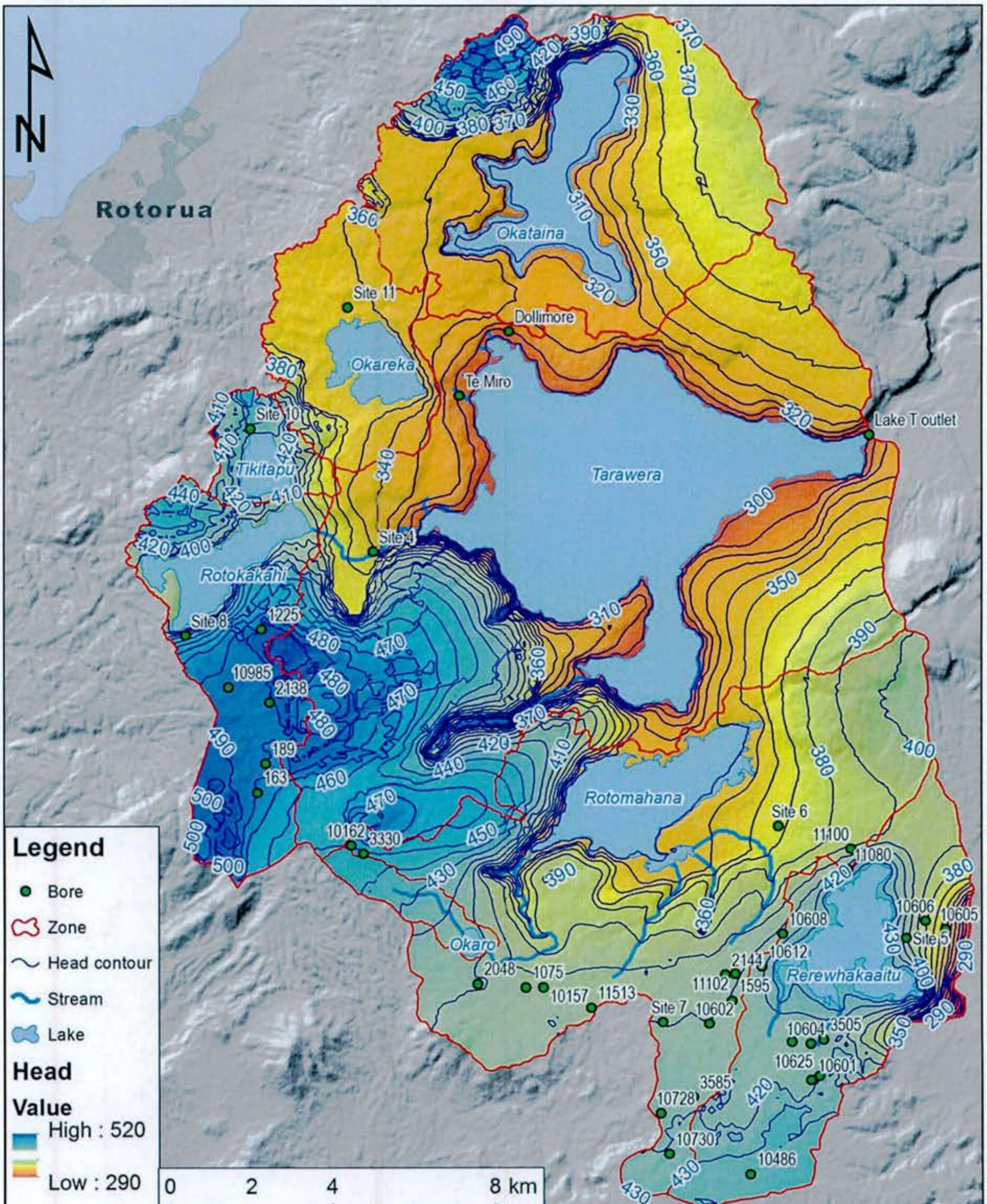

Figure 4.11 Simulated groundwater levels (head) across the greater lake Tarawera catchment. Model groundwater heads in the lake areas represent head in the aquifer below the lake bed.

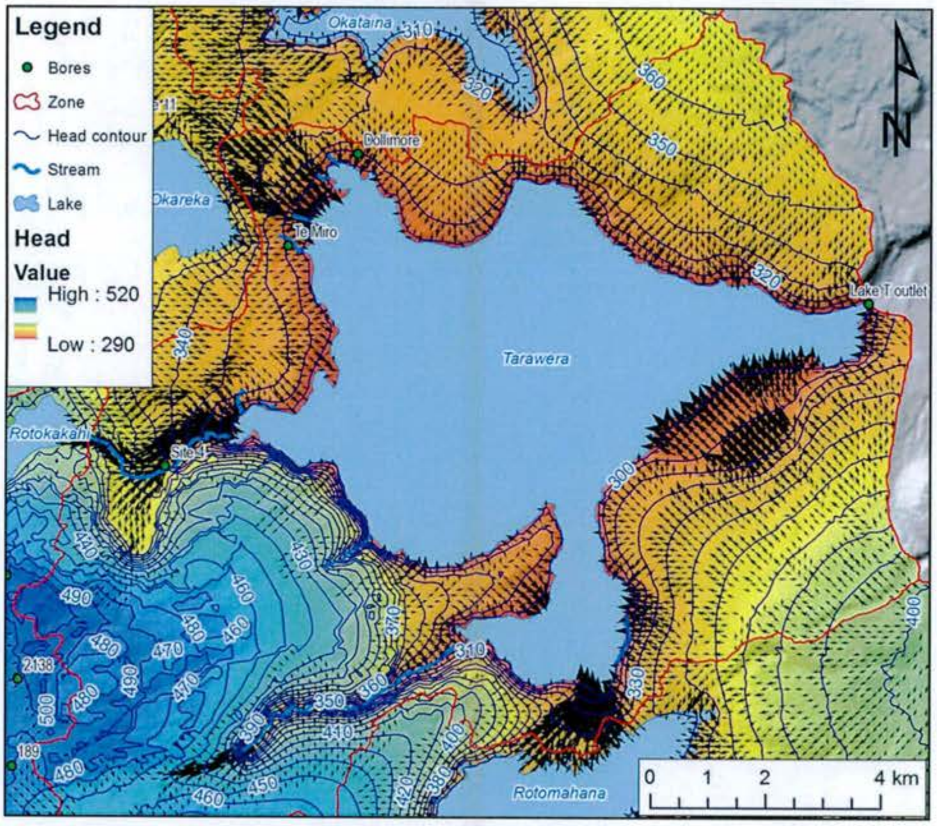

Figure 4.12 Simulated groundwater levels (head) and flow directions in the Lake Tarawera zone. The size of the arrows is proportional to Darcy flow velocity in the approximate range of 0.002 m/day (very small arrows) to 1.2 m/day (large arrows).

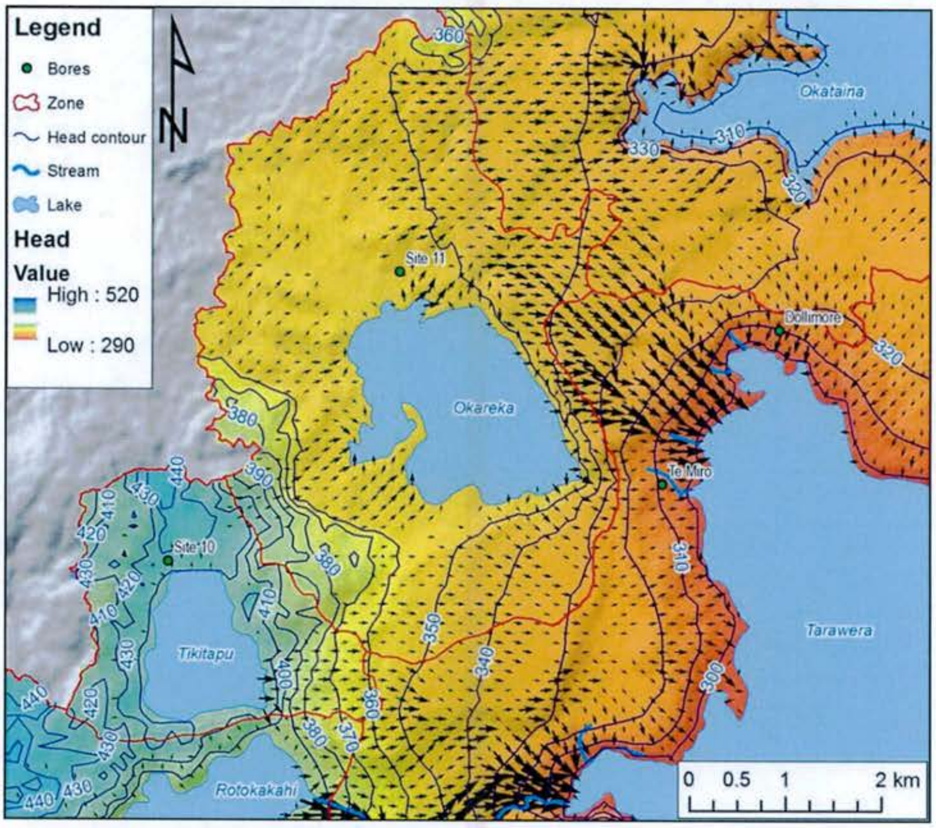

Figure 4.13 Simulated groundwater levels (head) and flow directions in the Lake Tikitapu and Lake Okareka areas. The size of the arrows is proportional to Darcy flow velocity in the approximate range of 0.002 m/day (very small arrows) to 1.2 m/day (large arrows).

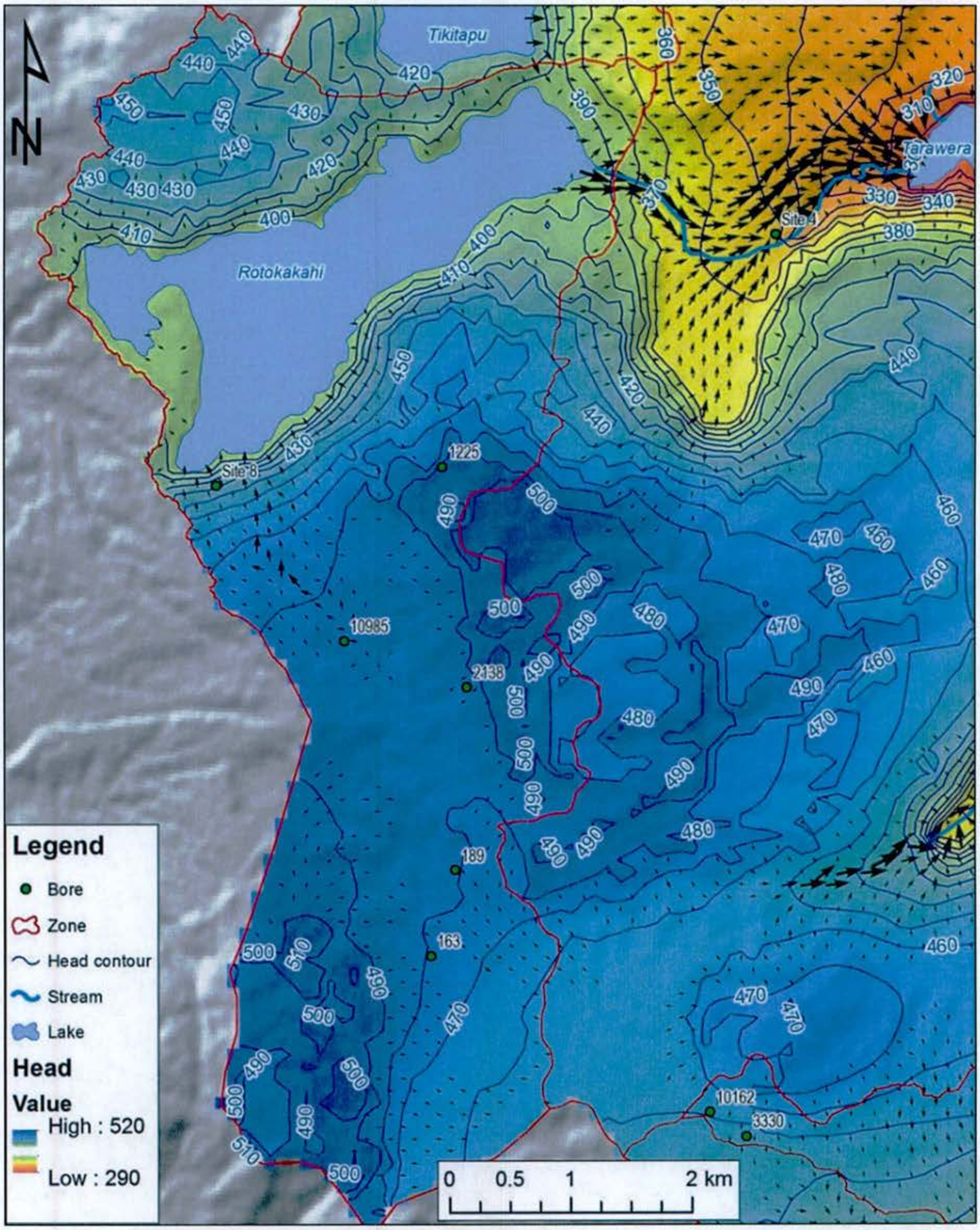

Figure 4.14 Simulated groundwater levels (head) and flow directions in the Lake Rotokakahi zone. The size of the arrows is proportional to Darcy flow velocity in the approximate range of 0.002 m/day (very small arrows) to 1.2 m/day (large arrows).

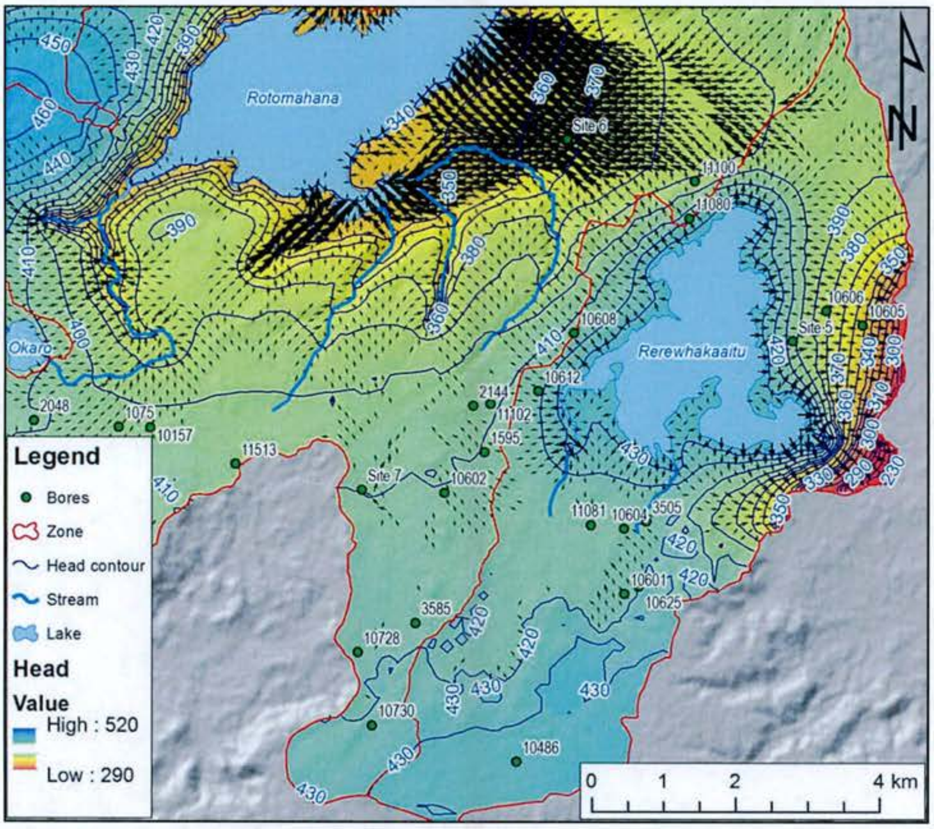

Figure 4.15 Simulated groundwater levels (head) and flow directions in the Lake Rerewhakaaitu area. The size of the arrows is proportional to Darcy flow velocity in the approximate range of 0.002 m/day (very small arrows) to 1.2 m/day (large arrows).

Groundwater levels plotted in Figure 4.11 include the aquifers under the lakes. Generally, calculated groundwater levels under lakes were different from the lake elevation (Table 3.4). This difference indicated the interaction between the groundwater systems and the lakes. For example, lakes are recharged by the groundwater system where calculated groundwater heads were higher than the lake stage, e.g., Lake Okataina (Figure 4.11). Groundwater inflow around lake edges was demonstrated for Lake Tarawera and Lake Rotokakahi (Figures 4.12 and 4.14, respectively). Typically, groundwater flow velocities were largest near lake edges and near streams.

Groundwater flow budgets show flow between each zone, and flow in and out of the groundwater system (Table 4.7). For example, the flow budget calculated groundwater flows of 625 l/s from the Okataina zone to the Tarawera zone and 175 l/s from the Tarawera zone to the Okataina zone. In this example, net flow from the Okataina zone to the Tarawera zone was 450 l/s (i.e., 625-175 l/s). Generally, the zone boundaries were close to a perpendicular to the hydraulic head contours, i.e., zone boundaries were similar to the groundwater catchment boundaries of lakes. However, the zone boundaries do not always match catchment boundaries, e.g., inflows to, and outflows from, the Tarawera zone occur across the boundary with the Okataina zone (Figure 4.12). Note that zones extend for all layers of the model, so exchanges of flows between zones may occur at any depth (up to 1,200 m), and not just the uppermost flowing layer (Figures 4.12 to 4.15).

The water budgets from each BC are listed in Table 4.7. Streams only flow out from the groundwater system, as they were implemented as drain BCs. The model allows groundwater to flow to, or from, the lakes. The outer flux is from the constant-flux well BCs southeast of Lake Rerewhakaaitu. As the groundwater model is steady-state, the total inflow and total outflow for each zone were nearly equal (i.e., differences in these flows are within a fraction of a percentage). A general description of the groundwater flow directions and zone budgets follows; Section 5 includes a discussion of some model calculations and their potential implications on the understanding of catchment hydrology and hydrogeology.

The Tarawera zone receives considerable groundwater inflows from five adjoining zones (i.e., Okataina, Rotomahana, Okareka, Rotokakahi and Tikitapu), Table 4.7. The largest inflow is from the Rotomahana zone (i.e., 1,128 l/s) with relatively large inflows from the Okataina, Okareka and Rotokakahi zones. Groundwater may cross multiple zone boundaries on its path to Lake Tarawera. For example, the route of groundwater from from the area north of Lake Okareka to Lake Tarawera may include three zones (Okareka, Okataina and Tarawera) before it reaches Lake Tarawera (Figure 4.13). Therefore, zone boundaries may not match catchment boundaries in the model area (see Section 5 and Section 6). Groundwater velocity estimates were relatively high in the area between Lake Tarawera and Lake Rotomahana, which was associated with the relatively large groundwater flow between these lakes (Figure 4.12). Groundwater flow direction estimates also indicated groundwater – stream water interactions. For example, groundwater flowed into Wairoa Stream upstream of Lake Tarawera.

The Okataina zone loses groundwater to the Tarawera zone, predominantly. This loss was from land located between the two lakes in the vicinity of Te Horoa dome, as indicated by groundwater flow vectors (Figures 1.1 and 4.12). The model calculated that the Okareka zone receives groundwater from the Tarawera and Tikitapu zones. Inflow from the Tikitapu zone in the vicinity of Okareka Loop Road was indicated by the shape of the groundwater contours (Figure 4.13). Groundwater generally flowed in two directions in the Rotokakahi zone south of Lake Rotokakahi. Flow directions were towards Lake Rotokakahi north of the approximate location of Tumunui (Figures 1.1 and 4.14). However, groundwater flow directions were towards the Tarawera zone south of the approximate location of Tumunui, including Earthquake Flat. Therefore, the groundwater flow from the Rotokakahi zone to the Tarawera zone (i.e., 158 l/s; Table 4.7) probably occurs from the Tumunui and Earthquake Flat areas, i.e., these areas are probably within the catchment of Lake Tarawera.

Groundwater outflow from the Okaro zone to the Rotomahana zone was an estimated 221 l/s (Table 4.7). Inflows to the Rotomahana zone were from the Okaro and Rerewhakaaitu zones. Inflows to the Rerewhakaaitu zone were from the Rotomahana zone (Figure 4.15). This inflow may occur in the vicinity of Brett Road (Figure 1.1) and may indicate that the zone boundary differs from the catchment bondary. Model calculations indicated that Lake Rerewhakaaitu is perched relative to the groundwater system because groundwater elevations in the catchment were lower than the elevation of the lake.

Table 4.7 Zone budgets for the fine grid MODFLOW-NWT simulation. Units are l/s, and '—' is shown for zones that are not connected. For example, the Okataina zone gains groundwater flow from two zones (i.e., Tarawera and Okareka) and loses groundwater flow to same two zones.

Inflow		**Zone name**							
		Tarawera	**Okataina**	**Rotomahana**	**Okareka**	**Rotokakahi**	**Okaro**	**Tikitapu**	**Rerewhakaaitu**
From zone	Tarawera		175	337	190	158	20	15	—
	Okataina	625		—	92	—	—	—	—
	Rotomahana	1,128	—		—	—	109	—	144
	Okareka	752	327	—		—	—	0	—
	Rotokakahi	559	—	—	—		—	193	—
	Okaro	0	—	221	—	—		—	—
	Tikitapu	103	—	—	228	34	—		—
	Rerewhakaaitu	—	—	442	—	—	—	—	
Recharge		4,629	2,231	1,775	478	650	83	148	747
Lakes		0	0	122	176	87	12	31	841
Total inflow		7,797	2,732	2,896	1,164	929	224	388	1,732

Outflow		Zone name							
		Tarawera	Okataina	Rotomahana	Okareka	Rotokakahi	Okaro	Tikitapu	Rerewhakaaitu
To zone	Tarawera		625	1128	752	559	0	103	—
	Okataina	175		—	327	—	—	—	—
	Rotomahana	337	—		—	—	221	—	442
	Okareka	190	92	—		—	—	228	—
	Rotokakahi	158	—	—	—		—	34	—
	Okaro	20	—	109	—	—		—	—
	Tikitapu	15	—	—	0	193	—		—
	Rerewhakaaitu	—	—	144	—	—	—	—	
Streams		359	0	389	0	0	0	0	0
Lakes		6,544	2,015	1,125	84	176	3	23	0
Outer flux		—	—	—	—	—	—	—	1,290
Total outflow		7,797	2,732	2,896	1,164	929	224	388	1,732
IN-OUT		1.30E-03	3.70E-09	1.00E-05	-2.80E-08	-8.10E-08	-1.40E-07	-5.00E-10	9.90E-06
Percent error		1.60E-05	1.30E-07	3.50E-04	-2.40E-06	-8.80E-06	-6.10E-05	-1.30E-07	5.70E-04

4.3 GROUNDWATER FLOW MODEL: NITROGEN FLOWS

Steady-state nitrogen concentrations in groundwater were calculated using the fine-resolution MODFLOW-2005 flow model with MT3DMS for the five land use scenarios (Figure 4.16). These figures demonstrate where nitrogen concentrations increase as land use intensifies. Current land use, i.e., Scenario 3, has a large effect on nitrogen concentrations in groundwater in the west and the south. This includes the areas of Earthquake Flat and parts of the Rotomahana zone and the Rerewhakaaitu zone.

Intensification beyond Scenario 3 is calculated to generally increase nitrogen concentrations in groundwater, and the area of higher nitrogen concentrations, in the west and south. Nitrogen concentrations remain low over large parts of the study area, primarily the areas of native forests.

The area bounded by Lake Rerewhakaaitu has low nitrogen concentrations in all land use scenarios, due to Lake Rerewhakaaitu being perched. Therefore intensification of land use around the lake will result in little additional nitrogen reaching the lake. Streams are the only way that nitrogen can travel to this lake from the catchment, according to the model, and flow in these streams is quite low (Figure 4.10 and Table 4.1). However, the model does not correctly represent part of the Lake Rerewhakaaitu zone north of the lake where groundwater is likely to flow to the lake (Section 5).

Nitrogen concentrations in surface water bodies (i.e., lakes and streams) are not represented in Figure 4.16. Nitrogen concentrations in these bodies could be estimated by a simple dilution equation (i.e., nitrogen inflow to the surface water body divided by water flow). However, denitrification (e.g., in-stream, in-lake and sedimentation; Elliot and Stroud, 2001; Hamilton, 2016) is not considered by the groundwater flow model. Therefore, nitrogen loadings to surface water will be less than the loadings calculated from the MODFLOW model. In addition, the transient response of nitrogen loadings of the lakes to land use change was not assessed by the steady-state model (see Section 2.4, Section 5 and Section 6).

These calculations demonstrate how nitrogen discharge increases from Scenario 1 to Scenario 5 (Table 4.8). For example, groundwater discharge to Lake Tarawera increases from approximately 73 tonnes N/year to 211 tonnes N/year between Scenario 1 and Scenario 5, respectively. Similarly, discharge to Putunoa Stream increases from approximately 0.7 tonnes N/year to 5.5 tonnes N/year between Scenario 1 and Scenario 5, respectively. In contrast, little, or no increase in nitrogen is calculated for Lake Rerewhakaaitu, and the streams around it, because these features are perched relative to the groundwater system (Section 5).

Nitrogen flows are routed in these calculations, i.e., nitrogen discharge from groundwater to lakes includes all relevant sources. Hence, the estimated nitrogen inflow with groundwater to Lake Tarawera is larger than nitrogen loadings on the Lake Tarawera zone, For example, nitrogen loading to the lake with groundwater is approximately 125 tonnes N/yr whereas nitrogen loading to the zone is approximately 68 tonnes N/yr (i.e., Tables 4.8 and 3.9 with land use Scenario 3, respectively). Lake inflows include groundwater and surface water. For example, nitrogen inflows into Lake Tarawera (i.e., including surface and groundwater sources) are summarised in Table 4.9. This table calculates an increase in nitrogen inflows to Lake Tarawera of approximately 138 tonnes N/year to 237 tonnes N/year between Scenario 3 and Scenario 5, respectively.

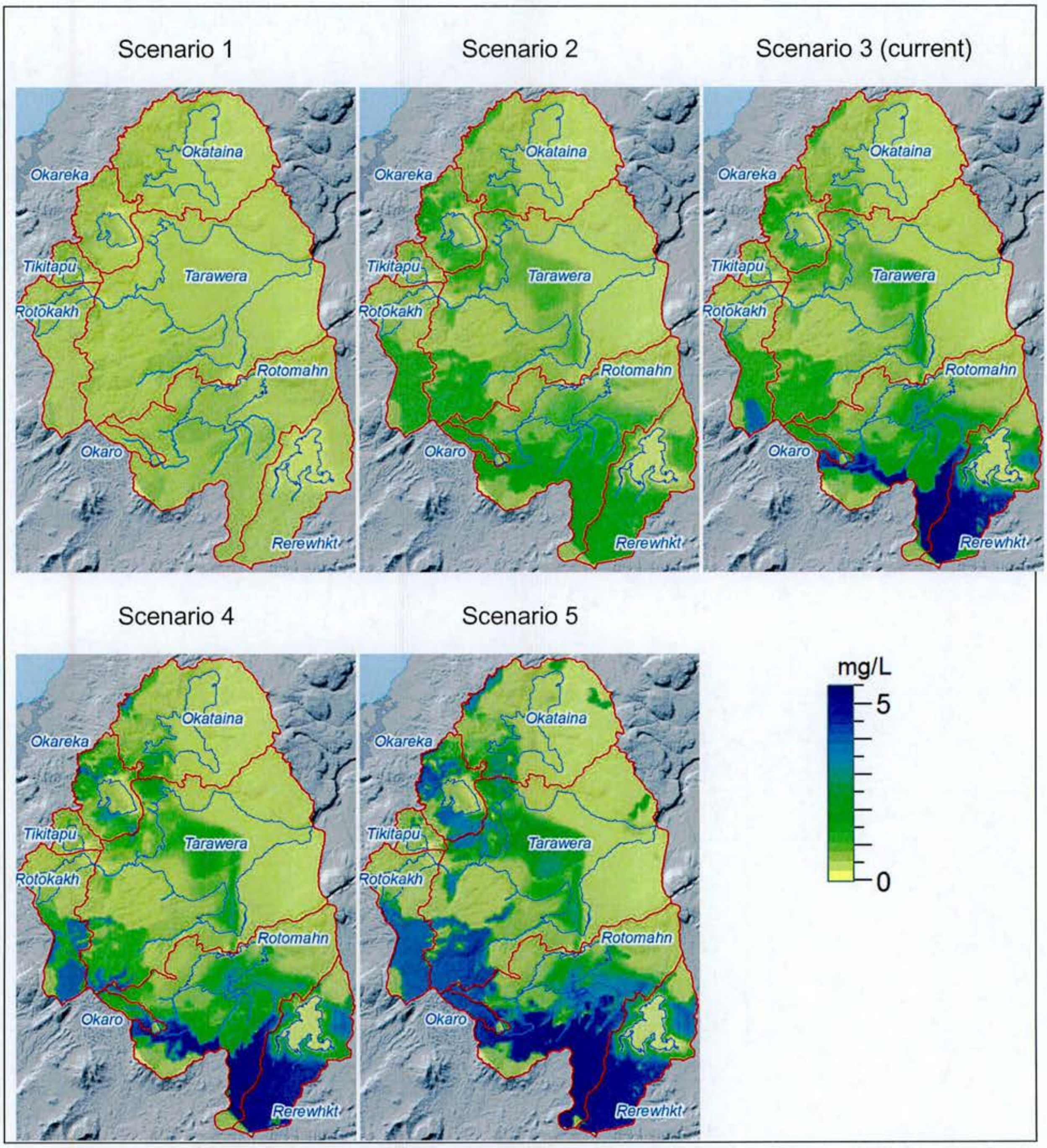

Figure 4.16 Concentrations of nitrogen for five scenarios. The concentrations in the uppermost flowing layer, which includes lake beds, of the groundwater model are shown.

Table 4.8 Steady-state nitrogen loading to surface water bodies from groundwater in the study area.

Surface water body	Nitrogen loading (kg N/year)				
	Land use scenario				
	1	2	3	4	5
Waterfall	34	34	35	35	35
Te Purku	165	165	165	165	173
Wairua	3127	4763	4763	4796	10453
Waitangi	21	42	42	47	116
Awaroa	0	0	0	0	0
Mangakino	0	0	0	0	0
Wairoa	1549	2147	2147	2159	5066
Te Kauae	1253	3180	6059	7057	9339
Waimangu	718	918	918	918	1515
Haumi2	191	208	208	209	258
Haumi1	2936	7557	13646	15706	21444
Te Toroa	0	0	0	0	0
Waitngui	88	143	143	236	349
Putunoa	731	1919	2512	2521	5482
SpencFrd	17	34	34	61	84
Orchard	0	0	0	0	0
TeWhekau	18	36	36	71	96
OkaroSt	14	44	58	94	136
RotomhSt	786	1765	1953	2013	4701
Lake Tarawera	73306	105338	124769	150885	211151
Lake Okataina	22068	25403	25403	29706	38205
Lake Rotomahana	17379	31225	48834	57746	76520
Lake Okareka	1264	1979	1979	2816	4124
Lake Rotokakahi	2639	3090	3090	3091	4445
Lake Okaro	72	185	393	478	525
Lake Tikitapu	351	372	372	372	435
Lake Rerewhakaaitu	8	9	13	46	13

Table 4.9 Steady-state nitrogen loading to Lake Tarawera from the greater Lake Tarawera catchment, including groundwater and surface water sources but excluding the lake surface.

Lake Tarawera feature name	Nitrogen loading (kg N/year)				
	Land use scenario				
	1	2	3	4	5
Waterfall	34	34	35	35	35
Te Purku	165	165	165	165	173
Wairua	3127	4763	4763	4796	10453
Waitangi	21	42	42	47	116
Wairoa	1549	2147	2147	2159	5066
Te Kauae	1253	3180	6059	7057	9339
Te Toroa	0	0	0	0	0
Waitngui	88	143	143	236	349
SpencFrd	17	34	34	61	84
Orchard	0	0	0	0	0
TeWhekau	18	36	36	71	96
Groundwater	73306	105338	124769	150885	211151
Sum	79578	115883	138193	165510	236864

5.0 DISCUSSION

Interaction between surface water and groundwater is demonstrated by characterisation and modelling of the hydrogeological system in the greater Tarawera lakes catchments (Section 4). Groundwater flows into lakes, and it seems that water from some lakes discharges into groundwater. Groundwater flow between lake catchments is also identified in Section 4. However, these deductions are subject to uncertainty. These uncertainties in the characterisation and modelling of the physical hydrogeological system can translate to uncertainties in the transport of nitrogen to the lakes. Therefore, the focus of this discussion is uncertainties in the following:

- catchment boundaries;
- groundwater interaction and lakes;
- groundwater flow between catchments; and
- land use and nitrogen loading.

This discussion centres on each catchment and the interpretation of surface water and groundwater flows and nitrogen transport (Section 4). In addition, the discussion comments on geothermal features (i.e., features mapped in the Section 4.1 figures) and their possible interaction with the hydrogeological system.

5.1 LAKE TARAWERA AND CATCHMENT

Catchment boundaries of Lake Tarawera may differ from the zone boundaries in the areas of Te Whekau crater, Te Horoa dome and Highlands Road (Figure 1.1 and Section 4.2). Therefore, identification of the catchment boundary in these areas is recommended (Section 6). Importantly, revision of the catchment boundary in these areas could result in zero modelled flow from the Tarawera catchment to the catchments of other lakes (i.e., lakes in the zones that receive flow from the Tarawera zone, Table 4.7).

Groundwater inflow to the Lake Tarawera zone from the Lake Rotomahana zone and the Lake Okataina zone has been proposed in the past. Quantification of these inflows requires the calculation of water budgets in adjacent catchments and lakes, which was completed in this report with the MODFLOW model. In this report, calculated inflows of 1128 l/s and 625 l/s from Lake Rotomahana and Lake Okataina zones were determined, respectively (Table 4.7). The inflow from Lake Rotomahana occurs across the isthmus between Lake Tarawera and Lake Rotomahana, including springs that flow from the Ngawhiro Rhyolite Dome (Figures 4.3 and 4.12). This result indicates that more groundwater flows from the Lake Rotomahana zone than is measured at the Ngawhiro Rhyolite Dome springs (i.e., 238 l/s measured at Camp Site and Waterfall springs, Table 4.1). The locations of springs in Kotukutuku Bay are generally associated with relatively high groundwater velocities estimated by the model (Figures 4.2 and 4.12). However, the occurrence of relatively large groundwater velocities is not a good predictor of the location of springs. For example, groundwater velocities are relatively high along large areas of the Lake Tarawera shoreline but are not associated with the locations of springs and spring-fed streams (i.e., compare Figure 4.1 with Figure 4.12).

The inflow from the Lake Okataina zone appears to occur through the area around the Dollimore bore and Humphrey's Bay (Figures 4.1 and 4.12). The groundwater velocity vectors do not provide strong evidence that groundwater is flowing from Lake Okataina to Lake Tarawera (Figure 4.12). This is because the vectors indicate that groundwater flow follows topographic gradients between these two lakes.

Groundwater inflow to Lake Tarawera occurs around the lake shore, and groundwater flow to streams is relatively uncommon (Figure 4.12). For example, groundwater flow is an estimated 6,544 l/s to the lake and an estimated 359 l/s to streams (Table 4.7). This means that: 1) nitrogen associated with land use will mostly discharge directly into the lake with groundwater; and 2) denitrification in spring- and seep- fed streams, (e.g., as described by Elliot and Stroud, 2001) is unlikely to operate on a large portion of lake inflows. Therefore, most nitrogen that discharges from the soil profile will travel to the lake with the groundwater system based on a reasonable assumption that the groundwater aquifer is not reducing.

The Lake Tarawera zone receives groundwater inflow from all surrounding zones, as demonstrated by water budgets, the groundwater flow model and nitrogen loadings. Therefore, management of land use in surrounding zones is relevant to water quality in Lake Tarawera. Most nitrogen that flows with groundwater to Lake Tarawera is sourced from the west and south (Figure 4.16). Nitrogen concentrations in the west of Lake Tarawera appear largest in the area around Highlands Road, Tumunui and Earthquake Flat. Therefore, this area is an important source area for the nitrogen discharging to the lake. However, the zone boundaries have some of the Highlands Road area in the Lake Tarawera catchment, when it could be in the Lake Rotokakahi catchment; calculation of groundwater catchment boundaries should clarify this uncertainty (Section 6). In addition, more work is required to prove that Tumunui and Earthquake Flat are in the groundwater catchment of Lake Tarawera (Section 2.2, Section 5.5 and Section 6). The model also calculates that Lake Rotomahana is an important source of nitrogen. However, as noted above the model does not consider denitrification in Lake Rotomahana. Therefore, nitrogen loadings from the Lake Rotomahana catchment will be less than calculated by the model.

Intensification of land use will result in increasing nitrogen discharge to Lake Tarawera (i.e., compare land use Scenarios 4 and 5 with current land use; Figure 4.16). Most of any increase will come from the land in the west and a lesser amount from the south (i.e., the Lake Rotomahana catchment). Additional work is recommended to improve understanding of groundwater catchment boundaries and aquifer properties in the western area (Section 6).

Geothermal features in the Lake Tarawera catchment are associated with two hydrothermal areas. In the north, brown staining on the shores of Humphrey's Bay seems associated with a similar feature on the southern shore of the lake (Figures 4.1 and 4.6). In addition, higher than normal lake floor temperatures occur near Humphrey's Bay (Nairn, 2002). Geothermal features in the south-eastern area include hot springs, warm water at the lake's edge, brown staining at the lakes edge (Figure 4.3) and elevated temperatures on the lake floor (Nairn, 2002). These features indicate that hot water, presumably from a relatively deep source, is mixed with relatively shallow, cold water. Firstly, the location of these two areas is influenced by the cold hydrological system, i.e., geothermal features located at, or near, the lake edge are associated with areas of cold groundwater discharge to the lake. Secondly, the temperature and chemistry of hot water indicates mixing of hot water with cold water (Nairn, 2002).

5.2 LAKE OKATAINA AND CATCHMENT

Topographic and groundwater table gradients are relatively high in the Lake Okataina catchment and groundwater catchment boundaries mostly coincide with topographic boundaries of the zone. Groundwater flow vectors calculated by the MODLFOW model indicate that the groundwater flow from Lake Okataina to Lake Tarawera is mostly "topographic". i.e., flow is associated with topography and the location of the boundary between Okataina and Tarawera zones. However, groundwater may flow from Lake Okataina to Lake Tarawera (i.e., a groundwater outflow of 399 l/s; Table 4.5). This possibly appears to be discounted by groundwater contours between the two lakes that are higher than lake level. Therefore, the water budget components estimated in Table 4.5 could be reconsidered (Section 6).

Forest dominates the Lake Okataina catchment (Figures 3.10 and 3.13). Therefore, the current nitrogen loading to the lake is relatively low, presumably reflected in the comparatively good water quality in the lake (Tables 2.1, 2.2 and 4.8). However, the land use intensification scenarios result in groundwater nitrogen concentrations increasing in the west (Figures 3.13 and 4.16). The Lake Okataina catchment boundary to the west is quite well defined as topography in the area is relatively steep. Therefore, it seems very likely that intensification of land use in this area will result in increased nitrogen discharge to the lake. Denitrification of this groundwater is likely to be minor. In-stream denitrification may not be significant as the two streams in the area probably have short reaches (Figure 4.6).

A small area of warm water was mapped on the shoreline of Lake Okataina (Figure 4.6). This area was associated with a similar feature in Humphrey's Bay, Lake Tarawera (Figure 4.1) by Nairn (2002); see above.

5.3 LAKE OKAREKA AND CATCHMENT

The Lake Okareka zone boundary generally follows topographic boundaries. However, groundwater may flow into Lake Okareka through the area of Okareka Loop Road (Figures 1.1 and 4.11, Section 5.4). This flow, which is an estimated 228 l/s (Table 4.7), may enter the lake directly as no permanent streams are observed near the lake (Figure 4.7). Groundwater inflows from other zones (i.e., Tarawera, Okataina) are also calculated in Table 4.7; however these inflows are probably due to zone boundaries that are not coincident with catchment boundaries (see above).

Potentially, groundwater flows from the Lake Okareka zone to the Lake Tarawera zone at an estimated 562 l/s (i.e., 752 l/s – 190 l/s) which is the net groundwater flow between the two zones. Most of the difference between these two loadings is probably due to flow through the Te Whekau crater area and the Okareka Rhyolite complex (Figures 1.1, 4.2 and 4.13). Most nitrogen that is produced in the catchment appears to discharge outside the catchment. For example, nitrogen loading on the Okareka zone is approximately 13 tonnes N/year (Table 3.9) yet nitrogen loading to the lake with groundwater is approximately 2 tonnes N/year (Table 4.8) with land use Scenario 3.

5.4 LAKE TIKITAPU AND CATCHMENT

The boundary of the Lake Tikitapu catchment is generally that of the Tikitapu zone, except for the area around Okareka Loop Road where the model calculates that groundwater flows to the Okareka zone (Figure 4.11 and Table 4.7), Section 5.3. This calculation is counter to observations of ground topography which show a catchment divide across Okareka Loop Road near Lake Tikitapu. Therefore, further investigations of groundwater level in this area are recommended (Section 6).

In addition, the flow model calculates that groundwater flows at a low rate from the Tikitapu zone to other zones (i.e., Tarawera and Rotokakahi, Table 4.7); probably because of minor differences between the location of the zone boundaries and catchment boundaries (Section 6). No known streams are located in the catchment; therefore all groundwater recharge in the catchment travels to the Lake Tikitapu or to the Okareka zone. Most nitrogen that is produced in the catchment appears to discharge outside the catchment. For example, nitrogen loading on the Tikitapu zone is approximately 3 tonnes N/year (Table 3.9) yet nitrogen loading to Lake Tikitapu with groundwater is approximately 0.4 tonnes N/year (Table 4.8).

Little change in nitrogen loading occurs in the Tikitapu zone with the intensification scenarios because these scenarios anticipate little land use change in this catchment (i.e., Figures 3.9 to 3.12).

5.5 LAKE ROTOKAKAHI AND CATCHMENT

The catchment boundary of Lake Rotokakahi is generally that of the Rotokakahi zone. In addition, the model calculates that groundwater outflow from this zone travels to the Tarawera zone through the area of the Wairoa Stream and north of the stream (Table 4.7 and Figure 4.14). The model also calculates that groundwater flows from the Rotokakahi zone to the Tikitapu zone (Table 4.7). For example, groundwater contours in the area located northwest of Lake Rotokakahi identify that groundwater flow crosses the boundary between the Lake Rotokakahi zone and the Lake Tikitapu zone (Figure 4.14).

The boundary of the Lake Rotokakahi catchment to the south, estimated with the model, is in the area of Highlands Road (i.e., across the area between the 480 m contour and the 490 m contour; Figures 4.14 and 1.1). However, horizontal groundwater gradients are not large in this area so uncertainty is associated with the boundary. Should the boundary be on Highlands Road, then the area of Tumunui, and most of Earthquake Flat, is in the Lake Tarawera catchment and part of the Earthquake Flat area is in the Lake Okaro catchment (see Section 5.1 and Section 6).

The current land use scenarios show land use intensification on the southern catchment of Lake Rotokakahi (i.e., Figures 3.8 to 3.12). Therefore, the model calculates that nitrogen loading to the lake will increase in this area should the boundary of the Lake Rotokakahi catchment be located at Highlands Road. To the north, no change in nitrogen loading to Lake Rotokakahi will occur because these scenarios anticipate no land use change in this part of the catchment. Like the Okareka and Tikitapu zones, most nitrogen that is produced in the Rotokakahi zone appears to discharge outside the zone (i.e., compare Table 3.9 with Table 4.8).

5.6 LAKE OKARO AND CATCHMENT

For the most part, the Lake Okaro catchment boundary is similar to the zone boundary. However, the model indicates that the Okaro zone takes groundwater from the Lake Tarawera zone and, therefore, from the Lake Rotokakahi in the Earthquake Flat area, and the Rotomahana zone (Table 4.7 and Figure 4.14). Therefore, the boundaries of four catchments (i.e., Okaro, Tarawera, Rotokakahi and Rotomahana) should be assessed in this headwaters area (Section 6). The model calculates that groundwater flows from the Okaro zone to the Rotomahana zone (Table 4.7). Presumably this flow is through the area east of Lake Okaro (Figure 4.11).

Little flow between groundwater and Lake Okaro is calculated by the model (Table 4.7). This could mean that little interaction occurs between the lake and the surrounding groundwater system which was not an expected result given the topographical setting of the lake. Further work is recommended with regard to the lake and characterisation of the groundwater system (Section 6).

Nitrogen loadings indicate land use intensification in the catchment (i.e., compare Scenario 3 with Scenario 1, Figure 3.13). Nitrogen concentrations in groundwater will generally increase from current levels with greater intensification, i.e., land use scenarios 4 and 5 (Figure 4.16). In addition, land use in the vicinity of Earthquake Flat may impact on groundwater quality in the Lake Okaro catchment. Like other zones, most nitrogen that is produced in the Okaro zone appears to discharge outside the zone (i.e., compare Table 3.9 with Table 4.8).

5.7 LAKE ROTOMAHANA AND CATCHMENT

The Rotomahana zone receives groundwater from three adjacent zones (Tarawera, Okaro and Rerewhakaaitu), Table 4.7. In addition, groundwater flows out of the Rotomahana zone to these same zones. The outflow to the Tarawera zone occurs through the isthmus between the two lakes (Figure 4.11 and Section 5.1). However, outflows to the Okaro zone and the Rerewhakaaitu zone are likely to be artefacts of zone boundary locations and, therefore, revisions to these boundaries are recommended (Section 5.6 and Section 6).

Relatively large groundwater outflows to Lake Rotomahana are calculated by the model (i.e., 1,125 l/s, Table 4.7) and the groundwater model heads indicate the lake receives groundwater (Figure 4.11). This outflow is relatively large because the streams flowing into Lake Rotomahana represent a relatively small portion of groundwater inflows (i.e., rainfall recharge and inflows from other catchments).

Nitrogen loadings indicate land use intensification in the catchment (i.e., compare Scenario 3 with Scenario 1, Figure 3.13). Nitrogen loadings to groundwater will generally increase from current levels with greater land use intensification (Figure 4.16). Nitrogen discharge to Lake Rotomahana is less than nitrogen loading in the Rotomahana zone. For example, nitrogen loading to Lake Rotomahana is approximately 49 tonnes N/year with current land use (Table 4.8) whereas loading in the zone is approximately 79 tonnes N/year (Tables 4.8 and 3.9, respectively). In addition, the Rotomahana zone receives nitrogen with groundwater flow from the Okaro and Rerewhakaaitu zones (Figure 4.15).

The location of hot springs in Haumi Stream is probably related to the emergence of groundwater flow from the west in the stream (Figures 4.9 and 4.11). At this location, the land surface is in the range of 380 m to 400 m a.s.l (above sea level) and groundwater head calculated by the model is approximately 380 m a.s.l (Figure 4.15).

5.8 LAKE REREWHAKAAITU AND CATCHMENT

The groundwater model calculates that groundwater flows to, and from, the Lake Rotomahana zone (Table 4.7). Therefore, revisions of the zone boundaries are probably required in the Brett Road area (Figure 1.1). Groundwater flows out from the Rerewhakaaitu zone to the Rangitaiki River catchment – this includes outflows that were set by the model BCs (Figure 3.6). Groundwater outflow to the Rotomahana zone (442 l/s) is a significant component of the total inflows to that zone (2,896 l/s), Table 4.7. Surface water in the Lake Rotomahana catchment probably receives some of this outflow. For example, this outflow probably provides some of the water flowing in Te Kauae Stream (i.e., 166 l/s; Figure 4.9 and Table 4.1).

The model calculates that Lake Rerewhakaaitu is perched. This is because the lake elevation (i.e., approximately 435 m; Table 3.4) is generally above the calculated groundwater head around the lake (i.e., the maximum head around the lake is approximately 430 m; Figure 4.11). Therefore, the inflow to groundwater from the lake is a calculated 841 l/s but the outflow from the groundwater system to the lake is 0 l/s (Table 4.7). This calculation is consistent with the lake water budget (Table 4.5, but note that the water budget calculates less inflow than the model). However, measurements of groundwater level identified that the north-eastern side of the lake was not perched (White *et al.*, 2003).

Nitrogen discharge with groundwater to Lake Rerewhakaaitu is a very small proportion of the nitrogen generated in the Rerewhakaaitu zone, which is consistent with a perched lake. For example, nitrogen loading to the lake is approximately 0.01 tonnes N/year with current land use (Table 4.8) but nitrogen loading in the zone is approximately 75 tonnes N/year (Table 3.9).

Land use scenarios indicate significant land use intensification in the Lake Rerewhakaaitu zone (i.e., compare Scenario 1 and Scenario 3, Figure 3.13). Two streams south of the lake provide the only route for nitrogen to enter Lake Rerewhakaaitu in the model because the lake is perched. These are the Mangakino Stream (permanently flowing) and Awaroa Stream, which is probably ephemeral (Figure 4.10 and Table 4.1). Therefore, calculation of nitrogen inflows to the lake could be further assessed by characterisation of the catchments of these streams (Section 6). The "vale" of low nitrogen concentrations around the lake is due to the discharge of lake water to the groundwater system (Figure 4.16). Nitrogen generated in the Rerewhakaaitu zone travels with groundwater either to the east or to the Rotomahana zone. A significant component of the nitrogen inflow to the Rotomahana zone is sourced from the Rerewhakaaitu zone.

An increase in nitrogen concentrations in groundwater is calculated with greater land use intensification in the Rerewhakaaitu zone (Figure 4.16). However, the increase is relatively small because current land use is relatively intense as most pasture in the zone is high-producing grassland, i.e., dairy, (Section 3.3.1 and Figure 3.13).

6.0 RECOMMENDATIONS

The following recommendations are made to build on the work in this report to improve the characterisation of the groundwater system in the greater Lake Tarawera area:

1. Groundwater catchment boundaries could be defined using the information including the following: zone boundaries used in the MODFLOW model; model calculations of groundwater flow directions; zone budgets; the Digital Terrain Model; BOPRC surface catchment boundaries; and groundwater elevation measurements. The areas that have been noted in this report, where groundwater catchment boundaries may differ from that provided by a topographic analysis, including the vicinities of: Te Whekau crater, Okareka Loop Road, Highlands Road, Tumunui, Earthquake Flat, the headwaters of the Lake Tarawera and Okaro zones, and Brett Road.

   In some of these areas, e.g., in the vicinity of Te Whekau crater, relatively flat topography makes it difficult to identify surface catchment boundaries with topographic analyses. In addition, groundwater divides are not identified by groundwater elevation measurements because of the lack of wells in the areas. In many ways, these issues are similar to those that occurred with the Lake Rotorua groundwater catchment boundary (White *et al.*, 2014). Methods to define groundwater catchment boundaries used by White *et al.* (2014) are relevant to boundaries in the greater Lake Tarawera catchment. These methods could also be used to identify the uncertainty in the catchment boundary position in land areas that may be crucial to the management of lakes in the study area.

   Additional work is also recommended to improve understanding of groundwater catchment boundaries and aquifer properties in the western area, should land use intensify (Section 5). This could include measurement of groundwater elevation, with the aim of identifying groundwater divides. The drilling of monitoring wells may be required because wells are typically sparsely located in this area.

2. Denitrification by lakes and by streams could be considered by the groundwater model to provide better estimates of nitrogen loadings to catchments, lakes and streams. In addition, the transient response of nitrogen loadings in water bodies (i.e., lakes and streams) to land use change could be calculated with the model. This work would aim to improve the current estimate of the response time for Lake Tarawera (Gillon, 2008), Section 2.4.

3. BOPRC could improve understanding of the surface hydrology of the area by measuring flows, and clarifying flow site names, of Lake Tarawera inflows in Kotukutuku Bay and the southeast of the lake. This is because the BOPRC database does not record flows at all spring sites (Section 4.1.1). In addition, it appears some of the sites on the BOPRC gauging database are incorrectly located and few recent gauging measurements are recorded. Terry Beckett may be able to assist BOPRC in the location of spring sites as he assisted with the January 2014 survey.

4. Two streams were identified that flow into Lake Okataina (Figure 4.6). However, it is unknown if these streams are permanently flowing. Therefore BOPRC could visit the locations of the streams to determine if flow is permanent and measure flow rates.

5. Further investigations of groundwater around Lake Okaro would be useful to clarify the interaction of this lake with the surrounding groundwater system. This could include well drilling and water quality sampling to assess whether groundwater flows out of the lake.

6. Further study of the hydrogeology of the Lake Rerewhakaaitu catchment would be useful to assess evidence that the lake is perched and assess hydraulic connections between the lake and its groundwater system. This characterisation would assist further understanding of the relation between land use and lake water quality. The proposed work could include a revisiting of White *et al.* (2003) with a survey of groundwater levels and integration of the estimates of groundwater outflows from the Rerewhakaaitu zone (i.e., Section 3.2.4; Section 5.8; and White and Tschritter, 2015). Assessment of the shallow groundwater systems associated with the small streams that flow to the lake will also be relevant the proposed study.

7.0 CONCLUSIONS

Bay of Plenty Regional Council (BOPRC) have developed policies based on community input that aim to reduce the discharge of nutrients (nitrogen and phosphorus) to the Rotorua lakes. These policies include the greater Lake Tarawera catchment. Eight lakes (Tarawera, Okaro, Rotomahana, Rerewhakaaitu, Okataina, Okareka, Tikitapu and Rotokakahi) are within the catchment, which drains to the Tarawera River. The groundwater system of the catchment is of key importance to the hydrology of the area because: 1) the lakes are commonly hydraulically linked through the groundwater system; 2) stream flow is dominated by baseflow (sourced from springs and seeps); and 3) many stream beds are dry, i.e., rainfall recharge typically flows directly into the groundwater system and then discharges into lakes.

Therefore, BOPRC commissioned GNS Science to assess groundwater resources and groundwater quality in the greater Lake Tarawera catchment in a three-phase programme of hydrogeological investigations. This report describes the results of the third phase of this programme, which developed a groundwater flow model of the greater Lake Tarawera catchment using data derived from the first two phases of the programme. This model was applied to an assessment of land use and nitrogen discharge to surface water (i.e., lakes and streams) relevant to surface water quality. The study area includes the estimated outer catchment boundary of the greater Tarawera lakes (Figure 1.1). Generally, this boundary follows the topographic catchment. However, the boundary also includes two areas outside the topographic catchment that may be within the greater Tarawera lakes groundwater catchment, i.e., Tumunui and Earthquake Flat, located within the Waikato Regional Council boundary; and part of the Lake Rerewhakaaitu catchment located within the Rangitaiki River topographic catchment.

Surface geology of the greater Lake Tarawera catchment is dominated by volcanic units, including ignimbrites and other pyroclastic deposits, as well as rhyolite lava domes and flows (Figure 2.1). Most of these deposits are sourced from the OVC. Two major OVC eruptions (the 61 ka Rotoiti Formation pyroclastics and 322 ka Matahina Formation ignimbrites) produced widespread deposits in the study area and a large basin structure that includes most of the greater Lake Tarawera catchment. These units are relatively permeable; however, fine-grained lithologies (e.g., air-fall layers) may act as aquicludes. Other units important for groundwater flow include: Tauranga Group which comprises Pliocene to Holocene alluvial sediments (in particular, sands and gravels), non-welded ignimbrite and tephra layers; and Okataina rhyolites that typically form domes in the study area.

In this report, a groundwater flow model has been developed to estimate nitrogen inflows to lakes associated with five land-use scenarios. Steady-state water budgets for lakes and their catchments were developed to estimate rainfall and evaporation in the lake catchments. These budgets are part of the characterisation of surface flows in streams and rivers, and groundwater flows to lakes, in the study area.

The steady-state groundwater flow model was developed with the following software: MODFLOW-2005 (Harbaugh, 2005), MT3DMS v5.3 (Zheng and Wang, 1999; Zheng, 2010) and MODFLOW-NWT (Niswonger *et al.*, 2011) running under GMS 10.0 (Aquaveo, 2014). Average autumn lake-stage levels in the eight lakes were used to represent lake levels, and rates of groundwater exchange with underlying aquifers were controlled using conductance values assigned for each lake during calibration. Static water levels from 40 wells were used to calibrate hydraulic heads in the groundwater system.

Surface water features relevant to the model and an assessment of the nitrogen loading to lakes, streams and groundwater were mapped in this report. In addition, the flows in these streams were calculated from BOPRC gauging measurements. For example, Lake Tarawera inflows include cold springs, hot springs and streams (Figure 4.1). Natural streams flowing into Lake Tarawera from the west include: Wairoa Stream, sourced from Lake Rotokakahi, that gains inflow from groundwater between Lake Rotokakahi and Lake Tarawera; Te Puroku Stream and Wairua Stream that are sourced from springs and seeps; and Waitangi Stream that is primarily sourced from the Lake Okareka drain. In addition, springs provide significant inflows to the lake. These are predominantly located in Kotukutuku Bay and the southeast of Lake Tarawera and are associated with rhyolite domes (i.e., the Okareka Rhyolite Complex and the Ngawhiro Rhyolite Dome, respectively).

Interaction between surface water and groundwater was demonstrated by characterisation and modelling of the hydrogeological system. Clearly, groundwater flows into lakes and streams and water from some lakes discharges into groundwater. In addition, the model generally indicated that lakes are recharged by groundwater and that groundwater flows between lake catchments. Commonly, groundwater flows into lakes, streams and springs around the lake edges. Typically, groundwater flow velocities are largest near lake edges and near streams.

Groundwater flow budgets were derived for model zones that loosely represent lake catchments (Figure 1.1). The water budgets aim to estimate groundwater flow between zones and identify groundwater flows into lakes and streams. For example, the flow budget calculated a groundwater flow of 625 l/s from the Okataina zone to the Tarawera zone and a groundwater flow of 175 l/s from the Tarawera zone to the Okataina zone. In this example, net flow from the Okataina zone to the Tarawera zone was 450 l/s (i.e., 625-175 l/s). Generally, the zone boundaries represent groundwater catchment boundaries. However, the zone boundaries did not always match catchment boundaries.

Nitrogen loadings to lakes and streams were calculated for five land use scenarios with the aim of contributing to the assessment of the impacts of land use on water quality in lakes, streams and groundwater. The model demonstrated the geographic location of sources of current nitrogen loading to the lakes. Current land use has a large effect on modelled nitrogen concentrations in groundwater in the west and the south of the study area, including Earthquake Flat and parts of two zones (i.e., Rotomahana and Rerewhakaaitu). Relatively high nitrogen concentrations in groundwater were calculated between Lake Tarawera and Lake Rotomahana. However, these concentrations were probably over-estimated because nitrogen losses (e.g., in-lake denitrification) were not considered by the model. The model also calculated that nitrogen discharge to lakes and streams, e.g., nitrogen loading to all lakes (except Lake Rerewhakaaitu, which was perched relative to the groundwater system) increased as land use intensifies in the scenarios.

This report includes recommendations for further work within the greater Lake Tarawera catchment. For example, groundwater catchment boundaries could be better defined using the information including the following: zone boundaries; model calculations of groundwater flow directions; zone budgets; the Digital Terrain Model; and additional measurements of groundwater level. The areas that have been noted in this report where groundwater catchment boundaries may differ from that provided by a topographic analysis (alone) include the vicinities of: Te Whekau crater, Okareka Loop Road, Highlands Road, Tumunui, Earthquake Flat, the headwaters of the Lake Tarawera and Okaro zones, and Brett Road.

Nitrogen losses (e.g., denitrification by lakes and streams; and sedimentation of particulate nitrogen in lakes) could be considered in the model. This is because calculated concentrations are probably greater than observed as the model only considers dilution when calculating TN concentrations in surface water bodies.

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