Groundwater resource investigations in the Upper Rangitaiki River Catchment, Bay of Plenty Region. Stage 1 – preliminary groundwater allocation assessment

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EXECUTIVE SUMMARY

Groundwater in the Upper Rangitaiki River catchment, Bay of Plenty (Figure 1.1) is primarily extracted for agricultural use, and is also used for commercial and municipal purposes. Bay of Plenty Regional Council (BOPRC) commissioned GNS Science to complete a preliminary assessment of groundwater in the area, with the aim of calculating groundwater available for allocation (GAA). This work is required to inform BOPRC policy decisions on groundwater allocation in the catchment.

A geological model of the Upper Rangitaiki River catchment has been constructed to describe the three-dimensional distribution of key geological units within fault blocks bounded by major faults. The model has an area of 2,822 km^2 and a gridding resolution of 100 m by 100 m. The vertical extent of the model is between -2,000 m and 1,000 m relative to mean sea level, which allows representation of the estimated basement surface throughout the model area. The model comprises eight major geological units within ten fault blocks. These geological units are:

- Basement: Permian to Jurassic greywacke and argillite with low groundwater potential;
- Mangakino and other older volcanics: undifferentiated volcanics and sediments older than Whakamaru Group; this formation has an unknown aquifer potential;
- Whakamaru Group: large-scale volcanic deposits sourced from the Whakamaru Caldera west of the model area; this formation is a known aquifer;
- Matahina Formation: volcanic deposits in the northern part of the model area and underlying the basins; this formation is a potential aquifer;
- Kaingaroa Formation: volcanic deposit that forms the Kaingaroa Plateau in the western part of the model area; this formation has an unknown aquifer potential;
- Q1-Q4 Okataina volcanics: Holocene to late Pleistocene volcanic lavas and pyroclastic deposits: this formation has the potential to supply groundwater;
- Tauranga Group: Pliocene to Holocene alluvial sediments that are mainly found in the Galatea and Waiohau basins; this unit is a known aquifer;
- Taupo Group: comprises Oruanui Formation and Taupo Pumice Formation, as well as other undifferentiated pyroclastic deposits sourced from the Taupo Caldera. This unit has a low potential to supply groundwater.

Nine zones are identified in the Upper Rangitaiki River catchment that could be used as groundwater allocation zones. These zones include the areas of volcanic lithologies in the south and west (i.e., Headwaters, Kaingaroa South, Kaingaroa North, Pokairoa and Matahina zones), basins formed of Tauranga Group sediments (Galatea Plain and Waiohau zones), and greywacke lithologies in the mountains to the east (Minginui and Ikawhenua zones). Water budgets were developed for these zones and rainfall, evapotranspiration, surface water flows (baseflow and quickflow) and estimated groundwater outflow across the zone boundary were calculated. The close connection between groundwater and surface water was demonstrated by the water budgets with the balance of rainfall and evapotranspiration flowing to surface water.

The GAA calculation assumes that the management target is protection of groundwater recharge (i.e., minimum flow in aquifers is 65% of the groundwater recharge) and the estimated minimum flow in streams (i.e., $Q_{5\ 7\text{-day}}$ surface flow which is a 7 day low flow minimum that has a 20% probability of occurring in any one year; Wilding, 2003). GAA is

large in the Upper Rangitaiki area. Total GAA is approximately 19.6 m^3/s and includes: 12.5 m^3/s in the zones of volcanic lithologies in the south and west; 0.9 m^3/s in the Galatea Plain and Waiohau zones; and 6.2 m^3/s, in greywacke lithologies (i.e., the Minginui and Ikawhenua zones).

Current groundwater allocation in the Upper Rangitaiki River catchment is 0.49 m^3/s. Most of this (0.43 m^3/s) is located in the Galatea Plain zone, where groundwater allocation is approximately 54% of GAA. In contrast, groundwater allocation is less than 4% of GAA in the zones of volcanic lithologies in the south and west, indicating a large potential for the increased use of groundwater in these zones. GAA is large (approximately 6.2 m^3/s) in the area of greywacke lithologies; however this is likely to remain unused because of the very limited opportunities for land use intensification (e.g., cultivation and irrigation) in these areas.

Recommendations for further investigations of groundwater resources in the Upper Rangitaiki area aim to improve groundwater budget components and refine GAA calculations. For example, a programme of low-flow gauging is recommended to improve knowledge of outflow from the groundwater system. These measurements could include a summer gauging programme for the purpose of measuring groundwater-surface water interaction, including baseflow discharge, and calculating $Q_{5\ 7\text{-day}}$ surface flow.

This report also recommends that BOPRC considers policies that integrate the management of groundwater and surface water, because these water bodies are linked. Policies could also consider management targets (i.e., a minimum groundwater recharge limit and a minimum surface flow limit), and rules associated with the portion of GAA that is allocated.

1.0 INTRODUCTION

GNS Science was commissioned by Bay of Plenty Regional Council (BOPRC) to complete an assessment of groundwater availability in the Upper Rangitaiki River catchment (Figure 1.1). This area includes the Upper Rangitaiki River catchment above Matahina Dam and is bounded by: the Lake Tarawera catchment and Kaingaroa Plateau in the west; the Taharua River catchment in the south; and mountain ranges (including Ikawhenua Range) to the east. This assessment is one of a series of GNS Science and BOPRC projects that aim to determine sustainable groundwater allocation in the Bay of Plenty (BOP) Region at the sub-regional scale (e.g., White *et al.*, 2010).

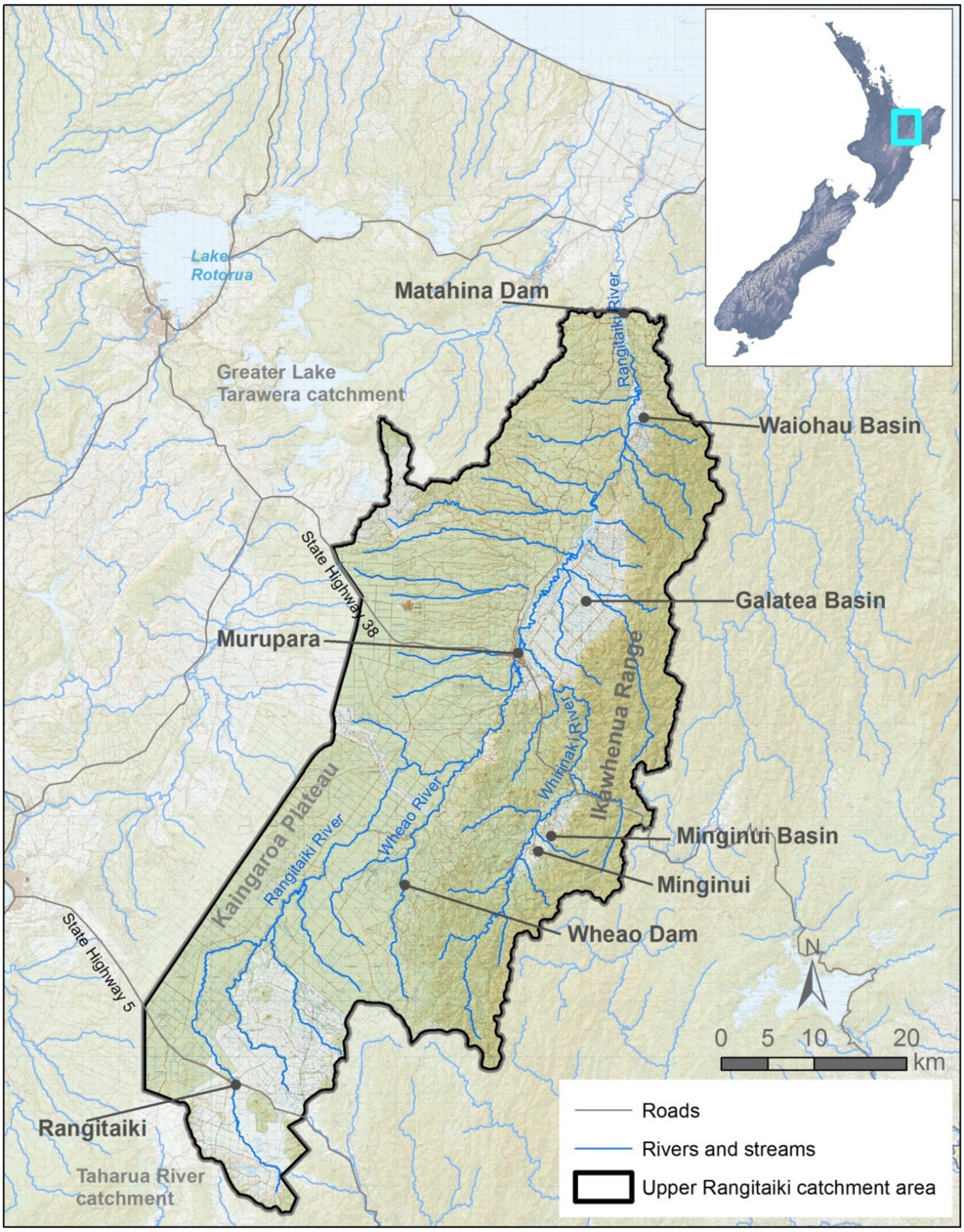

Figure 1.1 Location of the Upper Rangitaiki River catchment, from Rangitaiki in the south, to Matahina in the north.

Geology in the western study area is dominated by volcanic and volcaniclastic lithologies derived from Taupo Volcanic Zone (TVZ) eruptions. Here, the groundwater system is both an important water resource and a potential water supply. Features of groundwater systems in theses lithologies include a relatively high rate of recharge from rainfall (e.g., approximately 50% of rainfall recharges groundwater in the Lake Rotorua catchment; White *et al.*, 2007) and a large contribution of groundwater outflow to surface water (e.g., the mean base flow from volcanic units in the Upper Waikato is 93% of total stream flow; White, 2010). In the east, greywacke forms the mountain ranges, and therefore groundwater availability and the demand for groundwater is low. The Galatea Basin is located between volcanic/volcaniclastic rocks and greywacke mountains, and is an important area for agriculture. Groundwater recharge occurs from rainfall and from streams that cross the sedimentary Galatea Basin; this recharge flows to streams on the western side of the Basin, and then to the Rangitaiki River.

Groundwater resources in the BOP Region are important water supplies for agriculture, industry and municipal purposes that are coming under increasing usage pressure (White, 2005). For example, the Galatea Basin is the most heavily farmed area, and has the largest groundwater allocation, in the Upper Rangitaiki River catchment. This area is facing increased pressure from agriculture for groundwater allocation. Generally, groundwater allocation limits are necessary to maintain groundwater levels and stream flows because groundwater discharge is crucial to the support of base flow in streams. These limits are also relevant to surface water quality, as nitrogen generated from land use may discharge to surface water via the groundwater system. However, guidelines for groundwater allocation limits are not yet in place for the Upper Rangitaiki area.

This report aims to calculate groundwater available for allocation (GAA) in the Upper Rangitaiki area. Firstly, groundwater allocation zones are identified as part of this project. These zones have been defined to provide BOPRC with geographic units to manage groundwater use, while considering the potential effects of use such as reduced groundwater flow and reduced baseflow in streams. Zone identification includes an assessment of the groundwater boundary between the Upper Rangitaiki and Tarawera catchments, because groundwater may flow from Lake Rerewhakaaitu, located in the Upper Rangitaiki surface catchment, to the greater Lake Tarawera catchment (White *et al.*, 2003).

Secondly, a simplified 3D geological model is developed to describe flows in the groundwater system. Water budgets are then developed to estimate surface water and groundwater flows in the area. Estimates of surface flows include baseflow and quick flow in rivers and streams, which is relevant to surface water allocation in the management zone, and is also a useful contribution to the understanding of surface hydrology in the area.

Within groundwater allocation zones, GAA is calculated with a synthesis of geological information and water budgets. A measure of the sustainability of current allocation is provided with a comparison of GAA with current groundwater allocation. However, groundwater allocation limits are not calculated in this report because decisions on allocation policy are required by BOPRC before limits can be established.

This report also includes recommendations for further work in in the Upper Rangitaiki area, including investigations to improve our understanding of geology and water budget components. The recommendations also include consideration of policy development options that aim to ensure sustainable management of the important Upper Rangitaiki groundwater resource.

2.0 UPPER RANGITAIKI RIVER CATCHMENT – REVIEW OF GEOLOGY AND HYDROGEOLOGY

This section provides a brief overview over the geological history and structure of the Upper Rangitaiki River catchment area. The review includes information about the distribution, appearance and hydrogeology of the geological formations that are mapped at the ground surface and/or assumed at the subsurface within the study area.

2.1 GEOLOGICAL HISTORY AND STRUCTURE

The Upper Rangitaiki River catchment is located along the eastern boundary of the TVZ, a northeast striking zone of volcanic and geothermal activity, which extends from Mt Ruapehu in the southwest to beyond the BOP coastline in the northeast (Figure 2.1). The TVZ is on average 50 km wide and its formation, that commenced approximately 2 Ma (Ma = millions of years before present day), is linked to the oblique subduction of the Pacific Plate beneath the Australian Plate. The resulting rift zone, the Taupo Rift, is characterised by a narrow belt of active extensional faulting. In its central part, the TVZ includes seven rhyolitic calderas and caldera complexes with associated rhyolite lavas and lava domes (Nairn, 2002; Seebeck *et al.*, 2010). The north-eastern and south-western extents of the TVZ are characterised by andesitic to dacitic effusive volcanism and the absence of rhyolitic calderas (Houghton *et al.*, 1995).

Permian to Jurassic greywacke and argillite of the Waipapa and Torlesse composite terranes (and intrusive igneous bodies) form the basement of the TVZ (Sherburn *et al.*, 2003; Adams *et al.*, 2009). These basement rocks crop out on the ranges that flank the TVZ, including the Ikawhenua Range (Figure 2.2). Within the TVZ, typical depth to basement is from 1 km to > 3 km, beneath volcanic cover.

Ignimbrites from the TVZ characterise the western part of the Upper Rangitaiki River catchment area. Gorges and structural basins are two key features of the boundary between the ignimbrites in the west and the greywacke basement in the east. Most rivers, including the Rangitaiki River, have incised gorges into the ignimbrite. Structural basins, formed as actively subsiding pull-apart tectonic basins (Toulmin, 2006) include the Galatea and Waiohau plains.

The Galatea Basin is filled with alluvial material from pumice and greywacke sources. Pumiceous materials are derived from TVZ pyroclastic deposits, and are dominant along its northwest margin, whereas greywacke gravels are derived from the basement ranges, and prevail in the south-eastern parts of the basin (Healy, 1955). There are two main factors likely to have determined the distribution of these lithofacies and the migration of the Rangitaiki River to the north-western side of the plain (Healy, 1955). Firstly, the proximity of the Ikawhenua Ranges to the east resulted in a large volume of greywacke detritus over a long period. In contrast, relatively young pumiceous material in the west is easily eroded and has a low density that has favoured fluvial transport through the Upper Rangitaiki River catchment and outside the area.

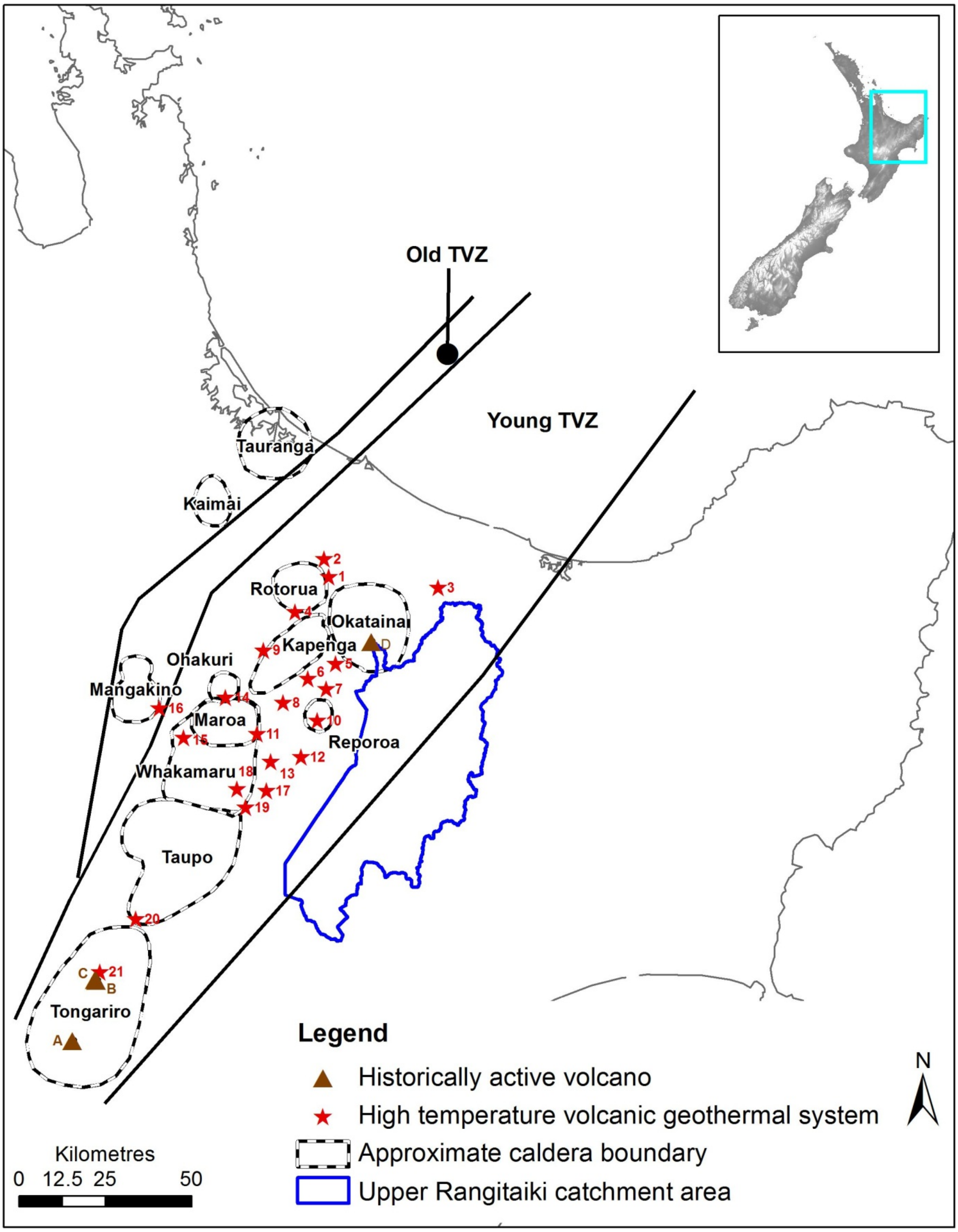

Figure 2.1 Calderas, historically active volcanoes and geothermal systems in the TVZ. Volcanoes: A: Ruapehu, B: Ngauruhoe, C:Tongariro, D: Tarawera; Geothermal systems: 1: Tikitere, 2: Taheke, 3: Kawerau, 4: Rotorua, 5: Waimangu, 6: Waikite, 7: Waiotapu, 8: Te Kopia, 9: Horohoro, 10: Reporoa, 11: Orakei Korako, 12: Ohaaki, 13: Ngatamariki, 14: Atiamuri, 15: Mokai, 16: Mangakino, 17: Rotokawa, 18: Wairakei, 19: Tauhara, 20: Tokaanu-Waihi, 21: Ketetahi Springs.

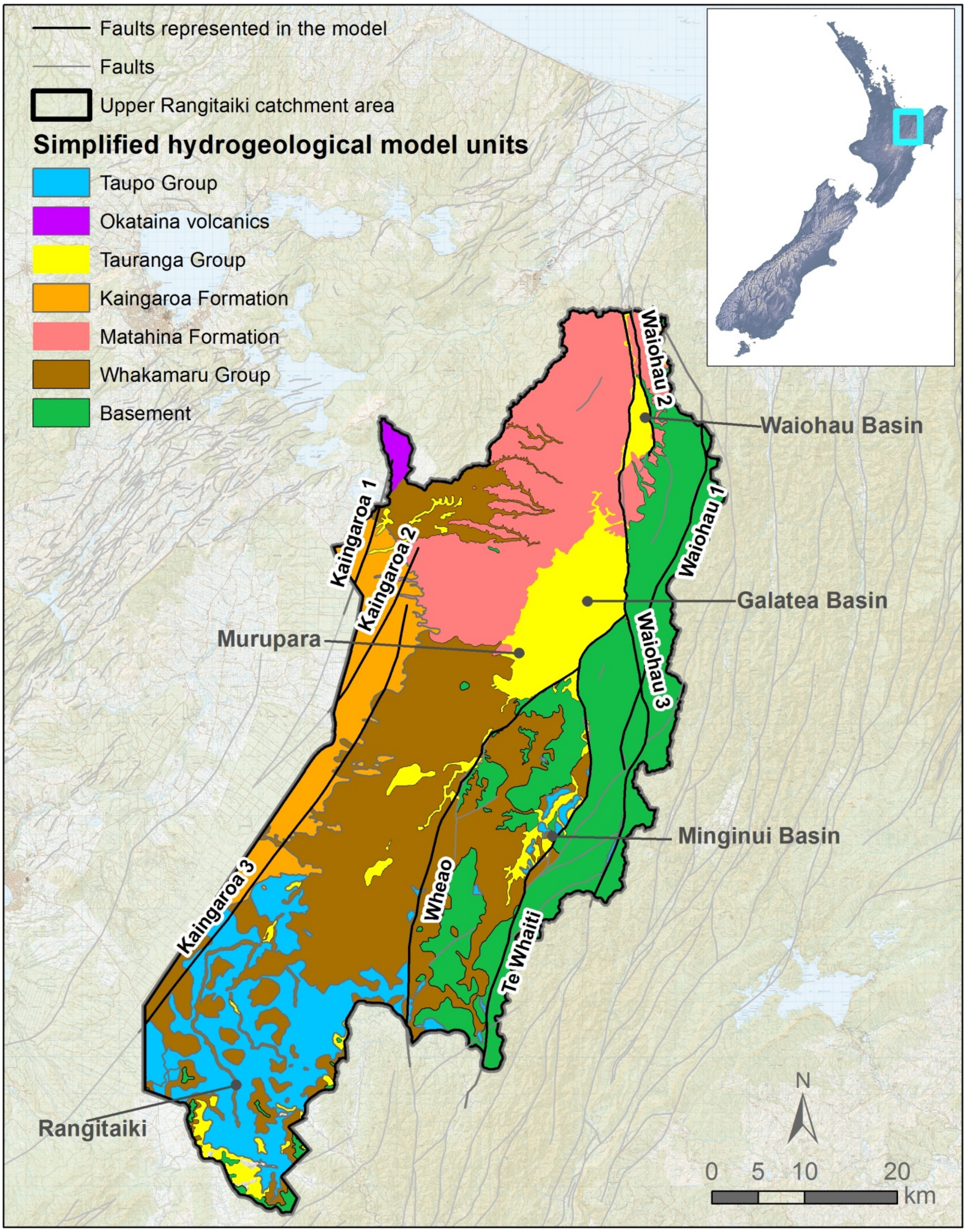

Figure 2.2 Simplified geology and structure of the Upper Rangitaiki River catchment (Leonard *et al.*, 2010). Labelled faults are represented in the 3D model.

Four main fault systems run through the Upper Rangitaiki River catchment: the Waiohau, Kaingaroa, Wheao and Te Whaiti fault systems (Leonard *et al.*, 2010). The Waiohau Fault System is a series of active N-S trending strike-slip faults that run along the eastern boundary of the Waiohau and Galatea basins (Healy *et al.*, 1964; Leonard *et al.*, 2010). Faults are classified as active if there is evidence for ground surface displacement within the last 25,000 years (within the Taupo Rift), or in the last 125,000 years (all areas outside of the Taupo Rift) (Litchfield *et al.*, 2013). The Waiohau faults have an average dip greater than 70° (Mouslopoulou *et al.*, 2007) and a slip rate of ca. 0.7 mm/year (Litchfield *et al.*, 2013). Williams (1979) suggests that an accumulated vertical displacement along these faults exceeding 2 km is necessary to form the present basement structure. A 1 km-wide zone between the two main faults of the Waiohau Fault System is likely to include a mélange of intensely crushed greywacke (Williams, 1979). The western boundaries of the Waiohau and Galatea basins are unlikely to be fault controlled because gravity data suggests that these basins deepen gradually (Williams, 1979); however, a fault is mapped on the western boundary of the Waiohau Basin (Figure 2.2).

A series of uplifted basement rocks underlie the Matahina Ignimbrite north of the Galatea Basin, where the Waiohau Fault System has been intersected by a system of NE-SW trending faults (Williams, 1979).

The Kaingaroa Fault System consists of three assumed NNW to SSE-trending faults (Leonard *et al.*, 2010) that become younger towards the east (Stagpoole, 1994). There is no visible trace of geologically-recent rupture for any of the faults, instead, their general location has been inferred through the interpretation of gravity data (Modriniak and Studt, 1959) and the erosional scarp (Stagpoole, 1994). Although the fault system is categorised as inactive, Villamor and Berryman (2001) suggest it to be the source of an earthquake in 1895. A slip rate of 0.5 mm/year is reported by Litchfield *et al.* (2013). The Wheao Fault is a broadly arcuate, N to NE-striking fault located in the central catchment area. It dips 80° to the west and is an active fault. The Te Whaiti Fault System has been mapped from geomorphic expressions and its slip rate is assumed to be similar to other fault systems in this region (Litchfield *et al.*, 2013).

2.2 GEOLOGICAL UNITS

The major geological units of the Upper Rangitaiki River catchment area (Figure 2.2) are summarised here including lithology, distribution and hydrogeological properties.

2.2.1 Basement

Jurassic to Early Cretaceous basement rocks of the Torlesse (composite) terrane outcrop at the Ikawhenua Ranges along the eastern margin of the Upper Rangitaiki River catchment area. In general, Torlesse (composite) terrane includes Kaweka and Pahau terranes, separated by the Whakatane Mélange. Most of the basement rocks within the catchment are assigned to Kaweka terrane, with only a small area of Whakatane Mélange in the north of the catchment. Pahau terrane has not been mapped within the study area (Leonard *et al.*, 2010).

The Jurassic Kaweka terrane comprises massive sandstone or greywacke as well as alternating sandstone, argillite and mélange (Leonard *et al.*, 2010). Whakatane Mélange was formed during the Early Cretaceous in the merging zone between the Kaweka and the Pahau terrane. It consists of more or less deformed blocks of rock that are a mixture of sandstone, mudstone, basalt, limestone etc., often within a matrix of scaly mudstone (Leonard *et al.*, 2010).

The depth to basement west of the ranges was deduced from gravity data to be 500 m under the eastern part of the Kaingaroa Plateau and about 2 km at Waiotapu (Modriniak and Studt, 1959). To the north at Kawerau, greywacke is intersected between 630 m and 1,230 m depth in geothermal wells (Milicich *et al.*, 2013). To the west, at Ohaaki geothermal field, the shallowest greywacke intersection is at approximately 970 m depth (Wood, 1983). Basement greywacke rocks generally are not productive aquifers in New Zealand. The bulk apparent porosity of the greywacke basement is low (typically <5%) and permeability is controlled predominantly by fracture defects in the rock (Yang *et al.*, 2001).

2.2.2 Mangakino and other older volcanics and sediments

Deeply buried volcanic strata and sediments that predate the 0.35 Ma Whakamaru Group have been inferred to overlie basement rocks within the Upper Rangitaiki River catchment (Leonard *et al.*, 2010), but their existence within the area is yet to be confirmed. These strata could potentially include Pakaumanu Group and/or Reporoa Group deposits, or equivalents thereof. Pakaumanu Group (~1.6 Ma to 0.95 Ma) comprises a series of welded and non-welded rhyolitic ignimbrite deposits considered to be sourced from the Mangakino Caldera (Briggs *et al.*, 1993; Edbrooke, 2005). These volcanics, including the Ongatiti, Ahuroa, Rocky Hill, and Marshall ignimbrites (Leonard *et al.*, 2010) are of regional extent in the Waikato region.

Reporoa Group rocks have been identified in several TVZ geothermal fields, including Ohaaki, Wairakei, and Ngatamariki. The group consists of two members: Tahorakuri Formation and Waikora Formation, which collectively are the volcanic and sedimentary deposits positioned between the 0.35 Ma Whakamaru Group and the basement. Age dating of Tahorakuri Formation pyroclastic deposits showed an upper limit of 1.89 Ma (Eastwood, 2013). Waikora Formation is a litho-stratigraphic term which refers to all pre-Whakamaru sedimentary units above basement, which contain greywacke pebbles (Gravley *et al.*, 2006).

2.2.3 Whakamaru Group

It is very likely that the entire Upper Rangitaiki River catchment west of the basement was once covered by one or more of the Whakamaru Group ignimbrites, and almost half of the area is mapped as this ignimbrite (Leonard *et al.*, 2010). Whakamaru Group comprises several individual welded ignimbrites (e.g., Brown *et al.*, 1998) that erupted approximately 340–350 ka from the Whakamaru Caldera in the central TVZ (Figure 2.1). At least one of these ignimbrites, Rangitaiki Ignimbrite, has been mapped at the ground surface within the study area and is likely present at depth in all parts of the study area (apart from the ranges), overlain by younger pyroclastic and sedimentary formations. The thickness of Rangitaiki Ignimbrite is assumed to be up to 300 m, on the basis of the mapped extent and thickness beyond the catchment area (Hikuroa *et al.*, 2006; Leonard, 2013).

Rangitaiki Ignimbrite is described as a moderately welded, dark grey, crystal rich tuff. The unit is a composite of lithotypes: coarse tuffs, pumice breccias and air fall deposits (Nairn, 2002). This unit is the deepest known aquifer. Based on aquifer tests, fracture-controlled flow provides the majority of groundwater available in this aquifer (Hadfield *et al.*, 2001). Groundwater quality is generally good (Hadfield *et al.*, 2001). Thorstad *et al.* (2011) estimated hydraulic conductivity values between 0.1 and 11.2 m/d for this ignimbrite north of Lake Rerewhakaaitu. Transmissivity of Rangitaiki Ignimbrite in the Reporoa area is estimated in the range of 2 to 30 m^2/d (Piper, 2005).

2.2.4 Matahina Formation

Matahina Formation ignimbrite (Bailey and Carr, 1994) was produced by a major caldera-forming eruption at approximately 322 ka from the Okataina Volcanic Centre (Leonard *et al.*, 2010) (Figure 2.1). The ignimbrite crops out in the northern part of the Upper Rangitaiki River catchment and has an assumed thickness of approximately 100–200 m (Leonard, 2013; Nairn, 2002). Within the greater Lake Tarawera catchment, Matahina Formation has been found directly overlying Whakamaru Group ignimbrites (Rose *et al.*, 2012).

The Matahina Ignimbrite comprises a basal pyroclastic fall deposit that is overlain by three pyroclastic flow units (Bailey and Carr, 1994). The ignimbrite is described as blue to pink, cream or grey ignimbrite that is compacted to moderately welded in the study area. Approximately 10% of the clasts are pumice and the matrix is gritty and rich in crystals.

Gordon (2001) reports low primary porosity and low groundwater yields from the upper, unwelded part of Matahina Ignimbrite, whereas yields in the deeper, welded parts are greater. The ignimbrite is likely to show increased yield in the compacted to moderately welded zones within the study area. However, groundwater investigations at Rerewhakaaitu Road southeast of Lake Rerewhakaaitu show few fractures and low groundwater yield in the upper 45 m of 50 m of Matahina Formation (Rose *et al.* (2012). Gordon (2001) reports transmissivities between 18 and 6000 m^2/day for unconsolidated deposits, which include the upper unwelded part of Matahina Formation, and transmissivities ranging between 6,000 and 12,000 m^2/d for fractured ignimbrite near Otakiri in the south-western Rangitaiki Plains. At Kawerau Geothermal Field north of the study area, the highly-welded central part of this formation is described as impermeable; which is due to the effects of hydrothermal alteration; while the upper and lower members have a high porosity and represent aquifers (Bignall and Milicich, 2012).

2.2.5 Kaingaroa Formation

Kaingaroa Formation erupted during creation of the Reporoa Caldera west of the Upper Rangitaiki River catchment at approximately 230 ka (Houghton *et al.*, 1995). Together with Whakamaru Group ignimbrites, this unit forms the Kaingaroa Plateau in the western part of the catchment (Figure 2.2). Here, it reaches an estimated thickness of up to 200 m (Leonard, 2013; Leonard *et al.*, 2010) and is underlain by Matahina Formation (potentially in north) and Whakamaru Group.

In some areas, other ignimbrite units of similar age (e.g., Mamaku/Ohakuri ignimbrites) possible occur below the Kaingaroa Formation. Using seismic and gravity data, Stagpoole (1994) deduced that the Kaingaroa Plateau consists of 650 m of ignimbrites overlying basement rocks. In drill holes at Murupara, Kaingaroa Formation was found to have a thickness of 30 m (Beresford and Cole, 2000).

The base of Kaingaroa Formation consists of several tephra layers that have a thickness of approximately 4 m (Nairn, 2002) and have been found deposited on a palaeosol overlying Onuku Pyroclastics (Beresford and Cole, 2000). These are overlain by three ignimbrite flow units. The lower unit consists of at least 50 m of non-welded, fine-grained ignimbrite that itself comprises several flow units (Beresford, 1997). This lower ignimbrite unit comprises pink to yellow pumice lapilli and lithic clasts in an ash-rich matrix (Beresford and Cole, 2000). The sandy black middle unit consists of a lightly welded, dark grey to black pumice tuff (Nairn, 2002). The upper ignimbrite unit is fine-grained, partially to densely welded and pumice poor (Beresford and Cole, 2000).

There is no information available regarding the hydrogeology of this formation. It can be assumed that the basal tephra zone and palaeosol together is likely to act as an aquitard. The overlying ignimbrite units are likely to exhibit similar hydraulic properties as texturally-comparable ignimbrite formations such as Mamaku Plateau Formation and Matahina Formation, but the actual properties will vary locally depending on the pore space and the degree of welding and jointing.

2.2.6 Tauranga Group sediments

Tauranga Group sediments comprise Pliocene to Holocene alluvial sediments as well as non-welded ignimbrite and tephra layers typically located in valleys and commonly associated with lakes. Within the Upper Rangitaiki River catchment, the deposits are primarily found within the Galatea, Waiohau and Minginui basins, where they form important aquifers. Tauranga Group deposits are mostly saturated, indicating good opportunities for groundwater supplies, however, most wells in this unit yield low rates of groundwater flow (up to 13 L/s; White, 2005).

2.2.7 Okataina volcanics

Pumiceous tephra and pyroclastic material from the Okataina Volcanic Centre occur in a small area in the northwest of the catchment. Surficial strata are predominantly Holocene pumice deposits overlying Late Pleistocene tephra and rhyolite lavas of the Waiohau and Okareka formations (Leonard *et al.*, 2010). Hydraulic conductivity values from comparable deposits northwest of the study area vary between 0.07 and 0.65 cm/sec, or approximately 60 to 560 m/day (Thorstad *et al.*, 2011; Rose *et al.*, 2012).

2.2.8 Taupo Group

Within the Upper Rangitaiki River catchment area, the Taupo Group deposits include the 25.4 ka Oruanui Ignimbrite, the 1.8 ka Taupo Pumice Formation, and pyroclastic layers of intermediate position and age which cannot be differentiated in driller's logs. All Taupo Group deposits are sourced from the Taupo Caldera. The thickness of Taupo Group deposits decreases dramatically with distance from the Taupo Caldera (e.g., Wilson and Walker, 1985). Immediately after the large-scale Oruanui eruption, the deposits had a thickness between 50 m and 240 m in the Lake Taupo Catchment, but a large volume has since been removed by erosion. Undifferentiated Taupo Group deposits have been drilled across the southern boundary of the Upper Rangitaiki River catchment, at Rangitaiki Station and Lochinver Station (Harvey, 2014). Here, these deposits have a thickness in the range of 5 to 22 m.

The Oruanui Formation is a composite of pumice-dominated flow (ignimbrite) and air fall deposits that formed and mantled the landscape (Wilson, 1991). The Oruanui Ignimbrite is characterised by an almost complete lack of jointing, but, in comparison with the Taupo Ignimbrite, is somewhat finer grained and somewhat less permeable (Hadfield *et al.*, 2001).

Taupo Pumice Formation covers most of the lowlands in the southern part of the study area. This unit comprises the products of the 1.8 ka Taupo eruption, including ignimbrite flow units and airfall deposits. The ignimbrite is entirely non-welded, but is occasionally compact where it is fine grained and matrix-rich.

3.0 METHODS

3.1 GEOLOGICAL MODEL

The 3D modelling software used in this project was EarthVision 8.1 (Dynamic Graphics Inc., 2013), a powerful geological modelling tool that allows the development of two different kinds of 3D models: stratigraphic models and property models. Stratigraphic “layer cake” models are built using the top surfaces of each geological unit. These are combined in a chronological (stratigraphic) order within fault blocks. Numerical property models calculate the probability of finding a certain parameter value at any given location within the study area using the provided scattered data points. This parameter can be, for example, a lithological descriptor (e.g., gravel), or a water quality indicator (e.g., nitrate concentration).

Property models are generally developed to inform the delineation of layer boundaries between heterogeneous deposits. However, property modelling was not carried out within the scope of this project due to the nature of the geological units encountered in the model area and the limitations of the currently available bore log dataset.

The geological model extends over an area of 2,822 km^2, and a gridding resolution of 100 by 100 m was chosen. This model grid is a lower resolution compared to the 80 by 80 m spatial resolution used for other sub-regional BOPRC 3D models (e.g., White *et al.*, 2010, 2012a) to accommodate modelling software limitations arising from the large model extent. The vertical extent of the model is between -2000 m and 1000 m RL, to allow the representation of the basement across the entire model area. The model is split by the Kaingaroa, Waiohau, Te Whaiti, and Wheao fault systems into ten fault blocks.

In the following sections, data sources used for the project are provided, and a general description of the main steps in the development of a 3D geological model are detailed. Subsections are arranged in the typical order of work flow during model development, but note that there are often several iterations of data checking and identification of appropriate layer boundaries before the 3D model is finalised.

3.1.1 Data sources

3.1.1.1 Topographic data

Topographic data is used to estimate the land surface elevation across the study area. The topographic datasets were used to develop a digital terrain model (DTM), which interpolates ground elevation between points at which measurements have been made. The DTM used in this report is an 8 m DTM provided by Geographx (Geographx, 2012). It was developed using Land Information New Zealand (LINZ) Topo50 contours and spot heights supplemented with Shuttle Radar Topography Mission data. This DTM was used to define the top surface (i.e., ground elevation) of the 3D geological model, including the elevations of geological units and faults that are mapped at the ground surface. The DTM was also used to estimate the elevations of well heads, allowing conversion of depths measured by bore logs into elevations relative to mean sea level.

3.1.1.2 Geological maps

Surface geology of the 1:250,000 QMAP Rotorua (Leonard *et al.*, 2010) was used in the construction of the 3D geological model to define the boundaries between geological units and the location of faults at the ground surface (Figure 2.2).

3.1.1.3 Bore log data

Lithological bore log data in the Upper Rangitaiki River catchment area was provided by BOPRC in the form of an Excel spreadsheet. The dataset comprised 131 individual bore logs (Figure 3.1) with most wells being located in the Galatea Plain. Other areas with dense well clustering are the Waiohau Plains and the area east and southeast of Lake Rerewhakaaitu. Only a few wells (6) are located outside of these three areas.

A typical bore log includes the following information: 1) a name or number that uniquely identifies the well; 2) location (easting and northing); 3) elevation of the ground surface or the top of the well casing (this study expresses all elevations relative to mean sea level); and 4) lithological descriptions with their associated depth intervals. Typically, this information was collected by drillers when the well was first installed, then passed to BOPRC for archiving in their electronic database.

The majority of the wells with lithological logs has a depth of less than 50 m and the deepest well in the catchment was 256 m deep (Table 3.1). The bore log data were subjected to a series of checks, prior to use in construction of the 3D geological model (Section 3.1.2). The ground elevation (m asl) of each well was interpolated using the DTM (Section 3.1.1.1). Subsequently, unit tops, bottoms, and the base elevation of each well were calculated using the interpolated ground elevation.

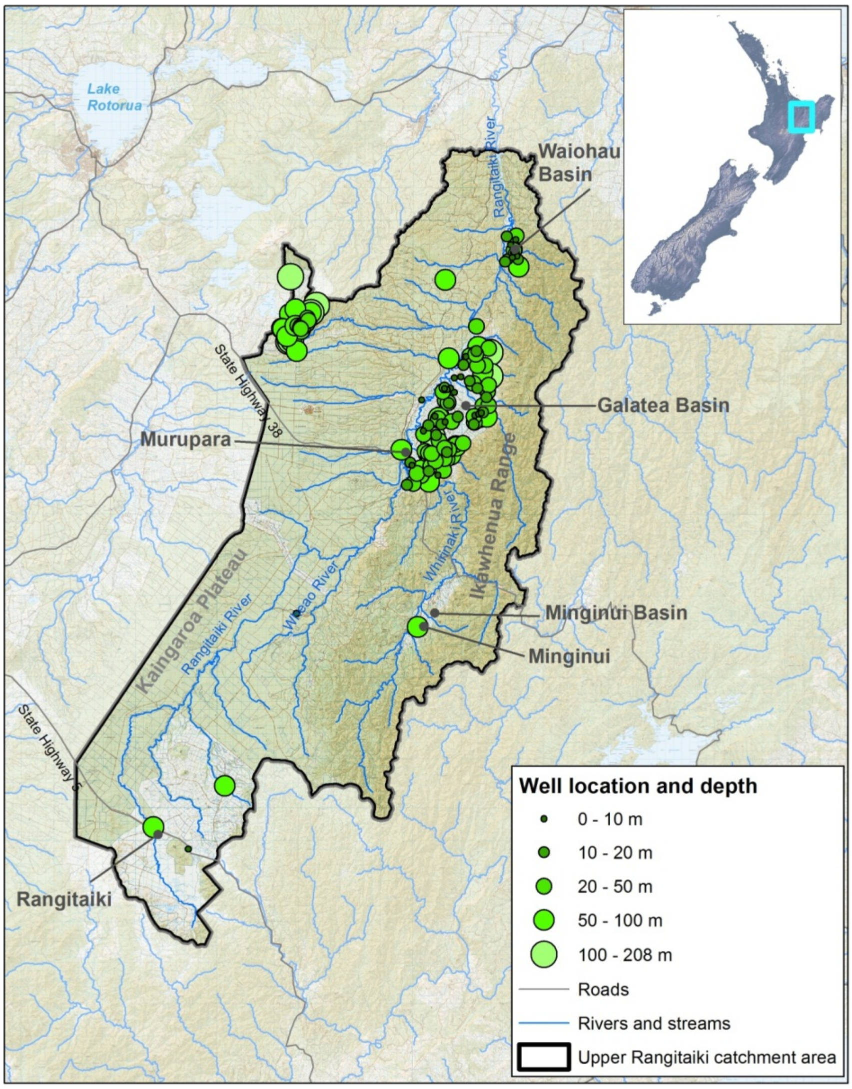

Figure 3.1 Bores with lithological logs listed in the BOPRC well database (Section 3.1.1.3).

Table 3.1 Depths of wells with lithological logs.

Well depth interval (m)	Number of wells
<10	22
10–20	33
20–50	44
50–100	25
100–256	7
Total	**131**

3.1.1.4 Other data sources

Aside from the data sources described above, there are many other information sources that contribute to the development of a 3D geological model, including: published geological investigations, cross sections and maps, geophysical data (e.g., seismic surveys), and radiometric dates obtained for sediment and other geological materials. Key information sources used in this study include the following:

- **Cross sections:** Geological cross sections (e.g., Leonard *et al.*, 2010) provided useful information on the subsurface distribution of formations and the nature of fault offsets.
- **Geophysics**: Geophysical is sparse in the model area. Seismic and gravity information was used to inform basement depth decisions in the Galatea Basin (e.g., Williams, 1979; Toulmin, 2006) and in the vicinity of Lake Matahina (Mouslopoulou, 2006).

3.1.2 Data checking

The 3D geological model accuracy is dependent on the accuracy and consistency of the input data from which it is developed. Hence assessment, verification and, where necessary, correction of the input data are early and critical steps in the overall 3D modelling work flow. This section focuses primarily on the procedures used to check bore log data, although other data sources are also checked carefully before 3D geological modelling commences.

In the first stage of data checking, bore logs with missing lithology information or missing top and bottom of lithological intervals were identified. Because of their ambiguity, these cannot be used for the 3D modelling. Affected bore logs were reported back to BOPRC and if possible, were completed by regional council staff using additional data sources held at BOPRC.

The second stage of checking the bore log data involves editing the lithological descriptions to ensure consistent use of terminology and spelling. This checking was performed for each individual bore log and also across the entire bore log dataset. For example, the lithological descriptions in the BOPRC bore log dataset use the terms “timber”, “wood”, “log”, “vegetation” and “organic”. In this study, these were all replaced with the lithological descriptor “organic”. Spelling corrections were also required, for example replacement of the word “ignambrite” with “ignimbrite”. All of these changes to the terminology and spelling in the lithological descriptions were completed for subsequent generation of pseudo-logs using the Excel *Find* function. The *Find* function is case-sensitive, and so all lithological descriptions were converted to lower case.

In the second stage of data checking, the bore logs were examined for geological inconsistencies that may represent errors in the lithological descriptions. For example, the occurrence of the descriptor ‘greywacke’ on top of a gravel interval in a lithological log is geologically unlikely. This is because the descriptor “greywacke” refers to basement rocks, which can only be overlain by other units. Thus it is presumed that the original description refers to “greywacke gravel”.

Although the data checking procedure was initiated prior to the development of the 3D geological model, it often becomes clear through the modelling process that information from individual bore logs is poor (e.g., lithological description, well location). For example, a particular bore log observation may be contradicted by neighbouring wells when the lithology is viewed in three dimensions. In such cases, additional queries to BOPRC were made for verification, and consequently corrections to the bore log dataset were made throughout the development of the 3D geological model.

3.1.3 Grouping of formations

By definition, models are simplifications of real life. However, there are also practical reasons, such as model purpose, resources and efficiency, which may result in additional simplifications of the model. The purpose of the Upper Rangitaiki River catchment geological model is to assess groundwater assessment and allocation. The availability of groundwater depends on the ability of the material to store and transmit water, and, therefore, is a direct result of the lithology and the degree of fracturing of the subsurface rocks. However, geological subsurface data (e.g., bore logs) is limited in the study area and this sparse data does not allow the development of a high-definition geological model. Therefore, model simplifications include the grouping of formations with close stratigraphical relations as they have presumably similar lithological and hydrogeological properties.

3.1.4 Definition of boundary surfaces for major geological units

A 3D geological model is generally composed of a series of units (layers) that are assembled with respect to their chronology and structural relationships. These units are defined and represented by a set of boundary surfaces. Thus, a key step in the modelling work was to determine how many boundary surfaces there should be, and where they should be positioned in 3D space. Not all stratigraphic units identified on the geological map or subsurface data are included as separate units into the 3D geological model. For simplicity of the model, stratigraphic units are combined into model units. The decision on how many model units are chosen was primarily based on the available data. For instance, it is preferable to keep the model as simple as possible where the available data, such as lithological drill hole data and geophysical data, does not allow a detailed sub-division. In addition, the number of layers is also based on the significance of stratigraphic units to groundwater resources in the study area.

Generally, surfaces were developed to represent the top of each model layer. The bottom of each model layer is then automatically represented by the top surface of the layer underneath it. For example, the 3D model in this study included a surface that represents the top of the (undifferentiated) basement. Where basement units crop out, the surface that defines “top of basement” was developed using ground-surface elevation data from the DTM. Where it is not mapped at the ground surface, the “top of basement” surface was based on bore logs that penetrate as far as the basement or interpretation of geophysical data such as seismic or gravity surveys. Elevation data and lithological descriptions from wells with adequate lithological logs are used to define surfaces that represent the geological contact between different geological units.

Additional information, as listed in Section 3.1.1, was used to support the definition of the boundary surfaces in the geological model. In areas where information is sparse or completely absent, the delineation of boundary surfaces was dependent on assumptions made by the modeller, based on expert opinion.

3.1.4.1 Basement

Outcropping basement rocks build the mountain ranges in the eastern part of the model area. However, there is no absolute information available about the depth of basement rocks in the central and western parts of the model area, i.e., no bore in these areas is deep enough to allow any constraint on the location of basement rocks at depth. Geophysical data is sparse and generally limited to the Galatea Plain. In the absence of any definite data, the subsurface extent of the basement layer is predominantly defined using cross-sections published by Leonard *et al.* (2010). The maximum depth to basement beneath the Galatea Plain was determined based on Williams (1979) at 1000 m below sea level. However, it should be noted that the basement beneath the Galatea Plain is potentially deeper than 2000 m below sea level (Toulmin, 2006).

3.1.4.2 Pre-Whakamaru Group volcanics and sediments

There are no rocks that are older than Whakamaru Group and younger than the basement that outcrop anywhere within the model area. Furthermore, there are no bores in the model area that are deep enough to give a clear picture about the geology and structure beneath the Whakamaru Group ignimbrites. Three bore logs described by Harvey (2014) report sandy deposits underlying Whakamaru Group ignimbrite in bores in the southern part of the study area. These bore logs provide the only discrete data points used for the delineation of this surface. In all other areas, the Pre-Whakamaru Group layer is primarily based on published cross-sections (Leonard *et al.*, 2010).

3.1.4.3 Whakamaru Group

The subsurface extent of this layer is based mainly on cross-sections by Leonard *et al.* (2010) and on BOPRC bore logs. The boundary between Whakamaru Group and Matahina Formation is possibly identified in BOPRC bore 204. The log of this bore shows 3 m of sand, a rhyolite (to a depth of 20 m) and then another rhyolite to a depth of 64 m. This bore is in close vicinity to outcrops of Matahina Formation and Whakamaru Group. Therefore, it is likely that the shallow rhyolite corresponds to the remnants of Matahina Formation, while the underlying rhyolite is most likely Whakamaru Group ignimbrite. However, without a better description of the rhyolites, there is still a high uncertainty in this interpretation.

3.1.4.4 Matahina Formation

The top surface of this formation was determined from the DTM, where the unit is exposed at the ground surface, and the isopach map published by Bailey and Carr (1994) as well as cross-sections provided by the Rotorua QMAP (Leonard *et al.*, 2010). Additional information has been sourced from driller’s logs held by BOPRC. For example, the log of BOPRC bore 11221 in the northern part of the Galatea Plains show that this bore has likely been drilled through the entire thickness of Matahina Formation, allowing identification of the top and the bottom elevation of this unit. The log shows 43.5 m of Tauranga Group alluvium at the surface, followed by 119.5 m of Matahina Formation including basal ash layers. The gravel sediments underlying Matahina Formation are likely to be equivalent to deposits of a pre-Matahina Rangitaiki River at the Matahina Dam site that are known as Luke’s Farm Formation (Bailey and Carr, 1994).

It is likely that BOPRC bore 11221 and bore 11032, in the northwest of the Galatea Plain, have identified the bottom surface of Matahina Formation at an elevation of 79 m asl.

3.1.4.5 Kaingaroa Formation

Kaingaroa Formation is at the ground surface along the Kaingaroa Plateau and, therefore, the top surface is identified by the DTM. None of the available bore logs allow for the determination of the thickness of this formation within the study area. In the model, the thickness of Kaingaroa Formation is controlled by the top elevation of the underlying Matahina Formation and Whakamaru Group.

3.1.4.6 Tauranga Group sediments

Within the model area, the largest distribution and volume of Tauranga Group sediments is located within the Galatea Basin. The basin has the highest number of wells in the study area, but most of them are relatively shallow and do not reach the base of the sediments. Direct constraints regarding the maximum depth of the sediments are provided by BOPRC wells in the north and south of the plains, where the ignimbrite units (Matahina Formation, Whakamaru Group) are found underlying the sediments at shallow depths. However, an indication of the minimum thickness of Tauranga Group sediments can be derived from driller's logs of wells that end in the sediments. For example, the driller's log of BOPRC well 1000110 in the southern central part of the basin shows that Tauranga Group sediments here have a thickness of at least 116.5 m.

Due to the limited quality of the driller's logs, no subdivision of the Tauranga Group sediments into Pleistocene and Holocene units (e.g., (White *et al.*, 2010) within the Galatea Plain, or in the other basins, was conducted.

3.1.4.7 Taupo Group

Driller's logs generally do not allow a clear distinction between Taupo Group deposits and Tauranga Group sediments that contain volcanogenic components. However, Taupo Group deposits were positively identified in the Rangitaiki Station area north of State Highway 5 (Harvey, 2014). Here, they have a thickness of up to 22 m and sit directly on Whakamaru Group ignimbrites. Generally, Taupo Group surficial sediments in bore logs were identified by the QMAP geological map (Leonard *et al.*, 2010).

3.1.5 Assembly of geological model incorporating faults and fault blocks

The integration of faults and fault blocks into the 3D geological model is an iterative process. As a first step, fault traces at the ground surface are sourced from the GNS Science Active Faults Database and from geological maps and cross sections (principally Leonard *et al.*, 2010). Due to the large scale of the model and the complexity of the geology in the model domain, it is not practical to include all faults in the 3D model. Therefore, the faulted model includes only major faults.

The study area is sub-divided into fault blocks, forming the basis for the integration of the faults with the BOPRC bore log data and boundaries of formations. The principal faults that displace the major model units are identified (Leonard *et al.*, 2010) and attributed with fault plane dips (Section 2.1), and the upthrown and downthrown fault blocks are identified. Then, the surface that represents the top of formations (Section 3.1.4) were modelled within the fault blocks.

3.2 GROUNDWATER ALLOCATION ZONES

Groundwater allocation zones were identified for the purposes of managing groundwater allocation and use. Boundaries of these zones were defined with an aim of identifying hydrological and hydrogeological areas that are relevant for groundwater and surface water management. For example, a groundwater catchment may include a surface water feature such as a spring, and management of the groundwater use in this catchment may aim to maintain base flow in the spring.

Nine groundwater catchments were defined with boundaries that follow topographic catchment boundaries defined by BOPRC (West, 2014) (Figure 3.2). Potential groundwater inflows to the study area occur at the topographic boundary of the Upper Taharua catchment and in the vicinity of State Highway 5 in the southeast of the catchment. In addition, previous work suggests that groundwater outflow from part of zone 6 may discharge towards Lake Rotomahana in the Lake Tarawera catchment (White *et al.*, 2003).

Therefore, the catchment boundary in the vicinity of Lake Rerewhakaaitu was assessed, using water budgets and specific discharge estimates. The surface catchment of Lake Rerewhakaaitu possibly drains to the west and to the east, i.e., to the Lake Rotomahana catchment and the Rangitaiki River catchment, respectively (Figure 3.2). However, BOPRC includes the whole Lake Rerewhakaaitu catchment within the Pokairoa Stream catchment, which is part of the Rangitaiki River catchment (West, 2014). The location of the groundwater divide is relevant to the water budgets in the Upper Rangitaiki and Lake Tarawera catchments as groundwater outflow from Lake Rerewhakaaitu may travel to either of these catchments. Lake Rerewhakaaitu is generally perched above the groundwater surface (White *et al.*, 2003), surface inflows are small, surface outflows are zero, and a lake water budget indicates that lake outflows to groundwater are approximately 194 L/s (Gillon *et al.*, 2009). In addition, the Te Kauae Stream subcatchment (located within the Lake Rotomahana catchment) was estimated because groundwater outflow from Lake Rerewhakaaitu may travel to this stream (Figure 3.2) (Reeves *et al.*, 2008).

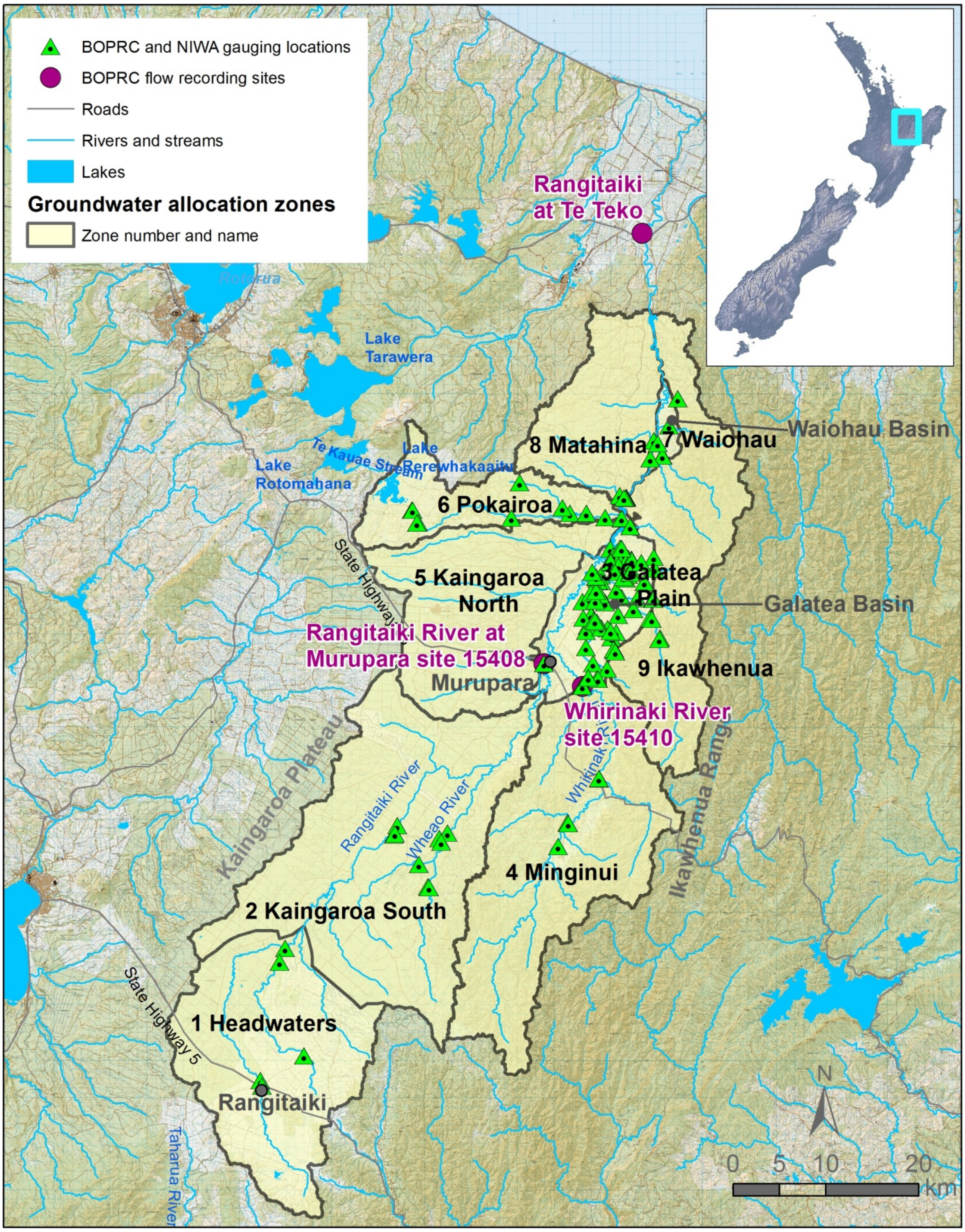

Figure 3.2 Groundwater allocation zones in the Upper Rangitaiki River catchment and flow recording sites.

3.3 WATER BUDGET AND GROUNDWATER FLOWS

A general water budget equation is used to describe the relationships between water inflow, water outflow and water storage within a defined area of a catchment (Scanlon *et al.*, 2002; Scanlon, 2012), and is used to estimate surface water allocation limits (Section 3.4) and GAA (Section 3.5).

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

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

Water inflows include:

P precipitation,

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

Q^{SW}_{IN} i.e., quick flow (Q^{SW}_{INBF}) + base flow (Q^{SW}_{INQF})

Q^{GW}_{IN} groundwater inflow

Water outflows include:

AET actual evapotranspiration

Q_{OUT} water flow out from the area

ΔS change in water storage.

With:

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

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

Q^{SW}_{OBF} surface water base flow outflow, i.e., base flow inflow plus baseflow generated in the area (i.e., discharge to surface water from the saturated portion of the groundwater system)

Q^{SW}_{OQF} surface water quick flow outflow, i.e., quick flow inflow plus quick flow generated in the area (i.e., interflow and runoff)

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:

$$P + Q^{SW}_{INBF} + Q^{SW}_{INQF} + Q^{GW}_{IN} = AET + Q^{SW}_{OBF} + Q^{SW}_{OQF} + U^{SW} + U^{GW} + Q^{GW}_{AOUT} \qquad (6)$$

With the convention that inflows are recorded with positive numbers and outflows are recorded with negative numbers, then:

$$P + Q^{SW}_{INBF} + Q^{SW}_{INQF} + Q^{GW}_{IN} + AET + Q^{SW}_{OBF} + Q^{SW}_{OQF} + U^{SW} + U^{GW} + Q^{GW}_{AOUT} = 0 \qquad (7)$$

The following text discusses each of the components, and simplifying assumptions, in this equation for the Upper Rangitaiki study area. This text also discusses the evidence for location of the groundwater catchment boundary in the vicinity of Lake Rerewhakaaitu (see Section 3.2).

3.3.1 Rainfall and evapotranspiration

Mean annual rainfall (P) was estimated by GIS from the nationwide National Institute of Water and Atmospheric Research (NIWA) dataset based on the rainfall measurements at individual climate stations, interpolated throughout New Zealand by NIWA and averaged for the period 1960–2006 (Tait *et al.*, 2006). Mean annual AET was estimated by GIS with 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).

3.3.2 Surface water inflow and groundwater inflow

Surface water inflow and groundwater inflow to each zone is assessed with the groundwater budget including gauging measurements (Figure 3.2). However, surface water inflow and groundwater inflow to the Upper Rangitaiki area (Q^{SW}_{IN} and Q^{GW}_{IN}, respectively) were assumed as zero as topographic boundaries are used to represent the area boundary and there is no evidence for groundwater inflows across the boundary of the study area.

Current drilling projects by BOPRC (Harvey, 2014) and Hawkes Bay Regional Council (HBRC), (Gordon, 2014), aim to further assess the groundwater catchment boundary in the Upper Rangitaiki area near the Taharua catchment, and in the vicinity of State Highway 5 near the south-eastern catchment boundary (Figure 3.2). However, groundwater inflows are assumed as zero in this report because the results of the BOPRC and HBRC drilling programmes have not been reported (as of October 2014).

3.3.3 Surface water flow: base flow and quick flow

Surface water flow is represented by base flow and quick flow components. Base flow is a high proportion of total surface flow in key volcanic lithologies in the Upper Rangitaiki area. For example, median flow is approximately 0.96 of the mean flow at the Rangitaiki at Murupara flow site (Table 3.2); this site records flow from a large area of the Upper Rangitaiki area including the Kaingaroa Plateau (Figure 3.2). In comparison, base flow from the greywacke Ikawhenua Range is 0.79 as measured at the Whirinaki River at Murupara site.

Table 3.2 Mean flow and median flow at BOPRC flow recording sites (Environment Bay of Plenty, 2001).

BOPRC flow site name	Site number	Median flow (m^3/s)	Mean flow (m^3/s)	Ratio of median flow to mean flow (base flow index (BFI))	$Q_{5\ 7\text{-day}}$ (m^3/s)	Period of record
Rangitaiki River at Murupara	15408	20.8	21.6	0.96	13.5	1949 to 2000
Rangitaiki River at Te Teko	15412	62.5	70.9	0.88	39.7	1949 to 2000
Whirinaki River	15410	11.7	14.8	0.79	4.3	1953 to 2000

In this report, base flow was assumed to be represented by median flow estimates, and quick flow as the difference between mean and median flow estimates, at the locations of continuous flow sites and gaugings (Figure 3.2). Hence, the BFI is represented with mean and median flow estimates, e.g.:

$$Q_T = Q^{SW}_{OBF} + Q^{SW}_{OQF} \tag{8}$$

$$BFI = Q^{SW}_{OBF} / Q_{OT} \tag{9}$$

With Q^{SW}_{OBF} = median outflow and Q_{OT} = mean outflow (as an estimate of total outflow), then:

$$BFI = Q_{Median} / Q_{Mean} \tag{10}$$

Calculation of base flow and quick flow was as follows:

- Q_{OT} is calculated to balance the water budget in some zones.
- BFI of 0.96 calculated from the flow record of the Rangitaiki at Murupara flow site was assumed to be representative of zones 1, 2, and 5, i.e., zones with similar geology as that in the catchment of the site.
- Similarly, a BFI of 0.79 calculated from the flow record of the Whirinaki River at Murupara site was assumed as representative of zones 4 and 9.
- BFI in other zones was calculated as a weighted average of BFI upstream zones.

Specific discharge estimates (i.e., stream flow divided by estimated catchment area in units of L/s/km^2) were also used to calculate water budget components.

3.3.4 Groundwater-surface water interaction

Groundwater-surface water interaction, i.e., Q^{SW}_{GW} (surface water discharge to groundwater) and Q^{GW}_{BF} (groundwater discharge to surface water), was assessed with available gauging data (Figure 3.2).

3.3.5 Groundwater outflow

Groundwater outflow from zones was calculated with the groundwater budget. An assessment of potential groundwater outflow to the Lake Tarawera catchment from zone 6 towards Lake Rotomahana in the Lake Tarawera catchment was completed in this report. This assessment used water budgets (including rainfall, AET and gauging measurements) and specific discharge estimates in zone 6 and the Lake Rotomahana catchment.

3.3.6 Water use

Consumptive uses of groundwater and surface water in the BOP Region includes: frost protection, irrigation, drinking water, and industrial applications (Figure 3.3). These water uses were estimated in three water use classes with assumptions on the use of consented allocation (Barber, 2014a) as follows:

- irrigation water use for 5 months in the year at the allocated daily rate (m^3/day);
- industrial water use for 365 days in the year at the daily allocated rate (m^3/day);
- municipal and community water use for 365 days in the year at the daily allocated rate (m^3/day).

Groundwater is used for frost protection in the BOP Region (e.g., White *et al.*, 2012a). However, no groundwater consents in the Upper Rangitaiki area are consented for frost protection.

Groundwater is also used by "permitted" users. These users may use relatively low volumes (i.e., up to 35 m^3/day/property; White *et al.*, 2012a) of groundwater to supply drinking water to humans and animals. However, this use is assumed as zero, as statistics on household wells and permitted use rates are not available in the Upper Rangitaiki area.

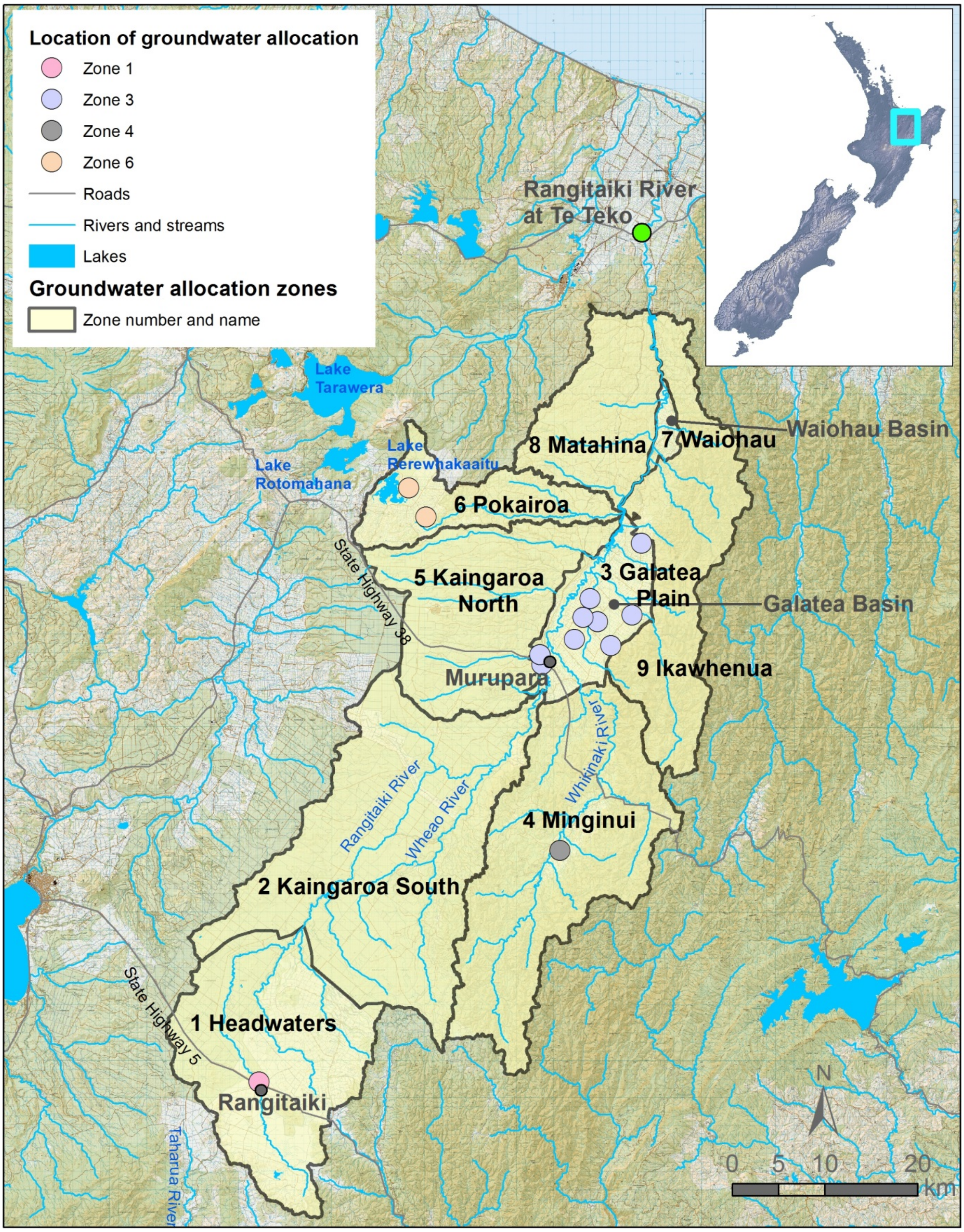

Figure 3.3 Locations of groundwater consented allocations.

3.3.7 Water budget calculations

Water budgets were developed for groundwater allocation zones in the Upper Rangitaiki area (Section 5.2). These budgets (Equation 7) included estimates of land area, P, and AET (Section 3.3.1), water inflows (Section 3.3.2) and surface flows (Section 3.3.3) with water outflow at zone boundaries set to balance the water budget to base flow and quick flow estimates in the Rangitaiki River at Murupara (for zone 2) and Whirinaki River at Murupara (for zone 4), Table 3.2. Therefore, minor adjustments to AET estimates in zone 4 and zone 8 were actioned. Assumptions in the water budget calculation include:

- Rangitaiki River flow was assigned to one zone where the zone boundary occurs along the river bed to simplify budget computation, i.e., zone 6 (Pokairoa) and zone 8 (Matahina);
- zone 9 (Ikawhenua) was divided into four areas with boundaries depending on the location of water outflow (Figure 3.4);
- zone 5 (Kaingaroa North) groundwater recharge was assumed to all flow to zone 3 (Galatea Plain) as no surface flows are measured in this zone (Figure 3.2); and
- additional assumptions as summarised in Section 5.2.

The budgets aim to represent natural flows. (i.e., U^{SW} and U^{GW} are equal to zero, Equation 7).

This water budget was then used to estimate water flows in each groundwater allocation zone prior to an assessment of GAA (Section 3.5). In addition, a more detailed water budget for Galatea Plain was developed because this area is an important area of groundwater use; this budget includes an assessment of groundwater-surface water interaction within the zone.

3.3.8 Zone 6: boundary of the groundwater catchment in the vicinity of Lake Rerewhakaaitu

The zone 6 catchment boundary was assessed using water budgets and specific discharge estimates in options for the area and location of subcatchment boundaries. Three options were associated with the Pokairoa Stream catchment boundary (i.e., the Upper Rangitaiki River catchment), and four options were associated with Te Kauae Stream catchment boundary (i.e., the Lake Rotomahana catchment; Figure 3.4):

- Mangaharakeke Stream option 1: the BOPRC surface catchment boundary;
- Mangaharakeke Stream option 2: a boundary coincident with the groundwater catchment boundary, migrated back to the subcatchment boundary based on a DTM of the area;
- Mangaharakeke Stream option 3: a boundary coincident with a topographic high that marks the approximate extent of relatively flat land east of Lake Rerewhakaaitu;
- Te Kauae Stream option 1: the BOPRC surface catchment boundary;
- Te Kauae Stream option 2: Te Kauae Stream catchment upstream of site 15378 and the area west of Mangaharakeke option 2;
- Te Kauae Stream option 3: Te Kauae Stream catchment upstream of site 15378, the area between this catchment and Lake Rerewhakaaitu, and the area of Lake Rerewhakaaitu;

- Te Kauae Stream option 4: the surface catchment boundary of the south branch of the stream in the area of Lake Rerewhakaaitu, and Lake Rerewhakaaitu.

Two Te Kauae Stream sub-catchment boundary options included the geographic area of Lake Rerewhakaaitu, because lake water may flow to this sub-catchment (White *et al.*, 2003; Reeves *et al.*, 2008). Option 4 was defined to assess the observation that most flow in Te Kauae Stream at site 15478 is sourced from the south branch of Te Kauae Stream (Reeves, 2014; Figure 3.4).

Gauged stream flow measurements were compared with estimates of flows, using: catchment water budgets; a water budget for Lake Rerewhakaaitu (Gillon *et al.*, 2009); and specific discharge estimates.

River flow gauging measurements in zone 6 and in part of zone 7 (the Pahekeheke and Waikowhewhe sub-catchments) were also relevant to this assessment (Figure 3.5). These gaugings included measurements by BOPRC and NIWA (Naysmith, 2013; Putt, 2014; and McGrath, 2013). Gauging measurements in four Lake Rotomahana sub-catchments were measured on 11/3/2014 (Putt, 2014). Other streams in the Lake Rotomahana sub-catchment are typically dry (Scott, 2014). Lake Okaro drains to Haumi Stream, as does Waimangu Stream and the Waimangu geothermal field (Figure 3.5). However, a water budget for Lake Okaro was not used in this assessment as the area of the lake is small.

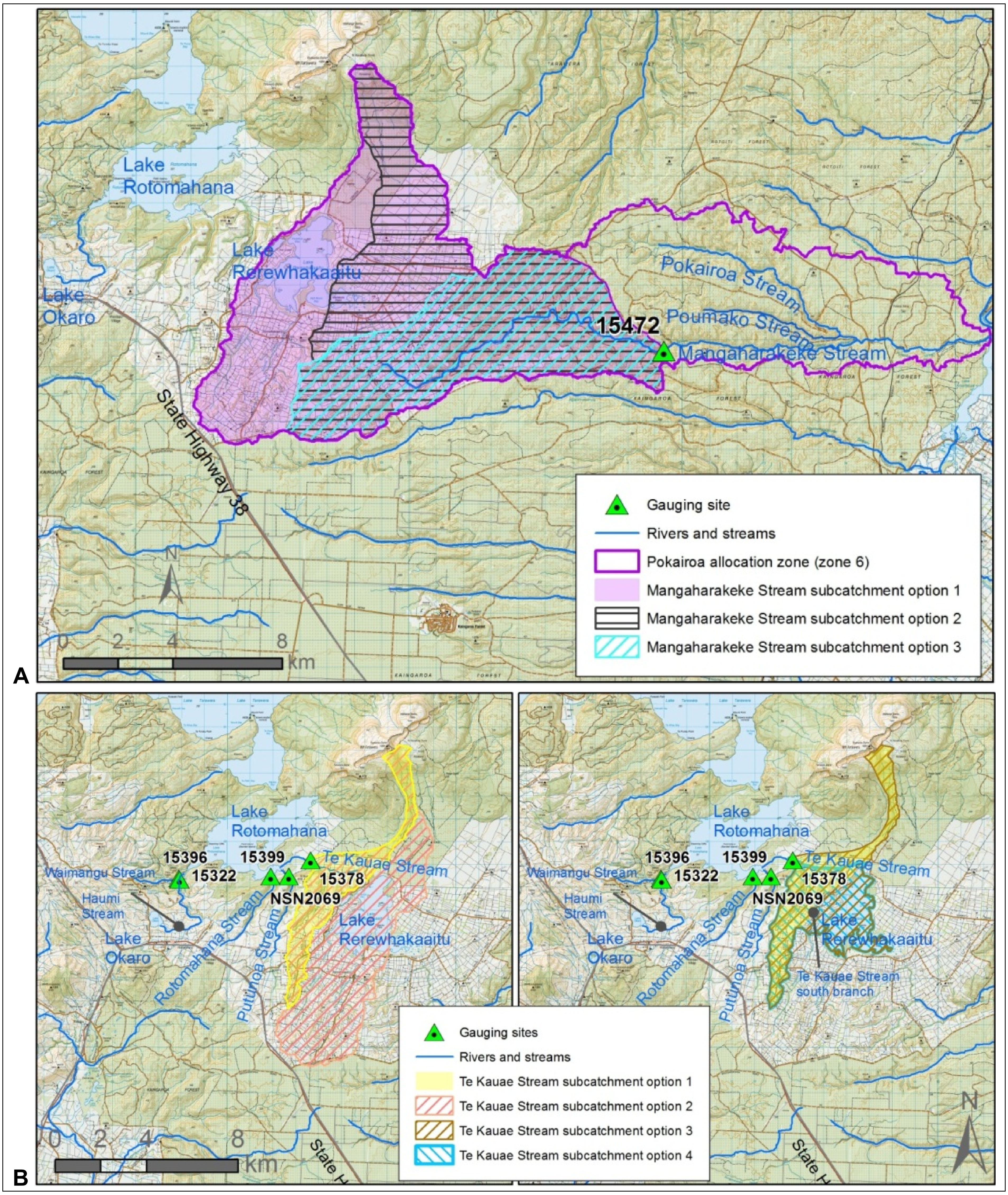

Figure 3.4 A: Options for the land area of the Pokairoa Stream sub-catchment (i.e., Mangaharakeke Stream sub-catchment), relative to gauging site 15472. B: Options for the Te Kauae Stream sub-catchment in the Lake Rotomahana catchment.

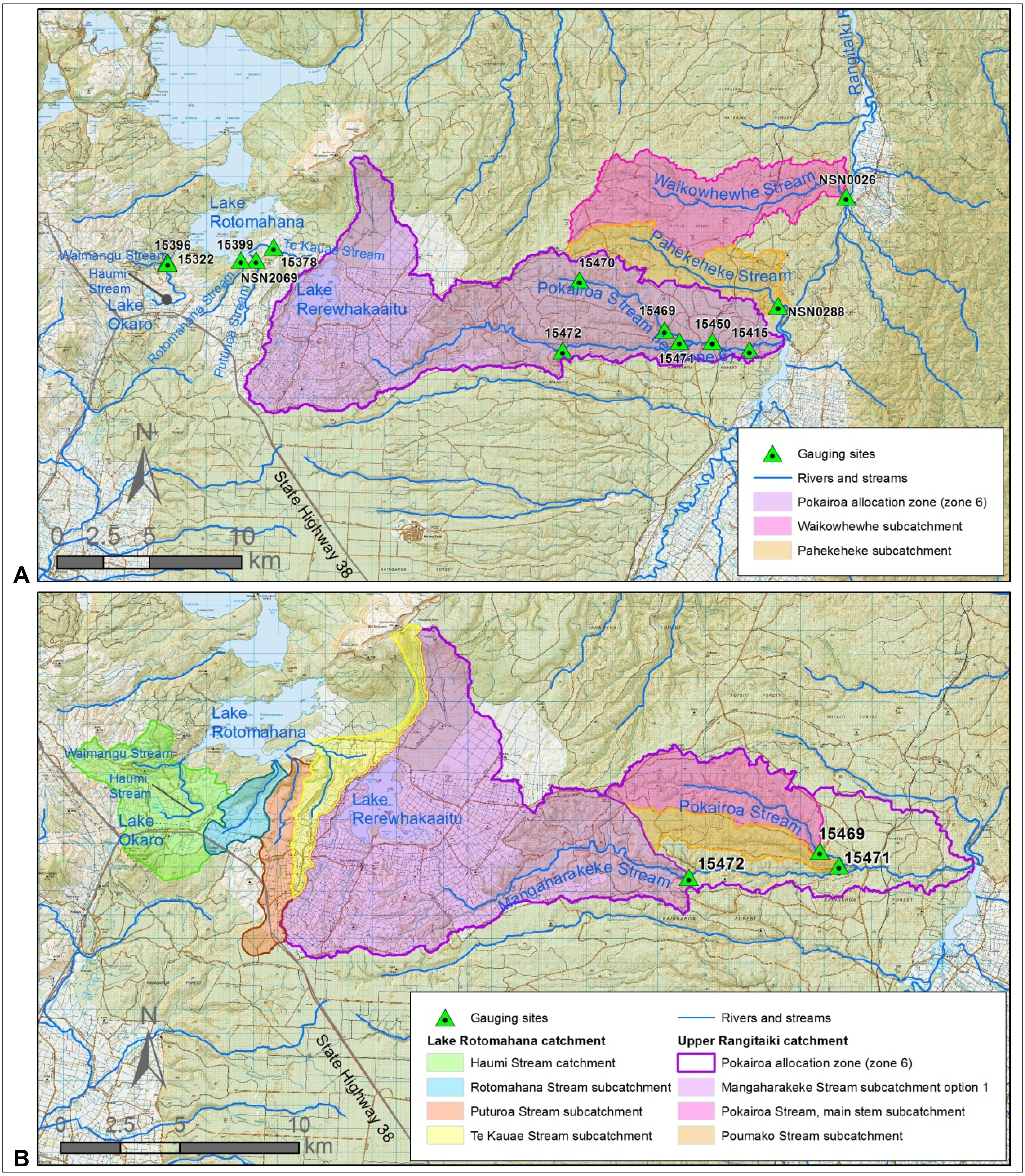

Figure 3.5 A: sub-catchments of Pokairoa Stream (i.e., zone 6), Pahekeheke Stream and Waikowhewhe Stream (West, 2014) and gauging sites. B: gaugings in the Lake Rotomahana catchment were measured on 11/3/2014 (Putt, 2014).

3.4 MINIMUM FLOW LIMITS

Minimum flow limits (MFLs) for groundwater were used to manage water allocation with aims including the preservation of groundwater levels (e.g., to preserve stream base flow) and maintenance of stream flow (e.g., to preserve ecological values in streams; Bloxham, 2008). These limits are the responsibility of BOPRC. Currently BOPRC has no policies on MFLs for the Upper Rangitaiki area and the development of policies is recommended (Section 6.0).

As a guide to groundwater allocation, BOPRC is using interim groundwater allocation limits (Ministry for the Environment, 2008), including:

"An allocation limit of, whichever is the greater of:

- 35% of the average annual recharge as calculated by the regional council;
- the total allocation from the groundwater resource on the date that the standard comes into force less any resource consents surrendered, lapsed, cancelled or not replaced."

"For groundwater that is shown to be connected to adjacent surface water, the environmental flow or water level set for the surface water body will also apply to the management of groundwater takes" (Ministry for the Environment, 2008).

The close connection between groundwater and surface water in the Upper Rangitaiki area was demonstrated by a high BFI (e.g., greater than 0.9 in the catchments that drain volcanic lithologies, Table 3.2) and by water budgets derived in this report that show that most of the balance of P and AET flows to streams as base flow (e.g., Section 5.2). This connection means that use of groundwater has a significant potential to impact on surface water flows. Therefore, this report calculates the GAA considering groundwater budgets and surface base flow (Section 3.5).

BOPRC also uses surface flow limits for consideration of surface allocation. For example, '$Q_{5\ 7\text{-day}}$' flow (i.e., 7 day low flow minimum, which is a minimum of annual mean flow for any 7 consecutive days, that has a 20% probability of occurring in any one year) as a measure of minimum flow (Wilding, 2003). $Q_{5\ 7\text{-day}}$ flows are available for the Rangitaiki River (two locations) and the Whirinaki River (Table 3.2). However, $Q_{5\ 7\text{-day}}$ flows are not generally available for streams in the area and it is beyond the scope of this report to calculate these flows from synthetic flow observations. Therefore, $Q_{5\ 7\text{-day}}$ flows in groundwater allocation zones were estimated with:

$$Q_{5\ 7\text{-day}} = AQ^{SW}_{OTZ} \tag{11}$$

where

A is the ratio of $Q_{5\ 7\text{-day}}$ and mean flow calculated in the Rangitaiki River at Murupara and the Whirinaki River at Murupara, i.e., 0.63 and 0.29, respectively.

Q^{SW}_{OTZ} is the surface outflow (i.e., baseflow and quick flow) from the zone.

Q^{SW}_{OTZ} is equal to Q_{OT} (equation 8) in the zones without surface inflows (i.e., zones 1, 4, 5, and 9). In other zones, Q^{SW}_{OTZ} is the difference between inflows to the zone (surface and groundwater) and surface outflows from the zone.

In this report, minimum flow for groundwater (MFL^{GW}) is the equal to the greater of:

- 65% of R (i.e., the minimum groundwater flow equivalent to an allocation limit of 35% of groundwater recharge; Ministry for the Environment (2008);
- $Q_{5\ 7\text{-day}}$ low flow in rivers and streams.

3.5 GROUNDWATER AVAILABLE FOR ALLOCATION

GAA was estimated in the Upper Rangitaiki area using water budgets and minimum flow estimates. BOPRC policies are crucial to the implementation of a water allocation regime in the Upper Rangitaiki area. In lieu of BOPRC policies, this report suggests a water allocation scheme for groundwater that is consistent with minimum groundwater flow guidelines (Ministry for the Environment, 2008) and preservation of surface water base flows. This approach was similar to that used to estimate GAA for BOPRC in the Opotiki area (White *et al.*, 2012a) that aimed to preserve low flows in streams.

The general equation to estimate GAA from the water budget in each groundwater allocation zone is as follows:

$$GAA = R - MFL^{GW} \tag{12}$$

with the convention that components are positive numbers; and

$$R \text{ (groundwater recharge)} = P + Q^{GW}_{IN} + AET + \Delta Q^{SW}_{QF} \tag{13}$$

with $\Delta Q^{SW}_{QF} = Q^{SW}_{OQF} + Q^{SW}_{INQF}$, i.e., the quick flow generated in the zone.

Equation 13 is derived from equation 7 assuming quick flow that is generated in the zone does not enter the groundwater system and that water use is zero with the convention that inflows are positive numbers and outflows are negative numbers, as per equation 7.

Conservative assumptions for equation 13, in regards of the GAA calculation, have:

- $Q^{GW}_{IN} = 0$, i.e., groundwater inflows from adjacent zones were not included in the GAA estimation. A conservative approach is to not allocate this inflow because errors in water budget components are compounded in these estimates. Therefore, groundwater allocation in one catchment is not dependent on groundwater outflow from another catchment; and
- $\Delta Q^{SW}_{QF} = 0$ where $Q^{SW}_{OQF} + Q^{SW}_{INQF}$ is greater than zero. This occurs where estimated quick flow in the Rangitaiki River decreases between the locations of inflow and outflow of zones 3 and 6 (Section 5.2), which is probably due to uncertainty in Rangitaiki River quickflow estimates.

Current groundwater allocation was compared with estimates of GAA for two purposes. Firstly, current groundwater allocation in the Upper Rangitaiki area is relevant to the Ministry for the Environment (2008) guideline. Secondly, an assessment of the relationship between current allocation and GAA is useful to BOPRC in assessing the sustainability of current groundwater allocation.

4.0 RESULTS: 3D GEOLOGICAL MODEL

4.1 UPPER RANGITAIKI RIVER CATCHMENT MODEL

4.1.1 Model description

The Upper Rangitaiki geological model consists of 8 geological layers within 10 fault blocks (Figure 4.1). The geological layers are:

- one layer representing all basement rocks;
- one layer representing all volcanic and sedimentary deposits between Whakamaru Group and Basement (Mangakino and other older volcanics);
- five layers representing volcanic deposits (Taupo Group, Kaingaroa Formation, Matahina Formation, Whakamaru Group); and
- one layer representing Tauranga Group sediments.

Faults used to split the model into fault blocks include the:

- Waiohau 1, Waiohau 2, and Waiohau 3 faults of the Waiohau Fault System;
- Kaingaroa 1, Kaingaroa 2, and Kaingaroa 3 faults of the Kaingaroa Fault System;
- Te Whaiti Fault; and
- Wheao Fault.

Basement rocks crop out in the Ikawhenua Range in the east and cover the entire model area at depth. This layer is the deepest in the west of the model area, where it has been down-faulted by the Kaingaroa Fault System to a maximum depth of c. -1,150 m RL. In the central part of the model area, basement is relatively shallow and crops out in relatively isolated areas; however, basement is located at a maximum depth of -1,000 m RL under the Galatea Plain.

Mangakino and other older volcanics are up to 1,000 m thick between basement and Whakamaru Group. These older volcanics overlie basement in the Waiohau and Galatea Plain. In the eastern part of the model area, Mangakino and other older volcanics have been eroded or have never been deposited.

Whakamaru Group deposits cover the eastern and central part of the model area at depth or at the ground surface. In the north and west they are overlain by Matahina Formation and Kaingaroa Formation. In the southern part of the model area, this unit is relatively shallow and only overlain by Tauranga Group and Taupo Group deposits. Whakamaru Group constitutes a potential deeper aquifer in the Galatea and Waiohau basins.

The Matahina Formation outcrops over a large part of the ground surface between the northern boundary of the study area and the Galatea Basin. At the subsurface, the formation extends into the Waiohau and Galatea Basins and is only covered by Tauranga Group deposits in these areas. This unit could also be a potential deeper aquifer in these basins. The Kaingaroa Formation only occurs at the ground surface in the study area. Here, it builds the Kaingaroa Plateau in the western part of the model area and has a maximum thickness of approximately 200 m.

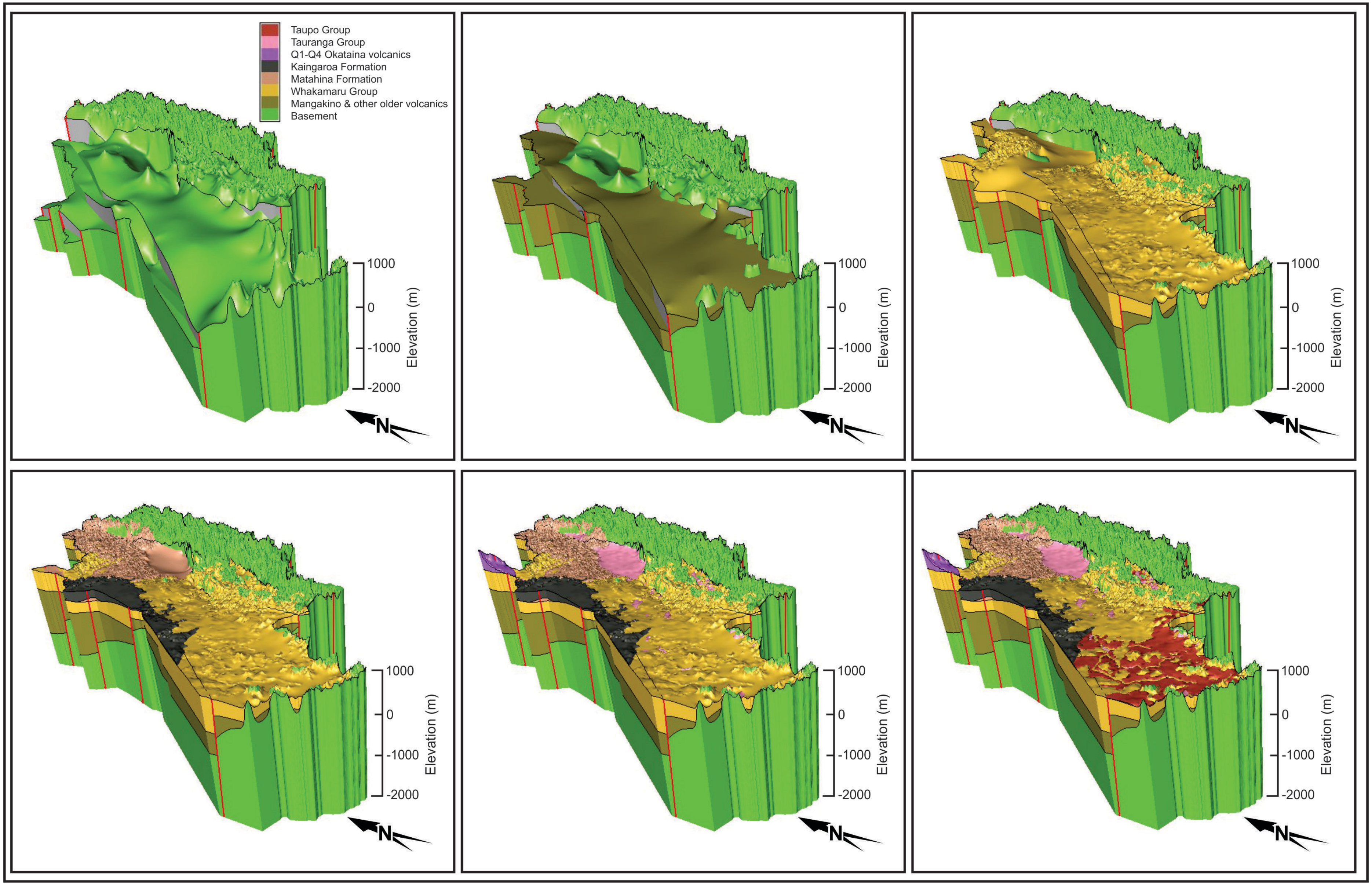

Figure 4.1 Views of the 3D geological model from the oldest to the youngest model unit.

Q1-Q4 Okataina volcanics only exist in a very limited zone in the northwest of the model area near the boundary with the greater Lake Tarawera catchment. In the western-most part of the model, which is closest to the source of these deposits, this unit has a maximum thickness of approximately 400 m that steeply decreases to only a few meters in the east.

The main volume of Tauranga Group sediments occurs in the Galatea Basin. Here, this formation has a maximum thickness of approximately 150 m and directly overlies Matahina Formation. Tauranga Group has also been deposited to a lesser extent in the Waiohau and Minginui Basins. This formation is an important aquifer in the model area. Taupo Group deposits are only located in the southern part of the model area, where they directly overlie Whakamaru Group. Their thickness in this area is limited to only a maximum of approximately 20–30 m.

4.1.2 Model datasets

The final version of the Upper Rangitaiki geological model uses datasets as summarised in Table 4.1.

Table 4.1 Upper Rangitaiki geological model: 2D and 3D model datasets of the final model version. The file formats are proprietary to EarthVision (Dynamic Graphics, Inc., 2013).

File name	Description
Entire_ur_boundary.ply	Study area boundary used to clip the model
UR11_DGI.seq	Sequence file used to define the stratigraphic and structural relationships between geological layers.
UR11_clip.unsliced.faces	3D volume file built using the sequence file

4.2 MODEL UNCERTAINTIES

Geological models are, by definition, a simplification of the Earth's stratigraphy and structure. These models are subject to uncertainty with regard to input data and model construction. Model input data has varying degrees of uncertainty. There are some data types whose uncertainty is solely linked to measurable resolution, for example ground elevation data (Section 3.1.1.1), whereas some datasets (such as bore logs) that are heavily influenced by unquantifiable personal interpretation. For example, bore logs are a construct of a driller's interpretation of the drilled materials, and some drillers note only very general descriptions of geological units.

The complexity of model generation is linked to the geological complexity being represented. Invariably, the model generation process is sufficiently complex to require both the skills of a geologist as well as an expert model builder. However, uncertainty analysis is not commonly used with geologic models (Lelliott *et al.*, 2009). Key issues that require expert judgment include correlation of strata identified in well logs and interpretations of structure based on geological maps. The use of expert judgement can reduce, but not eliminate, uncertainty in geological models.

The following sections aim to outline some of the uncertainties in the Upper Rangitaiki geological model. However, a full assessment of model uncertainty is complex and beyond the scope of this project.

4.2.1 Uncertainty in model input data

4.2.1.1 Topographic data

The 8 m Geographx DTM (Geographx, 2012) used for the modelling has been generated from 1:50,000 maps published by LINZ and 3-second Shuttle Radar Topography Mission data (Geographx, 2012).

The spatial accuracy of this topographic dataset, at the original 8 m grid resolution, is better than 22 m horizontally and lies within +/- 10 m vertically. However, due to the high computing power required to process large datasets, such a high resolution is not practical for geological modelling. Therefore, the DTM was down-sampled to the modelling resolution of a 100 m by 100 m grid. This results in a higher uncertainty than the uncertainty of the original dataset.

4.2.1.2 Geological map boundaries

Digital geological maps express map units as polygons and uncertainty is associated with these boundaries. The QMAP 1:250,000 Geological map of Rotorua (Leonard *et al.*, 2010) is the best data source for information on the geological conditions at the ground surface in the model area. The spatial accuracy of this map is estimated to be no better than +/- 100 m for ‘accurately’ located geological features and in some places may exceed 250 m. Geological data attributed as ‘approximately’ located will have a spatial accuracy no better than 250 m and in some places is expected to be significantly less accurate.

Additionally, geologic units might not be shown in a map if their thickness is below a certain value. QMAP, for instance, generally will not display a unit unless it is at least 10 m thick or very important. This can result in unit boundaries that are quite different than the actual geological boundary (Begg, 2011).

4.2.1.3 Subsurface geological data

Bore logs provided by BOPRC are the main source of subsurface data for the construction of the Upper Rangitaiki 3D geological model. Section 3.1.1.3 describes some of the limitations of this dataset. Generally, uncertainties associated with bore log data include data collection, storage, and/or spatial sampling uncertainties.

The uncertainties in bore log data collection can include:

- location and well depth estimates may be poorly identified;
- logging by drillers is of variable quality, with some drillers recording only very general descriptions of geologic units;
- drilling methods are variable and some are better than others for identifying geology. For example cable tool drilling provides more reliable geologic logging results than air rotary in unconsolidated sediments;
- commonly wells are not logged by a geologist or hydrogeologist, and so descriptions of formations are typically highly variable. For example ignimbrite may be variously named as ‘rhyolite’, ‘volcanic rock’, ‘rock’, or ‘ignimbrite’ by drillers. In addition, formation names are not often recorded by drillers and are generally unknown to them. The names may even be imperfectly identified by field geologists or hydrogeologists until verified by more experienced professionals or examined in the laboratory.

Data storage uncertainties associated with bore logs include incorrect data entries (e.g., typographic mistakes, incorrect decimal points in well depth or logged intervals) or wells that have been entered into a regional council data base more than once. Any obvious errors have been manually corrected. However, minor errors in the stored well data can be particularly problematic during the 3D model development as they often remain undetected and therefore poor quality data can be used to constrain layer surfaces.

Whereas storage uncertainties of well datasets often remain undiscovered, spatial sampling uncertainties are more obvious. Spatial sampling uncertainties consist of all uncertainties introduced by the limitations in the availability of information throughout the model area. In general, the denser the population of bore logs within a part of the model area is, the greater the certainty in model development for this area. The pattern of distribution of bore logs throughout the model area is another important factor. For example, models in areas without any bore logs, or with very few bore logs, have a far higher uncertainty than models in areas with evenly distributed bore logs. The uncertainty in geological layer location increases with depth. This is because wells are generally shallow (e.g., 95% of the wells with lithological logs within the Upper Rangitaiki River catchment are less than 100 m deep), and geophysical methods produce less certain results as the depth of the target increases.

4.2.2 Uncertainty in the model construction

4.2.2.1 Modelling software

The Upper Rangitaiki River catchment model was developed using EarthVision geological modelling software version 8.1 (Dynamic Graphics, Inc., 2013). The surfaces were interpolated using the EarthVision ‘Minimum Tension Gridding’ method at a horizontal resolution of 100 m x 100 m. This gridding method uses an iterative approach to calculate a smooth, evenly distributed grid while seeking to honour the input data.

4.2.2.2 Model structures

Uncertainties are associated with the location of faults and other large-scale geological features such as fault blocks. Faults and caldera boundaries in the Upper Rangitaiki model area are mapped at the ground surface (Leonard *et al.*, 2010). However, the distribution of these features at depth can be quite speculative. In addition, the estimates of the location of these features are not verifiable with current data. Therefore estimates of the uncertainties in Upper Rangitaiki model structures cannot be made.

4.2.2.3 Layer surfaces

Additional uncertainty may be introduced through the gridding algorithm used to interpolate the layer surfaces and the gridding resolution chosen for the model grids. Gridding is the process of interpolating a regular grid based on irregular data points space (e.g., interpreted bore log data) in a 3D space. The more data points that are available, the lower the uncertainty resulting from the gridding method. However, the uncertainty can only be quantified if ground-truthing data is available.

4.2.2.4 Layer distribution

Interpolation of input data to create layer surfaces subsequently generates a model of subsurface layer distribution. Uncertainty in the layer distribution, for layers below the ground surface, is relatively high compared to that in units exposed at the ground surface. Uncertainty in the vertical location of layer boundaries (i.e., layer tops and bottoms) may be near zero for layers exposed at the ground surface.

5.0 RESULTS: GROUNDWATER BUDGET

In this section, groundwater budget components are described. Firstly, groundwater zones are defined, including an assessment of the boundary of the groundwater catchment in the vicinity of Lake Rerewhakaaitu. Then, a water budget is developed and GAA is calculated and compared with current groundwater allocation.

5.1 GROUNDWATER CATCHMENT

Zone 1 (headwaters) includes the headwaters of the Rangitaiki River to the confluence with the Otamatea River (Figure 5.1). Land use in this area includes forest in the west and extensive pastoral farming in Lochinver Station and Rangitaiki Station to the south. Surficial geology includes Taupo Group sediments (Figure 2.2). Subsurface geology is characterised by Whakamaru Group ignimbrite over much of the area, with Kaingaroa Formation ignimbrite in the west and basement cropping out in the east.

Zone 2 (Kaingaroa South) includes the Kaingaroa Plateau in the west (i.e., Kaingaroa Formation ignimbrite) and basement ranges in the east (Figure 5.1). The valleys of the Rangitaiki and Wheao Rivers are included in zone 2. Forestry is the predominant land use in the zone, with plantation forestry over much of the Rangitaiki and Wheao river valleys with native forest in the eastern hills. This zone includes the Wheao Dam and is drained by the Rangitaiki River at the Galatea Plain.

Galatea Plain (zone 3) occupies an area between the Kaingaroa Plateau and Ikawhenua Range (Figure 5.2). Land use on the Galatea Plain is pasture, with dairy farms occupying much of the area. Many rivers and streams cross the Galatea Plain from the Ikawhenua Range to the Rangitaiki River. These include the Whirinaki River, Horomanga Stream, and Omahuru Stream; the Rangitaiki River is also within this zone.

Zone 4 (Minginui) includes the greywacke mountains of the Ikawhenua Range and includes the Minginui Basin (Figure 5.1). Native forest is the predominant land use in the zone.

Zone 5 (Kaingaroa North) includes the northern Kaingaroa Plateau and is bordered to the east by the Rangitaiki River (Figure 5.3). Forestry is the predominant land use in this zone.

Zone 6 (Pokairoa Stream catchment) includes the Rangitaiki River which bounds the zone to the east (Figure 5.3). This zone includes the Lake Rotomahana area, where the predominant land use is dairy; land use to the east of the lake is forestry. Matahina Formation is the predominate geology in this zone. Zone 7 is the alluvial Waiohau Basin; dairy is the main land use in this zone (Barber, 2014b; Figure 5.4).

The Matahina zone (zone 8) is bounded to the north by the Rangitaiki Plains and to the east by the Rangitaiki River, which is included in the zone. Matahina Formation is the predominate geology in this zone and plantation forest is the predominant land use. The Ikawhenua zone (zone 9) includes the greywacke mountains of the Ikawhenua Range that are covered by native forest.

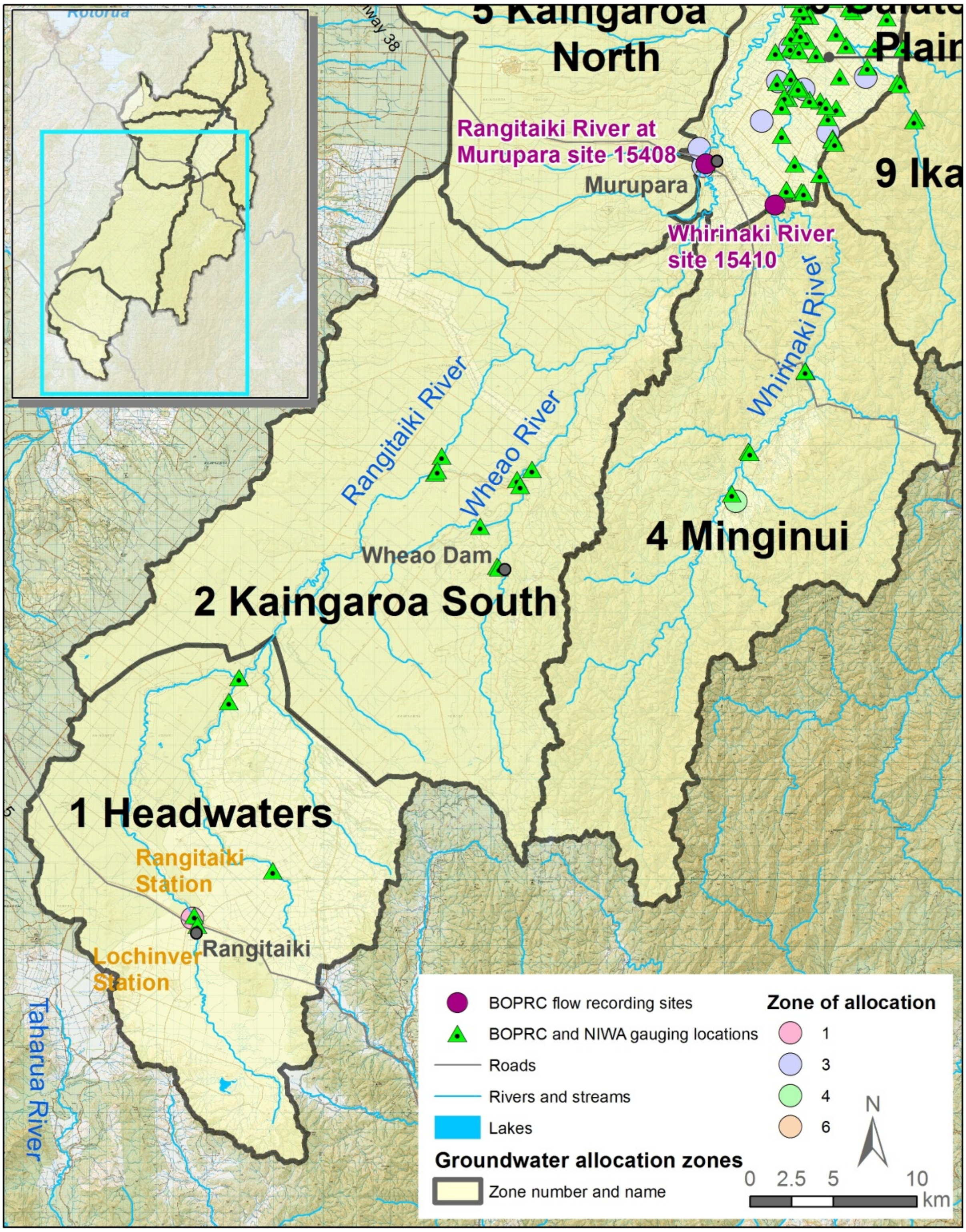

Figure 5.1 Features of zones 1, 2, and 4.

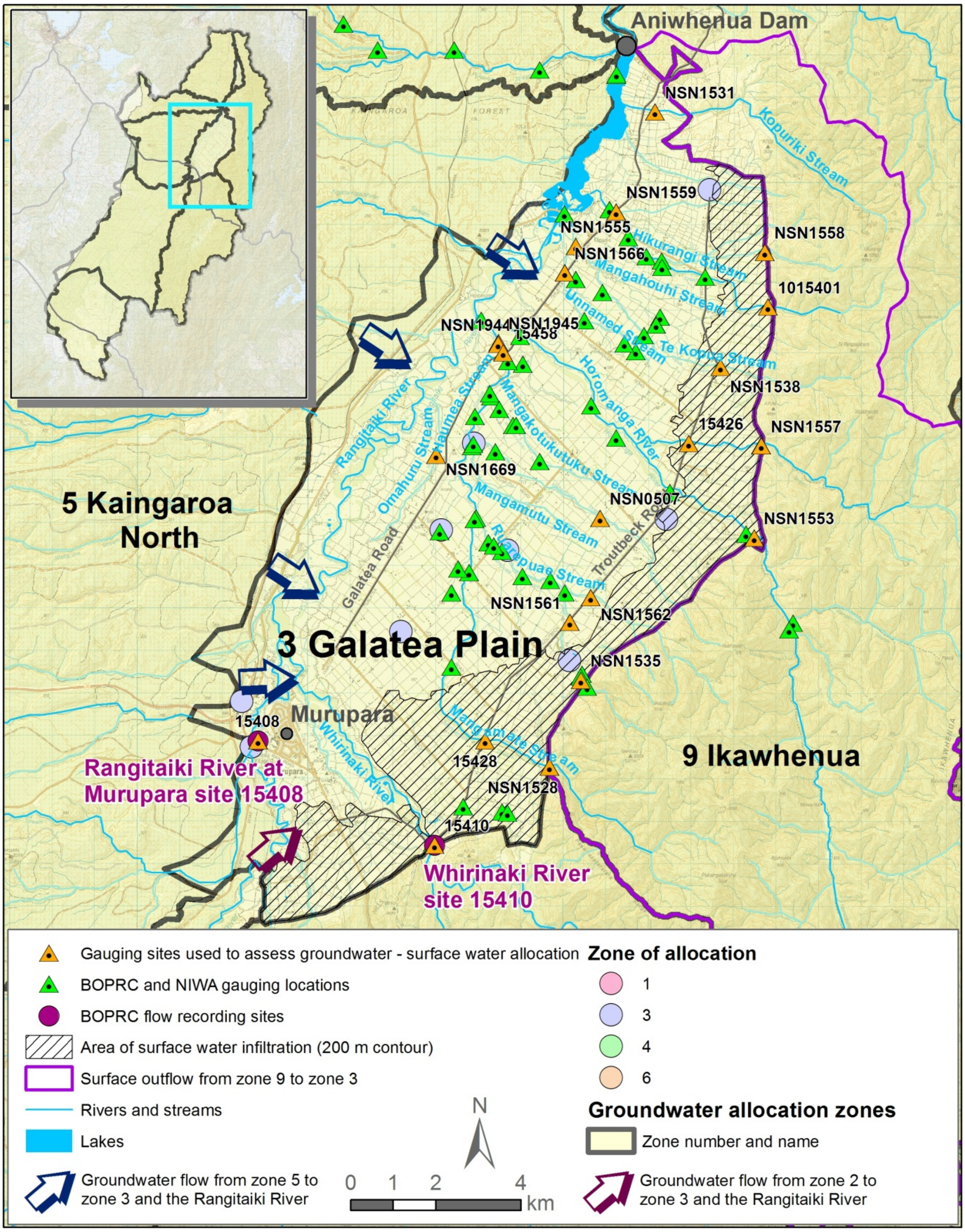

Figure 5.2 Features of zone 3.

Figure 5.3 Features of zones 5, 6, and 8.

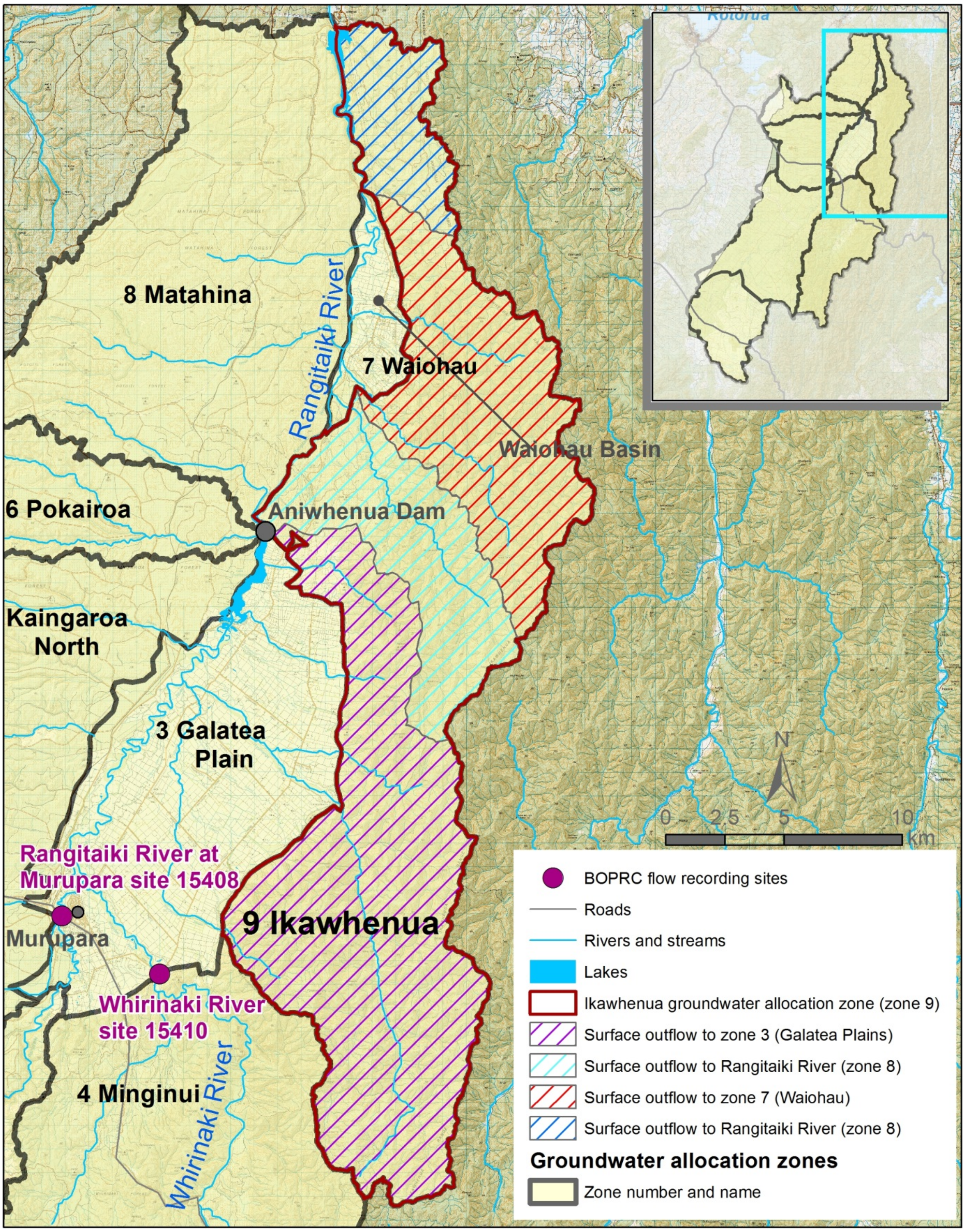

Figure 5.4 Features of zones 7 and 9.

5.1.1 Boundary of the groundwater catchment in the vicinity of Lake Rerewhakaaitu (zone 6)

Specific discharge from sub-catchments that drain to the Rangitaiki River (i.e., Pokairoa, Pahekeheke and Waikowhewhe), were largest in the Pokairoa Stream sub-catchment (Table 5.1). Surface flow in the Mangaharakeke Stream sub-catchment is the largest component of flow in Pokairoa Stream headwaters (Figure 3.4 and Table 5.1). For example, median flow in Mangaharakeke Stream is 1,729 L/s at site 15472, whereas median flow in the other subcatchments (Pokairoa Stream and Poumako Stream) totals 314 L/s.

The land areas in Mangaharakeke Stream options 1 or 2 (Figure 3.5) provide the observed flow at site 15472, i.e., rainfall – AET > median flow at the site (Table 5.2). In contrast, the land area of Mangaharakeke Stream option 3 is probably too small to support observed flow at site 15472, as evidenced by: 1) rainfall - AET that is significantly less than median flow at the site (Table 5.2); and 2) specific discharge (39 L/s/km^2) required to match median flow at the site that is much larger than that observed in other subcatchments (Table 5.1 and Table 5.3).

The boundary of Mangaharakeke Stream option 2 is common with the boundary of the Te Kauae Stream option 2 subcatchment. However, the area of Te Kauae Stream option 3 is too large as rainfall – AET is much larger than observed flow at gauging site 15378 (Table 5.2 and Table 5.3, respectively) and specific discharge is unusually low compared with the three Mangaharakeke Stream subcatchment options (Table 5.3). Therefore, the boundary between the Upper Rangitaiki and Lake Rotomahana catchments is likely to be west of Mangaharakeke Stream option 2.

Evidence that groundwater is flowing from the Lake Rerewhakaaitu area into Te Kauae Stream includes:

- specific discharge from the Te Kauae Stream subcatchment is larger than other Lake Rotomahana subcatchments (Table 5.1);
- specific discharge from the south branch of Te Kauae Stream (an estimated 17 L/s/km^2) assuming all water flow measured at site 15378 originates from the south branch, as suggested by Reeves (2014). This specific discharge is similar to specific discharge from Mangaharakeke Stream subcatchment options 1 and 2 (Table 5.3) yet average rainfall on the Te Kauae Stream subcatchment is less than that on Mangaharakeke Stream subcatchments (Table 5.2); and
- previous work, i.e., water budgets of the lake and catchment (White *et al*., 2003); and the chemistry of groundwater and surface waters (Reeves *et al*., 2008).

The area of Te Kauae Stream subcatchment option 4 was divided into three components: the south branch topographic subcatchment and two areas in the Mangaharakeke Stream subcatchment, i.e., land between the topographic subcatchment and Lake Rerewhakaaitu and Lake Rerewhakaaitu (Table 5.4). The components of surface flow at site 15378 were calculated with the average specific discharge (7 L/s/km^2) of other Lake Rotomahana subcatchments i.e.: Putunoa Stream, Rotomahana Stream and Haumi Stream (including Waimangu); and P – AET on Lake Rerewhakaaitu. These flow estimates indicate that the groundwater outflow from the Mangaharakeke Stream subcatchment option 1 to the Te Kauae Stream subcatchment is 118 L/s (i.e., 20 + 98 L/s, Table 5.4).

Table 5.1 Surface flows measured in gaugings and specific discharge.

Subcatchment	Subcatchment area of flow site (km^2)	Flow site number (Figure 3.4)	Median flow (L/s)	Specific discharge ($L/s/km^2$)	Source of flow data	Period (number of measurements)	Statistic
Pokairoa/full	163.9	15415	1911	11.7	NIWA	1989–1995 (3)	Median
Pokairoa	20.3	15469	268	13.2	NIWA	1993–2001(42)	Median
Pokairoa/Poumako	10.1	15471	46	4.6	NIWA	1993–2001(57)	Median
Pokairoa/Mangaharakeke	104.5	15472	1729	16.5	NIWA	1994–2001(55)	Median
Pahekeheke	25.2	NSN0288	190	7.5	BOPRC	1982 (1)	Single observation
Waikowhewhe	48.7	NSN0026	211	4.3	BOPRC	1974 (1)	Single observation
Te Kauae Stream	12.4	15378	166	13	BOPRC	2014(1)	Single observation
Putunoa Stream	9.8	NSN2069	26	3	BOPRC	2014(1)	Single observation
Rotomahana Stream	5.8	15399	56	10	BOPRC	2014(1)	Single observation
Haumi (includes Waimangu)	22.5	15396 and 15322	168	7	BOPRC	2014(1)	Single observation

Table 5.2 Estimated water budgets for Mangaharakeke Stream and Te Kauae subcatchment options.

Subcatchment	Catchment area (km^2)	Inflows		Outflows			Median surface flow (L/s)
		Median rainfall NIWA (mm/yr)	Rainfall flow (L/s)	Median AET NIWA (mm/yr)	AET flow (L/s)	P - AET (L/s)	
Mangaharakeke Stream option 1	104.5	1532	5080	807	2670	2410	1729
Mangaharakeke Stream option 2	74.2	1577	3710	811	1910	1800	1729
Mangaharakeke Stream option 3	47.7	1584	2400	821	1240	1160	1729
Te Kauae Stream option 1	12.4	1384	544	798	314	230	166
Te Kauae Stream option 2	42.8	1406	1908	796	1080	828	166
Te Kauae Stream option 3	19.4	1407	866	800	492	374	166
Te Kauae Stream option 4	14.9	1400	661	800	378	283	166

Table 5.3 Median flows and specific discharge estimates for Mangaharakeke Stream and Te Kauae subcatchment options.

Subcatchment	Subcatchment area of flow site (km^2)	Flow site number (Figure 3.4)	Median surface flow (L/s)	Specific discharge ($L/s/km^2$)
Mangaharakeke Stream option 1	104.5	15472	1729	17
Mangaharakeke Stream option 2	74.2	15472	1729	23
Mangaharakeke Stream option 3	47.7	15472	1729	36
Te Kauae Stream option 1	12.4	15378	166	13
Te Kauae Stream option 2	42.8	15378	166	4
Te Kauae Stream option 3	19.4	15378	166	9
Te Kauae Stream option 4	14.9	15378	166	11

Table 5.4 Estimated flows in three areas of the Te Kauae Stream subcatchment option 4.

Te Kauae Stream subcatchment option 4 area	BOPRC subcatchment	Area (km^2)	Contribution to flow at site 15378 (L/s)	Notes
Te Kauae Stream topographic catchment	Te Kauae Stream	6.9	48	Assume 7 $L/s/km^2$
Land to the east	Mangaharakeke Stream option 1	2.9	20	Assume 7 $L/s/km^2$
Lake Rerewhakaaitu	Mangaharakeke Stream option 1	5.1	98	To balance flow at site 15378
Total	Total	14.9	166	Flow at site 15378

Estimates of total Lake Rerewhakaaitu outflow to groundwater are: 100 L/s (i.e., P – AET for the 5.1 km^2 catchment) and 194 L/s (from a lake water budget calculation; Gillon *et al.*, 2009). Groundwater outflow from the lake to the Te Kauae Stream is within the approximate range of 50% (i.e., 98/194) to 100% (i.e., 98/100) of total lake outflow to groundwater. In this situation, groundwater outflow from the lake may travel to the Te Kauae Stream subcatchment, to the Mangaharakeke Stream subcatchment, or both.

Groundwater outflows to the Te Kauae Stream subcatchment are low relative to the Mangaharakeke Stream subcatchment water budget items (Table 5.2). Therefore, in this report it is assumed that the groundwater catchment boundary of zone 6 is coincident with the BOPRC catchment boundary. Additional surface gauging's in the Te Kauae Stream south branch would be useful to a further assessment of inflows to this stream from the Mangaharakeke Stream subcatchment (see Recommendations, Section 6.0).

5.2 GROUNDWATER BUDGET COMPONENTS

5.2.1 Rainfall and AET in the study area

The nine groundwater catchments cover a land area of 2,846.6 km^2 (Table 5.5). The difference between rainfall and AET is an estimated 61.5 m^3/s (Table 5.5), which reasonably represents median flow, but is less than mean flow, of the Rangitaiki River flow at Te Teko (62.5 m^3/s and 70.9 m^3/s, respectively; Table 3.2). On average, AET is approximately 54% of rainfall in the region (i.e., 72.1/133.6, Table 5.5). Therefore, evaporation is a significant component of the water budget.

Generally, rainfall is greater in the north of the study area, e.g., mean rainfall is greatest in the Matahina and Waiohau zones (zones 7 and 8). This indicates the influence of northerly rainfall on average rainfall and potential influence of northerly rainfall on rainfall recharge to groundwater (White *et al.*, 2007).

Table 5.5 Median rainfall and median AET in the study area.

Zone number	Zone name	Area (km^2)	P mean (mm/yr)	AET mean (mm/yr)	P mean (m^3/s)	AET mean (m^3/s)
1	Headwaters	431.2	1466	751	20	10.3
2	Kaingaroa South	674.4	1432	780	30.6	16.7
3	Galatea	150.8	1318	854	6.3	4.1
4	Minginui	517.6	1459	788	23.9	12.9
5	Kaingaroa North	347.9	1446	819	16	9
6	Pokairoa	163.9	1577	822	8.2	4.3
7	Waiohau	18.7	1671	906	1	0.5
8	Matahina	204.7	1779	874	11.5	5.7
9	Ikawhenua	337.4	1502	804	16.1	8.6
Sum		2846.6			133.6	72.1

5.2.2 Groundwater zone budgets

Water budgets, and assumptions used for water budget components, are summarised in Table 5.6 and Table 5.7, respectively. Minor adjustments were made to some water budget components to make the budget balance. For example, AET in zone 2 was adjusted to make Q_{OUT} equal to mean surface flows measured in rivers. Therefore, the sum of AET in the water budget (Table 5.6) is different to that in Table 5.5. In contrast, the AET was not adjusted to match mean flow in the Rangitaiki River at Te Teko. This was because the adjustment was too large (-7.7 m^3/s) to assign to zone 8 alone.

The water budget has zero groundwater outflow in all zones except zone 5. Groundwater outflow is non-zero in zone 5 because zero stream outflow was assumed for zone. However, no records of stream flows measurements are held by BOPRC or NIWA (Figure 3.2); therefore, stream gaugings are recommended for this zone (see Section 6.0).

Table 5.6 Water budgets in Upper Rangitaiki River catchment zones.

Zone number	Zone name	Inflows (m^3/s)				Outflows (m^3/s)			
		P	Q^{SW}_{INBF}	Q^{SW}_{INQF}	Q^{GW}_{IN}	AET	Q^{SW}_{OBF}	Q^{SW}_{OQF}	Q^{GW}_{AOUT}
1	Headwaters	20.0	0.0	0.0	0.0	-10.3	-9.3	-0.4	0.0
2	Kaingaroa South	30.6	9.3	0.4	0.0	-18.7	-20.8	-0.8	0.0
3	Galatea Plain	6.3	35.2	4.6	7.0	-4.1	-44.6	-4.4	0.0
4	Minginui	23.9	0.0	0.0	0.0	-9.1	-11.7	-3.1	0.0
5	Kaingaroa North	16.0	0.0	0.0	0.0	-9.0	0.0	0.0	-7.0
6	Pokairoa	8.2	44.6	4.4	0.0	-4.3	-48.7	-4.2	0.0
7	Waiohau	1.0	1.6	0.4	0.0	-0.5	-2.0	-0.5	0.0
8	Matahina	11.5	52.3	5.1	0.0	-5.7	-57.5	-5.7	0.0
9	Ikawhenua	16.1	0.0	0.0	0.0	-8.7	-5.9	-1.5	0.0
Sum		133.6				-70.4			

Table 5.7 Assumptions in the water budget calculation. In this table, 'T2006' is Tait *et al*. (2006) and 'W2006' is Woods, *et al*. (2006).

Zone number	Zone name	Inflows				Outflows			
		P	Q^{SW}_{INBF}	Q^{SW}_{INQF}	Q^{GW}_{IN}	AET	Q^{SW}_{OBF}	Q^{SW}_{OQF}	Q^{GW}_{AOUT}
1	Headwaters	T2006	Assumed		Assumed	W2006	Q_{TO} as P+AET within 0.1 m^3/s of Q_{TO} calc. with spec. discharge at site N2271		Assumed
2	Kaingaroa South	T2006	Assumed		Assumed	W2006, adjusted so that Q_{TO} matches Rangitaiki River mean flow at Murupara (Table 3.2)	Q_{TO} as calculated at Rangitaiki River at Murupara (Table 3.2)		Assumed
3	Galatea Plain	T2006	Q_{TO} from zones: 2, 4, part 9		Sum of outflow from zones: 2, 5	W2006	Q_{TO} to balance		Assumed
4	Minginui	T2006	Assumed			W2006, adjusted so that Q_{TO} matches Whirinaki River mean flow at Murupara (Table 3.2)	Q_{TO} as calculated at Whirinaki at Murupara (Table 3.2)		Assumed
5	Kaingaroa North	T2006	Assumed		Assumed	W2006	Assumed		Assumed
6	Pokairoa	T2006	Q_{TO} from zone 3		Assumed	W2006	Q_{TO} from zone 6 and zone 3		Assumed
7	Waiohau	T2006	Q_{TO} from part zone 9			W2006	Assumed		Assumed
8	Matahina	T2006	Q_{TO} from zone 6, 7 and part zone 9		Assumed	W2006	Q_{TO} to balance		Assumed
9	Ikawhenua	T2006	Assumed		Assumed	W2006, adjusted to balance sub-zone P and AET	Assumed		Assumed

5.2.3 Galatea Plain (zone 3) groundwater budget

A groundwater budget of the Galatea Plain was developed from the above water budget to include more detail on groundwater budget components, including groundwater-surface water interaction (Table 5.8). In particular, the budget extends Table 5.6 with a list of inflows and outflows by zone and a summary of groundwater-surface water interaction based on gauging measurements in the zone (Figure 5.2).

Groundwater inflows to the Galatea Plain include: rainfall recharge (i.e., P - AET); inflows from zone 5; and infiltration of surface water that discharges from zone 9. The Rangitaiki River receives all groundwater outflows. Groundwater outflow from zone 2 and zone 5 discharges through the true left bank (TLB) of the river. Groundwater outflow from zone 3 is through the true right bank (TRB) of the river, either as groundwater flow direct or as surface water flow that is sourced from groundwater.

Table 5.8 Groundwater budget components in the Galatea Plain.

Inflow			Outflow	
From Zone	Item	Flow (m^3/s)	Location of outflow	Flow (m^3/s)
3	P - AET	2.2	Rangitaiki River	-2.2
5	Q^{GW}_{IN}	7	Rangitaiki River TLB[1]	-7
9	From surface water[1]	1.4	Rangitaiki River TRB[1]	-1.4
Total		10.6	Total	-10.6

1 Inflow of 40% of estimated surface water inflow of 3.5 m^3/s from zone 9 (see following section).

5.2.3.1 Groundwater-surface water interaction in the Galatea Plain

Groundwater inflows from surface water occur in an area of surface water infiltration and through stream beds (Figure 5.2). The area of surface water infiltration is defined by two information sources: the locations of 'streams disappearing into ground' on the topographic map (Department of Survey and Land Information, 2000); and stream-flow losses that were generally identified by gaugings. The 200 m elevation contour is taken as the western boundary of the area of surface water infiltration, because disappearing streams and gauged losses occur above this elevation.

Surface water inflow from zone 9 is an estimated 3.5 m^3/s, which is not too dissimilar to the median inflow to Galatea Plain from zone 9 streams measured in gaugings, considering that gauging measurements are typically biased to low flows (Table 5.9).

The groundwater budget assumes that groundwater recharge is zero from the Rangitaiki River and the Whirinaki River. This is because an analysis of surface-groundwater interaction is not possible in these rivers as surface gaugings are only measured at one location in each of these rivers (i.e., sites 15408 and 15410; Figure 5.2).

Concurrent gaugings generally identify flow losses in the area of surface water infiltration (Table 5.10). Flow losses are shown by concurrent gaugings in Horomanga River (Ohutu Stream and main stem) and Mangamate Stream. Gaugings in Mangamate Stream show 100% inflow of surface water to groundwater between sites NSN1528 and 15428 at flows up to the maximum measured flow of 165 L/s (site NSN1528). However, gains across the area of surface water infiltration are shown by concurrent gaugings in the Ruarepuae Stream south branch. Site NSN1561 is below the 200 m contour, and therefore Ruarepuae Stream inflows below the 200 m contour may influence measured flow at this site.

In addition, streams may lose flow across Galatea Plain below the area of surface water infiltration. For example, concurrent gaugings of Horomanga River show losses of up to 210 L/s between Troutbeck Rd and Galatea Road Bridge (Table 5.11, Table 5.12 and Figure 5.2). Possibly, this flow loss may travel as groundwater in the gravel stream bed, as is common in other gravel-bed rivers and streams in New Zealand (e.g., White *et al.*, 2012b).

Average loss in the groundwater budget is taken as 40% of estimated surface water inflow from zone 9, i.e., approximately the average flow losses measured by concurrent gaugings in Horomanga River and Mangamate Stream (Table 5.10 and Table 5.12). Therefore, average groundwater inflow from surface water is 1.4 m^3/s (i.e., approximately 40% of the surface flow from zone 9; Table 5.8).

Groundwater flows to surface water in the lower elevations of the Galatea Plain (i.e., near the Rangitaiki River). For example: surface water outflows (Table 5.13) are a little greater than surface inflows (Table 5.9); spring-fed streams (i.e., the Omahuru Stream) are mapped; and springs (e.g., in Haumea Stream, which is a tributary of Horomanga River, near gauging site NSN1944) are observed. It is likely that the groundwater outflow from the area east of the Rangitaiki River to surface water occur at lower elevations between Galatea Road and the Rangitaiki River. However, existing gauging measurements are not suitable to estimate this flow and to identify the relative proportions of groundwater outflow and surface water to the Rangitaiki River.

More gauging measurements are recommended to further understand the pattern and quantity of surface flow losses to groundwater in the Galatea Plain (see Recommendations, Section 6.0). For example, gaugings could characterise surface and groundwater outflows through the TRB of the Rangitaiki River, and flow losses from Whirinaki River below site 15410 (see recommendations, Section 6.0).

Table 5.9 Summary of surface water inflows to the Galatea Plain from zone 9 (Ikawhenua Range).

River/Stream	Branch	Gauging site number	Median flow (m^3/s)
Kopuriki Stream	n/a	NSN1531	0.016
Hikirangi Stream	North	NSN1558	0.052
	South	1015401	0.232
Te Kopua Stream	n/a	No gauging site at eastern boundary	n/a
Horomanga River	North (Ohutu Stream)	NSN1557 and NSN1536 (at very similar locations)	0.434
	Main	NSN1553	0.991
Ruarepuae Stream	North	No gauging site at eastern boundary	n/a
	South	NSN1535	0.016
Mangamate Stream	n/a	NSN1528	0.072
		Total	1.813

Table 5.10 Summary of surface water flow change across the area of surface water infiltration shown by concurrent gaugings (Figure 5.2).

Stream and branch	Date of concurrent gauging	Site number and measured flow (L/s)		Change in flow
Horomanga River north branch (Ohutu Stream)		NSN1557	15426	
	22/03/1995	122	45	-77
Horomanga River (main stem)		NSN1553	NSN1548	
	22/03/1995	974	947	-27
	5/02/1998	991	780	-211
	16/02/1998	848	686	-162
	27/03/2003	659	601	-58
	Median	911	733	-110
Ruarepuae Stream south branch		NSN1535	NSN1561	
	5/02/1998	22	117	95
	16/02/1998	12	94	82
	24/01/2000	11.6	80	68.4
	27/03/2000	2	56	54
	Median	11.8	87	75.2
Mangamate		NSN1528	15428	
	22/03/1995	165	0	-165
	19/01/1998	82	0	-82
	5/02/1998	72	0	-72
	16/02/1998	36	0	-36
	15/02/2002	118	0	-118
	14/02/2003	47	0	-47
	27/03/2003	56	0	-56
	Median	72	0	-72

Table 5.11 Summary of surface water flow in Horomanga River measured by concurrent gaugings 22/03/1995 (Figure 5.2).

Date of gaugings	Zone 9 boundary (sum of flow at sites NSN1557 and NSN1553)[1]	Troutbeck Rd (sum of flow at sites 15426 and NSN1548)[1]	Galatea Rd (site 15418)	Change in flow between Troutbeck Rd and Galatea Rd
	Flow (L/s)			
22/03/1995	1069	992	827	-165

[1] i.e., Horomanga River main stem and Ohutu Stream.

Table 5.12 Summary of surface water flow in Horomanga River measured by concurrent gaugings (Figure 5.2).

Date of gaugings	Troutbeck Rd (site NSN1548)[1]	Galatea Rd (site 15418)	Change in flow between Troutbeck Rd and Galatea Rd
	Flow (L/s)		
22/03/1995	947	827	-120
5/02/1998	780	620	-160
16/02/1998	686	476	-210
27/03/2003	601	453	-148

[1] i.e., Horomanga River main stem only.

Table 5.13 Summary of surface water outflows from zone 9 (Ikawhenua Range) surface waters to Galatea Plain.

River/Stream	Gauging site number	Median flow (m^3/s)
Kopuriki Stream	NSN1531	0.016
Hikurangi Stream	NSN1559	0.066
Mangahouhi Stream	NSN1555	0.084
Unnamed	NSN1566/NSN1567	0.013
Horomanga River	15418	0.724
Horomanga River (Haumea Stream)	15458	0.994
Omahuru Stream	NSN1669	0.14
Total		2.04

5.3 GROUNDWATER AVAILABLE FOR ALLOCATION

GAA is large in the Minginui and Ikawhenua areas (Table 5.14). However, the demand for groundwater is likely to remain considerably less than GAA in these areas because they are mountainous with a low groundwater demand. The Whakamaru Group aquifer is prominent in the south and west (i.e., zones 1, 2, 5, 6, and 8) and GAA is large (12.5 m^3/s) where potential groundwater demand exists for agricultural use. GAA in the Galatea Plain (the most heavily farmed area in the Upper Rangitaiki River catchment) is an estimated 0.8 m^3/s and wells in this area take groundwater from the Tauranga Group aquifer.

Table 5.14 GAA in the Upper Rangitaiki area. GAA was calculated from groundwater recharge (R; Section 3.5, using the water budget components in Table 5.6) and minimum groundwater flow limits (MFL^{GW}; Section 3.4).

Zone number	Zone Name	Aquifer name	R (m^3/s)	MFL^{GW}		GAA (m^3/s)
				65% of R (m^3/s)	$Q_{5\ 7\text{-day}}$ (m^3/s)	
1	Headwaters	Whakamaru Group	9.3	6	6.1	3.2
2	Kaingaroa South	Whakamaru Group	11.5	7.5	7.5	4
3	Galatea Plain	Tauranga Group	2.2	1.4	1.4	0.8
4	Minginui	Greywacke Basement[1]	11.7	7.6	4.3	4.1
5	Kaingaroa North	Whakamaru Group	7	4.6	0	2.4
6	Pokairoa	Whakamaru Group and Matahina Formation	3.9	2.5	2.5	1.4
7	Waiohau	Tauranga Group	0.4	0.3	0.3	0.1
8	Matahina	Whakamaru Group and Matahina Formation	5.2	3.4	3.7	1.5
9	Ikawhenua	Greywacke Basement	5.9	3.8	2.1	2.1
Sum			57.1	37.1	27.9	19.6

[1] zone 4 includes Tauranga Group sediments in the Minginui Basin with the only consented groundwater use in the zone (Figure 5.1).

5.4 GROUNDWATER ALLOCATION AND GROUNDWATER USE

Most groundwater allocation and groundwater use is in the Galatea Plain (Table 5.15). Groundwater allocation totals approximately 0.06 m^3/s in all other zones, with zero allocation in many zones.

Table 5.15 Groundwater allocation and use in the Upper Rangitaiki area.

Zone number	Zone name	Number of consents	Consented allocation (m^3/s)	Estimated use of consents (m^3/s)
1	Headwaters	1	$0.05*10^{-3}$	$0.05*10^{-3}$
2	Kaingaroa South	0	0	0
3	Galatea Plain	9	0.43	0.21
4	Minginui	1	$2.5*10^{-3}$	$2.5*10^{-3}$
5	Kaingaroa North	0	0	0
6	Pokairoa	2	$55.5*10^{-3}$	$24*10^{-3}$
7	Waiohau	0	0	0
8	Matahina	0	0	0
9	Ikawhenua	0	0	0
Sum (rounded)		13	0.49	0.23

5.5 GROUNDWATER AVAILABLE FOR ALLOCATION, CURRENT ALLOCATION AND ESTIMATED USE

Current groundwater allocation in the Galatea Plain is approximately 54% of GAA (Table 5.16). However, allocation is typically a very low percentage of GAA, e.g., allocation is less than 0.1% of GAA in seven zones.

Table 5.16 GAA and groundwater allocation as a percentage of GAA (rounded to 0.1 m^3/s) in the Upper Rangitaiki area.

Zone number	Zone name	Aquifer name	GAA (m^3/s)	Allocation as a percentage of GAA (%)
1	Headwaters	Whakamaru Group	3.2	0
2	Kaingaroa South	Whakamaru Group	4	0
3	Galatea Plain	Tauranga Group	0.8	54
4	Minginui	Greywacke Basement	4.1	0
5	Kaingaroa North	Whakamaru Group	2.4	0
6	Pokairoa	Whakamaru Group and Matahina Formation	1.4	4
7	Waiohau	Tauranga Group	0.1	0
8	Matahina	Whakamaru Group and Matahina Formation	1.5	0
9	Ikawhenua	Greywacke Basement	2.1	0
Sum (rounded)			19.6	3

6.0 RECOMMENDATIONS

This section summarises recommendations required to improve environmental data collection for future improvements in the understanding of groundwater resources in the Upper Rangitaiki area, including the geological model and the water budget. These improvements will result in estimates of groundwater allocation that are more technically robust and that will allow greater confidence in groundwater allocation by BOPRC. Recommendations for the Upper Rangitaiki area follow those of the Opotiki area of the BOP Region (White *et al.*, 2012a) as many future information needs are common to both areas.

6.1 GEOLOGICAL DATA

The geological model of the Upper Rangitaiki area zone has been developed with available surface geological information and driller's log records held by BOPRC. Lithological data collected from the present drilling programme of BOPRC in the upper catchment (Harvey, 2014) and future drill holes will be used to refine this model, and the following recommendations aim to assist future model revisions:

- drill, log, and pump test shallow monitoring wells to assess interpretation of the distribution of key lithologies in this report, including Whakamaru Ignimbrite and Tauranga Group sediments in the Galatea Plain;
- an assessment of the distribution of relatively permeable sediments (e.g., gravel and sand) within Tauranga Group sediments in the Galatea Plain. These sediments provide most of the groundwater that is used in the Upper Rangitaiki area.

6.2 LOW-FLOW GAUGING MEASUREMENT PROGRAMME

BOPRC holds low flow measurements from the Upper Rangitaiki area. However, the distribution of low-flow gaugings is generally not suitable for the assessment of groundwater-surface water interaction, apart from some streams that cross the area of surface water infiltration on the Galatea Plain (Figure 5.2). Generally, targeted measurements of baseflow, with a programme of low flow gaugings, will improve the knowledge of outflow from the groundwater system. Therefore it is recommended that BOPRC review its low flow measurement programme in the Upper Rangitaiki water management zone with regard to:

- the location of flow gauging sites to estimate baseflow discharge from groundwater catchments identified in this report, i.e., gauging sites would ideally be located at the bottom of groundwater catchments. For example, no surface gauging sites are located at the base of zone 5 (Kaingaroa North; Figure 5.2) and so surface flow out of zone 5 is estimated as zero in this report. However, gaugings may identify that surface flow does leave this zone;
- characterisation of surface water outflows through the TRB of the Rangitaiki River in the Galatea Plain;
- the location of sites that could indicate surface water discharge to groundwater. For example, synoptic gaugings in the area of surface water infiltration on the Galatea Plain could improve estimates of inflow to the Galatea Plain aquifers, including possible inflows from the Whirinaki River below site 15410;
- groundwater-surface water interaction associated with zone 6 (Pokairoa) and Te Kauae Stream to improve understanding of the boundary between the Upper Rangitaiki and Lake Tarawera catchments; and
- identifying the ideal frequency of measurement.

It is also recommended that BOPRC identify priority sites for the measurement of low flow and calculation of baseflow discharge and $Q_{5\ 7\text{-day}}$ flow.

6.3 MINIMUM FLOW ESTIMATES

Minimum flow for groundwater (MFL^{GW}) is an important component of the GAA calculation (equation 12). MFL^{GW} is a function of groundwater recharge and $Q_{5\ 7\text{-day}}$ surface flow. Therefore, the quality of the estimates of groundwater recharge and $Q_{5\ 7\text{-day}}$ surface flow could be improved over time to produce more robust estimates of GAA. $Q_{5\ 7\text{-day}}$ surface flow could be calculated for all streams, ideally based on the results of a programme of multiple stream flow measurements including synoptic gaugings. Surface baseflows are estimated in this report for many un-gauged streams and the uncertainty in these estimates is unknown. Therefore, uncertainties in surface gaugings should be assessed from gauging measurements.

Groundwater recharge estimates primarily depend on the estimates of rainfall and AET, as these are the largest two components in the water budget. Ground-truthing of rainfall and AET is currently undertaken by BOPRC using drainage lysimeters at the Upper Rangitaiki rainfall recharge monitoring site (Harvey, 2014) and data collection at this site is recommended for a ten year period to assess the variability of rainfall recharge over time and to provide a comparison with NIWA's rainfall and AET models.

6.4 GROUNDWATER CHEMISTRY AND AGE DATING

Groundwater chemistry data in the Upper Rangitaiki area have not been reviewed in this report. Therefore, it is recommended that groundwater chemistry data should be reviewed to assess the effects of land use on receiving environments (e.g., groundwater quality and surface water quality) because the quality of these environments is important to ecosystems and to human users. This assessment will be particularly useful in the area where agriculture and groundwater use are most intensive, i.e., the Galatea Plain. Here, land use has the greatest potential to impact on groundwater quality and surface water quality.

Additionally, groundwater age dating is recommended to provide information on lag times of water movement through the unsaturated and saturated zones.

6.5 GROUNDWATER AND SURFACE WATER ALLOCATION POLICY

In this report, GAA is calculated for the Upper Rangitaiki area. However, BOPRC policies are required to define the groundwater allocation regime in the Upper Rangitaiki area, including the method of GAA calculation. Rules associated with the portion of GAA that is allocated could also be defined. For example, groundwater allocation in the Galatea Plain zone (approximately 54% of GAA; Table 5.16) would be larger than the groundwater allocation limit should BOPRC define the limit as 50% of GAA.

The close connection between groundwater and surface water is demonstrated by the water budgets calculated in this report where the balance of rainfall and evapotranspiration flows to streams (i.e., base flow coming from the groundwater system and stream quickflow). However, BOPRC may aim to set a groundwater use limit that preserves a surface flow that is different to $Q_{5\ 7\text{-day}}$ surface flow, e.g., median flow (White *et al.*, 2008). Therefore, it is recommended that BOPRC consider linking surface water allocation policies to groundwater allocation policies as surface water and groundwater are naturally linked (i.e., White *et al.*, 2012a).

Allocation of groundwater from storage could also be considered by BOPRC. Allocation of groundwater from storage (as opposed to groundwater flux) is not good practice as this can lead to mining of the groundwater resource. However allocation of groundwater from storage may be reasonable in emergency situations (e.g., fire, or failure of drinking water supplies in natural disasters). Therefore, stringent rules around allocation of groundwater from storage in emergency situations, and rules that identify an emergency situation, could be developed.

6.6 CURRENT GROUNDWATER ALLOCATION AND ESTIMATED USE

BOPRC could consider further groundwater investigations in catchments that have the largest potential stress from current groundwater use (i.e., the Galatea Plain, zone 3) to improve knowledge of groundwater recharge and groundwater use. These investigations would aim to assess, for example:

- estimates of baseflow in streams;
- hydrological properties e.g., hydraulic conductivity;
- effects of groundwater use on groundwater levels at the catchment scale;
- effects of pumping on groundwater level in neighbouring wells; and
- effects of groundwater pumping on stream flow.

It is also recommended that datasets are developed in a GIS format to allow convenient access to information on: groundwater flow, surface water flow, groundwater allocation (when determined by BOPRC from GAA estimates), surface water allocation and water availability (i.e., the difference between water allocation limits, when determined by BOPRC, and water allocation). BOPRC could also provide an information system on water allocation, and linked groundwater-surface water allocation, by integrating data on groundwater allocation with data on surface water allocation within common geographic units (e.g., groundwater catchments or water management zones).

6.7 ASSESSMENT OF UNCERTAINTY

Uncertainties in groundwater budget components and GAA estimates have not been rigorously assessed in this project. Therefore, this report uses a conservative approach to estimate GAA. A rigorous approach to estimating uncertainty in groundwater budget components and GAA is recommended to inform water management in the area. Ideally, this would come after improvements in estimations of groundwater budget components. Uncertainty in groundwater budget components and GAA could be expressed in GIS maps.

The uncertainty assessment could be piecemeal or include the whole project area. A piecemeal approach could focus on groundwater catchments where use is a large proportion of GAA, i.e., the Galatea Plain. This could follow targeted hydrological, and hydrogeological, investigations in these catchments.

6.8 MODEL OF GROUNDWATER RECHARGE AND FLOW

The model of groundwater recharge and surface water flows used in this report are quite simple but are appropriate as a first cut at estimating water, and groundwater, budgets in the Upper Rangitaiki area. Therefore, it is recommended that BOPRC consider more sophisticated models to improve the confidence of groundwater allocation estimates. A steady-state MODFLOW or FEFLOW groundwater model would be the next logical step to assess groundwater resources in the area. This model could consider geology, rainfall recharge, groundwater flow, groundwater recharge from streams, groundwater outflow to streams and surface water flows. Datasets developed in this report (e.g., the representation of geological layers, estimates of groundwater flow and calculated surface water quickflow and baseflow), are sufficient to commence development of this model. Ideally, model development could commence after collection of some of the data recommended in the above.

7.0 SUMMARY

Groundwater in the Upper Rangitaiki River catchment, BOP, is primarily extracted for agricultural users, and use of groundwater in the region is predicted to increase in the future (White, 2005). However, development of groundwater resources has occurred without estimates of groundwater availability. This report summarises geology and water budgets, as relevant to groundwater resources, with the aim of calculating GAA preliminary to BOPRC policy decisions on groundwater allocation in the zone.

Nine groundwater allocation zones were identified in this report, including the areas of volcanic lithologies in the south and west (i.e., Headwaters, Kaingaroa South, Kaingaroa North, Pokairoa and Matahina zones), basins formed of Tauranga Group sediments (Galatea Plain and Waiohau zones) and greywacke lithologies in the mountains to the east (Minginui and Ikawhenua zones).

A geological model of the Upper Rangitaiki area was built at a horizontal resolution of 100 m by 100 m. It is comprised of eight geological layers: Tauranga Group sediments, Taupo Group, Kaingaroa Formation, Matahina Formation, Whakamaru Group, Mangakino and older volcanics, and basement.

The main data sources used for the geological modelling consist of the DTM (Geographx, 2012), the QMAP geological map (Leonard *et al.*, 2010) and BOPRC bore logs. However the distribution of wells is sparse throughout large parts of the model area. A large number of wells are located within the Galatea Plain, but the driller's log descriptions are only of limited use, due to the general lack of marker beds within the Tauranga Group sediments.

Water budgets were developed for each of these zones that calculated rainfall, evapotranspiration, surface flows (baseflow and quickflow) and groundwater outflow across zone boundaries. The close connection between groundwater and surface water in each groundwater allocation zone is demonstrated by the water budgets. These budgets show that the balance of rainfall and AET flows to surface water, either stream baseflow or stream quickflow. Stream baseflow comes from the groundwater system. Therefore, use of groundwater has the potential to impact on stream baseflow.

GAA was calculated from these water budgets using estimates of minimum groundwater flows. These minimum flows aim to limit groundwater allocation so that: groundwater flow is greater than or equal to 65% of groundwater recharge; and surface flow remains at, or above $Q_{5\ 7\text{-day}}$ surface flow (i.e., a 7 day low flow minimum that has a 20% probability of occurring in any one year) (Wilding, 2003).

GAA is large in the Upper Rangitaiki model area. Total GAA is approximately 19.6 m^3/s with most of this (12.5 m^3/s) in the zones of volcanic lithologies in the south and west. GAA is approximately 0.9 m^3/s in the Galatea Plain and Waiohau zones (i.e., the area of Tauranga Group sediments). GAA totals approximately 6.2 m^3/s in the Minginui and Ikawhenua (i.e., the area of greywacke lithologies) and much of this is unlikely to be used because of the very limited opportunities for irrigation in the rugged mountains to the east.

Groundwater allocation is 0.49 m^3/s in the Upper Rangitaiki area. Most of this (0.43 m^3/s) is in the Galatea Plain zone where groundwater allocation is approximately 54% of GAA (Table 5.16). In contrast, groundwater allocation is zero, or close to zero, in other zones indicating a large potential for the use of groundwater in the Upper Rangitaiki area.

Recommendations for further investigations of groundwater resources in the Upper Rangitaiki area aim to improve groundwater budget components and refine GAA calculations. For example, improvements to estimates of rainfall recharge will result from continued measurement of rainfall recharge at the Upper Rangitaiki rainfall recharge monitoring site. A low-flow gauging measurement programme is recommended because the distribution of low-flow gauging records currently held by BOPRC is generally not suitable for the assessment of groundwater-surface water interaction and for the calculation of low flows. In particular, a gauging programme in the Galatea Plain zone will improve the understanding of groundwater-surface water interaction, including surface water infiltration to groundwater in the east of the zone and groundwater recharge to surface water west of Galatea Road (Figure 5.2). These investigations are particularly relevant to the estimation of GAA because minimum flows for groundwater in the GAA calculation are based on observations. Therefore, the quality of the estimates of groundwater recharge and $Q_{5\ 7\text{-day}}$ surface flow could be improved over time to produce more robust estimates of GAA.

This report also recommends that BOPRC considers policies that integrate the management of groundwater and surface water in the zones because geology and water budget assessment show that these water bodies are linked. Policies could consider management targets (i.e., a minimum groundwater recharge limit and a MFL) and rules associated with the portion of GAA that is allocated.

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