Catchment boundaries of lakes in the greater Lake Tarawera area

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CONTENTS

FIGURES

TABLES

APPENDICES

EXECUTIVE SUMMARY

Bay of Plenty Regional Council (BOPRC), and the local communities, aim to protect and restore water quality in the greater Tarawera lakes area, which includes eight lakes, i.e., Tarawera, Okataina, Okareka, Tikitapu, Rotokakahi, Okaro, Rotomahana and Rerewhakaaitu. An understanding of the groundwater system is important to this aim because most water inflow to these lakes has been identified as coming from spring-fed streams and direct groundwater discharge (Tschritter and White 2014; and White et al. 2016). Therefore, most nutrients that are generated from land use enter the lakes via the groundwater system.

As a result, BOPRC wished to identify the groundwater catchment boundaries of the lakes so that they could assess land uses and calculate nutrient flows within lake catchments. Therefore, BOPRC commissioned GNS Science to delineate groundwater catchment boundaries in the greater Lake Tarawera area. Best-estimate groundwater catchments were derived as seamless ArcGIS polygons at a scale of 1:5,000 from two principal lake catchment-boundary data sets, i.e., the best-estimate surface catchment, also delineated as part of this project, and the catchment calculated by the groundwater flow model of White et al. (2016).

The best-estimate groundwater catchments of the greater Lake Tarawera lakes, and lakes, had a total area of approximately 381.8 km^2. Steady-state water budgets for lakes and catchments calculated the major water-budget components including inflows (e.g., rainfall was approximately 20.1 m^3/s) and groundwater outflows, e.g., approximately 3.4 m^3/s from the Lake Tarawera catchment through the Tarawera River valley.

Best-estimate groundwater catchments addressed inconsistencies in land catchments identified by the principal lake catchment-boundary data sets. For example, the best-estimate groundwater catchment of Lake Okataina includes the headwaters of the Lake Okareka surface water catchment.

1.0 INTRODUCTION

The protection and restoration of water quality in the Tarawera lakes is an aim of the Bay of Plenty Regional Council (BOPRC) and the local community. BOPRC and research providers, including the Institute of Geological and Nuclear Sciences (GNS Science), are currently working across a range of lakes and lake catchments in the greater Lake Tarawera catchment with aims to protect, or restore, the water quality of these lakes.

The greater Lake Tarawera catchment includes eight lakes (Tarawera, Okataina, Okareka, Tikitapu, Rotokakahi, Okaro, Rotomahana and Rerewhakaaitu) that eventually drain partly, or wholly, to the Tarawera River. Groundwater provides most of the water inflow into these lakes through spring-fed streams and direct groundwater discharge, which is typical of the Taupo Volcanic Zone (e.g., White et al. 2007). Commonly, these lakes are hydraulically linked through the groundwater system. For example, lake levels, water budgets and spring flows indicate that groundwater outflow from Lake Rotomahana travels to Lake Tarawera (White et al. 2016).

Protection and restoration of lake water quality requires an understanding of the groundwater system. This is because land use (e.g., agriculture and human habitation) produces nutrients, and these nutrients travel with water (i.e., groundwater and surface water) to lakes. For example, nitrogen, in the form of nitrate, is highly mobile in the hydrological system, and large masses of nitrogen can travel with groundwater directly to lakes or via spring-fed streams (e.g., White et al. 2007).

Therefore, BOPRC commissioned GNS Science to assess groundwater in the greater Lake Tarawera area, including geology and groundwater flow with a three-phase programme:

- Phase 1: a drilling programme that described the lithological characteristics of drill holes and measured key aquifer properties including aquifer hydraulic conductivity, groundwater quality and groundwater age (Thorstad et al. 2011; Rose et al. 2012; and Lovett et al. 2012).
- Phase 2: a geological model of the greater Lake Tarawera catchment that identified key aquifers relevant to groundwater flows towards lakes and between lake catchments and included geological information identified by Phase 1 (Tschritter and White 2014).
- Phase 3: a groundwater flow model of the greater Lake Tarawera catchment that was applied to an assessment of land use and nitrogen discharge to surface water relevant to surface water quality in lakes and streams (White et al. 2016).

Together, this programme has provided a large information base that will be useful for future management of land and water in the area. Such management is commonly catchment-based (e.g., White et al. 2014). This report delineates the groundwater catchments of the eight greater Tarawera lakes. The report calculates ‘best-estimate’ groundwater catchment boundaries of the lakes by considering: best-estimate surface water catchment boundaries that are based on BOPRC ArcGIS polygons; lake catchment boundaries identified by the groundwater flow model of White et al. (2016); and the groundwater catchment of the adjoining Lake Rotorua catchment (White et al. 2014). The boundaries are delineated in ArcGIS at a 1:5,000 scale. Finally, a Discussion considers the groundwater catchments of each lake, including the uncertainty of boundary positions.

2.0 METHODS

In this report, best-estimate catchment boundaries were delineated for the eight lakes of the greater Lake Tarawera catchment: Tarawera, Okataina, Okareka, Tikitapu, Rotokakahi, Okaro, Rotomahana and Rerewhakaaitu. Based on these best-estimate groundwater catchment boundaries, water budgets were calculated as per White et al. (2016).

The catchment boundaries were defined using the following criteria:

- New Zealand Transverse Mercator (NZTM) was used as the coordinate system for eastings and northings.
- A 1:5,000 scale. This means that the maps should not be considered as reliable below this scale near catchment boundaries. For example, the maps should be considered as uncertain where they are used at finer scales than 1:5,000 to associate land areas with lake catchments.
- Boundaries between lake catchments that are seamless, i.e., common boundaries between lake catchments that are formed from exactly the same coordinates. This approach prevents gaps in the land coverage of adjacent catchment polygons.
- A seamless boundary between the western boundaries of the greater Lake Tarawera area and the eastern boundary of the Lake Rotorua catchment (White et al. 2014). This approach prevents gaps in the land coverage of the catchment polygons across catchments.
- Version control of ArcGIS catchment polygon file names as per White et al. (2014), using the format 'Lake_Catchment-type_Date-of-boundary-creation.shp'. This approach will provide clarity for the future use of the polygons with BOPRC's GIS system.

2.1 Best-estimate Surface Water Catchment Boundaries

White et al. (2014) observed that the previously-defined BOPRC Lake Rotorua catchment boundary failed to consistently represent the surface water catchment defined by the 1 m contours calculated from a 2006 LiDAR-derived digital terrain model (DTM) (Freeman 2006). In a similar manner, the greater Lake Tarawera catchment boundaries, as defined by BOPRC in 2014 (Figure 2.1), also fail to consistently represent the surface water catchment defined by the 1 m contours calculated from the BOPRC LiDAR-derived DTM.

Therefore, best-estimate surface water catchment boundaries (file names listed in Appendix 1) were calculated for the eight lakes, mainly at a 1:5,000 scale by:

- simplifying the boundaries of the BOPRC 2014 greater Lake Tarawera catchment polygons (Figure 2.1), using ArcGIS to a maximum allowable offset of 3 m;
- analysing the position of the BOPRC 2014 greater Lake Tarawera catchment boundary points (polygon vertices) in relation to 2011 LiDAR data derived contours (5 m contour interval as a first refinement step and 1 m contour interval as a second step). This boundary was edited where it did not represent the surface water divides defined by the 2011 LiDAR derived 1 m contours, i.e., the line was realigned according to the topographic divides.

The Land Information New Zealand (LINZ) 1:50,000 topographic map and 2016 aerial photographs were also utilised as a base map to help locating the natural and anthropogenic features of the greater Lake Tarawera catchment area such as lakes, streams, gullies, roads, etc. In addition, scales other than 1:5000 were used to refine the interpretation of the topographic features:

- in some cases, such as flat areas, it was necessary to use scales that were finer than 1:5,000 to precisely position the catchment boundaries according to the 1 m contour lines;
- in other cases, such those involving streams or gullies, it was necessary to use scales that were greater than 1:5,000 to locate the catchment boundaries according to the main topographic features.

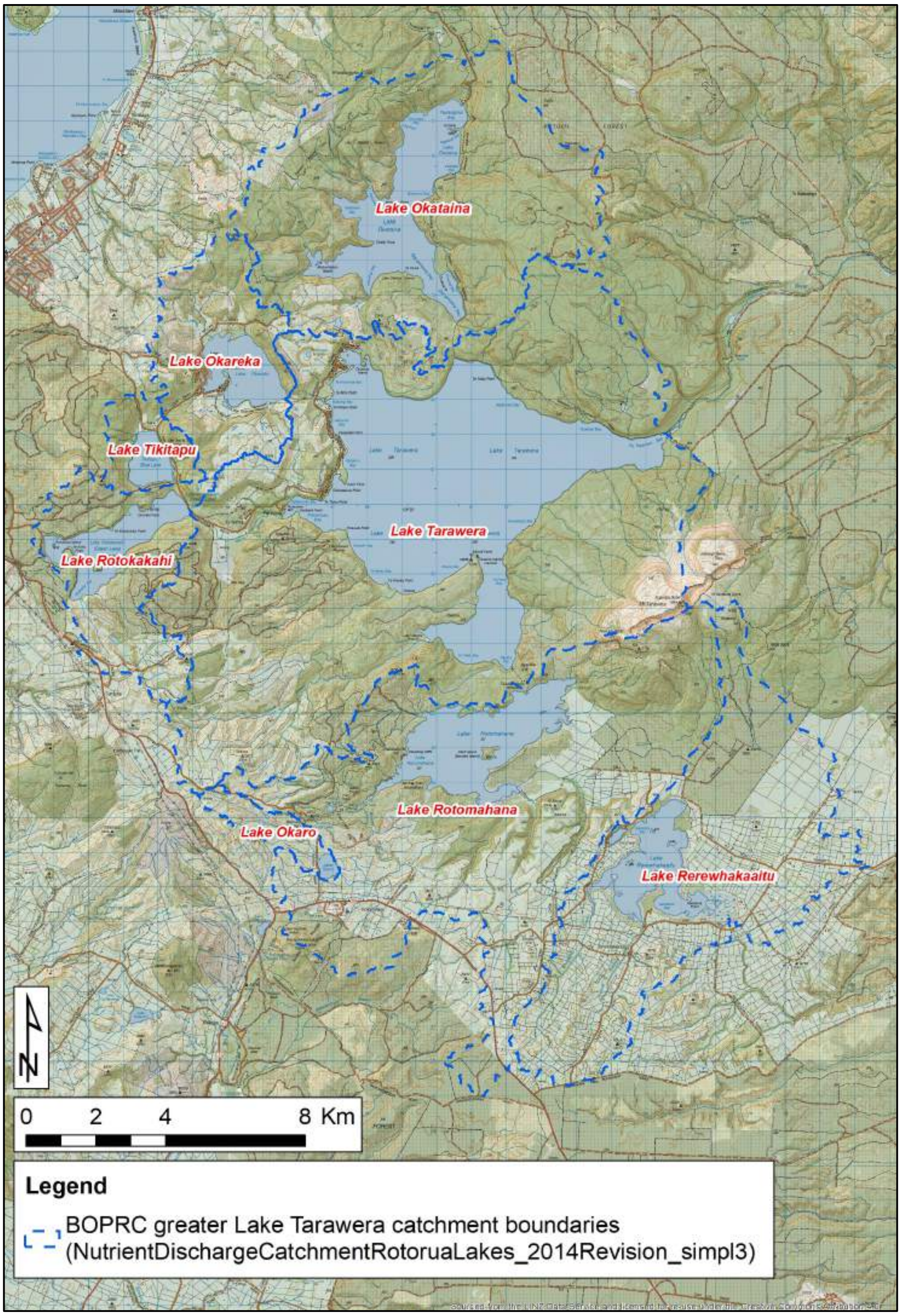

Figure 2.1 BOPRC 2014 surface water catchment boundaries for the greater Lake Tarawera catchment lakes.

2.2 Best-estimate Groundwater Catchment Boundaries

Best-estimate groundwater catchment boundaries of lakes in the greater Lake Tarawera catchment were defined with three main sources of information:

- the western boundary of the greater Lake Tarawera groundwater catchment is the eastern boundary of the Lake Rotorua groundwater catchment, i.e., including the catchments of Lake Okataina and Lake Rotokakahi (White et al. 2014);
- surface water catchment boundaries identified from the 2014 ArcGIS maps of BOPRC that were adjusted to topographic divides mapped from the BOPRC 2011 LiDAR-derived DTM; and
- lake catchment boundaries identified with the groundwater flow model of White et al. (2016).

The groundwater catchment boundaries were mapped at a 1:5,000 scale in ArcGIS. A variety of methods were used to define the best-estimate groundwater catchment boundaries:

- L1: groundwater catchment boundaries were set as the best-estimate surface water catchment boundary.
- L2: groundwater catchment boundaries were set to consider the groundwater flow model boundary.
- L3: groundwater catchment boundaries follow topography in three circumstances: 1) where the groundwater model boundary was adjacent to the lake (i.e., within 100 m of the lake edge) implying that the groundwater catchment was very narrow. Here, the best-estimate groundwater catchment includes the area around the lake up to the uppermost edges of its nearest cliffs or crater rims, e.g., Lake Okareka, Lake Tikitapu. Lake Rotokakahi and Lake Rerewhakaaitu. 2) the surface catchments of two small streams that flow into southern Lake Rerewhakaaitu mapped by Cho et al. (2017), using the approach of White et al. (2014), to match the measured surface flow. 3) to represent the upper reaches of the Lake Rotokakahi groundwater catchment where stream beds are incised into planar volcanic deposits.
- L4: at lake outlets where surface water and groundwater flow away from the lake. Here, groundwater catchment boundaries are set to follow the lake shore.
- L5: groundwater catchments that share a boundary with the Rotorua groundwater catchment (ArcGIS file: Lake_Rotorua_GW_1_2000_9_June_2014.shp, White et al. 2014) were set to that boundary.

The groundwater catchment boundaries were identified at a 1:5,000 scale to fit the 1 m contours, derived from BOPRC LiDAR data (ArcGIS geodatabase file: Contour_2011_1m_Rotorua).

The groundwater flow model developed by White et al. (2016) was used to simulate groundwater flow and delineate groundwater catchments in the Tarawera region. The 3D finite-element grid used to discretize the aquifer systems has a uniform 100 m grid resolution, with 24 layers that extent to a depth of around 1200 m. The steady-state groundwater flow model is based on MODFLOW-NWT (Niswonger et al. 2012), which simulates the hydrogeologic processes of the aquifer system. Groundwater catchments were delineated using MODPATH-6 (Pollock 2012), which is an advection transport model that simulates pathlines of particles from starting locations to discharge locations.

Groundwater catchments were delineated using 38,153 gridded particles generated at the centre of each model cell, at the recharge boundary. Groundwater pathlines were traced through the aquifer systems to their discharge locations, such as a lake or stream. Groundwater catchments were mapped at the gridded source locations based on the discharge zones for each lake (Figure 2.2). One exception is the southeast boundary (near Lake Rerewhakaaitu), where groundwater flows outside the model boundary.

2.3 Water Budgets

Water budgets of the greater Lake Tarawera catchments were calculated with the best-estimate groundwater catchment boundaries in accordance with the method, and nomenclature, of White et al. (2016). These budgets were integrated with lake budgets, also following this method.

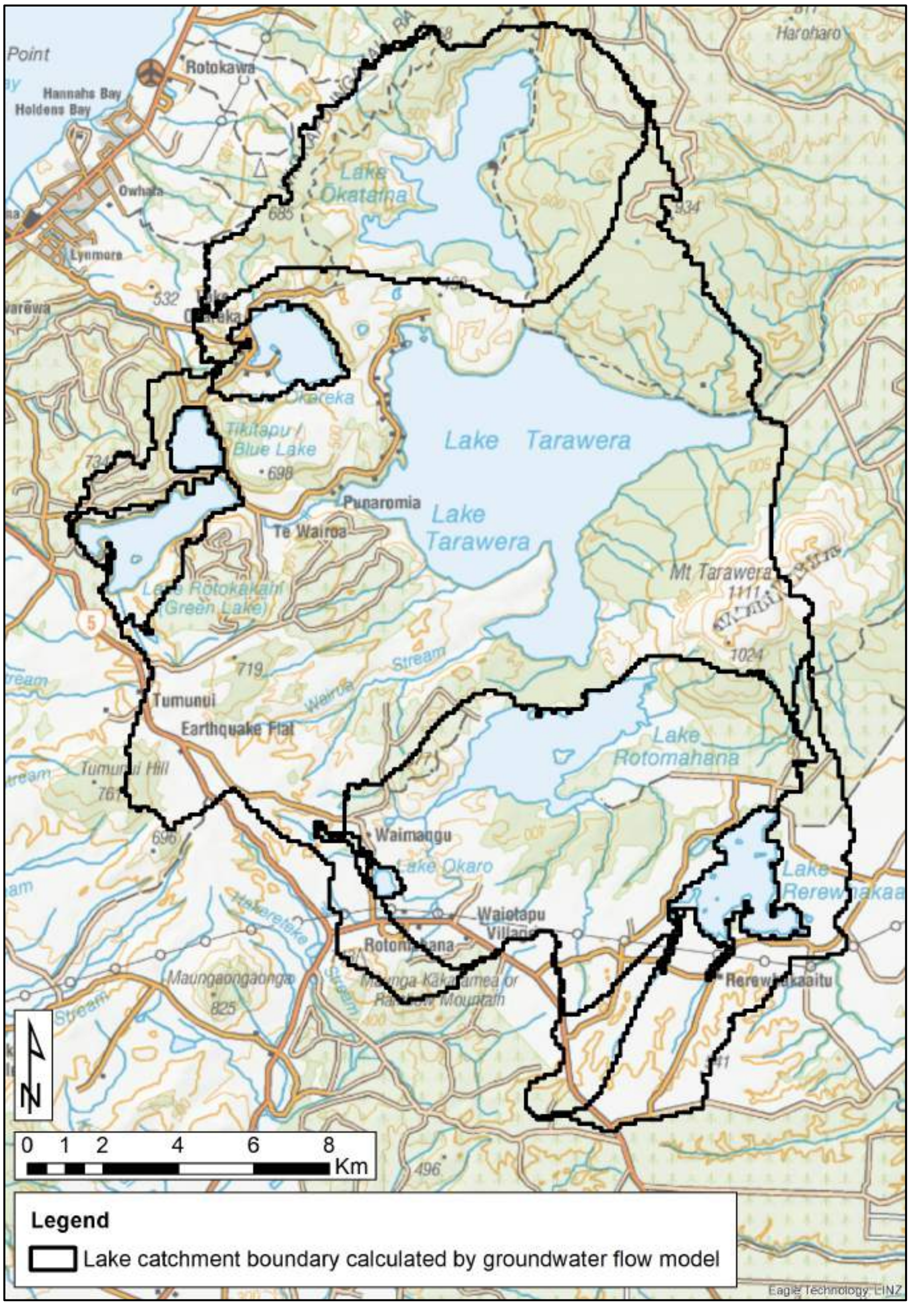

Figure 2.2 Lake groundwater catchment boundaries calculated by the groundwater flow model (White et al. 2016).

3.0 RESULTS

3.1 Best-estimate Surface Catchment Boundaries

The best-estimate surface water catchment boundaries generally coincide with the 2014 BOPRC greater Lake Tarawera catchment boundaries. However, for a few places, the interpretation of the surface water catchment boundaries differed. Causes of the differences between the best-estimate surface water catchment boundaries and the BOPRC greater Lake Tarawera catchment boundaries include:

- natural features, such as streams, gullies, ridges, valleys, etc.; and
- anthropogenic features, such as highways, roads, quarries and artificial drains.

These differences are 'major' and 'minor'. Maps of 'major' differences (i.e., Figure 3.1 to Figure 3.13) show how surface catchment boundaries were adjusted (summary in Table 3.1). Note that Lake Okaro is not listed in Table 3.1 because no major differences were observed in this catchment. Minor differences between catchment boundaries are not discussed in this report.

Table 3.1 The location and nature of major differences in surface water catchment boundaries between the best-estimate surface water catchment boundaries generated in the current project and the 2014 BOPRC greater Lake Tarawera catchment boundaries.

Lake catchment	Alteration ID	Topographic feature	Reference for the detailed map
Tarawera	TW1 (a and b)	Stream / gully	Figure 3.9 and Appendix 2
	TW2	Stream / gully	Appendix 2
	TW3	Stream / gully	Appendix 2
Okataina	OKN1	Relatively flat valley	Figure 3.10
	OKN2	Ridge	Appendix 2
Okareka	OKK1	Ridge	Appendix 2
	OKK2	Quarry	Figure 3.11
Tikitapu	TK1	Ridge	Appendix 2
	TK2	Ridge	Appendix 2
Rotokakahi	RK1	Road / highway	Figure 3.12
	RK2	Ridge	Appendix 2
Rotomahana	RM1	Road / highway	Appendix 2
	RM2	Road / highway	Appendix 2
	RM3	Ridge	Appendix 2
Rerewhakaaitu	RW1	Stream / gully	Appendix 2
	RW2	Artificial drain	Figure 3.13

3.1.1 Stream / Gully

In several cases, the BOPRC 2014 lake catchment boundaries were altered to consider streams indicated by the LINZ 1:50,000 map (Figure 3.9). Most of these streams are ephemeral (White et al. 2016).

3.1.2 Relatively Flat Valley

For the Lake Okataina catchment (Figure 3.10), a relatively flat valley was located along Lake Okataina Road, at an elevation of approximately 400 to 410 m above mean sea level (m AMSL). The BOPRC 2014 lake catchment boundary crosses this flat valley along its southern part, without following any major topographic feature. For this reason, the best-estimate surface water catchment boundary follows the main topographic features (using the 1 m contours lines), more specifically a small ridge located along the south of lakes Rotoatua and Rotongata (at an elevation of approximately 440 to 450 m AMSL).

3.1.3 Quarry

A quarry is partially located within Lake Okareka surface water catchment (Figure 3.11). The best-estimate surface water catchment boundary was the BOPRC 2014 lake catchment that was slightly adjusted with the 1 m contours. However, this boundary is uncertain because: the current elevation of the quarry may differ from the 1 m contours due to on-going excavation works; and drainage structures in the quarry, which are unknown to the authors, may direct run-off across the boundary.

3.1.4 Road / Highway

For a few locations, such as State Highway 5 (SH5), west of Highlands Loop Road within the Lake Rotokakahi catchment (Figure 3.12), the best-estimate surface water catchment boundary closely follows the topography and a small ridge located along the northeast of SH5, instead of the BOPRC 2014 lake catchment boundary, which crosses the highway. Another example is in the Lake Rotomahana catchment (RM1, Appendix 2).

3.1.5 Artificial Drain

The best-estimate surface water catchment boundary of Lake Rerewhakaaitu was defined as the “natural catchment” of the lake in the area southeast of Half Moon Bay (Figure 3.13). The BOPRC 2014 lake catchment boundary included an artificial drain present in the area and used to control the lake level. However, the drain is usually dry and therefore rarely intersects natural groundwater flow (White et al. 2016).

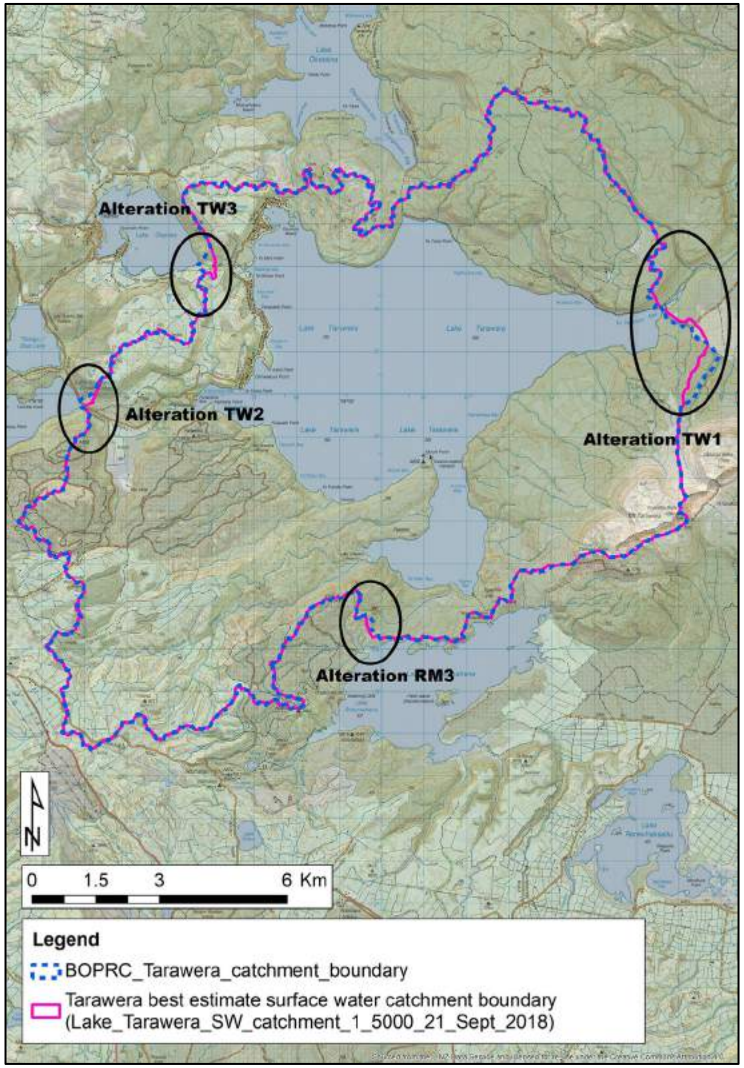

Figure 3.1 Lake Tarawera best-estimate surface water catchment boundary and 2014 BOPRC Lake Tarawera catchment boundary. These two boundaries are significantly different in the areas highlighted by the ovals.

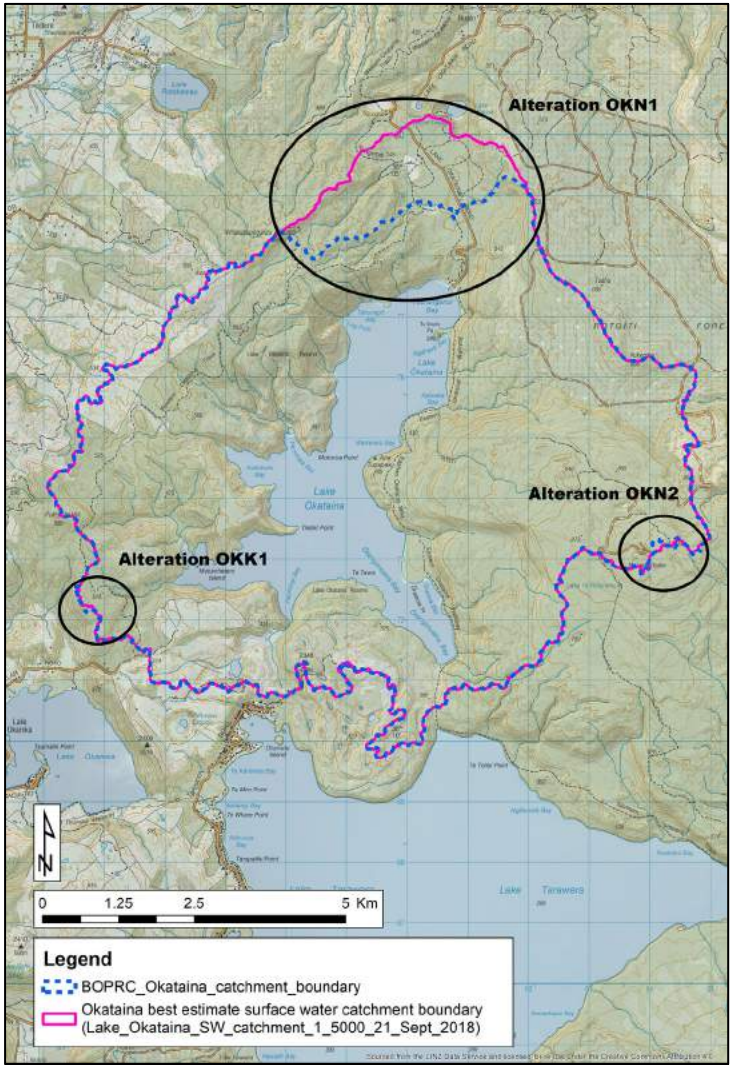

Figure 3.2 Lake Okataina best-estimate surface water catchment boundary and 2014 BOPRC Lake Okataina catchment boundary. These two boundaries are significantly different in the areas highlighted by the ovals.

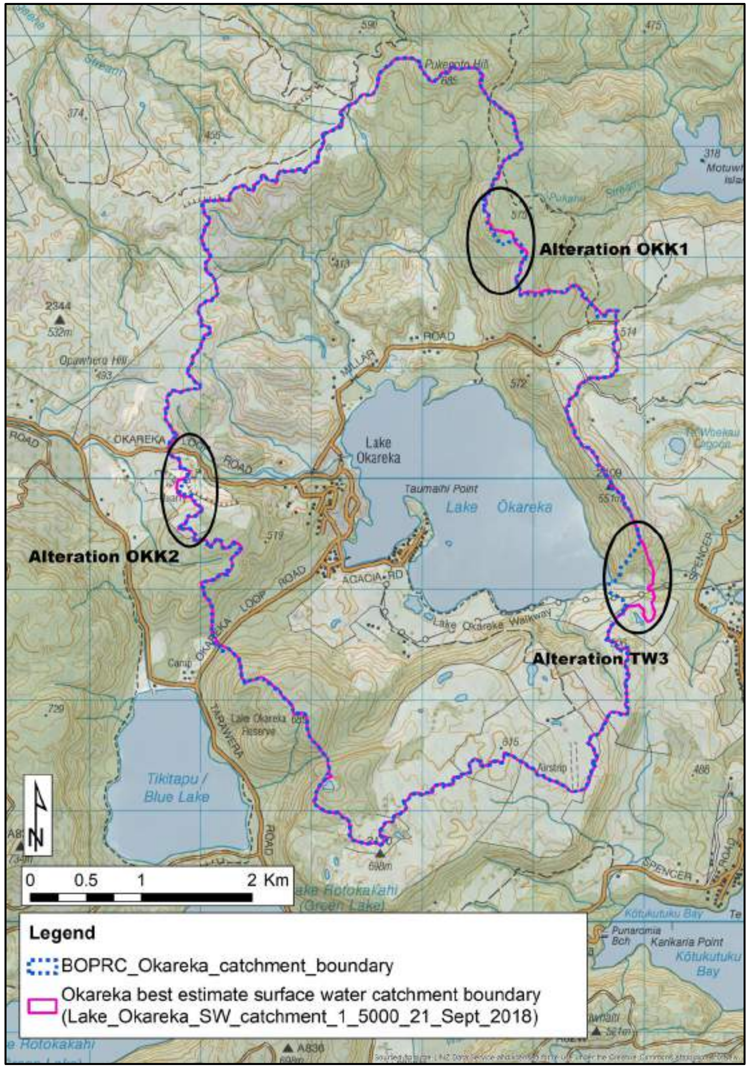

Figure 3.3 Lake Okareka best-estimate surface water catchment boundary and 2014 BOPRC Lake Okareka catchment boundary. These two boundaries are significantly different in the areas highlighted by the ovals.

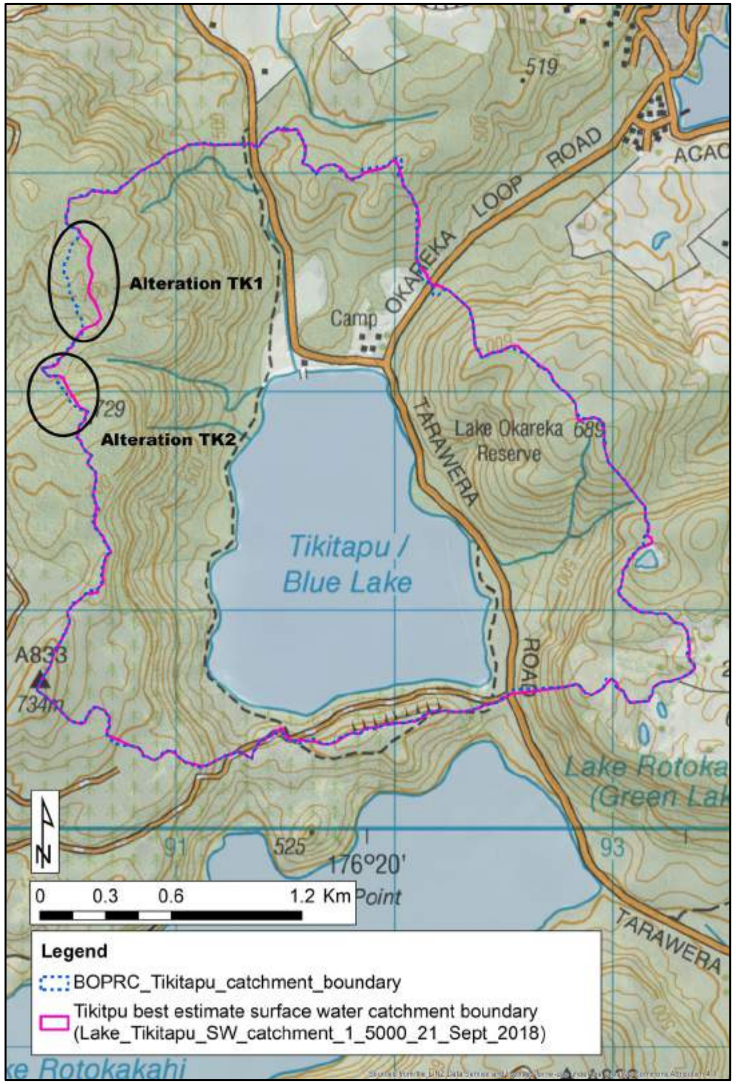

Figure 3.4 Lake Tikitapu best-estimate surface water catchment boundary and 2014 BOPRC Lake Tikitapu catchment boundary. These two boundaries are significantly different in the areas highlighted by the ovals.

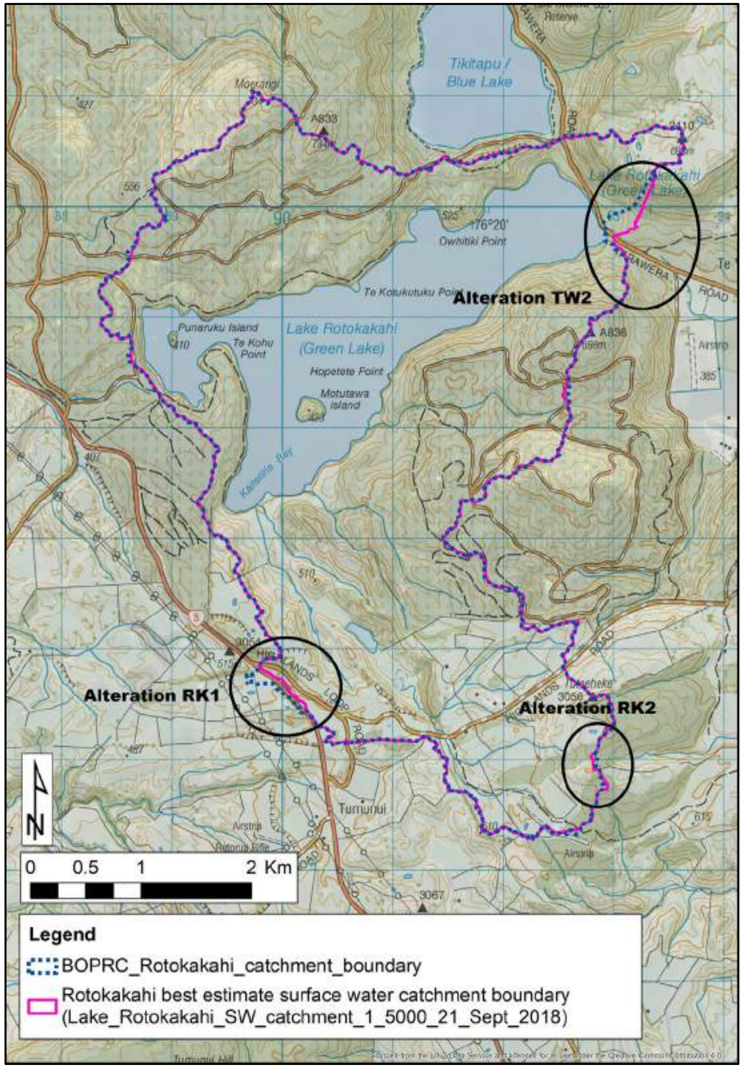

Figure 3.5 Lake Rotokakahi best-estimate surface water catchment boundary and 2014 BOPRC Lake Rotokakahi catchment boundary. These two boundaries are significantly different in the areas highlighted by the ovals.

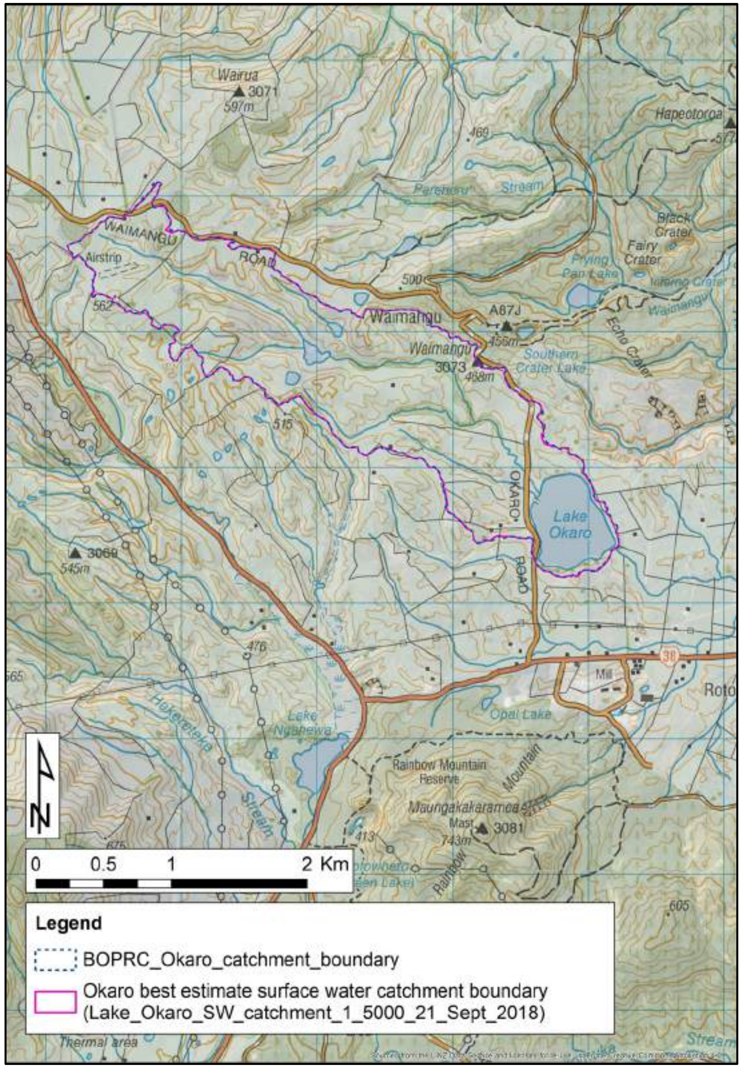

Figure 3.6 Lake Okaro best-estimate surface water catchment boundary and 2014 BOPRC Lake Okaro catchment boundary.

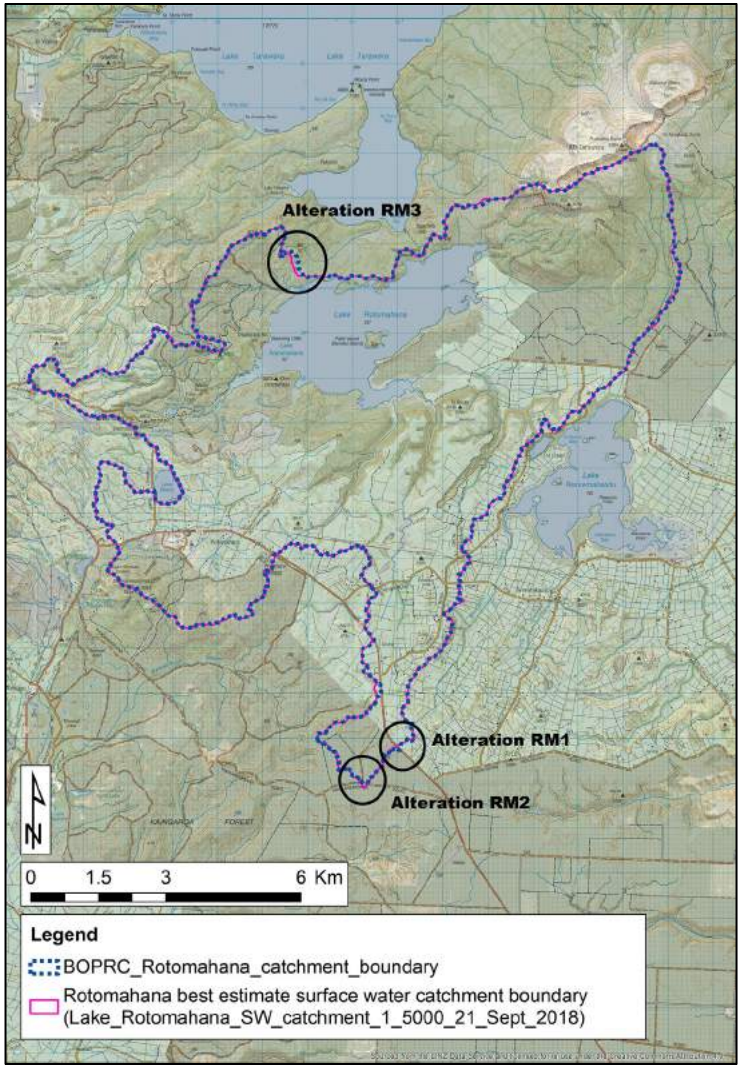

Figure 3.7 Lake Rotomahana best-estimate surface water catchment boundary and 2014 BOPRC Lake Rotomahana catchment boundary. These two boundaries are significantly different in the areas highlighted by the ovals.

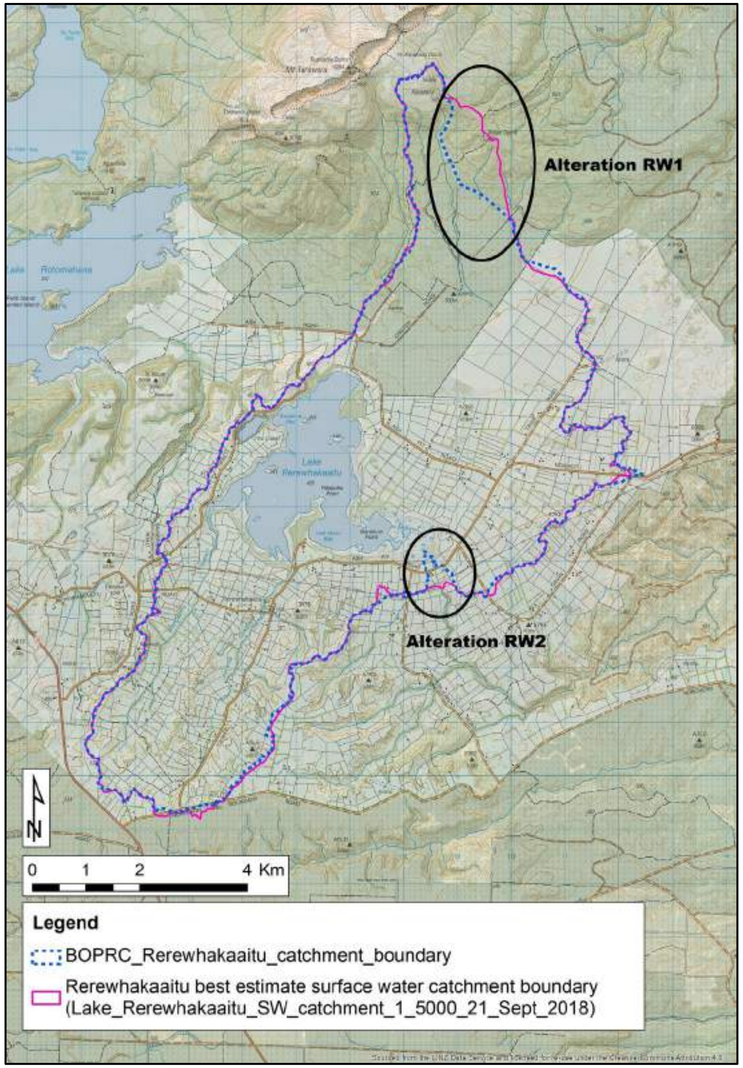

Figure 3.8 Lake Rerewhakaaitu best-estimate surface water catchment boundary and 2014 BOPRC Lake Rerewhakaaitu catchment boundary. These two boundaries are significantly different in the areas highlighted by the ovals.

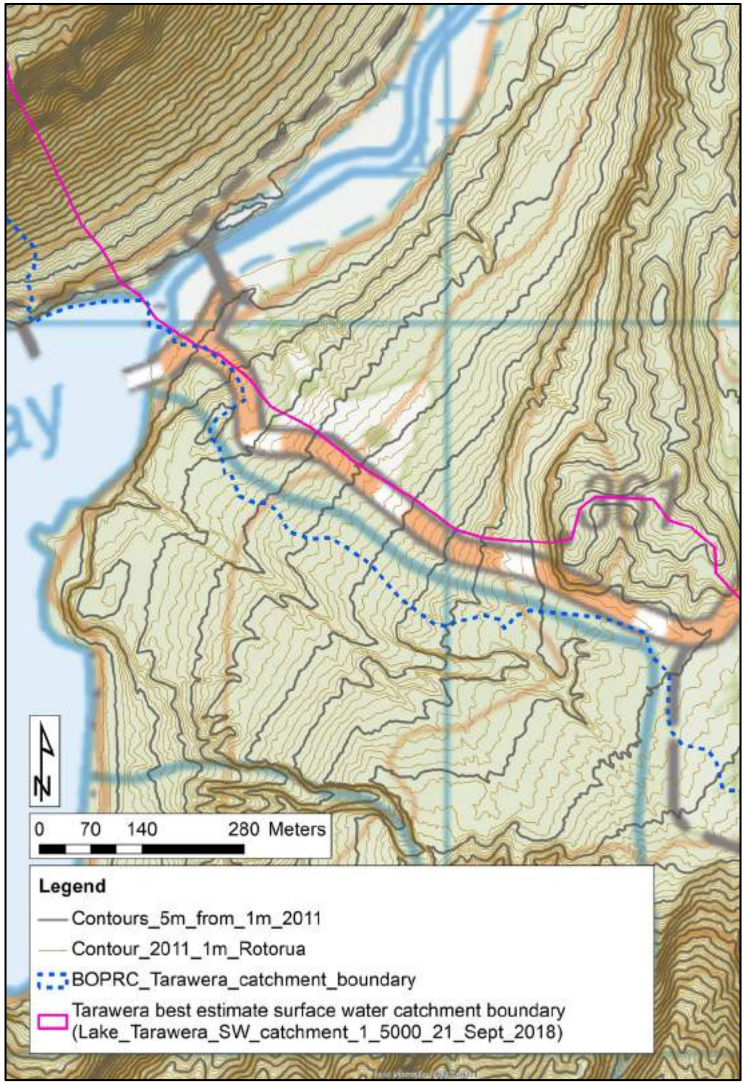

Figure 3.9 Lake Tarawera surface water catchment boundary, alteration TW1: stream/gully discharging into Lake Tarawera.

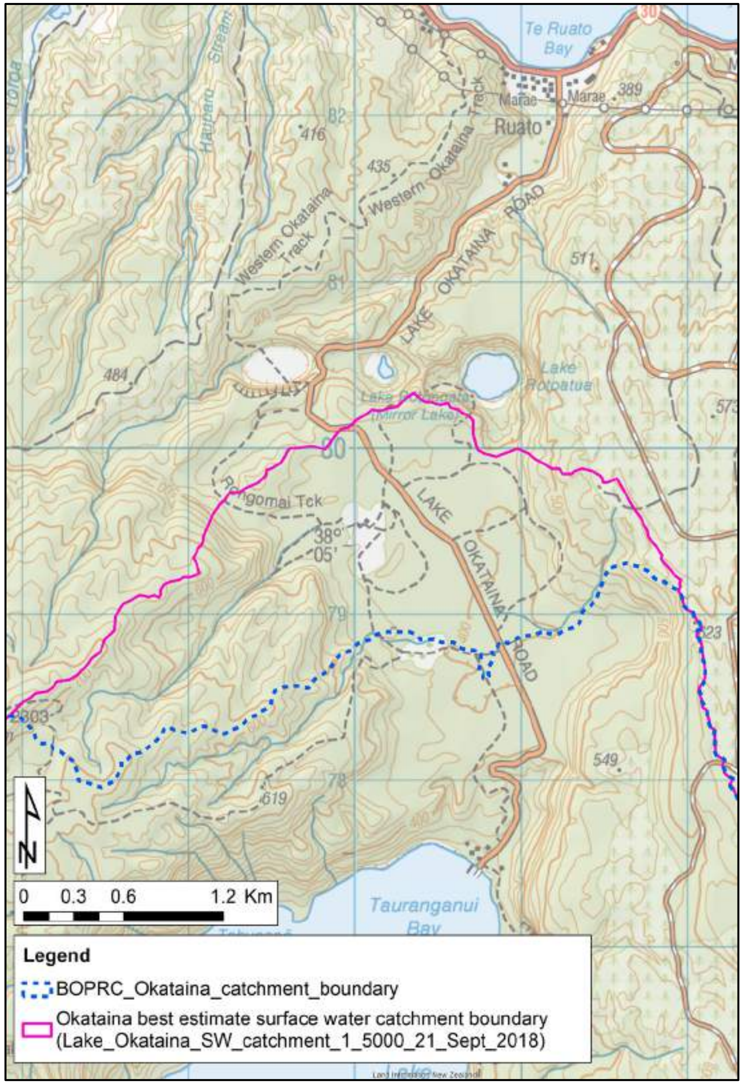

Figure 3.10 Lake Okataina surface water catchment boundary, alteration OKN1: valley north of Lake Okataina.

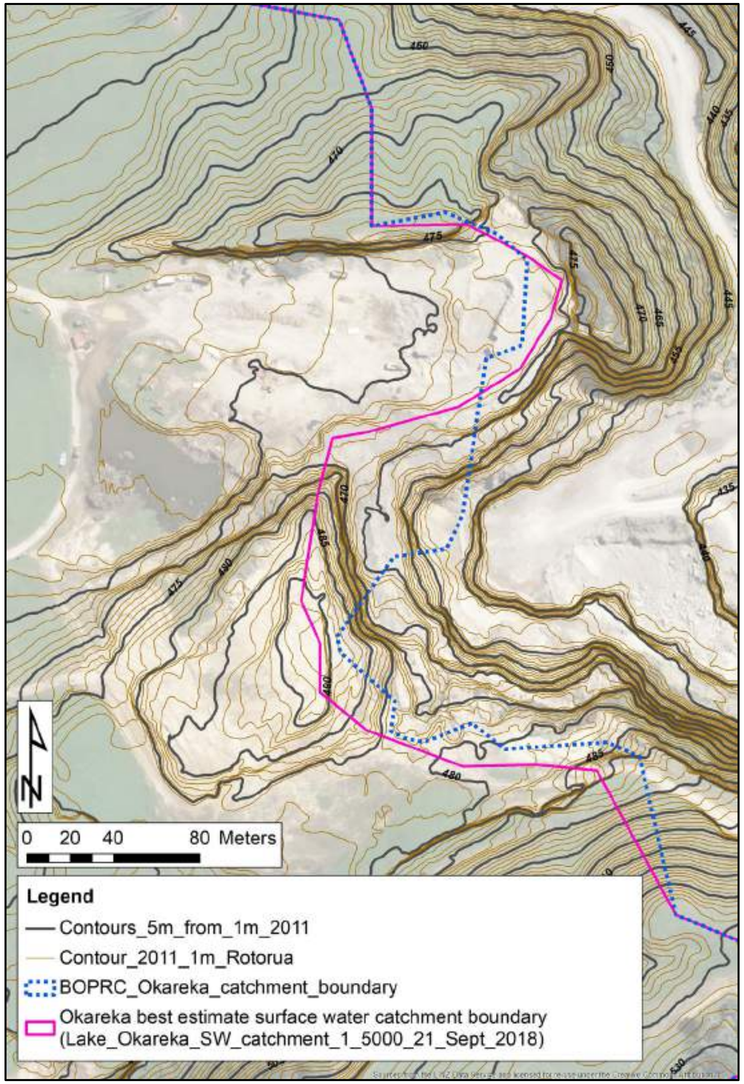

Figure 3.11 Lake Okareka surface water catchment boundary, alteration OKK2: interpretation of quarry topography.

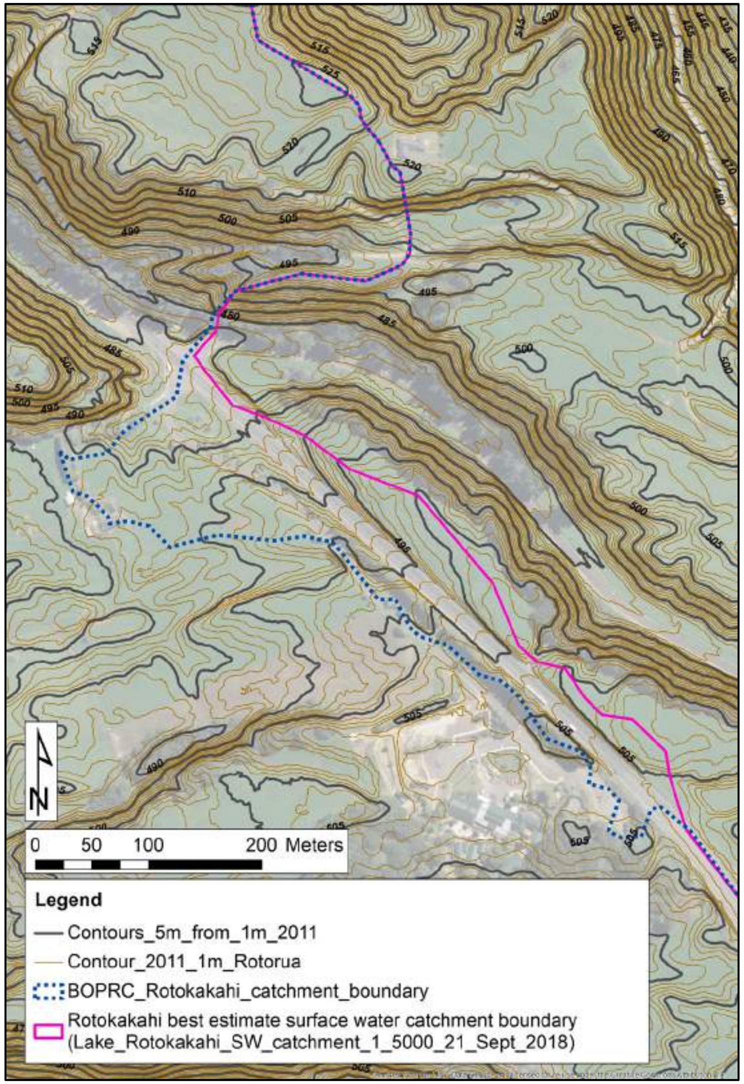

Figure 3.12 Lake Rotokakahi surface water catchment boundary, alteration RK1: interpretation of the topography along SH5.

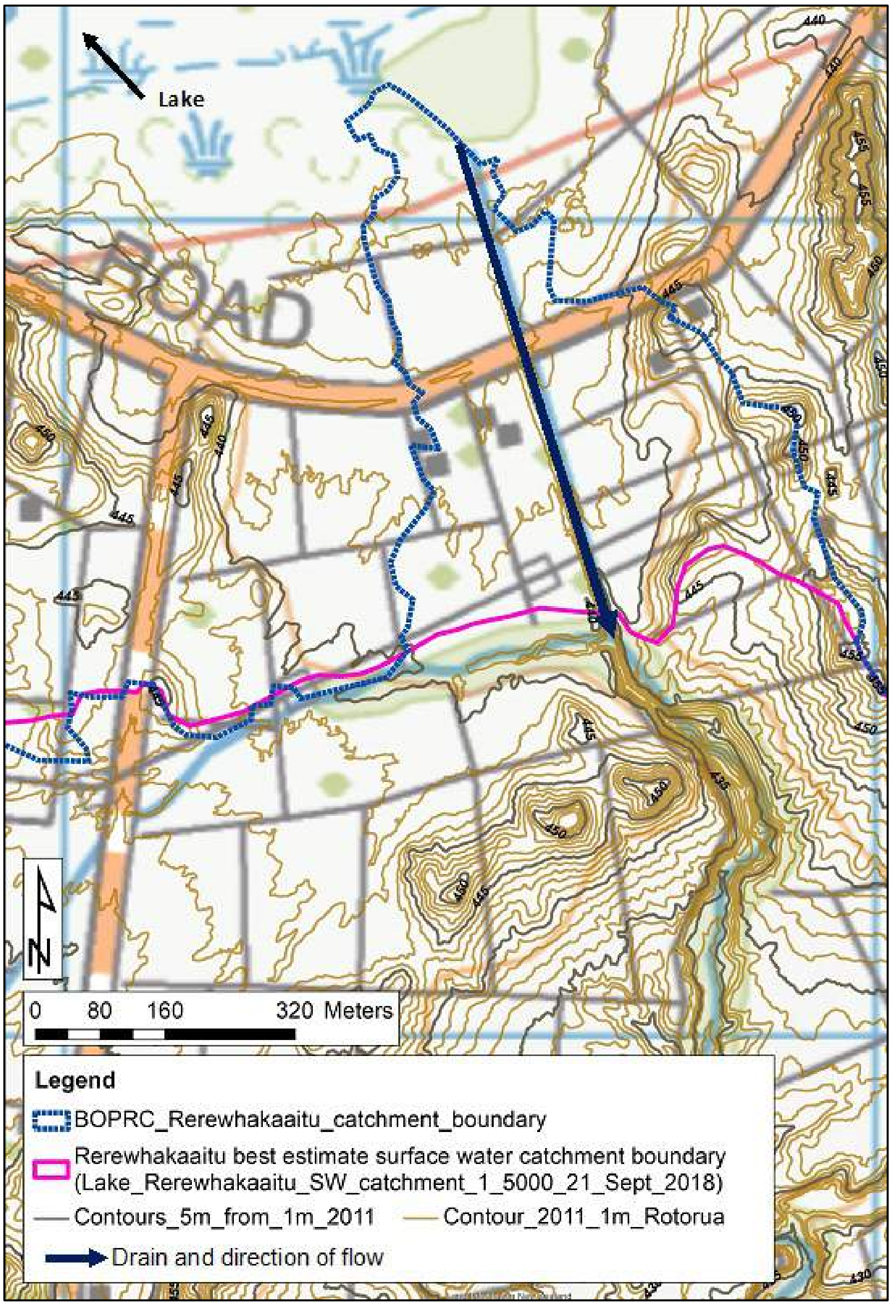

Figure 3.13 Lake Rerewhakaaitu surface water catchment boundary, alteration RW2 and the location of the artificial drain with the direction of flow.

3.2 Best-estimate Groundwater Catchment Boundaries

Best-estimate groundwater catchment boundaries were identified with a variety of methods (Figure 3.14 and Section 2.2); these boundaries are mapped with the areas of major differences between best-estimate surface catchment boundaries and groundwater model boundaries (Figure 3.15 to Figure 3.22; Table 3.2). Section 4 includes a discussion on the best-estimate groundwater catchment boundaries of the greater Tarawera lakes.

Table 3.2 The location and nature of major differences in catchment boundaries.

Feature	Best-estimate surface water catchment boundary	Groundwater model boundary
A	Lake Okataina topographic catchment	Defined by the groundwater model
B	Lake Okareka topographic catchment	Lake Okataina groundwater model
C	Lake Okataina topographic catchment	Lake Okataina groundwater model
D	Lake Okareka topographic catchment	Lake Tarawera groundwater model
E	Lake Okataina topographic catchment	Lake Okataina groundwater model
F	Lake Rotokakahi topographic catchment	Lake Rotokakahi groundwater model
G	Rifle Range crater outside boundary	Rifle Range crater inside boundary
H	Earthquake Flat outside boundary	Earthquake Flat inside boundary
I	Lake Okaro topographic catchment	Lake Okaro model boundary
J	Lake Rerewhakaaitu topographic catchment boundary	Lake Rotomahana groundwater model
K	Lake Rerewhakaaitu topographic catchment	Lake Rotomahana groundwater model
L	Lake Rerewhakaaitu topographic catchment	Lake Rerewhakaaitu groundwater model
M	Lake Tarawera topographic boundary	Defined by the groundwater model

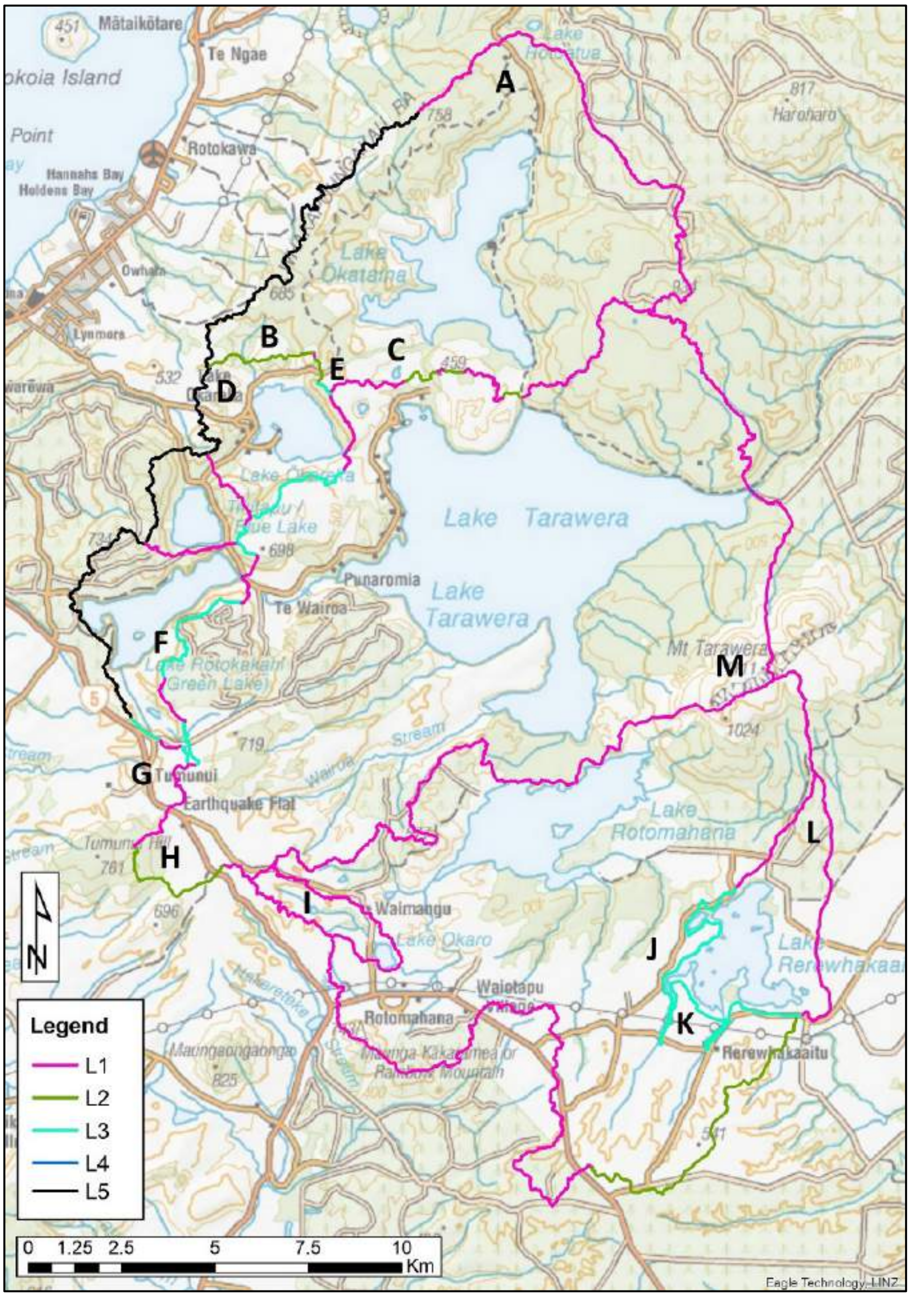

Figure 3.14 Groundwater catchment boundaries of the greater Lake Tarawera catchment with line segments that represent methods of acquirement (L1 – L5, Section 2.2), with the alphabetic codes (Table 3.2).

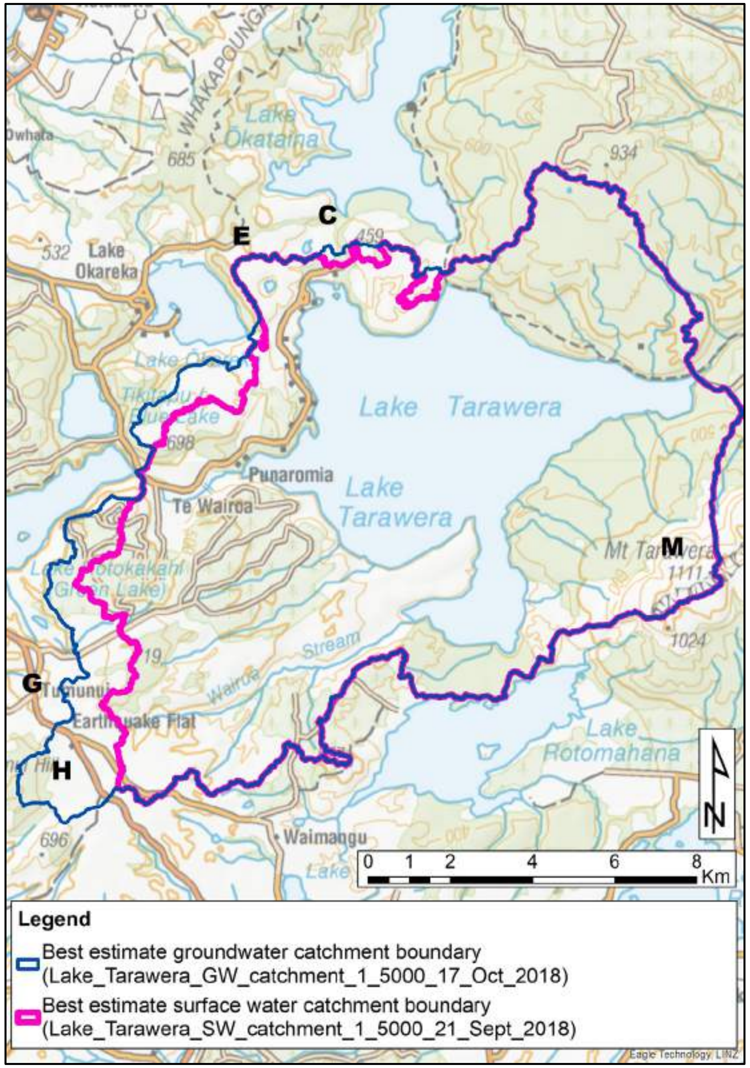

Figure 3.15 Lake Tarawera best-estimate groundwater catchment and best-estimate surface water catchment, with the alphabetic codes (Table 3.2).

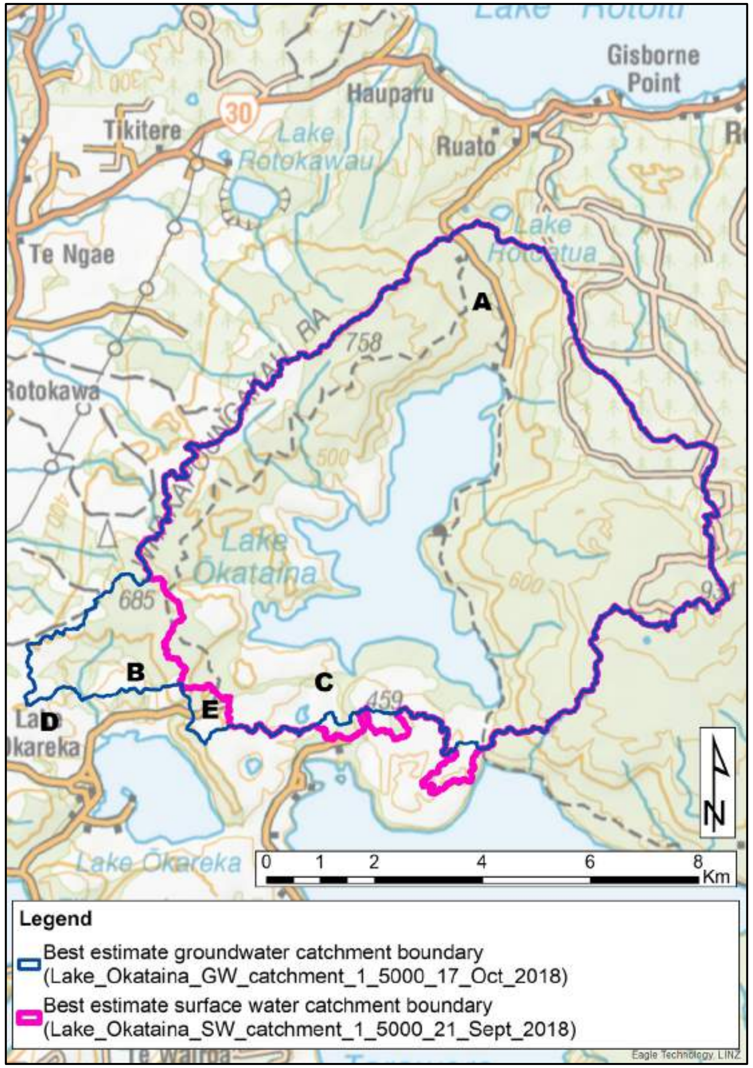

Figure 3.16 Lake Okataina best-estimate groundwater catchment and best-estimate surface water catchment, with the alphabetic codes (Table 3.2).

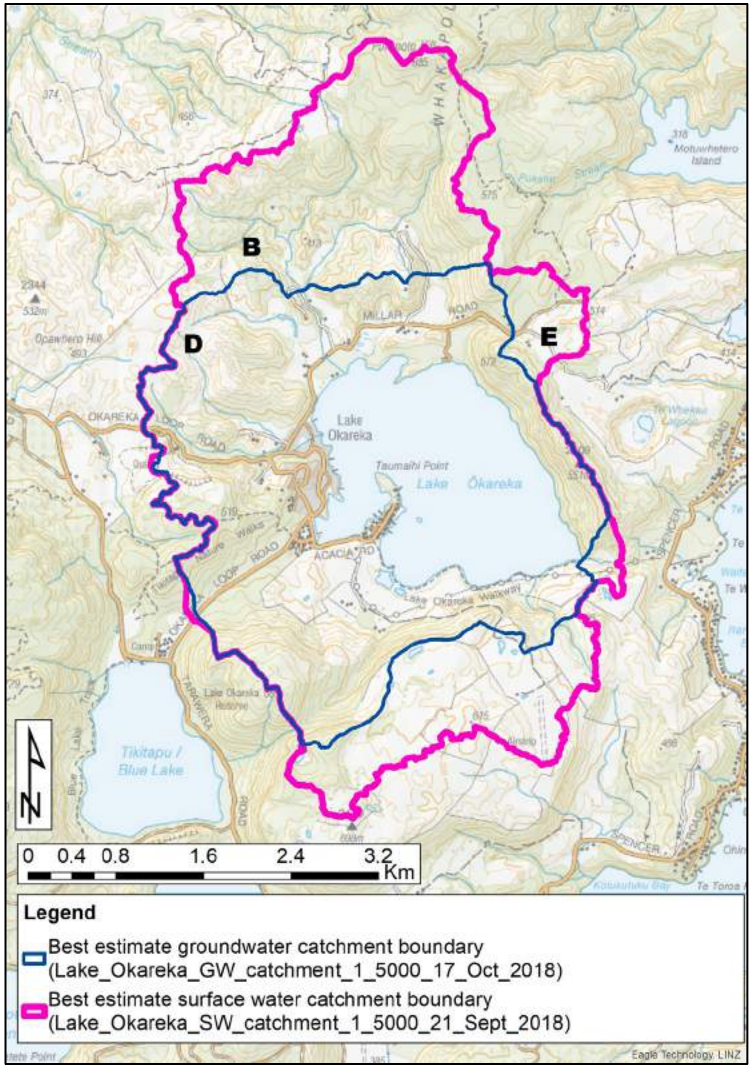

Figure 3.17 Lake Okareka best-estimate groundwater catchment and best-estimate surface water catchment, with the alphabetic codes (Table 3.2).

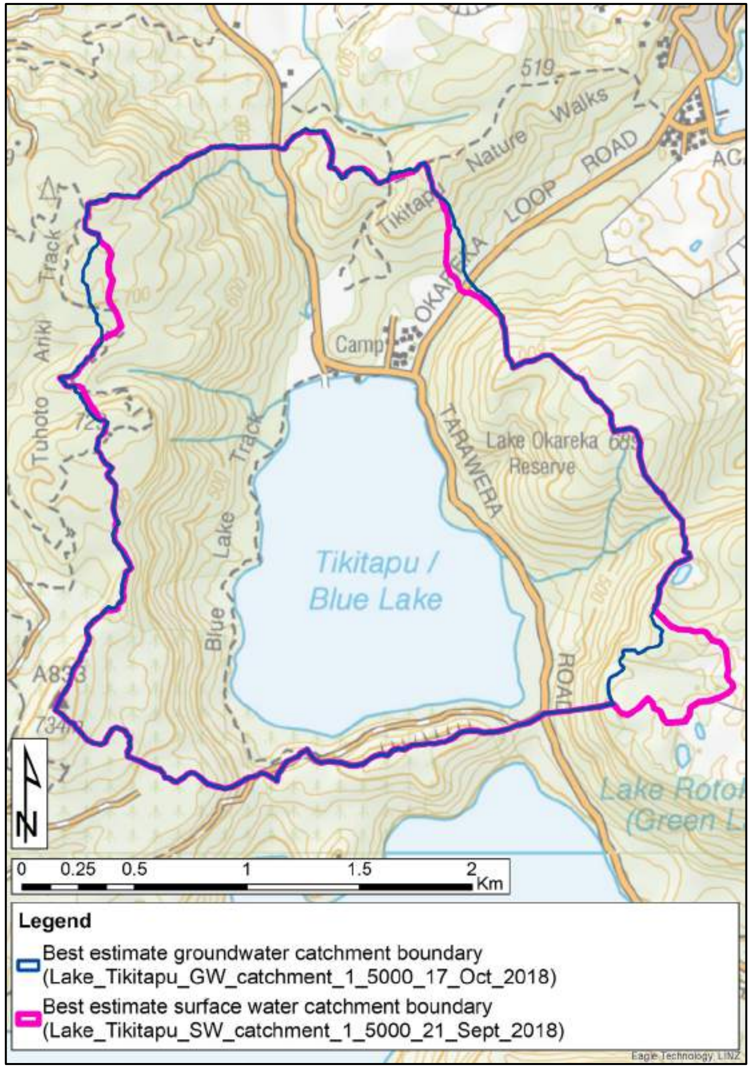

Figure 3.18 Lake Tikitapu best-estimate groundwater catchment and best-estimate surface water catchment, with the alphabetic codes (Table 3.2).

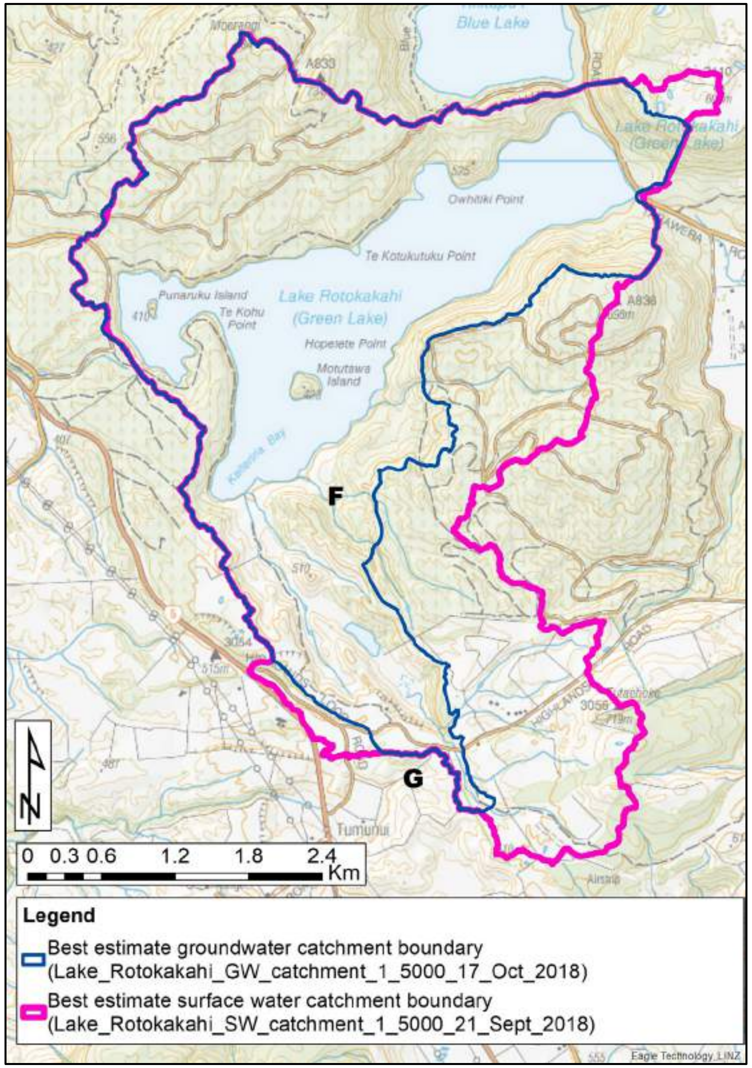

Figure 3.19 Lake Rotokakahi best-estimate groundwater catchment and best-estimate surface water catchment, with the alphabetic codes (Table 3.2).

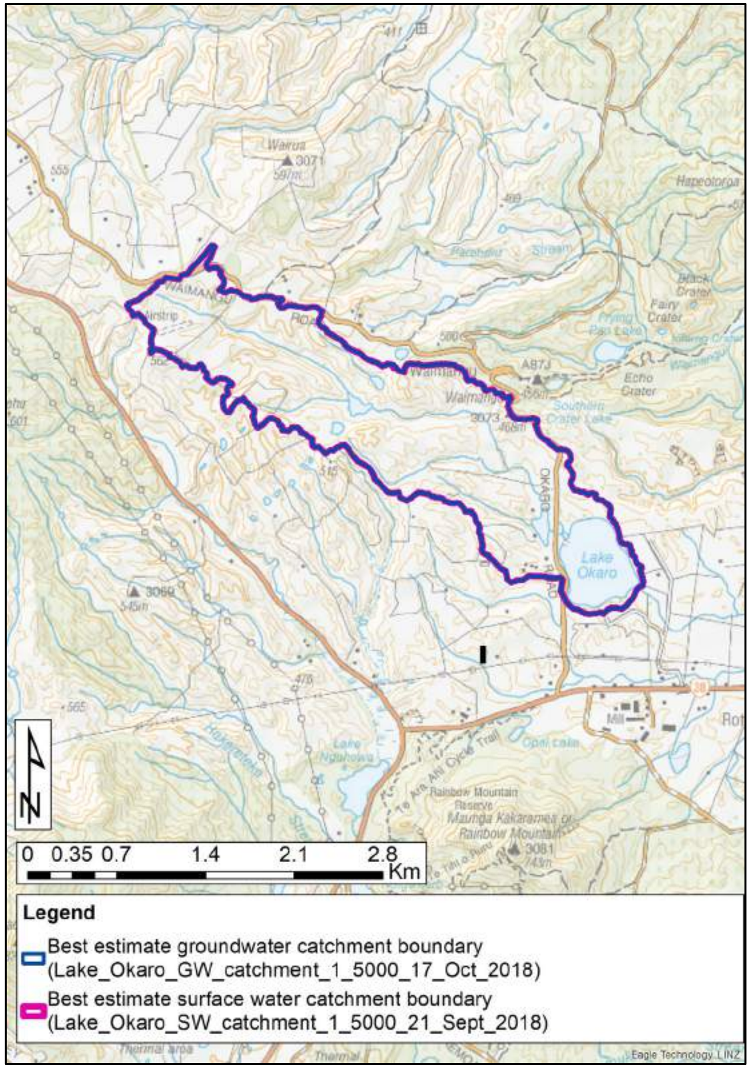

Figure 3.20 Lake Okaro best-estimate groundwater catchment and best-estimate surface water catchment, with the alphabetic codes (Table 3.2).

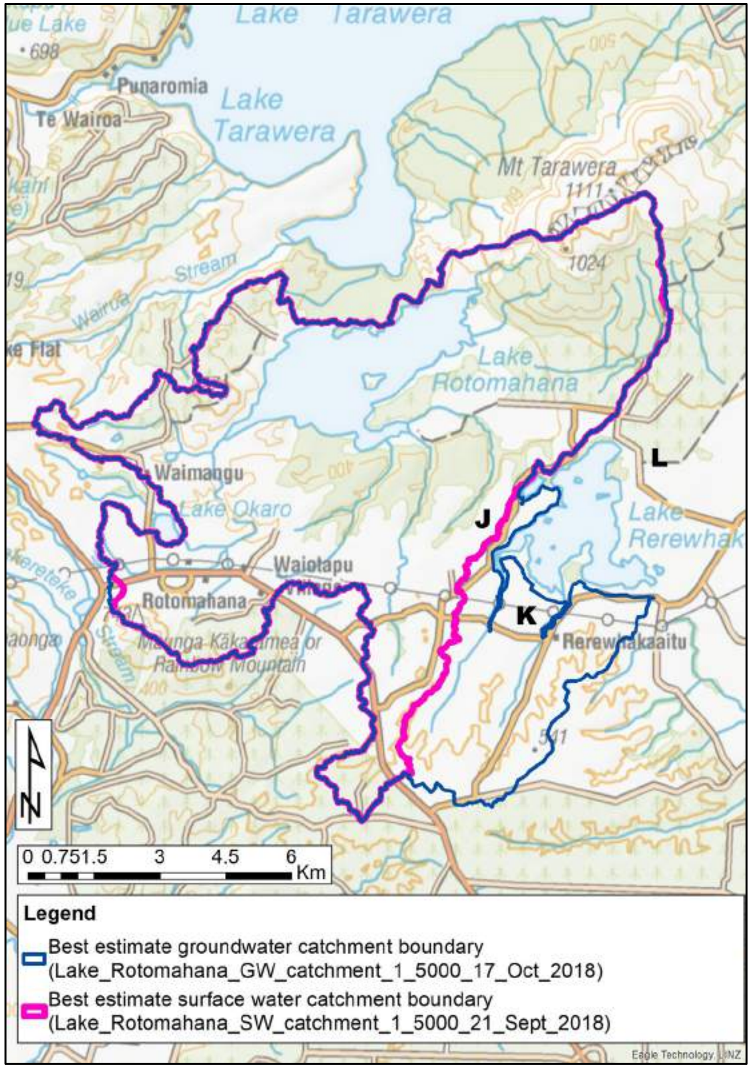

Figure 3.21 Lake Rotomahana best-estimate groundwater catchment and best-estimate surface water catchment, with the alphabetic codes (Table 3.2).

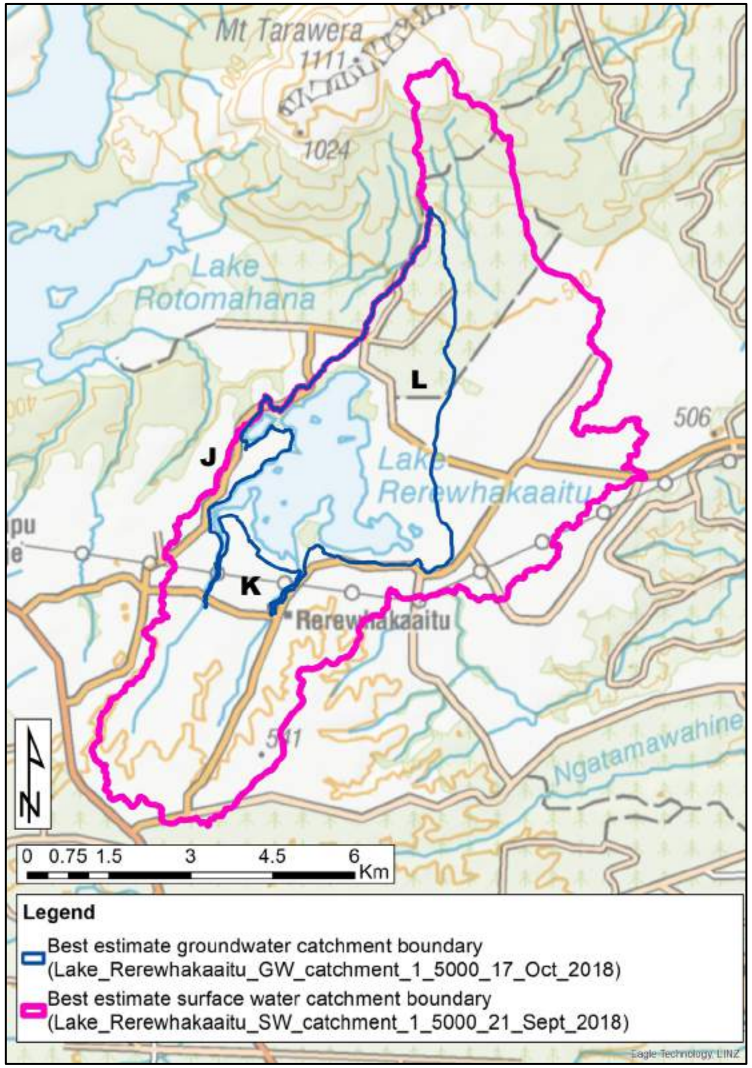

Figure 3.22 Lake Rerewhakaaitu best-estimate groundwater catchment and best-estimate surface water catchment, with the alphabetic codes (Table 3.2).

3.3 Water Budgets

Rainfall (P) and actual evapotranspiration (AET) associated with the best-estimate groundwater catchment boundaries totals, exclusive of lakes, was approximately 15.7 m^3/s and approximately 7.7 m^3/s, respectively (Table 3.3). The combined area of the greater Lake Tarawera catchment, including the lakes, was approximately 381.8 km^2; this area, and the summary water budgets, were similar to White et al. (2016).

The water budgets for lakes and catchments, with best-estimate groundwater catchment boundaries, calculated a rainfall total of 20.1 m^3/s and AET of 9.5 m^3/s (Table 3.4). The summary water budget included groundwater transfers between catchments (Table 3.4). Lake Tarawera has the largest surface water inflows and outflows (Q^{SW}_{IN} and Q^{SW}_{OUT}, respectively) of the greater Tarawera lakes. Calculated groundwater inflow (Q^{GW}_{IN}) to the Lake Tarawera catchment is the largest in the area.

The budget calculated groundwater outflows (Q^{GW}_{OUT}) from the greater Tarawera catchment, i.e.:

- 3.4 m^3/s (approximately) that flows east from Lake Tarawera below the Lake Tarawera outlet.
- 0.4 m^3/s (approximately) that flows east from Lake Rerewhakaaitu to the Rangitaiki River catchment.

Table 3.3 Rainfall and AET within lake catchments defined by the best-estimate groundwater catchment boundary. Inflows and outflows are denoted with positive numbers and negative numbers, respectively.

Lake catchment	Catchment area (km^2)*	P (m^3/s)	AET (m^3/s)
Lake Tarawera	118	6.1	-3.0
Lake Okataina	60	3.8	-1.5
Lake Okareka	9	0.4	-0.2
Lake Tikitapu	4	0.2	-0.1
Lake Rotokakahi	9	0.4	-0.2
Lake Okaro	3	0.2	-0.1
Lake Rotomahana	93	4.1	-2.3
Lake Rerewhakaaitu	10	0.5	-0.3
Total	**306**	**15.7**	**-7.7**

* Note that the area is catchment-only, i.e., the area inside the best-estimate groundwater catchment boundary, excluding the lakes.

Table 3.4 Lake and catchment (best-estimate groundwater catchment boundary) water budgets. Inflows and outflows are denoted with positive numbers and negative numbers, respectively.

Catchment and lake	Catchment and lake area (km^2)	Inflow (m^3/s)			Outflow (m^3/s)		
		P	Q^{SW}_{IN}	Q^{GW}_{IN}	AET	Q^{SW}_{OUT}	Q^{GW}_{OUT}
Lake Tarawera	159.2	8.6	0.5	5.0	-4.0	-6.7	-3.4
Lake Okataina	70.8	4.5	0	0	-1.8	0	-2.6
Lake Okareka	12.4	0.6	0	0.05	-0.3	-0.2	-0.2
Lake Tikitapu	5.6	0.3	0	0	-0.1	0	-0.1
Lake Rotokakahi	13.5	0.7	0	0.05	-0.3	-0.3	-0.08
Lake Okaro	3.7	0.2	0	0	-0.1	-0.03	-0.05
Lake Rotomahana	101.5	4.5	0.03	0.05	-2.5	0	-2.1
Lake Rerewhakaaitu	15.1	0.7	0	0	-0.4	0	-0.4
Total (rounded)	**381.8**	**20.1**	**0.5**	**5.2**	**-9.5**	**-7.2**	**-8.9**

4.0 DISCUSSION AND RECOMMENDATIONS

This Discussion considers the locations of best-estimate groundwater catchment boundaries, particularly uncertainties in these boundaries, and the implications of the water budget (Table 3.4) on catchment groundwater hydrology.

4.1 Lake Tarawera Groundwater Catchment

The extent of the Lake Tarawera groundwater catchment is larger than the boundary defined by the best-estimate surface catchment boundary (Figure 3.15). This was generally due to the 'L2' assumption (see above) which resulted in best-estimate groundwater catchment boundaries that were located west of the best-estimate surface catchment boundary. As a result, the Lake Tarawera groundwater catchment includes Earthquake Flat ('H'). In contrast, Earthquake Flat had previously been assigned to the Lake Rotokakahi zone by White et al. (2016).

The Earthquake Flat area ('H', Figure 3.15) is a source of Earthquake Flat pyroclastics that were deposited in the upper reaches of numerous greater Lake Tarawera catchments (i.e., Tarawera, Rotomahana, Okaro and Rotokakahi) and the Lake Rotorua catchment (Nairn 2002). Therefore, the area is possibly a groundwater headwaters catchment that may supply groundwater to these catchments. Potentially, groundwater is supplied from the area to other lake catchments, i.e., Rotomahana, Okaro and Rotokakahi; however, this report did not define the groundwater catchment boundaries across Earthquake Flat because no suitable data is available for this purpose.

The water budget calculated a groundwater outflow of 3.4 m^3/s (approximately) from the Lake Tarawera groundwater catchment (Table 3.4). This outflow probably travels east from Lake Tarawera below the Tarawera River (White et al. 2016). The calculated flow is generally consistent with flow gains in the Tarawera River below the outlet (White et al. 2016).

4.2 Lake Okataina Groundwater Catchment

The northern area of the best-estimate Lake Okataina groundwater catchment ('A', Figure 3.16) is probably a groundwater headwaters area for Lake Okataina. The area may also be a headwaters catchment for streams that flow north towards Lake Rotoiti (White et al. 2008).

Area 'B' is within the best-estimate groundwater catchment of the Lake Okataina catchment because:

- the stream that flows from the best-estimate surface catchment in area 'B' to Lake Okareka has a very low flow which indicates that rainfall recharge in the area is not draining to Lake Okareka; and
- it seems unfeasible that groundwater from area D is flowing directly to Lake Tarawera (see above).

However, area 'B' is possibly within the Lake Okareka catchment, as identified by the best-estimate surface catchment.

Area 'E' is included in the best-estimate Lake Okataina groundwater catchment because the land surface in the area, being relatively planar and generally dipping towards the north, has much in common with land to the immediate north in the Lake Okataina best-estimate groundwater catchment. However, it is possible that this land area is in the groundwater catchments of Lake Okareka or Lake Tarawera.

The water budget identifies a groundwater outflow from the best-estimate Lake Okataina groundwater catchment of approximately 2.6 m^3/s and assumes that this outflow travels to the Lake Tarawera catchment (Table 3.4). However, some of this outflow may travel to the best-estimate Lake Rotoiti groundwater catchment.

4.3 Lake Okareka Groundwater Catchment

The best-estimate Lake Okareka groundwater catchment is possibly smaller than the Lake Okareka surface water catchment (Figure 3.17). The northern part of the catchment possibly drains to the best-estimate Lake Okataina groundwater catchment (area 'B', see above). The location of the south-eastern boundary of the best-estimate Lake Okareka groundwater catchment was guided by the groundwater flow model, i.e., the 'L2' assumption, see above. The water budget of the best-estimate Lake Okareka groundwater catchment indicates a groundwater outflow of approximately 0.2 m^3/s, which probably travels to the Lake Tarawera catchment (Table 3.4).

4.4 Lake Tikitapu Groundwater Catchment

The groundwater flow model calculated a Lake Tikitapu groundwater catchment boundary that was similar to the Lake Tikitapu shoreline (Figure 3.18). The model calculated that groundwater travelled directly to Lake Tarawera from land located to the west of Lake Tikitapu. Groundwater outflow from the Lake Tikitapu groundwater catchment water is approximately 0.1 m^3/s (Table 3.4). This flow is assumed, arbitrary, to flow in equal portions into three surrounding groundwater catchments (i.e., Lake Tarawera, Lake Okareka and Lake Rotokakahi).

4.5 Lake Rotokakahi Groundwater Catchment

The best-estimate groundwater catchment of Lake Rotokakahi was, like the Lake Tikitapu groundwater catchment, generally close to the lake shore ('F', Figure 3.19). The best-estimate Lake Rotokakahi groundwater catchment excludes Rifle Range crater ('G', Figure 3.19), in contrast to White et al. (2016). This is because topographic contours in this area show that the crater opens to the west, i.e., groundwater probably flows from Rifle Range crater towards the Waikato catchment. The 'L2' assumption moved the eastern boundary of the catchment towards Lake Tarawera. The water budget calculates a groundwater outflow of less than 0.1 m^3/s (Table 3.4).

4.6 Lake Okaro Groundwater Catchment

The best-estimate Lake Okaro groundwater catchment (Figure 3.20) occupies topographic features associated with pyroclastic flow from Earthquake Flat ('H', Figure 3.15). Therefore, this catchment may receive groundwater outflow from Earthquake Flat. Groundwater outflow from the best-estimate Lake Okaro groundwater catchment is less than 0.1 m^3/s (Table 3.4).

4.7 Lake Rotomahana Groundwater Catchment

The best-estimate Lake Rotomahana groundwater catchment (Figure 3.21) has its headwaters near Earthquake Flat ('H', Figure 3.15). Therefore, the best-estimate Lake Rotomahana groundwater catchment may take groundwater outflow from Earthquake Flat, although the water budget assumes that no such flow occurs.

The best-estimate Lake Rotomahana groundwater catchment possibly includes the area south of Lake Rerewhakaaitu because (White et al. 2003):

- groundwater elevations measured in wells in this area indicate a north-westerly flow direction towards Lake Rotomahana (White et al. 2003);
- the spring-fed streams that drain the area flow into Lake Rotomahana (White et al. 2003; White and Tschritter 2015); and
- vertical leakage from Lake Rotomahama to groundwater may provide a hydraulic barrier that prevents groundwater flow from the area to west (White and Tschritter 2015).

The best-estimate Lake Rotomahana groundwater catchment may also take groundwater from the headwaters of the Lake Rerewhakaaitu best-estimate surface catchment (Figure 3.22). Groundwater probably discharges from the best-estimate Lake Rotomahana groundwater catchment to the best-estimate Lake Tarawera groundwater catchment (White et al. 2016); the water budget calculates that this discharge is approximately 2.1 m^3/s (Table 3.4).

4.8 Lake Rerewhakaaitu Groundwater Catchment

The groundwater catchment boundary south of Lake Rerewhakaaitu is very close to the lake, consistent with low surface water flows in the lake from the two streams on the southern lake shore and the generally perched lake (White et al. 2003; Cho et al. 2017), Figure 3.22. North of the lake, the topographic catchment includes the Mt Tarawera talus slope. Groundwater outflow from the catchment is approximately 0.4 m^3/s; this flow probably travels eastwards to the Upper Rangitaiki catchment (White and Tschritter 2015); some may travel to the best-estimate Lake Rotomahana groundwater catchment.

4.9 Uncertainties

Uncertainties are associated with groundwater catchment boundaries and with catchment water budgets. These uncertainties stem from the assumptions used in the identification of best-fit groundwater catchment boundaries and from the uncertainties in model input data. A full assessment of uncertainties is beyond the brief of this project. However, some comment on uncertainties is relevant to the use of boundaries and budgets for the calculation of estimating nutrient inflows to lakes (e.g., White et al. 2007).

4.9.1 Groundwater Catchment Boundaries

Five methods are used to draw groundwater catchment boundaries (i.e., L1 to L5; Figure 3.14). Uncertainties in these boundaries are ranked, from low to high, in the following.

The most certain boundary is the common catchment boundary of the greater Tarawera catchment and the Lake Rotorua catchment (i.e., L5) “Uncertainties in the minimum and maximum surface catchment boundaries are -20 m and +20 m, respectively, as a linear measure. These distances are the approximate range of -95% and +95% percentile differences between the best-estimate surface catchment boundary and the three tertiary catchment boundaries.” (White et al. 2014).

The L1 groundwater catchment boundaries were set as the best-estimate surface water catchment boundary. These boundaries are set with manual checking of BOPRC catchment boundaries against recently-collected LIDAR data at the 1:5000 scale. The manual checks and the use of the LIDAR data reduce the uncertainty in the BOPRC catchment boundaries. The uncertainty in these boundaries is estimated as +/- 50 m because the uncertainty of these lines is probably larger than with the ‘L5’ lines. Uncertainty in ‘L4’ boundaries, which are located at lake outlets are estimated as the same as the ‘L1’ boundaries, i.e., +/- 50 m.

The uncertainty in L2 and L3 boundaries are partially due to the use of the groundwater flow model to identify groundwater flow directions. These uncertainties were considered, along with other factors, in the assessment of best-estimate groundwater catchment boundaries, see above. For example, area ‘H’, with an ‘L2’ boundary (Figure 3.14), is assigned to the Lake Tarawera catchment because of the high ground to the west of the Earthquake Flat and the volcanic flow field in the direction in Lake Tarawera and Lake Okaro.

4.9.2 Groundwater Catchment Water Budget Components

The groundwater flow model provides a broad indication of groundwater catchment boundaries. However, uncertainties in water budget components are associated with the model. Groundwater catchment water budget components are a key part of the estimate of groundwater flow directions provided by the groundwater flow model.

Median annual rainfall (P) was estimated in model cells for the period 1960–2006 by the National Institute of Water and Atmospheric Research (NIWA), Henderson (2017) and Tait et al. (2006). These estimates should reasonably represent steady-state rainfall because of the wide time interval of the calculation. AET values from the land surface derived from a national-scale map developed by NIWA, and averaged for the period 1960–2006 without specific consideration of land use, land cover, soil type or groundwater recharge (Woods et al. 2006; Henderson 2017).

However, surface water flows vary with land use. For example, afforestation down stream of Lake Tarawera resulted in estimated reduction in flow at BOPRC Awakaponga flow measurement site of 4.5 m^3/s between 1964 and 1981 (Dons 1986), or approximately 15% of the mean flow at the site (30.6 m^3/s; 1949 to 2000, Environment Bay of Plenty 2001). Other BOPRC flow measurement sites in the vicinity also recorded a decrease in flow in the period 1964 and 1981 indicating that land use change and climate change impacted on surface flows, i.e.: Tarawera River at the Lake Tarawera outlet, Rangitaiki River (at Te Teko and Murupara) and possibly the Waioeka River at cableway (Environment Bay of Plenty 2001).

The effects of pine afforestation on stream flow was demonstrated in the Purukohukohu Stream catchment, located south of the greater Tarawera catchment (Dons 1981): “After seven years of tree growth there have been substantial reductions in the annual, seasonal and peak flows from the small afforested catchment which indicate beneficial effects of afforestation on gully erosion, sheet erosion and soil creep but detrimental effects on summer water supply and pollution dilution.” Specific yields from pasture were substantially larger than yields from planation forest, following forest-canopy closure in 1981 (Dons 1987). For example, the total surface flow from pasture was 543 mm/year and from pine was 254 mm/year. This difference was largely due evaporative differences, i.e., evapotranspiration from pasture was 784 mm/year and from pine was 1044 mm/year.

Clearly, forestation and deforestation will have impacts of water budgets in the greater Tarawera catchment and may have impacts on the locations of groundwater divides. A better rainfall recharge model may improve the understanding of groundwater catchment boundaries. However, information from a better rainfall recharge model is likely to be equivocal in the mapping of groundwater divides. Therefore, accurate mapping of groundwater divides is best achieved from drill holes and groundwater level measurements; numerous wells will be required to unequivocally identify all the groundwater divides between lake catchments.

4.9.3 Groundwater Nutrient Budgets

Uncertainties in groundwater nutrient budgets come from uncertainties in catchment boundaries and groundwater budgets. Future analysis of groundwater nutrient budgets could consider uncertainties. Chiefly, future work could consider uncertainty in the catchment area, i.e., groundwater catchment boundary uncertainties, and could derive improved water and nutrient budgets.

Land areas associated with groundwater boundary identifications L2 and L3, are particularly relevant to uncertainty analysis, e.g.:

- area ‘B’ which is probably in the catchment of Lake Okataina, but may be in the catchment of Lake Okareka;
- area ‘F’ in the groundwater catchment of Lake Rotokakahi may be wider than mapped in Figure 3.19 and therefore the groundwater catchment of Lake Tarawera may be narrower than mapped in this area (Figure 3.15);
- groundwater from area ‘H’ may partially discharge to the Lake Rotomahana groundwater catchment;
- groundwater from area ‘H’ may partially discharge to the Lake Okaro groundwater catchment;
- groundwater from area ‘K’ may partially discharge to the Rangitaiki River catchment.

An improved nutrient budget is recommended, following the nutrient budget of White et al. (2016); this budget could consider:

- developing a locally-based long-term average rainfall map from NIWA’s Virtual Climate Station Network (VCSN) data to specifically include topography in the calculation;
- an improved locally-based long-term average AET map that considers vegetation type (e.g., forest evaporation; Beets and Oliver 2007) and calibrates to the improved rainfall map and to net outflow (surface water and groundwater) from Lake Tarawera through the Tarawera River area;
- the new version of Overseer (OverseerFM) for calculating nitrogen outflow from crop type (Waikato Regional Council 2019);
- uncertainties in groundwater catchment boundaries.

5.0 CONCLUSIONS

Bay of Plenty Regional Council (BOPRC) commissioned GNS Science to assess the catchment boundaries of the eight lakes in the greater Lake Tarawera catchment (i.e., Tarawera, Okataina, Okareka, Tikitapu, Rotokakahi, Okaro, Rotomahana and Rerewhakaaitu) that eventually drain partly, or wholly, to eastern catchments, i.e., the Tarawera River and the Rangitaiki River. This project follows a three-phase programme of groundwater assessment in these lake catchments that was completed for BOPRC by GNS Science, which found that groundwater provided most of the water inflow into these lakes through spring-fed streams and direct groundwater discharge (Tschritter and White 2014; and White et al. 2016).

This report calculated the groundwater catchment boundaries of these lake catchments, following a recommendation of White et al. (2016). These boundaries were derived as ArcGIS polygons in the New Zealand Transverse Mercator projection at a scale of 1:5,000. Seamless boundaries were calculated within the greater Lake Tarawera area and between this area and the Lake Rotorua catchment. Best-estimate groundwater catchments of lake catchments were calculated by considering a best-estimate surface water catchment boundary and groundwater catchment boundaries derived from the groundwater flow model of White el al. (2016).

The steady-state water budgets for lakes and catchments calculated major water budget components, e.g., rainfall and actual evapotranspiration were approximately 20.1 m^3/s and 9.5 m^3/s, respectively. This budget calculated that groundwater flows to the east of the greater Lake Tarawera catchment, i.e., approximately 3.4 m^3/s from the Lake Tarawera catchment to the Tarawera River valley and approximately 0.4 m^3/s from the Lake Rerewhakaaitu catchment. Groundwater interaction between lake catchments was also estimated by the budgets, i.e., groundwater discharge from the Lake Rotomahana catchment to the Lake Tarawera catchment was approximately 2.1 m^3/s.

The Discussion considered uncertainties and assumptions in the land areas that were included, or excluded, from best-estimate groundwater polygons. For example, the area of the best-estimate Lake Tarawera groundwater catchment was less than the area of the catchment derived by the groundwater flow model. The Earthquake Flat area was included in the groundwater catchment of Lake Tarawera; this area was probably a headwater catchment that may supply groundwater to other greater Lake Tarawera catchments, i.e., Rotokakahi (possibly), Okaro and Rotomahana. The area of the surface catchment south of Lake Rerewhakaaitu was partitioned into two groundwater catchments, i.e., one that probably drains to the Lake Rotomahana groundwater catchment; and one that drains to Lake Rerewhakaaitu and includes the immediate topographic catchment of small streams that flow into the lake, consistent with Cho et al. (2017) and talus slopes from Mt Tarawera.

6.0 ACKNOWLEDGEMENTS

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APPENDICES

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APPENDIX 1 ARCGIS SHAPEFILE NAMES FOR BEST-ESTIMATE SURFACE WATER CATCHMENT BOUNDARIES

Order of processing for boundary realignment	Lake	Final ArcGIS file name
1	Rerewhakaaitu	Lake_Rerewhakaaitu_SW_catchment_1_5000_21_Sept_2018
2	Rotomahana	Lake_Rotomahana_SW_catchment_1_5000_21_Sept_2018
3	Okaro	Lake_Okaro_SW_catchment_1_5000_21_Sept_2018
4	Tarawera	Lake_Tarawera_SW_catchment_1_5000_21_Sept_2018
5	Rotokakahi	Lake_Rotokakahi_SW_catchment_1_5000_21_Sept_2018
6	Tikitapu	Lake_Tikitapu_SW_catchment_1_5000_21_Sept_2018
7	Okareka	Lake_Okareka_SW_catchment_1_5000_21_Sept_2018
8	Okataina	Lake_Okataina_SW_catchment_1_5000_21_Sept_2018

APPENDIX 2 SURFACE WATER CATCHMENT BOUNDARY ALTERATION MAPS

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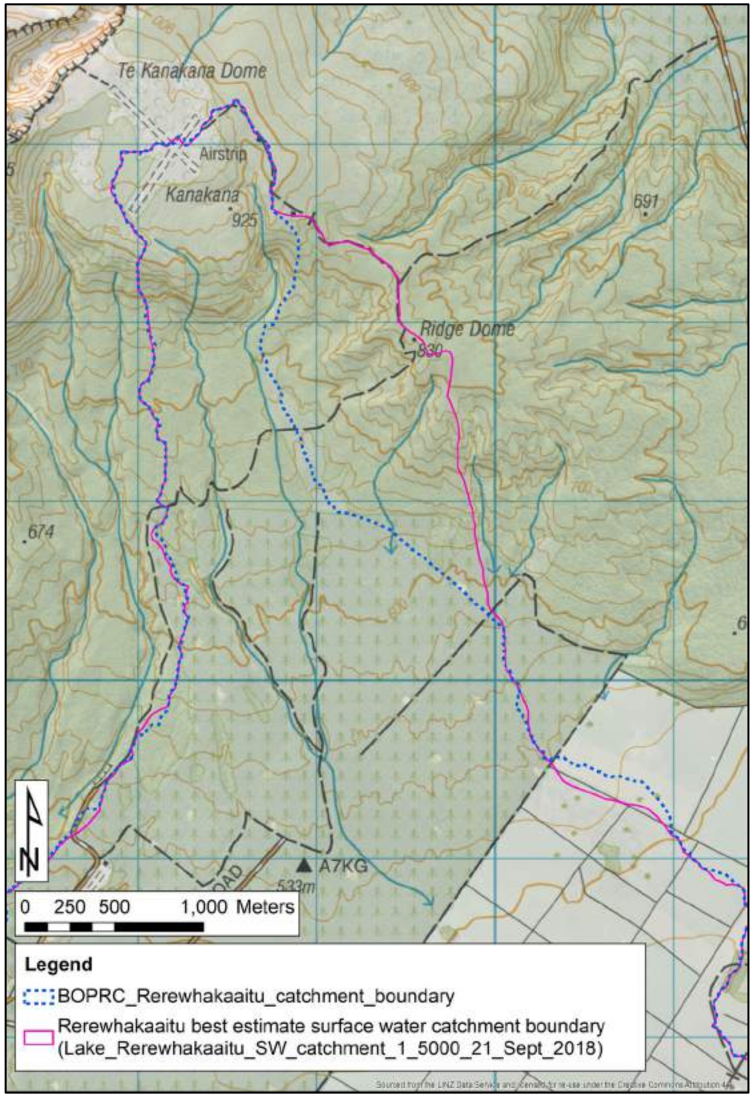
<tr><td>
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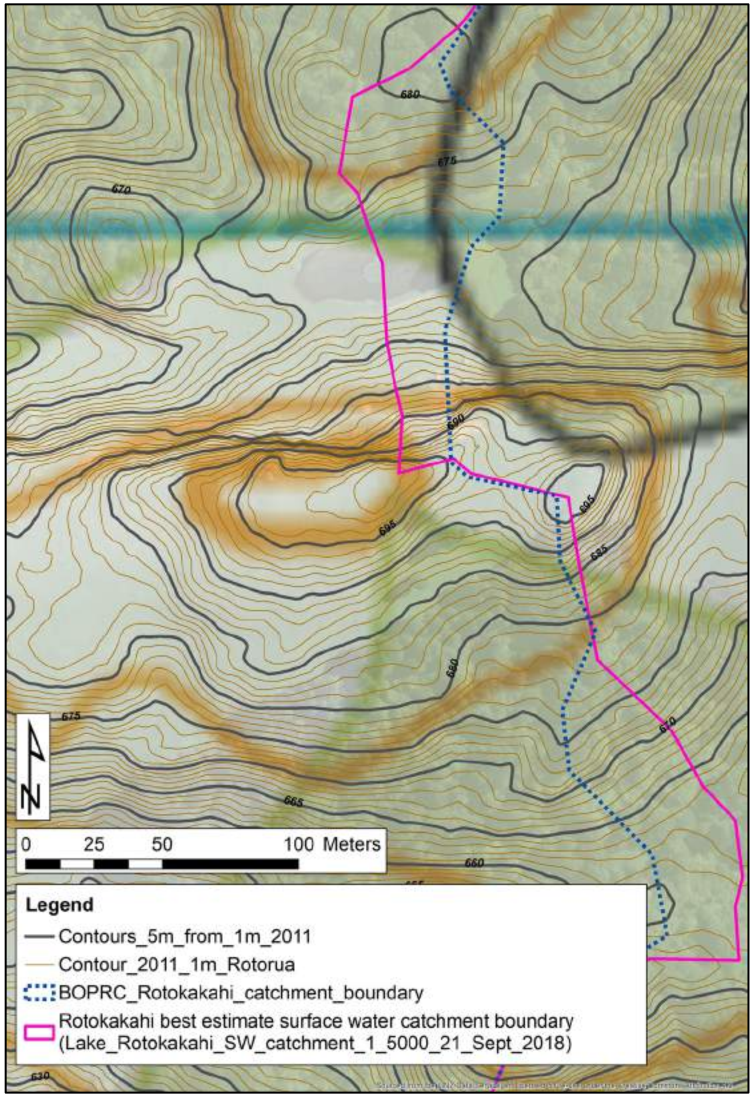
<td>
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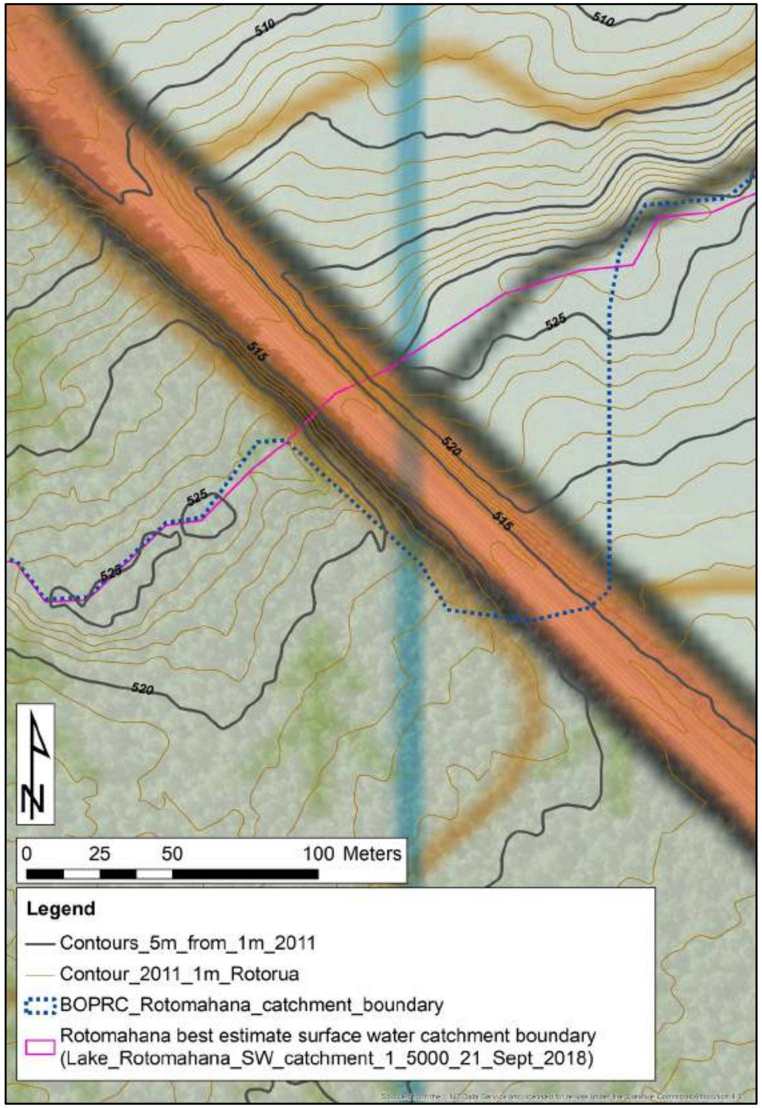
Rotomahana RM1	Rotomahana RM2

Rotomahana RM1



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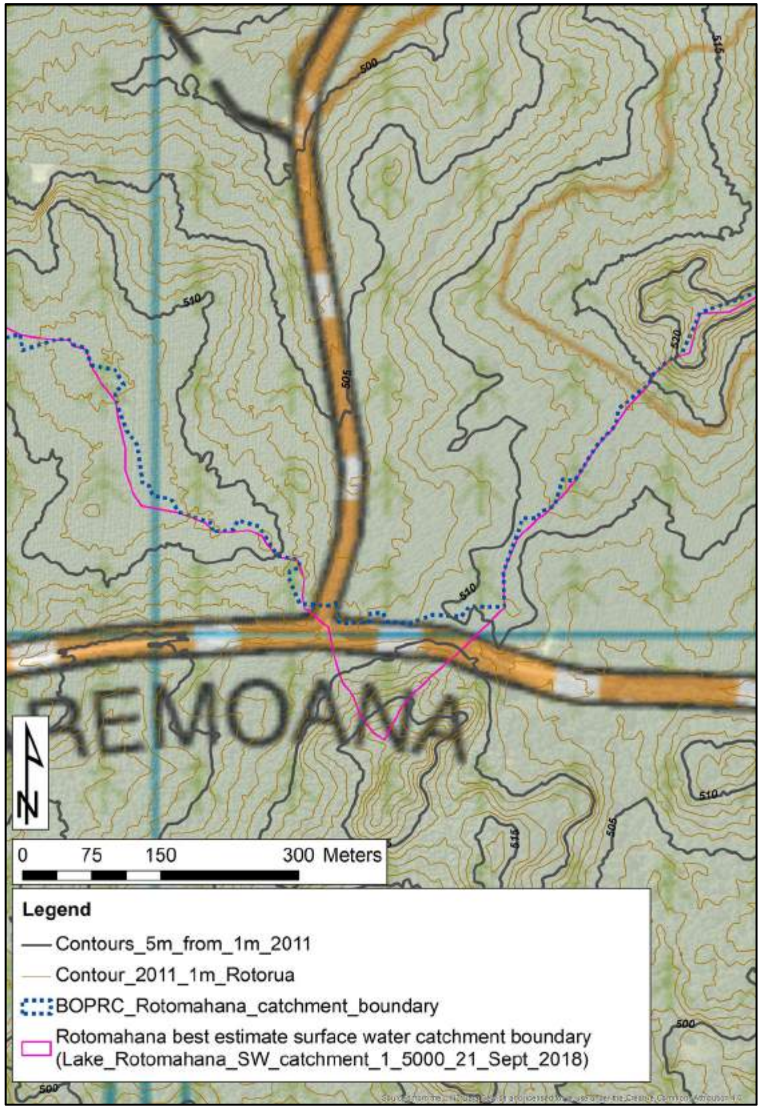

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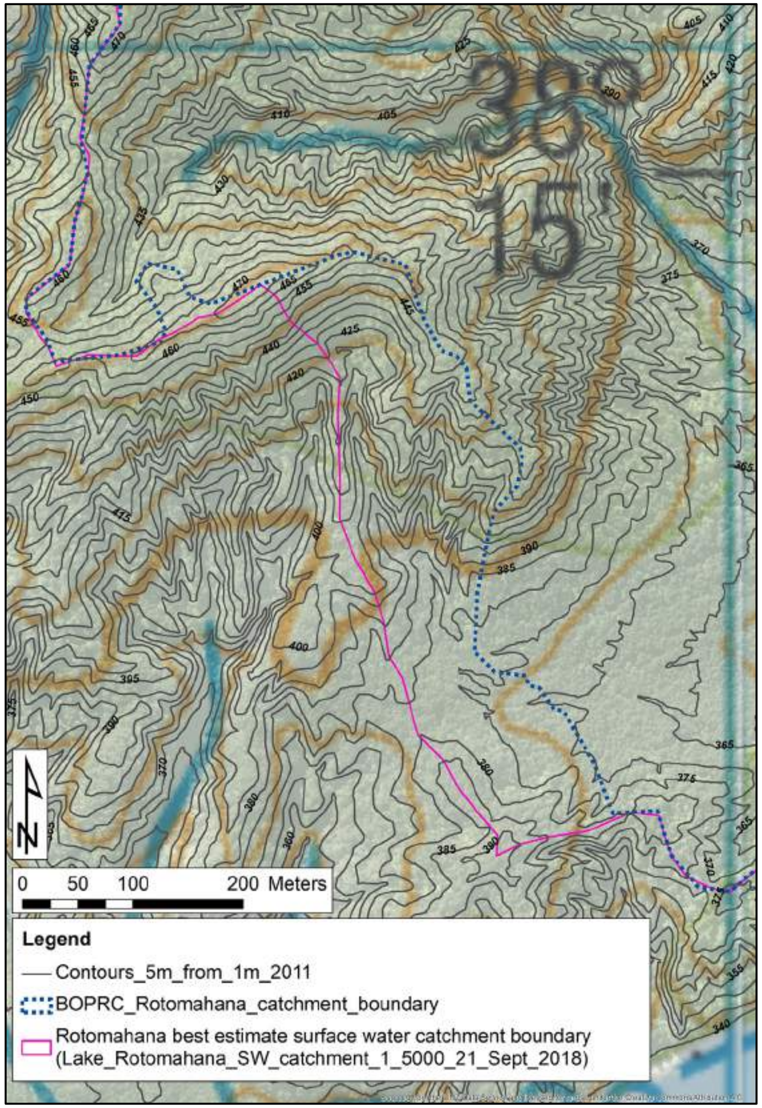
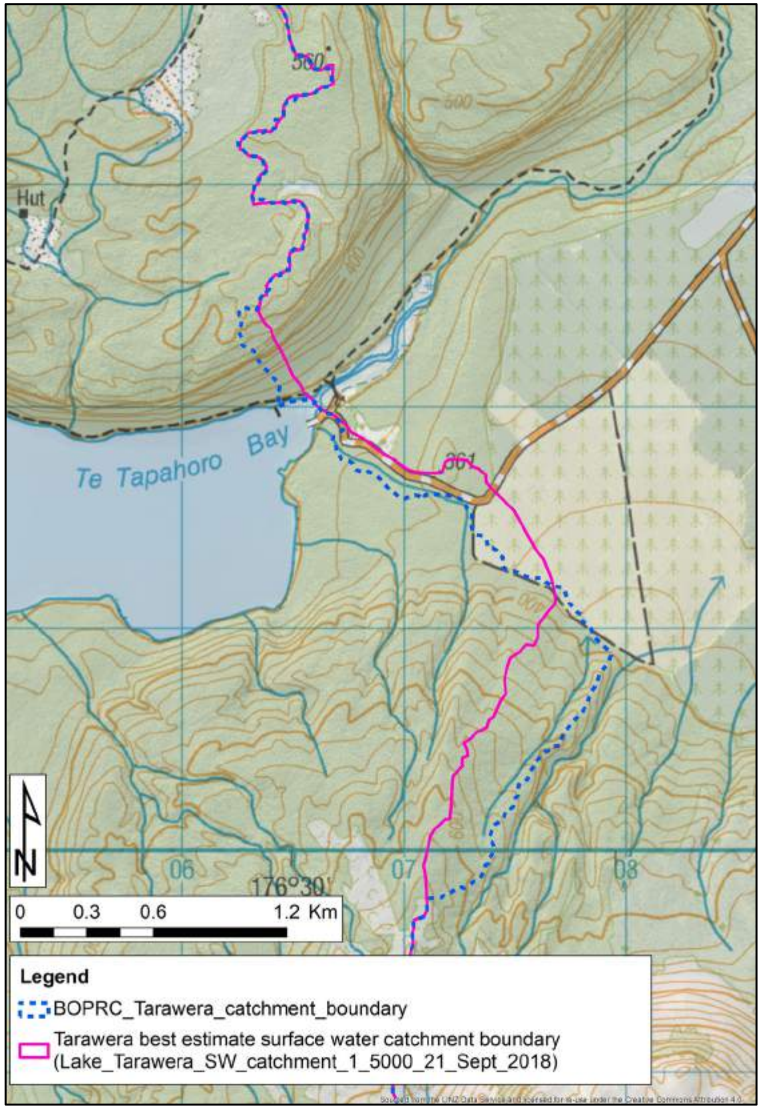
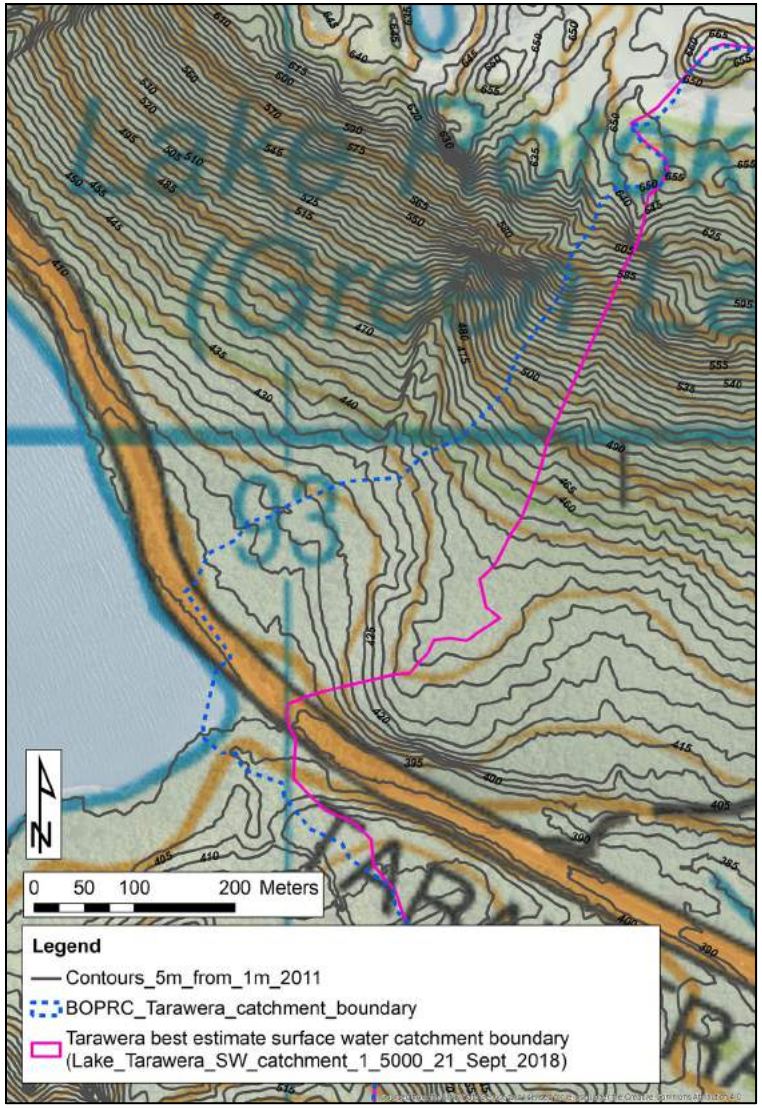
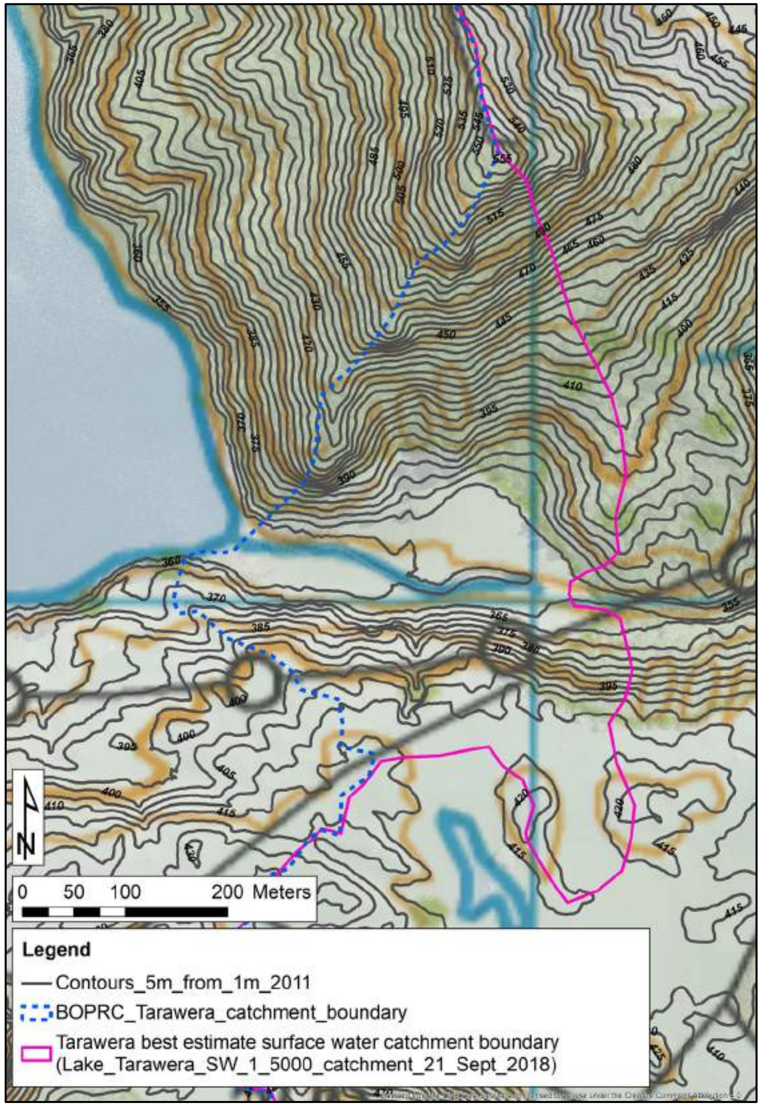
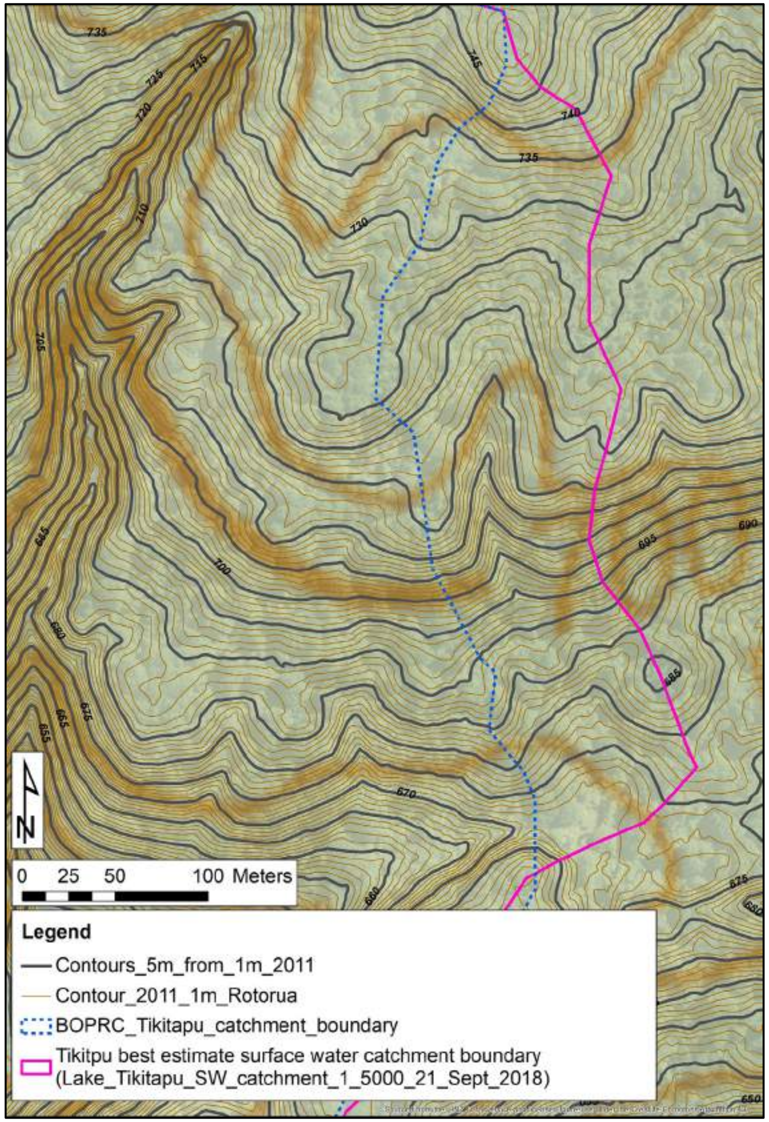
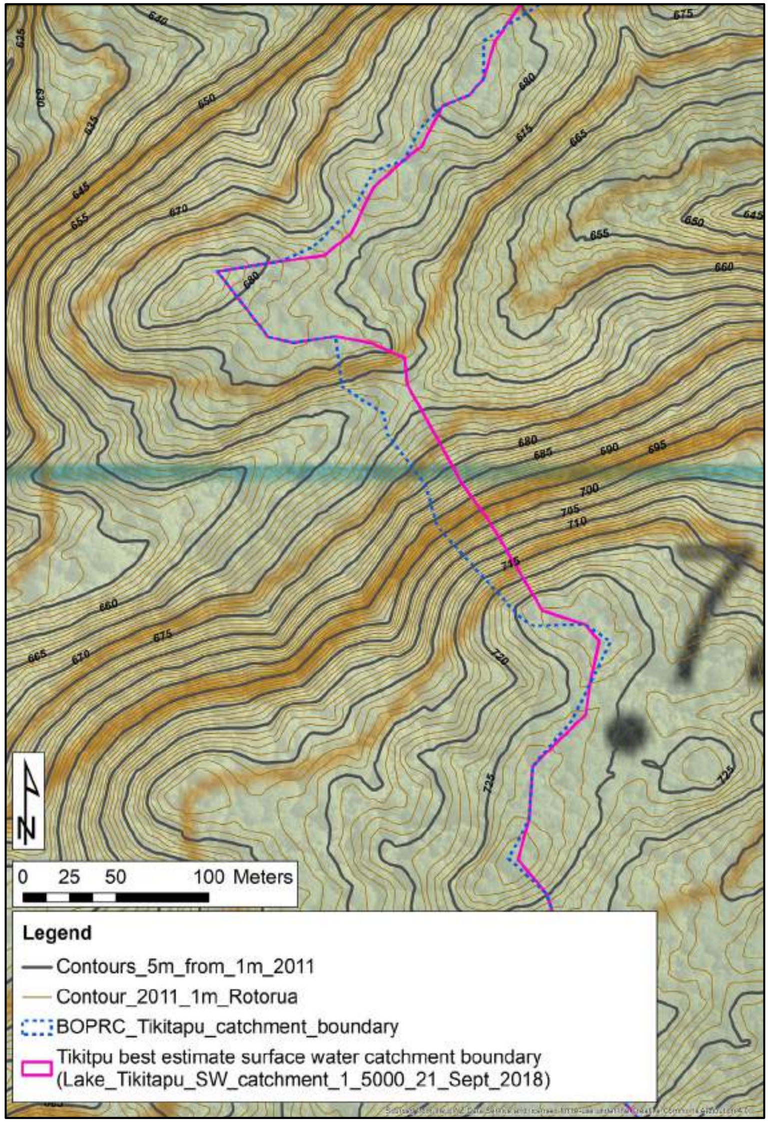
	

Tarawera TW2

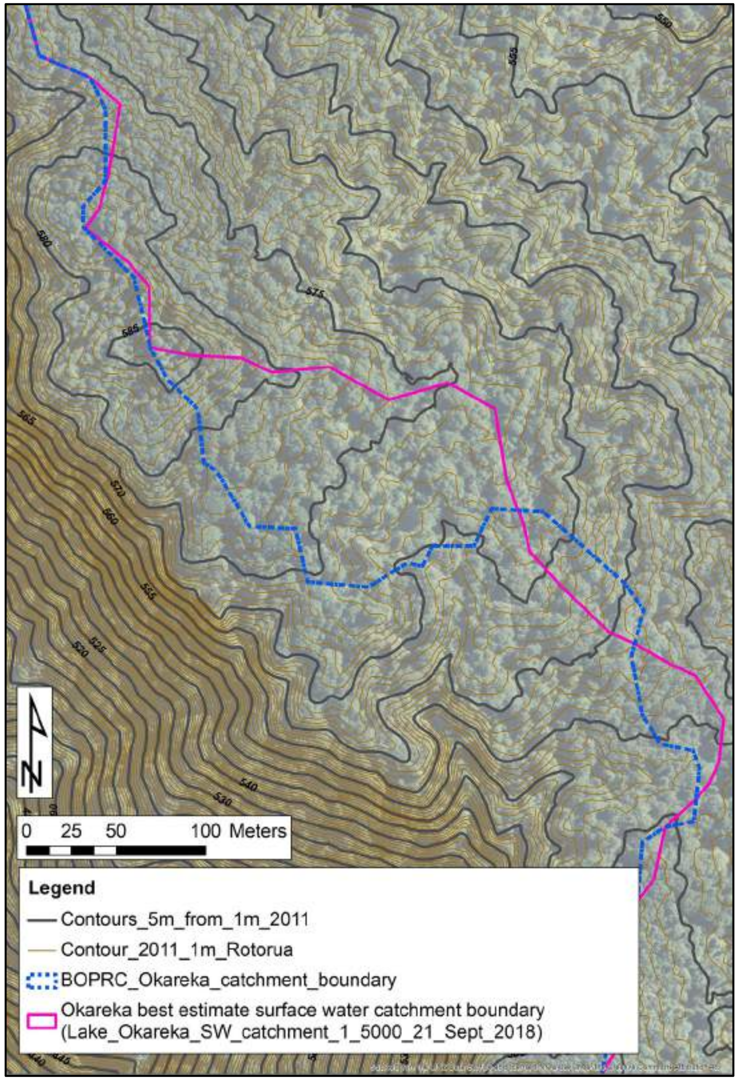


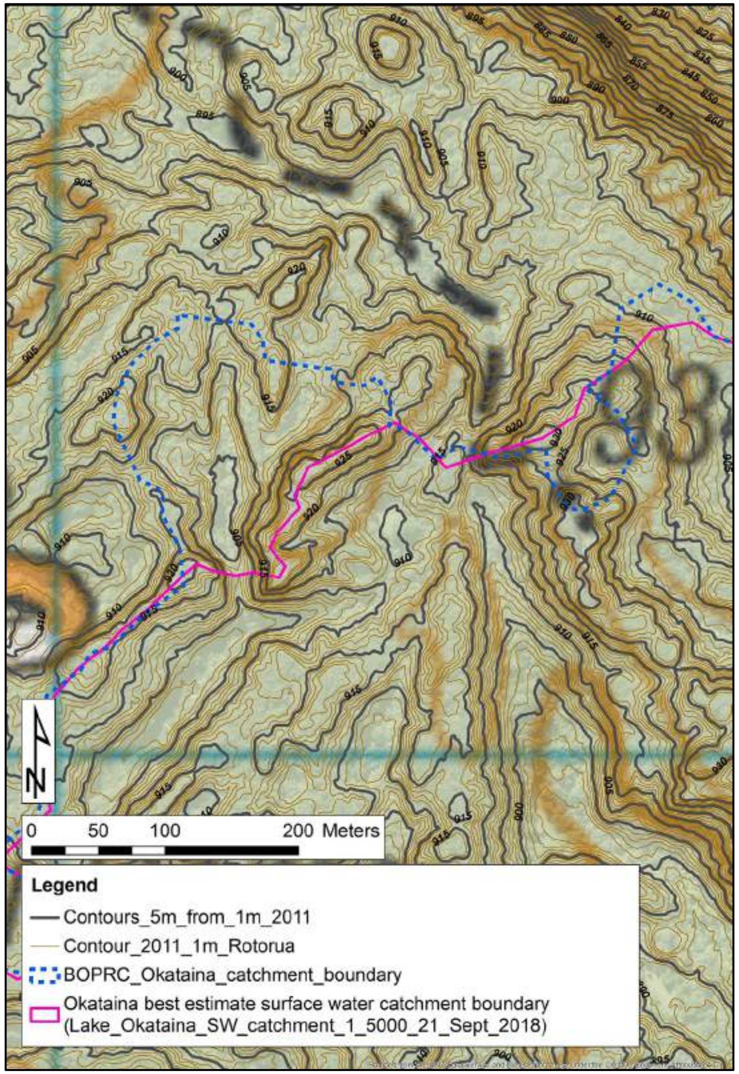
Tarawera TW3



Tikitapu TK1	Tikitapu TK2
	

Okareka OKK1	Okataina OKN2





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