Lake Rotorua catchment boundary relevant to Bay of Plenty Regional Council's water and land management policies

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EXECUTIVE SUMMARY

Bay of Plenty Regional Council (BOPRC) and the local community aim to restore water quality in Lake Rotorua with policies that include land-use controls within the Lake Rotorua catchment. An accurate boundary of the Lake Rotorua catchment boundary is essential to understand the hydrological system and put these measures in place. Therefore, BOPRC contracted GNS Science and the National Institute of Water and Atmospheric Research (NIWA) to define the Lake Rotorua catchment boundary and to quantify the uncertainty in this boundary.

The boundary of the Lake Rotorua catchment defined in this report was developed in two parts: a surface catchment boundary that includes most of the area between Kaharoa and Mamaku township; and a groundwater boundary on the Mamaku Plateau. The surface catchment was derived from topographic contours at a 1 m interval using the 2006/2007 LIDAR data collected by Rotorua District Council. The groundwater boundary on the Mamaku Plateau was derived using multiple data sets including: topographic contours and water budgets that used estimates of surface water flows (summarised by NIWA, Appendix 1) and gridded rainfall, surface flow, and groundwater recharge estimates (derived by NIWA, Appendix 2). The groundwater catchments of three spring-fed streams that drain the Mamaku Plateau (Hamurana, Awahou and Waiteti) were also considered, as the catchments of these streams provide a control on the location of the best-estimate groundwater boundary across Mamaku Plateau. These two parts combine to describe the "best-estimate Lake Rotorua groundwater catchment boundary".

The best-estimate Lake Rotorua groundwater boundary (including Lake Rotorua) has an area of 537.1 km^2, and produces an estimated mean flow of 16.5 m^3/s at Ohau Channel. This flow is equal to the mean observed flow at Ohau Channel (Appendix 1). Likewise, estimated groundwater catchments of Hamurana, Awahou and Waiteti streams produce average flows (2.6 m^3/s, 1.6 m^3/s, and 1.2 m^3/s respectively) that are equal to average observed flows in these streams. The best-estimate Lake Rotorua groundwater boundary is larger than the surface catchment boundary by approximately 35 km^2. Most of this land (33.2 km^2) is within the groundwater catchment of Hamurana Springs. The best-estimate Lake Rotorua groundwater catchment boundary was derived at a resolution of 1:2000, as this scale is suitable for policy purposes.

Uncertainty in the best-estimate groundwater boundary was estimated separately for the surface catchment boundary and the groundwater boundary on the Mamaku Plateau. The 95% confidence interval for the best-estimate surface catchment boundary was an estimated $\pm$20 m (i.e., between 20 m inside and outside the best-estimate boundary), which was derived from an analysis of the catchment boundary. Uncertainty in the best-estimate Lake Rotorua groundwater boundary on the Mamaku Plateau was an estimated $\pm$200 m in the Hamurana Stream catchment, and -640 m and +740 m on the Awahou and Waiteti catchments; these values represent $\pm$95% percentile differences, respectively, in the location of the boundary.

1.0 INTRODUCTION

Restoration of water quality in Lake Rotorua by Bay of Plenty Regional Council (BOPRC) and the local community requires specific policies that aim to reduce the discharge of nutrients (nitrogen and phosphorus) to the lake (BOPRC policies WL3B and WL6B; Bay of Plenty Regional Council, 2014). These policies include land-use controls within the Lake Rotorua catchment and therefore BOPRC water and land management policies within the Lake Rotorua catchment are different to policies outside the catchment. A definition of the Lake Rotorua catchment boundary is crucial because it identifies the land parcels that are relevant to the policy.

The boundary of the Lake Rotorua surface catchment has been estimated by BOPRC (Figure 1.1). However, the Lake Rotorua catchment extends beyond the surface catchment boundary because the size of the surface catchment is less than required to generate the observed inflows to the lake (White et al., 2004). This extension, plus the land inside the surface catchment, is often termed the ‘groundwater catchment’ of Lake Rotorua. Estimates of the area and location of the groundwater catchment (e.g., on the Mamaku Plateau; White et al., 2007) was defined by:

- ground elevation estimates;
- groundwater budgets using land areas, rainfall maps and measured spring flow;
- the location of groundwater divides near Kaharoa and Mamaku township. However, a groundwater divide is not defined across all the Mamaku Plateau because groundwater level is measured at relatively few locations across the Plateau.

Surface and groundwater catchment boundaries have previously been considered in various assessments of hydrology in the Lake Rotorua catchment (e.g., White et al., 2004; White et al., 2007; Rutherford et al., 2008; White and Rutherford, 2009). However, these boundaries are not suitable for policy purposes because they were not developed with consistent datasets of ground elevation, rainfall, baseflow, and evaporation, and they do not generally consider uncertainty in the input datasets.

This project aims to define the Lake Rotorua catchment boundary using the best-quality data sets available and includes an assessment of uncertainty. The project defines the Lake Rotorua catchment boundary in two parts: that which is defined by the surface catchment boundary outside the Mamaku Plateau and that which is defined by the groundwater catchment boundary in the vicinity of the Mamaku Plateau. The project was completed by staff from BOPRC, GNS Science and the National Institute of Water and Atmospheric Research (NIWA) staff.

Firstly, the surface catchment boundary was defined at a 1:2000 scale using topographic contours derived from LIDAR digital terrain measurements as this scale is suitable for the identification of boundaries at the paddock scale. Then, the groundwater catchment boundary in the vicinity of the Mamaku Plateau was defined at the same scale by data including: topographic contours derived from LIDAR digital terrain measurements, surface water flows, groundwater budgets, groundwater level measurements, and estimates of specific discharge in streams. Surface water flows and water budgets are described in two NIWA reports including: estimates of average outflow from the Lake Rotorua catchment (Appendix 1) and estimates of water budget components in gridded datasets in the Lake Rotorua area (Appendix 2).

Uncertainties in the location of the Lake Rotorua catchment boundary were calculated in two parts: the surface catchment boundary uncertainty was assessed with a topographic analysis; and an analysis of boundary position in the vicinity of the Mamaku Plateau that includes uncertainties in surface flows (Appendix 1) and the locations of spring-fed stream catchments. The boundary of the Lake Rotorua catchment, and uncertainties in this boundary, are developed in this report as ArcGIS data sets.

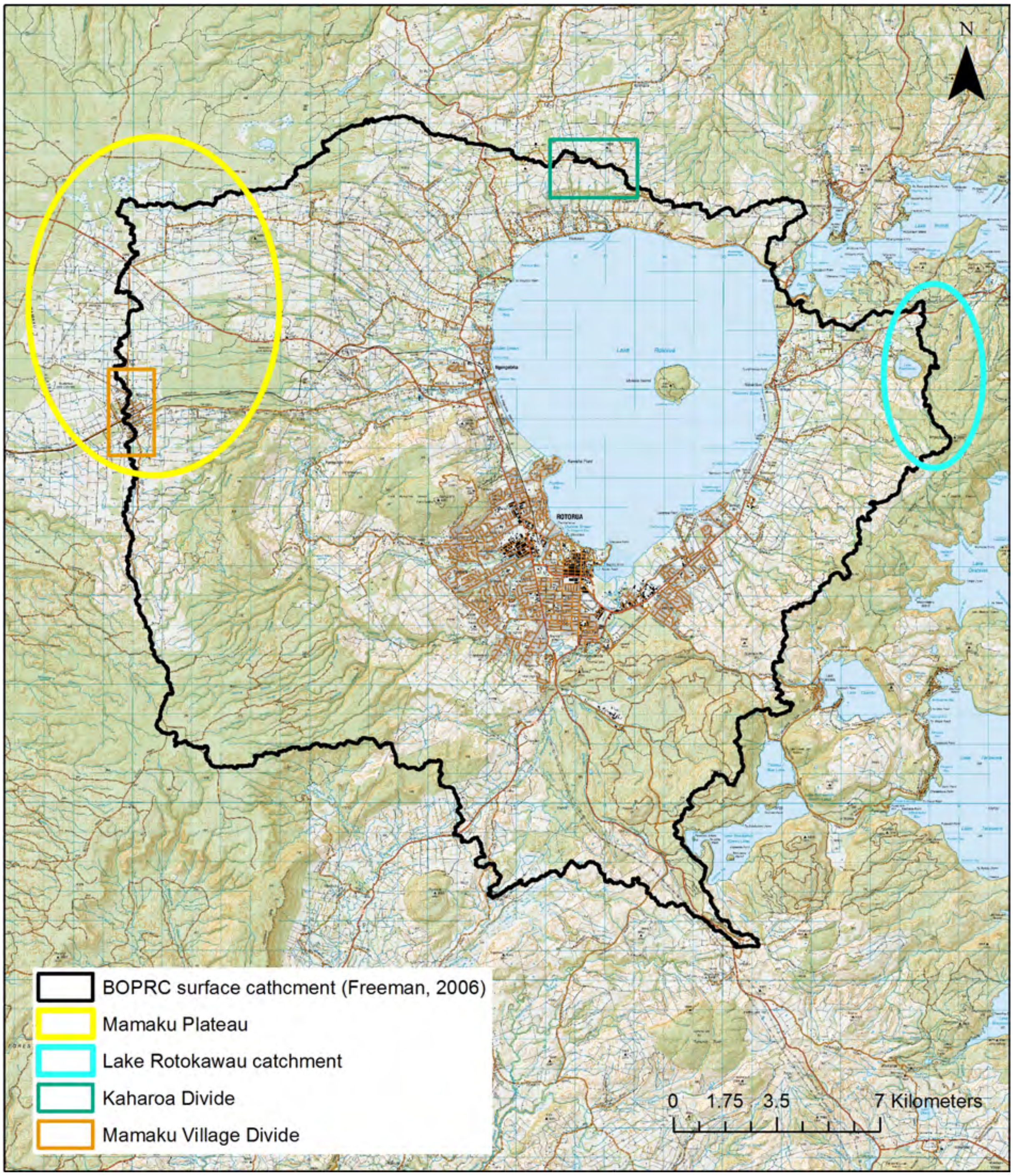

Figure 1.1 Boundary of the surface catchment estimated by BOPRC (derived from Freeman, 2006) and location of the Mamaku Plateau and the Lake Rotokawau catchment. Note that this boundary was derived from Freeman (2006) by BOPRC. The derived map, referred to as Freeman (2006) in this report, includes the Lake Rotokawau surface catchment in the Lake Rotorua catchment (White et al., 2007).

2.0 METHOD

The Lake Rotorua catchment has been defined in two parts (Figure 2.1):

1) the area located between approximately Kaharoa clockwise to approximately Mamaku Village where the surface water catchment (including the Lake Rotokawau catchment) is coincident with the groundwater catchment; and

2) the area located from approximately Mamaku Village clockwise to approximately Kaharoa; the groundwater catchment is outside the surface catchment boundary between these two locations.

The method aimed to: provide a best-estimate Lake Rotorua catchment boundary; and estimate ‘maximum’ and ‘minimum’ Lake Rotorua catchment boundaries, by considering uncertainty in catchment boundary estimates. Data that was used to estimate these boundaries included digital terrain models, stream flows and water budgets.

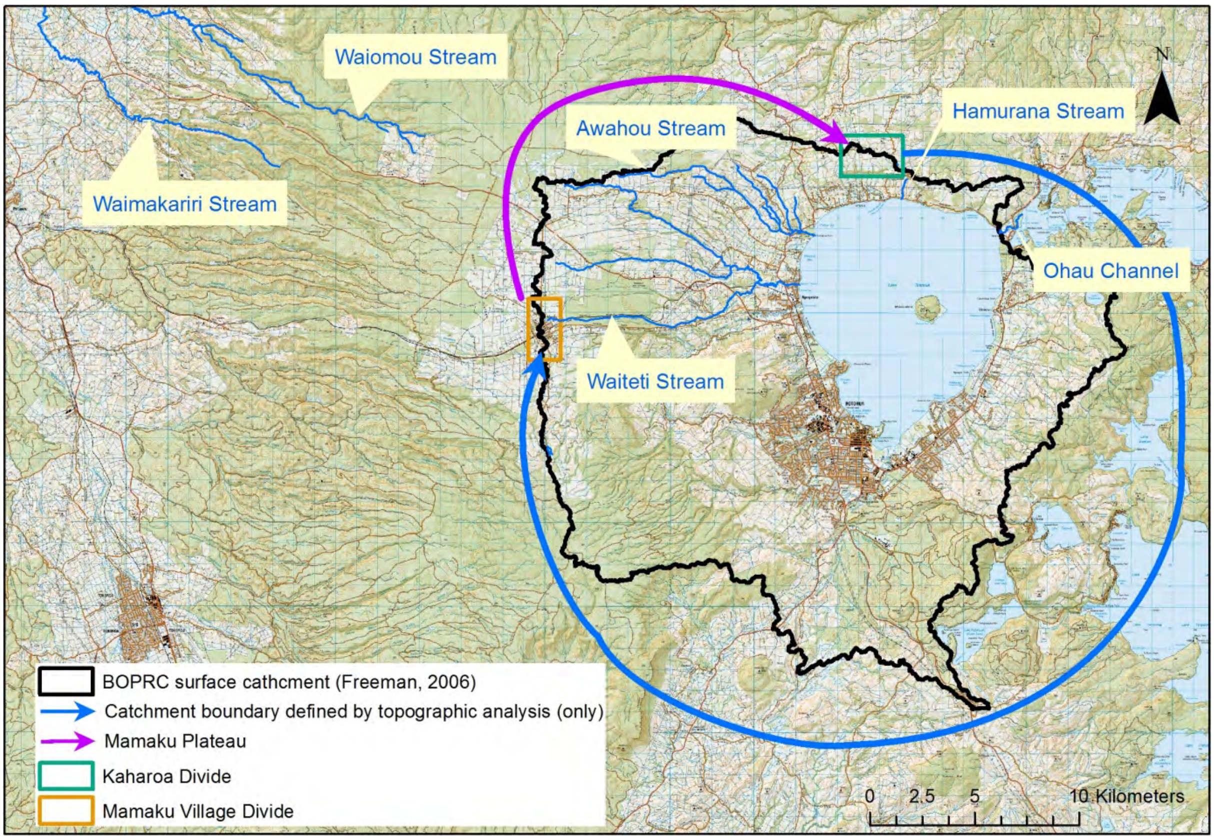

Figure 2.1 Area of the Lake Rotorua catchment boundary defined by a topographic analysis (only) and the area of the Mamaku Plateau. The locations of streams that are discussed in this report are also shown.

2.1 BEST-ESTIMATE LAKE ROTORUA CATCHMENT BOUNDARY

The best-estimate surface catchment around the whole Lake Rotorua circumference was derived at a 1:2000 scale from 2006/2007 RDC LIDAR data (Geosmart Limited, 2006). The extent of 2006/2007 RDC LIDAR data includes most of the Mamaku Plateau (Figure 2.2).

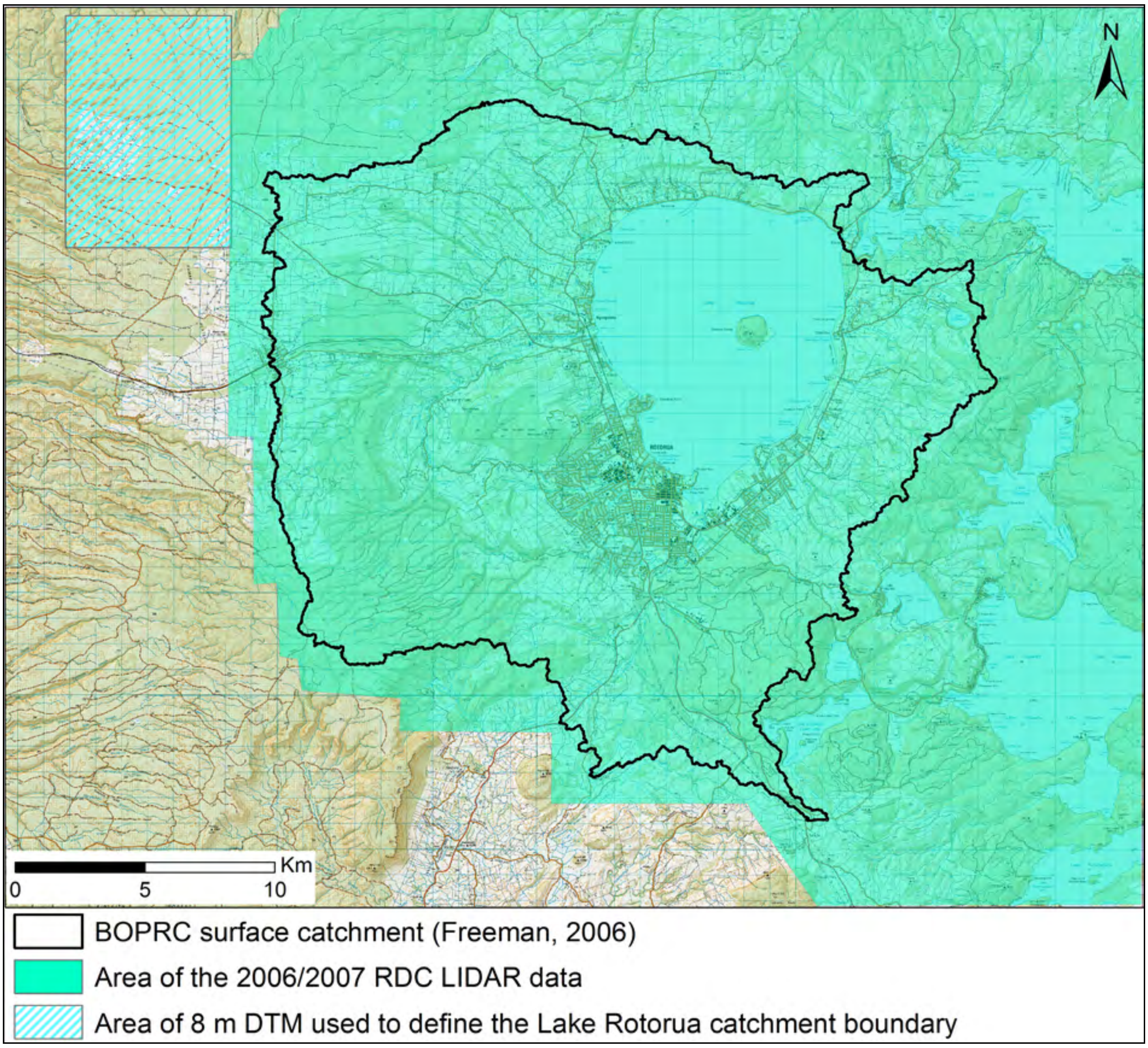

Figure 2.2 Extent of the 2006/2007 RDC LIDAR data shown by coloured rectangles and the area of the 8 m DTM used to define part of the Lake Rotorua catchment boundary on the Mamaku Plateau.

The surface and groundwater catchment boundaries were estimated using 2006/2007 RDC LIDAR data and a DTM derived at an 8 m grid from 20 m contours at the 1:50,000 scale for the area outside the extent of the LIDAR data (Geographx, 2012). Various LIDAR datasets have been collected by RDC including 2006/2007 and 2011. In this report, the 2006/2007 RDC LIDAR data was used because:

- as of July 2014, a DTM and 1 m contours for the 2011 LIDAR data were not available because the data had not been processed by BOPRC; BOPRC estimated this work is unlikely to be completed until March 2015;
- for the Mamaku area, the 2011 LIDAR data was captured to a higher specification than the 2006/2007 data. Therefore, processed 2011 LIDAR should be used to assess catchment boundaries (surface and groundwater) in the future. However, the 2011 LIDAR data was not captured to a higher specification than the 2006/2007 data in all other areas.

Manual surveying was used to check the quality of 2006/2007 RDC LIDAR data in the Mamaku Plateau with ground-level surveys at three localities in the area of State Highway 5 and Maraeroa Rd (Figure 2.3). At each locality, ground levels were measured within an area of approximately 20 m by 20 m. The mean difference between surveyed elevations and LIDAR estimates was 0.24 m (54 measurements), which was within the rated expected LIDAR accuracy of ±0.35 m.

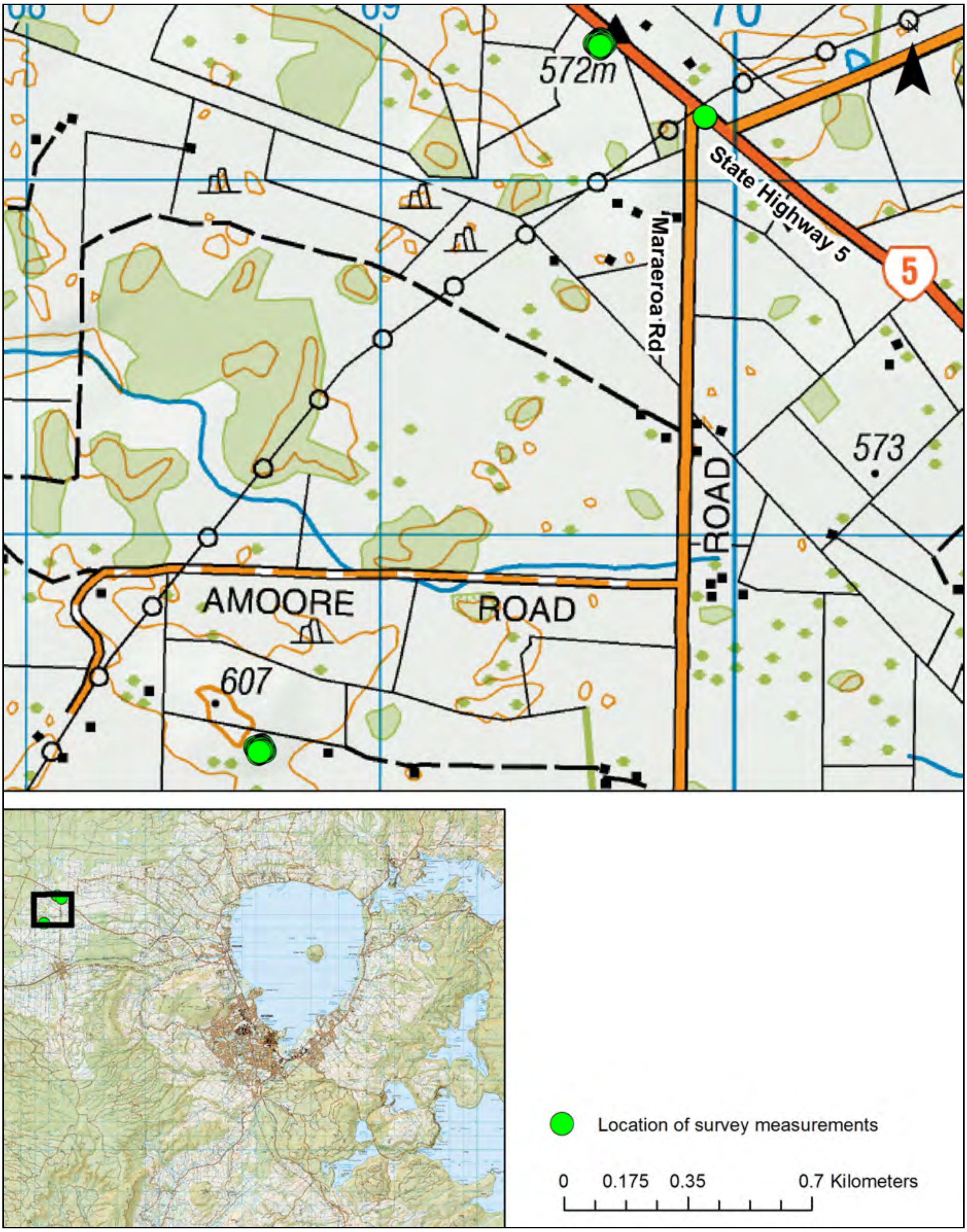

Figure 2.3 Location of survey measurements used to check the quality of the 2006/2007 RDC LIDAR data.

2.1.1 Best-estimate Surface Catchment Boundary

Initially, it was intended to represent the Lake Rotorua surface catchment boundary with the GIS polygon derived from RDC LIDAR data gridded at a 2 m interval, i.e., the 'BOPRC 2 m catchment boundary' (Freeman, 2006). However, this polygon failed to consistently represent the surface catchment defined by 1 m topographic contours calculated by Freeman (2006).

Therefore, a best-estimate surface catchment boundary was developed, at the 1:2000 scale, from the BOPRC 2 m catchment boundary. In most instances, the BOPRC 2 m catchment boundary was not altered because it matched the 1 m surface contours. The shapefile was edited where the BOPRC 2 m catchment boundary did not match the 1 m surface contours. The resulting best-estimate ArcGIS surface catchment boundary at a 1: 2000 scale was named 'Lake_Rotorua_SC_1_2000_12_May_2014'.

2.1.2 Best-estimate Groundwater Catchment Boundary

The best-estimate groundwater catchment boundary was derived from a topographic analysis in the area of the Mamaku Plateau between approximately Kaharoa in the north, and Mamaku Village in the west (Figure 2.1). This analysis used the 2006/2007 RDC LIDAR data and the 8 m DTM model (Geographx, 2012) outside the extent of the 2006/2007 RDC LIDAR data (Figure 2.2).

The analysis was completed in several steps. Firstly, the boundary was estimated at a scale of approximately 1:10000. An iterative procedure identified land areas that were part of four specific land areas: i.e., the Lake Rotorua catchment and the catchments of three large spring-fed systems that drain Mamaku Plateau (Hamurana, Awahou and Waiteti). The catchments of these spring-fed systems were included in the procedure as they informed the location of the Lake Rotorua groundwater catchment. The procedure was completed as follows:

- a Mamaku Plateau groundwater boundary was digitised within the areas of the 2006/2007 RDC LIDAR data (i.e., 1 m contours) and the 8 m DTM model considering groundwater catchment polygons estimated by White (*et al*., 2007);
- a Lake Rotorua groundwater catchment boundary was calculated by merging the Mamaku Plateau groundwater boundary with the best-estimate surface catchment boundary;
- potential groundwater catchment boundaries of Hamurana Stream, Awahou Stream and Waiteti Stream were identified within the Lake Rotorua groundwater catchment boundary, and were guided by: 1) the 2006/2007 RDC LIDAR data (i.e., 1 m contours), and the 8 m DTM model; and 2) groundwater catchment polygons (White *et al*., 2007);
- water flow within four polygons (Lake Rotorua groundwater catchment boundary, Hamurana Stream, Awahou Stream and Waiteti Stream) was calculated using GIS with ROTAN_LITE gridded data sets of rainfall, 'quick flow' and 'slow flow' (Appendix 2). The four polygons are attributed with the ROTAN_LITE data for the areas they encompassed using the ArcGIS 'Intersect' function. Then the actual areas for each ROTAN_LITE grid polygon within the boundary polygons were calculated and the attribute table for each polygon was exported to Microsoft Excel. Here the sums of 'rainfall', 'quick flow' and 'slow flow' were calculated for each of the four polygons in L/s and in m^3/s using the actual ROTAN_LITE grid polygon areas;

- observed mean flows at four sites (i.e., Ohau Channel, Hamurana Springs bridge, Awahou Stream bridge and Waitete Stream bridge; Table 2.1) were compared with calculated water flow within four polygons using GIS;
- the difference between calculated water flow and observed mean surface flows was computed and the groundwater boundaries were adjusted; and
- the above process was repeated until the calculated water flow was within one decimal place of observed mean flow.

Then, the best-estimate groundwater catchment boundary was calculated by adjusting the groundwater boundary to a 1:2000 scale using the 1 m contours within the area of the 2006/2007 RDC LIDAR data. However, the boundaries of the three large spring-fed systems that drain Mamaku Plateau were not adjusted to a 1:2000 scale because the primary purpose of this report was to estimate the external boundary of the Lake Rotorua catchment. The boundaries of the spring-fed systems are equal to the best-estimate groundwater catchment boundary at the 1:2000 scale where they are coincident with the best-estimate groundwater catchment boundary. Elsewhere, boundaries were guided by the 1 m contours at a 1:10000 scale.

Table 2.1 Mean surface water flows, with uncertainty estimates (Appendix 1).

Stream	Mean flows in a 13 year period (m^3/s)		
	-95% confidence in mean	Mean	+95% confidence in mean
Ohau Channel	15.3	16.5	17.7
Hamurana	2.3	2.6	2.9
Awahou	1.4	1.6	1.8
Waiteti	0.8	1.2	1.6

Surface flows and specific discharge estimates in other catchments that discharge from the Mamaku Plateau are also considered as these are relevant to groundwater catchment boundaries in the Lake Rotorua catchment. Other catchments include: the Mangorewa River which drains to the north of the Lake Rotorua catchment (Figure 2.4); and Waiomou Stream and Waimakariri Stream which flow in the Waikato Region west of the Mamaku Plateau (Figure 2.1). Flow statistics in the streams were from gauging sites 1174_3 (Waiomou Stream) and 1158_1 (Waimakariri Stream), Waikato Regional Council (2009). Mean flows and 95th percentile flows for the Waikato region streams are, respectively: 2.69 $m^{3/}s$ and 0.74 m^3/s (Waiomou Stream) with 4.34 m^3/s and 0.17 m^3/s in Waimakariri Stream. In addition, a site visit to the northwest Mamaku Plateau on 5th June 2014 allowed for a visual assessment of surface flows and swamps (Figure 2.4 and Table 2.2).

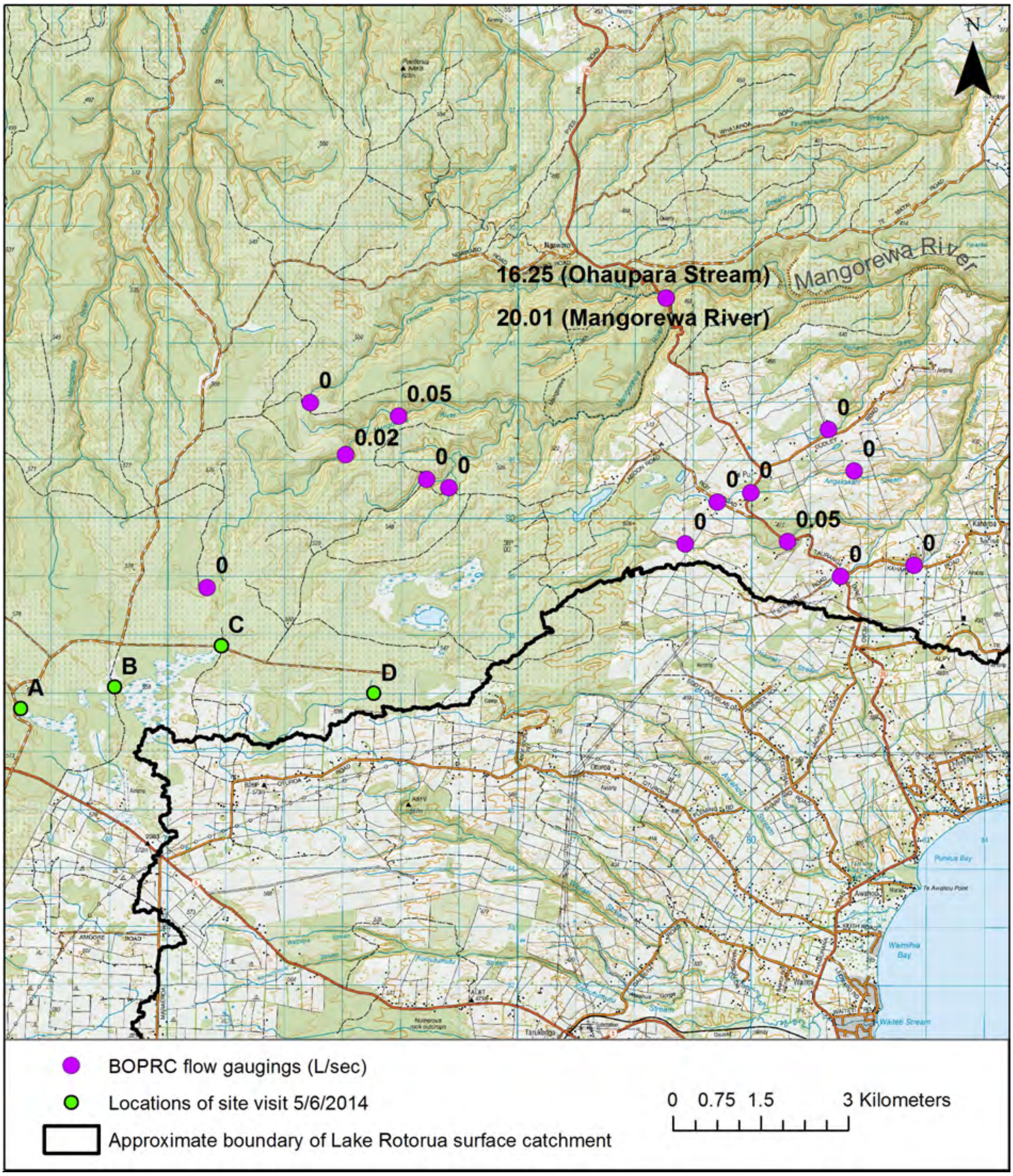

Figure 2.4 Low-flow gauging sites and flow measurements in the Mangorewa River surface catchment north of the Lake Rotorua catchment. The locations of sites that were visited in June 2014 are also shown.

Table 2.2 Observed flow conditions during a site visit (5/6/2014), Figure 2.4.

Location of site visit 5/6/2014	Notes
A	A swamp (east of the road) is impounded by the road. Manual inspection of the road embankment indicates no culvert beneath the road.
B	No flowing water and general swampy conditions
C	Flow in culvert of approximately 10 L/s (visual estimate) towards the north
D	No flowing water in a small ponded stream

2.2 UNCERTAINTY IN LAKE ROTORUA CATCHMENT BOUNDARIES

Uncertainty in the Lake Rotorua catchment boundaries were assessed with the following:

- surface catchment boundaries were derived to represent '+95%' and '-95%' polygons based on three alternative surface catchment boundaries that were derived from a 10 m DTM;
- groundwater catchment boundaries were derived to represent '+95%' and '-95%' polygons using a variety of alternative groundwater catchment boundaries based on the location of groundwater divides, DTMs, ROTAN_LITE calculations, groundwater flow direction calculations, estimated flows at four surface monitoring sites (Hamurana Springs, Awahou Stream and Waitete Stream and Ohau Channel) and measurements of specific surface water flows.

2.2.1 Uncertainty in the Surface Catchment Boundary

Uncertainty in the surface catchment boundary was assessed by:

- calculating three surface catchment boundaries based on a 10 m DTM;
- statistical comparison of the best-estimate surface catchment boundary with these three surface catchment boundaries;
- calculation of the 'maximum' and 'minimum' catchment boundaries based on this statistical comparison.

2.2.1.1 Catchment Boundaries Estimated from a 10 m DTM

Three software packages (Surfer, ILWIS and ArcMAP/ArcHydro) were used to calculate tertiary surface catchment boundaries using a 10 m DTM derived from the 2006/2007 RDC LIDAR survey.

Firstly, the 10 m optimal spatial resolution (i.e., pixel size) was determined for the DTM used in these calculations. A workable pixel size had to be determined for the DTM as the length of processing time and probability of success depended largely upon the size of the data set being processed. The optimal pixel size was determined by running the first step in catchment extraction (sink evaluation) and ensuring the run time was reasonable. The data set size was also limited by the maximum size that could be handled by the ILWIS program.

The 2 m DTM was then resampled to the optimal pixel size (10 m) and exported as a GeoTIFF file which was used as the input for conversion to the native format for both ILWIS and Surfer. All processing was then done using their native formats.

The standard processing flow for each software package was then carried out on the 10 m DTM with default gridding values for each package. These values were selected from menu choices within the Surfer package (i.e., Map; New; Watershed Map; Figure 2.5); ArcMap/ArcHydro and ILWIS required specification of stream threshold (500 pixels = 5000 m^2) and minimum drainage length (100 m).

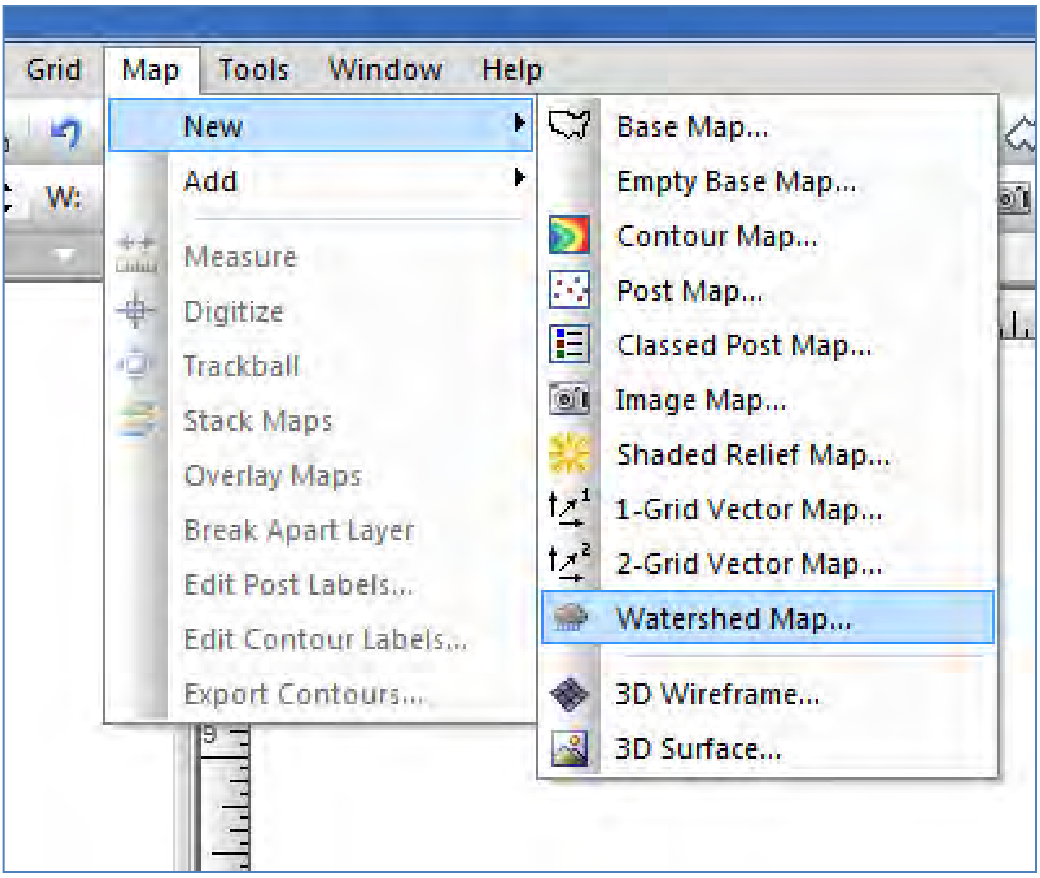

Figure 2.5 Surfer menu choice for creating a catchment/watershed.

The outputs for Surfer and ILWIS were then converted into shapefiles and imported into ArcMAP. However, the conversion/export from Surfer and ILWIS produced a shapefile that was not clean, as the lines and polygons representing drainage catchments/watersheds are not topologically corrected. For example, lines overlapped and therefore polygons included overlaps and negative areas, an indication that vertex sequence was inverted. All these errors were corrected and the shapefiles “cleaned” before they were used any further.

Catchments generated by the software were not automatically linked from headwaters to locations of outflow. Catchment polygons were selected by overlaying the drainage network and manually selecting only the polygons that drained in the same direction, based on the direction of stream flow. To assist in the manual selection process, existing catchment maps were used to make a preliminary grouping. After the catchments were identified, sub-catchments were then joined (“dissolved” is the geoprocessing term) to form the larger ‘tertiary’ catchments.

2.2.1.2 Statistical Comparison of the best-estimate Surface Catchment Boundary with the three Tertiary Surface Catchment Boundaries

The process to assign uncertainty of the best-estimate surface catchment boundary was conducted as follows (e.g., Figure 2.6):

1) The best-estimate and ‘tertiary’ surface catchment boundaries were digitised at a 1 m interval using ArcGIS.

2) The distance between each boundary point and the centroid of the best-estimate boundary was calculated.

3) The nearest tertiary surface boundary point to each best-estimate surface boundary point was identified.

4) The differences between centroid-point distances for all points in the three tertiary surface boundaries were tabulated, and statistics on differences (mean, median, +95% and -95%) were calculated. These statistics provide an estimate of the uncertainty in the location of each best-estimate point on the centroid-point line (Figure 2.6).

5) A radial distance of the ‘maximum’ and ‘minimum’ surface catchment boundary relative to the best-estimate boundary that envelopes the +95% and -95% distances was defined.

6) ArcGIS polygons of the ‘maximum’ and ‘minimum’ surface catchment boundaries were drawn by applying the +95% and -95% radial distances to expand, or contract, (respectively) the best-estimate boundary line polygon using the ArcGIS “Buffer” function.

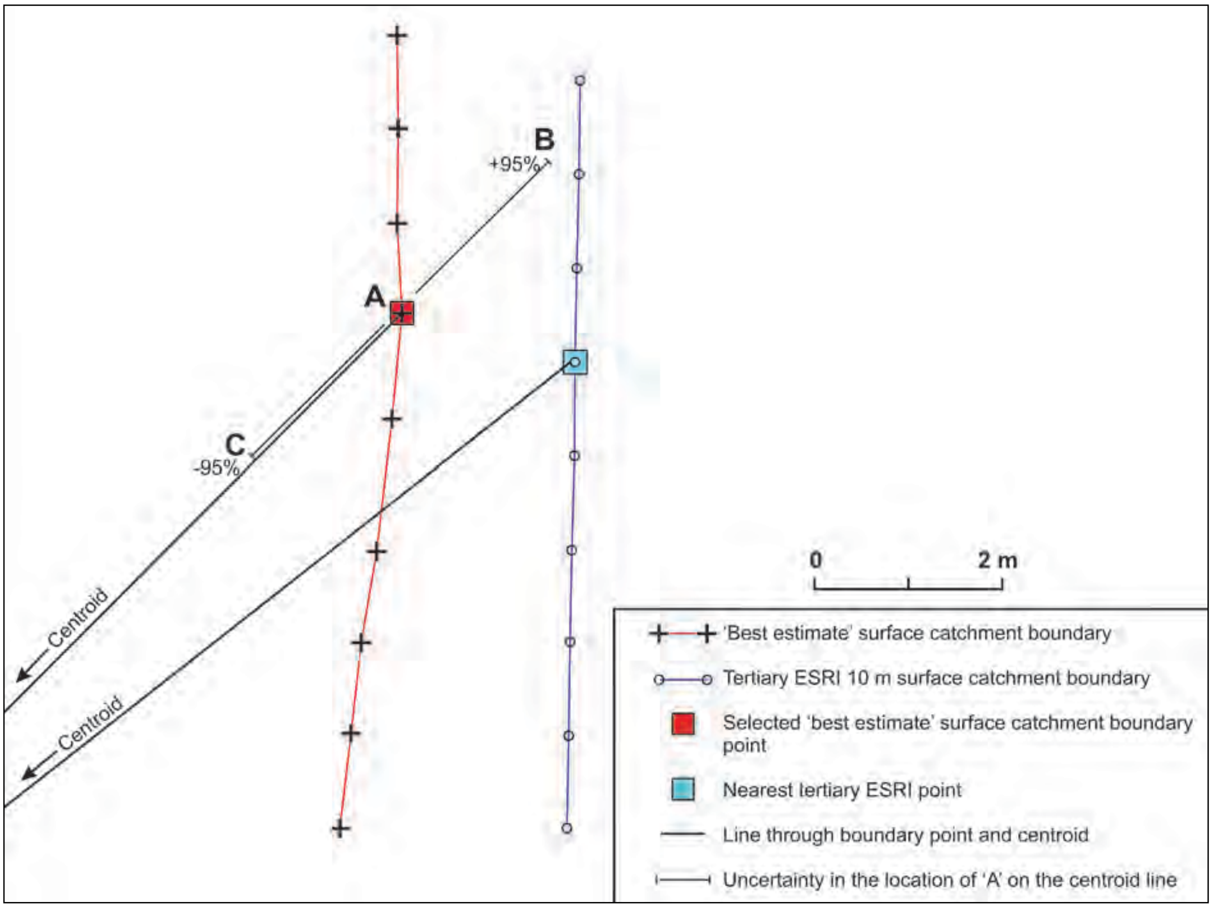

Figure 2.6 Best-estimate catchment boundary (A) with a demonstration of the locations of the ‘maximum’ (B) and ‘minimum’ (C) catchment boundary locations.

2.2.2 Uncertainty in the Groundwater Catchment Boundary

Uncertainty in the groundwater catchment boundary was represented by land areas inside and outside the best-estimate groundwater catchment. The ‘minimum’ Lake Rotorua catchment boundary aims to match the ‘-95%’ flows at four sites (Table 2.1). Likewise, the ‘maximum’ Lake Rotorua catchment boundary aims to match the ‘+95%’ flows at these sites. The method to calculate the groundwater catchment boundaries assigned all the uncertainty to the boundary of the catchment on the Mamaku Plateau. Therefore ‘internal’ boundaries (e.g., the boundary between Hamurana and Awahou groundwater catchments) were not adjusted. The method is summarised in the following:

1) a 'first estimate' of the minimum groundwater catchment of the Ohau Channel was made by calculating the 'best-estimate:radial_minus' polygon that is the 'best-estimate groundwater catchment' boundary, shrunk by the radial distance uncertainty in the surface catchment (Section 2.2.1) using the ArcGIS "Buffer" function. This procedure sets the minimum groundwater catchment equal to the minimum surface water catchment in the area outside the Mamaku Plateau;

2) 'first estimates' of the minimum catchments of three spring-fed streams (Hamurana Stream, Awahou Stream and Waiteti Stream) were calculated by clipping these spring-fed stream polygons to the 'best-estimate:radial_minus' polygon;

3) land area and water flow within the four 'first estimate' catchment polygons were calculated using GIS with ROTAN_LITE gridded data sets of rainfall, 'quick flow' and 'slow flow' (Section 3.1.2) data for the areas they encompassed. Then the actual area for each ROTAN_LITE grid polygon within the boundary polygons was calculated and the attribute table for each polygon was exported to Microsoft Excel. Here the sum of 'rainfall', 'quick flow' and 'slow flow' were calculated for each of the four polygons in L/s and in m^3/s using the actual ROTAN_LITE grid polygon areas;

4) observed mean flows at the four sites were compared with calculated water flow within four catchment polygons;

5) the land area was calculated to remove land area (L, equation 1) from each of the four catchment polygons to match '-95%' flows at the four sites using typical specific discharge for the Mamaku Plateau (equation 1);

$$L = 1000(C-Q)/M \qquad \text{equation 1}$$

L land area to remove from polygon (km^2)

C calibration target (m^3/s)

Q sum of 'quick flow' and 'slow flow' in the polygon

M specific discharge over a Mamaku Plateau polygon, i.e., slow flow + quick

flow divided by area ($L/s/km^2$)

$$R = L/E \qquad \text{equation 2}$$

R distance to shift the boundary inwards (km)

E length of outer boundary of catchment on the Mamaku Plateau (km)

6) the distance to shift the boundary inwards was calculated (equation 2), and the 'best-estimate:radial_minus' boundary was calculated using the ArcGIS "Buffer" function;

7) the sum of 'quick flow' and 'slow flow' of the new polygon was calculated and compared with the calibration targets;

8) the above steps from step 5 were repeated until Q was within 0.1 m^3/s of C.

As an example, -95th percentile flow at the Ohau Channel is 1.2 m^3/s less than the mean flow (Table 2.1) and the equivalent -95th percentile land area is 24.8 km^2 less than the best-estimate groundwater polygon (Table 2.3) This area is equivalent to a boundary that is inside the best-estimate groundwater boundary by 0.48 km.

9) then, the ‘minimum’ Lake Rotorua groundwater catchment boundary, that is consistent with all four calibration targets (i.e., Ohau Channel, Hamurana Stream, Awahou Stream and Waiteti Stream), was defined. This was done by selecting a boundary in each of three segments (i.e., the groundwater catchments of Hamurana Stream, Awahou Stream, and Waiteti Stream). In each segment, the selected boundary was either the -95th percentile Ohau Channel groundwater boundary or the stream groundwater boundary, whichever was the closest to the best-estimate groundwater polygon.

To demonstrate with an example, the -95th percentile Hamurana Stream groundwater boundary is closer to the best-estimate boundary than the -95th percentile Ohau Channel groundwater boundary (Table 2.3). Therefore, the ‘minimum’ Lake Rotorua groundwater catchment boundary is represented with the -95th percentile Hamurana Stream groundwater boundary in the Hamurana Stream catchment.

Table 2.3 Example of selection of polygon for ‘minimum’ Lake Rotorua groundwater catchment boundary.

Stream	**Difference from mean/best-estimate polygon**			**Polygon for -95% flow boundary**
	-95% flow (m^3/s)	**Land area (km^2)**	**Linear distance inside boundary (km)**	
Ohau Channel	-1.2	-24.8	-0.48	n/a
Hamurana	-0.3	-7.4	-0.18	Hamurana
Awahou	-0.2	-5	-1.25	Ohau Channel
Waiteti	-0.4	-9.9	-1.87	Ohau Channel

The method used to calculate the ‘maximum’ Lake Rotorua catchment boundary was the same as the above, but it calculated a ‘best-estimate:radial_plus’ polygon and compared this with polygons to match ‘+95%’ flows in the four areas (Table 2.1).

3.0 RESULTS

3.1 LAKE ROTORUA CATCHMENT BOUNDARY

3.1.1 Best-estimate Surface Catchment Boundary

The constructed best-estimate surface catchment boundary (‘Lake_Rotorua_SC_1_2000_12_May_2014’, Figure 3.1) generally coincides with the BOPRC 2m contours ‘BOPRC_2m_SC_2006’ (Figure 3.2). However, minor edits to this boundary were required to match the catchment boundary with 1 m contours, at the 1:2000 scale (e.g., Figure 3.3).

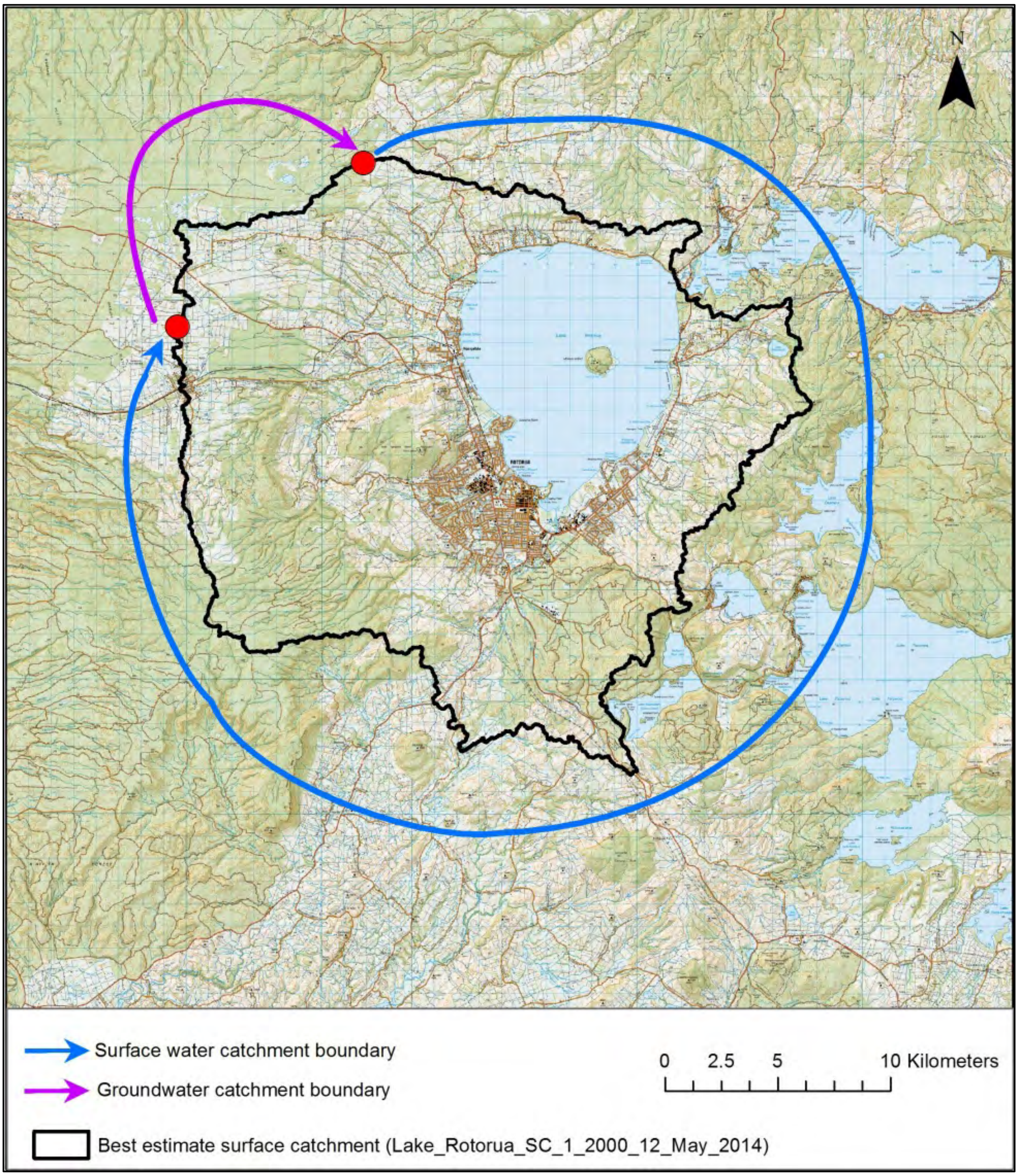

Figure 3.1 Best-estimate surface catchment boundary of Lake Rotorua. The surface boundary was developed at the 1:2000 scale between the red dots.

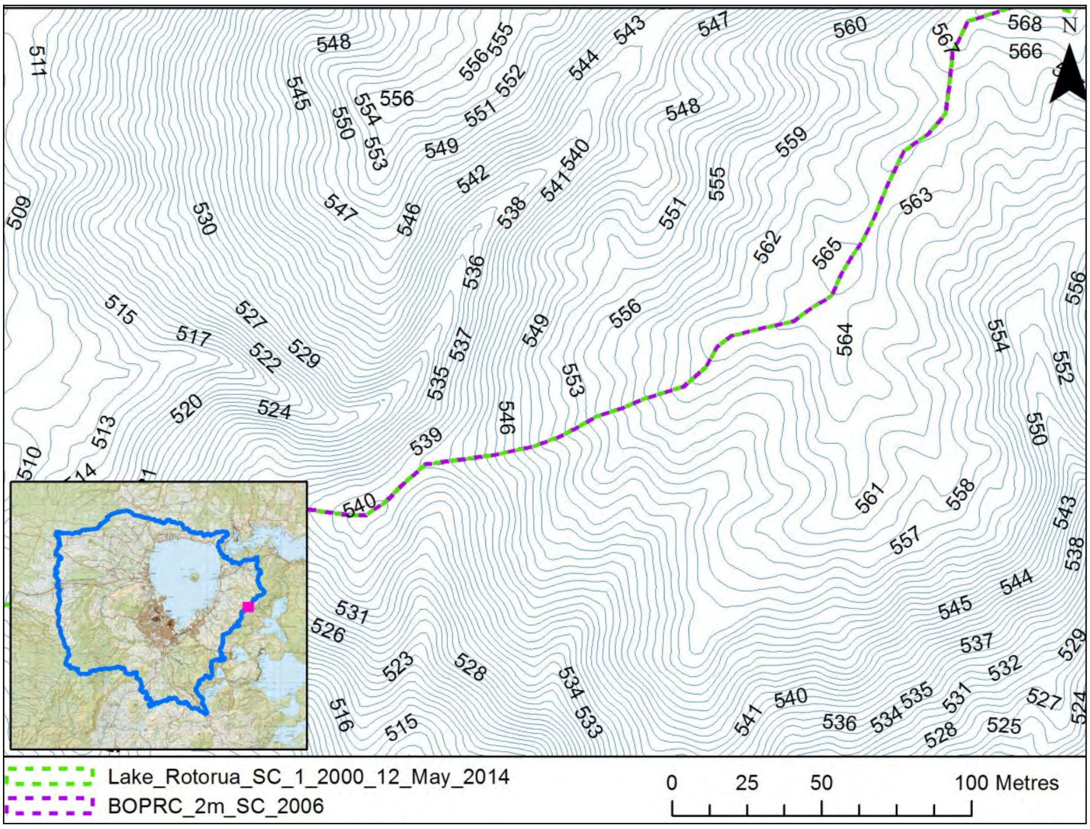

Figure 3.2 Example of where the best-estimate surface catchment boundary (ArcGIS file 'Lake_Rotorua_SC_1_2000_12_May_2014') is coincident with 'BOPRC_2m_SC_2006'. The inset shows the location of the example.

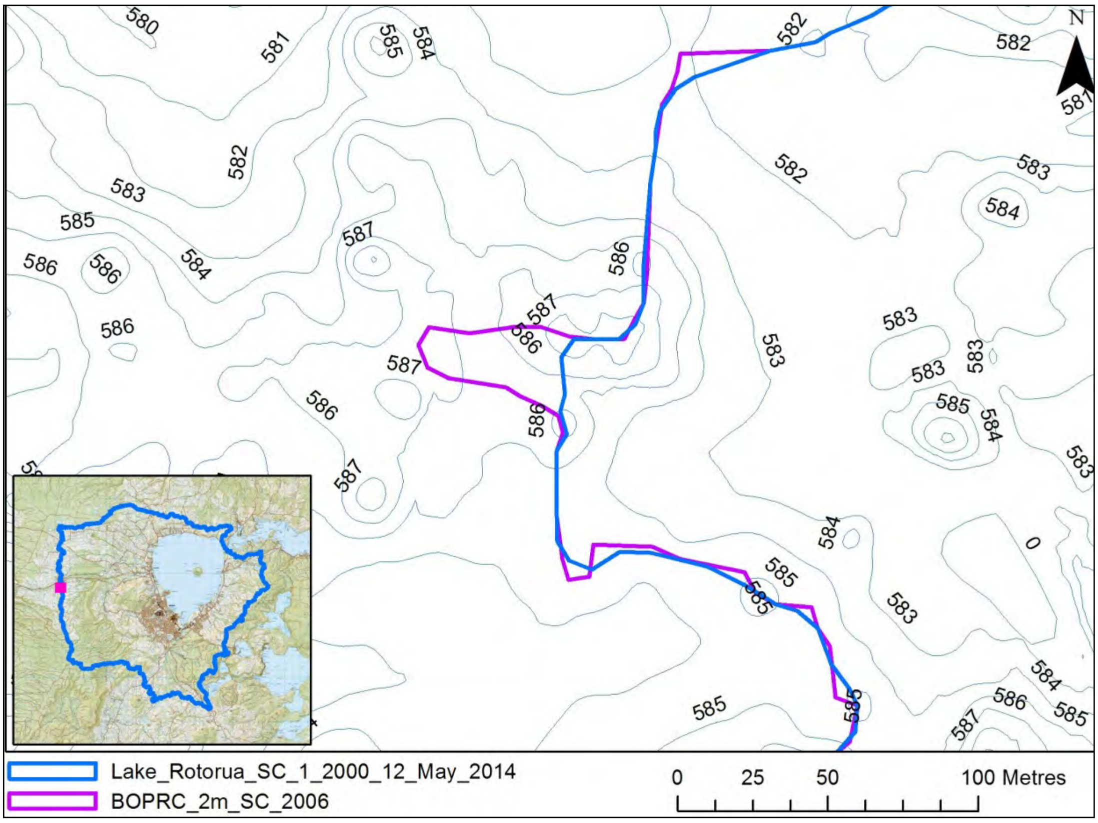

Figure 3.3 Example of where the best-estimate surface catchment boundary (ArcGIS file 'Lake_Rotorua_SC_1_2000_12_May_2014') was edited from 'BOPRC_2m_SC_2006' to match catchment boundaries estimated with 1 m contours at the 1:2000 scale. The inset shows the location of the example.

The best-estimate surface catchment boundary includes the Lake Rotokawau catchment (see Section 1), but excludes a small area of the upper Puarenga Stream catchment estimated by the 'BOPRC_2m_SC_2006' surface catchment boundary (Figure 3.4) that is probably outside the catchment of Lake Rotorua. This area is probably within the groundwater catchment of Lake Rotokakahi because groundwater below the area probably flows towards Lake Rotokakahi as topographic gradients from the area are largely towards Lake Rotokakahi. However, the area may, in part, be within the groundwater catchment of the Waikato region. This is because topographic gradients from the area are largely towards Waikaukau Stream and towards Tumunui, relative to the topographic gradient in the upper Puarenga Stream catchment towards Lake Rotorua. Therefore, groundwater may flow from the area in the unsaturated zone towards Tumunui, and then to Rotohouhou Stream, or towards the headwaters of Waikaukau Stream.

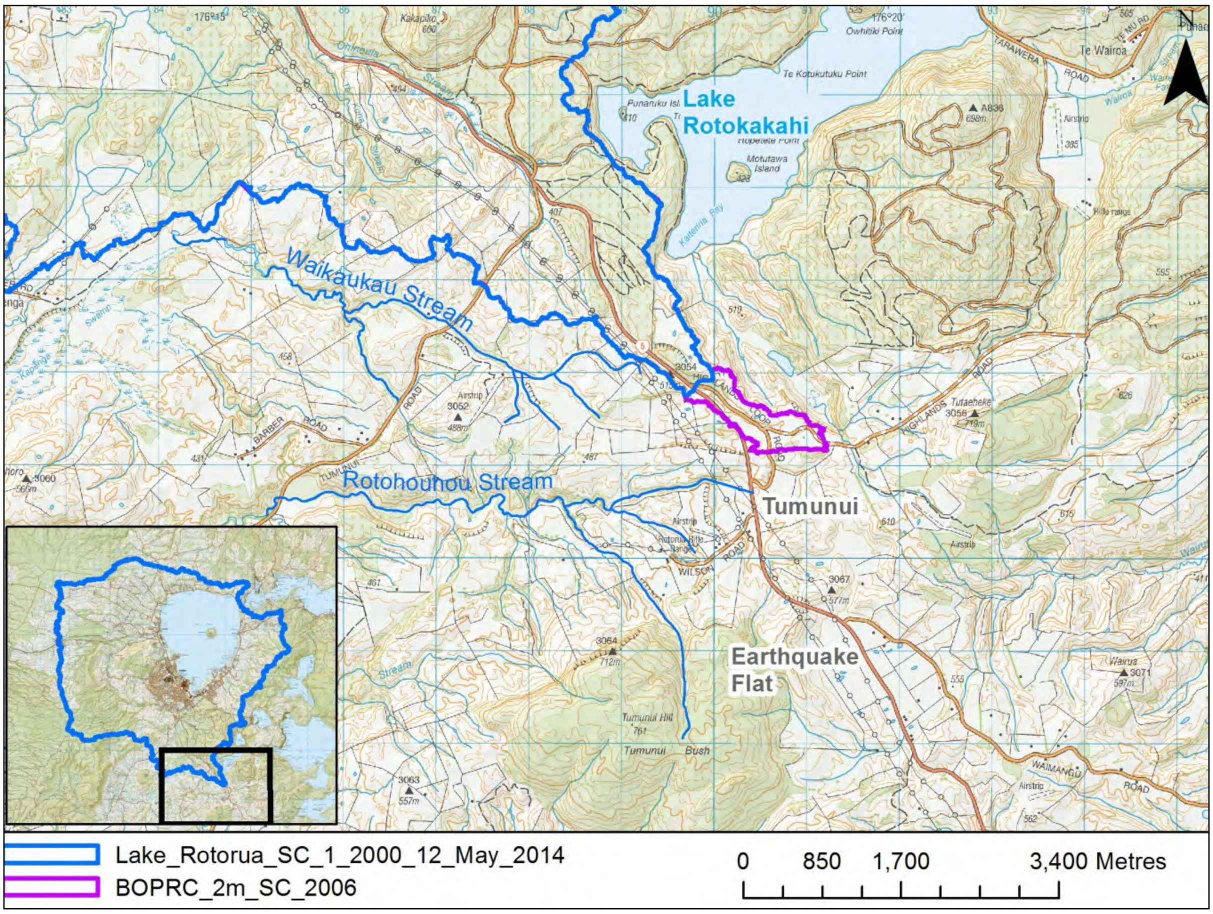

Figure 3.4 Best-estimate surface catchment boundary (ArcGIS file 'Lake_Rotorua_SC_1_2000_12_May_2014') and area of the upper Puarenga catchment (ArcGIS file 'BOPRC_2m_SC_2006') where groundwater probably does not flow towards Lake Rotorua. The inset shows the location of the area.

The best-estimate surface catchment has an area of 502 km^2 (Table 3.1). Water flow in the best-estimate surface catchment boundary is an estimated 15.0 m^3/s, which is considerably less than the observed mean flow of 16.5 m^3/s at the Ohau Channel (Table 2.1). Therefore, the groundwater catchment boundary is larger than the best-estimate surface catchment boundary.

3.1.2 Best-estimate Groundwater Catchment Boundary

The best-estimate groundwater catchment boundary (GIS file name: 'Lake_Rotorua_GW_1_2000_9_June_2014') includes a large portion of the Mamaku Plateau (Figure 3.5). Within this boundary, the groundwater catchment areas are sufficient to supply mean flows of three spring-fed streams (Hamurana Springs, Awahou Stream and Waiteti Stream), Figure 3.6, Table 3.1. The best-estimate groundwater catchment boundary is larger than the best-estimate surface catchment boundary by approximately 35 km^2 (Table 3.1), and most of this land is located in the Hamurana Springs catchment (Figure 3.7 and Table 3.2).

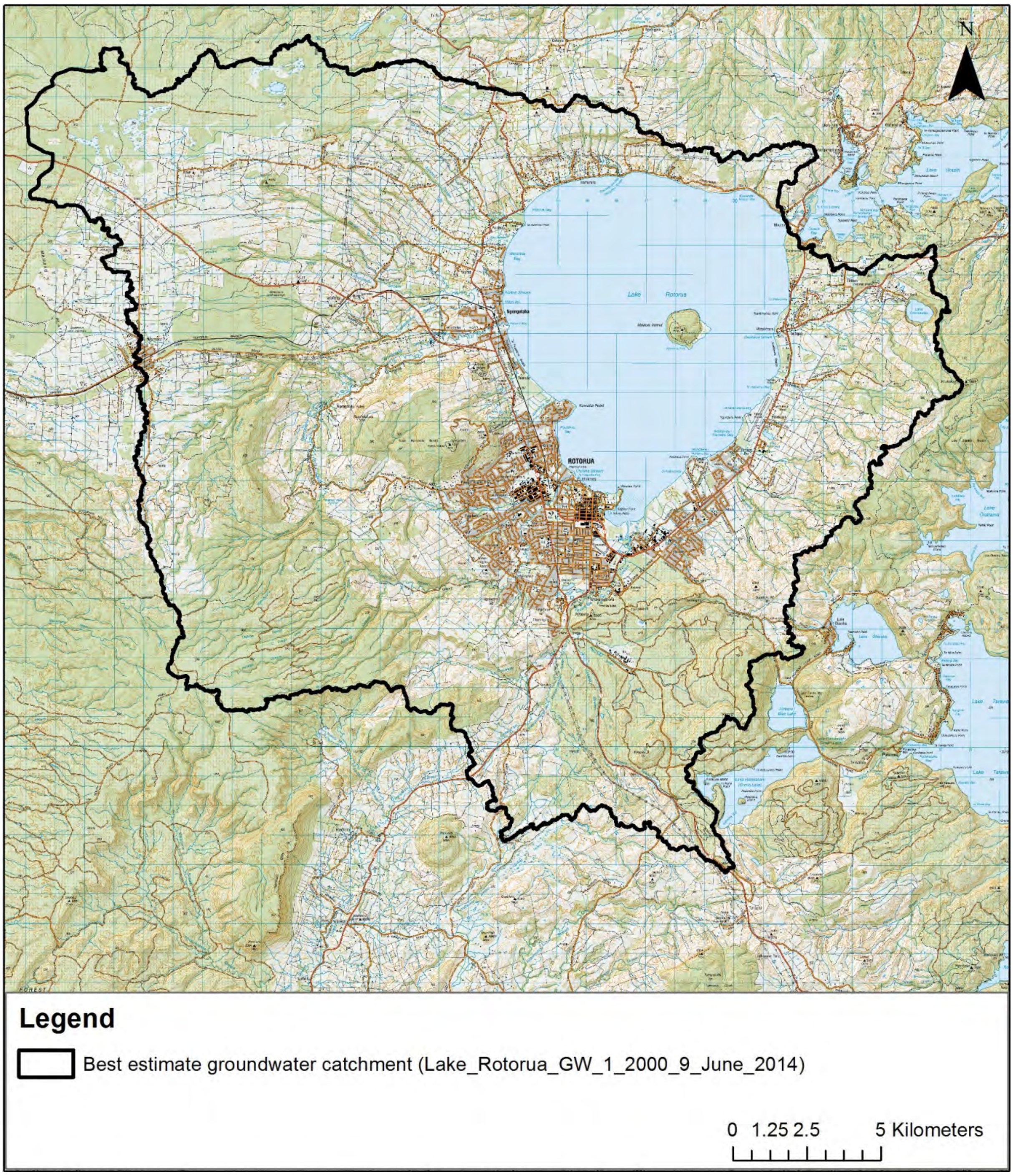

Figure 3.5 Best-estimate Lake Rotorua catchment boundary including the groundwater catchment on the Mamaku Plateau.

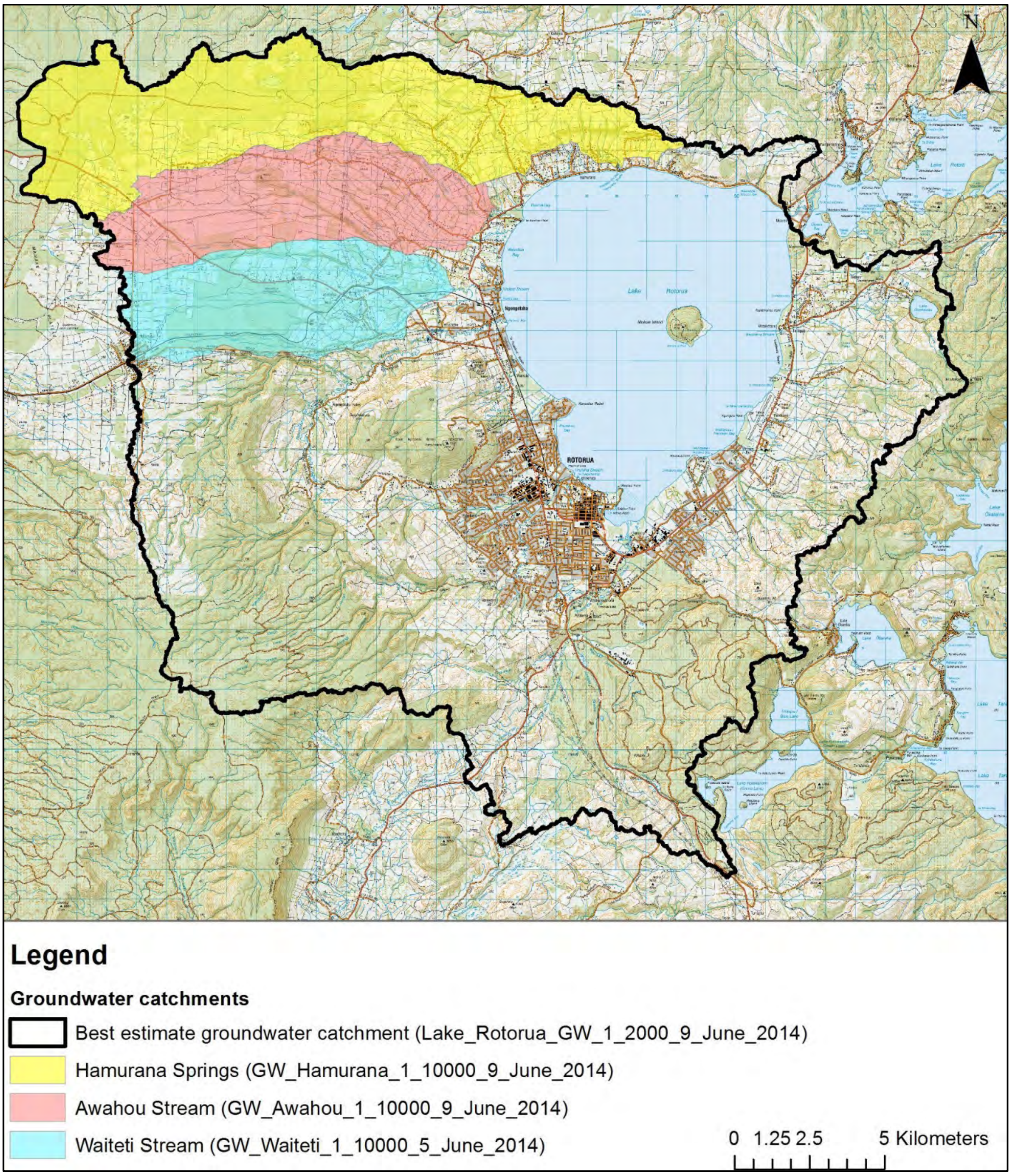

Figure 3.6 Groundwater catchments of Hamurana Springs, Awahou Stream and Waiteti Stream.

Table 3.1 Groundwater catchments of Lake Rotorua and three spring-fed streams (Hamurana Springs, Awahou Stream and Waiteti Stream) with catchment areas and estimated water flows calculated using GIS and ROTAN_LITE data, rounded to one decimal point.

Item	Polygon	Area (km^2)	Rainfall (m^3/s)	Slow flow (m^3/s)	Quick flow (m^3/s)	Sum of slow flow and quick flow (m^3/s)	Calibration target, Table 2.1 (m^3/s)
Best-estimate surface water catchment boundary of Lake Rotorua	Lake_Rotorua_SC_1_2000_12_May_2014.ply	502	31	8.6	6.4	15	na
Best-estimate groundwater catchment boundary of Lake Rotorua	Lake_Rotorua_GW_1_2000_9_June_2014	537.1	33.8	9.6	6.9	16.5	16.5
Hamurana Springs groundwater catchment boundary	GW_Hamurana_1_10000_9_June_2014	66.6	5	1.8	0.8	2.6	2.6
Awahou Stream groundwater catchment boundary	GW_Awahou_1_10000_9_June_2014	38.6	2.8	1.1	0.5	1.6	1.6
Waiteti Stream groundwater catchment boundary	GW_Waiteti_1_10000_5_June_2014	34	2.3	0.8	0.4	1.2	1.2
Mamaku Plateau Basin	Mamaku_Plateau_Central_10000_9_June_2014	12.4	1.0	0.3	0.2	0.5	na
Mamaku Plateau North	Mamaku_Plateau_North_10000_5_June_2014	20.8	1.7	0.5	0.3	0.8	na
Hamurana Springs groundwater catchment inside surface catchment	GW_Hamurana_SC_clip_10_June_2014	33.1	2.4	0.9	0.4	1.3	na

Table 3.2 Land areas that make up the Lake Rotorua groundwater catchment.

Item		Area (km^2)
Best-estimate surface catchment boundary of Lake Rotorua		502
Area outside surface catchment	Hamurana Springs groundwater catchment	33.5
	Awahou Stream groundwater catchment	1.9
	Waiteti Stream groundwater catchment	0.1
Sum		537.5 [1]

[1] Note that this sum does not equal the area of the best-estimate Lake Rotorua groundwater catchment (537.1 km^2, Table 3.1). Three sources are responsible for the difference: rounding errors, location of polygon points at the 1:10000 scale and the area calculation with GIS (Section 2.1.2). Areas are rounded to one decimal point.

Table 3.3 Groundwater catchments of Hamurana Springs catchment with areas and estimated water flows using GIS and ROTAN_LITE data, rounded to one decimal point.

Item	Polygon	Area (km^2)	Rainfall (m^3/s)	Slow flow (m^3/s)	Quick flow (m^3/s)	Sum of slow flow and quick flow (m^3/s)
Mamaku Plateau Basin	Mamaku_Plateau_Central_10000_9_June_2014	12.4	1	0.3	0.2	0.5
Mamaku Plateau North	Mamaku_Plateau_North_10000_5_June_2014	20.8	1.7	0.5	0.3	0.8
Hamurana Springs groundwater catchment inside surface catchment	GW_Hamurana_SC_clip_10_June_2014	33.1	2.4	0.9	0.4	1.3
Sum		66.3[1]	5.1	1.7	0.9	2.6

[1] Note that this sum does not equal the area of the Hamurana Springs groundwater catchment boundary (66.6 km^2, Table 3.1). Three sources are responsible for the difference: rounding errors, location of polygon points at the 1:10000 scale and the area calculation with GIS (Section 3.1.2).

Three geographic areas are identified in the Hamurana Springs groundwater catchment (Figure 3.7; Table 3.2):

1) The Mamaku Plateau Basin appears as an area of internal drainage. The 1 m surface contours indicate surface drainage towards the centre of the basin with low areas coinciding with swamps mapped on the topographic map. The centre of the basin is approximately 4 m lower that the edge of planar basin floor, as identified by contours of the 2006/2007 RDC LIDAR data. The boundaries of the basin were identified by: contours of the 2006/2007 RDC LIDAR data in the north, east and south; and by contours of the 8 m DTM in the west. The basin-edge elevation is relatively low in the west and north east, as indicated by ‘A’ and ‘B’, respectively (Figure 2.4). Ground conditions in this area are swampy, however no surface flow was observed at these locations during a field visit on 5/6/2014 (Table 2.2). Therefore, it is assumed that slowflow and quickflow in this area (Table 3.2) all drain to groundwater.

2) Mamaku Plateau North, where the ground surface is relatively flat near the Mamaku Plateau Basin and surface topographic gradients indicate that the ground slopes to the north. Swampy conditions are common in this area, particularly north east of the Mamaku Plateau Basin. It is assumed that slowflow and quickflow (e.g., Table 3.1) in this area mostly drain to groundwater. This is because little surface flow is observed in the area (i.e., ‘C’ and ‘D’, Table 2.2) and gauged surface flows in the upper Mangorewa River catchment are all close to zero (Figure 2.4).

3) Hamurana Springs groundwater catchment is inside the best-estimate surface catchment.

The sum of water flow estimates using ROTAN_LITE data (i.e., slowflow and quickflow) in these three areas equals the 2.6 m^3/s (Table 3.3), i.e., the mean flow of Hamurana Springs (Table 2.1).

The Waiomou Stream catchment probably does not require land in the Mamaku Plateau Basin to produce the observed surface water discharge. This is because the specific discharge of Waiomou Stream catchment (without the Mamaku Plateau Basin) is the same as the Hamurana Stream catchment (with the Mamaku Plateau Basin), Table 3.4. However, specific discharge estimates do not provide unequivocal identification of the destination of groundwater outflow from the Mamaku Plateau Basin, see Section 4.

Table 3.4 Estimates of specific discharge for steams that drain the Mamaku Plateau.

Stream	Specific discharge ($l/s/km^2$)[1]	
	Catchment without the Mamaku Plateau Basin	Catchment with the Mamaku Plateau Basin
Waiomou	39	33
Waimakariri	55	48
Hamurana	48	39
Awahou	41	31
Waiteti	35	na

[1] Mean flow estimates (Section 2.1.2) divided by catchment land area.

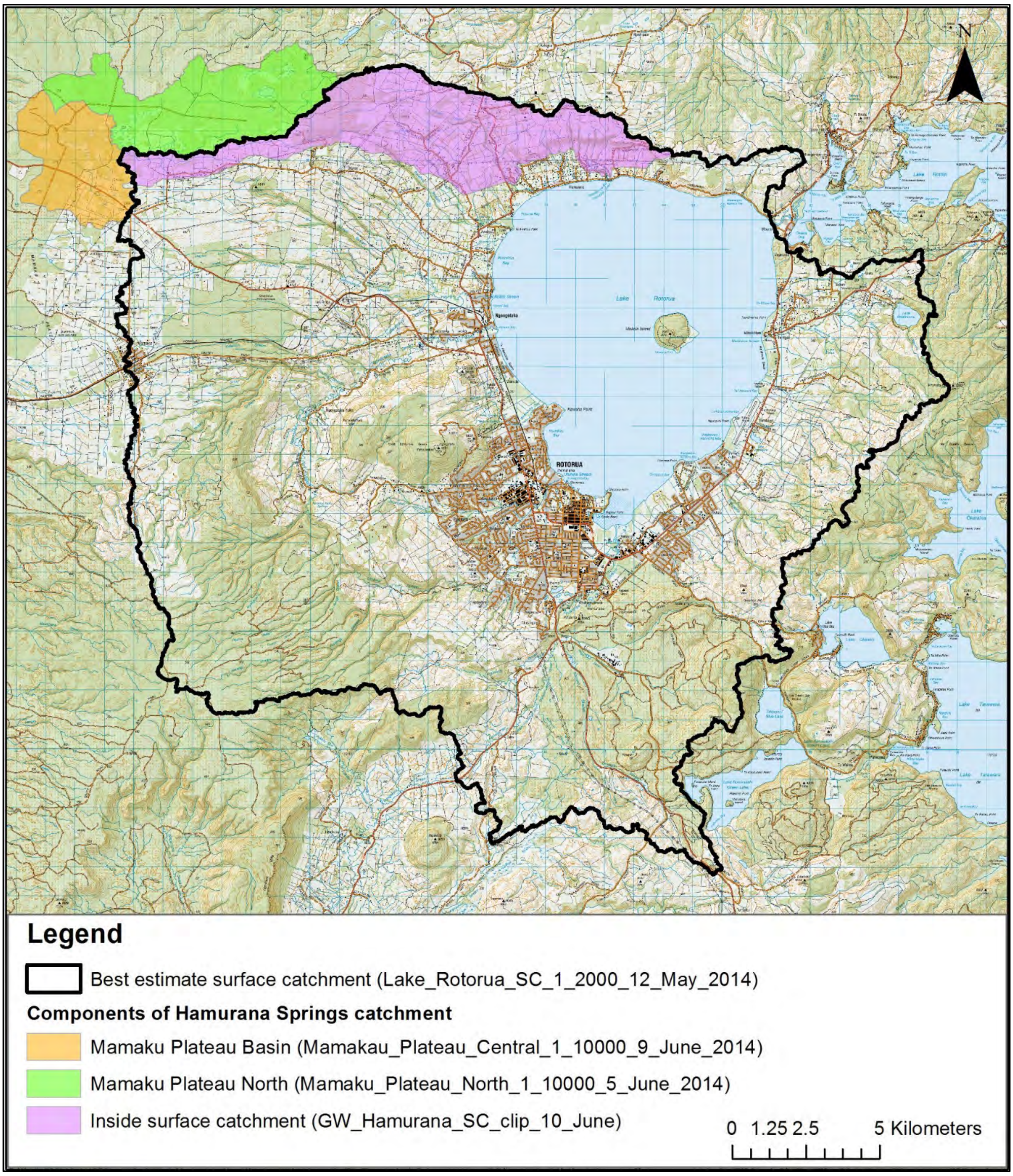

Figure 3.7 Three land areas that make up the Hamurana Springs groundwater catchment.

3.1.3 Uncertainty in the Surface Catchment Boundary

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 (Table 3.5).

Table 3.5 Differences between the best-estimate surface catchment boundary and the three tertiary catchment boundaries. These statistics were calculated on 147,673 values.

Item	Difference (m)		
	Best-estimate - ARC	Best-estimate - ILWIS	Best-estimate - SURFER
mean	0.81	1.07	1.39
median	0.02	0.02	0.02
+95th percentile	16.79	22.69	18.73
-95th percentile	-14.00	-20.29	-14.54
Standard deviation	73.65	89.16	74.80

The minimum and maximum surface catchment boundary GIS files are as follows:

- 'Lake_Rotorua_SC_1_10000_12_May_2014_minus95perc' which is the minimum surface catchment boundary (or -95th percentile).
- 'Lake_Rotorua_SC_1_10000_12_May_2014_plus95perc' which is the maximum surface catchment boundary (or +95th percentile).

The resolution of the boundary is a scale of 1:10000. This resolution is less than that of the best-estimate groundwater catchment boundary because the ArcGIS 'Buffer' function was used to calculate the -95% and +95% boundaries (see Section 4.3).

Clearly, the land area of the three surface catchment polygons is insufficient to supply the observed flows at Ohau Channel (Table 3.6). Therefore, it is likely that the groundwater catchment of Lake Rotorua is larger than the +95% surface catchment.

Table 3.6 Estimates of land area and water flows for the best-estimate surface catchment polygon and the -95th % and +95th % surface catchment polygons.

Item		Area (km^2)	Rainfall (m^3/s)	Slow flow (m^3/s)	Quick flow (m^3/s)	Sum of slow flow and quick flow (m^3/s)	Ohau Channel observed, Table 2.1 (m^3/s)
Lake Rotorua surface water boundary	-95%	499.1	30.8	8.6	6.4	15	15.3
	best-estimate	502	31	8.6	6.4	15	16.5
	+95%	504.9	31.2	8.7	6.4	15.1	17.7

3.1.4 Uncertainty in the Groundwater Catchment Boundary

Minimum and maximum Lake Rotorua groundwater catchment boundaries represent the land areas that provide for the uncertainty in surface water flows of Hamurana Springs, Awahou Stream, Waiteti Stream, and Ohau Channel. These boundaries are relatively wide on the Mamaku Plateau (Figure 3.8). Outside the Mamaku Plateau, the uncertainty in the boundaries is $\pm$20 m, which is the uncertainty in the surface catchment (e.g., Figure 3.9).

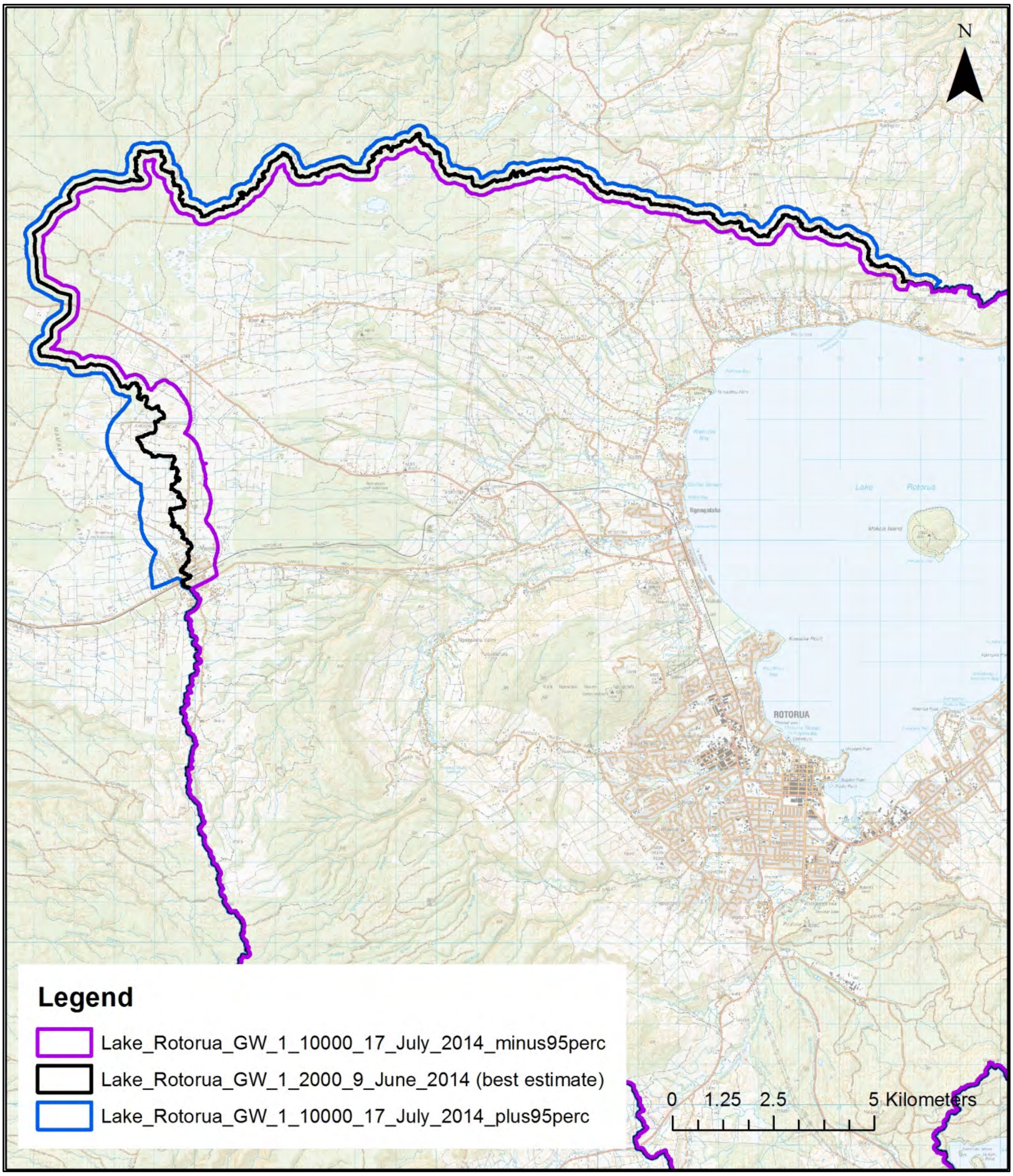

Figure 3.8 Map of the minimum, best-estimate, and maximum Lake Rotorua groundwater catchment boundaries in the Mamaku Plateau area.

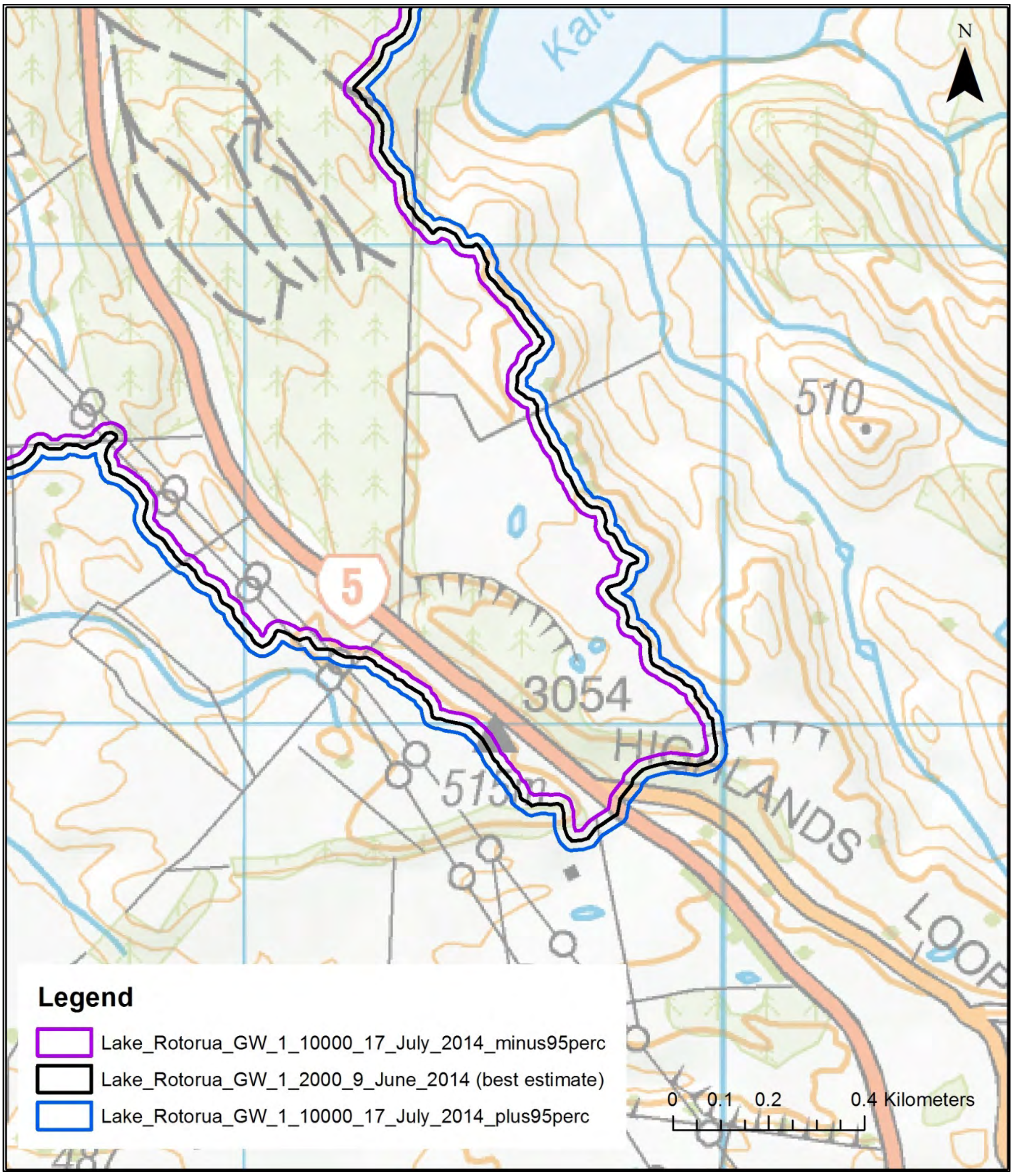

Figure 3.9 Map of the minimum, best-estimate, and maximum Lake Rotorua groundwater catchment boundaries in the south eastern catchment area.

However, Ohau Channel flows estimated with the -95th and +95th percentile polygons differ from uncertainty in observed flows at this location (Table 3.7). Therefore, the derivation of the -95th and +95th percentile polygons is described to demonstrate method (Section 2.2.2).

Table 3.7 Land area and water flows for the best-estimate Lake Rotorua groundwater catchment polygon and the -95th and +95th percentile groundwater catchment polygons.

Item		Area (km^2)	Rainfall (m^3/s)	Slow flow (m^3/s)	Quick flow (m^3/s)	Ohau Channel estimated (m^3/s)	Ohau Channel observed, Table 2.1 (m^3/s)
Lake Rotorua groundwater boundary	-95%	523.5	32.8	9.2	6.7	15.9	15.3
	best-estimate	537.1	33.8	9.6	6.9	16.5	16.5
	+95%	551.2	34.8	9.9	7	16.9	17.7

The -95th percentile groundwater catchment boundary is inside the best-estimate Lake Rotorua groundwater boundary, however the distance between these two boundaries is variable on the Mamaku Plateau (Figure 3.10). This is because the -95th percentile groundwater catchment boundary on the Mamaku Plateau is a composite of the -95th percentile boundaries of two catchments: Hamurana Springs and Ohau Channel. The -95th percentile boundary of the Hamurana Springs catchment is selected because it is closer to the best-estimate boundary than the -95th percentile boundary of Ohau Channel.

However, the -95th percentile boundary of Ohau Channel is chosen for the Awahou and Waiteti stream catchments because it is closer to the best-estimate boundary than the -95th percentile boundaries of these streams. For example, the -95th percentile boundary of Ohau Channel is approximately 640 m inside the best-estimate boundary (Table 3.8) whereas the -95th percentile boundary of Waiteti Stream is approximately 3 km inside the best-estimate boundary. The difference between these distances is largely due to uncertainties of surface water flow. The uncertainty in Ohau Channel flow is 7 % (i.e., $\pm$1.2 m^3/s of mean flow), whereas the uncertainty in Waiteti Stream is 33% (i.e., $\pm$0.4 m^3/s of mean flow), Table 2.1. Alternatively, the -95th percentile groundwater catchment boundary could have been chosen to represent the -95th percentile boundaries of Awahou and Waiteti streams. However, this would have resulted in a step-wise boundary across the Mamaku Plateau that would make little hydrological sense and would not represent the -95th percentile boundary of Ohau Channel.

The large uncertainty in Waiteti Stream flows is also demonstrated by the +95th percentile boundaries that are used to estimate the maximum groundwater catchment boundary (Figure 3.11). Here, the +95th percentile catchment boundary of Waiteti Stream extends approximately 3 km west of the best-estimate boundary. The +95th percentile catchment boundary of Ohau Channel is within approximately 740 m of the best-estimate boundary and so is selected as the maximum groundwater boundary in the Waiteti Stream catchment.

Table 3.8 Approximate linear distance between -95th and +95th percentile Lake Rotorua groundwater catchment polygons and the best-estimate groundwater catchment polygon[1].

Area		Approximate distance between polygons (-95% and best-estimate) (m)	Approximate distance between polygons (+95% and best-estimate) (m)
Surface catchment		-20	+20
Mamaku Plateau	Hamurana Springs	-200	+200
	Awahou Stream	-640	+740
	Waiteti Stream	-640	+740

[1] Note that the linear distances are approximate because a relatively smooth line results from iterative application of the ArcGIS Buffer function (Section 2.2.2).

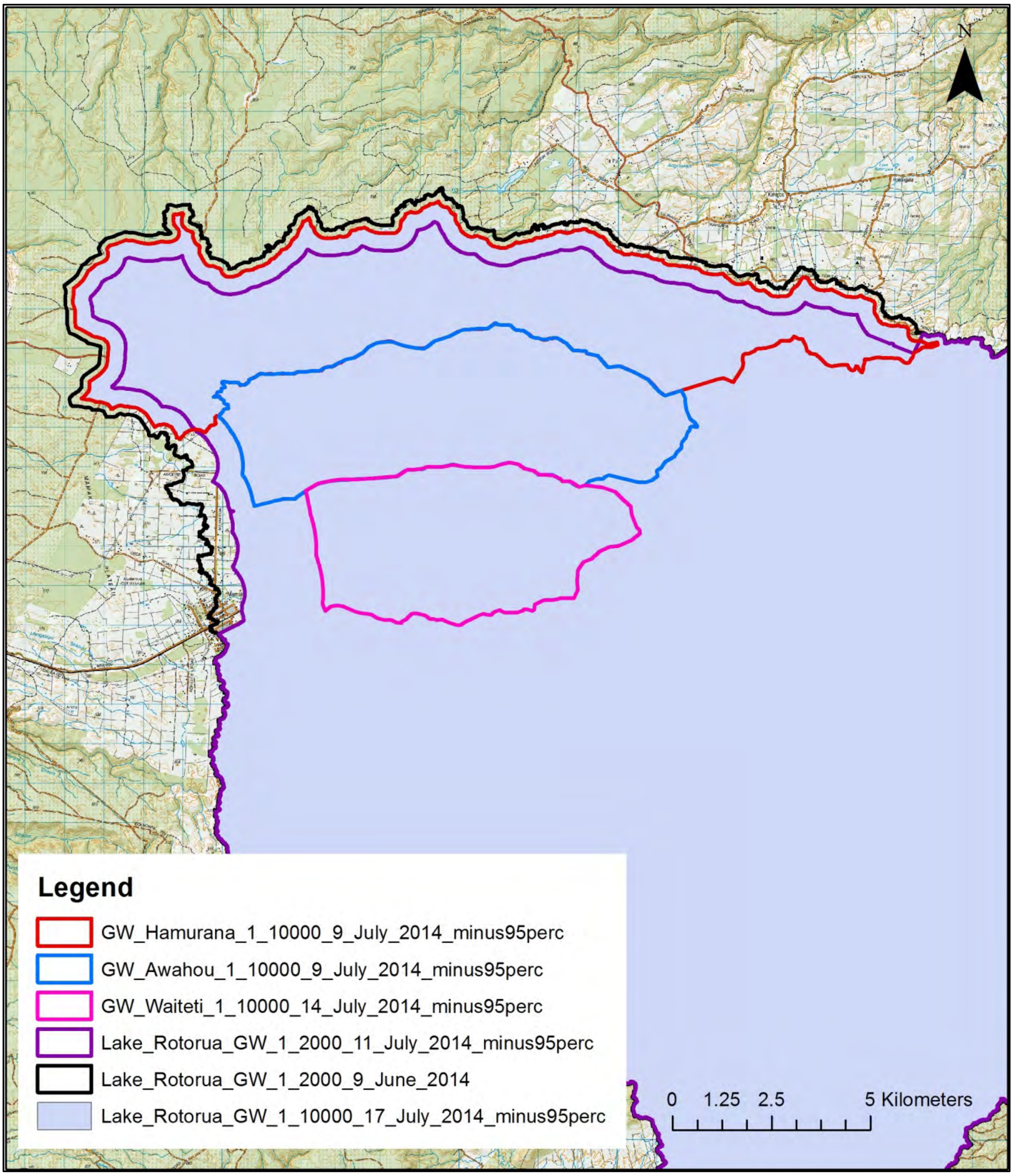

Figure 3.10 The minimum Lake Rotorua groundwater catchment boundary (i.e., 'Lake Rotorua_GW_1_10000_17_July_2014_minus95perc') is coloured in solid blue. Also shown are the polygons that represent the minimum groundwater catchments of Hamurana, Awahou, Waiteti and Ohau Channel and the best-estimate groundwater catchment of Lake Rotorua (black line).

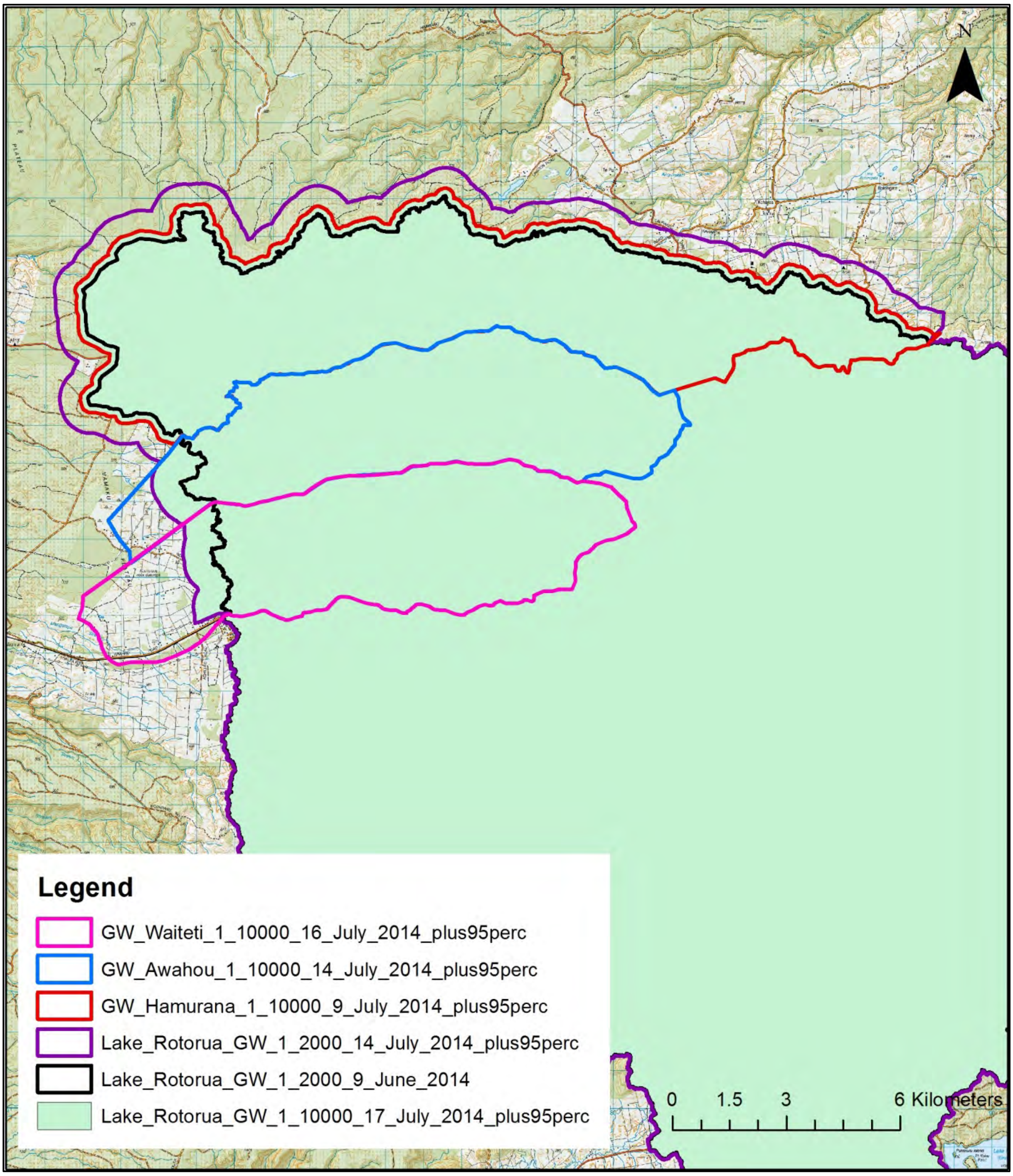

Figure 3.11 The maximum Lake Rotorua groundwater catchment boundary (i.e., 'Lake Rotorua_GW_1_10000_17_July_2014_plus95perc') is coloured in solid green. Also shown are the polygons that represent the maximum groundwater catchments of Hamurana, Awahou, Waiteti and Ohau Channel and the best-estimate groundwater catchment of Lake Rotorua (black line).

4.0 DISCUSSION

4.1 GROUNDWATER CATCHMENTS OF HAMURANA, AWAHOU AND WAITETI

The principal aim of this project was to identify the Lake Rotorua catchment boundary. However, the groundwater catchments of Hamurana, Awahou and Waiteti Streams were also used to verify the location and uncertainty of the Lake Rotorua groundwater catchment boundary.

Most of the area of the Lake Rotorua groundwater catchment boundary outside the surface catchment boundary is associated with the Hamurana groundwater catchment (Figure 3.7 and Table 3.2). In comparison, the western boundaries of Awahou and Waiteti groundwater catchments are approximately consistent with the Lake Rotorua surface catchment boundary (Table 3.2). Hamurana Springs requires 1.3 $m^{3/}$s of flow from outside the surface catchment boundary (Table 3.3). Most likely, this comes from the Mamaku Plateau Basin and Mamaku Plateau north (Figure 3.7).

Most water must leave the Mamaku Plateau Basin as groundwater outflow because surface water outflow is minimal (Section 3.1.2). Possible destinations of the groundwater outflow are to the catchments of Lake Rotorua, the Mangaorewa River (to the north), and the Waihou River (to the west). The most likely destination is the Hamurana catchment, and subsequently Lake Rotorua, because of the following:

- The Hamurana Stream catchment requires approximately 0.5 m^3/s of groundwater flow (Table 3.3) outside the ‘Mamaku Plateau North’ area and the Mamaku Plateau Basin adjoins the north area (Figure 3.7). In addition, a Hamurana Stream catchment located northwest of Hamurana Springs (Figure 3.6) is consistent with estimates of groundwater flow based on a groundwater flow model (White *et al*., 2007).
- Mangaorewa River catchment is an unlikely for outflow, as a groundwater divide is located in the vicinity of Kaharoa that appears to rule out the area in the Mangaorewa Stream north of Hamurana (Figure 2.2). Additionally, base flows are very low, or zero, in the upper Mangaorewa Stream (Figure 2.4).
- The Waiomou Stream catchment probably does not require land in the Mamaku Plateau Basin to produce the observed surface water discharge in this stream. This is because the specific discharge of this stream (without the area of the Mamaku Plateau Basin) is the same as the Hamurana Stream catchment (with the area of the Mamaku Plateau Basin) and similar to the Awahou Stream catchment (without the area of the Mamaku Plateau Basin), Table 3.4. However, specific discharge estimates do not provide unequivocal identification of the destination of groundwater outflow from the Mamaku Plateau Basin. For example, the specific discharge of Hamurana Stream (without the area of the Mamaku Plateau Basin) is the same as Waimakariri Stream (with the area of the Mamaku Plateau Basin).

Two common groundwater catchment boundaries were chosen between the catchments of Hamurana, Awahou and Waiteti. For example, Hamurana-Awahou and Awahou-Waiteti are chosen between these three catchments based on 1 m contours derived from the 2006/2007 RDC LIDAR survey and groundwater budgets. In addition, lake-side boundaries were chosen so that they are at a higher elevation than the main area of inflows (White *et al*., 2007) to the streams. The resolution of these boundaries is less than the resolution of the Lake Rotorua groundwater catchment (see Section 4.3).

4.2 UNCERTAINTY IN THE LAKE ROTORUA GROUNDWATER CATCHMENT AREA

The uncertainty in the best-estimate Lake Rotorua groundwater catchment (Table 3.7) is less than the uncertainty in the catchment area calculated in Appendix 1, because:

1) most of the Lake Rotorua groundwater catchment boundary is defined by a topographic analysis of the surface catchment; the uncertainty in the surface catchment boundary is $\pm$20 m (Table 3.8), which translates to a small uncertainty in catchment area ($\pm$2.9 km^2); and

2) the Hamurana Springs groundwater catchment occupies a considerable portion of the boundary of the Lake Rotorua groundwater catchment across the Mamaku Plateau (Figure 3.6). Therefore, the uncertainty in the area beyond the surface catchment is mostly associated with the uncertainty in the area of the Hamurana Springs groundwater catchment. Uncertainty in Hamurana Spring flow ($\pm$0.3 m^3/s) is less than that of Ohau Channel, ($\pm$1.2 m^3/s), Table 2.1. Therefore, the uncertainty in the catchment area for the Hamurana Spring groundwater catchment is less than the uncertainty in the Ohau Channel catchment. These uncertainties are also demonstrated in a comparison of the uncertainty of the boundary for Hamurana Spring catchment ($\pm$200 m linear metres) with that of Awahou and Waiteti streams (+740 m and -640 m linear metres), Table 3.8. Note that the uncertainty in the boundary for Ohau Channel catchment was applied to Awahou and Waiteti streams as it is less than the uncertainty in the boundary of these streams (Section 3.1.4).

4.3 RESOLUTION OF CATCHMENT BOUNDARIES

The resolution of catchment boundaries derived in this report is either:

- 1:2000 i.e., the surface catchment outside the Mamaku Plateau and the Lake Rotorua groundwater catchment (Figure 3.1 and Figure 3.5, respectively). Note most of the Lake Rotorua groundwater catchment is defined with the 2006/2007 RDC LIDAR DTM. However, part is defined by the 8 m DTM (Figure 2.2). The boundary was defined at a 1:2000 scale in the area of the 8 m DTM, but this DTM has a poorer resolution than the 2006/2007 RDC LIDAR DTM.
- 1:10000 i.e., the groundwater catchment minimum and maximum (Figure 3.8 and Figure 3.9 respectively) and groundwater catchments of three spring-fed streams (Hamurana, Awahou and Waiteti; Figure 3.6).

The resolution of the minimum and maximum groundwater catchment boundaries are less than 1:2000 because boundaries were calculated by iterative use of the ArcGIS ‘Buffer’ function (Section 2.2.2).

5.0 CONCLUSIONS

Bay of Plenty Regional Council (BOPRC) and the local community aim to restore water quality in Lake Rotorua, with policies that include land-use controls within the Lake Rotorua catchment. An accurate boundary of the Lake Rotorua catchment boundary was developed in this report by BOPRC, GNS Science and the National Institute of Water and Atmospheric Research.

The "best-estimate Lake Rotorua groundwater catchment boundary" was developed in two parts: a surface catchment boundary that includes most of the area between Kaharoa and Mamaku township; and a groundwater boundary on the Mamaku Plateau. Uncertainty in the best-estimate groundwater boundary was estimated separately for these boundaries. The surface catchment was derived from topographic contours at a 1 m interval and the groundwater boundary on the Mamaku Plateau was derived using multiple data sets including: topographic contours and water budgets that used estimates of surface water flows (Appendix 1) and gridded rainfall, surface flow, and groundwater recharge estimates (Appendix 2). The groundwater catchment areas of spring-fed streams that drain the Mamaku Plateau (particularly the Hamurana, Awahou and Waiteti in the Lake Rotorua catchment) were also considered, as these catchments provide a control on the location of the best-estimate groundwater boundary. The best-estimate Lake Rotorua groundwater catchment boundary was derived at a resolution of 1:2000, as this scale is suitable for policy purposes.

The best-estimate Lake Rotorua groundwater catchment boundary (including Lake Rotorua) has an area of 537.1 km^2, and produces an estimated mean flow of 16.5 m^3/s, equal to the mean observed flow at Ohau Channel. Likewise, estimated groundwater catchments of Hamurana, Awahou and Waiteti streams produce average flows (2.6 m^3/s, 1.6 m^3/s, and 1.2 m^3/s, respectively) that are equal to average observed flows in these streams. The best-estimate Lake Rotorua groundwater boundary is larger than the surface catchment boundary by approximately 35 km^2 and most of this land (33.2 km^2) is within the groundwater catchment of Hamurana Springs.

Therefore, the area of the Hamurana Springs groundwater catchment is of key importance to the identification of area of the Lake Rotorua groundwater catchment outside the surface water catchment. The Hamurana Springs groundwater catchment was divided into three areas (Figure 3.7):

1) The Mamaku Plateau Basin appears as an area of internal drainage that provides 0.5 m^3/s of flow to Hamurana Stream, i.e., all the flow that is net of rainfall and actual evapotranspiration flows to groundwater. It was assumed that no surface flow leaves this area as ground conditions at locations of possible surface drainage were swampy, and no surface flow was observed at these locations during a field visit on 5/6/2014.

1) Mamaku Plateau North provides 0.8 m^3/s of flow to Hamurana Stream. This area is relatively flat with surface topographic gradients indicating that the ground slopes to the north. Swampy conditions are common in this area, particularly north east of the Mamaku Plateau Basin. It was assumed that no surface flow leaves this area because little, or no, surface flow was observed in the area during a field visit on 5/6/2014 and gauged surface flows in the upper Mangorewa River catchment are all close to zero.

2) Hamurana Springs groundwater catchment inside the best-estimate surface catchment, which provides 1.3 m^3/s of flow to Hamurana Stream.

Uncertainty in the best-estimate Lake Rotorua groundwater catchment boundary, estimated at the 95% confidence level, was calculated separately for the surface catchment boundary and the groundwater boundary on the Mamaku Plateau. The 95% confidence interval for the best-estimate surface catchment boundary was an estimated ±20 m. Uncertainty in the best-estimate Lake Rotorua groundwater boundary on the Mamaku Plateau was assessed for each of the spring-fed streams in the Lake Rotorua catchment. This uncertainty was an estimated ±200 m in the Hamurana Stream catchment, and -640 m and +740 m on the Awahou and Waiteti catchments; these values represent ±95% percentile differences, respectively, in the location of the boundary. The uncertainty in the Hamurana Stream flow is less than that of the other two streams; therefore the uncertainty in the Hamurana Stream catchment boundary flow is less than that of the other two streams.

6.0 ACKNOWLEDGEMENTS

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APPENDICES

APPENDIX 1 LAKE ROTORUA CATCHMENT BOUNDARIES PHASE 2 WATER BUDGET.

Lake Rotorua catchment boundaries

Phase 2 water budget

Prepared for Bay of Plenty Regional Council

May 2014

Lake Rotorua catchment boundaries

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Executive summary

GNS-Science and Bay of Plenty Regional Council have analysed recent LiDar data and re-drawn the boundaries of the surface catchment of Lake Rotorua. This report examines rainfall, evaporation and stream flow data in the Rotorua catchment, and compares calculated catchment runoff (rainfall minus evaporation) with measured lake outflow. It is concluded that:

1. For the 13 year period (1976-1978, 1992-1995 and 2005-2010) when concurrent measurements are available, annual runoff expressed as a fraction of catchment-average rainfall at the lake outlet (Ohau Channel) was 61 ± 6-7% and in four major streams not affected by groundwater (Utuhina, Puarenga, Waingaehe and Waiohewa) was 52 ± 8-17%. The quoted uncertainties are the upper and lower bounds on the 95% confidence interval. The upper bound is an extreme 'worst case' and uncertainty is almost certainly less than this value.
2. Average runoff in the Ohau Channel was 9% higher than in the four streams. If there is no difference in 'true' runoff between the lake outlet and the four streams then, based on the lower bound uncertainties, there is 7% chance of observing a difference of 9% or greater. However, the uncertainty in the difference in runoff is high (9 ± 10%, mean ± 95% CI).
3. Based on the upper bound uncertainties, there is 33% chance of observing the 9% difference when there is no difference in 'true' runoff. The uncertainty in the difference is very high (9 ± 18%, mean ± 95% CI) but uncertainty is almost certainly less than the upper bound.
4. High runoff in the Ohau Channel is unlikely to be an artefact of under-estimating catchment rainfall and a possible explanation is groundwater inflow from outside the surface catchment of the lake.
5. The 'missing' flow is estimated to be 2.1 ± 1.5 $m^3 s^{-1}$ (lower bound uncertainty) and 2.1 ± 2.8 $m^3 s^{-1}$ (upper bound uncertainty). Based on the lower bound uncertainties there is a 95% probability that the 'missing' flow lies in the range 0.6 to 3.7 m^3/s. However, based on the upper bound uncertainties this range becomes -0.7 to 4.9 m^3/s.
6. There is a chance the 'missing' flow is zero (viz, that no groundwater flows into Lake Rotorua from outside the surface catchment) or negative (viz., that some groundwater flows out of the surface catchment). There is also a chance the 'missing' flow exceeds 4 m^3/s.
7. If the 'missing' flow originates on the Mamaku Plateau where the rainfall scaling factor is 1.3, and 100% of runoff drains to the lake, then the 'missing' area is estimated to be 33 ± 24 km^2 (lower bound uncertainties) and 33 ± 43 km^2 (upper bound uncertainties). A previous study (Rutherford et al. 2008) assumed 50% drainage and estimated the 'missing' area to be 60 km^2 (range 5-80 km^2).
8. The water budget approach used in this study is not able to provide any guidance on the location of the 'missing' area. It may be possible to refine the current estimate of

the size of the 'missing' area on the basis of topography and hydro-geology, and to estimate its location.

9. The average flows during the 13 years studies were estimated to be:

    a. Ohau Channel 16.5 ± 0.3-1.2 m^3/s.

    b. Hamurana Stream 2.6 ± 0.3 m^3/s.

    c. Awahou Stream 1.6 ± 0.2 m^3/s.

    d. Waiteti Stream 1.2 ± 0.1-0.4 m^3/s.

    Figures are mean ±95% CI. There is uncertainty in the 95% CI values which we were able to quantify for the Ohau Channel and Waiteti Stream but not for the Hamurana and Awahou.

1 Introduction

An earlier study (Rutherford et al. 2008, White 2009) postulated that groundwater flowed into Lake Rotorua from an aquifer on the Mamaku Plateau that lies outside the surface catchment of Lake Rotorua (hereafter called the Mamaku aquifer). The most likely estimate of the aquifer area was 60 km^2 (range 5-80 km^2) based on the assumption that deep drainage (termed 'slow flow') made its way into the lake but that 'quick flow' (viz., shallow sub-surface and overland flow) did not (Rutherford et al. 2008).

Bay of Plenty Regional Council contracted GNS-Science and NIWA to refine current estimates of the area and location of the boundaries of the Mamaku aquifer. The role of NIWA in the project was to:

1. Re-analyse historic and recent rainfall and stream flow data and provide advice to GNS-Science about the likely size of the Mamaku aquifer.

2. Use the ROTAN model to check the water balance for Lake Rotorua once GNS-Science has determined the location of the Mamaku aquifer.

This report addresses step 1 above. It examines the available stream flow data and calculates the average runoff (expressed as a percentage of rainfall) from catchments where net groundwater inflows and outflows are considered to be negligibly small. This average catchment runoff is compared with measured runoff in the Ohau Channel (the lake outlet) taking account of lake rainfall and evaporation. The difference is used to estimate the area of the Mamaku aquifer. Note that a water balance of this kind is unable to determine the location of the Mamaku aquifer but GNS-Science have addressed this issue using their knowledge of hydrogeology.

2 Methods

2.1 Flow data

Time series of daily flow at nine sites at Rotorua were obtained from BoPRC or NIWA, together with a list of gaugings. Flows in the Hamurana (HAM) and Awahou (AWA) are dominated by springs and varied only slowly over time. Water level recorders are not currently installed at these sites and reported flows were occasional gaugings (typically monthly)[1].

Flow in the Ohau Channel (OHC) was estimated from continuously monitored lake levels and rating curves derived from occasional gaugings. Flow varied only slowly at this site and the channel was comparatively stable. Flow was affected by changes in stream inflows, backwater effects from Lake Rotoiti, seiching in Lake Rotorua and changes to the flow structures in the Ohau Channel used to control lake water levels.

At the six streams sites (Ngongotaha (NGO), Waiowhiro (WWH), Utuhina (UTU), Puarenga (PUA), Waingaehe (WNG) and Waiohewa (WHE)) continuous water level recorders had been installed, and flow was determined from water level using rating curves derived from the results of occasional gaugings. At these six stream sites flows varied over time more quickly during rainfall events than at the other three sites. The stream channels also changed over time as a result of changes in stream vegetation, and bank and bed erosion or deposition.

2.2 Uncertainty in individual flow measurements

At stream sites where flow was determined from continuous water level measurements using rating curves, the uncertainty in each estimate of flow had three components[2]: gaugings errors, rating curves errors, and instrument errors.

Herschy (1978) (quoted in McKerchar 1986) determined that the random uncertainty of a standard flow gauging decreases as the number of verticals increases, and as the number of velocities in the vertical increases. With 20 verticals and a current meter calibrated to ISO standards the coefficient of variation for random errors is 6.3% where velocity is measured at 0.6 depth, and 5.5% when velocity is measured at 0.2 and 0.8 depth (McKerchar 1986, Table 2). Gauging with 20 verticals is recommended. With 15 verticals the coefficients of variation increase to 8.2% and 7.5% and with 10 verticals to 11.3% and 10.5%. McMillan et al. (2012) summarize reported uncertainties in single estimates of gauged flow and quote uncertainties of 2.3% (standard error (SE = standard deviation (SD) /mean), Carter & Anderson 1963), 4-40% (95% confidence interval (CI), Pelletier 1988), 4% (root mean square error (RMS) for wading gaugings, Sauer & Meyer 1992), 6% (SE, Herschy 2002) and 5% (SD, Hudson & Fraser 2002). The 95% CI is typically twice the SD, SE or RMS. Thus the uncertainty (95% CI) of a single gauging is typically ±10% although it may be as high as 40%. Gauging errors are normally assumed to be random (Juston et al. 2013).

[1] In 1976-1977 Hoare (1980) gives daily flows for the Hamurana and Awahou Streams. Visual inspection of the Hamurana daily flow time series suggests that linear interpolation had been used between gaugings (viz. the time series comprised a series of straight lines). Interpolated values were omitted. For the Awahou two 'events' can be seen in the daily flow record which suggests that either a water level recorder had been installed during Hoare's study or that flows were interpolated from another site. After 1978 only occasional gaugings are available in the Hamurana and Awahou.
[2] Variation over time is discussed separately

Rating and measurement errors are normally assumed to be non-random (Juston et al. 2013). Instrument errors arise from improperly calibrated velocity meters, faulty distance and depth measuring devices. McKerchar (1986) quotes Herschy (1978) in saying that errors in meter calibration, tapes, cables and winches are estimated to increase uncertainty by only c. 0.6%. The estimation of rating errors is the subject of considerable debate in the scientific literature and ongoing research (Juston et al. 2013). Rating errors arise from (random) errors in the gaugings used to derive the rating curves, and (non-random) errors in the relationship between water level and flow (viz., errors in the rating curve itself) together with instrument errors.

In this study we did not have access to the rating curves used to derive the time series of daily flow, but we did have access to the list of gaugings for each stream. Our approach was to lump gauging, rating and instrument error together and to quantify 'total' error by comparing reported daily mean flow with gauged flow on days when both were reported. We calculated the error variance

$$\sum[Q_i - G_i]^2 / N \qquad 1$$

where Q_i= reported daily mean flow and G_i= reported gauged flow, both on day *i*. As described in the following sections, we also used the maximum and minimum differences

$$\max(Q_i - G_i) \qquad 2$$

$$\min(Q_i - G_i) \qquad 3$$

and the root mean square error

$$\sqrt{\sum[Q_i - G_i]^2 / N} \qquad 4$$

In order to compare errors for several streams, we calculated the relative error variance

$$\sum[(Q_i - G_i)/G_i]^2 / N \qquad 5$$

It was assumed that flow could not be measured to better than 1% accuracy and the minimum value of the error variance was set to 0.0001 (viz., the square of 1%).

The error variance can be calculated easily from the available flow time series and gaugings. However, it is approximate for two reasons. Firstly, if the flow varies during the day, then the daily average flow may differ from the flow at the time of the gauging. As a result the relative error variance may over-estimate uncertainty. This bias could be reduced in future studies by comparing hourly flows with the gaugings. Secondly, gaugings are used to update the rating curve. Consequently, the reported daily flow on the day of a gauging may have a lower uncertainty than other reported flows. It would require a detailed re-examination of water level records, gaugings, inspection reports and rating curves to improve upon the uncertainty estimates made using Eq 1-5 and such data were not sought for this study.

2.3 Uncertainty in average flow

Uncertainty in long-term average flow (e.g., annual mean flow or in this study the 13 year average flow) has two components: temporal changes in 'true' flow, and gauging, rating and instrument errors which may be random or non-random.

We examined time series of daily mean flows and used standard statistical methods to estimate the average, variance, standard deviation and 95% confidence interval of the average flow. The standard statistical methods in EXCEL assume that each daily mean flow is a random, independent sample from a normally distributed population. This assumption is invalid for several reasons. Firstly, flows are usually serially correlated (viz., the flow on Day *i* is correlated with the flow on Days *i* -1, *i* - 2 etc.,) which means that daily flows are not independent. For similar reasons, errors (see Eq. 1-5) are also likely to be serially correlated. Secondly, flow is rarely distributed normally with constant variance although transformations (e.g., log transformations) may help overcome this difficulty. Thirdly, as a result of rating, gauging and instrument errors, errors in flow estimates may not be random.

One way in which these problems manifest themselves is when using standard statistical methods to determine the 95% CI on the average flow. If random, independent samples from a normally distributed population are found to have a standard deviation of *S* then standard statistical methods say that the standard deviation of the mean is $S/\sqrt{N}$ where N = the number of samples. In our 13 year study N ~ 4,000 days and $S/\sqrt{N}$ was very small. However, because of serial correlation in flows and in their errors, there were not N independent samples and the formula $S/\sqrt{N}$ furnishes a seriously biased (under) estimate of uncertainty in the average flow.

Our approach to estimating the uncertainty in the long-term average flow was to estimate upper and lower bounds on the likely uncertainty[3].

In Method 1 the upper bound uncertainty was taken as twice the RMS difference between reported daily mean flow and gauged flow on days when gaugings were done

$$2\sqrt{\sum[Q_i - G_i]^2 / N} \qquad 6$$

The factor a 2 arises from the fact that for a normally distributed, independent random variable, 95% of values lie within ± 2 SD and the RMS error is akin to the SD. For example, in the Ohau Channel the RMS error was 0.61 m^3/s giving a 95% CI of ±1.2 m^3/s (7% of mean flow). Method 1 furnishes an extreme 'worst case' (over) estimate of uncertainty which ignores the fact that some values of $Q_i - G_i$ are positive while others are negative, so that to some extent errors cancel when calculating the long-term average.

In Method 2 it was assumed that errors were uniformly distributed (rather than normally distributed) and error bounds were defined using the average of the absolute values of the maximum and minimum deviations. For example, in the Ohau Channel the minimum and maximum deviations were -2.0 and +2.1 m^3/s, giving a confidence interval of ± 2.0 m^3/s (12%). Method 2 then attempted to 'model' the distribution of errors and account for the fact that they can be either positive or negative. The steps involved were:

1. Calculate the maximum and minimum differences between reported daily mean flow and gauged flow (Eq 2 and 3), average their absolute values and assume that this quantifies the rating error (RE) (units m^3/s).

2. Calculate the gauging error (GE) as 10% of mean flow (units m^3/s).

[3] The approach is termed *Uncertainty'* in the literature (e.g., Juston et al. 2013)

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3. Calculate the total error (TE) (units m3/s).

$$TE = \sqrt{RE^2 + GE^2} \qquad 7$$

4. Calculate the average interval between gaugings (typically 30 days).

5. For each 30 day period, estimate a value of uncertainty by taking a random sample from a uniform distribution whose upper and lower bounds were $\pm TE$. In this manner uncertainty TE_i (where *i* is day number) is the same for each of the 30 days in a period, but undergoes a step change between periods. Note that a random number generator is used in this step which means that a different time series of uncertainties is generated each time the model is run.

6. Estimate the serial correlation coefficients r_n between values of $Q_i - G_i$, where r_n is the correlation coefficient between errors *n* days apart. Hence determine the serial correlation coefficient when *n* = 1 assuming

$$r_1 = 10^{\left(\frac{\log r_n}{n}\right)} \qquad 8$$

8. Re-calculate the daily uncertainty to account for serial correlation

$$TE_i^* = r_1 TE_{i-1} + (1 - r_1)TE_i \qquad 9$$

9. Estimate the 'true' daily flow

$$Q_i^* = Q_i + TE_i^* \qquad 10$$

10. Run the model 100 times and store the average flows.

11. Determine the 5th and 95th highest flows which determine the upper and lower 95%iles (LCL and UCL) and hence the 95% CI (units m^3/s)

$$CI = \pm(UCL - LCL)/2 \qquad 11$$

Method 2 involves making assumptions about the distribution of the variables (uniform in Step 5 and normal elsewhere) which cannot be tested with the available data. It is unclear how the 'true' and 'assumed' distributions might affect the resulting uncertainties. It is likely, however, that our second approach under-estimates uncertainties and hence that the 'true' uncertainty in long-term average flow lies between our estimates made using Methods 1 and 2[4].

2.4 Uncertainty in runoff

Runoff (mm y^{-1}) is the ratio of flow / area. The uncertainties in flow and area were the 95% CI expressed as a percentage of average flow and area (units %). The uncertainty in runoff (expressed as a percentage of average runoff) was then estimated as the square root of the sum of the squares of the uncertainties in flow and area (each expressed as a percentage of the mean flow or area). Similarly %runoff is the ratio of flow / area x rainfall. The uncertainty in %runoff (expressed as a percentage of the average %runoff) was estimated as the square

[4] Steps 1-11 were also adapted to work with log transformed flow as discussed below.

root of the sum of the squares of the uncertainties in flow, area and rainfall (each expressed as a percentage of the mean flow, area or rainfall).

The 95% CI in area was calculated using the estimates given by Hoare (1980) and re-calculated from the REC (this study). The uncertainty in rainfall was estimated by Tait (in Rutherford et al. 2008) to be 5-10%. We used the upper bound of 10% to quantify the 95% CI for average rainfall and calculated the error variance to be $(CI/2)^2$. The uncertainty in flow was discussed in the previous section.

Calculations were performed in EXCEL. The standard deviation and variance were calculated using the STDEV and VAR.S formulae. The 95% CI was calculated using the VARIANCE formula which requires the STDEV and N (the number of samples). These calculations assume that flow, area and rainfall are normally distributed and that each value is a random and independent sample.

3 Catchment area

Table 1 shows the areas of the surface catchment as estimated by Hoare (1980) and as calculated for this study using the REC stream and catchment shape files. Also tabulated are the proportions of pasture, forest, urban and water within each sub-catchment based on 2010 land use, and the average rainfall scaling factor re-calculated for this study.

The catchment areas of the eight major streams differ slightly between Hoare (1980) and the REC (this study). Considering the eight major streams (AWA, WWH, NGO, WTT, PUA, UTU, WNG and WHE) the 95% confidence intervals for the total area[5] and each individual area[6] were 1.9% and 14% respectively. Two sub-catchments (AWA and WTT) not used in the runoff calculations contributed to the high (14%) variance. Considering just the four sub-catchments where net groundwater inflows and outflows are thought to be negligible (PUA, UTU, WNG and WHE) the 95% confidence intervals for the total area and each individual area were 2.3% and 3.5% respectively. On this basis, we assumed a 95% confidence interval of 3.5% for the areas of the sub-catchments. Hoare (1980) does not state the area of the total catchment, but we assumed a 95% confidence interval of 2% based on the uncertainty in the total area of the eight major streams.

[5] Calculated using the CONFIDENCE formula in EXCEL with the variance (VAR.S) of the total areas and N=2.
[6] Calculated using the CONFIDENCE formula with the average of the variances for each sub-catchment (VAR.S) and N=8.

4 Rainfall

Long-term average rainfall varied spatially across the catchment. Dr Andrew Tait, NIWA, Wellington developed a raster map quantifying the ratio of long-term average rainfall at various locations in the catchment to the long-term average reference rainfall (Rutherford et al. 2008). Reference rainfall was the average rainfall at the Rotorua Airport and Dalbeth Road sites – sites for which long-term records exist. The Tait map was derived using rainfall measured by a dense network of gauges deployed within the catchment in 1976-1977 (Hoare 1980) together with longer term rainfall records from within and outside the catchment.

Figure 1 shows contours of the rainfall scaling factor. Rainfall is significantly higher to the west and north of the lake than to the east and south. Note that the boundary of the surface catchment shown in Figure 1 is from an earlier study (Rutherford et al. 2008) and is not that developed by GNS-Science and used for the water balance calculations in this report. Table 2 summarises annual average rainfall 1970-2013. The Dalbeth Road site was closed in 2006 and for 2007-2009 rainfall at Dalbeth Road was set to the rainfall at Okere Falls scaled by 95% – the ratio of the cumulative total at the two sites from 1975-2005. The Okere Falls site was closed in 2010, and for 2010-2013 rainfall at Dalbeth Road was set to the rainfall at Rotorua Airport scaled by 133% – the ratio of the cumulative total at the two sites from 1975-2005. Year-to-year variability in rainfall is 16-18% (standard error) and the uncertainty in long-term average rainfall (95% confidence interval) is 5-6%.

For this study the average rainfall factors (RF) were calculated from the Tait raster map for the entire catchment, and for the sub-catchments of the major streams. The boundary of the surface catchment was defined by GNS-Science and Bay of Plenty Regional Council hereafter called 'Lake_Rotorua_SC_1_2000_7_Mar_2014'. The rainfall factors were used to estimate the annual average rainfall for the entire catchment and in each sub-catchment (Table 3). The sub-catchment of the Waiteti Stream received on average 30% more rainfall than the reference rainfall while the sub-catchment of the Waingaehe Stream received 10% less.

Tait (in Rutherford et al. 2008) estimated the 'extrapolation' uncertainty (confidence interval) in annual rainfall for a given sub-catchment to be 5-10%. In this study we used the upper bound of 10% to estimate the 95% CI of average rainfall.

Catchment	Code	Area km^2 Hoare 1980	Area km^2 REC	RF	Forest	Pasture	Urban	Water
Awahou	AWA	21.5	16.4	1.282	21%	79%		
Hamurana	HAM	-	2.8	1.206	17%	83%		
Ngongotaha	NGO	73.3	73.4	1.301	51%	49%		
Puarenga	PUA	74.8	73.6	1.001	69%	28%	3%	
Utuhina	UTU	59.6	61.6	1.179	57%	24%	19%	
Waingaehe	WNG	9.6	10.1	0.900	26%	64%	10%	
Waiohewa	WHE	11.1	13.4	1.079	40%	56%		4%
Waiowhiro	WWH	4.4	8.2	1.061	30%	27%	43%	
Waiteti	WTT	71.0	62.2	1.295	31%	69%		
Other		-	98.0	1.070	25%	61%	14%	
Catchment		-	419.7	1.153	43%	48%	8%	
Lake		80.6	80.6	1.007				100%
Catchment + lake	OHC	-	500.3	1.129	36%	41%	7%	16%

Table 1: Summary of sub-catchment area, land cover and rainfall scaling factor (RF) in the catchment of Lake Rotorua. Areas are from Hoare (1980) and calculated in this study using the REC. Land cover is from LCDB2. RFs are calculated using 1975-2010 rainfall data. File: Summary_Major_Flow_Sites_1975_2012_Version5.

Figure 1: The spatial distribution of rainfall at Rotorua. Contour labels denote the rainfall scaling factor (RF multiplied by 1000) which is multiplied by the annual reference rainfall. Reference rainfall is the average at the Dalbeth Rd RG and Airport RG sites (solid circles). The outer catchment boundary shown is the surface catchment boundary derived using the REC which differs slightly from the surface catchment boundary used in this study (Lake_Rotorua_SC_1_2000 _7_Mar_2014).

5 Stream flow

Table 5 gives summary statistics for measured stream flows for the period 1975-2012. For spring-fed streams (e.g., Hamurana, Awahou) only occasional (typically monthly) gaugings were made, but flows in these streams changed only slowly over time. The other streams had flow recorders for at least parts of the study period, and reported daily average stream flows were analysed. Some flow recorders were closed for parts of the period 1975-2012 and so daily flow records were not complete. Statistics in Table 5 are shown for the entire period of measurements regardless of gaps (viz., flows in Table 5 were not normalised to a common period when records were available at all sites simultaneously, although this was done for the water budget analysis).

Figure 2: Catchments of the nine major inflow stream. Also shown (dots) are the flow recorder sites.

Table 4 summarises annual average runoff (flow divided by the area of the surface sub-catchment) for selected years when concurrent measurements exist. Runoff was similar in the NGO, PUA, WNG and WHE Streams. As has been found previously, runoff is very high in the HAM and AWA Streams, almost certainly because they receive groundwater from outside their surface catchments. Runoff is also high in the WWH Stream – suggesting that it may also receive groundwater from outside its surface catchment. Runoff is higher in the UTU and lower in the WTT Streams, than in the NGO, PUA, WNG and WHE Streams. This may be because of differences in rainfall or because of groundwater inflows/outflows. Runoff in the Ohau Channel (OHC) is higher than in the streams PUA, WNG, WHE, UTU and WTT thought not to be affected by significant net groundwater inflows or outflows.

Year	Reference	Dalbeth Rd	Okere Falls	Airport
1970	1870	2098.1		1641.1
1971	2102	2156.9		2046.2
1972	1498	1740.7		1254.3
1973	1280	1438.3		1122.4
1974	1932	2222.9		1640.8
1975	1557	1559.2	1841.2	1555.3
1976	1685	1901.7	2048.7	1468.7
1977	1413	1527.3	1598.9	1299.6
1978	1192	1327.3	1440.9	1057.3
1979	2014	2281.6	2326	1745.7
1980	1505	1852.7	1494.2	1157.1
1981	1826	2188.4	2019.4	1464.3
1982	1240	1433.3	1457	1045.7
1983	1567	1864.2	2048.3	1270.3
1984	1563	1806.9	1817.2	1319.5
1985	1799	2123.4	2198.5	1474.6
1986	1592	1773	1874.5	1411.5
1987	1466	1763.5	1567.4	1168.7
1988	1900	2226.2	2144.1	1573.3
1989	1778	2058.5	2247.4	1496.6
1990	1626	1696.3	2051.4	1554.9
1991	1453	1617.6	1737	1287.5
1992	1521	1763.7	1815.1	1278.6
1993	1170	1376.4	1327.2	964.2
1994	1549	1762.2	1788.2	1335
1995	2037	2251.2	2681.1	1823.2
1996	1831	2038.2	2029.7	1623.2
1997	1449	1619	1608	1279.8
1998	1694	1951.7	2251.5	1437
1999	1546	1692.7	2238.1	1400.2
2000	1528	1761.3	1887.1	1294.4
2001	1775	1987.9	2307.2	1563
2002	1184	1409.3	1292.1	958.8
2003	1526	1845.8	1828.7	1206.6
2004	1848	2076.6	2380.7	1619.9
2005	1544	1828.1	2024.2	1260.4
2006	1714	1953	2057.2	1474.6
2007	1431	1762	1856.3	1100.4
2008	1778	2074	2184.9	1481.1
2009	1421	1679	1768.3	1164.2
2010	1672	1909		1435.6
2011	2326	2656		1997.4
2012	1277	1457	1245.9	1096
2013	1380	1575		1184.6
Average	**1615**	**1843**	**1902**	**1387**
SE	**16%**	**16%**	**18%**	**18%**
95% CI	**76**	**85**	**110**	**74**
95% CI/average	**5%**	**5%**	**6%**	**5%**

Table 2: Summary of annual rainfall at Rotorua. Reference = the average of Dalbeth Road and Airport rainfall. Figures in red have occasional missing values and the annual total = daily average x 366. Figures in blue = Okere Falls x 0.95. Figures in green = Airport x 1.33. SE = standard error (standard deviation/average). 95% CI = 95% confidence interval of the annual means. File: Summary_Major_Flow_Sites_1975_2012_Version5.

Year	OHC	HAM	AWA	WWH	NGO	PUA	WNG	WHE	UTU	WTT
1976	1903	2032	2160	1788	2192	1687	1517	1818	1987	2182
1977	1596	1705	1812	1500	1839	1415	1272	1525	1666	1830
1978	1346	1438	1529	1265	1551	1193	1073	1286	1406	1544
1992	1717	1835	1950	1614	1979	1523	1369	1641	1793	1970
1993	1321	1411	1500	1242	1523	1171	1053	1263	1380	1516
1994	1748	1868	1985	1643	2015	1550	1394	1671	1826	2005
1995	2300	2457	2612	2161	2650	2039	1833	2198	2402	2638
2005	1743	1862	1980	1638	2009	1546	1390	1666	1821	2000
2006	1935	2067	2197	1818	2230	1716	1542	1849	2021	2219
2007	1616	1726	1835	1519	1862	1433	1288	1544	1688	1854
2008	2007	2144	2279	1886	2313	1779	1600	1918	2096	2302
2009	1605	1714	1822	1508	1849	1423	1279	1534	1676	1841
2010	1888	2017	2144	1774	2175	1674	1505	1804	1971	2165
average	**1748**	**1867**	**1985**	**1643**	**2014**	**1550**	**1394**	**1671**	**1826**	**2005**
95%CI	**145**	**155**	**165**	**136**	**167**	**129**	**116**	**139**	**152**	**167**

Table 3: Annual rainfall in the catchments of the outflow and the nine major streams. Rainfall is the reference rainfall multiplied by the rain factor derived by Dr Andrew Tait (see Rutherford et al. 2008 for details). Rainfall is not corrected for gauge under-catch. File: Summary_Major_Site_Flows_1975_2012_Version6.

	OHC	HAM	AWA	WWH	NGO	PUA	WNG	WHE	UTU	WTT
Area km2	**500.3**	**2.8**	**16.4**	**8.2**	**73.4**	**73.6**	**10.1**	**13.4**	**61.6**	**62.2**
1976	1122	33989	3319	1586	839	871	847	876	1032	707
1977	1071	32540	3370	1332	832	791	812	789	977	654
1978	968	27183	2739	1129	639	618	718	730	833	515
1992	957	29615	3064	1492	715	790	710	883	949	587
1993	836	27752	2899	1049	598	704	624	587	811	521
1994	936	26375	2890	1266	644	785	672	675	1005	500
1995	1138	27461	2957	1355	894	928	699	921	1121	618
2005	1166	27869	2946		753	874	770			
2006	1219	30071	3217		873	872	841			
2007	1114	27117	3178		715	713	784			
2008	1123	26917	3072		756	790	786			
2009	1054	27219	3194		753	685	744			
2010	1074	27890	3117		735	633	767			
average	**1060**	**28615**	**3074**	**1315**	**750**	**773**	**752**	**780**	**961**	**586**
95%CI	**58**	**1262**	**100**	**140**	**50**	**53**	**36**	**91**	**81**	**58**

Table 4: Observed annual runoff in the outflow and the nine major inflowing streams for selected years. Runoff (units mm y^{-1}) is observed annual flow/catchment area. Catchment area is the value re-calculated from REC shape files and differs from the value in Hoare (1980) notably for AWA, WHE, WWH and WTT. Hoare (1980) does not give a catchment area for the Hamurana. OHC = Ohau Channel, HAM = Hamurana, AWA = Awahou, NGO = Ngongotaha, PUA = Puarenga, UTU = Utuhina, WNG = Waingaehe, WWH = Waiowhiro, WHE = Waiohewa and WTT = Waiteti. Note that the 95%CI quantifies variation over time but not uncertainty associated with measurement errors. File: Summary_Major_Site_Flows_1975_2012_Version6.

Site Code	Hamurana at road bridge HAM	Awahou at Tauranga Direct Rd AWA	Ngongotaha at SH5 Bridge NGO	Puarenga at FRI or SH30 PUA	Utuhina at SH5, Old Taupo Rd or Depot UTU
Area km^2	2.8	16.4	73.4	73.6	61.6
Count	218	2300	13689	9956	7823
mean $m^3 s^{-1}$	2.60	1.62	1.79	1.78	1.86
median $m^3 s^{-1}$	2.51	1.59	1.60	1.57	1.67
SD $m^3 s^{-1}$	0.28	0.20	1.00	0.81	0.79
95% CI $m^3 s^{-1}$	0.04	0.01	0.02	0.02	0.02
CI/mean	1.4%	0.5%	0.9%	0.9%	0.9%
Site Code	**Waingaehe at SH30 WNG**	**Waiowhiro at Bonnington's Farm WWH**	**Waiohewa at SH30 Br WHE**	**Waiteti at Tauranga Direct Rd WTT**	**Ohau channel OHC**
Area km^2	10.1	8.2	13.4	62.2	500.3
Count	7152	1892	2504	2923	11539
mean $m^3 s^{-1}$	0.243	0.343	0.328	1.19	16.46
median $m^3 s^{-1}$	0.238	0.307	0.293	1.09	16.05
SD $m^3 s^{-1}$	0.043	0.156	0.159	0.50	4.23
95% CI $m^3 s^{-1}$	0.001	0.007	0.006	0.02	0.08
CI/mean	0.4%	2.1%	1.9%	1.5%	0.5%

Table 5: Summary of measured daily flows 1975-2012. Count = number of days when flow was measured or recorded and CI denotes confidence interval. Statistics were calculated for measured/recorded flows (viz., gaps were not filled). Area = area of the surface catchment above the flow measurement site re-calculated for this study using REC shape files. Note that the 95%CI quantifies variation over time but not necessarily measurement error. File: Summary_Major_Site_Flows_1975_2012_Version6.

6 Catchment runoff

There is no direct evidence of groundwater flows into or out of the six sub-catchments NGO, WTT, UTU, PUA, WNG and WHE. However, average runoff expressed as a fraction of rainfall in NGO and WTT was lower than in UTU, PUA, WNG and WHE (Table 6). This suggests either that there are groundwater losses from the NGO and WTT sub-catchments or that rainfall has been over-estimated in these catchments.

The four 'closed' sub-catchments UTU, PUA, WNG and WHE had an average runoff of 52 ± 3% (mean ± 95% CI). Reported values of runoff are typically c. 50% and so these runoff estimates are plausible, while the estimates for NGO and WTT (34 ± 5%) are lower than expected. Runoff from the four 'closed' catchments is used in the water balance (described below) to estimate expected runoff elsewhere in the Rotorua catchment.

Year	OHC	HAM	AWA	WWH	NGO	PUA	WNG	WHE	UTU	WTT
1976	59%	1672%	154%	89%	38%	52%	56%	48%	52%	32%
1977	67%	1909%	186%	89%	45%	56%	64%	52%	59%	36%
1978	72%	1890%	179%	89%	41%	52%	67%	57%	59%	33%
1992	56%	1614%	157%	92%	36%	52%	52%	54%	53%	30%
1993	63%	1966%	193%	84%	39%	60%	59%	46%	59%	34%
1994	54%	1412%	146%	77%	32%	51%	48%	40%	55%	25%
1995	49%	1118%	113%	63%	34%	46%	38%	42%	47%	23%
2005	67%	1496%	149%		37%	57%	55%			
2006	63%	1455%	146%		39%	51%	55%			
2007	69%	1571%	173%		38%	50%	61%			
2008	56%	1256%	135%		33%	44%	49%			
2009	66%	1588%	175%		41%	48%	58%			
2010	57%	1383%	145%		34%	38%	51%			
average	**61%**	**1564%**	**158%**	**83%**	**38%**	**50%**	**55%**	**48%**	**55%**	**31%**
SD	**7%**	**253%**	**23%**	**10%**	**4%**	**6%**	**7%**	**6%**	**5%**	**5%**
NUM	**13**	**13**	**13**	**7**	**13**	**13**	**13**	**7**	**7**	**7**
95% CI	**4%**	**138%**	**12%**	**8%**	**2%**	**3%**	**4%**	**4%**	**3%**	**4%**

Table 6: Observed annual runoff expressed as a percentage of sub-catchment rainfall. SD and 95% CI quantify variation over time but not necessarily uncertainty associated with measurement errors. File: Summary_Major_Site_Flows_1975_2012_Version6

7 Water balance at the Ohau Channel

7.1 Lake outflow

Over the 13 study years (1976-78, 1992-95 and 2005-10) Ohau Channel (OHC) flow averaged 16.3 ± 0.2 m^3/s (mean ± 95% CI)[7]. The 95% CI (1% of mean flow) quantifies variability in the long-term average flow assuming that each value of daily flow is an independent, random sample from a normally distributed population with constant variance and no measurement error. This CI quantifies the effects of temporal (day-to-day) changes in flow on the average flow during the 13 year study period. If measurement errors are random, uncorrelated (independent) and normally distributed with constant variance, and the 'true' flow does not vary over time, then the 95% CI quantifies the uncertainty in the estimate of 'true' average flow from the values measured in the 13 year study. However, we are not concerned in this study with estimating the 'true' value of average flow in the Ohau Channel over say 100 years. We want to know the uncertainty in the average value over the 13 years studied so that we can compare it with stream inflows over the same period. In the following analyses we omit day-to-day or year-to-year variations from our analysis and focus on estimating errors. As detailed above, we use two different methods to estimate uncertainty in average flow.

Method 1.

There are 105 gaugings at OHC over the 13 years that coincide with reported daily flows, for which the RMS difference is 0.63 m^3/s (4% of mean flow)[8]. Assuming that errors are normally distributed and independent, the 95% CI for a single estimate of flow is twice the RMS error, 1.2 m^3/s (7% of mean flow). This may under-estimate the 'true' error if, for example, error is distributed uniformly rather than normally. Method 1 makes the extreme 'worst case' assumption that the uncertainty in the average flow equals the uncertainty in a single flow estimate. This implies a 95% CI for average flow of ±1.2 m^3/s (7% of mean flow). Method 1 almost certainly over-estimates the true uncertainty for the reasons discussed earlier.

Method 2.

The minimum and maximum differences between reported daily flow and gauged flow on the same day were -2.06 and +2.03 m^3/s. Errors were assumed to be uniformly distributed and the rating error RE in Method 2 was set to ±2 m^3/s (12% of mean flow). The gauging error GE in Method 2 was taken as 1.6 m^3/s (10% of mean flow). Our estimate of 10% for gauging error is similar to the values given by Sauer & Meyer (1992, 8%), Herschy (2002, 12%) and Hudson & Fraser (2002, 10%) for the uncertainty in a single flow gauging. Using the values of RE = 2 m^3/s and GE = 1.6 m^3/s gave the total error TE of 2.6 m^3/s (16% of mean flow) (see Eq. 7).

Values of $Q_i - G_i$ remained either positive or negative for several (2-3) consecutive gaugings, which indicates that errors in the OHC flow time series were serially correlated. The correlation between residuals c. 30, 60 and 90 days apart were 0.097, 0.098 and 0.018 respectively. From Eq. 8 the correlation between residuals 1 day apart is 0.92-0.96 and we

[7] This value of 16.3 m3/s is the average of reported daily flows during the 13 year study period. It differs slightly from 16.5 m3/s in Table 5 which is the average for the 37 year period 1975-2010. It also differs slightly from the value of 16.8 m3/s stated elsewhere because the latter is the average of 13 annual averages from a time series where there are some gaps.
[8] The are 395 gaugings over the 37 year period 1975-2012, for which the RMS error is similar at 0.61 m3/s (4% of mean flow).

used a value of 0.95 in Eq. 9. However, the 30 and 60 day correlations were weak and may have arisen by chance, so we also assumed that errors were uncorrelated.

The error model in Method 2 furnished a 95% CI for the long-term average flow in the Ohau Channel of 0.23 m^3/s (1.4% of mean flow) when $r_1 = 0$, and 0.26 m^3/s (1.6%) when $r_1 = 0.95$. We suspect that these values may under-estimate the true uncertainty.

Overall we conclude that the average flow in the Ohau Channel during the 13 year study period was 16.3 m^3/s and that the uncertainty (95% CI) lay between 0.3 m^3/s (2% of mean flow) (Method 2) and 1.2 m^3/s (7% of mean flow) (Method 1).

7.2 Runoff at the lake outlet

Observed annual runoff from the entire catchment measured in the Ohau Channel (OHC), as a percentage of rainfall, averaged 61 ± 4% (average ± 95% CI) (Table 6). The 95% CI quantifies year-to-year variations in annual average lake outflow, but not the uncertainty arising from errors in flow, rainfall and area.

The relative uncertainties in flow, rainfall and area estimated earlier were: flow 2-7%, rainfall 10% and area 2%. Combining these uncertainties using the method described in Section 2.4 gave a relative uncertainty for runoff of 10-12%. Multiplying by the mean runoff gave an uncertainty for the long-term average runoff of ± 6-7%.

We conclude that, for the 13 years considered, annual runoff in the Ohau Channel expressed as a percentage of catchment-average rainfall was 61 ± 6-7% (mean ± 95% CI).

7.3 Stream inflows

Observed annual runoff in the four 'closed' sub-catchments (UTU, PUA, WNG and WHE) averaged 52 ± 3% (mean ± 95% CI). The 95% CI quantifies temporal variation but not uncertainty in catchment area, rainfall and flow, and hereafter was omitted from calculations.

Figure 3 indicates that the relative error variances in the four 'closed' sub-catchments (range 0-0.4) were often larger than in the Ohau Channel (range 0-0.02) and larger uncertainties in average flow would be expected. The RMS errors expressed as a percentage of mean flow ranged from 43% (PUA) to 140% (WHE). Thus, using untransformed flows, Method 1 suggests that the uncertainty in average flow may be as high as 43-140%. However, the maximum errors (viz., maximum values of $(Q_i - G_i)$) were 3-8 times larger than the absolute value of the minimum value because the error variance increased with increasing flow. In this situation Method 1 is likely to have furnished biased (high) estimates of the 95% CI for average flow. When flows were log transformed, the maximum errors were only 1-2.5 times larger than the minimum errors. Method 2 (described previously) was adapted to work with log transformed flow and predicted 95% CIs for average flow (expressed as a percentage of mean flow) of 4% (WNG), 5% (PUA and UTU) and 9% (WHE).

McMillan et al. (2012) summarize reported uncertainties in estimates of flow made from water level measurements using rating curves. For instantaneous flows measured using methods similar to those at Rotorua, the quoted uncertainties are 26% (average) (Di Baldassarre & Montanari 2009) and 22% (average) and 10-46% (range) (McMillan et al. 2012). For average flows, those most relevant to Rotorua are 42% (daily averages), 100-

200% (low flows) and 100% (high flows) (Harmel and Smith 2007). Our estimates of 4-9% from Method 2 were smaller than reported values but related to longer averaging periods.

We conclude that the uncertainty in long-term average stream flow:

1. May be in the range 4-9% based on our Method 2 using log-transformed data
2. Is unlikely to be as high as 43-140% estimated by our Method 1.
3. Is unlikely to be as high as 42% (a published value for daily mean flow) or 100-200% (published values for low and flood flows).

Our 'best guess' is that the uncertainty in long-term average stream flow lies in the range 10-30%.

Combining the relative uncertainties in sub-catchment area (3.5%), rainfall (10%) and flow (10-30%) as previously gave a relative uncertainty for runoff (expressed as a percentage of average runoff) in the range 15-32%[9]. The average runoff was 52% of rainfall and so the absolute uncertainty in runoff (expressed as a percentage of rainfall) lay in the range 8-17%. Note that these calculations apply to the four 'closed' streams. In the spring dominated Hamurana and Awahou Streams, rating errors are smaller and so the overall uncertainty is lower than in other streams. The Hamurana and Awahou are not used in this study to estimate catchment runoff.

GNS-Science requested that we summarise our estimates of average flow, and its uncertainty, at four key sites. The average flows during the 13 years studies were estimated to be:

1. Ohau Channel 16.5 ± 0.3-1.2 m^3/s.
2. Hamurana Stream 2.6 ± 0.3 m^3/s.
3. Awahou Stream 1.6 ± 0.2 m^3/s.
4. Waiteti Stream 1.2 ± 0.1-0.4 m^3/s.

These figures are average flow and the uncertainty is the 95% CI. There is uncertainty in the 95% CI values which we were able to quantify for the Ohau Channel and Waiteti Stream but not for the Hamurana and Awahou.

[9] Note that the relative uncertainty of 15-32% quantifies the uncertainty in runoff expressed as a percentage of the average runoff. The absolute uncertainty in runoff is therefore the average runoff multiplied by the relative uncertainty in runoff. It is a potential source of confusion that both variables have the units % but the relative uncertainty relates to the percentage of the average runoff, while the absolute uncertainty relates to the percentage of rainfall.

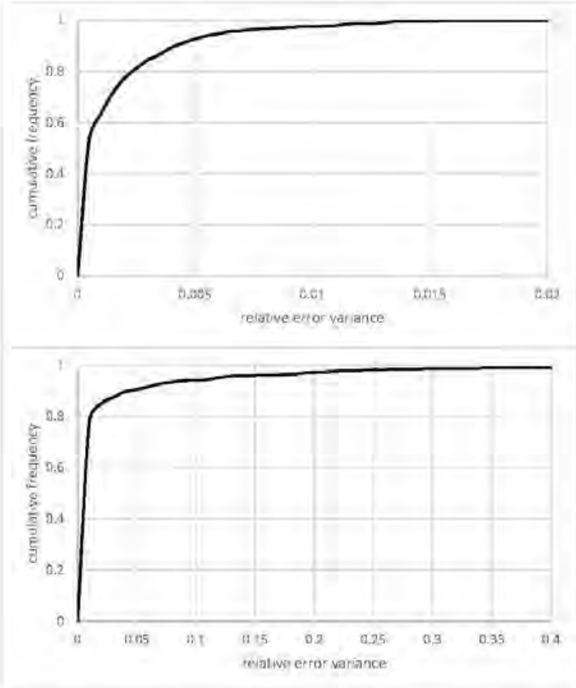

Figure 3: Cumulative frequency distributions of relative error variance for flow in the Ohau Channel (top) and the four 'closed' sub-catchments (bottom).

7.4 Comparison between lake inflow and outflow

For the 13 years considered, runoff in the Ohau Channel expressed as a percentage of catchment-average rainfall was estimated to have been 61 ± 6-7% while runoff in the four 'closed' sub-catchments (CAT) averaged 52 ± 8-17%.

Using the lower bound uncertainties, runoff in the OHC (61 ± 6%) was higher than runoff in the four 'closed' sub-catchments (52 ± 8%). If we assume that runoff is normally distributed then for the lower bound uncertainties 20% of the area under the CAT distribution lies to the right of the lower 95% confidence limit of the OHC distribution, while 39% of the area under the OHC distribution lies to the right of the upper 95% confidence limit of the CAT distribution[10] (Figure 4). Stated in a different way, the 9% difference in runoff has a 95% CI of ± 10%[11]. Thus, if the 'true' OHC and CAT runoff are the same, the probability of getting the 9% difference that we calculated is 7%. This indicates that there is a fairly high probability (c. 90%) that OHC runoff is higher than would be expected based on runoff from the four

[10] These figures were arrived at by calculating the values of the cumulative normal distribution at 1% intervals of runoff from 50% to 70% for OHC and CAT knowing the mean and 95% CI. Calculations were coded in EXCEL as part of this study.
[11] 10% = sqrt (6%^2 + 8%^2) where 6% and 8% are the 95% CI of OHC and CAT runoff respectively

'closed' catchments. Note, however, that there is still a fairly high uncertainty in difference in runoff (9 ± 10%, mean ± 95% CI).

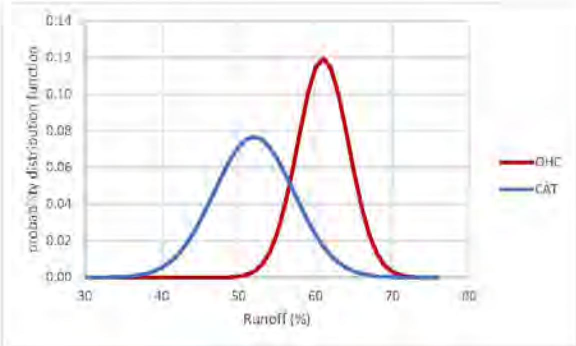

Figure 4: Probability distribution function of runoff at the Ohau Channel (OHC) and four streams in the catchment (CAT). Uncertainty is assumed to follow a normal distribution with the lower bound estimates detailed in the text.

Using the upper bound uncertainties for OHC (± 7%) and CAT (± 17%), the 9% difference has a 95% CI of ± 18%. 37% of the area under the CAT distribution lies to the right of the lower confidence limit of the OHC distribution, while 93% of the area under the OHC distribution lies to the left of the upper confidence limit of the CAT distribution (Figure 5). If the 'true' OHC and CAT runoff were the same, the probability of getting a difference of 9% or greater would be 33%. Thus there is lower probability (67%) that runoff differs between OHC and CAT and the uncertainty in the difference is very high (9 ± 18%, mean ± 95% CI)

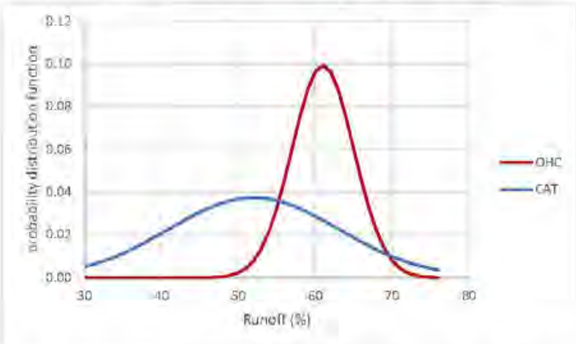

Figure 5: Probability distribution function of runoff at the Ohau Channel (OHC) and four streams in the catchment (CAT). Uncertainty is assumed to follow a normal distribution with the upper bound estimates detailed in the text.

7.5 Discussion

Runoff at the Ohau Channel includes rainfall falling on the lake surface minus open-water evaporation. For the 13 years examined in this study, open-water evaporation estimated using the model of Jobson (1975) averages 647 ± 98 mm/y which equates to 42 ± 10% of rainfall on the lake (mean ± 95% confidence interval). Hoare (1980) gives lake evaporation in 1976 as 2 $m^3 s^{-1}$ which equates to 790 mm/y and 47% of 1976 rainfall on the lake. These two estimates of lake evaporation are not significantly different ($p < 0.001$). AET from land within the catchment (the difference between rainfall and runoff) averages 47 ± 17% of rainfall on land. Evaporation from land and water, expressed as a percentage of rainfall, are not significantly different ($p < 0.001$) and consequently observed runoff at the Ohau Channel was not 'corrected' for differences between open-water evaporation and AET from land.

Standard rain gauges tend to underestimate precipitation. Dr Martyn Clark (formerly of NIWA) concluded that precipitation under-catch in and around the Rotorua catchment was likely to be 5-10% (see Rutherford et al. 2008 for details). If rain gauge under-catch is uniform across the catchment then it will not affect the difference between Ohau Channel and sub-catchment runoff values. A 'worst-case' assumption is that all the rain gauge under-catch occurs outside the four 'closed' sub-catchments. When catchment rainfall at the Ohau Channel was increased by 10%, this reduced runoff to 55 ± 9% (mean ± 95% CI, N = 13) which is similar to average runoff from the four 'reference' sub-catchments (53 ± 17%, mean ± 95% CI, N = 60).

If average rainfall for the entire catchment had been under-estimated, then runoff at the Ohau Channel, expressed as a percentage of rainfall, would have been over-estimated. At the Ohau Channel, observed runoff and catchment-average rainfall were 1060 and 1748 mm/y respectively with a ratio of 61%. For the four 'closed' sub-catchments the ratio of runoff to rainfall averaged 52%. If runoff as a percentage of rainfall at the Ohau Channel matched the average for the four 'closed' sub-catchments, then catchment rainfall at the Ohau Channel would need to average 2040 mm/y. This is 17-22% higher than the catchment averages estimated by Tait (in Rutherford et al. 2008) (1670 mm/y in 1975-2012) and by Hoare (1980) (1750 mm/y in 1976). Uncertainty in average rainfall was estimated by Tait (in Rutherford et al. 2008) to be c. 10% and it is unlikely that rainfall for the entire catchment had been under-estimated by 17-22%.

We conclude that:

1. There is no direct evidence of net groundwater gains or losses in the four 'closed' sub-catchments (PUA, UTU, WNG and WHE). The lower than expected runoff in the NGO and WTT sub-catchments suggests that they may lose groundwater.

2. Using the lower bound estimates of uncertainty, average runoff at the Ohau Channel (61 ± 6% of rainfall) is 9% higher than expected based on observed runoff from four 'closed' sub-catchments (52 ± 8%). Assuming runoff is normally distributed then, if true runoff were the same at the Ohau Channel and in the four 'closed' sub-catchments, there would be a 7% chance of observing a 9% difference. This indicates a 93% probability that runoff is higher at the Ohau Channel than would be expected based on runoff from the four 'closed' catchments. However, the lower bound estimates may under-estimate the 'true' uncertainty and the uncertainty in the difference in runoff is high.

3. Using the upper bound estimates of uncertainty, average runoff at the Ohau Channel (61 ± 7% of rainfall) again differs by 9% from runoff in the four 'closed' sub-catchments (52 ± 17%) but the probability that runoff does not differ between OHC and CAT increases to 33%. However, the upper bound estimates almost certainly over-estimate uncertainty.
4. It is possible that groundwater inflow from outside the surface catchment enters the lake, but the uncertainty in estimating the 'missing' flow based on measured runoff in streams is high.

8 Inflow from outside the surface catchment

The water budget at the lake outlet (the Ohau Channel) described above was used to re-examine earlier estimates (Rutherford et al. 2008, White 2009) of the 'missing' inflow and land area of the additional 'Mamaku aquifer'.

Table 7 lists the surface areas of the 9 major sub-catchments and the ungauged area. The rainfall factor (RF) for each sub-catchment was estimated from Figure 1 and the rainfall in each sub-catchment was calculated from the RF and the long-term average reference rainfall (1548 mm/yr). The reference rainfall was not corrected for rain gauge under-catch because the average runoff/rainfall factor of 52% was estimated using un-corrected rainfall. The expected runoff from each sub-catchment was calculated from the sub-catchment rainfall multiplied by the average runoff/rainfall factor for the four 'closed' sub-catchments 52%. Flow was runoff multiplied by sub-catchment area.

Note that the calculated flows from the individual sub-catchments ignore any groundwater exchanges between sub-catchments. However, only the cumulative sum of all the inflows (12.3 $m^3 s^{-1}$ from land within the surface catchment) is used in the water balance. It is assumed that any groundwater exchanges between sub-catchments do not affect the cumulative sum of the inflows. Effectively 12.3 $m^3 s^{-1}$ is the total inflow to the lake from land within the surface catchment that would be expected if the runoff/rainfall ratio averaged the 52% observed in four 'closed' sub-catchments.

The total inflow 14.7 $m^3 s^{-1}$ includes net rainfall on the lake surface. The uncertainty (95% CI) in lake inflow (1.2 m^3/s) is 8% of the total inflow based on the earlier finding that the lower bound uncertainty for runoff from the four 'closed' catchments. The uncertainty in lake outflow (1.0 m^3/s) is 6% of outflow based on the earlier finding for the lower bound uncertainty on lake outflow.

The uncertainty in missing flow (1.5 m^3/s) is the sqrt of the sum squares of the uncertainties in lake inflow and outflow. This uncertainty is only slightly smaller the mean value of missing flow (2.1 m^3/s). This arises because the uncertainties in the estimates of average lake inflow and outflow measurements are both high, meaning that the uncertainty in their difference is very high.

Table 7 estimates the 'missing' flow to be 2.1 ± 1.5 $m^3 s^{-1}$. Assuming this originates on the Mamaku Plateau where the rainfall scaling factor is 1.30 and assuming 100% of runoff drains into the lake then the 'missing' area is 33 ± 24 km^2. If some runoff flows away from the lake then runoff from the 'missing' area may be less than 53% of rainfall and the 'missing' area may be larger.

Table 8 uses upper bounds on uncertainty and estimates the 'missing' flow to be 2.1 ± 2.8 $m^3 s^{-1}$ and the 'missing' area to be 33 ± 43 km^2.

9 Discussion

An earlier study (Rutherford et al. 2008) estimated the 'likely' area of the 'Mamaku aquifer' to be 60 km^2 assuming that drainage to groundwater is 50% of total runoff. This study estimates 33 km^2 assuming that drainage is 100% which equates to 66 km^2 if drainage is 50%. Thus the two studies yield very similar estimates of the 'most likely' area of the Mamaku aquifer.

The earlier study estimated the uncertainty in 'missing' area to be from 5-80 km^2 assuming 50% drainage. The current study estimates a higher uncertainty. For the lower bound uncertainty estimates, the 'missing' area lies in the range 9 to 57 km2 (100% drainage) and 18 to 115 km2 (50% drainage). For the upper bound uncertainty estimates, the 'missing' area lies in the range -10 to 76 km2 (100% drainage) and -20 to 153 km2 (50% drainage).

10 Conclusions

1. The best estimate of 'missing' flow is c. 2 m^3/s.
2. Based on the lower bound uncertainties there is a high (c. 95%) probability that the 'missing' flow lies in the range 0.6 to 3.7 m^3/s while based on the upper bound uncertainties this range becomes -0.7 to 4.9 m^3/s. The lower bound is thought to under-estimate, while the upper bound almost certainly over-estimates the 'true' uncertainty.
3. There is a chance the 'missing' flow is zero (viz, that no groundwater flows into Lake Rotorua from outside the surface catchment) or negative (viz., that some groundwater flows out of the surface catchment). There is also a chance the 'missing' flow exceeds 4 m^3/s.
4. The water budget approach used in this study is not able to provide any guidance on the location of the 'missing' catchment.
5. It may be possible to refine the current estimates of the size of the 'missing' area, and to estimate its location, on the basis of topography and hydro-geology (work being undertaken by GNS-Science).

Sub-catchment	Code	Area km²	RF	Rainfall mm y⁻¹	Runoff mm y⁻¹	Flow m³ s⁻¹	Cum m³ s⁻¹
Awahou	AWA	16.4	1.282	1985	1032	0.53	0.53
Hamurana	HAM	2.8	1.206	1867	971	0.09	0.62
Ngongotaha	NGO	73.4	1.301	2014	1047	2.44	3.06
Puarenga	PUA	73.6	1.001	1550	806	1.88	4.94
Utuhina	UTU	61.6	1.179	1825	949	1.85	6.79
Waingaehe	WNG	10.1	0.900	1393	724	0.23	7.02
Waiohewa	WHE	13.4	1.079	1670	869	0.37	7.39
Waiowhiro	WWH	8.2	1.061	1642	854	0.22	7.61
Waiteti	WTT	62.2	1.295	2005	1042	2.06	9.67
Ungauged		98.0	1.070	1656	861	2.67	12.3
Total land		**419.7**	**1.153**				
Lake		80.6	1.007	1559	920	2.35	14.7
Lake + land	**OHC**	**500.3**	**1.129**	**1748**			
						mean	95% CI
Lake inflow						14.7	1.2
Lake outflow						16.8	1.0
Missing flow						**2.1**	**1.5**
Missing area km2						**33**	**24**
	Runoff/Rainfall	95% CI					
Land	52%	8%		four 'closed' sub-catchments			
Lake	61%	6%		Jobson open-water ET			
Rainfall	1548	10%		Uncorrected for gauge under-catch			

Table 7: Water balance for Lake Rotorua 1976-78, 1992-95 and 2005-10 based on average runoff from the four 'closed' sub-catchments assuming lower bound uncertainties. Area = total sub-catchment area which may exceed the catchment area at the flow recorders given in Table 1, RF = rainfall factor. Rainfall is reference rainfall (uncorrected for under-catch) x RF. Runoff = rainfall x 52% (where 52% is the average runoff/rainfall from the four 'closed' sub-catchments). Flow = runoff x area. For lake inflow and outflow the 95% CI = lower bound uncertainty associated with measurement or estimation errors (see text). The uncertainty in the missing flow = sqrt of the sum of squares of the uncertainties in predicted and observed flow. Missing Area is calculated assuming a RF of 1.30 and that 100% of runoff reaches the lake.

Sub-catchment	Code	Area km^2	RF	Rainfall $mm\ y^{-1}$	Runoff $mm\ y^{-1}$	Flow $m^3\ s^{-1}$	Cum $m^3\ s^{-1}$
Awahou	AWA	16.4	1.282	1985	1032	0.53	0.53
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Total land		**419.7**	**1.153**				
Lake		80.6	1.007	1559	920	2.35	14.7
Lake + land	**OHC**	**500.3**	**1.129**	**1748**			
						mean	95% CI
Lake inflow						14.7	2.5
Lake outflow						16.8	1.2
Missing flow						**2.1**	**2.8**
Missing area km2						**33**	**43**
	Runoff/Rainfall	95% CI					
Land	52%	17%			four 'closed' sub-catchments		
Lake	61%	7%			Jobson open-water ET		
Rainfall	1548	10%			Uncorrected for gauge under-catch		

Table 8: Water balance for Lake Rotorua 1976-78, 1992-95 and 2005-10 based on average runoff from the four 'closed' sub-catchments assuming upper bound uncertainties. For lake inflow and outflow the 95% CI = upper bound uncertainty associated with measurement or estimation errors (see text).

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APPENDIX 2 LAKE ROTORUA CATCHMENT BOUNDARIES PHASE 3 WATER BUDGET CALCULATIONS

NIWA
Taihoro Nukurangi

Lake Rotorua catchment boundaries

Phase 3 water budget calculations

Prepared for GNS-Science and Bay of Plenty Regional Council

June 2014

NIWA – enhancing the benefits of New Zealand's natural resources www.niwa.co.nz

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Lake Rotorua catchment boundaries

Executive summary

This report uses previously published data on the spatial variation of rainfall to calculate weekly runoff from 1975-2012, and to develop long-term water budgets for the lake outlet and four major stream inflows. A simplified version of the ROTAN model, RO_FLOW_LITE, was developed to do this. The model coefficients were calibrated so that the sum of predicted long-term average flow (1975-2012) in four 'calibration' streams not unduly affected by groundwater inflows or outflows matched observed long-term average flow (4.20 ± 0.78 m^3/s) (Calibration 1). It was found, however, that predicted AET was higher than published values. The model was also calibrated to match published AET values (Calibration 2) although less reliance can be placed on this second calibration. It was not possible to identify model coefficients that matched both flow in the 'calibration' streams and published AET values.

An earlier analysis of uncertainty (Rutherford and Palliser 2014b) concluded that the long-term average lake outflow in the Ohau Channel over 13 years between 1975 and 2012 was 16.8 ± 1.0-1.2 m^3/s (mean ± upper and lower bound 95% confidence intervals). This figure was the average over the 13 years when stream flow measurements were available of the 13 annual average flows. In this study we re-calculated the average flow over the 13 year study period after including additional data and concluded that the average flow was 16.5 ± 1.0-1.2 m^3/s (mean ± upper and lower bound 95% confidence intervals). Over this period lake outflow should match lake inflow (including streams, groundwater direct and net rainfall on the lake).

Using the outer boundary of the surface catchment supplied by GNS-Science (called SC_1_2000_7_Mar_2014) and model coefficients determined by Calibration 1 it was predicted that the average Ohau Channel outflow should be 14.9 ± 1.5 m^3/s (mean ± 95% confidence interval) which is 90% of the observed flow. Using model coefficients determined by Calibration 2, predicted outflow was 17.3 ± 1.7 m^3/s which exceeds the observed outflow by 5%. Less reliance can be placed on predictions based on Calibration 2. The modelling suggests the possibility of 'missing' inflow (e.g., groundwater entering the lake from outside the surface catchment).

There is a high uncertainty in the estimates that can be made of this 'missing' flow arising from uncertainties in catchment-average rainfall, AET and observed stream flows used in model calibration. The 'missing' flow estimated based on Calibration 1 is 1.6 ± 1.9 m^3/s (mean ± 95% confidence interval). There is a >5% probability of the 'missing flow' being zero or less, and a 5% probability of it exceeding 3.5 m^3/s.

It is conceivable that under Calibration 1 the model over-estimates AET at high rainfall. If so then the model may under-estimate runoff from the high rainfall area to the north-west of Lake Rotorua where the 'missing area' probably lies. This adds to the uncertainty in estimating the 'missing flow'.

Using the outer boundary supplied by GNS-Science (called GW_1_2000_16_Mar_2014 _max1) long term average flow in the Ohau Channel was predicted to be 15.8 ± 1.6 m^3/s. This is 4% lower than the long term average flow measured in the Ohau Channel but there is high probability that the difference of 0.7 ± 2.0 m^3/s is not significantly different from zero.

An earlier study, which used a different methodology but the same rainfall and stream flow data, derived an estimate for the 'missing' flow of 2.1 ± 1.5-2.8 m^3/s (Rutherford and Palliser 2014b). It was only possible to estimate upper and lower bounds on the 95% confidence interval on 'missing' flow.

1 Background

The Bay of Plenty Regional Council (BoPRC) contracted GNS-Science and NIWA to refine current estimates of the area and location of the boundaries of the Lake Rotorua catchment with particular focus on the boundaries of the so-called 'Mamaku aquifer' in the north-west of the catchment. The role of NIWA in the project, as originally agreed, was to:

1. Re-analyse historic and recent rainfall and stream flow data and provide advice to GNS-Science about the likely size of the Mamaku aquifer.
2. Use the ROTAN model to check the water balance for Lake Rotorua once GNS-Science has determined the location of the Mamaku aquifers.

The methods used for Step 2 were subsequently changed – a simplified model RO_FLOW_LITE was developed and used in place of ROTAN.

Two earlier reports addressed step 1:

a. Rutherford and Palliser (2014a) reviewed and updated flow measurements and provided summary statistics to GNS-Science and BoPRC.

b. Rutherford and Palliser (2014b) examined annual average flows and concluded that:

c. For the 13 year period (1976-1978, 1992-1995 and 2005-2010) when concurrent measurements are available, annual runoff expressed as a fraction of catchment-average rainfall at the lake outlet (Ohau Channel) was 61 ± 6-7% and in four major streams not affected by groundwater (Utuhine, Puarenga, Waingaehe and Waiohewa) was 52 ± 8-17%. The quoted uncertainties are the upper and lower bounds on the 95% confidence interval. The upper bound is an extreme 'worst case' and uncertainty is almost certainly less than this value.

d. Average runoff in the Ohau Channel was 9% higher than in the four streams. If there is no difference in 'true' runoff between the lake outlet and the four streams then, based on the lower bound uncertainties, there is 20-40% chance of observing the 9% difference.

e. Based on the upper bound uncertainties, there is no significant difference in runoff between the Ohau Channel and the four streams. However, uncertainty is almost certainly less than the upper bound.

f. High runoff in the Ohau Channel is unlikely to be an artefact of under-estimating catchment rainfall and a possible explanation is groundwater inflow from outside the surface catchment of the lake.

g. The 'missing' flow is estimated to be 2.1 ± 1.5 $m^3 s^{-1}$ (lower bound uncertainty) and 2.1 ± 2.8 $m^3 s^{-1}$ (upper bound uncertainty). Based on the lower bound uncertainties there is a 95% probability that the 'missing' flow lies in the range 0.6 to 3.7 m^3/s. However, based on the upper bound uncertainties this range becomes -0.7 to 4.9 m^3/s.

h. There is a chance the 'missing' flow is zero (viz, that no groundwater flows into Lake Rotorua from outside the surface catchment) or negative (viz., that some groundwater flows out of the surface catchment). There is also a chance the 'missing' flow exceeds 4 m^3/s.

i. If the 'missing' flow originates on the Mamaku Plateau where the rainfall scaling factor is 1.3, and 100% of runoff drains to the lake, then the 'missing' area is estimated to be 33 ± 24 km^2 (lower bound uncertainties) and 33 ± 43 km^2 (upper bound uncertainties). A previous study (Rutherford et al. 2008) assumed 50% drainage and estimated the 'missing' area to be 60 km^2 (range 5-80 km^2).

The water budget approach used in this study is not able to provide any guidance on the location of the 'missing' area. It may be possible to refine the current estimate of the size of the 'missing' area on the basis of topography and hydro-geology, and to estimate its location.

This report addresses step 2. It uses previously published data on the spatial variation of rainfall to calculate weekly runoff from 1975-2012, and to develop long-term water budgets for the lake outlet and four major stream inflows. A simplified version of the ROTAN model, RO_FLOW_LITE, was developed to do this.

2 Methods

2.1 Background

The original intention for this phase of the study was to use the ROTAN model (Rutherford et al. 2011) to calculate long-term average flows in the Ohau Channel (lake outlet) and nine major streams that flow into the lake. It was subsequently agreed (email Paul White, 7th January 2014) to only report results for four stream inflows – Hamurana, Awahou, Waiteti and Ngongotaha.

The aim of this phase of the study is to compare observed and predicted flows, and to address two questions. Firstly, are the observed flows consistent with rain falling within the surface catchment of the lake minus evapotranspiration? Secondly, if not, what is the likely area of land outside the surface catchment of the lake which contributes flow to the lake?

2.2 Revised methodology

Since being developed in 2007, the computer programmes that make up ROTAN (ESRI ArcGIS and MicroSoft ACCESS) have undergone substantial upgrades. ESRI no longer support VBA (the main programming language in ROTAN) which has been replaced by VB.Net. In addition MS Access has been updated and many of the calls in ROTAN no longer work. Significant re-programming and testing is required to upgrade ROTAN but there was not enough time to complete this work within the deadlines of the project.

In the short term a simplified spreadsheet model (called RO_FLOW_LITE) was developed which reproduces the essential elements of ROTAN's long term water budget. In the medium term NIWA is committed to upgrading ROTAN.

2.2.1 The RO_FLOW_LITE model

ROTAN models water flow and nitrogen transport in groundwater and streams at weekly intervals (Rutherford et al. 2008). The focus of this project, however, is on decadal water budgets, and the details of weekly flow changes can be safely neglected. RO_FLOW_LITE is an EXCEL spreadsheet model which calculates weekly runoff from land parcels and sums these results to give decadal water budgets for the lake outlet and major streams. Note that RO_FLOW_LITE does not model aquifers and, therefore, does not model groundwater lags. While this simplification affects spring flows and stream flows on time scales of weeks-years, it does not affect decadal water budgets.

ROTAN sub-divides the catchment into functional units (FUs) that have the same soil type, land cover and rainfall, and calculates weekly water budgets for each FU. The code to do this was copied from ROTAN to RO_FLOW_LITE.

Initially the same FU coefficients used in ROTAN were used in RO_FLOW_LITE. These coefficients determine the weekly values of soil water, actual evapotranspiration (AET), quick flow (viz., runoff that contributes to surface or stream flow) and slow flow (viz., runoff in the form of drainage to deep groundwater) generated by each functional unit. FU coefficients were subsequently re-calibrated as described below. In addition, the relationship between the ratio of AET/PET and soil water content (SW) was altered. In ROTAN it was assumed that AET = 0 when SW < WP (the wilting point), AET = PET when SW > CV (critical value) and varies linearly when WP < SW < CV. In RO_FLOW_LITE it is assumed that AET = 0 when SW < WP (as before) but that AET = PET/2 when SW = CV. This change means that, by setting CV to a low value, AET can be made to increase rapidly with SW near the WP – behaviour which gives a better match to published AET values.

GNS-Science provided NIWA with ArcGIS maps of several possible alternative outer boundaries of the Lake Rotorua catchment. NIWA intersected these outer boundaries with existing maps of current land cover (forest, pasture, urban and water), rainfall scaling factor, internal surface catchment boundaries (the CAT_70 boundaries used in Rutherford et al. 2008), and internal aquifer boundaries (the AQU_70 boundaries used in Rutherford et al. 2008). Soil type was assumed to be spatially uniform. The rainfall scaling factor map was derived from a map of long-term average rainfall (the Tait_2008_rainfall surface) divided by the long-term average reference rainfall (the average of rainfall at Rotorua Airport and the Dalbeth Road sites).

For each unique FU the RO_FLOW_LITE model:

1. calculated weekly values of rainfall, knowing the rainfall factor for that FU and the weekly reference rainfall, and
2. calculated weekly values of AET, soil water, quick flow and slow flow for each unique FU – using the same code as ROTAN.

For the specified outer catchment boundary it then:

1. intersected maps of land cover, rainfall factor and outer boundary to produce a map of FUs (viz., polygons where land cover and rainfall were the same)
2. assigned to each polygon the appropriate weekly values of rainfall, AET, quick flow and slow flow – calculated in Step 1
3. summed quick flows from all FUs within each surface catchment and over all weeks, to get long-term average quick flow at the catchment outlet
4. summed slow flows from all FUs within each groundwater catchment and over all weeks, to get long-term average slow flow at the aquifer outlet
5. in the four streams of interest, summed quick flow and slow flow to give long-term average stream flow
6. determined weekly flow generated by rain falling on the lake surface (minus evaporation), and summed to give long-term average lake flow, and
7. summed stream flows and lake flow to determine the expected lake outflow through the Ohau Channel.

2.2.2 Testing and calibration

The RO_FLOW_LITE code was tested by running simplified test cases (constant and uniform rainfall and PET) which confirmed that water was being conserved.

The FU coefficients were then calibrated in two ways. Firstly, FU coefficients were calibrated so that observed and predicted flows in the four 'calibration' streams matched. These four streams – Puarenga (PUA), Waingaehe (WNG), Waiohewa (WHE) and Utuhina (UTU) – are thought not to be affected by groundwater inflows or outflows, as discussed in Rutherford and Palliser (2014b). Secondly, FU coefficients were calibrated so that evapotranspiration rates (AET) matched published values over a range of rainfalls.

For calibration, aquifers and surface catchments were defined by intersecting AQU_70 (the aquifers used in ROTAN) and CAT_70 (the surface catchments used in ROTAN) with SC_1_2000_7_Mar_2014 (the outer boundary provided by GNS-Science).[1]

2.3 Uncertainty in measured and predicted flow

In order to address Question 1 above '…Are the long term average observed flows consistent with rain falling within the surface catchment of the lake minus evapotranspiration…' uncertainties in observed and predicted flows must be estimated.

2.3.1 Uncertainty in predicted flow

Model uncertainty was estimated in two different ways. Firstly, the calibration process resulted in two different sets of FU coefficients which gave different values for the total flow in the four 'calibration' streams. The percentage difference in predicted total flow is one measure of model uncertainty. Secondly, the difference between observed and predicted flows in each of the four 'calibration' streams (viz., the error variance) is another measure of model uncertainty. The two methods furnished similar uncertainty estimates.

When the model was calibrated to match the observed sum of the long-term average flows in the four 'closed' sub-catchments, the ratio of predicted/observed flow in each of these sub-catchments ranged from 91% (PUA) to 121% (WHE). The sum of the error variances

$$\sum_{i=1}^{4}(P_i - O_i)^2 = 0.0396$$

where P_i and O_i = predicted and observed average flows in stream i. Assuming that the observed average flows are unbiased and identically normally distributed, this indicates a 95% CI of ± 9% on the total flow in the four 'calibration' streams (4.20 m^3/s). Error variances in the other streams provides no information on model goodness of fit because groundwater inflows and outflows are either known or suspected. Similarly the goodness of fit to observed flow in the Ohau Channel cannot be used to assess model uncertainty because of suspected groundwater inflows from outside the modelled catchment.

When the model was calibrated to match published AET values, the sum of flows in the four 'closed' sub-catchments was 5.04 m^3/s. This is 0.84 m^3/s (20%) higher than the observed value (4.20 m^3/s).

We conclude that model uncertainty is of the order ± 10%.

[1] When CAT_70 and AQU_70 were subsequently intersected with GW_1_2000_16_Mar_2014_max1, slightly larger aquifers and catchments were obtained in the four 'calibration' streams. This is because the outer boundaries of GW_1_2000_16_Mar_2014_max1 represent the '+95 percentile' and extend further from the lake in all catchments. As a result, total flow in the four 'calibration' streams was slightly higher using GW_1_2000_16_Mar_2014_max1 than using SC_1_2000_7_Mar_2014.

2.3.2 Uncertainty in measured flow

There are three sources of uncertainty in the long-term average observed flow: (1) changes on flow over time, (2) errors in the methods used to measure (viz., gauge) or predict (e.g., using continuous water level measurements and rating curves), and (3) errors caused by faulty meter calibration, and in measured depth and distance. Uncertainty in average flow arising from changes in (true) flow over time is quantified by the 95% confidence limit on the mean of the reported daily flows. To this must be added the uncertainty arising from random and systematic errors in measurement or prediction.

Lake outflow

Flow in the Ohau Channel varies only slowly over time because lake level rises and falls slowly. The outlet channel is stable and the relationship between water level and flow rate (viz., the rating curve) does not vary over time as much as it does in streams flowing into Lake Rotorua. The uncertainty in Ohau Channel flow is, therefore, dominated by the uncertainty in the gaugings. Ohau Channel flow is only gauged occasionally (typically monthly).

For the Ohau Channel, Rutherford and Palliser (2014b) calculated the RMS difference to be 0.61 m^3/s (4% of mean flow) on the 395 occasions when both gaugings and daily mean flows (estimated from measured water level using rating curves) were reported. This implies a 95% confidence interval (CI) of 8% for a single estimate of flow[2]. They then determined that upper and lower bound estimates of the 95% CI for the long-term average flow were ± 6-7%. Details of the methods used are given elsewhere (Rutherford and Palliser, 2014b).

Herschy (1978) (quoted in McKerchar 1986) determined that the random uncertainty of a standard flow gauging decreases as the number of verticals increases, and as the number of velocities in the vertical increases. With 20 verticals and a current meter calibrated to ISO standards the coefficient of variation for random errors is 6.3% where velocity is measured at 0.6 depth, and 5.5% when velocity is measured at 0.2 and 0.8 depth (McKerchar 1986, Table 2). Gauging with 20 verticals is recommended. With 15 verticals the coefficients of variation increase to 8.2% and 7.5% and with 10 verticals to 11.3% and 10.5%. Errors in meter calibration, tapes, cables and winches are estimated to increase uncertainty, but only by c. 0.6%. McMillan et al. (2012) summarize reported uncertainties in single estimates of gauged flow. They quote uncertainties of 2.3% (SD, Carter & Anderson 1963), 4-40% (95% CI, Pelletier 1988), 4% (RMS for wading gaugings, Sauer & Meyer 1992), 6% (SE, Herschy 2002) and 5% (SD, Hudson & Fraser 2002). The 95% CI is typically twice the SD, SE or RMS.

Our estimates for the 95% CI of a single flow measurement (8%) and the long-term average flow (6-7%) are consistent with published uncertainties.

Stream inflows

For most of the study period, flow in the major streams was determined from continuous water level recordings and occasional gaugings using rating curves. Rutherford and Palliser (2014b), using the same methods as for the Ohau Channel, examined the differences between daily mean flow and gauged flow on days when both were reported and estimated

[2] Assuming the 95% CI is 2 x the RMS error

the 95% CI for long-term average flow to be 10-30%. Details of the methods used are given elsewhere (Rutherford and Palliser, 2014b).

Ibbitt (1975) (quoted in McKerchar 1986) analysed the random uncertainty in a single discharge estimated from a rating curve. While the errors quoted in McKerchar apply to the particular circumstances that Ibbitt considered, they illustrate the likely magnitude of uncertainties. Ibbitt's results relate to a river where water level was measured using a Foxboro recorder with ±3 mm resolution and 26 gaugings. He reported that the rating curve gave rise to uncertainties at median and minimum flows of 3.8% and 7.4% respectively. Errors in water level measurement of 10 mm increased uncertainty at low flow to 8.0% but hardly affected uncertainty at median flow (Figure 2 in McKerchar 1986). Ibbitt (1975) points out that this is the uncertainty near the mean flow and that the reliability of the rating curve decreases at high and low flows. This is especially true for flood flows where the rating curve may be unreliable. McMillan et al. (2012) summarized reported uncertainties in estimates of flow made from water level measurements using rating curves. For instantaneous flows, methods similar to those used at Rotorua the uncertainties are: 25.6% (average) (Di Baldassarre & Montanari 2009) and 22% (average) and 10-46% (range) (McMillan et al. 2012). For average flows (e.g., monthly averages), those most relevant to Rotorua are: 42% (Harmel and Smith 2007), and (daily averages) 42% (average), 100-200% (low flows) and 100% (high flows) (Harmel and Smith 2009). Our estimate of 10-30% for the 95% CI of the long-term average flow is similar to average reported values.

3 Results

3.1 Calibration 1

Table 1 summarises the FU coefficients in RO_FLOW_LITE calibrated to match the sum of observed flows in the four 'calibration' streams (WHE, WNG, PUA and UTU). The sum of the observed flows, averaged over the period 1975-2012, was 4.20 ± 0.78 m^3/s. The uncertainty in measured flow is the sum of uncertainties in each of the four streams estimated using the method described earlier. The FU coefficients were calibrated so that the sum of predicted flows averaged 4.20 m^3/s. As detailed above, the uncertainty in the model was estimated to be ±10% meaning that the sum of the predicted flows was 4.20 ± 0.42 m^3/s.

Figure 1 compares published estimates of actual evapotranspiration (AET) (from Table 3 in Rutherford et al. 2008) with predictions made using the re-calibrated FU coefficients in Table 1. Where rainfall is c. 1500 mm/y, predicted AET for pasture matches the upper bound of observations but over-estimates the lower bound by 8% of rainfall. Predicted AET for forest also matches the upper bound of observations, but over-estimates the lower bound by 9%. Average rainfall in the Rotorua catchment ranges up to 2600 mm/y but there is only one set of published observations at high rainfall which makes it difficult to assess with confidence model goodness of fit. At 2400 mm/y of rainfall, the model over-estimates the single published figures of AET by 7% for forest and 3% for pasture. We conclude that when model coefficients are calibrated to match the sum of stream flows in the four 'closed' catchments, the model predictions of AET over-estimate published values of AET by 3-8% of rainfall.

Land Use	Layer	Drainage (mm/w)	Outflow (mm/w)	Int (mm)	SC (mm)	FC (mm)	CV (mm)	WP (mm)
Pasture	1	100	0	0	650	565	50	0
Pasture	2	0	50	0	650	565	50	0
Pasture	3	0	25	0	650	565	50	0
Forest	1	50	0	4	650	565	50	0
Forest	2	0	50	0	650	565	50	0
Forest	3	0	25	0	650	565	50	0
Urban	1	100	0	0	650	565	50	0
Urban	2	0	50	0	650	565	50	0
Urban	3	0	25	0	650	565	50	0
			Outflow (/w)					
Lake	1	NA	0.1	NA	NA	NA	NA	NA

Table 1: Calibration 1: FU coefficients in the RO_FLOW_LITE model calibrated to match stream flows in the four 'closed' sub-catchments. SW = soil water content, Int = interception, SC = saturation capacity (the SW above which surface flow occurs), FC = field capacity (the SW above which drainage occurs), CV = SW at which AET = PET/2, and WP = SW at which AET = 0. Drainage rate from soil Layer 1 is independent of SW. The proportions of drainage from Layer 1 to Layers 2, 3 and groundwater are 20%, 10% and 70%. There is no drainage to groundwater from Layers 2 or 3, which lose water to streams. Lake outflow is a linear function of lake level. Further details of functional units are given in Rutherford et al. (2008).

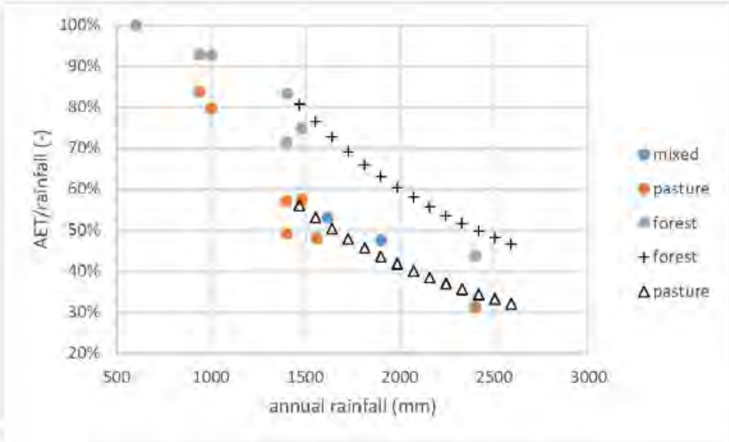

Figure 1: Calibration 1: observed (coloured) and predicted (triangles and crosses) evapotranspiration (AET) as a fraction of rainfall. Predictions are average values for pasture and forest functional units in 14 different rainfall zones for the period 1975-2012 made using RO_FLOW_LITE with FU coefficients calibrated to match the sum of the observed flows in the four 'calibration' catchments. Published estimates of AET are from Table 3 in Rutherford et al. (2008).

3.2 Calibration 2

By varying the FU coefficients, it was possible to reduce predicted AET to better match published values. Figure 2 shows the goodness of fit to published AET values for the calibrated FU coefficients in Table 2. Using these FU coefficients, the sum of predicted flow in the four 'calibration' catchments was 5.04 ± 0.50 m^3/s compared with the observed value of 4.20 ± 0.78 m^3/s. Thus, reducing AET to match published values increased predicted runoff by c. 20%. However, the uncertainty is such that the difference between observed and predicted flow is not statistically significant.

Land Use	Layer	Drainage (mm/w)	Outflow (mm/w)	Int (mm)	SC (mm)	FC (mm)	CV (mm)	WP (mm)
Pasture	1	100	0	0	650	300	50	0
Pasture	2	0	50	0	650	300	50	0
Pasture	3	0	25	0	650	300	50	0
Forest	1	50	0	4	650	300	50	0
Forest	2	0	50	0	650	300	50	0
Forest	3	0	25	0	650	300	50	0
Urban	1	100	0	0	650	300	50	0
Urban	2	0	50	0	650	300	50	0
Urban	3	0	25	0	650	300	50	0
			Outflow (/w)					
Lake	1	NA	0.1	NA	NA	NA	NA	NA

Table 2: Calibration 2: FU coefficients in the RO_FLOW_LITE model calibrated to match published AET values. See the previous table for a description of the variables.

Lake Rotorua catchment boundaries 15

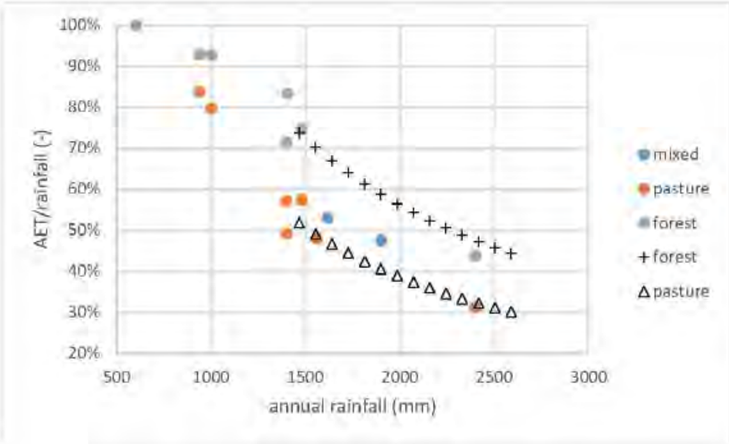

Figure 2: Calibration 2: observed (coloured) and predicted (triangles and crosses) evapotranspiration (AET) as a fraction of rainfall. Predictions are average values for pasture and forest functional units in 14 different rainfall zones for the period 1975-2012 made using RO_FLOW_LITE with FU coefficients calibrated to match published AET values. Published estimates of AET are from Table 3 in Rutherford et al. (2008).

Stream	Calibration 1 to stream flows	Calibration 2 to published AET	Observed mean m^3/s	Observed 95% CI m^3/s
Puarenga	1.69	2.01	1.78	0.53
Utuhina	1.87	2.28	1.86	0.56
Waingaehe	0.25	0.29	0.24	0.07
Waiohewa	0.40	0.46	0.33	0.10
Total	**4.22**	**5.04**	**4.20**	**0.78**

Table 3: Observed and predicted streams flows in the four 'calibration' streams. The four streams are not significantly affected by groundwater, as discussed in Rutherford and Palliser (2014b). The 95% confidence interval (CI) for the six streams is estimated as outlined in the text. Calibration 1 involved matching observed streams flows. Calibration 2 involved matching published AET estimates.

3.3 Water budget for the surface catchment boundary

3.3.1 Introduction

GNS-Science supplied NIWA with the outer boundary of the surface catchment which was developed at a 1:2000 scale by BoPRC and GNS-Science based on recent LiDar observations. This boundary is labelled 'SC_1_2000_7_Mar_2014' by GNS-Science.

3.3.2 Rainfall and land cover

Figure 3 shows the spatial distribution of average rainfall clipped by the SC_1_2000_7_Mar_2014 boundary. The rainfall surface was derived by Dr Andrew Tait, NIWA, Wellington as detailed in Rutherford et al. (2008). There is a strong rainfall gradient from north-west to south-east. Of note is the high rainfall on the Mamaku Plateau in the north-west, which is where the topography is flat and the surface catchment boundary is hard to define.

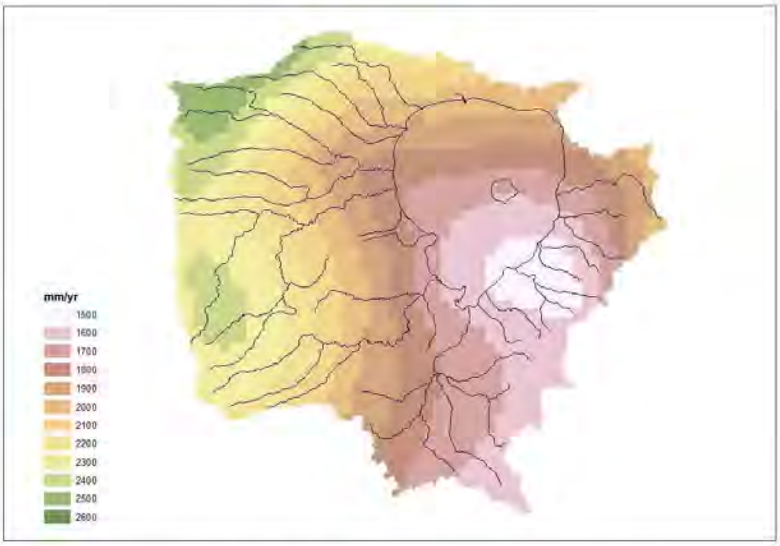

Figure 3: Spatial distribution of average rainfall. The outer boundary is SC_1_2000_7_Mar_2014 supplied by GNS-Science.

Figure 4 shows the spatial distribution of land cover. The FU coefficients for pasture and urban land are the same, but differ from the coefficients for forest and water (see Table 1). The time series of weekly PET used in the model were estimated using different models – pasture (Penmann-Monteith), forest (modified Priestley-Taylor) and open water (Jobson). Further details on the calculation of PET and AET are given in Rutherford et al. (2008).

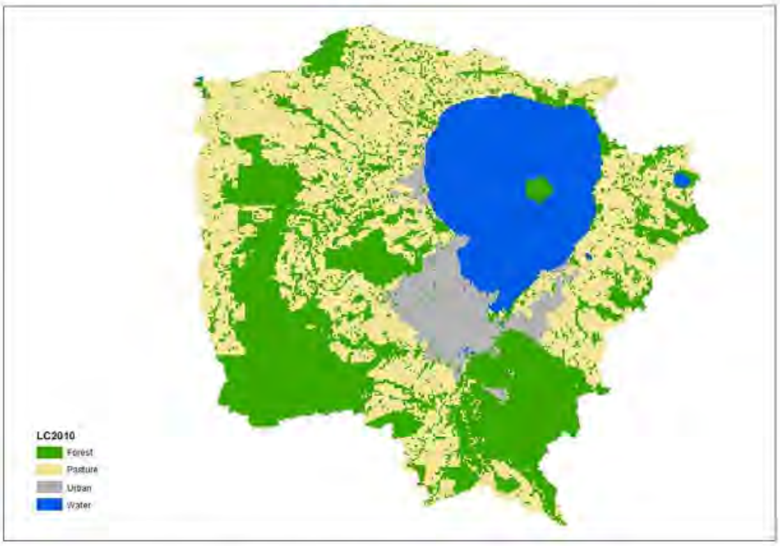

Figure 4: Land cover in 2010. The outer boundary is SC_1_2000_7_Mar_2014 supplied by GNS-Science. Land cover is the same as that detailed in Rutherford et al. (2008).

3.3.3 Surface and groundwater sub-catchments

Figure 5 and Figure 6 show the boundaries of the surface sub-catchments and aquifers. RO_FLOW_LITE calculated weekly values of 'quick flow' and 'slow flow' from each FU. Quick flow represents surface flow (which occurs very rarely) and shallow sub-surface flow which cause rapid increases and decreases in stream flow. Slow flow represents deeper drainage to groundwater which re-emerges in springs near the lake and gives rise to very gradual rises and falls in stream flow.

Quick flow values for all FUs in a given surface sub-catchment were summed over space and time to give the long-term average quick flow contribution to stream flow at the catchment outlet. To this was added the sum of the slow flow values for all FUs in aquifers that discharge into the stream. The connections between streams, surface sub-catchments and aquifers were the same as those used in ROTAN and detailed in Rutherford et al. (2008).

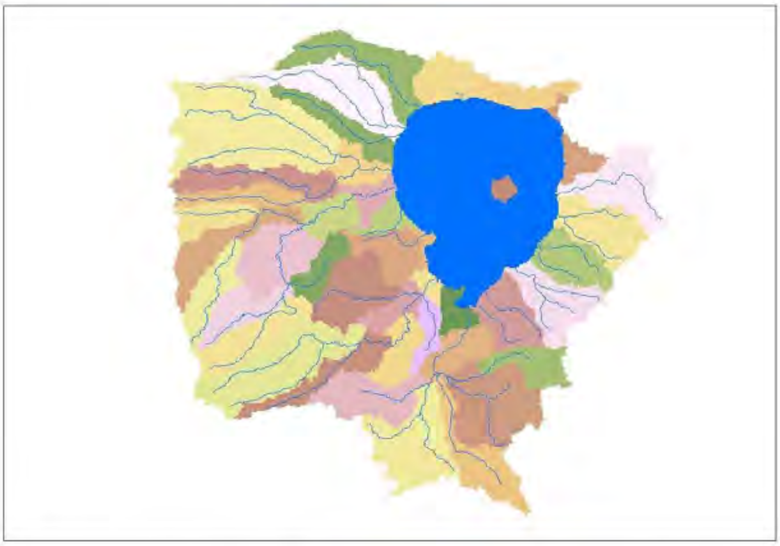

Figure 5: Surface sub-catchments. The catchments are those labelled CAT_70 in Rutherford et al. (2008) extended out to, or clipped by, the boundary SC_1_2000_7_Mar_2014. Also shown are the major streams.

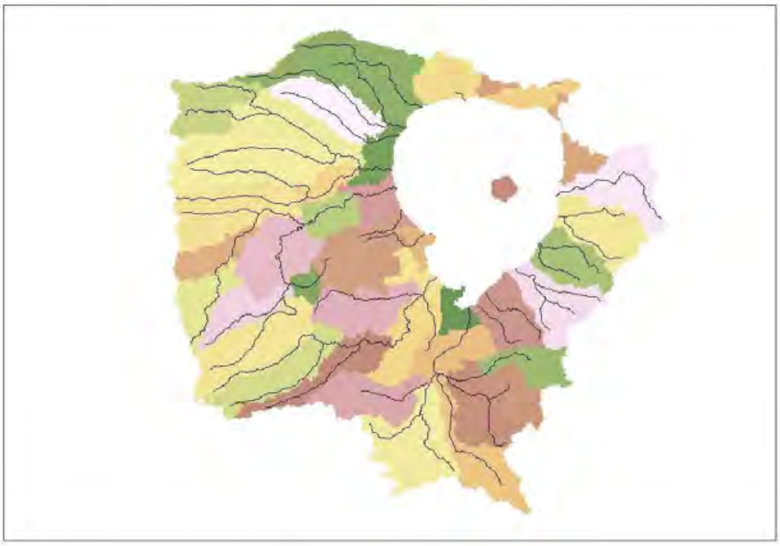

Figure 6: Aquifers. The aquifers are those labelled AQU_70 in Rutherford et al. (2008) extended out to, or clipped by, the boundary SC_1_2000_7_Mar_2014. Also shown are the major streams.

3.3.4 Predicted water budgets

Calibration 1

Table 4 summarises the water budget for the boundary SC_1_2000_7_Mar_2014 predicted using FU coefficients from Table 1. It is predicted that on average 12.2 m^3/s flows into the lake from the catchment. Of this 8.5 m^3/s (70%) is 'slow flow' (viz., drainage from FUs which has passed through an aquifer but may have emerged as spring flow into a stream prior to reaching the lake). The remaining 3.7 m^3/s (30%) of lake inflow is 'quick flow' (either surface runoff or shallow sub-surface flow which enters streams high up in the sub-catchments). A further 2.7 m^3/s of quick flow is generated from rain falling on the lake surface minus open water evaporation.

The long-term average lake outflow must equal the sum of the average stream inflows plus the net rainfall on the lake, assuming there are no unmeasured groundwater inflows or outflows. Using the Calibration 1 FU coefficients, it is predicted that the average Ohau Channel outflow should be 14.9 m^3/s. Hoare (1980) estimated the total lake inflow (including net rainfall on the lake surface) in the wet year 1976 to be 20.3 m^3/s, and during two dry periods in 1976 to be 13.3 and 14.1 m^3/s.

The predicted average lake inflow of 14.9 m^3/s is 90% of the observed flow in the Ohau Channel of 16.5 m^3/s (Table 4). This implies a 'missing' flow of 10% or 1.6 m^3/s (viz., that an additional flow of 1.6 m^3/s into the lake is required to close the water balance). As detailed earlier, model uncertainty is estimated to be ± 10% and so the predicted lake inflow is 14.9 ± 1.5 m^3/s. Assuming the upper bound uncertainty on observed lake outflow (7%), the difference between predicted lake inflow and observed lake outflow (1.6 ± 1.9 m^3/s) is not significantly different from zero.

	Predicted			Observed 1975-2012			
Stream	Slow flow m^3/s	Quick flow m^3/s	Total m^3/s	Mean m^3/s	95% CI m^3/s	95% CI/ mean	Prd/ Obs
Unnamed	1.19	0.68	1.87				
Awahou	1.26	0.20	1.46	1.62	0.49	30%	90%
Hamurana	1.25	0.08	1.33	2.60	0.78	30%	51%
Ngongotaha	1.10	0.62	1.72	1.79	0.54	30%	96%
Puarenga	1.23	0.46	1.69	1.78	0.53	30%	95%
Utuhina	1.21	0.66	1.87	1.86	0.56	30%	101%
Waingaehe	0.18	0.07	0.25	0.24	0.07	30%	103%
Waiohewa	0.27	0.13	0.40	0.33	0.10	30%	122%
Waiowhiro	0.30	0.07	0.37	0.34	0.10	30%	107%
Waiteti	0.52	0.68	1.19	1.19	0.36	30%	100%
Total land	**8.51**	**3.65**	**12.16**				
Lake		2.71	2.71				
Land + lake	**8.51**	**6.36**	**14.87**	**16.46**	**1.16**	**7%**	**90%**
Calibration streams			4.22	4.20		30%	100%

Table 4: Calibration 1: water budget for the catchment boundary SC_1_2000_7_Mar_2014. FU coefficients in the model were calibrated to match total flow matched in the four 'calibration' streams not significantly affected by groundwater. Note that the upper bound uncertainties on observed flows are assumed.

Calibration 2

Table 5 summarises the water budget for the boundary SC_1_2000_7_Mar_2014 predicted using FU coefficients from Table 2 which were calibrated to match published AET values.

Stream inflow from the surface catchment is predicted to be 14.4 m^3/s. This is higher than for Calibration 1 (12.2 m^3/s) because Calibration 2 gave higher runoff and lower evapotranspiration, to better match published AET values. Total lake inflow (including net rainfall on the lake surface) is predicted to be 17.3 ± 1.7 m^3/s which is 5% higher than the observed lake outflow of 16.5 ± 1.2 m^3/s. This contrasts with Calibration 1 for which predicted lake inflow was 10% lower than the observed lake outflow. Because of the high uncertainty, the difference between observed outflow and predicted inflow for Calibration 2 is not significantly different from zero.

	Predicted			Observed 1975-2012			
Stream	Slow flow m^3/s	Quick flow m^3/s	Total m^3/s	Mean m^3/s	95% CI m^3/s	95% CI/ mean	Prd/ Obs
Unnamed	1.36	0.79	2.15				
Awahou	1.48	0.23	1.71	1.62	0.49	30%	106%
Hamurana	1.47	0.10	1.57	2.60	0.78	30%	60%
Ngongotaha	1.34	0.75	2.09	1.79	0.54	30%	116%
Puarenga	1.45	0.55	2.01	1.78	0.53	30%	113%
Utuhina	1.49	0.80	2.28	1.86	0.56	30%	123%
Waingaehe	0.20	0.08	0.29	0.24	0.07	30%	117%
Waiohewa	0.31	0.15	0.46	0.33	0.10	30%	140%
Waiowhiro	0.36	0.07	0.43	0.34	0.10	30%	126%
Waiteti	0.62	0.81	1.42	1.19	0.36	30%	120%
Total land	**10.08**	**4.34**	**14.41**				
Lake		2.71	2.71				
Land + lake	**10.08**	**7.05**	**17.31**	**16.46**	**1.16**	**7%**	**104%**
Calibration streams			5.04	4.20		30%	120%

Table 5: Calibration 2: water budget for the catchment boundary SC_1_2000_7_Mar_2014. FU coefficients in the model were calibrated to match published AET values. Note that the upper bound uncertainties for flow are assumed.

3.3.5 Discussion

For Calibration 1 the difference between predicted lake inflow (14.9 ± 1.5 m^3/s) and observed lake outflow (16.5 ± 1.2 m^3/s) is 1.6 ± 1.9 m^3/s. The uncertainty of the difference is the square root of the sums of the squared uncertainties in observed and predicted flows. For Calibration 2 inflow (17.3 ± 1.7 m^3/s) exceeds outflow and the difference is -0.80 ± 2.1 m^3/s. An important question is whether to place equal reliance on Calibrations 1 and 2.

Calibration 1 relies on the assumption that the four 'calibration' streams neither gain nor lose groundwater. There is no direct evidence of groundwater inflows or outflows in these catchments, and the observed stream yields are typical of published values (Rutherford and Palliser 2014b).

Calibrations 1 and 2 both rely on catchment-average rainfall being determined accurately. The spatial distribution of rainfall was estimated by Dr Andrew Tait who interpolated rainfall surfaces between the available rain gauges from 1958-2010. Dr Tait determined year-to-year variations in annual average rainfall (Figure 7). In the four 'calibration' sub-catchments, the

95% CI for annual average rainfall over 16 representative years varied from <10% (WHE and WNG on the eastern side of the lake) to <15% (UTU and PUA to the south and south-west of the lake). Allowance was made for a random ±10% uncertainty in interpolation when estimating the uncertainty in observed flow. It is conceivable that interpolated rainfall was biased in the four 'calibration' catchments. For example, if rainfall was consistently under-estimated in the 'calibration' sub-catchments, then calibration would result in under estimating AET and *vice versa.* Dr Tait included in his analysis rainfall data from 1976-1977 collected by Dr Ray Hoare at a network of 31 rain gauges, including several gauges in the 'calibration' sub-catchments. This dense network of gauges is likely to result in low bias in rainfall in the 'calibration' catchments provided the spatial distribution of rainfall was similar in 1976-1977 and the study period 1975-2012. There is insufficient rainfall data to quantify any time trends in the spatial distribution of rainfall apart from the information presented in Figure 8.

Calibration 2 relies on the published AET values being accurate and representative of conditions at Rotorua. The uncertainty of individual estimates was not stated in the original references. However, and estimate of uncertainty can be determined from the variability in AET at a given rainfall which was in the range 5-10% of rainfall. The published AET values include estimates from near Rotorua. However, those at high rainfall are from the West Coast, South Island, and may not apply under the warmer Rotorua conditions.

We conclude that greater weight should be given to Calibration 1 than Calibration 2 results.

For Calibration 1 the difference between predicted lake inflow and observed lake outflow (viz., 'missing flow') is 1.6 ± 1.9 m^3/s (mean ± 95% CI). This estimate is made based on rainfall and estimated evapotranspiration. Rutherford and Palliser (2014b) derived an independent estimate of 2.1 ± 1.5-2.8 m^3/s for 'missing flow' based on an analysis of stream flow yields. The two estimates are similar but both have high uncertainties.

Figure 7: Variation in rainfall factor over time. Contours plotted are the 95% confidence interval on the average rainfall factor calculated from the annual rainfall factor maps generated by Dr Andrew Tate, NIWA, Wellington for 16 representative years between 1968-2005.

Overall the analysis indicates that:

1. There is evidence that runoff from outside the surface catchment flows into Lake Rotorua. The 'missing flow' is most likely to be approximately 2 m^3/s.
2. There is a large uncertainty in 'missing flow' (estimated to be a 95% CI of ±2 m^3/s) arising from uncertainty in catchment-average rainfall, AET and stream flow measurement.
3. There is >5% probability that the 'missing flow' is zero and a 5% probability that it could be as large as 3.5 m^3/s.
4. The estimates of 'missing' flow are similar to previous estimates of 2.1 ± 1.5-2.8 m^3/s made by Rutherford and Palliser (2014b) using different methods.

3.4 Water budget for an extended catchment boundary

GNS-Science supplied NIWA with the boundary labelled 'GW_1_2000_16_Mar_2014_max1'. This boundary differs significantly from SC_1_2000_7_Mar_2014 in the north-west where an 'extra' area extends away from the lake outside the surface catchment of the lake. It also differs in that it extends outwards from the lake by a small distance in all other sub-catchments to represent the maximum surface catchment area (the '+95 percentile').

Figure 8 shows the spatial distribution of average rainfall. Of special note is that the 'extra' area extends north-west into the high rainfall region on the Mamaku Plateau. Figure 9 shows that the land cover in the 'extra' area includes a substantial amount of forest and several small lakes. The surface sub-catchments (Figure 10) and aquifers (Figure 11) were estimated by extending the previous boundaries outwards. Note that it is assumed that both quick flow and slow flow generated by FU in the 'extra' area make their way to the lake. It is conceivable that quick flow drains to the north away from the lake while slow flow drains into the lake.

Extending the outer catchment boundary to the north-west increased the total catchment area from 5020 km2 to 5294 km2. This was predicted to increase the long term average flow in the Ohau Channel from 14.9 ± 1.5 m^3/s to 15.8 ± 1.6 m^3/s. The uncertainty in both predicted flows is ±10% as detailed earlier. 15.8 ± 1.6 m^3/s is on average 4% lower than the long term average flow measured in the Ohau Channel 16.5 ± 1.2 m^3/s. However, there is high probability that the difference of 0.7 ± 2.0 m^3/s is not different from zero. The uncertainty in the difference is the square root of the sum of the squared uncertainties in observed and predicted flows.

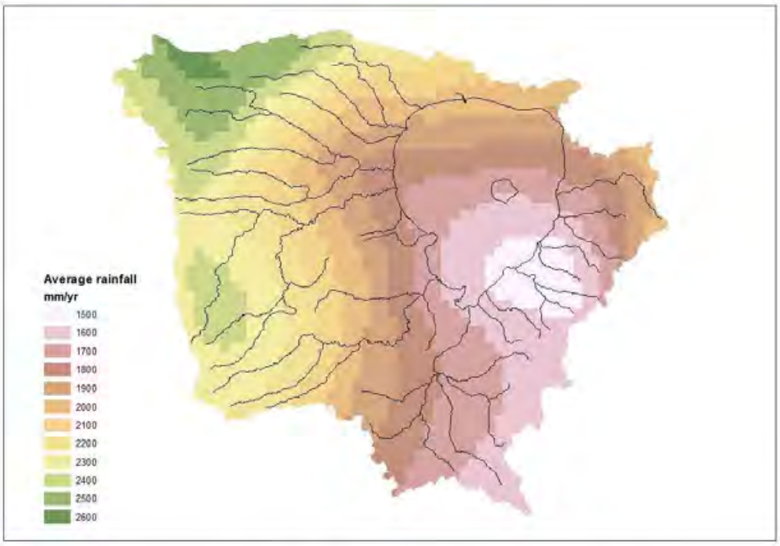

Figure 8: Spatial distribution of average rainfall. The catchment boundary is GW_1_2000_16_Mar_2014_max1 supplied by GNS-Science.

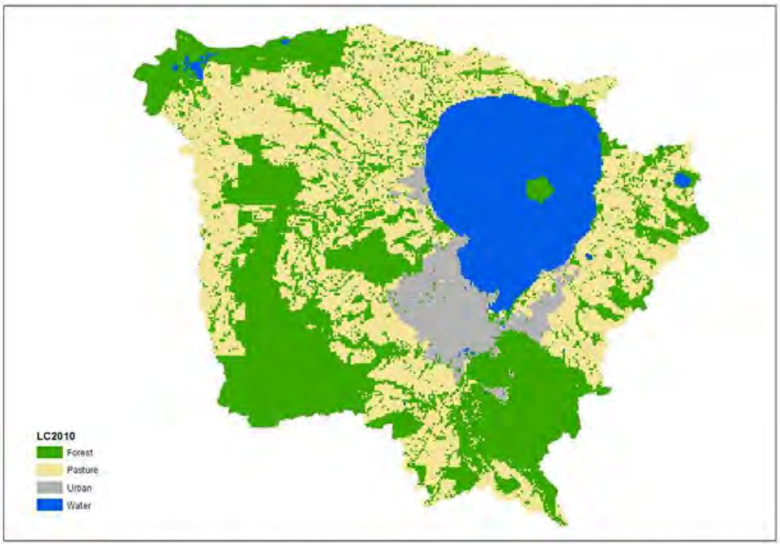

Figure 9: Land cover in 2010. The catchment boundary is GW_1_2000_16_Mar_2014_max1 supplied by GNS-Science. Land cover is the same as that detailed in Rutherford et al. (2008).

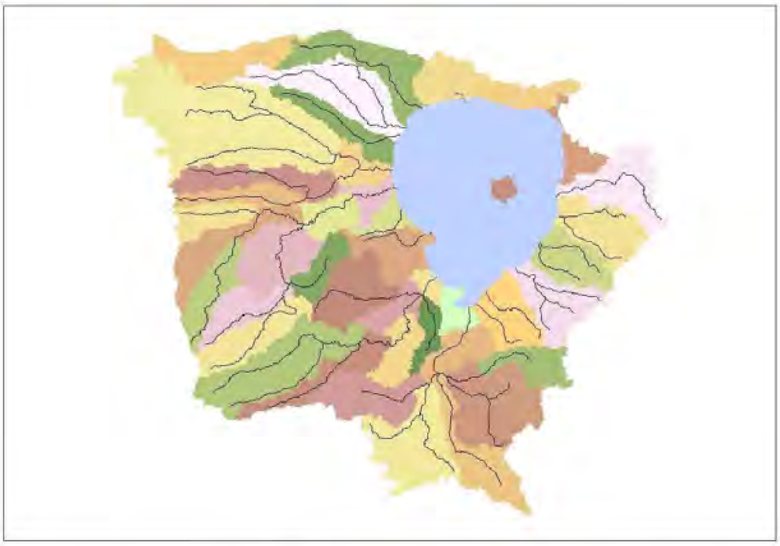

Figure 10: Surface sub-catchments. The catchments are those labelled CAT_70 in Rutherford et al. (2008) extended out to, or clipped by, the boundary GW_1_2000_16_Mar_2014_max1. Also shown are the main streams.

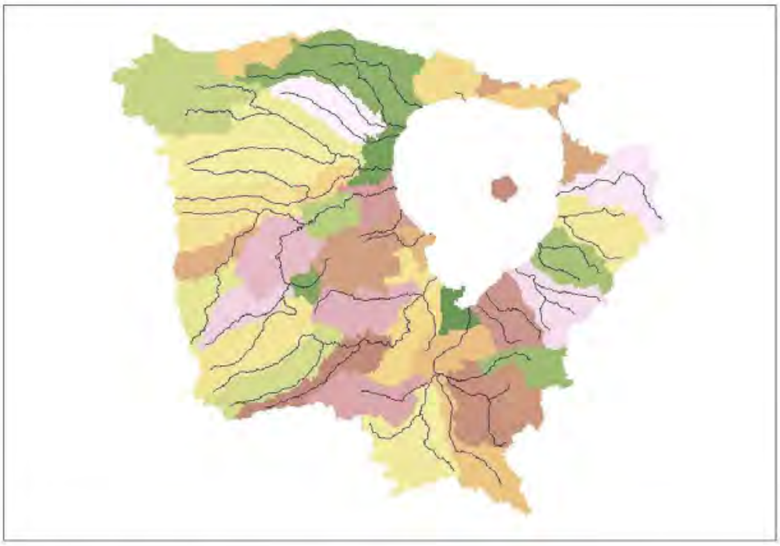

Figure 11: Aquifers. The catchments are those labelled AQU_70 in Rutherford et al. (2008) extended out to, or clipped by, the boundary GW_1_2000_16_Mar_2014_max1. Also shown are the main streams.

Stream	Predicted Slow flow m^3/s	Predicted Quick flow m^3/s	Predicted Total m^3/s	Observed 1975-2012 Mean m^3/s	Observed 1975-2012 95% CI m^3/s	95% CI/ Mean	Prd/Obs
Unnamed	1.20	0.69	1.89				
Awahou	1.30	0.35	1.66	1.62	0.49	30%	102%
Hamurana	1.82	0.09	1.90	2.60	0.78	30%	73%
Ngongotaha	1.11	0.62	1.73	1.79	0.54	30%	96%
Puarenga	1.25	0.46	1.71	1.78	0.53	30%	96%
Utuhina	1.22	0.66	1.88	1.86	0.56	30%	101%
Waingaehe	0.18	0.07	0.25	0.24	0.07	30%	104%
Waiohewa	0.27	0.11	0.38	0.33	0.10	30%	117%
Waiowhiro	0.30	0.07	0.37	0.34	0.10	30%	107%
Waiteti	0.52	0.85	1.36	1.19	0.36	30%	114%
Total land	**9.16**	**3.97**	**13.13**				
Lake		2.71	2.71				
Land + lake	**9.16**	**6.68**	**15.84**	**16.46**	**1.16**	**7%**	**96%**
Calibration streams			4.22	4.20			100%

Table 6: Water budget for the catchment boundary GW_1_2000_16_Mar_2014_max1.

26 Lake Rotorua catchment boundaries

4 Acknowledgements

Alastair McCormack, BoPRC, provided input data and useful comments. The study has been conducted in collaboration with Dr Paul White, GNS-Science, Wairakei who has provided input data and useful comments on the water budget calculations. Graham Timpany, NIWA, Rotorua provided input data.

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