6 May 2009

Environment Bay of Plenty
P O Box 364
Whakatane 3158
BAY OF PLENTY

Wairakei Research Centre
114 Karetoto Road
Wairakei
Private Bag 2000, Taupo
New Zealand
T +64-7-374 8211
F +64-7-374 8199
www.gns.cri.nz

Attention: Andy Bruere

Dear Andy

**Groundwater catchment boundaries of Lake Rotorua**

## 1.0 INTRODUCTION

The boundaries of Lake Rotorua catchment are determined in part by topography and in part by the characteristics of the groundwater system. Topography demarks some, but not all, surface catchment boundaries. The groundwater system is important to the hydrology of Lake Rotorua because much of the water in the catchment travels in the groundwater system at some time and springs are very important hydrological features in the Lake Rotorua catchment. However the boundaries of groundwater catchments are not well established by groundwater level measurements in some cases.

Estimation of the catchment boundaries in the Lake Rotorua catchment is important because:

- the community aims to restore the quality of Lake Rotorua so the land area associated with the lake catchment should be identified;
- possible actions for land use change relevant to lake restoration are commonly on a catchment-by-catchment basis, so identification of boundaries between catchments assist in identifying the geographic area relevant to possible actions..

Current estimates of Lake Rotorua catchment boundaries come from two published sources:

- groundwater boundaries for springs, seeps and land areas where no surface flow occurs, derived from a groundwater flow model (White et al. 2007);
- boundaries for ROTAN model catchments, determined by water balance calculations (Rutherford et al. 2008 and 2009).

This report reviews the *external* boundary proposed for the Lake Rotorua catchment. The report also reviews annual rainfall maps, with a summary of uncertainties discussed by Rutherford et al. (2008). A model of rainfall and evapotranspiration discussed by Rutherford et al. (2008) is compared with observations of rainfall recharge. *Internal* boundaries proposed for catchments within the Lake Rotorua catchment by the ROTAN model and by the groundwater flow model are not reviewed as part of this report.

## 2.0 ANNUAL RAINFALL AND RAINFALL RECHARGE

The rainfall map for 1976-1977 used in calibration of the 'phase 3' groundwater flow model (White et al. 2007, derived from the measurements of Hoare 1980) (Figure 2.1) is similar to the long term average rainfall map of Rutherford et al. (2009), (Figure 2.2). In other words, the pattern of rainfall is similar in the two maps. For example, both maps show relatively high rainfall on Mamaku Plateau and relatively low rainfall northeast of Rotorua City.

However, there are some important differences in the rainfall map of Rutherford et al. (2009) compared to the rainfall map from White et al. (2007). Specifically:

- the rainfall map of Rutherford et al. (2009) has slightly higher rainfall on the Mamaku Plateau, compared to the map derived by White et al. (2007);
- the rainfall map derived by White et al. (2007) has higher rainfall gradients than Rutherford et al. (2009) east of Mt Ngongotaha and maybe higher rainfall on Mt Ngongotaha than Rutherford et al. (2009).

### 2.1 Rainfall site distribution

The rainfall map of Rutherford et al. (2009), described in Rutherford et al. (2008), is for the long term average rainfall and was developed by Dr Andrew Tait, NIWA, Wellington, using all available observations in and around the Lake Rotorua catchment. No rainfall sites are located in the high rainfall area of the Mamaku Plateau northwest of Lake Rotorua catchment. However, Tait included historic data from Mamaku Airport and Omanawa which, together with Kaharoa and Mamaku township, surround the northwest corner of the catchment.

Rainfall estimates in the "high rainfall area" which lies to the northwest are greater than 2300 mm/yr (Figure 2.2). The nearest sites to the "high rainfall area" of the Mamaku Plateau are at Kaharoa (average annual rainfall 2261 mm, 1950-2006) and Mamaku (average annual rainfall 2086 mm, 1950-2006). Note there are 3 to 4 different sites at Kaharoa and Mamaku – the average rainfall figures are averages of rainfall at all sites. These sites record significantly less rainfall than the "high rainfall area".

Groundwater recharge from the high rainfall area probably travels towards Lake Rotorua and forms a significant part of the recharge for Hamurana Springs, Awahou Springs and the Waiteti catchment. Therefore estimation of catchment area for Hamurana Springs, Awahou Springs and the Waiteti catchment is quite dependent on the rainfall that actually occurs in the high rainfall area. Unfortunately no rainfall sites are located in the high rainfall area to provide a check on the interpolation based on rainfall maps.

### 2.2 Uncertainty

Rutherford et al. (2008) estimate uncertainties in average rainfall, rainfall undercatch and actual evapotranspiration (AET) as:

- 5% (or +/- 100 mm) when calculating average rainfall in a catchment;
- 5% on rainfall undercatch, i.e. the difference between rainfall measured in a standard raingauge and rainfall that falls on the ground;
- forest AET in the range 1000 to 1200 mm/yr;
- pasture AET about 800 mm/yr..

In order to close the water balance for the lake, Rutherford et al. (2008) postulate an 'extra' area of about 60 $km^2$ which contributes groundwater flow (but not stream flow) to the lake. The uncertainties described above are translated by Rutherford et al. (2008) into an uncertainty on this 'extra' area of ±35-45 $km^2$.

### 2.3 Time series of rainfall recharge

Rainfall and potential evapotranspiration (PET) is estimated by Rutherford (pers. comm. 13th February 2009) at the Kaharoa rainfall recharge site (White et al. 2008) for the purpose of assessing the difference between rainfall and PET in the ROTAN model. Rainfall and PET are estimated for:

- site location: 2797100 6349300;
- current land use at site - pasture;
- data for period: 1/1/1920 to 7/8/2008;
- daily timestep;
- rainfall is the average of airport and Dalbeth Road gauges with Kaharoa scaled by 1.25 – 'the average rainfall scaling factor' (Rutherford pers. comm. 13th February 2009) for the above co-ordinates.

In the period of simulation (32362 days):

- the sum of estimated daily rainfall at Kaharoa in the simulation period is 179796 mm or 2028 mm/yr rainfall;
- the sum of estimated daily PET at Kaharoa in the simulation period is 85960.29 mm or 970 mm/yr PET.

Rainfall recharge to groundwater, estimated as the difference between long term average daily rainfall and long term average daily PET, termed the 'model' rainfall recharge is:

- approximately 93836 mm in the simulation period, i.e. 179796 mm – 85960 mm;
- approximately 52% of rainfall, i.e. 93836 mm as a percentage of 179796 mm;
- approximately 1058 mm/yr, i.e. 93836 mm/32362 days* 365 days/year.

This is only a rough estimate of recharge because it ignores differences between AET and PET (important when the soil is dry) and the fact that drainage occurs when the soil is saturated. ROTAN uses the Porteous model to account for daily variation in soil moisture and the effects this has on AET and drainage.

The estimate of rainfall recharge as 52% of rainfall for period 1/1/1920 to 7/8/2008 is only approximate but is consistent with:

1) estimated rainfall recharge to groundwater of 52% of rainfall derived from Dell (1982a) and Dell (1982b). Dell (1982a) and Dell (1982b) summarise a

water balance study for the western Mamaku Plateau. He calculates that rainfall recharge of 990 mm is required to support the long-term baseflow of 10 $m^3$ $s^{-1}$ in the rivers in the study area. With rainfall of 1896 mm $year^{-1}$, the evapotranspiration (ET) loss is 906 mm in each of 1979/80, 1980/81 and 1981/82; and

2) observed rainfall recharge in Lysimeter 1 at the Kaharoa site that is 49% of ground-level rainfall in the period August 2005 to July 2006, Table 2.1 (White et al. 2007). Clearly this is the best estimate available of recharge, albeit at only one point in the catchment.

Estimated rainfall recharge, at 52% of rainfall for period 1/1/1920 to 7/8/2008, is a little higher than measured rainfall recharge at Kaharoa in the period 27th September 2006 and 8th January 2008. This is reasonable, as 'model' rainfall recharge calculated here doesn't account for AET and 'model' rainfall recharge calculated here doesn't account for rainfall undercatch. Observed rainfall recharge in lysimeter 1 in this period is approximately:

- 36% of rainfall in the period between 27th September 2006 and 8th January 2008, i.e. 994.1 mm (recharge)/ 2765.4 mm (ground-level rainfall) as a percentage (Table 2.1).

**Table 2.1** Observed and 'model' rainfall and rainfall recharge at Kaharoa.

| | | **August 2005 to July 2006** | **27th September 2006 to 8th January 2008** |
|---|---|---|---|
| Observed rainfall (mm) in period | Kaharoa ground-level recorder | 2439 | 2765 |
| Observed rainfall recharge (mm) in period | Kaharoa lysimeter 1 | 1207 | 994 |
| Observed rainfall recharge as percentage of observed rainfall | | 49 | 36 |
| Model rainfall (mm) in period | Rutherford pers. comm. 13th February 2009 | 2356 | 1895 |
| Model rainfall recharge (mm) in period (i.e. rainfall – PET for period) | Rutherford pers. comm. 13th February 2009 | 1397 | 487 |
| Model rainfall recharge as percentage of model rainfall | | 59 | 26 |

Generally, it would be expected that estimates of rainfall recharge as rainfall – PET over a short period would differ from measurements of rainfall recharge. This is because estimates of rainfall recharge given by rainfall – PET do not consider soil moisture levels. ROTAN uses the Porteous model to account for daily variation in soil moisture.

### 2.4 Daily rainfall recharge – comparison of Rutherford (pers. comm. 13th February 2009) estimates with observations

Rainfall recharge data at Kaharoa are observed at Kaharoa between 27th September 2006 and 8th January 2008 (White et al. 2008) at approximately monthly intervals (Table 2.2). These data are compared with daily modelled rainfall minus modelled PET in Table 2.2. Modelled PET is commonly greater than rainfall, so the sum of rainfall-PET is commonly less than zero (Table 2.2), indicating zero rainfall recharge. Generally, the trends in observed rainfall recharge are similar to the trends in rainfall – PET (Figure 2.3).

**Table 2.2** Observed and 'modelled' rainfall and rainfall recharge at Kaharoa.

| Period | Date of measurement | Observed rainfall recharge Lysimeter 1 (mm) | Modelled rainfall - PET (mm) from Rutherford pers. comm. 13th February 2009 |
|---|---|---|---|
| 1 | 25/10/2006 | 28.7 | 3 |
| 2 | 4/12/2006 | 33.7 | -38 |
| 3 | 4/01/2007 | 1.7 | -14 |
| 4 | 24/01/2007 | 121.4 | 54 |
| 5 | 28/02/2007 | 0 | -95 |
| 6 | 2/04/2007 | 189.4 | 136 |
| 7 | 1/05/2007 | 48.6 | 43 |
| 8 | 2/07/2007 | 131.1 | 191 |
| 9 | 30/07/2007 | 182.8 | 153 |
| 10 | 29/08/2007 | 98.1 | 141 |
| 11 | 1/10/2007 | 50.5 | 61 |
| 12 | 1/11/2007 | 64.9 | -7 |
| 13 | 3/12/2007 | 13.3 | -84 |
| 14 | 8/01/2008 | 29.9 | -60 |

## 3.0 MODEL CALIBRATION

Model calibration is described by:

- Rutherford et al. (2008) and Rutherford et al. (2009) for the ROTAN model;
- White et al. (2007) for the groundwater flow model.

Further to White et al. (2007) the groundwater flow model has recently been re-calibrated with average rainfall recharge estimated from the difference between:

- average rainfall from the rainfall model of Rutherford et al. (2008);
- average AET estimated by Rutherford et al. (2008).

## 4.0 EXTERNAL CATCHMENT BOUNDARIES

The following text compares catchment boundaries estimated by Rutherford et al. (2009) to catchment boundaries estimated by the groundwater flow model using estimates of rainfall recharge with Rutherford et al. (2008) rainfall and Rutherford et al. (2008) PET.

## 4.1 Rutherford et al. (2009)

The external boundary of the ROTAN model, Figure 4.1, is based on ground topography (for surface flow) plus an 'extra' (c. 60 $km^2$) aquifer catchments (to supply the 'missing' groundwater flow).

## 4.2 Groundwater flow model

The 'Phase 6' GNS groundwater boundaries, (Figure 4.2), are based on:

- generally, White et al. (2007) recommended boundaries that considered groundwater flow directions and a water balance calibrated to measurements of base flow;
- boundaries identified for Mt Ngongotaha catchment (Kovacova and White 2008 in prep.).

An assessment of the outer catchment boundary is based on:

- groundwater polygons near the boundary, (Figure 4.3);
- 'Phase 6' GNS internal groundwater boundaries;
- estimated rainfall recharge using the Rutherford et al. (2008) rainfall and PET.

Figure 4.3 represents possible groundwater catchment areas in the west of the Lake Rotorua catchment as GIS polygons:

- possible Hamurana catchment (numbers 1, 1a, 1b, 1c, 1d and 1e);
- possible Awahou catchment (numbers 2, 2a and 2b and possibly 1a and 1e);
- possible Waiteti catchment (numbers 4, 4a and 4b and possibly 2a and 2b);
- possible Ngongotaha catchment (numbers 6, 6a and 6b);
- possible Utuhina catchment (numbers 14, 14a and 6a).

The 'Phase 6' groundwater model area in the northwest (Figure 4.2) is represented by polygons (Figure 4.3): 1, 1a, 1b, 2, 2a, 4, 4a, 6, 6a and 14.

Sufficient rainfall recharge to support spring-flow calibration targets (Table 4.1) is provided by land areas as follows:

- Hamurana catchment polygons 1, 1a and 1b;
- Awahou catchment polygons 2, and 2a;
- Waiteti catchment polygons 4, 4a and 4b.

**Table 4.1** Rainfall recharge and polygon number in Hamurana, Awahou and Waiteti catchments with Rutherford et al. (2008) rainfall recharge model.

| Catchment | Polygons | Sum rainfall recharge (L/s) | Calibration target (L/s) |
|---|---|---|---|
| Hamurana | 1 | 2164 | 2750 |
| Hamurana | 1+1a | 2402 | |
| Hamurana | 1+1a+1b | 2758 | |
| Hamurana | 1+1a+1b+1c | 2911 | |
| Hamurana | 1+1a+1b+1c+1d | 3123 | |
| Hamurana | 1+1a+1b+1c+1d+1e | 3205 | |
| Awahou | 2 | 742 | 1200 |
| Awahou | 2+1a | 979 | |
| Awahou | 2+2a | 1762 | |
| Awahou | 2+1a+2a | 1999 | |
| Awahou | 2+1a+2a+1e | 2081 | |
| Awahou | 2+1a+2a+1e+2b | 2302 | |
| Waiteti | 4 | 697 | 1300 |
| Waiteti | 4+4a | 1362 | |
| Waiteti | 4+4a+4b | 1414 | |
| Waiteti | 4+2a | 1718 | |
| Waiteti | 4+2a+2b | 1939 | |
| Waiteti | 4+2a+4a | 2382 | |
| Waiteti | 4+2a+4a+2b+4b | 2656 | |
| Waiteti | 4+2a+4a+2b | 2603 | |

### 4.3 Comparison

External boundaries of the ROTAN models and the ‘Phase 6’ boundary, adjusted for the Rutherford et al. (2008) rainfall and PET models (Section 4.1.2), are compared in Figure 4.4, Figure 4.5, Figure 4.6 and Figure 4.7. Generally, the Rutherford et al. (2009) boundaries are more crenulated than boundaries in the groundwater flow model. This is because Rutherford et al. (2009) boundaries are based on ground elevation and groundwater flow model boundaries are based on estimates of groundwater level. The surface representing groundwater level is smoother than the surface representing ground level. Both of these methods have their draw-backs in ‘setting’ boundaries including:

- boundaries based on ground level are dependent on the quality of the digital terrain model and these models may poorly represent catchment boundaries where the terrain is relatively flat, such as on the Mamaku Plateau;
- groundwater level maps depend on measurements of groundwater level, and few observations of groundwater level exist in some areas (e.g. the northwest of the Mamaku Plateau and eastern boundary of the catchment).

Comparison of boundaries by geographic area has:

- minor differences north of Ohau Channel and the Lake Rotokawau catchment (Figure 4.4);
- a difference in the land area that is ‘required’ by the groundwater flow model to support flow in the Tikitere geothermal field (Figure 4.4). The difference in boundaries will make a major difference to the recharge available to support

baseflow at Tikitere. ROTAN matches the Waiohewa observed flow fairly well. ROTAN aquifer boundaries have now been adjusted to match the GNS 'Phase 6' boundaries;

- minor differences in the catchment boundary in the east (Figure 4.4), in the southeast (Figure 4.5) and in the south west (Figure 4.6). These differences have an insignificant effect on the water budgets;
- minor differences in the external boundaries of Hamurana, Awahou and Waiteti springs in the northwest (Figure 4.7). The differences in boundaries will make a minor difference to the recharge available to support baseflow in these springs;
- minor differences in the catchment boundary in the north (Figure 4.6). These differences have an insignificant effect on the water budgets.

## 5.0 UNCERTAINTY

Uncertainties in model calibration include:

- measurement error and model error for rainfall recharge (e.g. Section 2.2);
- measurement error for calibration targets.

A key issue for the Lake Rotorua catchment is the representation of uncertainty as a catchment boundary. The following describes a method for representing uncertainty on groundwater catchment boundaries.

Uncertainties in rainfall recharge and possible catchment area are assessed in Table 4.1. For example:

- the Hamurana catchment, with a calibration target of 2750 L/s (White et al. 2007), may consist of polygons 1, 1a and 1b;
- rainfall recharge may be 10 % less than the mean estimate for Rutherford et al. (2008) (see Section 2.2);
- land areas 1+1a+1b+1c provide sufficient rainfall recharge for Hamurana Springs base flow of 2750 L/s when rainfall recharge is 10% less than the mean estimate of Rutherford et al. (2008);
- other combinations of land area also provide approximate rainfall recharge for Hamurana Springs base flow of 2750 L/s when rainfall recharge is 10% less than the mean estimate of Rutherford et al. (2008). For example land areas 1+1b+1c+1d+1e provide 2700 L/s of groundwater recharge.

The external catchment boundary of the Lake Rotorua catchment should be set conservatively, i.e. land that is possibly in the catchment should be included in the catchment. Land that is possibly in the Lake Rotorua catchment (based on the water balance and the rainfall recharge estimate of Rutherford et al., 2008 and a 10% uncertainty) includes the green polygon in Figure 4.8 (i.e. polygons labelled 1c, 1d, 1e, 2b, and 4b in Figure 4.3), because this green polygon accounts for uncertainties in the Rutherford et al. (2008) rainfall recharge model.

## 6.0 LAKE ROTORUA CATCHMENT AREA

Lake Rotorua catchment area is estimated as:

- ROTAN model approximately 466 $km^2$ including Mokoia Island (1.4 $km^2$) and an 'extra' aquifer (43.9 $km^2$);
- groundwater model approximately 475 $km^2$ i.e. the blue polygon in Figure 4.8;

- a possible extra land area of approximately 20 $km^2$ i.e. the green polygon in Figure 4.8, to allow for uncertainty in rainfall and PET.

## 7.0 SUMMARY

Rainfall recharge to groundwater, estimated as the difference between average rainfall and average PET, from the Rutherford et al. (2008) model is approximately 52% of rainfall in the period 1/1/1920 to 7/8/2008 which is consistent with:

1) Estimated rainfall recharge to groundwater of 52% of rainfall derived from Dell (1982a) and Dell (1982b). Dell (1982a) and Dell (1982b) summarises a water balance study for the western Mamaku Plateau;

2) Observed rainfall recharge in Lysimeter 1 at the Kaharoa site of 49% of ground-level rainfall in the period August 2005 to July 2006, Table 2.1 (White et al. 2007).

Rainfall recharge to groundwater, estimated as the difference between daily rainfall and daily PET, from the Rutherford et al. (2008) model is broadly consistent with observed rainfall recharge at Kaharoa in lysimeter 1 collected at monthly intervals in the period October 2006 to January 2008.

The external boundary of the Lake Rotorua catchment is generally not determined directly by hydrogeological measurements. A smoothed boundary probably represents the hydrological nature of the boundary.

Differences of the external boundary of the Lake Rotorua catchment between the Rutherford et al. (2009) and groundwater flow model boundaries are now minor. The ROTAN aquifer boundaries have recently been extended near the Tikitere geothermal field to match the GNS ‘Phase 6’ boundaries in this area.

The catchment of Lake Rotorua probably includes the land within the blue polygon in Figure 4.8. The catchment of Lake Rotorua possibly includes land within the green polygon in Figure 4.8, considering the Rutherford et al. (2008) estimates of uncertainty in rainfall, rainfall undercatch and AET.

The external catchment boundary of the Lake Rotorua catchment could be set conservatively, i.e. land that is possibly in the catchment could be included in the catchment. Therefore land within the catchment of Lake Rotorua could include the green polygon in Figure 4.8 and the blue polygon in Figure 4.8.

## REFERENCES


Dell, P.M. 1982a. The effect of afforestation on the water resources of the Mamaku Plateau region. A thesis submitted in partial fulfilment of the requirements for the degree Master of Science in Earth Science, University of Waikato. 319p.

Dell, P.M. 1982b. The water resource of the Mamaku Plateau region. New Zealand Hydrological Society Annual Symposium, Auckland.

Hoare, R.A. 1980. Inflows to Lake Rotorua. Journal of Hydrology (New Zealand) 19(1) 49 – 59.

Kovacova, E., White, P.A. 2008 in prep. Groundwater catchments of large and small springs in the Ngongotaha and Waiowhiro catchments west of Lake Rotorua. Poster paper for the annual conference of the Rotorua Lakes Water Quality Society, Rotorua, August 2008.

Rutherford K., Tait A., Palliser, C., Wadwha, S., Rucinsky D. 2008. Water balance modelling in the Lake Rotorua catchment. NIWA client report for Environment Bay of Plenty.

Rutherford K., Palliser C., Wadwha S. 2009 in prep. Nitrogen exports from the Lake Rotorua catchment. NIWA client report for Environment Bay of Plenty.

White P.A, Zemansky G., Hong T., Kilgour G., Wall M. 2007. Lake Rotorua groundwater and Lake Rotorua nutrients – phase 3 science programme technical report. GNS Client report 2007/220 for Environment Bay of Plenty. 402p.

White, P.A., Silvester, W., Cameron, S.G., Raiber, M. 2008. Nutrient discharge to groundwater at the Kaharoa rainfall recharge site, Rotorua. GNS Science report 2008/320 for Environment Bay of Plenty.

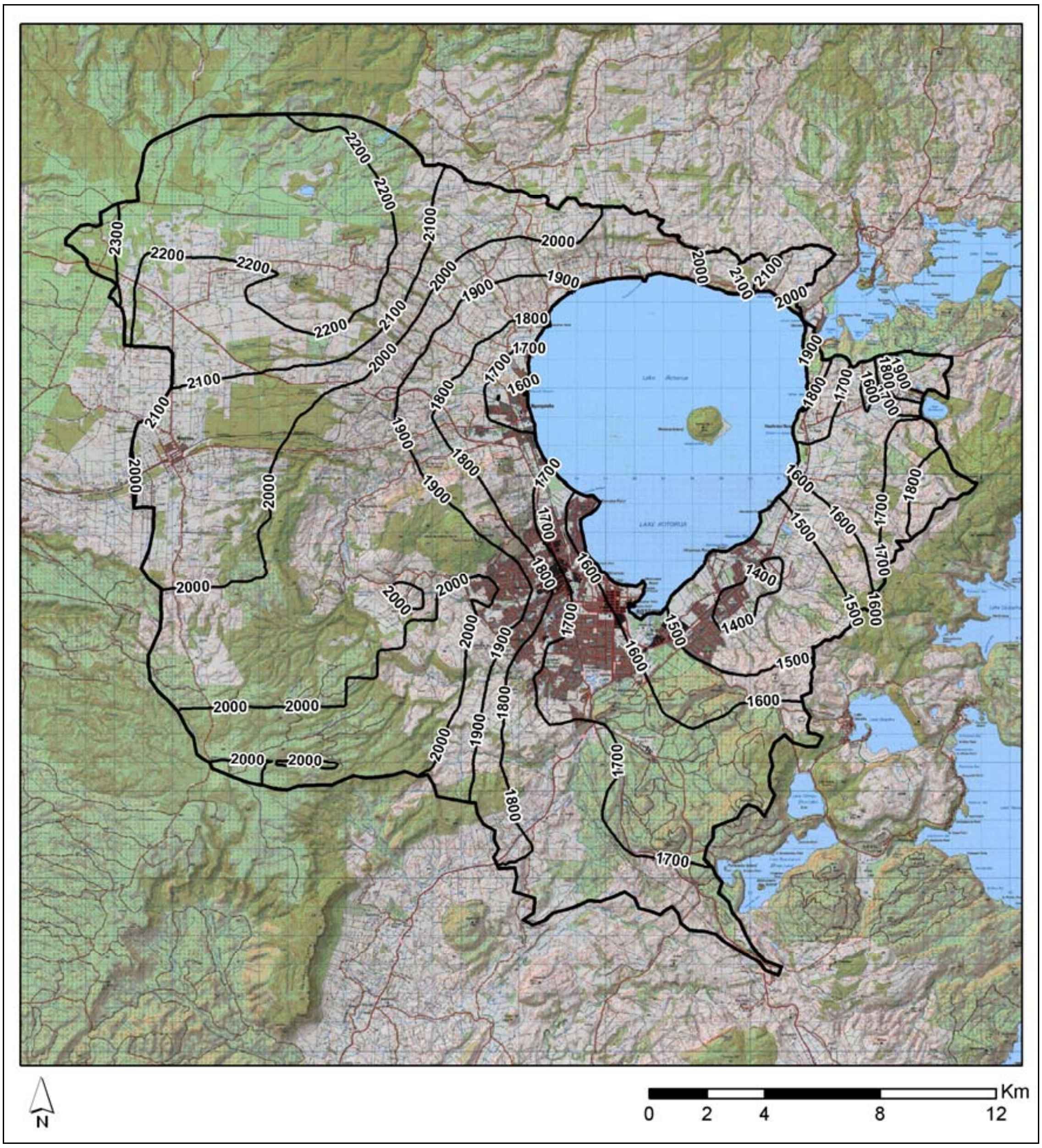


**Figure 2.1** Annual rainfall (mm) in the Lake Rotorua groundwater catchment based on Hoare (1980).

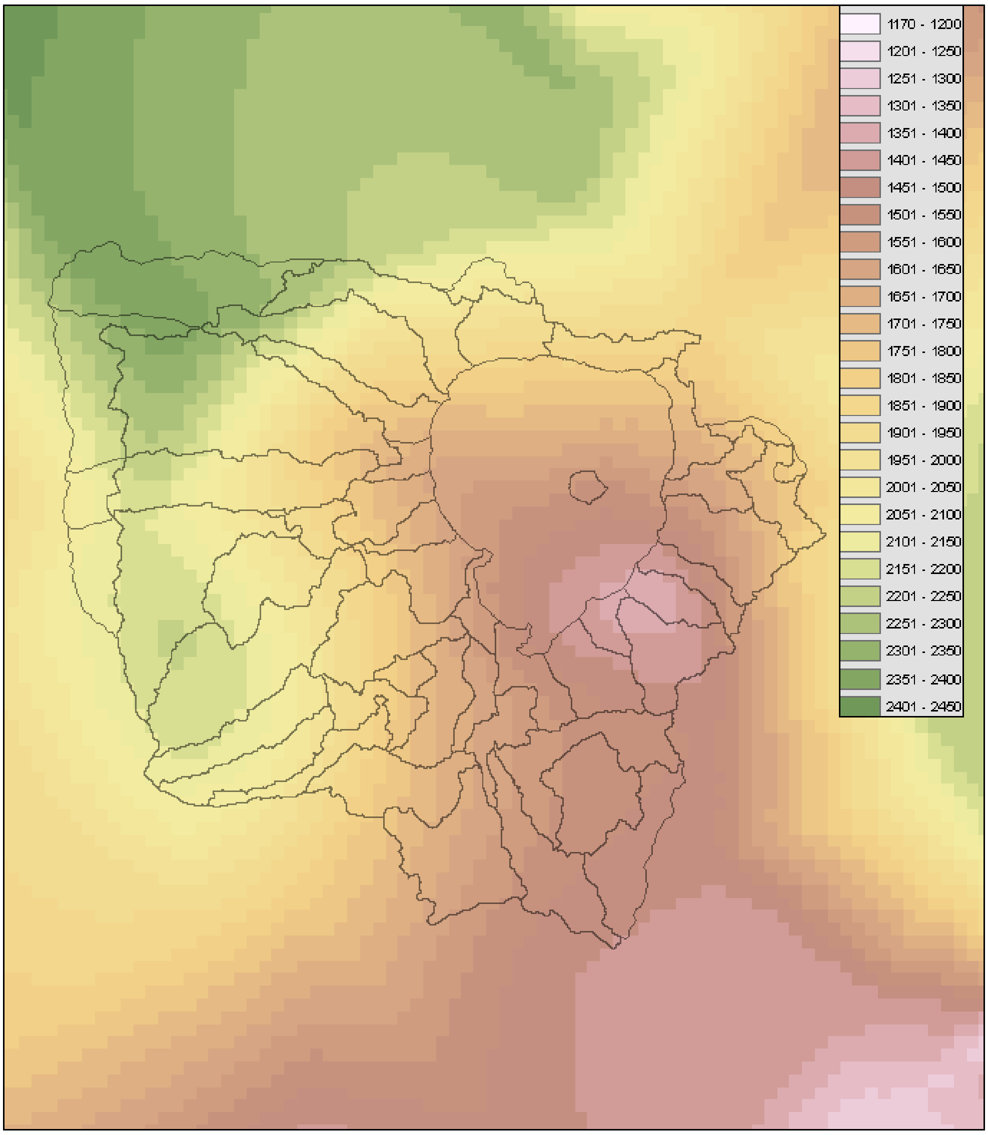


**Figure 2.2** Annual rainfall (mm) in the Lake Rotorua groundwater catchment based on Rutherford et al. (2009).

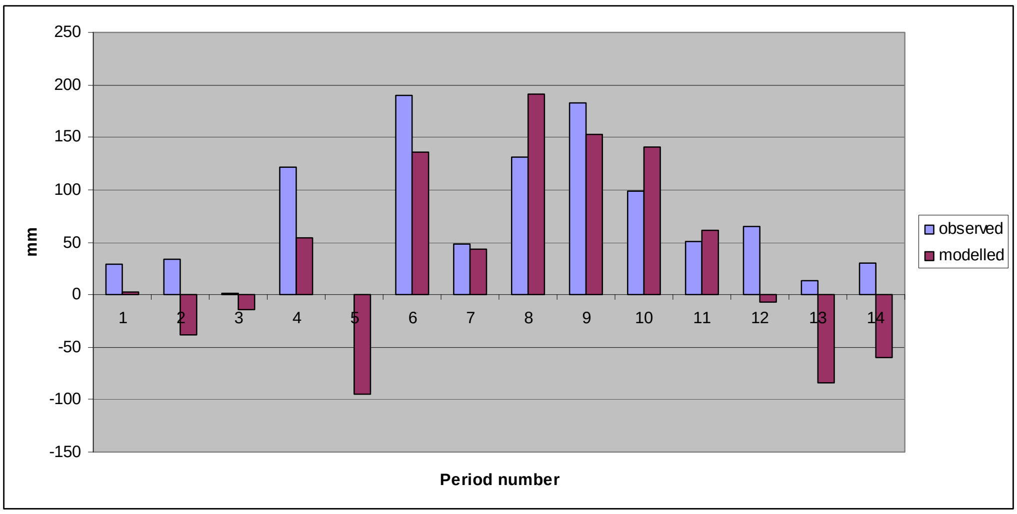


**Figure 2.3** Sum of observed rainfall recharge and sum of modelled daily rainfall – ET between 27th September 2006 and 8th January 2008.

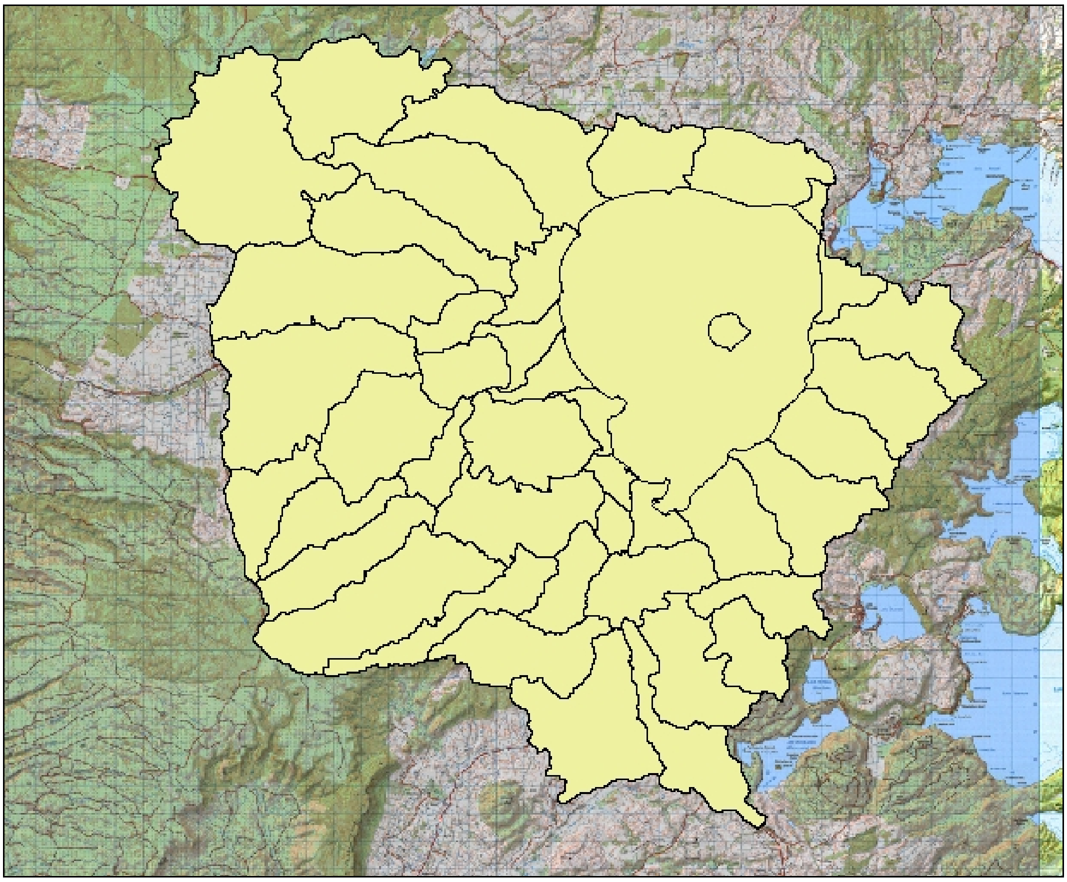

**Figure 4.1** ROTAN model boundaries (Rutherford et al. 2009) include an external model boundary and internal model boundaries as aquifers (shown here) and surface catchments.

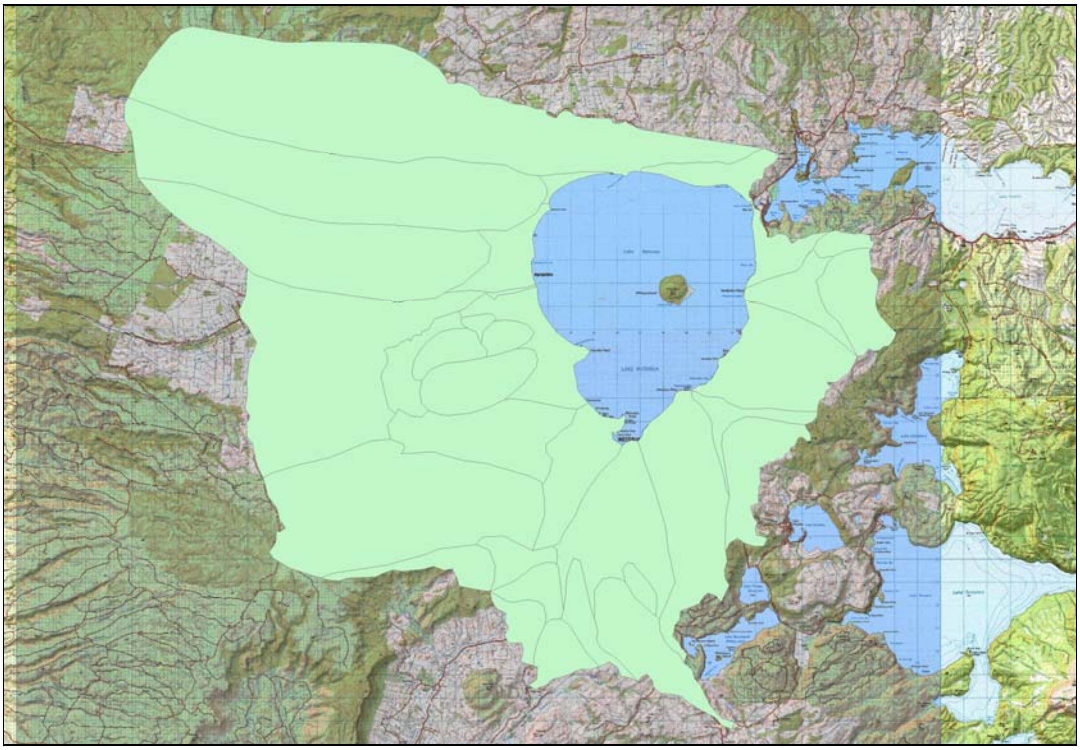

**Figure 4.2** Groundwater flow model "Phase 6' groundwater catchment boundaries.

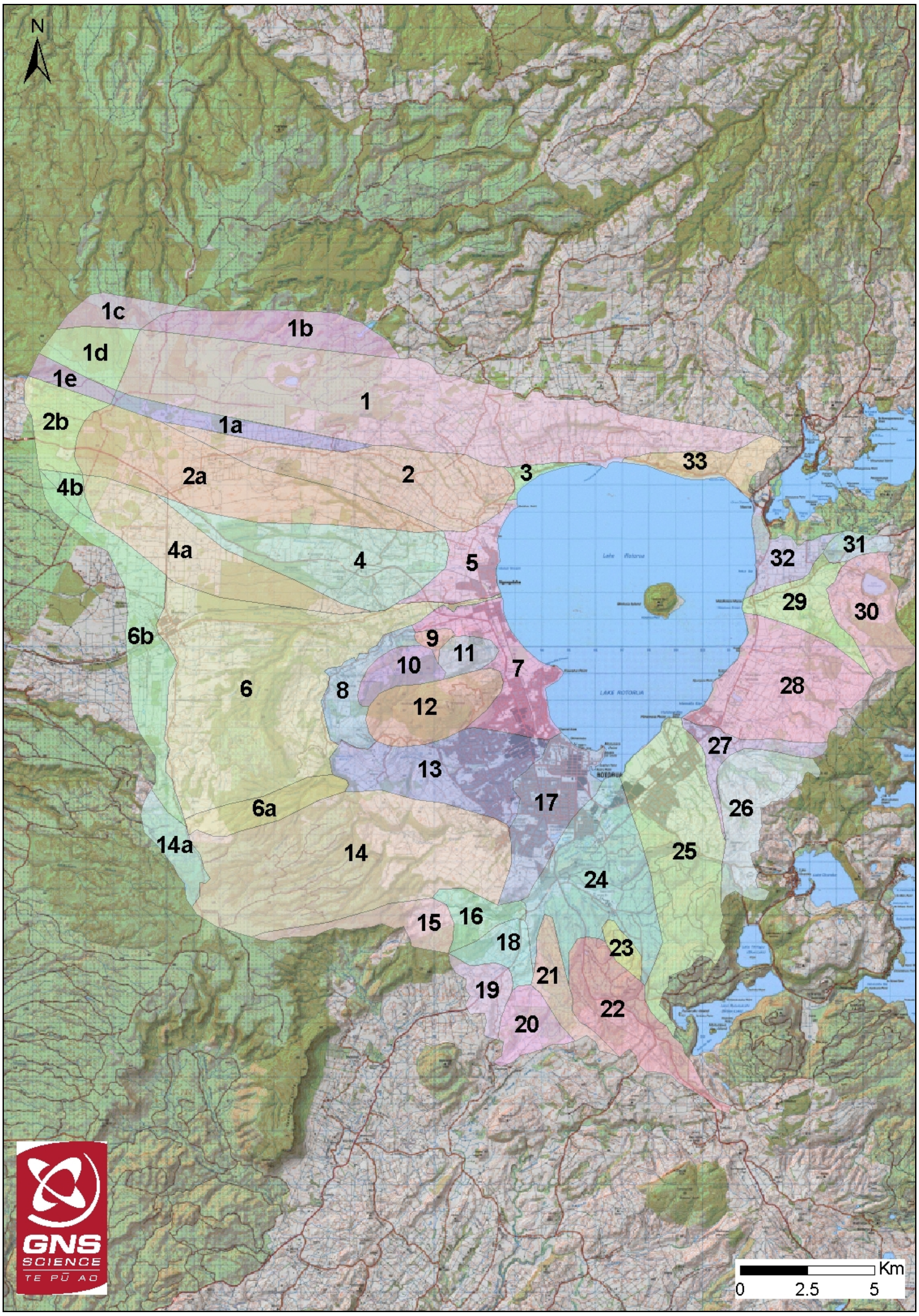


**Figure 4.3** Potential groundwater catchment boundaries in the west of the Lake Rotorua catchment for an assessment of the Rutherford et al. (2008) rainfall and PET and uncertainty.

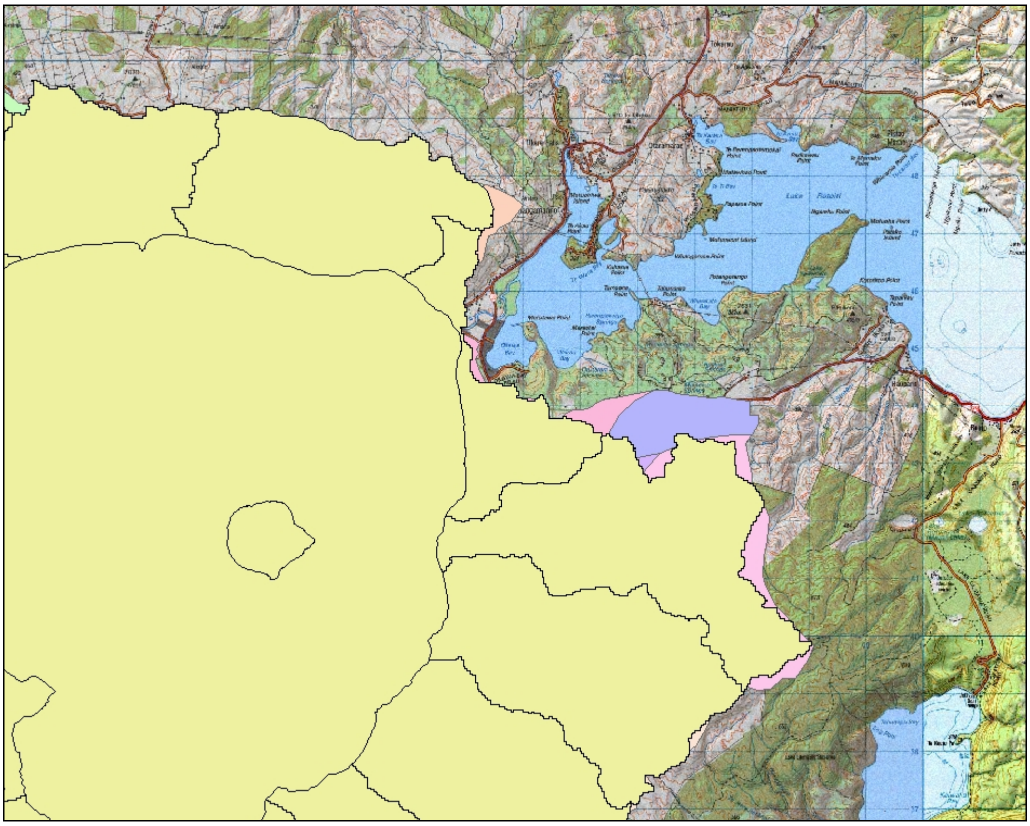

**Figure 4.4** Comparison of Lake Rotorua catchment external boundaries, northeast area.

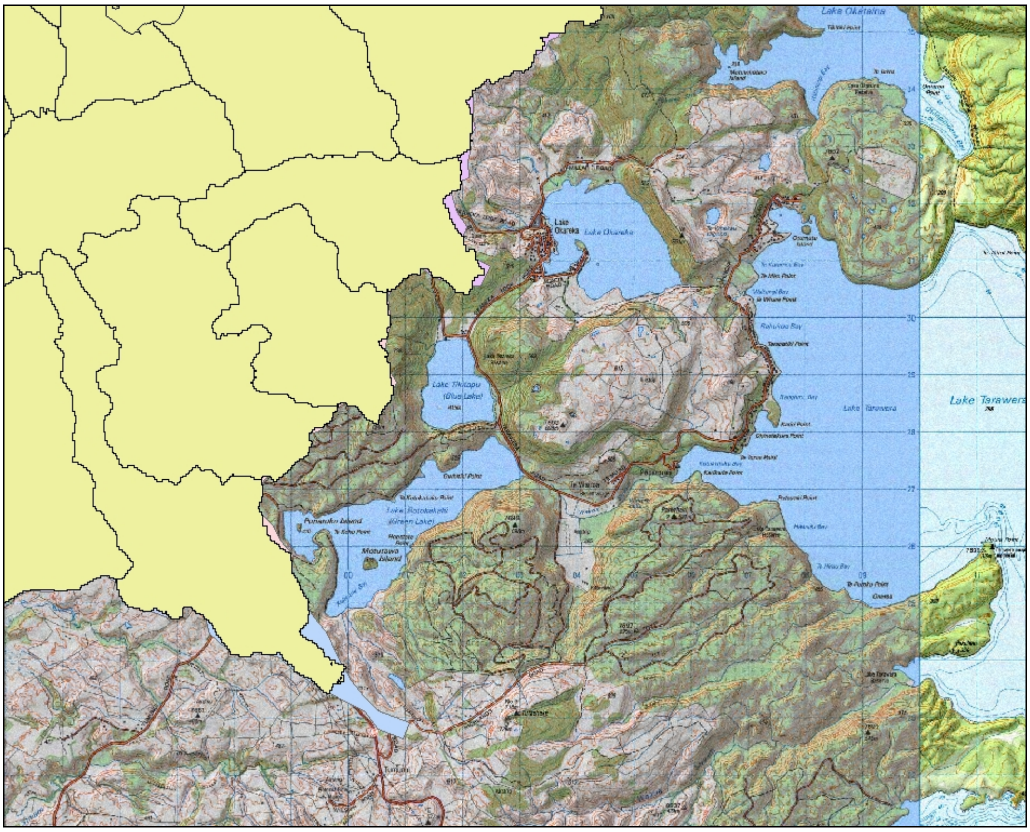

**Figure 4.5** Comparison of Lake Rotorua catchment external boundaries, southeast area.

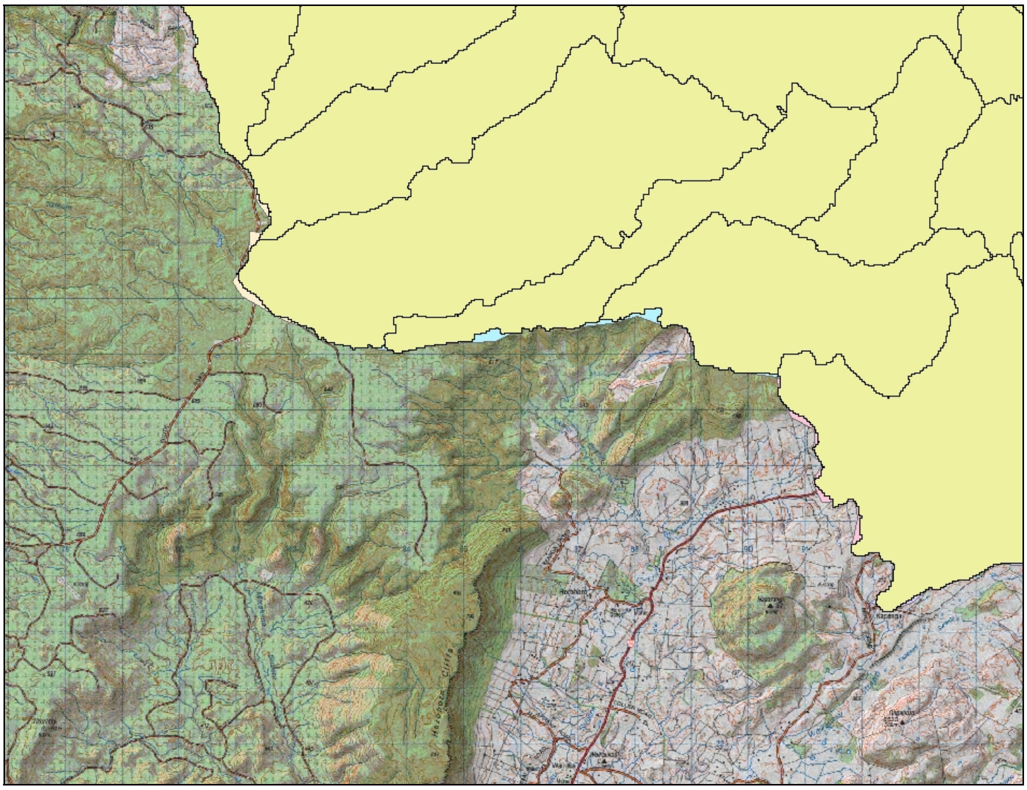

**Figure 4.6** Comparison of Lake Rotorua catchment external boundaries, southwest area.

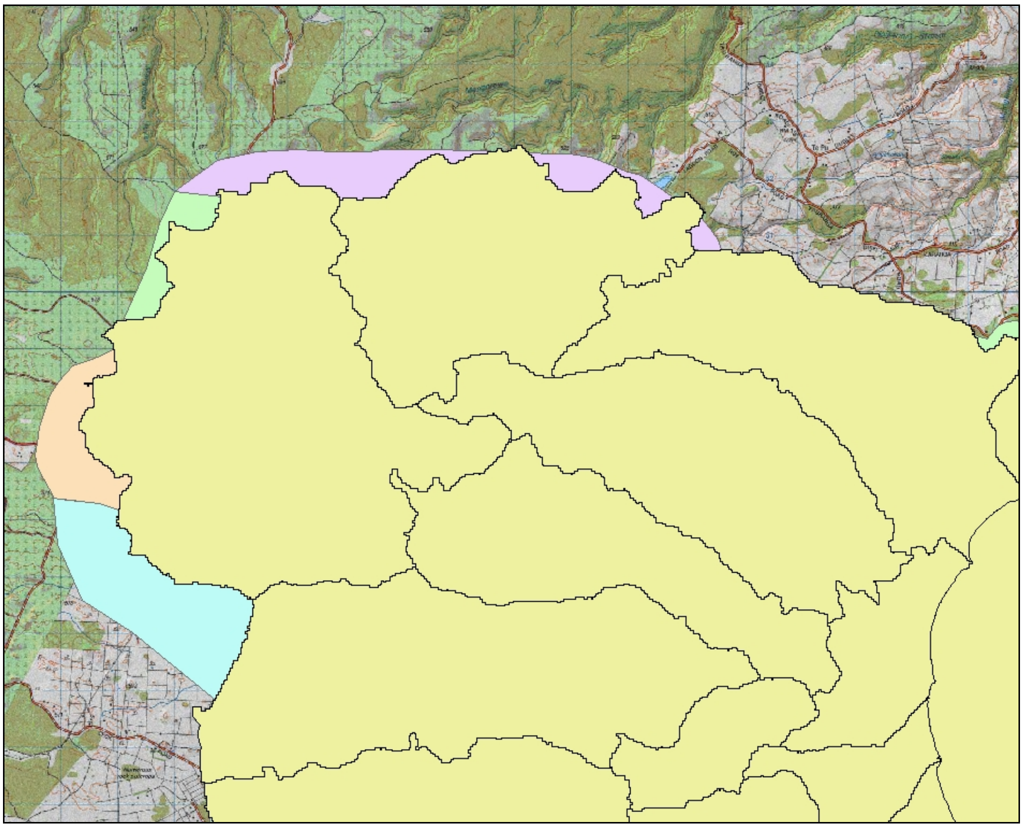

**Figure 4.7** Comparison of Lake Rotorua catchment external boundaries, northwest area.

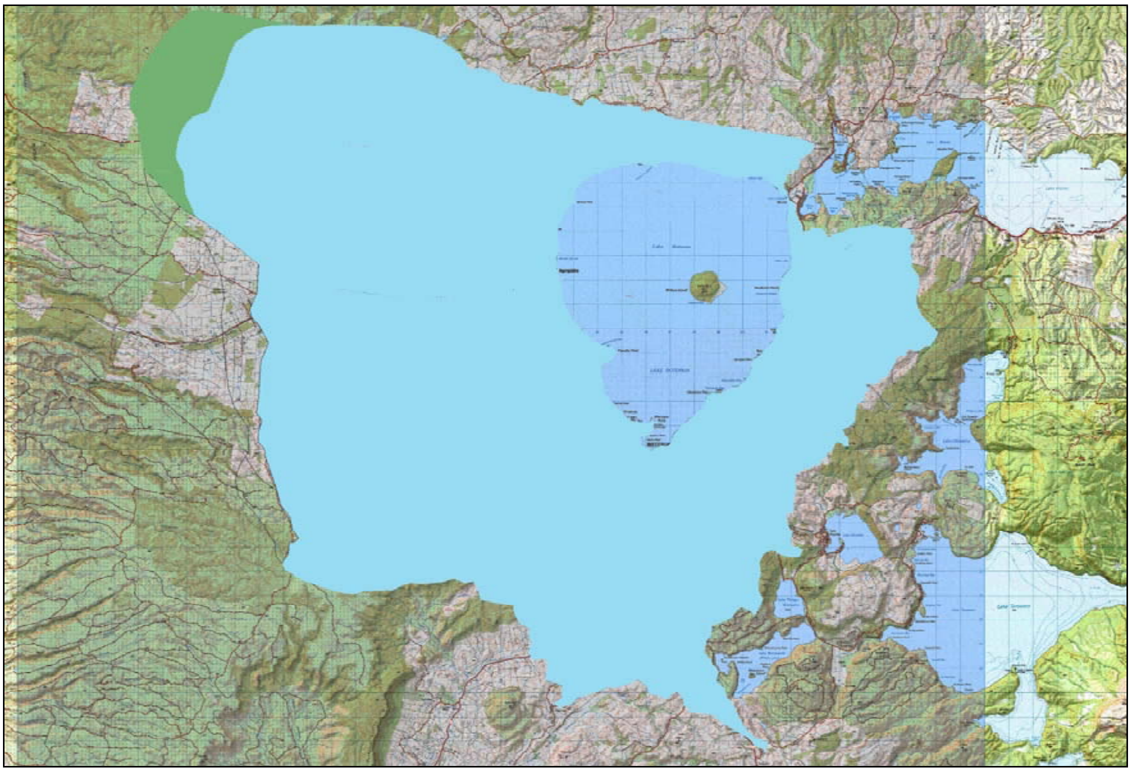

**Figure 4.8** Probable catchment of Lake Rotorua (blue-coloured polygon) and possible extension to catchment (green-coloured polygon to the west) that accounts for Rutherford et al. (2008) estimates of uncertainty in: rainfall, rainfall undercatch and AET.

Yours sincerely

Paul White
**Groundwater Modeller, GNS Science**

Kit Rutherford
**Principal Scientist, NIWA**

Gil Zemansky
**Senior Groundwater Scientist, Reviewer**