Groundwater in the Lake Rerewhakaaitu catchment

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ENVIRONMENT BAY OF PLENTY

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Lake Rerewhakaaitu **Photograph: K Palmer**

LIST OF CONTENTS

Page

Page

LIST OF APPENDICES

Page

LIST OF FIGURES

Page

LIST OF TABLES

EXECUTIVE SUMMARY

- Lake Rerewhakaaitu was formed quite recently; 700 years ago material from the Kaharoa eruption of Mt Tarawera impounded the lake.

- Groundwater flow must be considered in Lake Rerewhakaaitu water balance calculations.

- Water will generally flow out of the lake to groundwater because groundwater levels are generally below the level of the lake. Lake water probably discharges into the Rangitaiki Ignimbrite Aquifer and this water travels west, south and east of the lake.

- The Rangitaiki Ignimbrite Aquifer is the most important aquifer in the area and most wells are in this aquifer.

- Land use in up to one third of the catchment could impact on lake water quality.

- Rangitaiki Ignimbrite Aquifer water flowing to the west and south probably discharges, eventually, to Lake Rotomahana. Groundwater in this aquifer flowing to the east probably discharges, eventually, to the Rangitaiki River catchment.

- Lake Rerewhakaaitu possibly receives groundwater from the northeast and possibly from gravity-associated drainage in the Awaroa and Mangakino stream valleys.

- Groundwater originating from the area east of Awaroa Stream and the area east of the northern arm of Lake Rerewhakaaitu could enter the lake.

- Impacts of land use on groundwater quality and stream water quality are observed. The nitrogen concentrations in streams are tending to increase over time.

- Nitrogen levels observed in the lake are significantly less than levels predicted by simple nitrogen flux models. Denitrification processes are probably occurring in the lake.

1.0 INTRODUCTION

Environment Bay of Plenty (EBOP) commissioned the Institute of Geological & Nuclear Sciences (GNS) to complete a study of the groundwater in the Lake Rerewhakaaitu catchment (Appendix 1). The aims of this study are to: assess the nature of the shallow and deep aquifer resources, to determine groundwater flow directions, assess if groundwater is discharging to the lake, and assess the groundwater nutrient flux to the lake.

This report does this by interpreting shallow geology in terms of aquifers, reviewing land use and catchment hydrology, and interpreting likely groundwater flow directions in the catchment. Groundwater discharge into Lake Rerewhakaaitu is discussed and water balance equations are used to assess groundwater flow and groundwater nutrient fluxes to the lake.

Environment Bay of Plenty completed the Lake Rerewhakaaitu Project (McIntosh et al., 2001) with objectives to determine the intensity of land use in the lake catchment (Figure 1), examine the quality of the lake water and its inflows, determine the effectiveness of conservation plantings, and formulate an action plan for future management of the lake.

The Lake Rerewhakaaitu Project identified that groundwater recharge, flow, discharge, and quality are poorly understood in the lake catchment. The effects of land use are often translated through the groundwater system to receiving environments such as streams and lakes. Therefore, knowledge of the groundwater system in the catchment will assist in assessing the potential effects of land use on water quantity and quality.

2.0 LAND USE

The largest land use in the Lake Rerewhakaaitu catchment (Figure 1) is farming. Pasture (Figure 2) occupied an estimated 77% of the land in the catchment in 1996 (McIntosh et al., 2001). Exotic forest (15%), indigenous forest/scrub (6%) and wetlands (2%) were other land uses. Pasture is used for sheep and dry cattle (7% of the land area) and for dairy (70% of the land area). Some conversion of sheep and cattle land to dairying occurred in the late 1990s (McIntosh et al., 2001). The margins of Lake Rerewhakaaitu are reserves owned by Department of Conservation and Rotorua District Council and are not farmed (McIntosh et al., 2001). These reserves are typically 100-120 metres wide. A reserve of 800 m width is maintained beside the south eastern corner of the lake as a wetland.

'Lake Rerewhakaaitu is unique among Rotorua lakes in having a major portion of its catchment in dairy farming' (McIntosh et al., 2001). The intensification of dairying in the catchment (e.g. higher stocking rates and some land conversion to dairy) led McIntosh et al. (2001) to recognise the need to investigate methods of reducing the impact of increasing nutrient loadings.

3.0 GEOLOGY AND HISTORY OF THE LAKE REREWHAKAAITU CATCHMENT

Stratigraphy and lithology of the Lake Rerewhakaaitu catchment area (Table 1, Figure 3) are taken from the 1:50 000 geology map (Nairn in press). The surface catchment of Lake Rerewhakaaitu is elongated over approximately 14 km from the Kaingaroa ignimbrite plateau in the south, across the buried rim of Haroharo caldera, to the upper slopes of Mt Tarawera inside the caldera to north (Figure 3). The maximum east-west surface catchment width is about 7 km.

The Rangitaiki Ignimbrites are thought to be part of the Whakamaru group ignimbrites erupted from Whakamaru caldera. The overlying Matahina Ignimbrites were erupted from Haroharo caldera; Kaingaroa Ignimbrites were erupted from Reporoa caldera.

3.1 Lake basin history

The present lake occupies a shallow, now partly sediment-infilled, basin near the centre of the catchment. The basin is inferred to have a complex origin (Nairn in press). The basin area originally drained to north through a deep and narrow valley cut down into the welded Rangitaiki Ignimbrites that form the caldera rim. This now buried valley was probably cut down to about 360 m elevation, and would have been similar to the three adjacent deeply entrenched valleys which cut through the caldera rim between lakes Rerewhakaaitu and Rotomahana. It was probably somewhat larger as it has a larger catchment. Tarawera eruptions at 11 ka and 0.7 ka built up a large pyroclastic fan that locally filled the caldera, overflowed the caldera rim, and dammed the valley outlet from the lake basin. The present Lake Rerewhakaaitu has thus been in existence for a geologically very brief time. A small lake may have been impounded after the 11 ka eruption. The lake reached its present form after the 0.7 ka Kaharoa eruption at Tarawera. Based on this interpretation, the northern arm of Lake Rerewhakaaitu will be underlain by a deep narrow valley, now infilled with up to 40 m of pyroclastics and sediments. This buried valley, partly filled with Onuku Pyroclastics, may extend under the southern arm of the lake into the valley now occupied by Yankee Road.

There are major differences in the geology of the catchment areas to south and north of the lake. These catchment areas are here described as the southern sub-catchment and northern sub-catchment.

3.2 Geology of the southern sub-catchment

The lake sits on an eroded surface cut into the relatively flat-lying Rangitaiki Ignimbrites. This partly-welded ignimbrite sheet is exposed at several points around the lakeshore, and in the gullies, cliffs and craters to north and west of the lake (where the sheet is >100 m thick), including three deeply entrenched stream valleys out to 3 km east of the lake (Figures 1 and 3). The base of the Rangitaiki Ignimbrite is not exposed in the Rerewhakaaitu region, but this ignimbrite sheet is 130 m thick in an investigation well drilled adjacent to Northern Boundary Road (Nairn, 1984) 5.5 km southeast of the lake (Figure 3). The Rangitaiki Ignimbrites provide a local "basement" for the geology of the Rerewhakaaitu catchment, although ejecta from the Rerewhakaaitu fissures (Section 3.4) indicate that the ignimbrite sheet is here directly underlain by gravel-bearing sediments.

To the west and southwest of the lake, the Rangitaiki Ignimbrites are directly overlain by the non-welded, pumiceous Onuku Pyroclastics (~50 m thick) which form a dissected surface mantled only by recent (post-20 ka) pyroclastic and alluvium deposits (Table 1).

Directly to south of the lake, the ground surface rises onto the northern margin of the relatively flat-lying Kaingaroa Ignimbrite plateau, which is dissected into north and northeast-trending valleys. Although contacts are not exposed within the catchment area, the available surface exposure suggests that here the Kaingaroa Ignimbrite (~60 m thick) directly overlies Onuku deposits to the west, and Rangitaiki Ignimbrites to the east (Figure 3).

To the east and west of the catchment area, the Rangitaiki and Kaingaroa ignimbrite sheets are separated by (in upward succession) the Bonisch Pyroclastics, Matahina Ignimbrite, and Onuku Pyroclastics (Table 1). The Bonisch and Matahina formations are not mapped at the surface within the catchment but may be present at depth. Drillhole information within the southern Rerewhakaaitu sub-catchment is inadequate to determine the presence of these intervening units but it appears they were largely removed by erosion during the 120 000 years between the Rangitaiki and Kaingaroa eruptions.

The geology of the southern sub-catchment can thus be summarised as comprising a near flat-lying sequence of welded ignimbrite and non-welded pyroclastic sheets, with variable truncation by erosion but everywhere underlain by thick Rangitaiki Ignimbrites. The dissected ignimbrite or pyroclastic ground surface is largely conformably mantled by an approximately 10 m thick sequence of recent tephra deposits.

Table 1. Stratigraphy, chronology and lithologies of geological formations in the Rerewhakaaitu catchment as shown on Figure 3 (Nairn in press).

Symbol	Formation	Age (ka)	Lithology
fa	Alluvium		Pumiceous sediments
bk	Kaharoa Pyroclastics	0.7	Rhyolite ash and pumice flow deposits, plus lava block-and-ash flows
lw	Waiohau Pyroclastics	11	Rhyolite ash and pumice flow deposits
vr	Rerewhakaaitu Pyroclastics	15	Rhyolite ash and pumice flow deposits
ho_3	Okataina Rhyolites	0.7, 11, 15, 18	Rhyolite lava domes and flows
kg_2	Kaingaroa Ignimbrites	230	Weakly to moderately welded tuffs
o	Onuku Pyroclastics		Moderately compacted pumiceous tuffs
na	Matahina Ignimbrite	280	Welded tuffs
b	Bonisch Pyroclastics		Moderately compacted pumiceous tuffs
ra	Rangitaiki Ignimbrites	350	Crystal-rich welded tuffs

3.3 Geology of the northern sub-catchment

Geology of the northern sub-catchment is very different. The Rangitaiki Ignimbrite sheet is cut off by the rim of Haroharo Caldera (Figure 3) and deeply downfaulted to the north into the caldera, with a displacement probably greater than 500 m. Caldera collapse in this area is thought to have accompanied the Matahina Ignimbrite eruption at 280 ka. Thick Matahina, Onuku and Kaingaroa deposits are likely to have accumulated deep within the southern caldera basin. The caldera rim is clearly evident in the topography as forming the north-facing cliffs to the west of Lake Rerewhakaaitu. Northeast of the lake the caldera rim is buried by a thick pyroclastic fan (the Kaharoa Pyroclastics) erupted from Mt Tarawera during the last 18 000 years (Figure 3). The exact position of the caldera rim under this fan is unknown but it is inferred to connect the Rangitaiki Ignimbrite exposures at the north end of Brett Road and at the north end of Pakipaki Road (Figure 1).

The pyroclastic fan slopes down to the south from the Tarawera source vents at Kanakana dome (for the 11 ka eruption) and Ruawahia dome (for the 0.7 ka eruption) (Figure 3). Within the northern sub-catchment, only the 0.7 ka pyroclastics are exposed in the fan. They consist of rhyolitic pumice and ash pyroclastic flow deposits, interbedded with very similar debris flows, and overlain by coarse block-and-ash flow deposits formed by collapse of the growing Ruawahia lava dome. Total thickness of the 0.7 ka deposits in the fan is thought to range from 10 m to greater than 30 m. To the west of the northern sub-catchment, the 0.7 ka pyroclastics overlie poorly-exposed, but apparently similar, pyroclastic flow deposits associated with the 11 ka eruption. The 11 ka eruptives lack coarse block-and-ash flow deposits, but contain some phreatomagmatic units with more fine ash. The base of the 11 ka eruptives is not exposed within the northern sub-catchment but they are likely to exceed a total thickness of 30 m in the fan.

3.4 Rerewhakaaitu fissures

Two subparallel lineaments of coalescing, and individual, explosion craters occur to west of Lake Rerewhakaaitu (Nairn 1981, Nairn in press; Heppenstall 1999), extending southwest from the Haroharo Caldera margin (Figure 3). The Awaatua crater on the western shore of Lake Rerewhakaaitu occupies the largest individual crater (600 x 180 x 30 m deep) in the eastern lineament, but the longest (1500 m) continuous fissure of coalescing craters occurs near the middle of the western lineament.

All the craters are formed in welded Rangitaiki Ignimbrites overlain by eroded Onuku/Bonisch pyroclastics. The craters are up to 60 m deep, have steep walls and flat, sediment-infilled floors. The crater lineament cuts obliquely across the earlier formed north-northeast trending drainage pattern deeply incised into the Onuku/Rangitaiki Ignimbrite surface, and craters are located independently of topography, occurring in pre-existing valleys and on ridge tops. The craters are little eroded, and all appear to have formed contemporaneously and to be of recent age.

Ejecta from both lineaments is similar and very poorly sorted. Ejecta has a lithic coarse fraction (>2 mm) dominantly comprising angular blocks of Rangitaiki Ignimbrites with minor pumice, rhyolite, greywacke, and rare basalt/andesite lapilli, in a weathered vitric ash matrix. All clasts are relatively fresh and are not strongly hydrothermally altered. The explosion breccias from both lineaments occupy identical stratigraphic positions - interbedded between the 11 ka Waiohau Tephra and the 9 ka Rotoma Tephra. Weakly developed paleosols occur at both the upper and lower contacts of the breccia, indicating an eruption age of ~10 ka.

The eruptive mechanism that caused the craters to be formed has yet to be firmly established, but the ejecta provides a useful insight into the stratigraphy to west of Lake Rerewhakaaitu. The eastern lineament indicates the existence of a permeable fracture zone through the Rangitaiki Ignimbrites immediately to west of the lake.

4.0 CATCHMENT HYDROLOGY

The Lake Rerewhakaaitu catchment (Figure 1) is approximately 3816 ha in area. Physical and chemical hydrological measurements and models are reviewed, and a conceptual model of the hydrology of the system is discussed.

4.1 Review

McIntosh et al. (2001) discuss the hydrological balance of Lake Rerewhakaaitu in terms of a water balance equation relating lake storage to stream flow input/output, groundwater input/output, rainfall input, and evaporation output.

Groundwater inflows and outflows were ‘difficult to assess’ (McIntosh et al., 2001) so groundwater was not considered in the balance equation. Stream flow was also not considered in the balance equation because stream flow information on the two main inflows to the lake (Awaroa Stream and Mangakino Stream, Figure 1) are poor. Mangaharakeke Stream (Figure 1) is the only surface water outlet. This stream only flows when the lake level is high.

Changes in Lake Rerewhakaaitu volume are reasonably explained by changes in precipitation and evaporation over the lake (McIntosh et al. 2001) in the period May 1983 to August 2000. A model of mean precipitation and evaporation (McIntosh et al. 2001) predicts total lake volumes reasonably well. McIntosh et al. (2001) also considered a model of rainfall, evaporation and a constant 80 L/s flowing underground out of the lake to appear in Te Kauae Stream (Figure 1). This did not model Lake Rerewhakaaitu water volumes particularly well over the study period.

Total nitrogen concentrations in Lake Rerewhakaaitu are variable over time with a typical annual variation of around 0.1 g/m^3 (McIntosh et al. 2001). Total nitrogen increased from around 0.3 g/m^3 in 1990 to around 0.55 g/m^3 in 1998, and then declined to be around 0.37 g/m^3 in 2001. The increase in nutrient levels in the lake to 1998 is speculated as due to a 2 m rise in lake level between March 1995 and September 1996 that may have released nitrogen around the lake margin.

Mangakino and Awaroa Streams drain about 20% of the catchment (McIntosh et al, 2001). Mangakino Stream typically has a very low flow. The average flow of Mangakino Stream at County Bridge between July 1995 and July 2001 was 24 L/s, with a maximum of 172 L/s. Awaroa Stream at Rerewhakaaitu Village is commonly dry. Twenty gaugings at this location between July 1995 and July 2001 recorded zero flow on 18 occasions. The maximum recorded flow in this period was 6 L/s.

Total nitrogen in Mangakino Stream increased from a median of 1.213 g/m^3 in the 1970s to 2.355 g/m^3 in 2000 (McIntosh et al., 2001). The median total nitrogen was 3 g/m^3 in Awaroa Stream in the 1970s and 8.43 g/m^3 in the 1990s. A total nitrogen concentration of 18.36 g/m^3 was recorded in Awaroa Stream in the 1990s. Total nitrogen concentrations appear to be increasing over time in both the streams. The streams, when they are flowing, discharge into wetlands in the lake where it is likely that nutrient reduction will occur.

McIntosh et al. (2001) used a model of rainfall, evaporation, and nutrient concentrations in Mangakino Stream in 2000/2001 to estimate a total nitrogen export of 24.5 kgN/ha/yr from the 2927 ha of pastoral land in the Lake Rerewhakaaitu catchment. Vant and Huser (2000) indicated that a dairy stocking rate of 2-3 cows/ha is associated with nutrient export of 20-35 kgN/ha/yr in land typical of the Taupo catchment. Riparian zones are established around the lake and in the lower reaches of the Mangakino, Awaroa, and Mangaharakeke (north) streams. A number of farmers are also retiring land on stream boundaries to reduce the impact on stream water quality.

4.2 Conceptual model of the hydrology of the catchment

4.2.1 Water inputs to the catchment

The sole source of water input to the catchment is rainfall. The groundwater catchment boundary (Figure 1) is taken as a topographic boundary on all sides except the north east where the boundary has been chosen to match a possible groundwater divide in the Kaharoa/Waiohau Pyroclastics. This boundary aims to represent the maximum extent of the groundwater system that could be discharging into Lake Rerewhakaaitu. Groundwater occurring east of the groundwater catchment will likely travel in a north-easterly direction to the Tarawera River catchment, or in an easterly direction to the Rangitaiki River catchment. Groundwater west of the groundwater catchment (Figure 1) will likely travel towards Lake Rotomahana.

4.2.2 Water outputs from the catchment

Four water outputs from the catchment are: evaporation, evapotranspiration, groundwater flow, and sporadic stream flow. Evaporation from the land surface and the lake is likely to be a significant component of the water balance. Groundwater discharge though the western boundary is likely as the springs in the headwaters of Te Kauae Stream are sourced from Lake Rerewhakaaitu. These springs discharge from the Rangitaiki Ignimbrite and geological formations younger than the Rangitaiki Ignimbrite, to provide base flow for Te Kauae Stream. Groundwater discharge across the catchment boundary is possible from the northern end of Lake Rerewhakaaitu into Haroharo caldera through the Kaharoa/Waiohau/Rerewhakaaitu Pyroclastics and then down to Lake Rotomahana. Groundwater discharge may also occur southeast and east of Lake Rerewhakaaitu into the Rangitaiki Ignimbrite and then to the Rangitaiki River catchment.

The only stream that passes across the catchment boundary is the Mangaharakeke Stream which drains into the Rangitaiki River catchment. This stream does not normally flow (McIntosh et al., 2001), except when the lake level is high. Stream flow out of the catchment, therefore, is taken as nil.

4.2.3 Water transfers within the catchment

Rainfall recharge (i.e. the net of rainfall minus evaporation or evapotranspiration) will occur to Lake Rerewhakaaitu, groundwater, streams and wetlands.

A considerable portion of the rainfall recharge will travel into the groundwater system because specific drainage is low. Low specific drainage is typical of the geological materials in the region. Recharge will then move downwards through the unsaturated zone to the saturated zone. Movement of water in the unsaturated zone is generally vertically downwards. However, movement in unsaturated ignimbrite may be sub vertical, with a significant horizontal component of flow following the pattern of fractures. Movement of water in the saturated zone is generally in a direction that is indicated by contours of groundwater level.

The interaction of groundwater with surface water is controlled by a number of factors including the relative level of water in the aquifer and the level of water in the surface water body. For example, groundwater will discharge to a lake where groundwater levels are greater than lake level.

5.0 GROUNDWATER HYDROLOGY

5.1 Data sources

Geological information is available from well logs of holes drilled in the area by the Lands and Survey and private well owners. A total of 119 wells are identified in the area by Environment Bay of Plenty (Appendix 2, Table A2.1 and Figure 4). Not all these wells have geological information and groundwater level information. This makes for difficulties of interpretation because the name of the aquifer tapped by a well is often unknown and therefore water levels associated with aquifers are often unknown.

Three sets of groundwater level information are available. The first set, provided by Environment Bay of Plenty on 19/6/02, measures well water depth in 15 wells that are possibly in the groundwater catchment of Lake Rerewhakaaitu. These data were collected from well drillers' logs so needs to be treated with caution. Surveyed wellhead elevations were not available. Elevations were estimated from the relationships of well locations to the 20 m contours on the NZMG 1:50 000 V16 Tarawera map, within a probable error range of ± 10 m. However, many of the well locations were in error, so that well elevations were also in error. The range in measured groundwater level is 380 m above mean sea level to 450 m above mean sea level. This range indicated the potential for groundwater to be recharged by Lake Rerewhakaaitu (at a level of 435 m amsl) and for the lake to be recharged by groundwater. The date of measurement of the water levels is unknown (Gordon, pers. comm. July 2003).

The second set of data produced by EBOP was collected in the period November 2003 to March 2003, includes 90 wells that were surveyed by GPS for location and elevation. The survey updated well water level and well location information from well-driller logs. Groundwater levels were measured in 53 of these wells. The range in measured groundwater level is 362 m above mean sea level to 470 m above mean sea level.

The third set of data are from drillers' records of water level made as wells were drilled when the Lands and Survey Department were developing farms in the area.

The locations of wells with geological logs and/or measurable groundwater levels (Figure 4) provide a good coverage of groundwater level information through the catchment (Figure 5). Data on well depths, casing depths and measured water levels have been combined with the geology inferred from drillers logs and the Okataina 1:50 000 geology map (Nairn in press), to determine the likely lithology in each well and therefore the name of the aquifer where each water level is measured.

The vertical component of groundwater flow is generally downwards, as the depth to groundwater is generally greater in deeper wells (Figure 6), indicating that aquifers are probably unconfined in the area. No flowing artesian wells are known in the region.

5.2 General description of groundwater levels

5.2.1 Southern sub-catchment

Groundwater levels are generally below the level of Lake Rerewhakaaitu (Figure 7) south of the lake.

Most of the wells appear to be cased into the Rangitaiki Ignimbrite and are open in this formation; one well is cased into sediments above the Rangitaiki Ignimbrite but is also open in the ignimbrite. Some shallow wells do not reach the Rangitaiki Ignimbrite, and are open into the Onuku Pyroclastics, Bonisch Pyroclastics and Kaingaroa Ignimbrite. These wells have the higher apparent water levels (433-470 m a.s.l.), presumably controlled by shallow perched aquifers. The other wells have water levels mostly between around 390 m to 420 m, which is taken to represent pressures over most of the Rangitaiki Ignimbrite aquifer. This water level is generally below that of Lake Rerewhakaaitu (taken as 435 m amsl), suggesting that the lake mostly acts to recharge the aquifer.

Rangitaiki Ignimbrite wells with water levels outside this range are 15, 5 and 67. Wells 15 and 5 are both located close to Rerewhakaaitu School, about 1 km south of the lake, and have water levels around 440 m, i.e. higher than the lake level at 435 m r.l. The ignimbrite aquifer tapped by wells 15 and 5 may be feeding groundwater into a pyroclastic and sediment-filled gully thought to underlie the lake (see Section 3.1), and thus into the lake itself. The driller's log for well 3505 suggest these wells have the ignimbrite aquifer capped by less permeable (?) Onuku or Bonisch pyroclastics, and sediments. The deep aquifer pressures here appear controlled by proximity to a major recharge zone situated beneath the 530-540 m a.s.l. Kaingaroa Ignimbrite plateau surface to east and south of the Rerewhakaaitu Village.

The Kaingaroa Ignimbrite plateau surface located to north of Northern Boundary Road and on either side of Yankee Road is the main groundwater recharge zone feeding northwards from the southern sub-catchment. Remnant drains, form the headwaters of the Mangaharakeke

Stream. To the south of Northern Boundary Road and SH38, the plateau drains south into the Ngatamawahine Stream (Rangitaiki Catchment) and southwest into the Reporoa basin and Waikato River catchment. It is likely that only a small fraction of the total groundwater outflow from beneath this plateau remnant will follow the surface drainage north towards Lake Rerewhakaaitu.

Groundwater levels to the west of Lake Rerewhakaaitu are generally below the level of the lake. This is consistent with lake water draining to springs and eventually to Lake Rotomahana.

5.2.2 Northern sub-catchment

A shallow aquifer is formed by the young pyroclastic fan, consisting of Kaharoa and Waiohau pyroclastics, sloping south from Mt Tarawera across the caldera rim and towards the lake. The pyroclastic fan appears to sit directly on the near-flat, eroded surface of the Rangitaiki Ignimbrite to north of Ash Pit Road between Crater Road and Tawa Road. The Kaharoa eruptives forming the fan surface are highly permeable, and no permanent flowing streams exist anywhere on the fan surface. The underlying Waiohau Pyroclastics are known from other areas to include finer-grained beds of lower permeability and these may act as a local aquiclude to perch a shallow water table in which flow passes south into the lake basin. The buried caldera rim (Figure 3) is likely to form a subterranean dam to deeper groundwater (beneath the Waiohau Pyroclastics) flowing south from the Tarawera massif towards Lake Rerewhakaaitu. This groundwater will be diverted west towards Lake Rotomahana.

An important question is whether an aquiclude exists above the Rangitaiki Ignimbrite surface to perch the shallow groundwater contained in the pyroclastic fan deposits. If not, this water may largely drain into the ignimbrite.

Groundwater level in two wells in the Rangitaiki Ignimbrite Aquifer are higher than lake level to the north east of the lake (Figure 8). This indicates that groundwater could recharge the lake in this area. Groundwater levels to the east of Lake Rerewhakaaitu are below lake level and consistent with a general eastward direction of groundwater flow in the Rangitaiki Ignimbrite Aquifer in this area.

5.3 Lake Rerewhakaaitu outflows

Surface overflow only occurs when the lake is high following periods of high cumulative rainfall. Overflow occurs from the eastern arm of the lake into a shallow channel draining to the Mangaharakeke Stream and Rangitaiki River. At these times the lake also overflows west into the large Awaatua explosion crater excavated to >30 m depth in Rangitaiki Ignimbrite adjacent to Brett Road. Seepage outflow occurs from the Awaatua crater, passing ~120 m to north through tephra deposits over Onuku Pyroclastics, to feed the Te Kaue spring at the head of a vertical-walled gully (at V16/152183) which drains to the Rotomahana catchment. Flow of this spring was about 6 L/s in 1972, when samples were taken for isotope analyses (Taylor et al. 1977). These analyses showed the spring water to contain about 88% of subsurface drainage from Lake Rerewhakaaitu.

A larger subsurface outflow probably occurs from the northern arm of the main lake, along the pyroclastic-infilled buried valley cut to north through the Rangitaiki Ignimbrite of the caldera rim (see above). This valley will act as a porous pipe allowing lake water to drain north into the caldera, where deep groundwater levels are ultimately controlled by Lake Rotomahana with surface at around 337 m. The permeability barrier controlling this outflow from Lake Rerewhakaaitu is probably limited to recent fine sediments deposited on the lake floor. More well data would be required to confirm and quantify this inferred northward outflow from Lake Rerewhakaaitu into the caldera.

The lake is likely to also be discharging through its floor into the regional ignimbrite aquifer as the 435 m elevation of the Lake Rerewhakaaitu exceeds piezometric levels measured in wells and spring elevations in deep gullies entrenched to <400 m above sea level to the west of the lake.

6.0 RANGITAIKI IGNIMBRITE AQUIFER

6.1 Extent and nature

The Rangitaiki Ignimbrite Aquifer occurs as a continuous unit present everywhere south of the rim of the Haroharo Caldera (Figure 3). The unit is mapped at the ground surface as adjoining the eastern shore of Lake Rerewhakaaitu, and east of the lake. The unit also appears in outcrop west of the lake. This aquifer occurs below the other major units in the region such as the Kaharoa/Waiohau pyroclastics, Kaingaroa Ignimbrite, and Onuku Pyroclastics. The Rangitaiki Ignimbrite Aquifer is therefore considered as the 'base' of the groundwater system in the area as it is the deepest-known aquifer.

The aquifer thickness is assumed to be 130 m because this is the greatest thickness of the unit found in a drill hole (Section 3.2). No physical properties of the aquifer have been measured in the Lake Rerewhakaaitu district. However, from well tests in the Rangitaiki Ignimbrite and other ignimbrite aquifers in the Taupo Volcanic Zone (Hadfield, 2001) it is assumed that the majority of water available to users comes from fractures in the ignimbrite. It is also assumed, like other ignimbrite aquifers (Hadfield, 2001) that natural groundwater quality is relatively good. Transmissivities and groundwater velocities in ignimbrite aquifers can be relatively high. For example Hadfield (2001) has a range of 340 to 2500 m^2d^{-1}, and a groundwater velocity of 5 to 16 md^{-1} for the Waiotapu Ignimbrite Aquifer near Kinleith. No other transmissivity values for the Rangitaiki Ignimbrite Aquifer have been measured.

In the Te Puke-Maketu basin of the Western Bay of Plenty, transmissivity values in ignimbrite aquifers are between 350 m^2/day and 800 m^2/day. On the Rangitaiki Plains transmissivity values of the Matahina Ignimbrite range 16 to 6000 m^2/day in the unwelded ignimbrite. Transmissivity values within the welded fractured ignimbrites near Otakiri, in the southwestern Rangitaiki Plains, are in the range 6000 to 12000 m^2/day (Gordon, 2001).

Water quality within the deeper ignimbrites of the Rangitaiki Plains in the Eastern Bay of Plenty is generally very good and water is widely used for irrigation and potable supplies (Gordon, 2001).

6.2 Groundwater levels

Groundwater levels measured in wells drilled into this aquifer are all below ground level. Groundwater levels within the bores 3, 5, 21, 22, 29, 30, 32, 70, 71, 77, 88, and 89 (north east and west of Lake Rerewhakaaitu) are possibly above the assumed top of the Rangitaiki Ignimbrite Aquifer. This indicates that the aquifer is possibly confined over this area. All other bores identified within the Rangitaiki Ignimbrite Aquifer are below the assumed top of the aquifer, indicating unconfined conditions.

Groundwater levels are assigned to the Rangitaiki Ignimbrite Aquifer by assuming: 1) all wells drilled in the area mapped as Rangitaiki Ignimbrite are in this aquifer, 2) wells that are deeper than the combined thickness of overlying aquifers are assumed as in the Rangitaiki Ignimbrite Aquifer. It follows from these assumptions that 33 of the wells in the region with known water levels draw water from the Rangitaiki Ignimbrite Aquifer.

Groundwater levels are relatively high in the Awaroa Stream valley area to the south of Lake Rerewhakaaitu (Figure 8) and under the Kaharoa/Waiohau pyroclastics to the northeast of Lake Rerewhakaaitu.

Table 2. Rangitaiki Ignimbrite Aquifer with Environment Bay of Plenty well number (well ID) and well geology. The confidence of concluding that the wells draw water from the Rangitaiki Ignimbrite Aquifer is indicated.

Well ID	Assumed Geology	Confidence
3	bk/lw/ra	Assumed
5	fa/kg/o/ra	Known
7	Hol/o/ra	Known
11	kg/o/ra	Known
14	fa/kg/ra	Assumed
15	fa/o/ra	Known
19	ra	Assumed
21	bk/lw/ra	Known
22	bk/lw/ra	Assumed
24	ra	Assumed
29	bk/lw/ra	Assumed
30	bk/lw/ra	Known
32	bk/lw/ra	Assumed
33	Hol/ra	Known
34	Hol/ra	Known
36	o/ra	Assumed
37	bk/seds/ra	Known
38	fa/kg/ra	Assumed
40	ra/gravels?	Known
42	Hol/o/ra	Known

Well ID	Assumed Geology	Confidence
44	ra	Assumed
45	o/ra	Assumed
47	ra	Known
50	ra	Assumed
51	ra	Assumed
52	ra	Assumed
53	ra/gravels?	Known
54	ra	Assumed
57	Hol/ra	Known
60	o/ra	Assumed
67	na/b/ra	Known
70	fa/o/ra	Known
71	o/ra	Known
76	bk/lw/vr/ra	Assumed
77	o/ra	Assumed
78	ra	Assumed
84	Hol/o/ra	Known
86	Hol/ra	Known
88	o/ra	Known
89	fa/o/ra	Assumed

Groundwater discharges from the Rangitaiki Ignimbrite Aquifer through springs to the west (e.g. Figure 9) of Lake Rerewhakaaitu; this water flows to streams and then to Lake Rerewhakaaitu.

6.3 Groundwater flow directions

These piezometric levels are interpreted as groundwater level contours and groundwater flow directions (Figure 10). Groundwater flow is predicted to flow towards the lake in the area of the aquifer underlying the Kaingaroa Ignimbrite Aquifer south of Lake Rerewhakaaitu. Groundwater levels are above lake level east of the lake in the area of the aquifer below the Kaharoa/Waiohau Pyroclastics. This is therefore predicted as an area where groundwater flow is possibly towards the lake. The western, and eastern areas of the lake are areas where water will flow from the lake to the groundwater if the conductance of the lake bed is sufficient to allow the passage of water.

Two groundwater divides GD1 and GD2 are proposed for the Rangitaiki Ignimbrite Aquifer (Figure 10). Groundwater in the aquifer between Awaroa Stream and GD1 may travel westward towards Lake Rerewhakaaitu. Groundwater east of this boundary will travel east. Groundwater between the lake and GD2 will potentially travel westwards in the aquifer and potentially in the direction of the lake. Groundwater east of this line will likely travel eastwards in the aquifer.

7.0 ONUKU PYROCLASTIC AQUIFER

7.1 Extent and nature

The Onuku Pyroclastic Aquifer is located southwest of Lake Rerewhakaaitu (Figure 3). It is approximately 50 m thick and lies above the Rangitaiki Ignimbrite Aquifer.

7.2 Groundwater levels

Groundwater level data (Appendix 2) suggest that up to four bores draw water from the Onuku Pyroclastic Aquifer (Figure 11). Groundwater levels are between 412 m to 452 m and groundwater levels in two bores (66, outside the catchment, and 79) are above the level of Lake Rerewhakaaitu.

Table 3. Onuku Pyroclastic Aquifer with Environment Bay of Plenty well number (well ID) and well geology. The confidence of concluding that wells draw water from the Onuku Pyroclastic Aquifer is indicated.

Well ID	Geology	Confidence
2	Hol/o	Known
66	Hol/o/na/b	Known
79	o/ra	Assumed
95	Hol/o	Assumed

7.3 Groundwater flow directions

Groundwater levels in the aquifer (Figure 11) cannot be interpreted as groundwater flow directions because the data is sparse.

It is possible that groundwater from this aquifer discharges into Lake Rerewhakaaitu as groundwater levels in one well within the catchment (well 79, Fig. 11) is above the level of the lake. Groundwater levels are greater than the levels in the underlying Rangitaiki Ignimbrite Aquifer. Therefore the Onuku Pyroclastic Aquifer is potentially a source of recharge for the Rangitaiki Ignimbrite Aquifer.

8.0 KAINGAROA IGNIMBRITE AQUIFER

The Kaingaroa Ignimbrite Aquifer occurs south of Lake Rerewhakaaitu. The aquifer occurs in a terrace approximately 60 m thick lying on top of the Rangitaiki Ignimbrite. No properties of this aquifer have been measured. No wells have been identified from this study to draw water from the Kaingaroa Ignimbrite Aquifer. Wells that may draw water from the Kaingaroa Ignimbrite Aquifer are located near Yankee Road and Republican Road. However, it is assumed that these wells draw water from the Rangitaiki Ignimbrite aquifer; these wells are likely to be deeper than the contact between the Kaingaroa and Rangitaiki ignimbrite units. Recharge from the Kaingaroa Ignimbrite to the Rangitaiki Ignimbrite Aquifer may be responsible for the groundwater divide GD2 observed in the Rangitaiki Ignimbrite Aquifer (Figure 10).

9.0 KAHAROA/WAIOHAU PYROCLASTIC AQUIFER

This aquifer occurs to the east, and northeast of Lake Rerewhakaaitu outside the Haroharo caldera boundary (Figure 3). The aquifer is between 30 m and 40 m thick and overlies the Rangitaiki Ignimbrite Aquifer. No hydraulic properties are measured in this aquifer. The pyroclastic aquifer is likely to have a high permeability as no streams drain the area, probably because of most rainfall recharge soaks to ground through the recent volcanic deposits.

Wells that potentially draw water from the Kaharoa/Waiohau Pyroclastic Aquifer are on farms adjoining the section of Ash Pit Road east of Lake Rerewhakaaitu. Wells 21, 29, 30 and 37 are in this vicinity. It is assumed these wells take water from the Rangitaiki Ignimbrite Aquifer. Three of the wells are deeper than 60 m so are likely to take water from the Rangitaiki Ignimbrite Aquifer. One well (well 29) is 33 m deep and may take water from the Kaharoa/Waiohau Pyroclastic Aquifer. We make the assumption that well 29 is in the Rangitaiki Ignimbrite Aquifer because this aquifer is the predominant source of groundwater in the area.

10.0 KAHAROA/WAIOHAU/REREWHAKAAITU PYROCLASTIC AQUIFER

10.1 Extent and nature

The Kaharoa/Waiohau/Rerewhakaaitu Pyroclastic Aquifer occurs north, and northwest of Lake Rerewhakaaitu within the downfaulted edge of the Haroharo Caldera. No aquifer properties have been measured in this area or other areas and the thickness of the units are unknown.

10.2 Groundwater levels

Three wells (well numbers 69, 73 and 76) are assumed to take groundwater from the Kaharoa/Waiohau/Rerewhakaaitu Pyroclastic Aquifer (Figure 12) in the absence of any information about sub-surface lithology in this area.

10.3 Groundwater flow directions

Groundwater levels in the aquifer are lower than the level of Lake Rerewhakaaitu and so there is a potential for groundwater from the lake to travel through this aquifer.

Recharge is possible in the area of the northern arm of Lake Rerewhakaaitu through the Kaharoa eruption deposits that impound the lake near Ash Pit Road. Groundwater levels are greater than the level of Lake Rotomahana, indicating groundwater may flow from Lake Rerewhakaaitu through the Kaharoa/Waiohau/Rerewhakaaitu Pyroclastic Aquifer towards Lake Rotomahana (Figure 12).

11.0 PERCHED AQUIFERS

11.1 Groundwater levels

Wells 9 and 43 (Figure 13) have groundwater levels that are significantly higher than surrounding groundwater levels (Figure 7). This may indicate that these wells draw water from perched aquifers. There is no well depth information or geological logs for these wells. A conclusion about the presence of perched aquifers is speculative.

11.2 Extent

Wells 9, and 43 are in relatively close proximity (Figure 13). These wells may indicate a shallow aquifer south of Lake Rerewhakaaitu.

12.0 WATER BALANCE MODELS

Surface water and groundwater flows in the catchment are modelled with water balance equations to estimate water transfers between aquifers and water transfers between the lake and groundwater. These equations are of the form:

Water in	=	water out
Water in		is the water flow into an aquifer, lake or stream
Water out		is the water flowing out of an aquifer, lake or stream

The water balance equations assume steady-state conditions, i.e. water fluxes are constant and there is no change in storage in any of the components of the system. These equations are a first step in understanding the water flows e.g. from rainfall to aquifer, from aquifer to stream, and from groundwater into the lake.

Each of the hydrological components of the catchment are addressed in the following sections. Estimates of rainfall and evaporation are made for the catchment. Stream flows are estimated from observations and water balance equations are defined for each aquifer and Lake Rerewhakaaitu. Assumptions about water flows in the catchment are required where no measurements exist. These assumptions are listed with each water balance equation. Some of these assumptions provide the authors' upper estimate of groundwater input into the lake and therefore upper estimate of nutrient input into the lake (Section 13).

Groundwater use is not considered in these equations as groundwater use is likely to be a small portion of the total groundwater recharge.

12.1 Rainfall, evapotranspiration, and evaporation

It is assumed that rainfall and evapotranspiration are the same everywhere in the Lake Rerewhakaaitu catchment, and that evaporation from the surface of Lake Rerewhakaaitu is as estimated by McIntosh et al. (2001).

Rainfall within the defined catchment boundary (Figure 2) to each aquifer is estimated as a mean of 1319 mm/yr at rainfall recorder site 862402 and 1800 mm/yr at rainfall recorder site 863601 (Appendix 4). McIntosh et al. (2001) use the mean of rainfall at these two sites to represent changes in the volume of Lake Rerewhakaaitu. The rainfall used in this work to represent the mean rainfall in the catchment is 1600 mm/yr which is the mean (rounded) of the two rainfall figures.

Estimated mean evaporation/evapotranspiration in the catchment was assumed by McIntosh et al. (2001), from modelling of rainfall and evaporation in the Ngongotaha catchment, as 490 mm. The mean rainfall on the catchment and the lake is an average of 2180 L/s (Table 4). An estimated 730 L/s of rainfall is evaporated or transpired (Table 4) from the catchment and the lake.

Evaporation from Lake Rerewhakaaitu is calculated from the 12 times the mean of the estimated monthly evaporation on the lake in the period April 1983 to April 2002 (Ellery, pers. comm.). Monthly evaporation estimates are made by applying an open-water body correction to pan evaporation observations (McIntosh et al., 2001).

Table 4. Estimated rainfall and evaporation/evapotranspiration in the catchment.

Unit	Area* (km^2)	Mean Rainfall (mm/yr)	Mean rainfall to unit (L/s)#	Mean E/ET (mm/yr)	Mean E/ET (L/s)#
Rangitaiki Ignimbrite Aquifer	6.08	1600	310	490	95
Onuku Pyroclastic Aquifer	8.48	1600	430	490	130
Kaingaroa Ignimbrite Aquifer	11.31	1600	570	490	170
Kaharoa/Waiohau Pyroclastic Aquifer	10.32	1600	520	490	160
Lake Rerewhakaaitu	5.34	1600	270	852[1]	140
Kaharoa/Waiohau/Rerewhakaaitu Pyroclastics	0.67	1600	30	490	10
Other	0.96	1600	49	490	15
Total	43.16	-	2180	-	730

*Area measurement taken from within the catchment boundary

Rainfall and ET calculations are rounded to two significant figures.

[1] Mean evaporation from the lake, April 1983 to April 2000 (McIntosh et al., 2001).

12.2 Stream flows

12.2.1 Mangakino Stream

Gauging data on this stream include 67 measurements of flow at the County Bridge between 3 January 1973 and 27 July 2001. The average flows measured by season are: summer 145 L/s, autumn 11 L/s, winter 85 L/s and spring 61 L/s. The mean of these numbers is the assumed mean flow of the stream of 76 L/s. Most measurements are in spring which may bias the mean away from lower flows in autumn but the seasonal average calculation may balance against this somewhat. Gauged flow rates range between 1 L/s and 1791 L/s in the period of record.

12.2.2 Awaroa Stream

Measurements of flow at Rerewhakaaitu Village are recorded on 46 occasions between 19 June 1944 and 17 June 1996. Mean seasonal flows calculated from these data are: summer 49 L/s, autumn 5 L/s, winter 77 L/s and spring 48 L/s. The mean flow of this stream is assumed as 45 L/s which is the mean of the four seasonal flows. Most flow measurements are in spring, which may bias the mean away from low flows in autumn. Gauged flow rates range between 0 L/s and 419 L/s in the period of record.

12.2.3 Te Kauae Stream

Te Kauae Stream drains from the north and east of Lake Rerewhakaaitu. McIntosh et al. (2001) proposed that this stream was spring-fed in the headwaters because flows measured in gaugings are relatively consistent over the period of measurements. Sixteen gauging measurements between 24 September 1974 and 21 May 1998 record a mean flow of 190 L/s (McIntosh et al., 2001). The range of flow measured was 134 L/s to 249 L/s in the period of records. A mean flow is estimated as 197 L/s (Gordon, pers. comm. June 2003).

12.2.4 Stream flow out of Lake Rerewhakaaitu

Stream flow out of the lake does not normally occur (McIntosh et al., 2001) except at times when lake level is high and lake water flows into a drain at the eastern end of the lake. Lake outflow through this drain is set to zero.

12.3 Water balance equations, Rangitaiki Ignimbrite Aquifer

Water in = $R_R + W_{KR} + W_{OR} + W_{LIR} + W_{KWR} + W_{SIR}$

R_R direct rainfall on the aquifer in the area of outcrop (Figure 3), section 12.1

W_{KR} groundwater flow from the Kaingaroa Ignimbrite Aquifer to the Rangitaiki Ignimbrite Aquifer

W_{OR} groundwater flow from the Onuku Pyroclastic Aquifer to the Rangitaiki Ignimbrite Aquifer

W_{LIR} groundwater flow from the lake to the Rangitaiki Ignimbrite Aquifer

W_{KWR} groundwater flow from the Kaharoa/Waiohau Pyroclastic Aquifer to the Rangitaiki Ignimbrite Aquifer

W_{SIR} groundwater flow from streams to the Rangitaiki Ignimbrite Aquifer

Water out = $ET_R + W_{RL} + W_{RS} + W_{RB} + W_{RKW}$

ET_R evapotranspiration of rainfall in the area of outcrop (Figure 3), section 12.1

W_{RL} groundwater flow from the Rangitaiki Ignimbrite Aquifer to the lake

W_{RS} groundwater flow from the Rangitaiki Ignimbrite Aquifer to streams

W_{RB} groundwater flow from the Rangitaiki Ignimbrite Aquifer across the outflow boundaries of the aquifer

W_{RKW} groundwater flow from the Rangitaiki Ignimbrite Aquifer to the Kaharoa/Waiohau Pyroclastic Aquifer

Assumptions: Assumptions for W_{OR}, W_{KR} and W_{KWR} are made in sections 12.4, 12.5, and 12.6, respectively.

W_{SIR} assume as zero because streams are ephemeral and it is assumed that gaining streams are not losing water to the Rangitaiki Ignimbrite Aquifer.

W_{RL} assume as zero because Rangitaiki Ignimbrite Aquifer groundwater levels are generally below lake level.

W_{RS} assume as the mean flow of Te Kauae Stream = 197 L/s

W_{RB} assumed as 1208 L/s to balance the flux in the aquifer

12.4 Onuku Pyroclastic Aquifer

Water in = R_O

R_O direct rainfall on the aquifer in the area of outcrop (Figure 3), section 12.1

ET_O evapotranspiration of rainfall in the area of outcrop (Figure 3), section 12.1

Water out = $ET_O + W_{OR} + W_{OL} + W_{OS} + W_{OB}$

ET_O evapotranspiration of rainfall in the area of outcrop (Figure 3), section 12.1

W_{OR} groundwater flow from the Onuku Pyroclastic Aquifer to the Rangitaiki Ignimbrite Aquifer

W_{OL} groundwater flow from the Onuku Pyroclastic Aquifer to the lake

W_{OS} groundwater flow from the Onuku Pyroclastic Aquifer to streams

W_{OB} groundwater flow from the Onuku Pyroclastic Aquifer across the outflow boundary of the aquifer

Assumptions:

W_{OR} assume 50% of the balance of net (rainfall recharge – W_{OS}) is going vertically downwards to the Rangitaiki Ignimbrite Aquifer

W_{OL} assume 50% of the balance of net (rainfall recharge – W_{OS}) is discharging to the lake through the groundwater

W_{OS} Assume the total flow to streams is 49 L/s made of: Onuku Pyroclastic Aquifer flow to the Mangakino Stream (section 12.2.1) of 38 L/s

Onuku Pyroclastic Aquifer flow to Awaroa Stream (section 12.2.2) of 11 L/s.

W_{OB} assumed zero is moving westwards through the western boundary

These assumptions are equivalent to assuming that land use in 58% of the area in the catchment covered by the aquifer could potentially impact on lake water quality.

12.5 Kaingaroa Ignimbrite Aquifer

Water in = R_K

R_K direct rainfall on the aquifer in the area of outcrop (Figure 3), section 12.1

Water out = $ET_K + W_{KR} + W_{KS}$

ET_K evapotranspiration of rainfall in the area of outcrop (Figure 3), section 12.1

W_{KR} groundwater flow from the Kaingaroa Ignimbrite Aquifer to the Rangitaiki Ignimbrite Aquifer

W_{KS} groundwater flow from the Kaingaroa Ignimbrite Aquifer to streams

Assumptions:

W_{KR} assume that the balance of net rainfall – W_{KS} is going to the Rangitaiki Ignimbrite Aquifer

W_{KS} assume one half of the Mangakino Stream flow is from the Kaingaroa Ignimbrite Aquifer, or 38 L/s assume three quarters of the Awaroa Stream flow is from the Kaingaroa Ignimbrite Aquifer, or 34 L/s

These assumptions are equivalent to assuming that land use in 18% of the area in the catchment covered by the aquifer could potentially impact on lake water quality.

12.6 Kaharoa/Waiohau Pyroclastic Aquifer

Water in = R_{KW}

R_{KW} direct rainfall on the aquifer in the area of outcrop (Figure 3), section 12.1

Water out = $ET_{KW} + W_{KWR} + W_{KWL}$

ET_{KW} evapotranspiration of rainfall in the area of outcrop (Figure 3), section 12.1

W_{KWR} groundwater flow from the Kaharoa/Waiohau Pyroclastic Aquifer to the Rangitaiki Ignimbrite Aquifer

W_{KWL} groundwater flow from the Kaharoa/Waiohau Pyroclastic Aquifer to the lake

Assumptions:

W_{KWR} assume 50% of the net rainfall recharge goes to the Rangitaiki Ignimbrite Aquifer

W_{KWL} assume 50% of the net rainfall recharge goes to the lake because recharge in the area west of GD1 (Figure 10), representing about 50% of the land area covered by this aquifer, has the potential to travel to the lake

12.7 Lake Rerewhakaaitu

Water in = $R_L + W_{RL} + W_{OL} + W_{KWL} + S_{IL}$

R_L rainfall on the lake, section 12.1

W_{RL} groundwater flow from the Rangitaiki Ignimbrite Aquifer to the lake

W_{OL} groundwater flow from the Onuku Pyroclastic Aquifer to the lake

W_{KWL} groundwater from the Kaharoa/Waiohau Pyroclastic Aquifer to the lake

S_{IL} stream inflow into lake

Water out = $E_L + W_{LIR} + W_{LKWR} + S_{OL}$

E_L evaporation from the lake, section 12.1

W_{LIR} groundwater flow from the lake to the Rangitaiki Ignimbrite Aquifer

W_{LKWR} groundwater flow from the lake to the Kaharoa/Waiohau/Rerewhakaaitu Pyroclastic Aquifer

S_{OL} stream flow out of the lake

Assumptions:

S_{IL} is the sum of Mangakino and Awaroa Streams (121 L/s)

W_{OL} assume 50% of the balance of net rainfall recharge – W_{OS} is discharging to the lake through the groundwater

W_{KWL} assume 50% of the net rainfall recharge goes to the lake

W_{LIR} assumed as the sum of inflows to the lake

W_{LKWR} assumed as zero

S_{OL} assumed as zero

12.8 Kaharoa/Waiohau/Rerewhakaaitu Pyroclastic Aquifer

Lake Rerewhakaaitu water probably discharges water into this aquifer, as discussed in Section 10. However this aquifer is not considered in the water balance equations as: 1) consideration of rainfall on this aquifer from the Mt Tarawera area to the north will complicate the water balance equations; and 2) any discharge from the lake into this aquifer, and subsequent recharge to Te Kauae Stream, is accounted for in the water balance equations for the Rangitaiki Ignimbrite Aquifer.

12.9 Summary of water balance estimates

Water inflows to, and outflows from, the four largest aquifers and Lake Rerewhakaaitu are balanced for the catchment in Table 5. For example the total inflow to the Rangitaiki Ignimbrite Aquifer is estimated at 1405 L/s. An upper estimate of Lake Rerewhakaaitu inflows from surface water and groundwater is 556 L/s.

The model assumes a relatively large proportion of rainfall recharge will flow into the lake from groundwater in the Onuku, Kaingaroa, and Kaharoa/Waiohau aquifers. This will probably give an upper estimate to nutrient entering the lake in Section 13.

Many of these figures are assumed, so any conclusions should be treated with scepticism. However some observations are useful:

- Groundwater flow is largest in the Rangitaiki Ignimbrite Aquifer.

- Groundwater fluxes are generally larger than stream flows – this probably reflects the relatively high rates of soakage of rainfall to the soil and the relatively high permeability of the geological units.

- An estimated 556 L/s is flowing from Lake Rerewhakaaitu to groundwater and all of this is going into the Rangitaiki Ignimbrite Aquifer. This is significantly greater than the estimated 80 L/s (and variable over time) estimated by McIntosh et al. (2001) to be leaving the lake.

Table 5. Summary of water flow estimates in the Lake Rerewhakaaitu catchment.

Unit:	Rangitaiki Ignimbrite L/s	Onuku Pyroclastic L/s	Kaingaroa Ignimbrite L/s	Kaharoa/Waiohau Pyroclastic L/s	Lake Rerewhakaaitu L/s	
WATER IN:						sums:
Rainfall	310	430	570	520	270	2100
ET	95	130	170	160	140	695
R-ET	215	300	400	360	130	1405
KR	328	-	-	-	-	
OR	126	-	-	-	-	
KWR	180	-	-	-	-	
LIR	556	-	-	-	-	
SIR	0	-	-	-	-	
RL	-	-	-	-	0	
OL	-	-	-	-	125	
KWL	-	-	-	-	180	
SIL	-	-	-	-	121	
SUM:	1405	300	400	360	556	
WATER OUT:						
RL	0	-	-	-	-	
RS	197	-	-	-	-	
RB	1208	-	-	-	-	
OL	-	125	-	-	-	
OS	-	49	-	-	-	
OR	-	126	-	-	-	
OB	-	0	-	-	-	
KR	-	-	328	-	-	
KS	-	-	72	-	-	
KWR	-	-	-	180	-	
KWL	-	-	-	180	-	
LIR	-	-	-	-	556	
SOL	-	-	-	-	0	
SUM:	1405	300	400	360	556	
Balance in-out	0	0	0	0	0	

is a cell with an equation

- Estimated recharge to the lake from groundwater and streams, at a sum of about 426 L/s is greater than estimated net rainfall on the lake of around 130 L/s.

- An estimated 1208 L/s is flowing out through the Rangitaiki Ignimbrite Aquifer boundary to Lake Rotomahana in the west and Rangitaiki catchment in the east. A transmissivity of approximately 625 m^2/day (within the range of transmissivity for the Waiotapu Ignimbrite aquifer, Section 6.1), flow face of 8km (from Figure 10), and groundwater gradient of 0.02 (from Figure 10) is sufficient to transport water at around this rate.

- Specific discharge into the lake, where groundwater is potentially discharging to the lake, is likely to be relatively low. For example, the specific discharge from the Kaharoa/Waiohau Pyroclastic Aquifer is estimated as approximately 40 L/s/km of lakeshore (180 L/s assumed discharging from the aquifer across approximately 5 km of lakeshore).

- The maximum land area that potentially impacts on lake water quality is estimated as 12 km^2, or 31% of the catchment around the lake. This area is the sum of land areas for three aquifers: Onuku Pyroclastic Aquifer (58% of 8.48 km^2), Kaingaroa Ignimbrite Aquifer (18% of 11.31 km^2) and Kaharoa/Waiohau Pyroclastic Aquifer (50% of 10.32 km^2).

13.0 NITROGEN INPUTS TO LAKE REREWHAKAAITU

Lake Rerewhakaaitu was classed as a ‘mesotrophic lake’ in 2002 as it had a Trophic Level Index (TLI) of 3.3 (Gibbons – Davies, 2003). The mean annual TLI for Lake Rerewhakaaitu has ranged between 3.2 and 4.3 between the 1990 and 2002. Total nitrogen in the lake increased by 0.004 g/m^3 N per year (average) between 1990 and 2002 (Gibbons – Davies, 2003). Streams and groundwater are potential carriers of nitrogen to the lake. The measured levels of total nitrogen concentrations in the lake are greater than the levels of nitrate-nitrogen in the lake; a ratio of total nitrogen to nitrate-nitrogen is about 5 (mean of 34 measurements between 1990 and 2003).

13.1 Streams

Mangakino Stream and Awaroa Stream flow into Lake Rerewhakaaitu through wetland areas. McIntosh et al. (2001) expected the 'nutrient reductions would occur' in these wetland areas.

Nitrogen observations in these streams (Table 6) show that:

1) Mangakino Stream has lower nitrogen levels than Awaroa Stream, and

2) nitrogen is tending to increase over time in the streams. Awaroa Stream may have relatively high concentrations of nitrogen because of discharge from the adjacent Kaingaroa Ignimbrite.

Table 6. Nitrogen observations in Mangakino and Awaroa streams (McIntosh et al. 2001).

	Median Total Nitrogen (g/m^3)		
Stream	**1970s**	**1990s**	**2000**
Mangakino	1.21	1.64	2.36
Awaroa	3	8.4	

13.2 Groundwater and springs

Groundwater quality samples of nine wells in the region (Appendix 5) in 2002 and 2003 detected nitrogen in the ammonia and nitrate forms. The range of nitrate – nitrogen observation is 0 g/m^3 (i.e. below detection limits) to 7.6 g/m^3. (Figure 14). These nitrate – nitrogen levels are less than Ministry of Health (2000) guideline for drinking water of 11.3 g/m^3. Ammonia is detected in three of the wells at levels less than the Ministry of Health (2000) guideline of 1.5 g/m^3 for aesthetic determinands.

The occurrence of nitrogen in groundwater indicates that land use is having an effect on groundwater quality. Typically, in New Zealand groundwater, the nitrate – nitrogen levels decrease as the depth to water increases (Rosen 2001). However nitrate – nitrogen levels, for the wells where no ammonium is measured, show no significant relation to water depth in the Lake Rerewhakaaitu area (Figure 15). Figure 15 does not include groundwater in wells with measurable ammonium. Measurable ammonium concentrates indicate that either the groundwater is relatively near to source and the nitrogen has not had sufficient time to convert to the relatively stable nitrate form, or the aquifer has chemically reducing conditions.

Relatively high nitrate – nitrogen concentrations were measured in shallow groundwater in the Awaroa Stream bed in July 2003 (Appendix 5). A median nitrate – nitrogen concentration of 8.27 g/m^3 is calculated from these observations.

Water from seven springs was sampled in 2003 (Appendix 5) to the west of Lake Rerewhakaaitu (Figure 14). All spring water contained some ammonium. Nitrate – nitrogen concentrations in these springs are typically less than the concentrations observed in groundwater. Nitrate-nitrogen are typically less than 1 g/m^3 for most springs which is comparable to nitrate-nitrogen concentrations in the lake. This is not inconsistent with Lake Rerewhakaaitu being a source of water for these springs.

13.3 Nutrient flux to Lake Rerewhakaaitu

A nitrogen balance for Lake Rerewhakaaitu considers the estimated flow rates in the lake from rainfall, streams and groundwater (Table 5) and the nitrogen (as nitrate – nitrogen) concentrations for each source (Table 7). The nitrogen concentrations of each potential source are estimated for the Onuku and Kaharoa/Waiohau aquifers using the nitrate – nitrogen concentrations in the Mangakino Stream. The concentration in the Awaroa Stream is taken as the median, and rounded, 2003 shallow groundwater observations (Appendix 5).

Table 7. Estimated nitrogen inputs to Lake Rerewhakaaitu.

Source	**L/s**	**m^3/day x 10^3**	**Nitrate – nitrogen conc g/m^3**	**N flux KgN/day**
Rainfall - evaporation	130	11	0	0
Onuku Aquifer	125	11	1.6	18
KW Aquifer	180	16	1.6	26
Mangakino Stream	76	7	1.6	11
Awaroa Stream	45	4	8.3	33
Total	556	48*		88

* does not sum, due to rounding

Water flowing into the lake is estimated to have a mean nitrate – nitrogen concentration of 1.8 g/m^3 i.e. 88 kg/day divided by $48x10^3$ m^3/day. This is an upper estimate as lake inflow water volumes in Table 5 are also upper estimates. The estimate of 1.8 g/m^3 is significantly greater than the 0.39 g/m^3 average Lake Rerewhakaaitu observed total nitrogen concentration in the period 1990 to 2002 (Gibbons – Davies 2003) indicating that de-nitrification processes are probably acting on the inflowing waters. A model with rainfall and streams as the sole source of water estimates a concentration of 2 g/m^3 in the lake (i.e. 44 kgN/day divided by $22x10^3$ m^3/day). This estimated concentration is also significantly greater than total nitrogen levels observed in the lake and significantly greater than the estimated nitrate-nitrogen concentrations in the lake.

14.0 SUMMARY

Five significant episodes in the geological history of the Lake Rerewhakaaitu area give us the geological structure we see today:

- Rangitaiki Ignimbrite was erupted from the Maroa Caldera, in the Wairakei-Atiamuri area 350,000 years ago,

- Okataina Caldera formed in the Rotoiti to Rotomahana area,

- Kaingaroa Ignimbrite erupted from the Reporoa Caldera 230,000 years ago,

- Mt Tarawera began forming 21,000 years ago and significantly altered the drainage in the area,

- Lake Rerewhakaaitu reached its present shape and elevation with the Kaharoa eruption from Mt Tarawera 700 years ago.

Geological information about the stratigraphy and structure of the Rerewhakaaitu region has been combined with the available well data to produce a conceptual model of the Lake Rerewhakaaitu catchment:

- The lake occupies a shallow basin developed on the eroded Rangitaiki Ignimbrite surface,
- Land use in up to one third, approximately, of the catchment could impact on lake water quality. This land is in two areas: 1) north east of the lake between the lake and GD1 (Figure 10), and 2) south of the lake between GD2 (Figure 10) and the western boundary of the catchment. In this second area rainfall recharge makes its way to the lake via groundwater or streams,
- Streams entering the lake from the south are fed by shallow aquifers perched within Kaingaroa Ignimbrite and other recent geological units,
- The main aquifer is the Rangitaiki Ignimbrite Aquifer and most wells take water from this aquifer,
- Recharge to the Rangitaiki Ignimbrite Aquifer is from vertically-percolating rainfall and from Lake Rerewhakaaitu; the aquifer drains to lower country in the west, south and east,
- Groundwater levels in the Rangitaiki Ignimbrite Aquifer are commonly below the level of Lake Rerewhakaaitu meaning that the lake may recharge this aquifer,
- The westward flow from the Rangitaiki Ignimbrite Aquifer is directed towards Lake Rotomahana into the drainage sink formed by Haroharo caldera through deep valleys eroded into the caldera rim,
- The eastward flow from the Rangitaiki Ignimbrite Aquifer is directed towards the Rangitaiki River catchment,
- Shallow inflows to the lake may occur from the pyroclastic and alluvial deposits. For example, groundwater and associated with the Mangakino and Awaroa streams may flow into the lake.

A water balance model gives some indication of the water flow in aquifers and the interaction between lake and aquifers, for example:

- The Rangitaiki Ignimbrite Aquifer has the largest flow of groundwater, at an estimated 1405 L/s,

- Total net water flow into the lake is estimated as up to 556 L/s from rainfall, streams and shallow aquifers.

Nitrogen in stream water and groundwater show the influence of land use:

- Nitrogen concentrations in the Mangakino and Awaroa streams have increased over the period between the 1970s and 2000,

- Median total nitrogen concentrations in the 1990s were 1.6 g/m^3 in Mangakino Stream and 8.4 g/m^3 in Awaroa Stream,

- Nitrate-nitrogen concentrations in groundwater were up to 7.6 g/m^3 in a 2002/2003 survey,

- Nitrate-nitrogen concentrations are less than Ministry of Health guidelines for drinking water.

An upper estimate of nitrogen input to the lake is 88 kg N/day. This estimate is based in the water balance model and assumptions of influent nitrogen concentrations. This rate of nitrogen input to the lake is much higher than that required to give the observed nitrogen concentrations in the lake. Therefore it is concluded that de-nitrification processes are acting on the lake recharge. It is likely that a significant mass of influent nitrogen is removed before these nutrients are mixed with the lake water.

15.0 RECOMMENDATIONS

GNS's recommendations aim to build on the information collated and interpreted in this report to further improve information about the groundwater system around Lake

Rerewhakaaitu. The recommendations also aim to provide the information so that models of groundwater flow, and nutrient balance, can be revised and improved in the future.

Information from wells:

- measure well depths, where this is unknown, as wells become available. This information will allow improved identification of aquifers,

- continue to collect information from drillers as wells are drilled,

- obtain pump test information from drillers as wells are drilled to estimate aquifer transmissivity and storativity.

Groundwater level information:

- Improve the quality of water level measurements in the EBOP database. Well water level measurements used in the current study come from a multiple sources. A re-survey of these levels in the future will improve the confidence of interpretations of groundwater flow directions and could better define the areas where land use potentially impacts on lake water quality,

- Identify wells suitable for regular monitoring of groundwater level. Quarterly measurement should be sufficient. This will be useful for long-term monitoring of resource quantity.

Groundwater use information:

- Estimate groundwater resource use and compare with estimates of recharge to ensure sustainability of resource use.

Water quality data:

- Sample well water for groundwater quality. Not many groundwater quality analyses are the database at present and more information would be helpful to understanding land-use impacts,

- Identify a small number of wells for regular (quarterly or six-monthly) monitoring of groundwater quality,

- Measure Mangakino, Awaroa and Te Kauae stream quality, and flow, on a regular basis (quarterly or six-monthly).

Future models of water flows and nutrient flux:

- The models of water flows and nutrient flux should be improved in the future as more data are collected. Some of the following recommendations aim to check predictions of the current models and fill current gaps in information. Improvement of the current model could be followed by more complex modelling e.g. computer models of steady-state and transient flow and quality,

- Improve identification of areas of groundwater inflow into the lake. For example shallow wells could be drilled in area immediately around the lake in the northwest and across the valleys of the Mangakino and Awaroa streams to provide more information on groundwater levels relative to lake levels and therefore groundwater flow directions,

- Provide better estimates of groundwater flowing from the Rangitaiki Ignimbrite Aquifer to Lake Rotomahana across the caldera margin west of Lake Rerewhakaaitu by measuring spring flows,

- Investigate groundwater discharge from Lake Rerewhakaaitu through the northern boundary into the Kaharoa/Waiohau/Rerewhakaaitu Pyroclastic Aquifer by completing hydrogeological investigations and drilling shallow wells,

- Investigate nitrogen concentrations of discharge from the Rangitaiki Ignimbrite Aquifer to Lake Rotomahana and the Rangitaiki River catchment by measuring groundwater quality in discharge areas.

Water dating:

- measure water ages, using the tritium and CFC techniques, to determine residence times of groundwater in the system. This will allow an understanding of the time scales of response of groundwater quality to land use changes.

16.0 ACKNOWLEDGEMENTS

The authors thank Dougall Gordon, Kelly Palmer and Sarah Higham, Environment Bay of Plenty, for collating and supplying: photographs, well information, water quality measurements, and well levels. We also thank Brad Scott for providing well information. Russell West from Rotorua Farm and Industrial Pumping Ltd supplied well information and assisted with water level and water quality surveys. Thanks also to the farmers in the district for allowing access to wells. We also thank Peter Booth, Landcorp Taupo, for providing the well logs of Lands and Survey wells drilled in the 1950s and 1960s. Thanks to Chris Daughney and Dougall Gordon for reviewing the report.

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Appendix 1. Description of contract

Objectives

To enable Environment B.O.P to effectively manage lake water quality a better understanding of the nature and extent of the groundwater resource in the Lake Rerewhakaaitu catchment is needed according to the following objectives:

3.1 An assessment of the nature and extent of the deep aquifer resource and assess the likely recharge area of the deep aquifer resources.

3.2 Determine the direction of deep groundwater flow. This could be to the other Rotorua lakes or to the Rangitaiki catchment to the east.

3.3 Investigate if there are perched shallow aquifers present within the lake catchment including an assessment of shallow groundwater flow direction of the perched shallow aquifers and confirm if the perched shallow aquifers directly discharge to the lake.

3.4 Investigate the likely recharge zone of the shallow aquifer aquifers. Environment B.O.P is particularly concerned about the catchment area to the east of the lake on light soils - Tarawera Ash. Is there groundwater discharge to lake from this area or does the groundwater discharge to the Rangitaiki River catchment to the east.

3.5 Assess the groundwater flux to the lake.

Note: At this stage it is expected that the project will be a desktop type study with view to developing conceptual model of groundwater flux of the lake and catchment and may include site visits with Environment B.O.P staff.

Scope & Nature of the Services:

Proposed methodology:

1) Site visit.
- GNS (White and Reeves) and Environment BOP

2) Near-surface geology of the Lake Rerewhakaaitu Catchment with regard to potential groundwater flow paths.
- collect relevant data from Environment BOP
- review this and other information

3) Hydrology of the Lake Rerewhakaaitu Catchment.
- collect relevant data from Environment BOP
- review

4) Review the landuse of the Lake Rerewhakaaitu Catchment with regard to nutrient generation.
- based on 'Lake Rerewhakaaitu Project', McIntosh et al. June 2001

5) Groundwater

The following addresses points 1, 2, 3, 4 and 5 of the project scope:

- **5.1** Schematic map to indicate groundwater flow directions in the Lake Rerewhakaaitu Catchment/ Lake Rotomahana/Lake Tarawera area
- **5.2** Interpretation of near-surface geology of the Lake Rerewhakaaitu Catchment and groundwater hydrology assessing evidence for:
- a shallow, perched aquifer, and 2) a deep aquifer
- **5.3** Schematic model of the groundwater flow direction in any perched shallow aquifer in the Lake Rerewhakaaitu Catchment
- **5.4** Schematic model of the groundwater flow direction in any deep aquifer in the Lake Rerewhakaaitu Catchment
- **5.5** Identification of the recharge zone for any perched shallow aquifer in the Lake Rerewhakaaitu Catchment
- **5.6** Identification of the recharge zone for any deep aquifer in the Lake Rerewhakaaitu Catchment
- **5.7** Discussion of any likely groundwater discharge to Lake Rerewhakaaitu in the area east of the lake on light soils
- **5.8** Estimate steady-state groundwater flux to the lake and compare with surface water flux
- **5.9** Estimate steady-state groundwater nutrient flux to the lake and compare with surface water nutrient flux

6) Report

Appendix 2. Well data used in the study.

Information on wells in the groundwater catchment of Lake Rerewhakaaitu was provided on the 19/6/02 by Environment Bay of Plenty and over the period June 2002 to August 2003.

Table A2.1 Summary information on wells with water level measurements in the Lake Rerewhakaaitu area from the Environment Bay of Plenty database.

EBOP Pump No.	Allocated Well No.	Geology (assumed*)	Aquifer	Well Depth (m)	Static Water Level (m rl)	Well Elevation (mrl)	Static Water Depth (m)	Drillers water level (m)
	1	o/ra*	Rangitiki Ignimbrite	76	455.685	479.685	24	24
1595	2	o	Onuku Pyroclastic	38.5	431.801	457.801	26	
	3	bk/lw/ra*	Rangitiki Ignimbrite		433.574	457.074	23.5	
	4	o/ra	Rangitiki Ignimbrite	98	433	460		27
247	5	fa/kg/ra*	Rangitiki Ignimbrite	84.47	443	455	12	
	6	fa/kg/ra	Rangitiki Ignimbrite	79	438	470		32
3585	7	o/ra	Rangitiki Ignimbrite	139	409	475	66	66
	9	fa*	Perched	30	462.856	478.856	16	
10486	11	kg/o/ra*	Rangitiki Ignimbrite	138	415	504.791	90	80
	12	kg/ra	Rangitiki Ignimbrite	244	409	500		91
	14	fa/kg/ra*	Rangitiki Ignimbrite		431.711	479.311	47.6	
3505	15	fa/kg/ra	Rangitiki Ignimbrite	50	437.334	448.834	11.5	
3505	16	fa/kg/ra	Rangitiki Ignimbrite	60	437.5	449		11.5
1075	17	ra	Rangitiki Ignimbrite	67.1	404.191	414.791	10.6	
	18	ra*	Rangitiki Ignimbrite		384.4	410	25.6?	
	19	ra*	Rangitiki Ignimbrite	49	415.8	440	aprox 24.4?	19
	20	bk/lw/ra	Rangitiki Ignimbrite	67	434	450		16
	21	bk/lw/ra	Rangitiki Ignimbrite	61	435.709	449.209	13.5	15
	24	ra*	Rangitiki Ignimbrite		424.6	440	15.4	
	29	bk/lw/ra	Rangitiki Ignimbrite	33.5	434.683	458.683	24	
	30	bk/lw/ra	Rangitiki Ignimbrite	67	420.6	435	14.4	
	32	bk/lw/ra*	Rangitiki Ignimbrite		426.105	442.305	16.2	
2114	33	ra	Rangitiki Ignimbrite	81.5	412	440	28	
1267	34	fa/ra	Rangitiki Ignimbrite	58	410	430	20	
	36	o/ra*	Rangitiki Ignimbrite		403.047	485.547	82.5	
10169	37	ra	Rangitiki Ignimbrite	69	419.849	439.649	19.8	
	38	fa/kg/o/ra	Rangitiki Ignimbrite	140	426.77	461.37	34.6	29
10485	40	ra/gravels?	Rangitiki Ignimbrite	120	397.673	464.473	66.8	92
3586	42	o/ra	Rangitiki Ignimbrite	154	408	490	82	82
	43	??	Perched		460	490	aprox 30?	
	45	o/ra*	Rangitiki Ignimbrite		409.111	466.111	57	
	47	ra	Rangitiki Ignimbrite	94.5	427.3	445	aprox 17.7?	
	50	ra*	Rangitiki Ignimbrite		428.63	457.43	28.8	
	51	ra*	Rangitiki Ignimbrite		391.704	445.904	54.2	
	52	ra*	Rangitiki Ignimbrite		398.708	470.508	71.8	

EBOP Pump No.	Allocated Well No.	Geology (assumed*)	Aquifer	Well Depth (m)	Static Water Level (m rl)	Well Elevation (mrl)	Static Water Depth (m)	Drillers water level (m)
	53	ra/gravels?	Rangitiki Ignimbrite	171	397.882	470.682	72.8	73
	54	ra*	Rangitiki Ignimbrite		399.069	470.869	71.8	
1210	57	ra	Rangitiki Ignimbrite	93.5	408	455	47	
	60	o/ra*	Rangitiki Ignimbrite	88	391.64	467.64	76	
	62	kg/ra	Rangitiki Ignimbrite	100-120	462	490		28
	63	fa/kg/ra	Rangitiki Ignimbrite	112	400	485		85
1583	66	o	Onuku Pyroclastic	51.8	452	470	18	
248	67	o/ra	Rangitiki Ignimbrite	121	409	470	61	
	69	bk/lw/vr	Pyroclastics	37	356.4	360		3.6
2144	70	o/ra	Rangitiki Ignimbrite	61	417	460	43	
	71	o/ra	Rangitiki Ignimbrite	91	428.63	459.63	31	
	73	bk/lw/vr*	Pyroclastics		361.6	370	8.4	
	76	bk/lw/vr*	Pyroclastics		416	420	4	
	77	o/ra*	Rangitiki Ignimbrite		426.309	473.409	47.1	
	79	o	Onuku Pyroclastic	42	437	470	approx 33	
143	84	o/ra	Rangitiki Ignimbrite	103.7	389	450	61	
	85	o/ra	Rangitiki Ignimbrite	110	439	480		41
2128?	86	ra	Rangitiki Ignimbrite	78.5	409.371	448.871	39.5	
3099	88	o/ra	Rangitiki Ignimbrite	153	418.261	441.761	23.5	21
	89	fa/o/ra*	Rangitiki Ignimbrite		412.9	450	37.1	
	91	o/ra	Rangitiki Ignimbrite	73	420	440		20
	92	ra	Rangitiki Ignimbrite	140	388	440		52
	93	ra	Rangitiki Ignimbrite	128	406	440		34
10483	94	ra	Rangitiki Ignimbrite	90	432	450		18
10481	95	o	Onuku Pyroclastic	36	414	440	26	26
	114	fa/ra	Rangitiki Ignimbrite	61	410	430	20	
	117	o/ra*	Rangitiki Ignimbrite	183	416	465		49
	119	o/ra	Rangitiki Ignimbrite	78	413	440		27

Notes: Geology is inferred from 1: 50 000 geology map (Nairn in press) and drillers logs (where available). Key is: bk – Kaharoa Pyroclastics; lw – Waiohau Pyroclastics; fa – alluvium; Hol – Holocene tephras; o – Onuku Pyroclastics; na – Matahina Ignimbrite; b – Bonisch Pyroclastics; ra – Rangitaiki Ignimbrites.

Appendix 3. Hydrological data used in the study

Data supplied by Environment Bay of Plenty.

Physical hydrology

Lake Rerewhakaaitu levels					
TIDEDA Site	**File**	**Site**	**On**	**Off**	**Comments**
Homestead Arm	1015310.mtd	1015310	830420	011231	
Awaatua Bay	150308.mtd	15308	821215	830325	
Rainfall					
Lake Rerewhakaaitu rainfall	862402.mtd	862402	770102	020401	Daily rainfall
Pokairoa at Pylons Road	863601.mtd	863601	930923	020313	Inst. rainfall

Stream gaugings

Lakereregaugings.xls, consisting of:

Site 15350 - Mangakino @ County Bridge V16: 143 149
- 67 gaugings between 03/01/75 and 27/07/01

Site 15349 - Awaroa @ Rerewhakaaitu V16: 155 145
- 58 gaugings between 19/05/44 and 27/07/01

Appendix 4. Estimation of mean rainfall.

Mean rainfall is calculated in the catchment as 1319 mm (site 862402) and 1800 mm (site 863601). These are the sum of monthly means for the period of record (Appendix 3) for the months where a full month of record exists. Data is missing in intervals from October 1992 to May 1993 and June 1997 to July 1997 in the record of 862402. Data estimated to 'patch' these gaps is as follows:

Oct 92	185
Nov 92	88
Dec 92	155
Jan 93	15
Feb 93	50
Mar 93	64
Apr 93	52
May 93	141
Jun 97	180
Jul 97	68

This was provided by Glenn Ellery (EBOP pers. comm. 2003) from the relationship of the monthly record at this site with the monthly record at site 861362 – Wilson (R^2 = 0.87).

Appendix 5. Water chemistry – surface water, groundwater and springs.

Description	Source	Collect Date	Ammonia-N g/m3-N	Nitrate-N g/m3	Total Nitrogen g/m3-N
Rerewhakaaitu Road	Mangakino Stream	31/08/2000	0.112	1.2	2.76
Rerewhakaaitu Road	Mangakino Stream	27/09/2000	0.098	2.1	0.57
Rerewhakaaitu Road	Mangakino Stream	27/10/2000	0.06	1.9	0.377
Rerewhakaaitu Road	Mangakino Stream	1/12/2000	0.028	1.9	0.327
Rerewhakaaitu Road	Mangakino Stream	13/12/2000	0.034	1.8	0.329
Rerewhakaaitu Road	Mangakino Stream	2/04/2003			
Lake Edge	Lake Rerewhakaaitu	13/03/2001	0.006	0.003	
Half Moon Bay	Lake Rerewhakaaitu	7/03/2001	0.024	0.018	
Half Moon Bay	Lake Rerewhakaaitu	7/03/2001	0.019	0.013	
Domain	Lake Rerewhakaaitu	7/03/2001	0.008	0.0005	

Description	Owner	Collect Date	DRP; g/m3-P	Ammonia - N (NH4); g/m3-N	Nitrate - N g/m3
Groundwater Bore	Pearce	4/03/2002	0.043	0.14	0.00
Groundwater Bore	Moselen	4/03/2002	0.042	0.00	7.20
Groundwater Bore	Way	4/03/2002	0.015	0.09	0.08
Groundwater Bore	Smith	4/03/2002	0.031	0.00	5.00
Groundwater Bore	O'Donnell #1	4/03/2002	0.078	0.00	3.00
Groundwater Bore	O'Donnell #2	4/03/2002	0.021	0.00	5.40
Groundwater Bore	Mascall	4/03/2002	0.097	0.00	1.60
Groundwater Bore	Sutton	4/03/2002	0.05	0.00	7.60
Spring	Way	11/04/2003			
Spring - 50m up Gully	Way	2/04/2003	0.072	0.17	0.00
Spring (Shallow)	Pearce	17/03/2003	0.028	0.03	2.70
Spring (Shallow)	Way	17/03/2003	0.024	0.11	0.13
Spring (Shallow)	Mascall	17/03/2003	0.016	0.03	0.02
Spring Lower Gully	Way	2/04/2003	0.104	0.16	0.00
Spring Upper Gully	Way	2/04/2003	0.095	0.20	0.03
Well	Pacey Well	17/03/2003	0.098	0.02	0.00

Chemical analysis of shallow groundwater in the Awaroa Stream Valley.

Location: A hand-dug hole, in the dry Awaroa Stream channel, to about 1 m. The samples were taken immediately above a low-permeability layer. Considerable groundwater flow was occurring above the layer.

Map coordinate of sample: NZMS V16 150 146

Nutrients in three samples, taken in June 2003, are as follows:

DRP	NH_4-N	NO^3-N
0.044	0.14	8.27
0.046	0.15	8.32
0.052	0.12	8.04

All analyses are g/m^3

Groundwater chemistry reports

- Rerewhakaaitu School, Well 3505, water chemistry report 05/06/91 from DSIR chemistry
- Rerewhakaaitu School - Report on the quality of the water. ESR Health report 10/05/95
- Rerewhakaaitu School - Analytical report. ESR Health 30/10/96
- Rerewhakaaitu School - Analytical report. ESR 09/05/97
- Rerewhakaaitu School - Analytical report. ESR 25/06/97
- Rerewhakaaitu School - Analytical report. Agriquality 17/05/2001

Nitrate-nitrogen concentrations were not measured in all of these tests. Samples of water at a variety of locations in the school, including taps, had nitrate-nitrogen concentrations of:

2.9 g/m^3 on the 30/4/91
3.9 g/m^3 on the 20/3/95
4.0 g/m^3 on the 15/4/97
4.0 g/m^3 on the 4/6/97

Water analysis reports

- water analysis report for Pacey (well 88) by Contamination Control Limited, 20 July 1999
  - water had low: pH, total dissolved solid and hardness
  - water had high: free carbon dioxide (15 g/m^3)
  - nitrate < 1 g/m^3

- water analysis report for Pacey by NZ Hydroponics Ltd
  - water acceptable for domestic and irrigation use
  - high carbon dioxide (30 g/m^3)

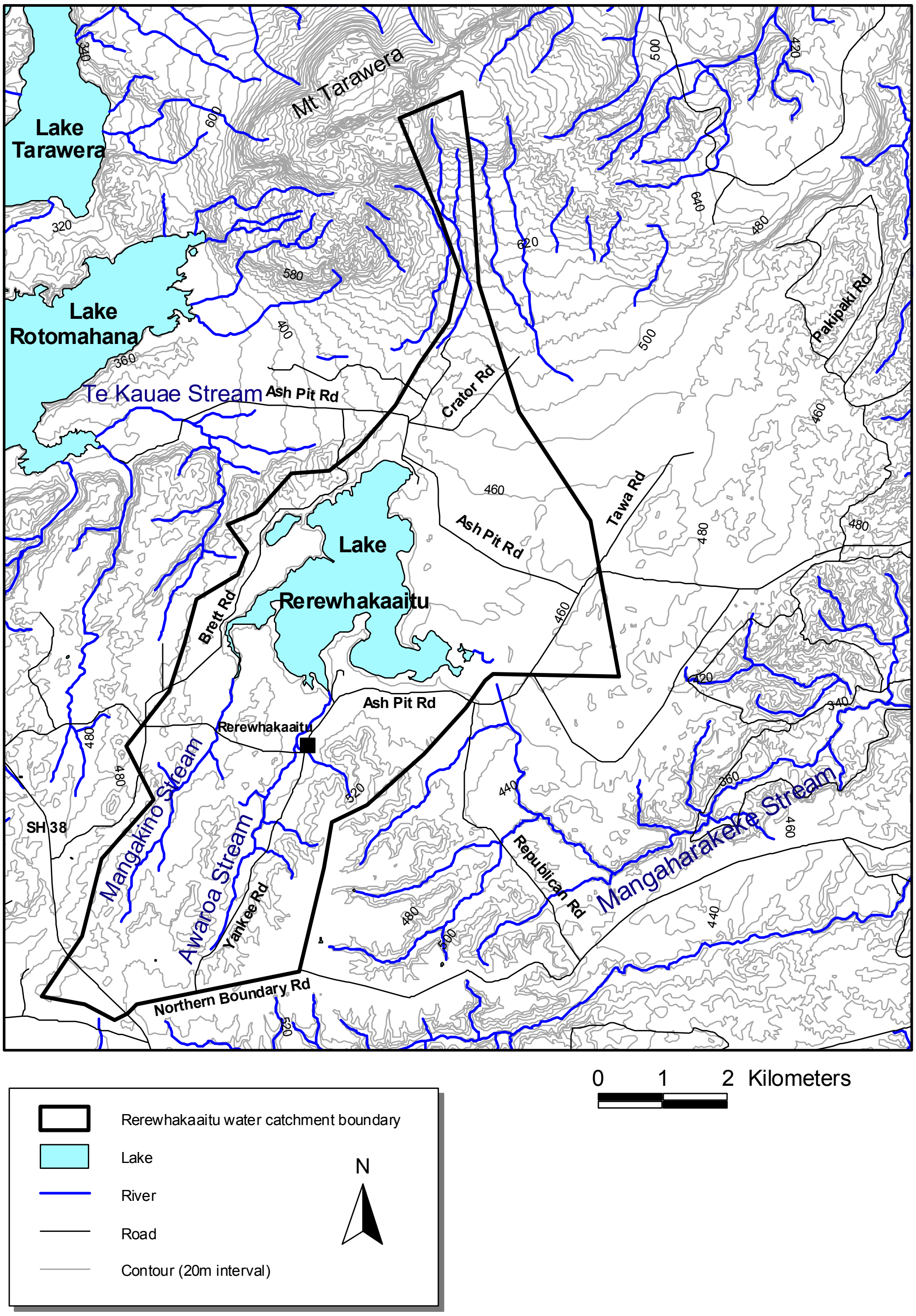

Figure 1. Map showing Lake Rerewhakaaitu, streams, topographic features, roads, and the Lake Rerewhakaaitu topographic catchment boundary. Topographic data obtained from Eagle Technology under licence from LINZ.

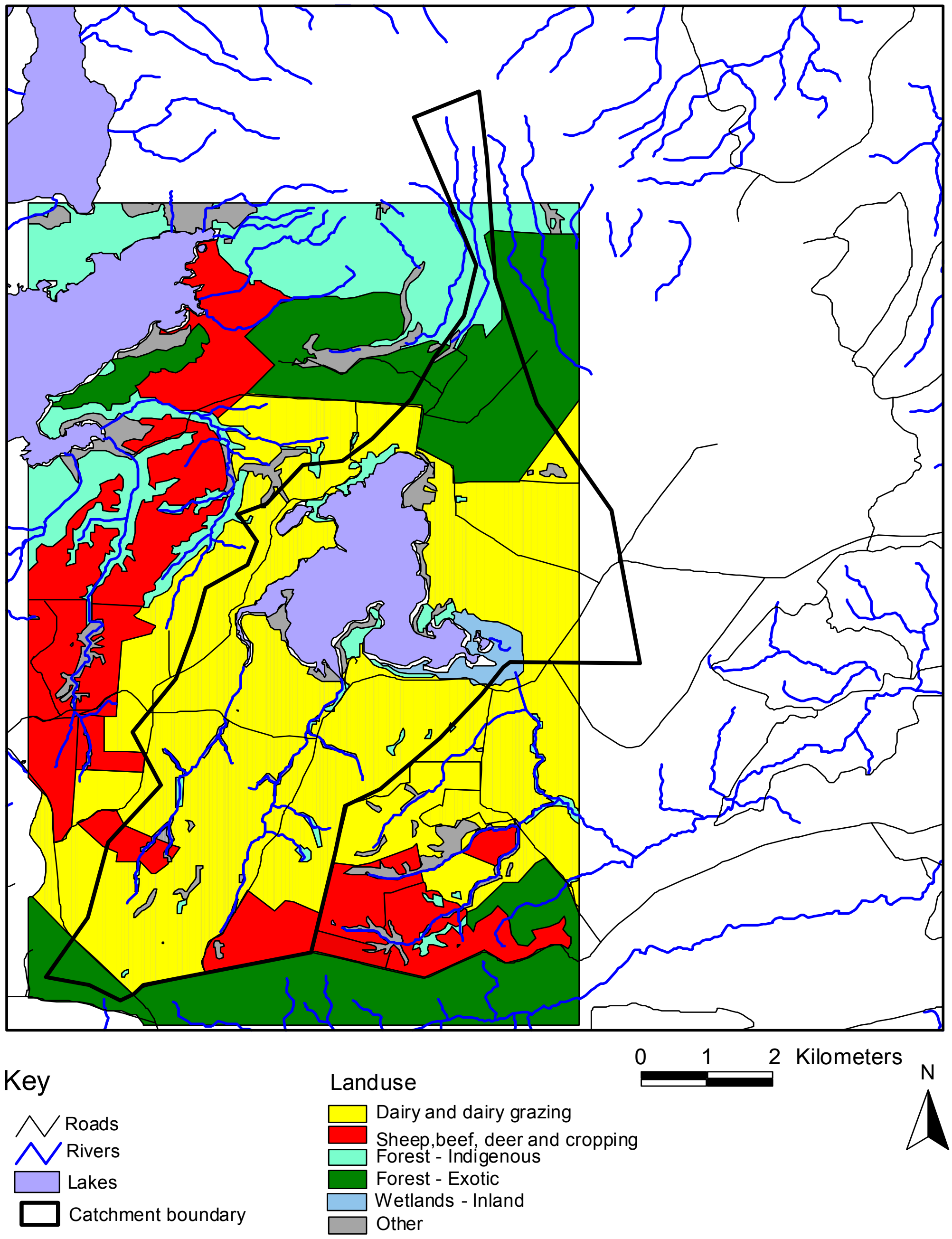

Figure 2. Land use in the Lake Rerewhakaaitu catchment. Land use data obtained from Environment Bay of Plenty.

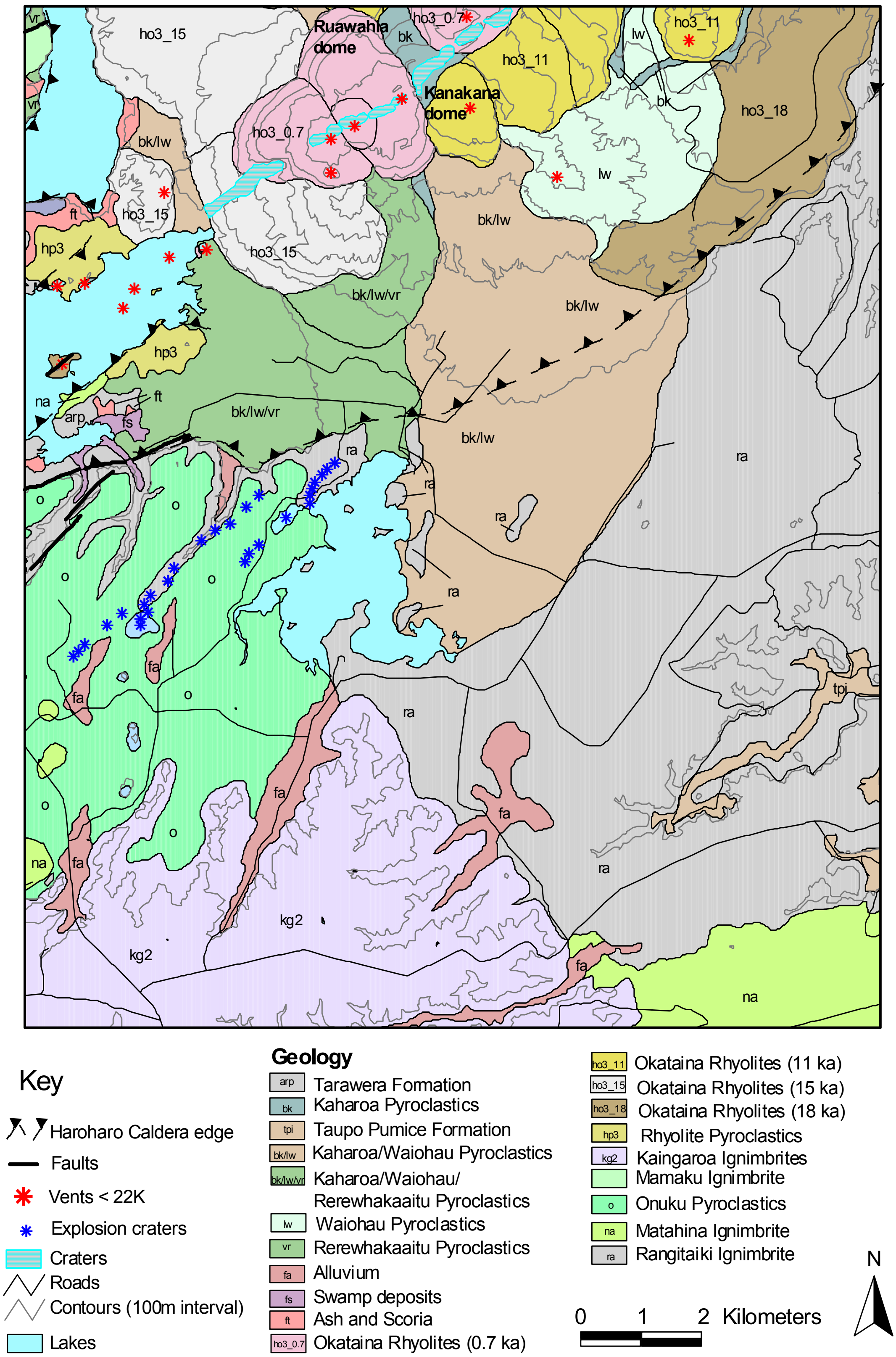

Figure 3. Map showing geology and structure, Lake Rerewhakaaitu catchment. Geology modified from Nairn (in press). Original map scale 1:50 000.

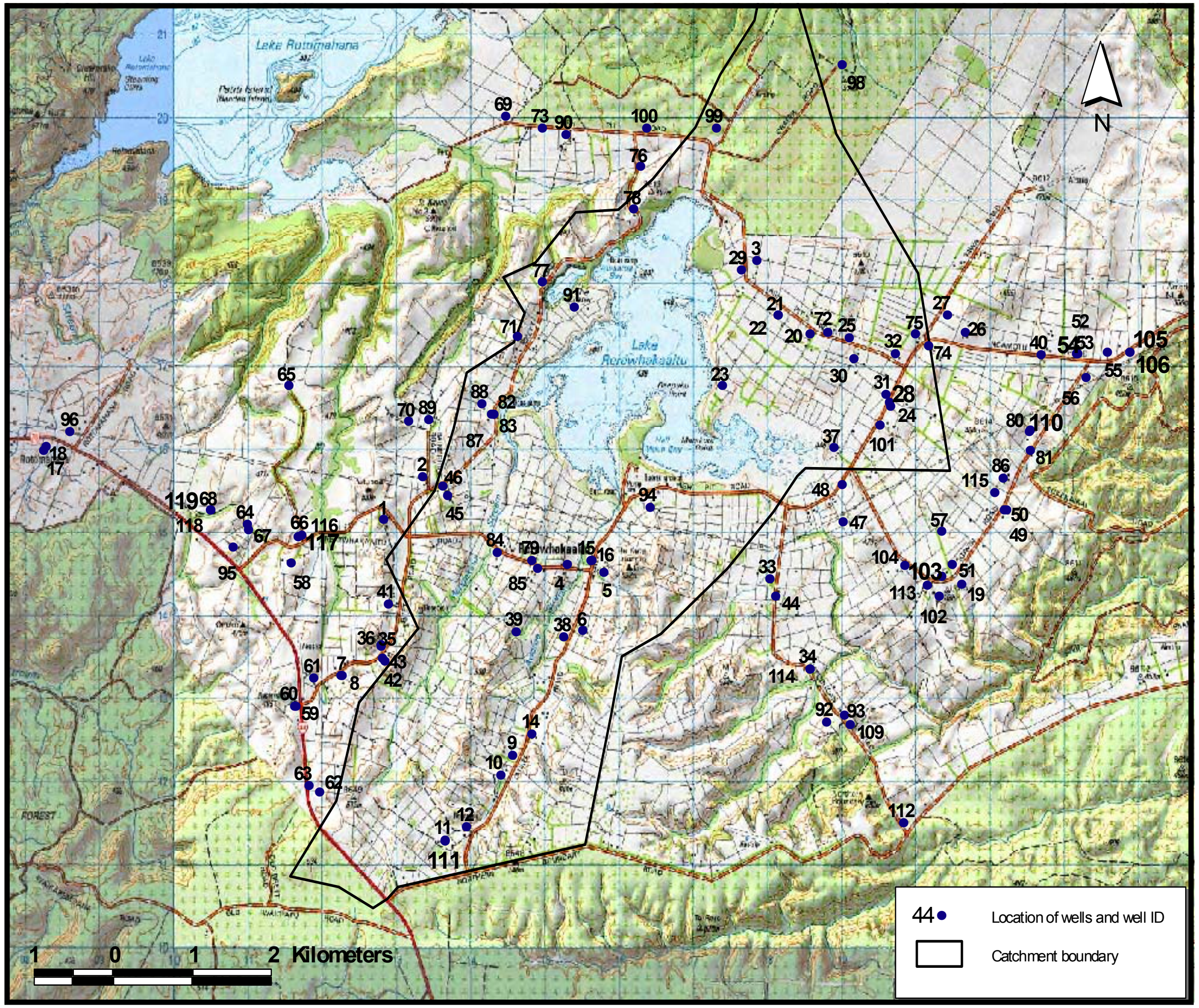

Figure 4. Location of all known wells from the Environment Bay of Plenty database.

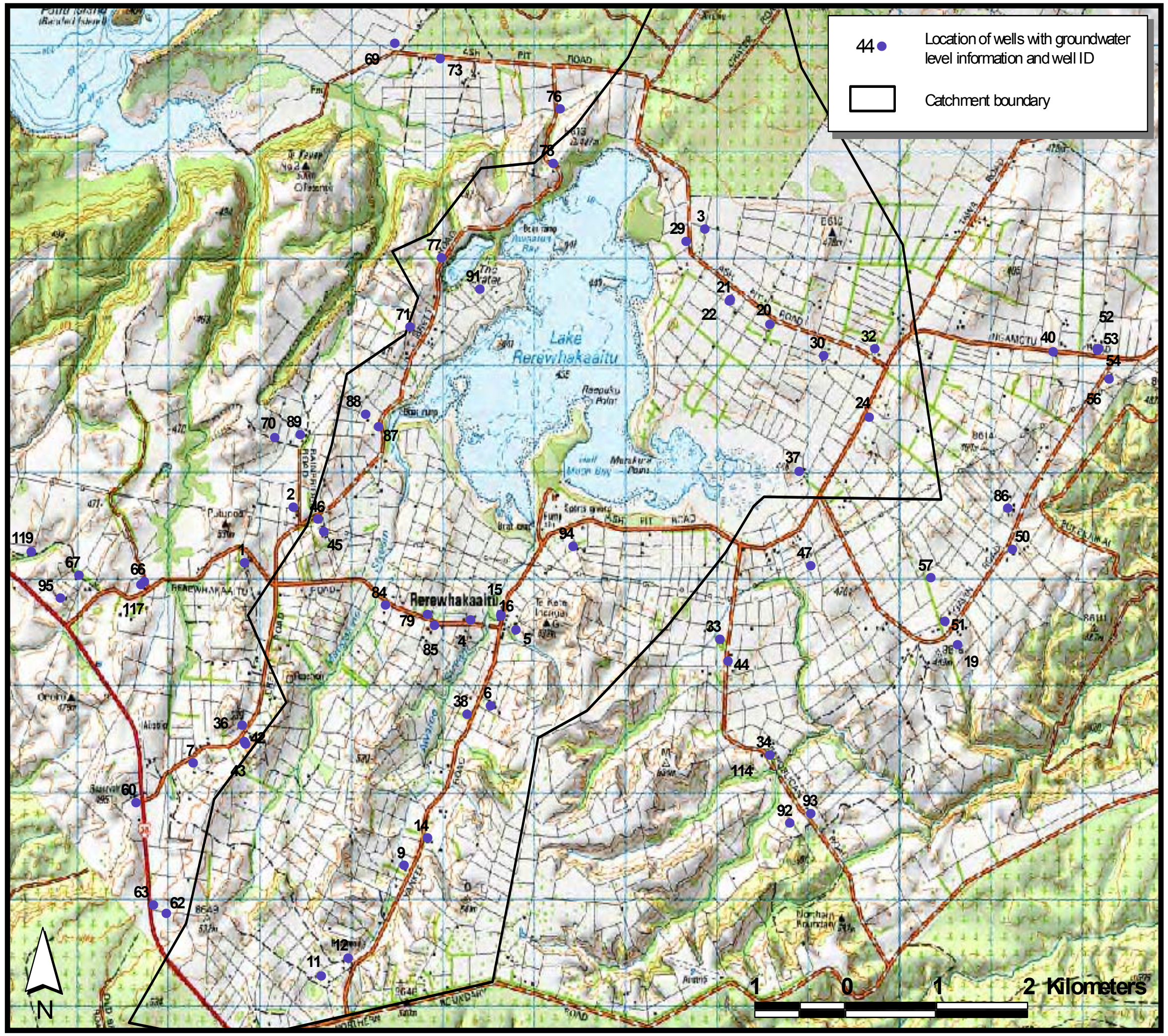

Figure 5. Location of wells with groundwater level information.

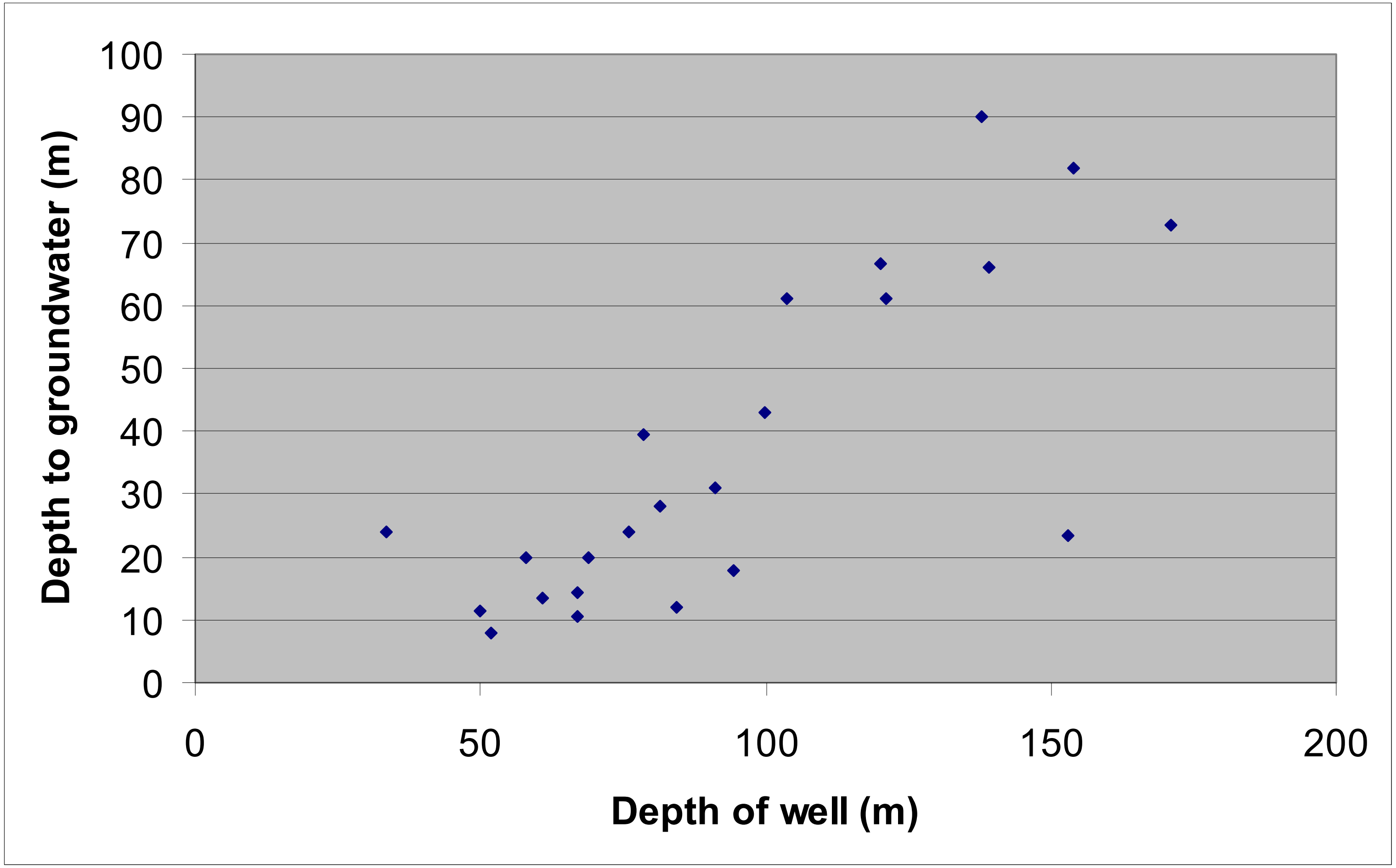

Figure 6. Depth to groundwater in wells versus depths of wells in the Lake Rerewhakaaitu area.

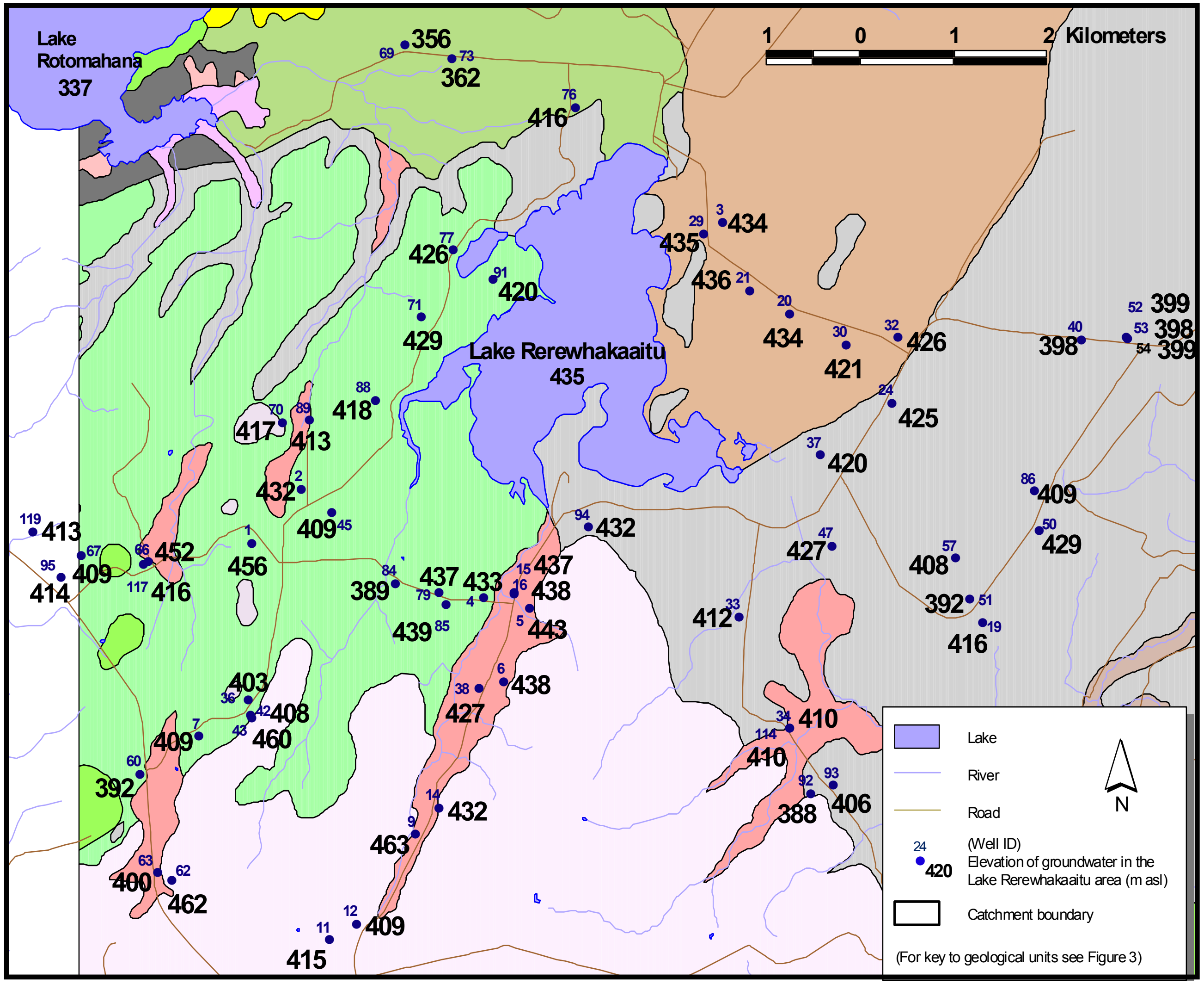

Figure 7. Elevation of groundwater in wells within the Lake Rerewhakaaitu area (meters above mean sea level).

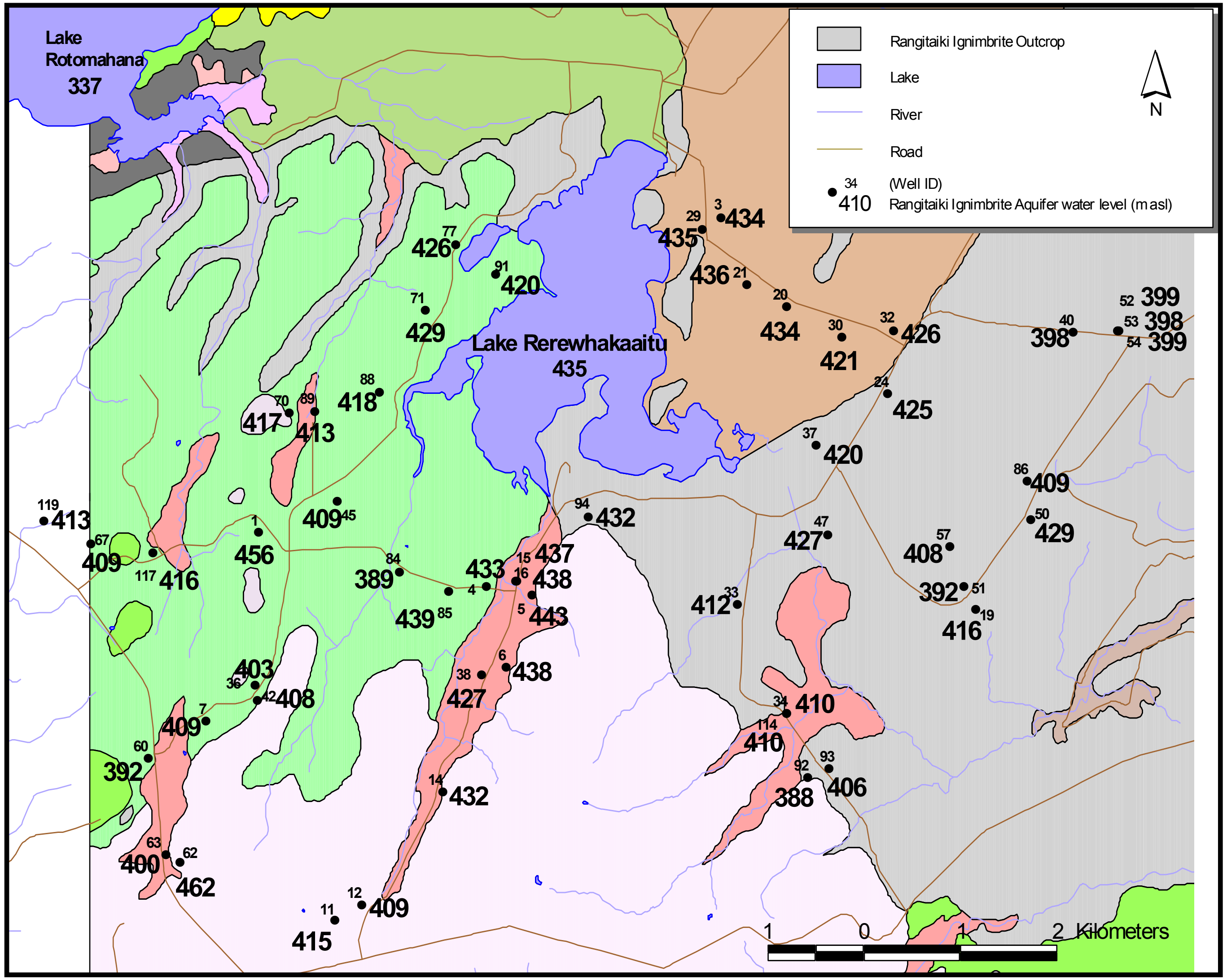

Figure 8. Groundwater levels in the Rangitaiki Ignimbrite Aquifer.

Figure 9. Spring at the base of a steep slope near the northern corner of Brett Road and Ashpit Road (Gordon, pers. comm.).

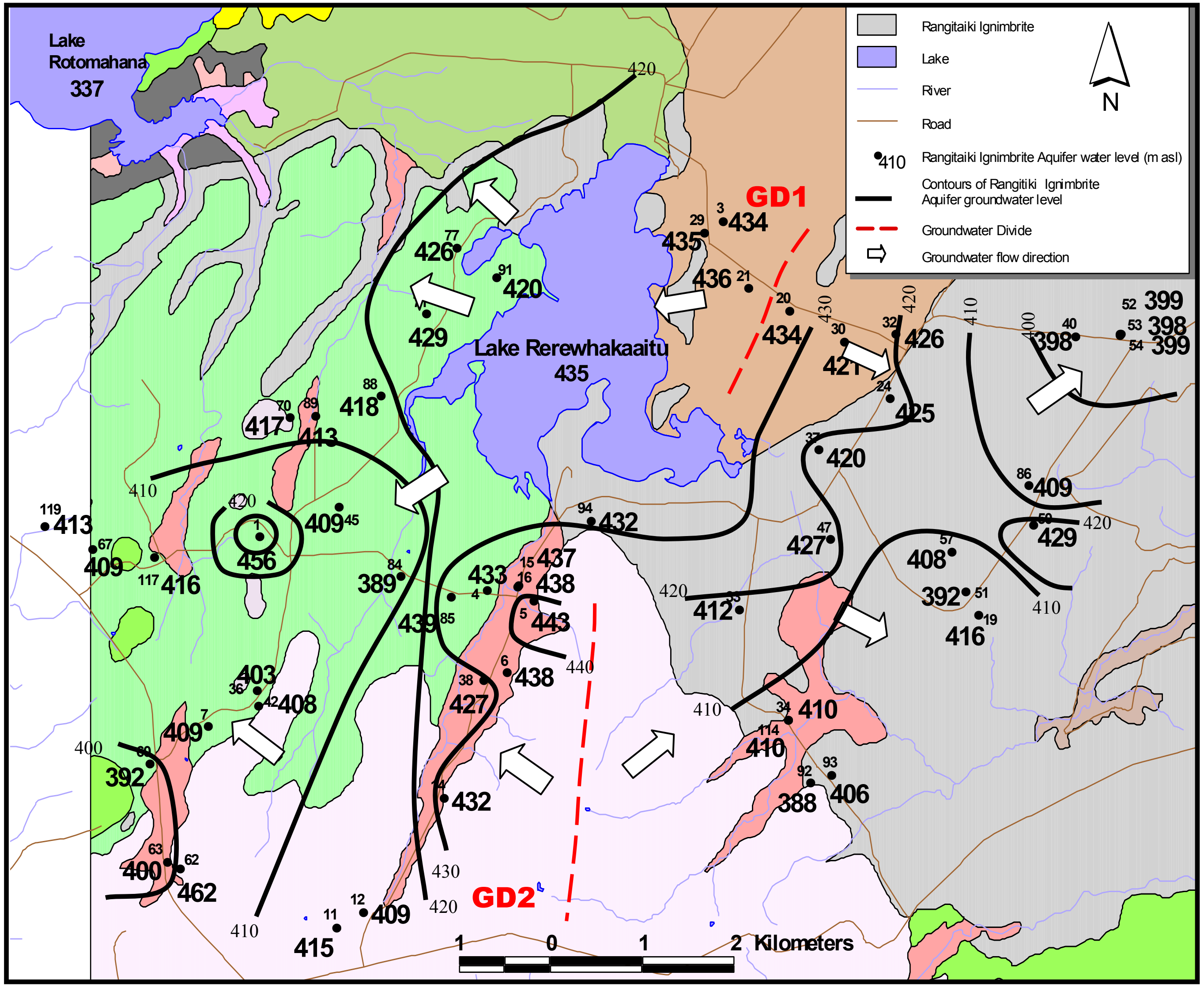

Figure 10. Groundwater level contours and groundwater flow directions in the Rangitaiki Ignimbrite Aquifer.

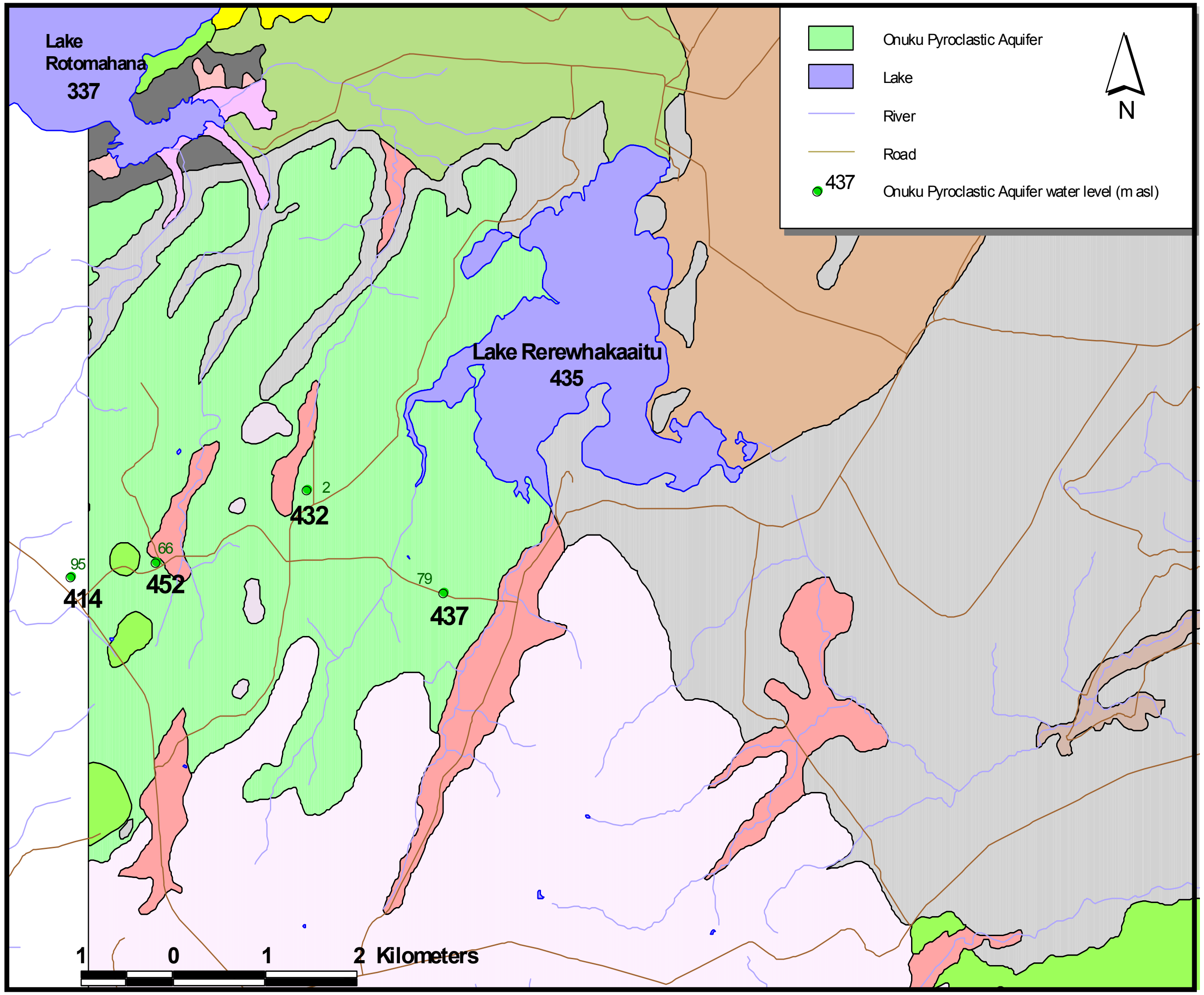

Figure 11. Groundwater levels in the Onuku Pyroclastic Aquifer.

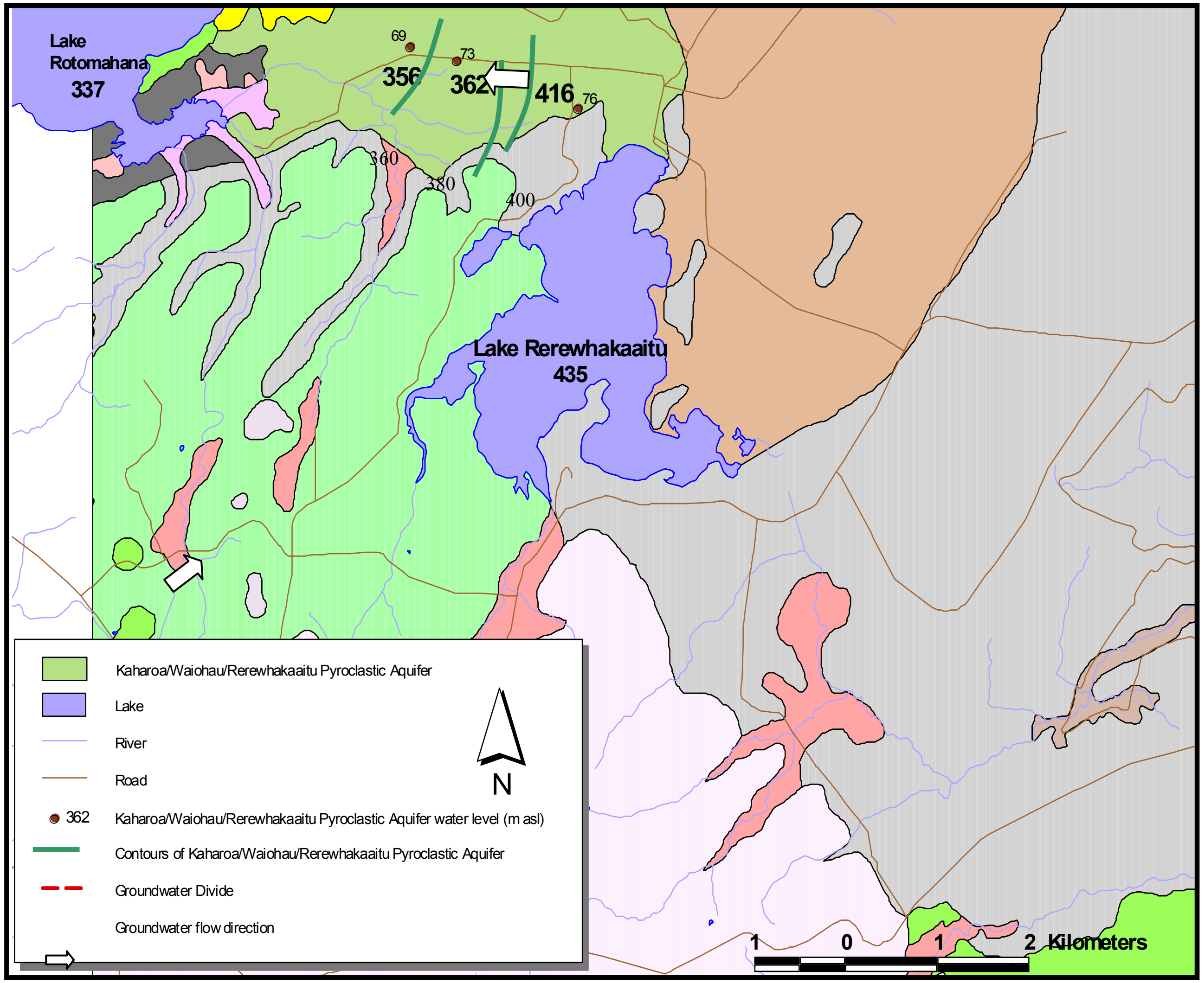

Figure 12. Groundwater level contours and groundwater flow direction in the Kaharoa/Waiohau/Rerewhakaaitu Pyroclastic Aquifer.

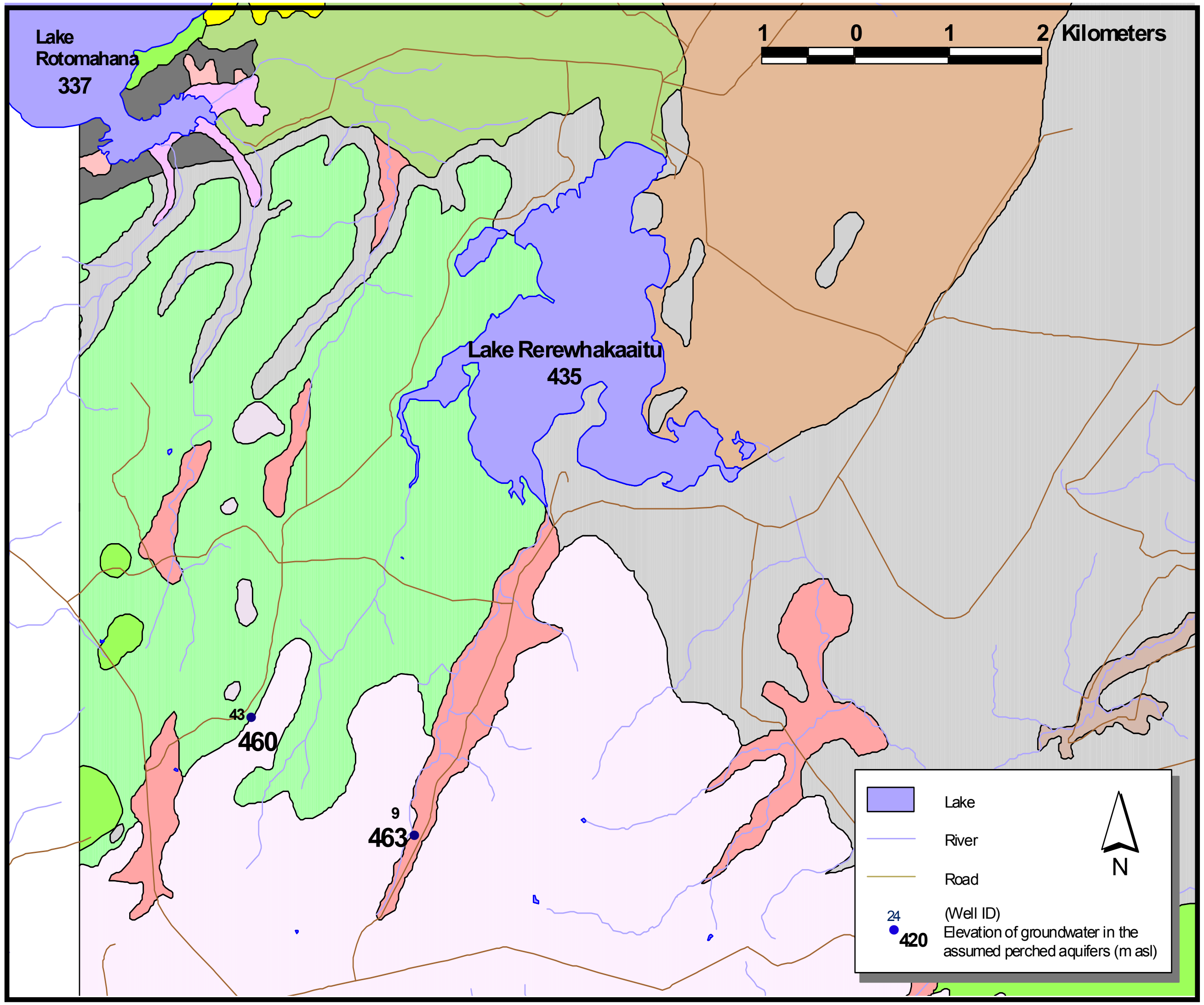

Figure 13. Groundwater levels in aquifers assumed as perched.

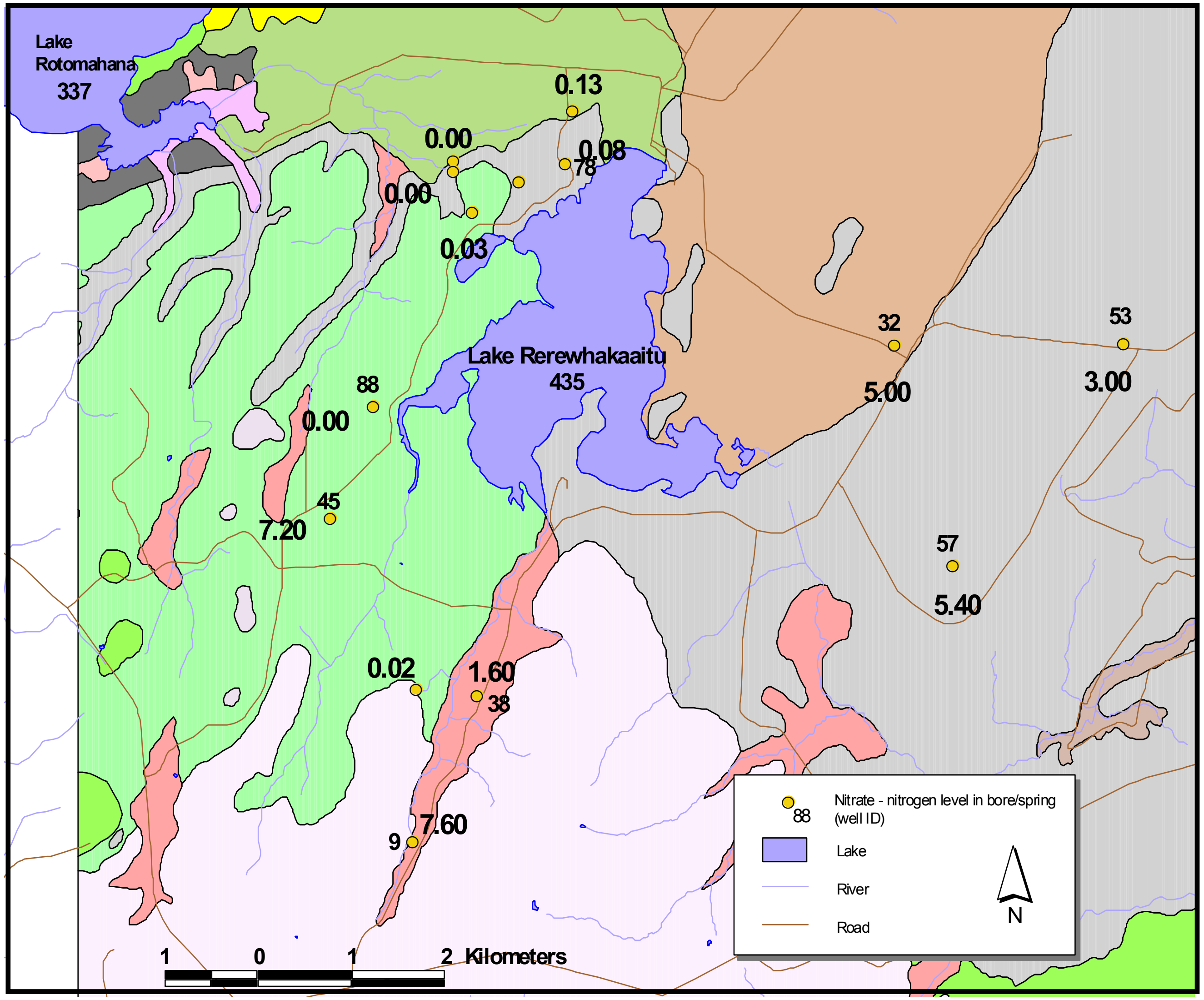

Figure 14. Nitrate-nitrogen in springs and groundwater (g/m^3).

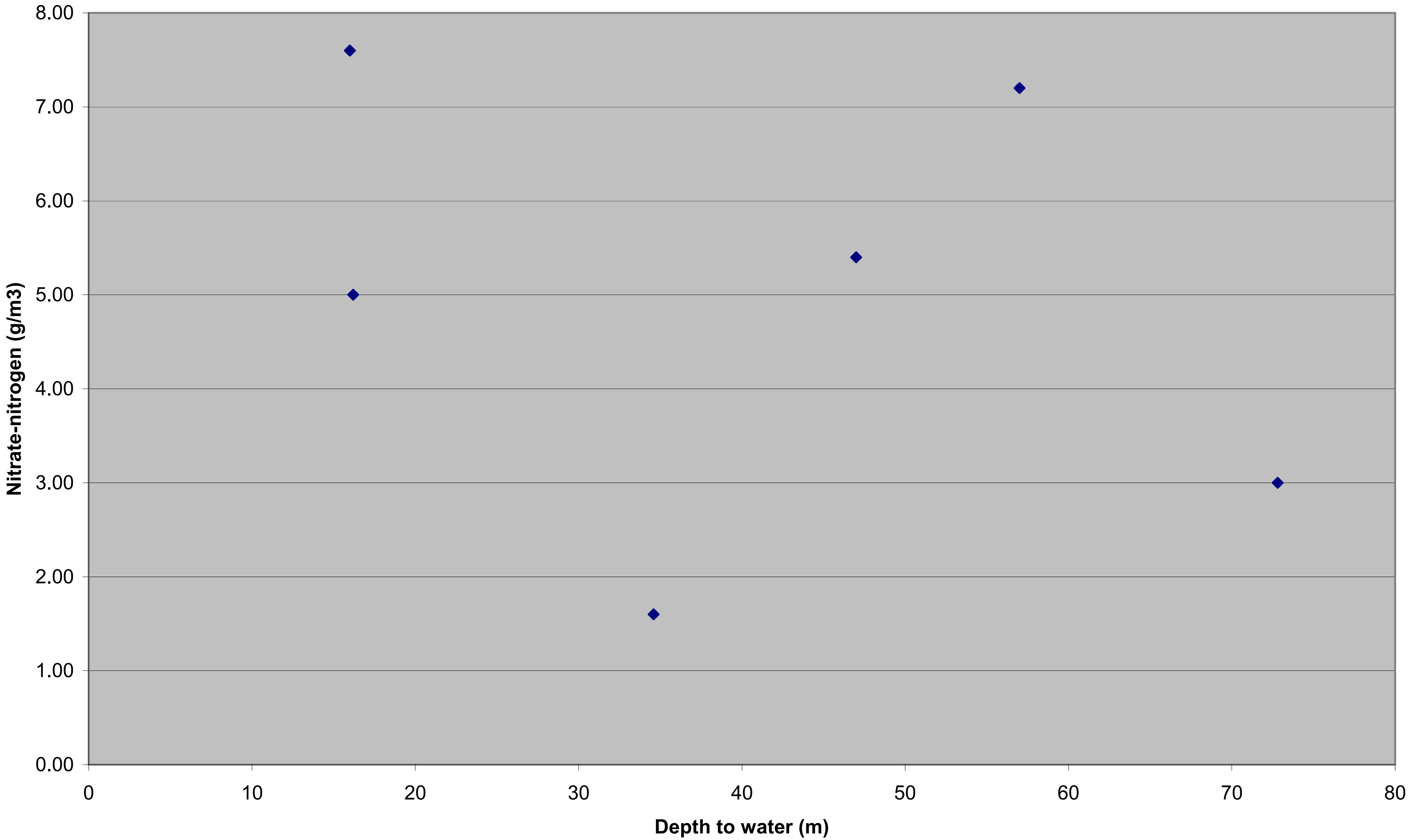

Figure 15. Nitrate-nitrogen in groundwater (g/m^3) versus depth to groundwater in wells (m).