Water Quality and Water Dating of the Rerewhakaaitu Groundwater

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EXECUTIVE SUMMARY

Environment Bay of Plenty (EBOP) and GNS Science (GNS) are studying the role of Lake Rerewhakaaitu in the hydrological system in the Rerewhakaaitu water catchment. Identifying water leakage from Lake Rerewhakaaitu to groundwater as a source of groundwater recharge and its possible influence on groundwater quality.

The objective of this study is to assess groundwater quality data in the Lake Rerewhakaaitu catchment and identify relationships to water age and isotopic data. This was undertaken using a combination of water chemistry, stable isotopes and water dating techniques.

Twenty one water samples were collected from bores, streams, springs and the lake from the Lake Rerewhakaaitu area. All water samples were analysed for major anions, major cations, nutrients, oxygen-18 and deuterium. Eleven samples were analysed for water dating tracers (tritium and/or CFCs). The results show:

- In general, the water quality of the groundwater in the Lake Rerewhakaaitu area is good relative to the NZ drinking water standards.
- Strong reducing conditions were found at 3 sites. These sites were characterised by elevated NH_4-N, Fe and Mn concentrations. All sites occur to the north /northwest of Lake Rerewhakaaitu and are suspected of containing a large proportion of water recharged by Lake Rerewhakaaitu.
- Oxygen-18 and deuterium isotopes clearly demonstrate leakage of water from Lake Rerewhakaaitu on the north and western side of Lake Rerewhakaaitu. This is discussed in more detail in Reeves et al. (2007).
- Mean residence times (MRT) are between 1 and 145 years for water samples collected as part of this study.
- In general, increasing MRT is related to:
  - increasing depth
  - increasing ORP
  - decreasing pH
  - decreasing K
  - increasing DRP
  - increasing SiO_2
  - increasing F
- NO_3-N concentrations are generally higher in younger waters suggesting an anthropogenic origin for the NO_3-N e.g., Site 180486 (MRT of 145 years) has a NO_3-N concentration of <0.002 g m^{-3} compared to Site 120101 (MRT of 1 year) having a NO_3-N concentration of 3.6 g m^{-3}. This is probably due to leaching of nitrogen into the groundwater from land use practices.
- One site has very high NH_4-N concentrations. The cause for this is unknown.

1.0 INTRODUCTION

Environment Bay of Plenty (EBOP) and GNS Science (GNS) are seeking to better understand the role of Lake Rerewhakaaitu (Figure 1) in the hydrological system in the Rerewhakaaitu catchment. Identifying water leaking from Lake Rerewhakaaitu to groundwater as a source of groundwater recharge, and its possible influence on groundwater quality, are of particular interest.

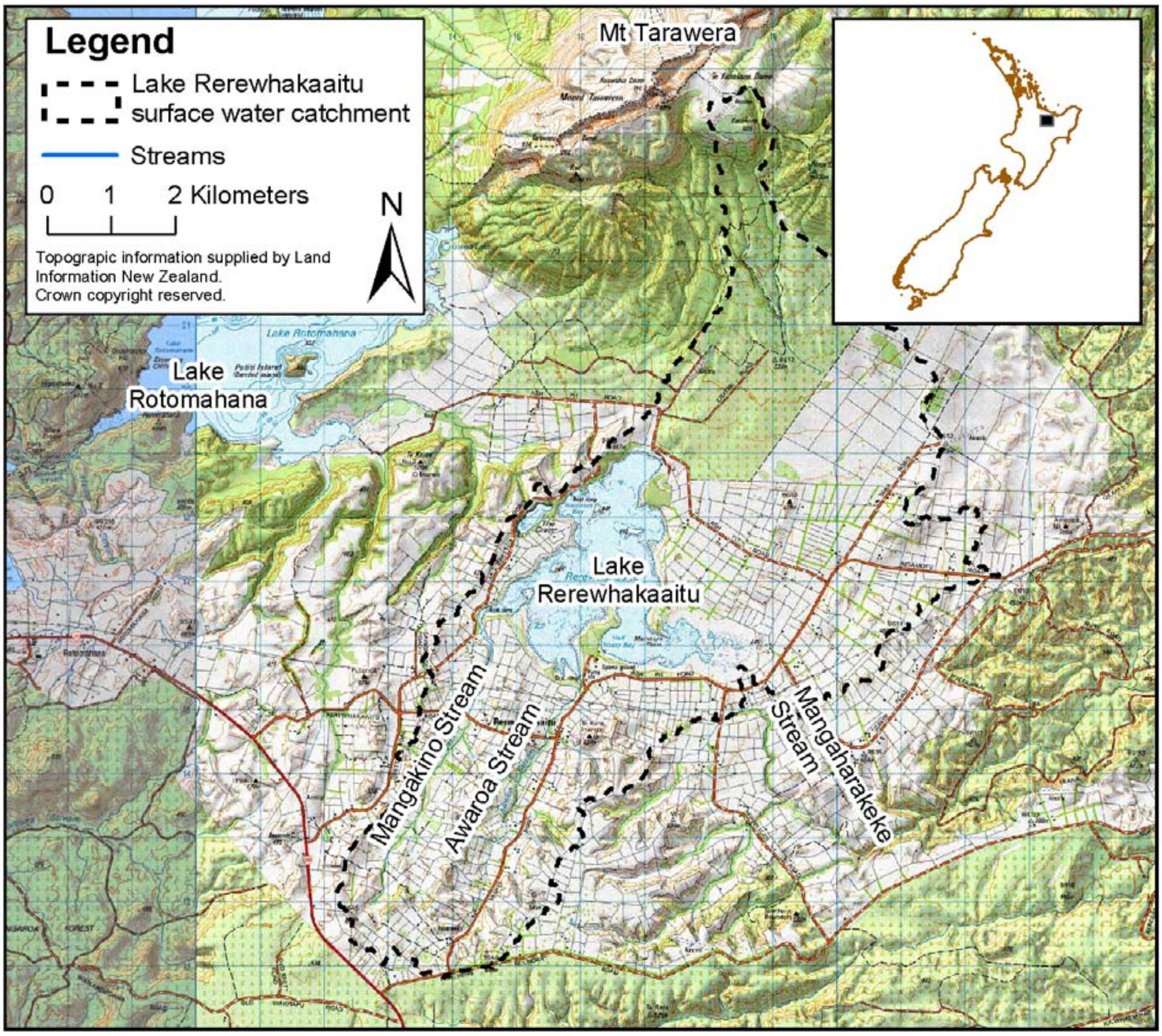


Figure 1 Map of the Rerewhakaaitu area.

Lake Rerewhakaaitu is one of twelve lakes in the Rotorua area (the 'Rotorua lakes') monitored regularly by EBOP. Regular cyanobacterial blooms have occurred in Lakes Rotorua and Rotoiti since 1997 and these have invigorated public concerns about the declining water quality of these two lakes, and possibly in the other nine Rotorua Lakes (Lakes Water Quality Society, 2001). Nutrient inputs (nitrogen and phosphorous), their effects on the lakes, and how the lakes can be managed to improve or maintain current water quality are of particular importance. Environment Bay of Plenty has been coordinating research programmes involving iwi, regional government, local government and scientific organizations to improve the understanding of the nutrient cycle in the Rotorua Lakes area. Knowledge of nutrient levels, nutrient inputs, nutrient transport mechanisms, nutrient transport times, lake processes, and effects of land use are key scientific areas that need to be better understood in seeking to solve the issues. To date, much scientific work in the Rotorua Lakes area has focused on Lakes Rotorua and Rotoiti (e.g. Lakes Water Quality Society Inc (2003), Hamilton (2003), and Morgenstern (2006)) in line with the priorities set by EBOP. The work in this paper will assist EBOP develop policies in the Lake Rerewhakaaitu area, where there is currently a limited understanding of the groundwater system.

The objective of this study was to assess groundwater quality data in the Lake Rerewhakaaitu catchment and identify relationships to water age and isotopic data. This was done using a combination of water chemistry, stable isotopes and water dating techniques.

2.0 HYDROGEOLOGY OF THE LAKE REREWHAKAAITU AREA

Understanding the physical hydrogeology of the area is important to interpreting water quality and water dating data. Hydrogeology in the Lake Rerewhakaaitu area is largely constrained by the physical properties of the geological deposits in the area. Physical properties of the geological deposits that influence catchment hydrology include:

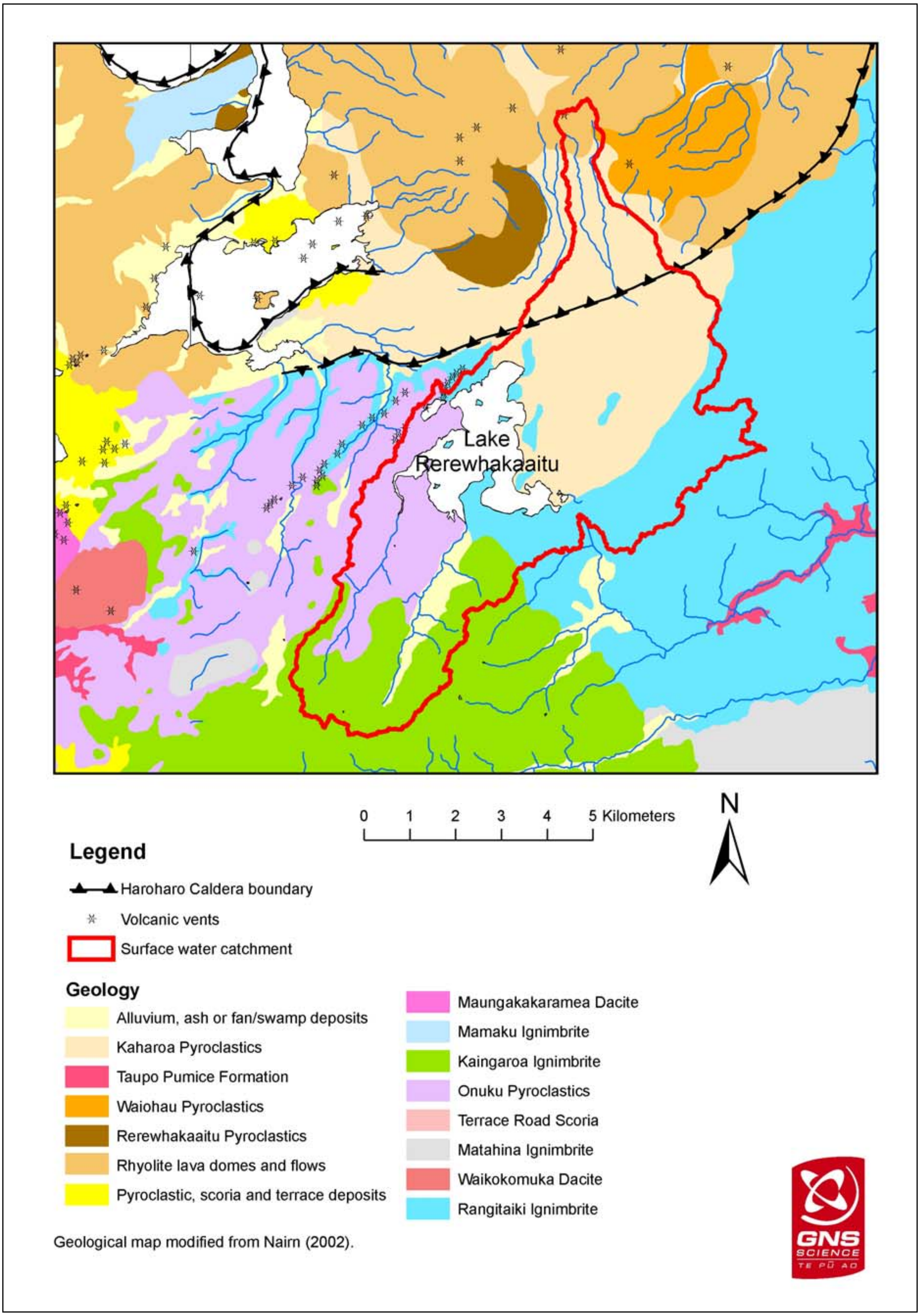
- Permeability of deposits i.e. does the deposit act as groundwater aquifer or a groundwater aquitard.
- Deposit hardness – controlling the type of permeability (i.e. fracture flow or bulk flow) and how well the deposit erodes.
- Deposit topography – dictating preferred water runoff patterns and where streams form.

These properties will influence groundwater recharge mechanisms, aquifer properties, stream-groundwater interactions, lake-groundwater interactions and ultimately influence how contaminants move from land based sources into Lake Rerewhakaaitu.

2.1 Geology

The geology of the Rerewhakaaitu area is dominated by volcanic and fluvial deposits and is complex due to the number of processes that have contributed to what is seen today. The geology of the area is summarised by Nairn (2002) and White (2003). This section will provide a summary of this work.

Lake Rerewhakaaitu lies on a partly in-filled basin which sits on an eroded Rangitaiki Ignimbrite surface (Figure 2). Nairn (2002) suggests the lake was formed approximately 11,000 years ago when pyroclastic flows from Mt Tarawera dammed the northern outlet channel. The channel was thought to be a deep and narrow cut into the Rangitaiki Ignimbrite, similar to adjacent valleys between Lakes Rerewhakaaitu and Rotomahana (White, 2003). The height of the dam was extended by the Kaharoa Pyroclastics deposited by Mt Tarawera 700 years ago, allowing the lake to reach its current level.



Geological map modified from Nairn (2002).

Figure 2 Geological map of Rerewhakaaitu area.

The Rangitaiki Ignimbrite is described by Nairn (2002) as a moderately welded, dark grey, crystal rich tuff. The unit includes coarse tuffs, pumice breccias and air fall deposits. It is the oldest unit (0.34 Ma) mapped in the Rerewhakaaitu area. The unit outcrops to the east of Lake Rerewhakaaitu (Figure 2) and in the steeply incised valleys to the west of Lake Rerewhakaaitu. The Rangitaiki Ignimbrite is considered to be the base unit in this study.

The Onuku Pyroclastics (estimated age 0.23 – 0.28 Ma) are mapped to the south and southwest of Lake Rerewhakaaitu. It is a relatively thin unit (approximately 50m thick) described as a “moderately compacted pumicious pyroclastic fall and flow units”, with some ash layers and accrectionary lapilli.

The Bonish pyroclastics, Matahina Ignimbrite and other smaller pyroclastic deposits are not mapped at the surface near Lake Rerewhakaaitu (Nairn, 2002). These units would be expected to be present between the Onuku pyroclastics and the Kaingaroa Ignimbrite. However, these units have probably largely been removed by erosion between the Onuku and Kaingaroa events in this area (White, 2003).

The Kaingaroa Ignimbrite (estimated age of 0.23 Ma) is mapped to the east and south of Lake Rerewhakaaitu. It lies on the Onuku pyroclastics. Nairn (2002) describes this unit as a lightly welded, dark grey to black pumice tuff. The unit also contains a pink-grey lenticulite near Lake Rerewhakaaitu. The unit is estimated to be about 60 m thick.

Various small pumicious alluvial deposits are mapped to the south of Lake Rerewhakaaitu. The largest alluvial deposit occurs in the Awaroa Stream valley.

Recent volcanic deposits are mapped to the north of the Haroharo Caldera boundary. Mt Tarawera located approximately 5 km north from Lake Rerewhakaaitu is made up of several Okataina rhyolitic domes ranging in age from 0.7 ka to 21 ka. The Kaharoa pyroclastics (0.7 ka) which erupted from a vent on Mt Tarawera are mapped coming from the vent zone down to the northern and eastern shores of Lake Rerewhakaaitu. Nairn (2002) describes this deposit as massive pyroclastic flow deposits, cross-bedded surge deposits and stratified fall deposits. White (2003) estimates the thickness of this deposit to be between 10 m to 30 m.

The 0.7 ka pyroclastic deposit is thought to be underlain by the Waiohau pyroclastics. This 11 ka pyroclastic deposit is similar to the 0.7 ka deposit but was erupted from a different vent on Mt Tarawera. The Waiohau pyroclastic deposit is thought to be in excess of 30m thick in the area around Lake Rerewhakaaitu.

Deposits from the 1886 eruption of Mt Tarawera are not mapped by Nairn (2002) due to the low amount of material deposited relative to other deposits. The 1886 eruption occurred through a series of vents extending 9km southwest from Mt Tarawera, through Lake Rotomahana, to Waimangu (Nairn, 1979). Deposits include mud (accretionary lapilli), scoria and ejecta.

Nairn (2002) maps 2 lineaments of northeast/southwest trending coalescing individual explosion craters approximately 0.5 – 1 km west of Lake Rerewhakaaitu. All craters are formed in the Rangitaiki Ignimbrite and their origins are not known. Awaatua crater is the largest crater and forms part of Lake Rerewhakaaitu.

2.2 Hydrology

The surface water catchment is approximately 3816 ha in area, with elevations ranging from 435m relative to sea level (rsl) at the lake to approximately 1100m rsl on Mt Tarawera in the north of the catchment (Figure 1). The elevation of the top of the surface water catchment to the east, south and west of Lake Rerewhakaaitu is between 420 m and 530 m rsl. The surface water catchment is mainly to the south of the lake, with narrow catchment areas to the north, east and west.

Lake Rerewhakaaitu is described as a mesotrophic lake in average condition (Scholes and Bloxham, 2005). Land use in the catchment is dominated by dairy farming. McIntosh (2001) estimates 77% of the catchment is pasture, 15% exotic forest, 6% indigenous forest/scrub and 2% ‘other’. Of the 77% pasture, 70% is used for dairy cows and 7% for sheep/cattle. Intensification of dairying and increased use of fertilizers between 1990 and 2000 has occurred, with relatively high fertilizer application rates (>300 kg/ha/year) of nitrogen based fertilizers (McIntosh et al., 2001).

The lake is shallow, having a mean depth of 6.3m and a maximum depth of 15m. The lake receives water from rainfall, streams and shallow groundwater systems (White, 2003). Mean rainfall is about 1600 mm per year. The Mangakino Stream and the Awaroa Stream are the only two streams that flow into Lake Rerewhakaaitu. Both streams flow into a wetland at the southern end of the lake, and both streams have a shallow groundwater aquifer as their source. The Mangakino Stream has a mean flow of 24 $l\ s^{-1}$ (from measurements between 1995 and 2001) measured approximately 1 km upstream from Lake Rerewhakaaitu. The Awaroa Stream is commonly dry, and was dry at the time of this work. The only surface water outlet to Lake Rerewhakaaitu is an upper tributary of the Mangaharakeke Stream that flows from the southeast corner of the lake. This tributary only flows when the lake level is high.

All major geological units in the Lake Rerewhakaaitu catchment, except the Okataina Rhyolites, are identified as having groundwater aquifers. The Rangitaiki Ignimbrite is the main groundwater aquifer that is used to supply water for domestic and farming purposes. Groundwater levels in the Rangitaiki Ignimbrite aquifer are generally lower than the level in Lake Rerewhakaaitu, suggesting the lake could be a possible source of groundwater recharge to the aquifer.

Groundwater flow directions are variable in the Rangitaiki Ignimbrite aquifer near Lake Rerewhakaaitu. White (2003) shows that Lake Rerewhakaaitu is situated on a groundwater divide, with groundwater flowing to the west on the west side of the lake, and groundwater flowing to the east on the east side of the lake (Figure 3). A small groundwater flow from the Rangitaiki Ignimbrite aquifer could be entering Lake Rerewhakaaitu from the northeast. An assessment of groundwater flow directions for the other aquifers is difficult to determine due to an absence of data. White (2003) estimates Lake Rerewhakaaitu loses 556 $l\ s^{-1}$ of water to groundwater aquifers. Most of this is probably going into the Rangitaiki Ignimbrite aquifer; however, other smaller aquifers need to be considered. Reeves (2007) identified lake water in the Rangitaiki Ignimbrite aquifer on the western and northern sides of Lake Rerewhakaaitu.

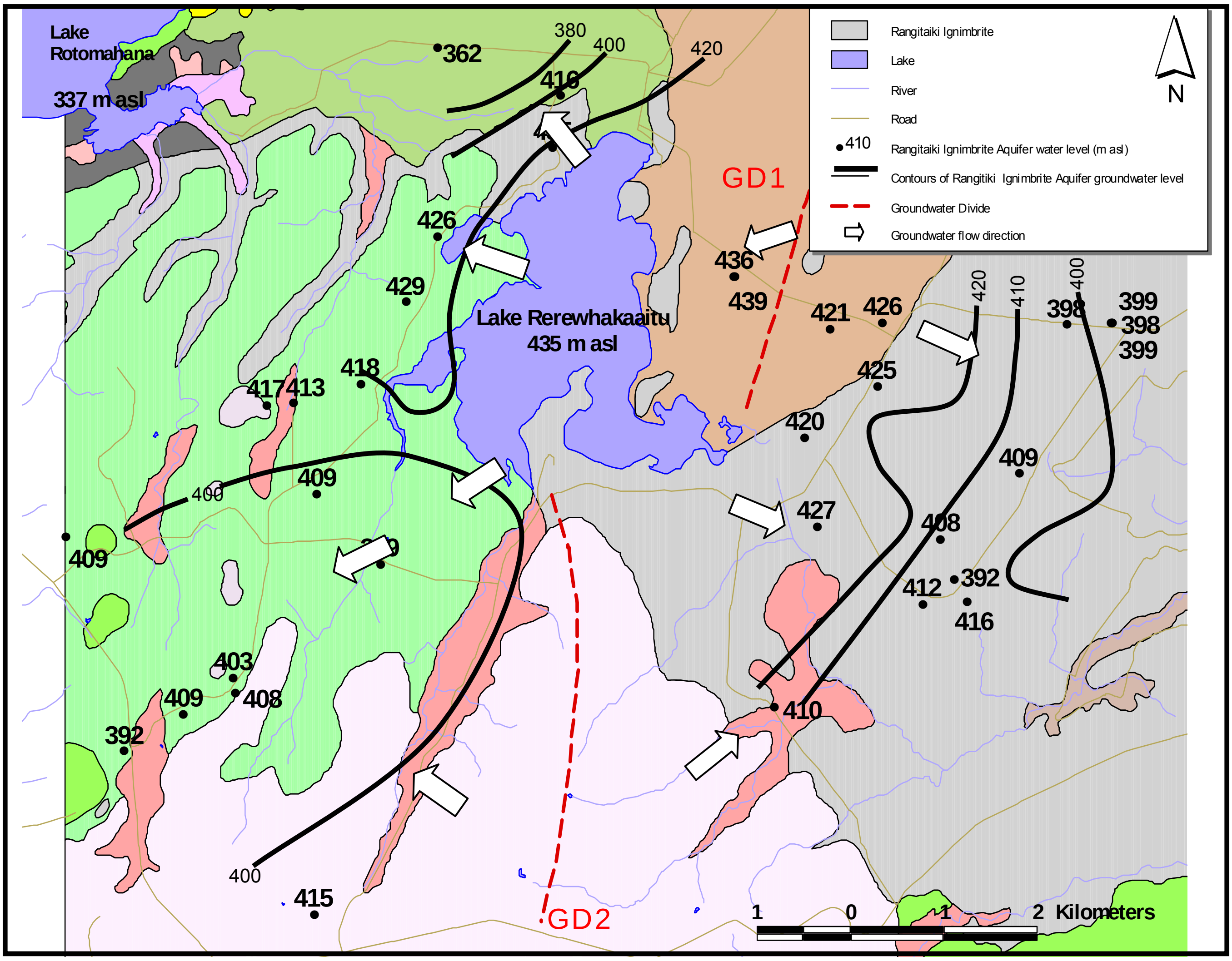


Figure 3 Water level map of the Rangaitaiki Ignimbrite (from White, 2003).

A number of small seeps and springs are observed near the base of gullies and depressions near the northern and north western parts of Lake Rerewhakaaitu. Many of these springs contain significant amounts of lake water (Taylor, 1977; Reeves et al., 2007) based on stable isotope measurements. White (2003) speculated that Lake Rerewhakaaitu may also be loosing water through a subsurface flow along the pyroclastic buried valley cut into the Rangitaiki Ignimbrite flowing under the lake to the north. Data presented by Reeves et al. (2007) supports this hypothesis.

3.0 METHODS

3.1 Sample sites

Sample sites were selected by GNS in conjunction with EBOP staff. Sample sites were selected based on their 'potential' to receive water from Lake Rerewhakaaitu based on groundwater flow directions derived by White (2003) (Figure 3) and previous isotope studies (Taylor, 1977). Sample sites included groundwater bores, springs (mainly to the north west of Lake Rerewhakaaitu), a stream, and Lake Rerewhakaaitu (Table 1, Figure 4). Bore sites were selected from the EBOP database where basic collar information (e.g. bore depth, location) was known. Spring sites were selected from known springs in the area and springs found as part of the field work. A water sample was collected from the lake site to obtain an indication of the water quality potentially recharging the groundwater aquifers. The location of the lake water sample was selected based on the probable location of leakage from Lake Rerewhakaaitu.

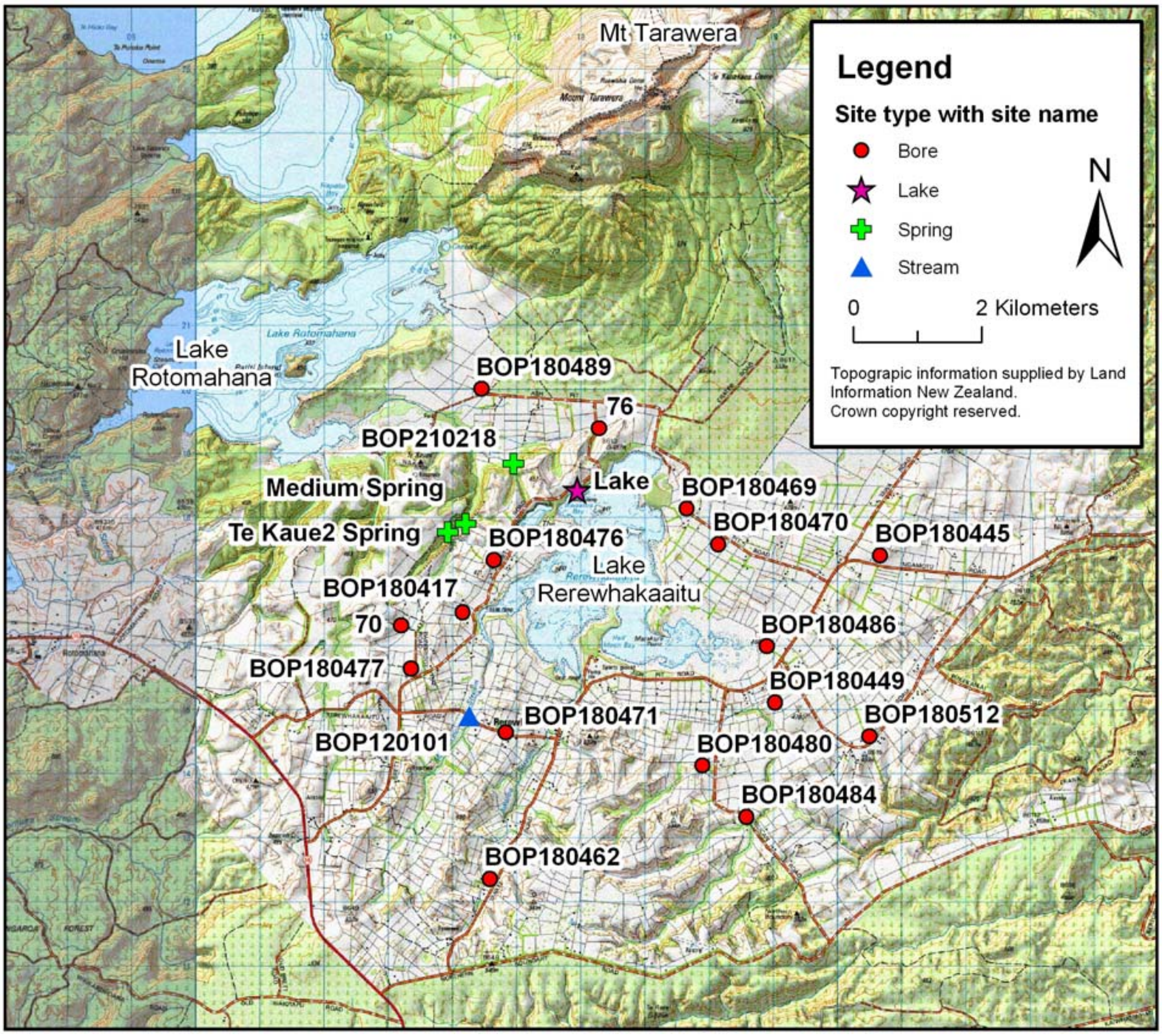


Figure 4 Location of sites sampled by GNS.

Table 1 Summary of site data.

Site	EBOP Bore #	Type	Easting	Northing	Bore depth (m)	Casing depth (m)	SWL (m rsl)	Depth to water (m)	Elevation (m rsl)	Source of elevation data	Calculated rl bore depth (m)	Aquifer
70		Bore	2813193	6316312	61	32	417	43	460	EBOP	399	Rangitiki Ignimbrite
76		Bore	2816280	6319391	2.61		416	4	420	EBOP	418	Rangitiki Ignimbrite
BOP120101		Stream	2814252	6314901	0				460	DTM	460	
BOP180417	10612	Bore	2814152	6316520	153		418.261	23.5	441.761	EBOP	288.761	Rangitiki Ignimbrite
BOP180445	11086	Bore	2820664	6317407	24.4				457.66	DTM	433.26	Rangitiki Ignimbrite
BOP180449	11087	Bore	2819021	6315113	94.5	64	427.3	approx 17.7?	445	EBOP	350.5	Rangitiki Ignimbrite
BOP180462	11085	Bore	2814579	6312362	30		462.856	16	478.856	EBOP	448.856	Perched
BOP180469	11076	Bore	2817647	6318135	33.5		434.683	24	458.683	EBOP	425.183	Rangitiki Ignimbrite
BOP180470	10606	Bore	2818139	6317587	61	56	435.709	13.5	449.209	EBOP	388.209	Rangitiki Ignimbrite
BOP180471	11081	Bore	2814820	6314648	42		437	approx 33	470	EBOP	428	Onuku Pyroclastic
BOP180476	10608	Bore	2814641	6317340	91	39	428.63	31	459.63	EBOP	368.63	Rangitiki Ignimbrite
BOP180477	1595	Bore	2813346	6315648	38.5	38.5	431.801	26	457.801	EBOP	419.301	Onuku Pyroclastic
BOP180480	11078	Bore	2817889	6314128	81.5	39	412	28	440	EBOP	358.5	Rangitiki Ignimbrite
BOP180484	10621	Bore	2818576	6313334	58	19.5	410	20	430	EBOP	372	Rangitiki Ignimbrite
BOP180486	10169	Bore	2818889	6315990	69	26	419.849	19.8	439.649	EBOP	370.649	Rangitiki Ignimbrite
BOP180489	10729	Bore	2814446	6320007	37	31			360	DTM	323	bk/lw/vr
BOP180512	11098	Bore	2820495	6314585	54		391.704	54.2	445.904	EBOP	445.904	Rangitiki Ignimbrite
BOP210218		Spring	2814950	6318840	0				380	DTM	380	Rangitiki Ignimbrite
Lake		Lake	2815936	6318429	0				440	DTM	440	
Medium spring		Spring	2814200	6317900	0				428.29	DTM	428.29	Rangitiki Ignimbrite
Te Kaue2 Springs		Spring	2813926	6317771	0				426.17	DTM	426.17	Rangitiki Ignimbrite

Source of elevation data

EBOP = data supplied by EBOP
DTM = estimated from a 1:50,000 digital terrain model

🟪 possible aquifer

3.2 Sampling and analyses

GNS collected water samples from groundwater bores, springs, streams and the lake from the Lake Rerewhakaaitu study area in January-February 2006. Grab samples were obtained for spring, stream and lake samples. Spring water samples were collected as close as possible to the point of emergence. Groundwater bores were purged and sampled with existing pumps used to extract water for farm and/or domestic purposes. The field parameters temperature, conductivity, pH, and turbidity were monitored during purging. The field parameters were recorded immediately prior to sampling. Bore samples were collected as close to the bore-head as possible once the field parameters were stable.

Water samples were collected in bottles appropriate for the required analyses using appropriate methods (Rosen et al., 1999; van der Raaij, 2004). This included, 1) a raw sample in a 250 ml polyethylene bottle (chilled to <4°C) to be analysed for alkalinity, 2) a field-filtered (0.45 micrometer pore size) sample in a 100ml polyethylene bottle chilled to less than 4°C to be analysed for major anions and nutrients, 3) a field filtered sample in a 100ml polyethylene and acidified with concentrated HNO_3 to be analysed for major cations, 4) a raw sample in a 15ml Bijou bottle to be analysed for ^{18}O and ^{2}H stable isotopes, 5) raw sample in a 1.1l Nalgene bottle to be analysed for tritium, and 6) two raw samples in 125ml glass bottles to be analysed for chloroflurocarbons (CFCs).

The Wairakei Analytical Facility (GNS Science) analysed the water samples for alkalinity (HCO_3) and pH using a Metrohm autotitrator. Magnesium (Mg), calcium (Ca), iron (Fe), manganese (Mn), potassium (K), silica as SiO_2 (SiO_2) and sodium (Na) were analysed using a Thermo Jarrell Ash inductively coupled plasma optical emission spectrometer. Chloride (Cl), sulphate (SO_4), nitrate as nitrogen (NO_3-N), bromide (Br), fluoride (F) and dissolved reactive phosphate as phosphorous (DRP) were analysed using a Dionex ion exchange chromatograph. Ammonia as nitrogen (NH_4-N) was analysed by Hill Laboratories (Hamilton) using an auto analyzer. Isotrace (Dunedin) analysed samples for oxygen 18 (^{18}O) and deuterium (^{2}H) using a mass spectrometer. The GNS Water Dating Laboratory analysed for tritium using low-level liquid scintillation spectrometry and for CFCs using a gas chromatograph. Appendix 1 summarises the background and the methodology to calculating mean residence times from the tritium and CFC data.

4.0 RESULTS AND DISCUSSION

4.1 Overview

Tables 1, 2 and 3 summarise data supplied to GNS by EBOP and contain the chemical results from water samples collected during the GNS 2006 sampling round.

In general, water quality of the groundwater and streams in this study (Table 2) is good compared to the New Zealand Drinking Water Standards (NZDWS) (Ministry of Health, 2005). Mn is the only parameter above the NZDWS maximum allowable value (0.4 g m^{-3}). This occurs at sites BOP180489 and BOP210218. Both sites occur to the northwest of Lake Rerewhakaaitu and also contain high concentrations of dissolved Fe, and trace amounts of NH_4-N. This suggests anaerobic groundwater conditions in the groundwater aquifer in this area.

Table 2 Summary of chemical results.

					Field Parameters					Laboratory Parameters																		
Site name	GNS Site	Date	Sample no	Turbidity (NTU)	Field pH (pH Units)	Electrical conductivity (uS/cm @ 25°C)	Oxidation - reduction potential (mV)	Water temperature (°C)	Dissolved oxygen (g m^{-3})	Alkalinity (as HCO$_3$) (mg/L)	Lab pH (pH Units)	Analysis Temperature (°C)	Ammonium (as N) (g m^{-3})	Bromide (g m^{-3})	Calcium - soluble (g m^{-3})	Chloride (g m^{-3})	Dissolved Reactive Phosphorous (g m^{-3})	Fluoride (g m^{-3})	Iron - soluble (g m^{-3})	Magnesium - soluble (g m^{-3})	Manganese - soluble (g m^{-3})	Nitrate (as N) (g m^{-3})	Potassium - soluble (g m^{-3})	Silica (as SiO2) (g m^{-3})	Sodium - soluble (g m^{-3})	Sulphate (g m^{-3})	δ^{2}H (‰)	δ^{18}O (‰)
70	70	19/01/2006	17	0.9	6.74	169	540	7.4	6.6	40	6.25	19	<0.01	<0.04	6.6	4.9	0.044	0.095	<0.02	3.5	<0.005	1.8	5.6	73	13.1	19.6	-28.4	-6.44
76	76	18/01/2006	11	71	8.08	584	-2	9.2	1.1	333	7.58	20	62.5	<0.04	5.4	8.4	0.079	0.008	13.2	3.9	0.12	0.052	16.6	5.2	7.6	0.18	-23	-3.7
BOP120101	Mangakino stream @ bridge	19/01/2006	15	3	7.58	146	480	8	9.5	28	7.11	18	<0.01	<0.04	7.5	11.5	<0.004	0.032	0.11	2.7	0.005	3.6	6.3	59	10.1	8.1	-37.5	-6.57
BOP180417	88	18/01/2006	14	10.1	8.09	121	477	9.1	2.7	66	6.52	17	<0.01	<0.04	6.6	3.7	0.085	0.13	0.37	4.4	0.05	<0.002	4.8	72	9.4	0.92	-22.7	-3.15
BOP180445	26	17/01/2006	7	5.5	7.45	140	538	7	8.8	24	5.95	16	<0.01	0.36	5.3	8.3	<0.004	0.03	<0.02	2	0.006	3.4	6.9	73	11.8	13.2	-34.1	-6.13
BOP180449	47	17/01/2006	8	1.7		96	514	7.8		33	6.28	16	<0.01	<0.04	3.4	6.3	0.054	0.11	<0.02	2	0.01	<0.002	4.9	73	9.7	6.5	-29	-5.94
BOP180462	9	18/01/2006	13	4.5	7.96	180	492	6.9	6.9	32	6.07	16	<0.01	<0.04	7.8	12.3	0.022	0.035	0.02	4	<0.005	8	6.7	74	12.9	2.9	-35.2	-6.66
BOP180469	29	17/01/2006	3	0.9	6.22	127	506	7.2	6	28	6.14	14	<0.01	<0.04	3.1	6.3	0.046	0.057	0.04	1.1	<0.005	2.3	3.8	74	14.2	9.8	-32.1	-6.54
BOP180470	21	17/01/2006	6	2.1	7.7	134	522	7.8	3	22	6.02	15	<0.01	<0.04	3.6	9.3	0.062	0.059	<0.02	1.8	<0.005	2.3	4.5	73	15.2	16.9	-36.1	-6.51
BOP180471	79	19/01/2006	20	8.2	6.64	78	580	8.4	9.4	23	6.36	19	<0.01	<0.04	3	4.6	0.013	0.059	0.28	1.4	0.01	2.8	4.4	75	9	1.4	-41.9	-7.2
BOP180476	71	16/01/2006	1	0	6.92	160	387	8.7	1.3	48	6.44	13	<0.01	<0.04	7.7	6.2	0.05	0.08	<0.02	3.7	0.09	2.5	5.6	55	9.7	10.2	-21.4	-3.89
BOP180477	2	19/01/2006	19	1.1	6.36	131	564	7.3	6.2	28	6.35	19	<0.01	<0.04	5	6.3	0.043	0.078	<0.02	2.5	0.005	3.9	5.6	72	9.2	4.5	-33	-6.08
BOP180480	33	17/01/2006	9	1.1	7.64	157	498	7.6	7.1	23	5.96	16	<0.01	<0.04	6.9	9.3	0.035	0.052	<0.02	2.9	<0.005	4.8	6.5	76	11.5	12.5	-33.3	-6.85
BOP180484	34	17/01/2006	10	0.9	7.54	94	452	7.1	9	26	6.11	16	<0.01	<0.04	3.3	5.2	0.056	0.056	<0.02	1.5	<0.005	2.6	4.3	78	10.6	2.2	-33.6	-6.99
BOP180486	37	17/01/2006	4	0.7	7.17	77	457	6.6	1.7	39	6.35	14	<0.01	<0.04	3.1	3.5	0.14	0.11	0.11	2	0.19	<0.002	3.7	75	8.2	1.2	-40.4	-6.79
BOP180489	69	19/01/2006	18	0	6.78	128	343	8.3	1	64	6.62	19	0.05	<0.04	3.6	5	0.111	0.16	5.7	1.6	0.43	0.002	1.3	70	15.3	1.7	-26.7	-3.98
BOP180512	51	17/01/2006	5	2.3	7.97	105	485	7.3	9.1	22	6.14	15	<0.01	<0.04	3.6	5.1	0.101	0.066	<0.02	1.8	<0.005	2.7	4.5	67	8.6	4.7	-34.9	-6.55
BOP210218	Spring 21021	18/01/2006	12	5.3	7.95	112	378	6.8	0.7	53	6.56	15	0.13	<0.04	4.4	5.2	0.077	0.1	3.4	2.6	2	<0.0020	3.2	42	8.1	0.97	-16.4	-2.37
Lake	Lake	19/01/2006	16	0.3	7.78	57	490	17.3	9	23	7.49	18	<0.01	<0.04	2.2	5.2	<0.004	0.051	0.05	2.4	<0.005	0.008	1.1	1	6.5	2.6	-9.1	-1.56
Medium spring	Medium spring	16/01/2006	2	0	7.74	172	440	6.8	7.1	42	6.43	13	<0.01	<0.04	7.6	5.6	0.05	0.067	<0.02	3.6	<0.005	2.9	5.5	61	11.1	14.9	-34.5	-4.59
Te Kaue2 Springs	Te Kaue2 Springs	28/02/2006	21	0.1	6.4	183	469	11.9	4.3	50	6.23	17	<0.01	<0.04	10.5	5.8	0.071	0.06	<0.02	4.9	<0.005	2	5.3	70	14.5	25	-36.5	-5.41

Table 3 Table of water dating results.

Site Name	Site type	Sample No	Date	TR	sigTR	cfc11 [pptv]	cfc12 [pptv]	E%PM	Mean Residence Time (MRT) (years)	Aquifer status
70	Bore	**17**	19/01/2006	0.656	0.03	178	440	70	81	Unconfined
BOP180476	Bore	**1**	16/01/2006	1.02	0.04	106	269	70	34	Confined
BOP180486	Bore	**4**	17/01/2006	0.071	0.019	86	219	70	145	Confined
BOP180512	Bore	**5**	17/01/2006	0.801	0.033	243	521	70	59	Unconfined
Te Kaue2 Springs	Spring	**99**	28/02/2006	0.839	0.032	87	284	90	50	Confined
BOP180462	Bore	**13**	18/01/2006	1.28	0.04	287	754	70	5	Unconfined
BOP180477	Bore	**19**	19/01/2006	0.648	0.029	152	360	70	76	Unconfined
Medium Spring	Spring	**2**	16/01/2006	0.881	0.032	170	411	90	43	Confined
BOP210218	Spring	**12**	18/01/2006	1.32	0.04	98	265	90	4 or 44	Confined
BOP120101	Stream	**15**	19/01/2006	1.59	0.05			90	1	
BOP180489	Bore	**18**	19/01/2006	1.18	0.04	113	287	70	7 or 40	Unconfined
Anaerobic										
Strongly anaerobic										

TR = Tritium ratio
sigTR = 1 sigma standard measurement error for the tritium result
cfc11 = cfc 11 result
cfc12 = cfc 12 result
E%PM = percentage of exponential flow assumed in the model

Reducing conditions in the groundwater are also clearly apparent at site 76 which is also north of Lake Rerewhakaaitu. This is based on the NH_4-N concentration being higher than the NO_3-N concentration, significant concentrations of Fe and Mn, and low oxidation-reduction potentials. This may indicate that the groundwater aquifer is confined in the area around this site.

4.2 Lake recharge to groundwater

The naturally occurring stable isotopes, oxygen-18 and deuterium can be used to distinguish between rain water and other waters (e.g. lake water, river water) based on measuring their isotopic concentrations relative to rainwater. This is possible because the lighter water molecules (which contain the lighter isotopes of hydrogen and oxygen) preferentially evaporate from surface water bodies, leaving behind heavier molecules and producing isotopically enriched water. Evaporation depends on local meteorological conditions such as air temperature, wind, humidity and elevation.

Oxygen-18 concentrations determined in this investigation range from -7.2 ‰ to -1.56 ‰ and deuterium concentrations range from -41.9 ‰ to -9.1 ‰. Figure 5 shows how the $^{18}O/^{2}H$ ratio compares to expected rainwater ratios (the meteoric water line). $^{18}O/^{2}H$ ratios that fall below the meteoric water line indicate sites where lake water could be acting as a recharge source for groundwater (see Reeves et al., (2007) for a detailed examination of the relationship between water from Lake Rerewhakaaitu and surrounding groundwater). The stable isotope results demonstrate possible lake leakage at seven sites to the north and east of Lake Rerewhakaaitu (sites BOP210218, BOP180417, BOP180489, 76, BOP180476, Medium Spring and Te Kaue2 Spring). Hydrological conditions at all seven sites except for Medium Spring and Te Kaue2 Spring, are reducing groundwater environments.

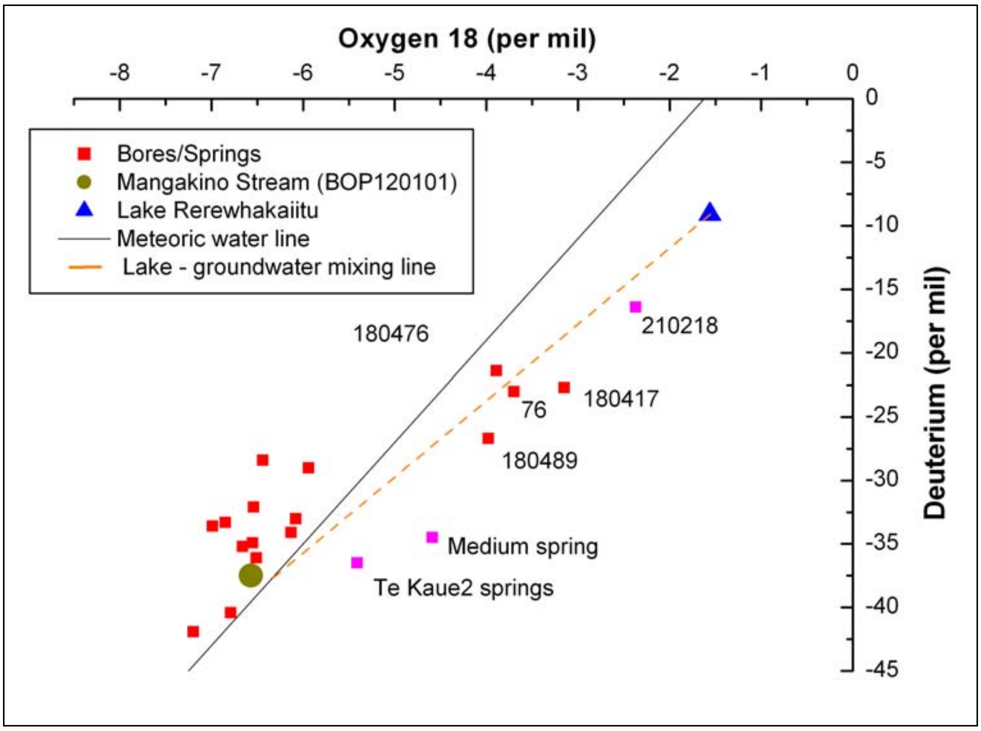


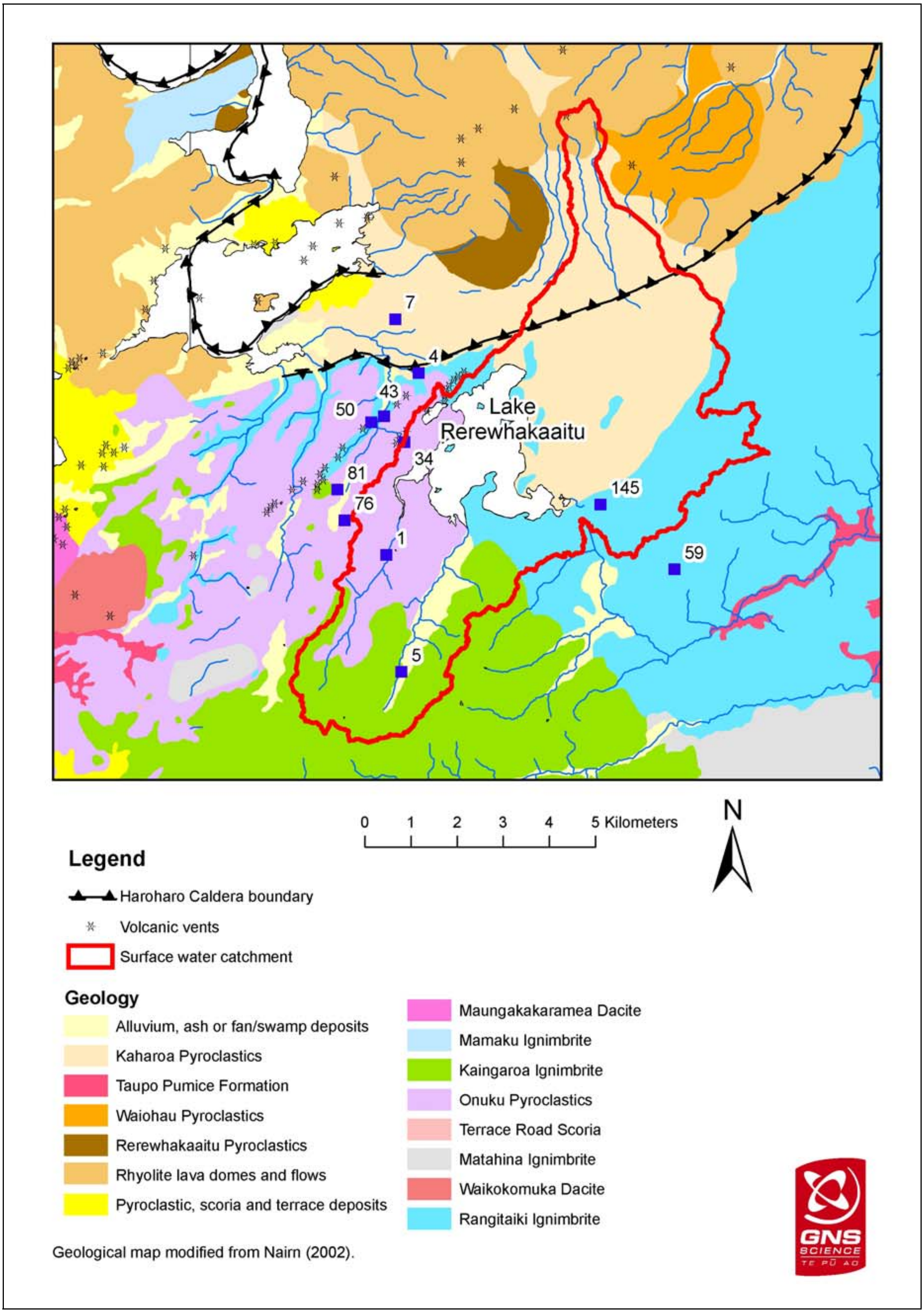
Figure 5 Plot of ^{18}O vs ^{2}H (modified from Reeves et al., 2007).

4.3 MRT relationships

4.3.1 MRT and hydrology

Mean residence times (MRT) can be calculated for 11 sites based on the tritium and CFC data obtained in this study (Table 3). Two sites (BOP210218 and BOP180489) have ambiguous MRT interpretations based on the water dating data. Ambiguous MRT's can be obtained from tritium data in some cases, depending on the concentration of tritium in the water sample (see Appendix 1). The youngest age is most probable at these sites, based on water chemistry, isotope data and the hydrological setting (Reeves et al., 2007) and is used in this report.

Calculated MRTs range from 1 year at site BOP120101 (Mangakino Stream) to 145 years at site BOP180486 (Figure 6). Most of the groundwaters are old (MRT >30 years). Only spring site BOP210218 and bore BOP180489 in the northwest of Lake Rerewhakaaitu (Figure 6) have young MRT's of 4 and 7 years respectively, suggesting leakage of young lake water or rain water. Te Kaue2 Spring, Medium Spring, and bore BOP180476 west of the lake have similar MRT's of between 34 and 50 years whereas bores 70 and BOP180477 toward the southwest of Lake Rerewhakaaitu have significantly older water (MRT 76-81 years). Bore BOP180486, east of the lake, contains the oldest water (MRT 145 years). The Mangakino Stream and bore BOP180462 (close to the Awaroa Stream) have young water (MRT 1-5 years).



Geological map modified from Nairn (2002).

Figure 6 Map of MRTs for each site on the geological map. Numbers next to each site indicate MRT in years.

Five sites sampled around the lake for water dating are from reduced aquifers. Sites BOP180417, BOP180471 and BOP180486 have groundwater that is slightly reduced, and sites BOP210218 and BOP180489 in the northwest contain young groundwater from highly reduced aquifers. This is surprising because in other NZ groundwaters it is usually the opposite: active flow with young water occurs in 'clean' aquifers, while aquifers with carbon material that favour anaerobic conditions are normally clogged and allow only slow water movement resulting in old water.

Most of the sites follow the expected trend of increasing MRT with increasing depth (Figure 7). Only site BOP180476 is significantly outside of this trend, containing young water for its depth. This site, which is close to the lake leakage area, is probably recharged at least partly by young water leaking from Lake Rerewhakaaitu. Note also that the stable isotope composition is consistent with a lake water component at this site.

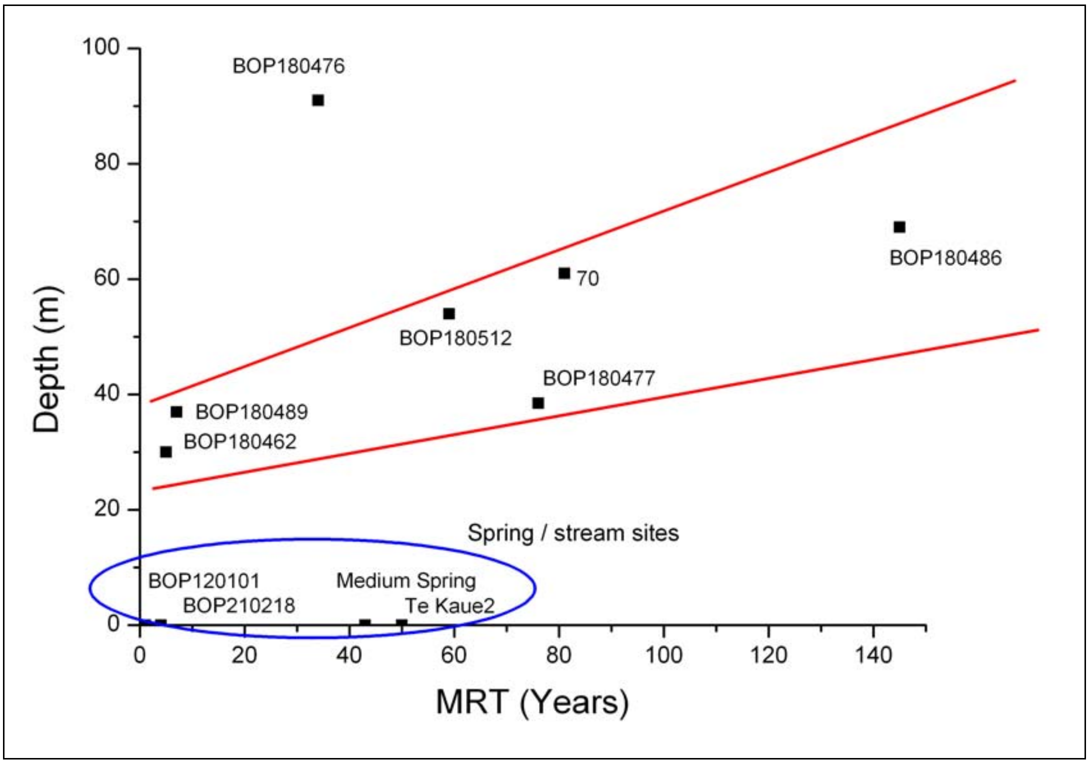


Figure 7 Plot of MRT versus bore depth.

A plot of elevation (relative to sea level) vs MRT (Figure 8) shows that the sites with young waters. Sites BOP210218, BOP180489 and BOP180476 all lie at the lowest RL, suggesting that these waters could contain leakage water from the lake. Te Kaue2 and Medium Spring discharge old water at higher elevation. Bore BOP180486 is outside the trend indicating that this might be a separate hydrogeologic system. Bore BOP180486 is on the groundwater divide (Figure 3) and may tap slow moving groundwater.

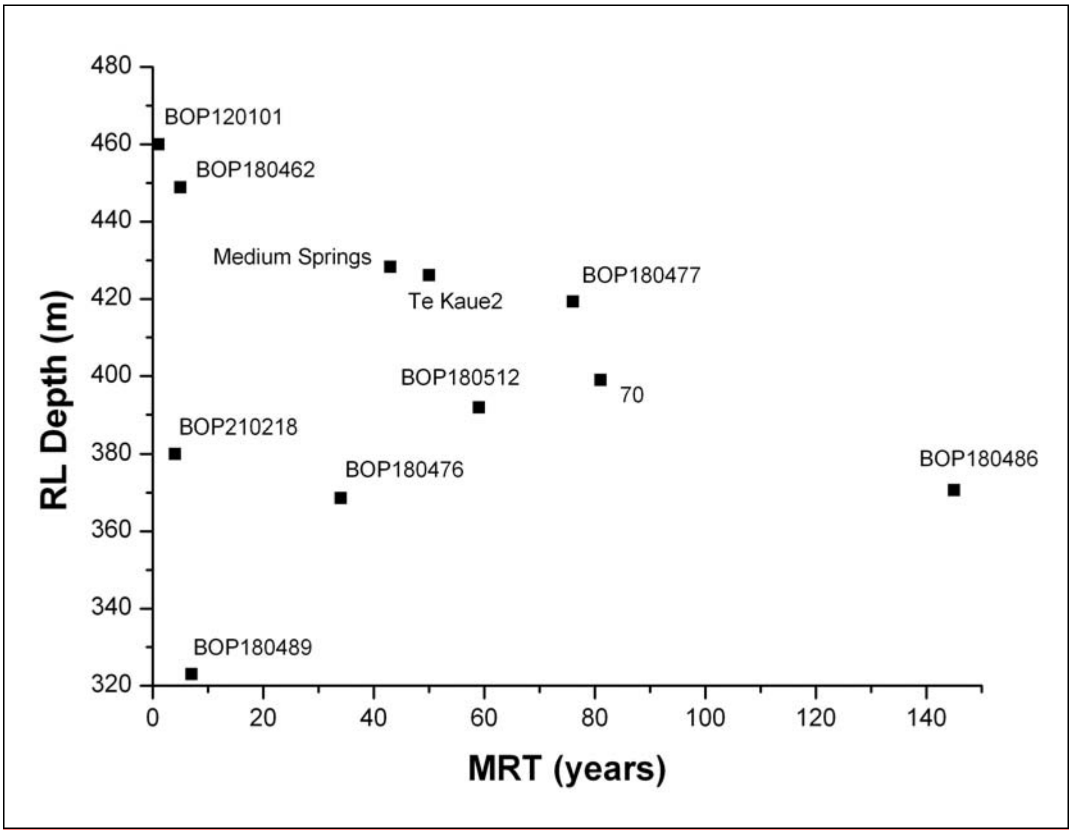


Figure 8 Plot of MRT versus RL Depth.

4.3.2 MRT and hydrochemistry

Conductivity, water temperature, and dissolved oxygen all show no trend versus MRT. However, site BOP180486 has unusually low values for its old age. This again may indicate that site BOP180486 lies within a separate hydrogeologic system. A trend for these data would not be expected.

The oxidation - reduction potential (ORP) does show a clear trend of increasing ORP with increasing MRT (Figure 9). Sites BOP180462, BOP120101 (Shallow bore close to the Awaroa Stream and the Mangakino Stream site) and site BOP 180486 (indicated as different hydrogeologic system by most of the parameters) are excluded from this trend. ORP increases with increasing MRT i.e. ORP increases with evolution of the groundwater due to increasing contact time of the water with the aquifer matrix. This is a surprising result, because most groundwater systems become more anoxic with time, meaning that ORP decreases along the flow path. There is no obvious explanation why the data from this investigation reveal the opposite pattern. However, the good correlation provides some evidence that these samples originate from the same hydrogeologic system.

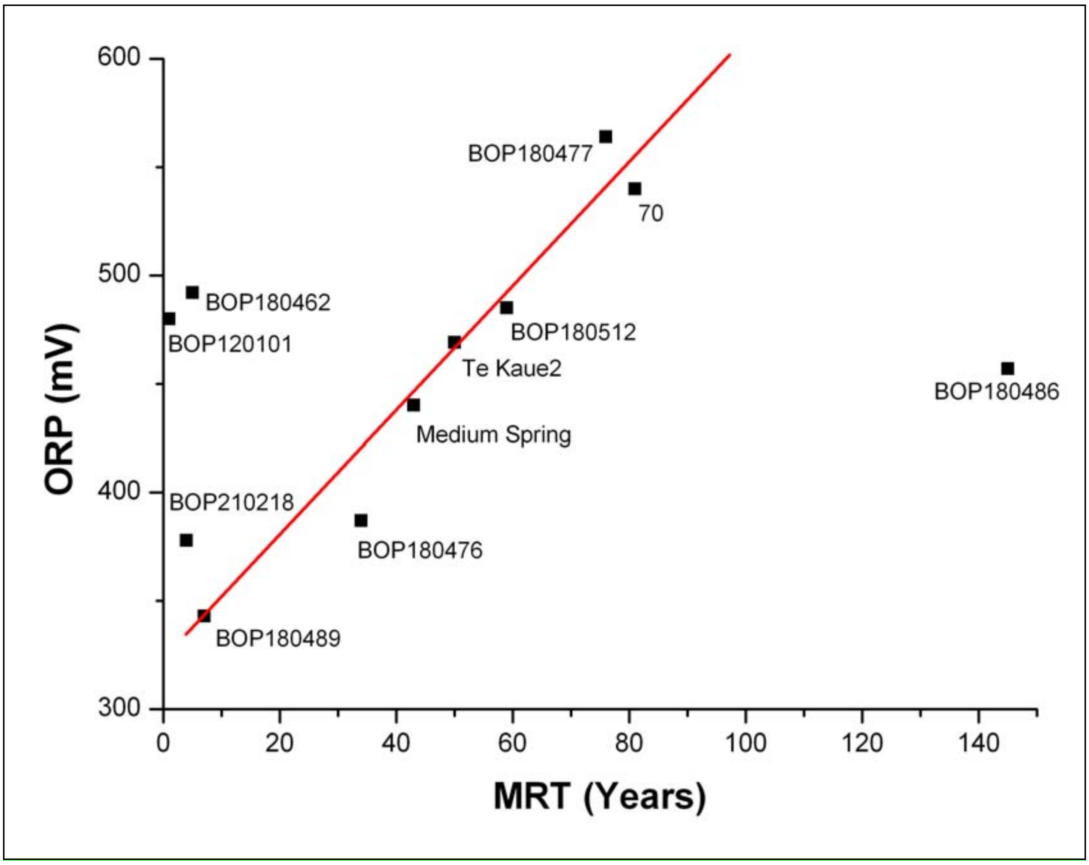


Figure 9 Plot of MRT versus ORP.

The lab measured pH of the groundwaters show a general trend of decreasing pH with increasing MRT (Figure 10). Site BOP180486 was not used in the trend determination due to the anomalous groundwater conditions at this site. Chemical reactions during water-rock interaction can result in higher pH as the groundwater comes closer to equilibrium with increasing contact time with the aquifer materials.

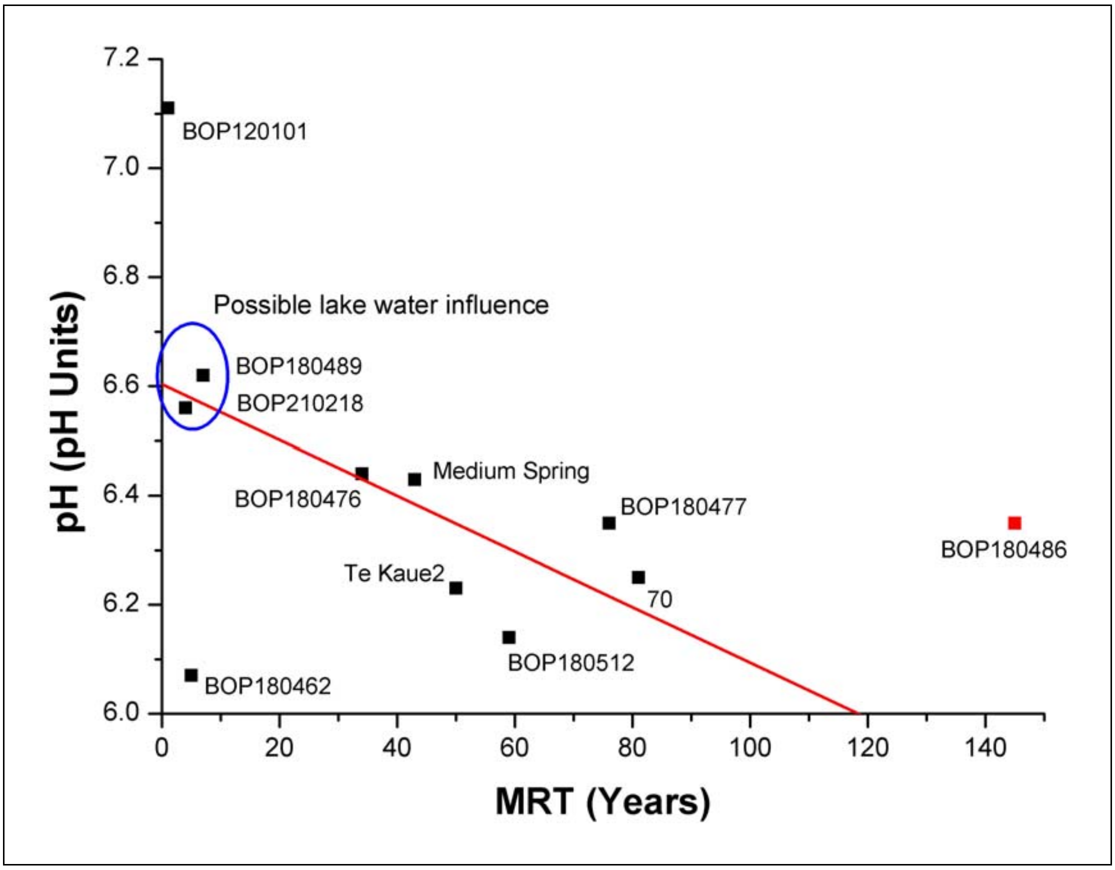


Figure 10 Plot of MRT versus pH. Site BOP180486 not used to determine the trend line.

While HCO_3 does not show a trend with MRT, it is observed that sites BOP210218, BOP180417, 76 and BOP180489 have the highest alkalinities. All these sites have large proportions of lake water identified as a source of groundwater recharge (Reeves et al., 2007) and have reducing groundwater conditions. The increased HCO_3 could be due to microbial respiration. This suggests that pathways of leakage from the lake may be entrained in organic carbon given that the lake has a low concentration of HCO_3. Further work would be required to establish this.

Mg and Ca do not show a clear trend with MRT. Ca concentrations are slightly elevated for all ground and stream water compared to the lake, but do not show a clear trend over time.

Relationships between SO_4 and MRT are complex. Some sites with young groundwater (e.g., site BOP210218) have very little SO_4, but this is due to reduction of SO_4 in a highly anaerobic environment. The groundwaters with MRT 30 - 80 years have relatively high SO_4 (up to 25 g m^{-3}). This might indicate anthropogenic origin of the SO_4 at some of these sites. The oldest sample (Site BOP180486) has very little SO_4 accompanied by slightly elevated Fe and Mn, which again suggests that the SO_4 has been removed in an anaerobic environment.

Na does not show a trend with MRT in the aquifers around Lake Rerewhakaaitu despite that a clear trend of increasing Na with increasing MRT was observed in the Lake Rotorua catchment for waters with similar MRT's (10 to 180 years) (Morgenstern, 2004). Cl does not show a trend with MRT (Figure 11). The Cl concentration in Lake Rerewhakaaitu (5.2 g m^{-3})

is about the same as the expected concentration of rainwater in the central North Island. Most groundwaters in this study have a similar Cl concentration indicating that no Cl is leached from the aquifer. The Mangakino stream (Site BOP120101) and site BOP180462 have the highest Cl concentrations relative to other sites in the study. Both sites are in different surface water catchments, south of Lake Rerewhakaaitu. This suggests possible leaching of Cl into groundwater (and therefore also into groundwater fed streams) from surface sources south of the Lake. The Na/Cl ratio is significantly above that of rain (c. 0.6) for all samples, indicating Na is leaching from the aquifer matrix. The samples from the Mangakino Stream (BOP120101) and bore 76 have relatively low Na/Cl ratios due to Cl leaching in excess to Na.

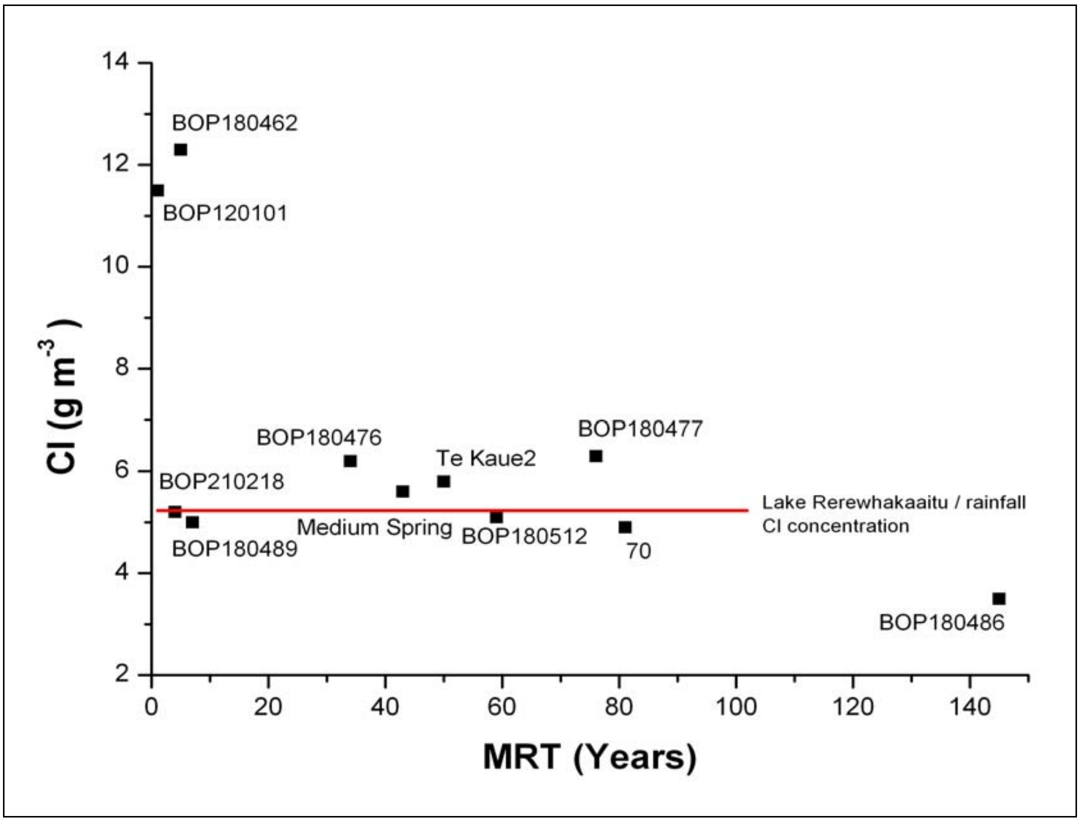


Figure 11 Plot of MRT versus Cl.

K shows a trend of decreasing K with increasing MRT (Figure 12). This strongly suggests that the elevated concentrations are due to the leaching of K into the groundwater systems from land use activities (e.g., applications of fertilizer). A similar trend has been observed in the Lake Rotorua catchment (Morgenstern et al., 2004). Water samples collected from sites Lake Rerewhakaaitu, BOP180489 and BOP210218 do not match this trend. These sites have the lowest K concentrations of the samples collected in this study. If fact, their K concentrations are even lower than the K concentration of the oldest water sample collected in this study (BOP180486). The K concentration at site BOP180486 gives us a good estimate of background concentrations, as it can be assumed that changes in land use practices have not affected groundwater at this site yet. Lower K concentrations at the Lake site (1.1 gm^{-3}) may be due to K been removed from the lake water by plants and algae that use it as a nutrient. Lower K concentrations in the young waters at sites BOP210218 and

BOP180489 may be due to the lower K concentration lake water contributing to the recharge of the groundwater aquifers in these areas.

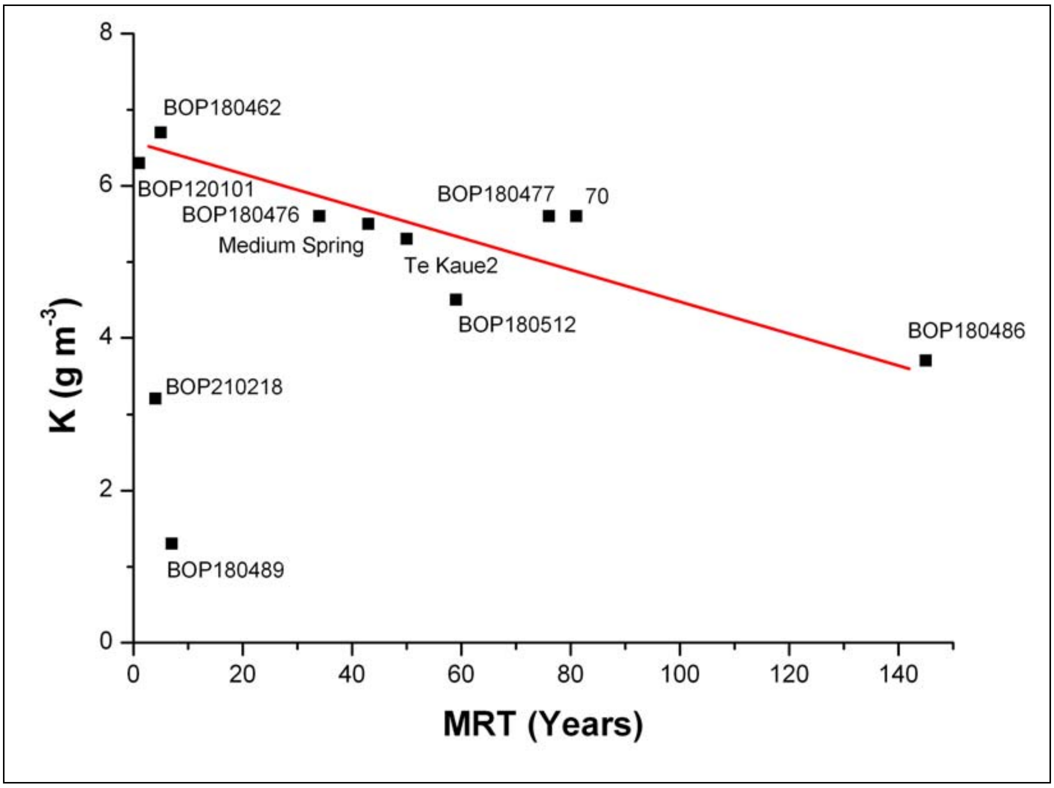


Figure 12 Plot of MRT versus K.

DRP concentrations vary from below the detection limit (<0.004 g m^{-3}) at sites BOP180445, BOP120101 and the Lake to 0.14 g m^{-3} at site BOP180445. Low DRP concentrations are apparent in the shallow aquifers and in the Mangakino Stream to the south of the lake. No other geographic pattern is apparent. A general trend of increasing DRP with depth can be seen (Figure 13). DRP generally increases with increasing age (Figure 14). This increase is caused by continued DRP leaching from the volcanic rock with time. This leaching process is slow and does not lead to DRP saturation concentrations within 150 years. This was also found in the Lake Rotorua catchment (Morgenstern et al., 2006). Sites BOP210218 and BOP180489 have unusually high DRP concentrations given their MRTs. This is likely to be caused by enhanced DRP release from the aquifer matrix in the anaerobic environment seen at these sites.

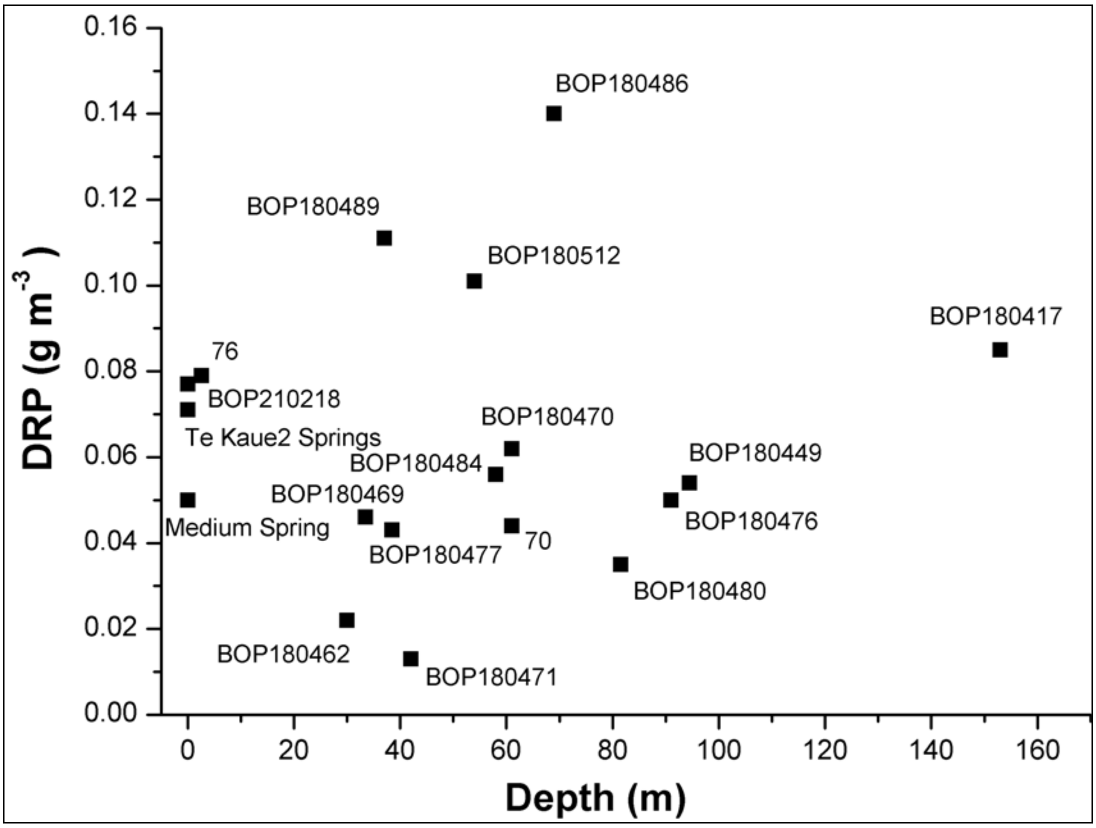


Figure 13 Plot of Depth versus DRP.

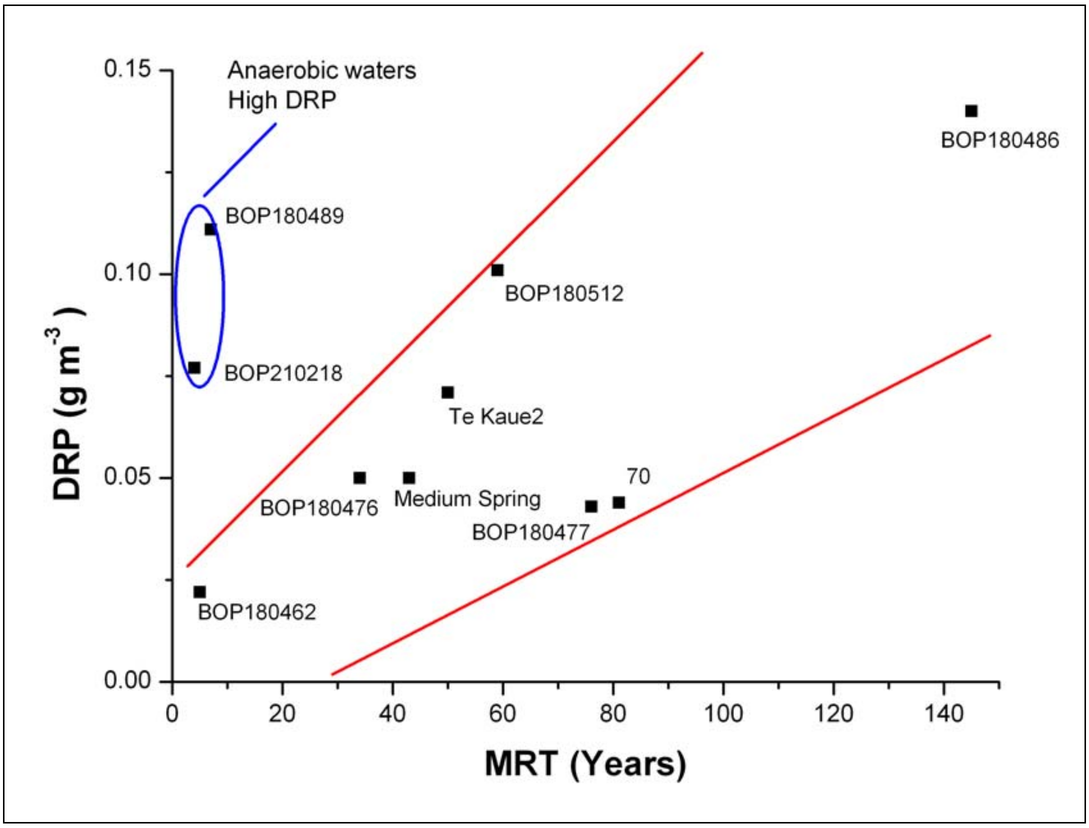


Figure 14 Plot of MRT versus DRP.

SiO_2 shows a general increasing trend with increasing MRT (contact time of the water with the aquifer material) (Figure 15). This is also found in other aquifers throughout NZ (Morgenstern et al., 2006). However, sites BOP120101 (Mangakino Stream), BOP180489 and BOP180462 do not follow the general trend. Site BOP180486 might indicate the SiO_2 saturation concentration (75 g m^{-3}) of the groundwater in the Rangitaiki aquifer given that this bore has the largest MRT, and therefore, its water is in contact with the aquifer material for the longest time. This compares favourably to waters in the Lake Rotorua catchment where the SiO_2 saturation for the ignimbrite aquifers is also estimated to be 75 g m^{-3} achieved with waters having MRT's of 130 years (Morgenstern et al., 2006). The SiO_2 concentration of the lake is extremely low with a concentration of 1 g m^{-3}. This is likely to be caused by silica removal by diatoms. It is unclear why the young waters that do not follow the trend have reached high silica concentration after a short period.

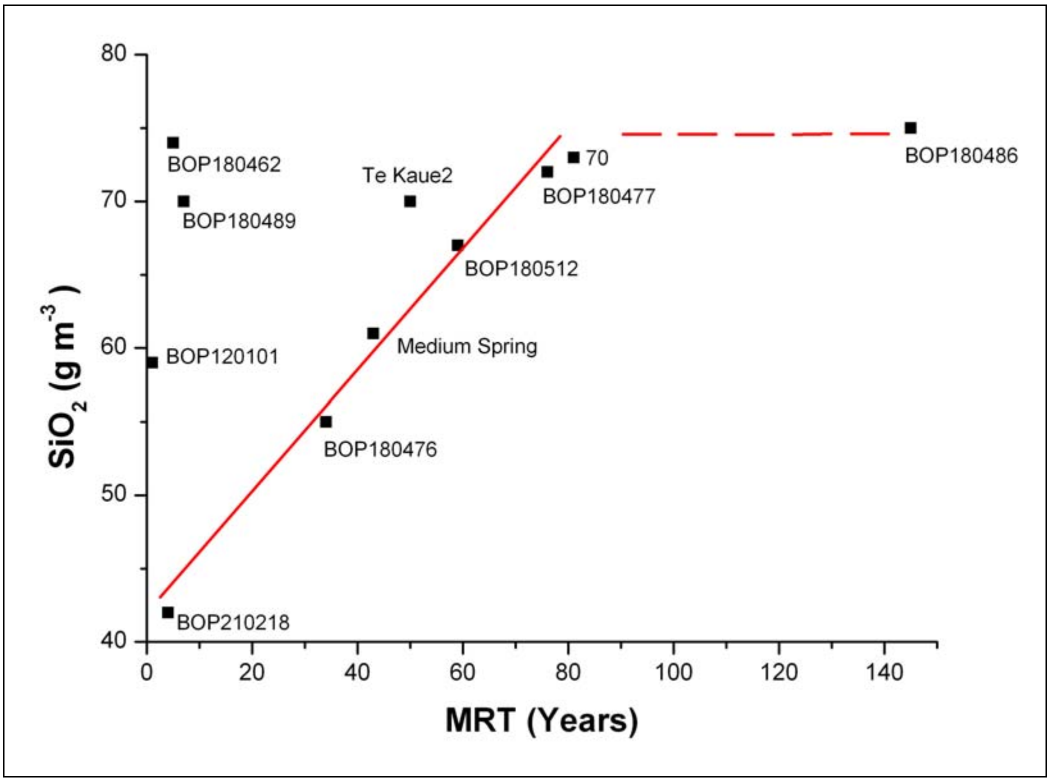


Figure 15 Plot of MRT versus SiO_2.

The F concentration shows a clear trend of increasing F with MRT (Figure 16). This is due to the leaching of F from the aquifer matrix. Only sites BOP210218 and BOP180489 from the high anaerobic environment to the north west of Lake Rerewhakaaitu show evidence of accelerated leaching in such anaerobic environment. Site BOP180476 shows slightly elevated F, and suggests a possible area where lake water may be passing through the aquifer. This is consistent with conclusions from Reeves et al. (2007) at this site.

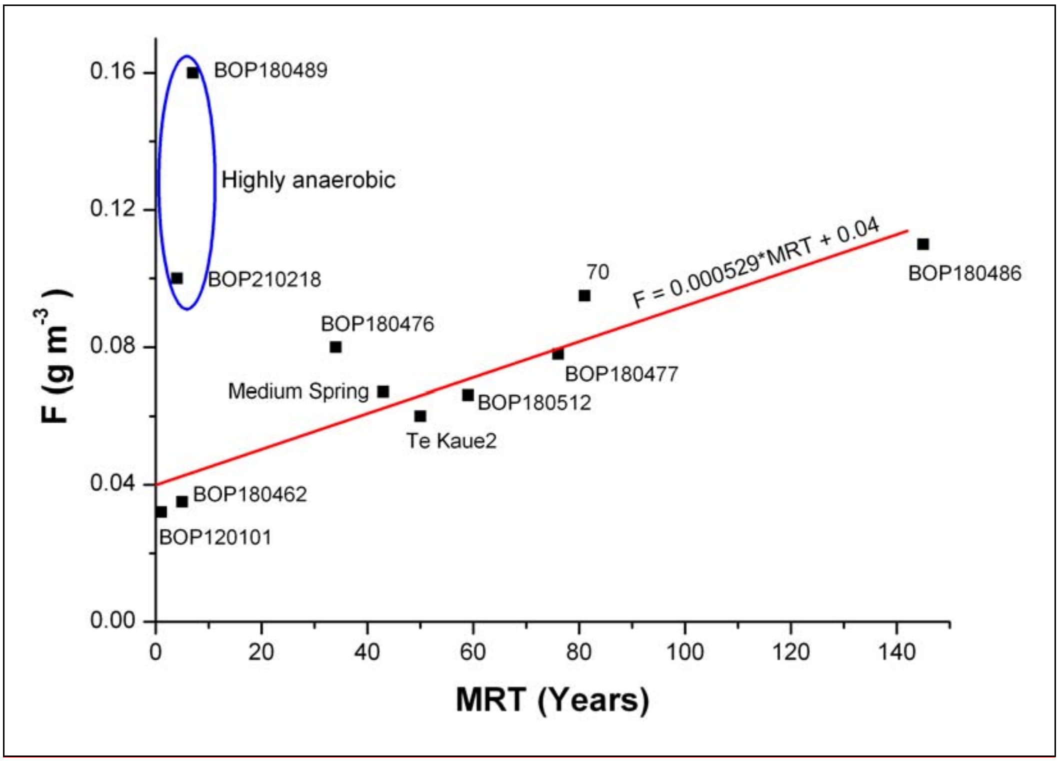


Figure 16 Plot of MRT versus F.

Nitrate concentrations range from below the detection limit (<0.002 g m^{-3}) at sites BOP180417, BOP180449, BOP180486 and BOP210218 to 4.8 g m^{-3} at site BOP180480. The Mangakino stream site (EBOP120101) has a NO_3-N concentration of 3.6 g m^{-3}, suggesting that there are nutrient inputs from surface flows entering the stream, or that shallow groundwater is feeding the stream. Site 76 has a nitrate concentration of 0.052 g m^{-3}, however, it has an NH_4-N concentration of 62.5 g m^{-3} demonstrating this site has significant levels of nitrogen in the groundwater. High concentrations of Fe and Mn (13.2 g m^{-3} and 0.12 g m^{-3} respectively) at site 76 also demonstrate reducing conditions in the groundwater at this site.

NO_3-N concentrations are generally higher in young waters compared to the older waters (Figure 17). This strongly suggests an anthropogenic origin for the NO_3-N, probably from land use practices. Sites BOP210218 and BOP180489 represent young waters from a highly anaerobic environment with related denitrification. Sites BOP180462 and BOP180477 have elevated NO_3-N concentrations relative to the general trend and may indicate locally higher NO_3-N inputs in these areas. The fact that most of the samples follow a trend over time indicates a relatively well mixed groundwater reservoir.

The lake water contains very little nitrate. This is likely due to a combination of two effects: (1) there is little interaction between land use area recharged groundwater and lake water, and (2) small amounts of nitrate in the lake water are being removed by biologic activity in the lake.

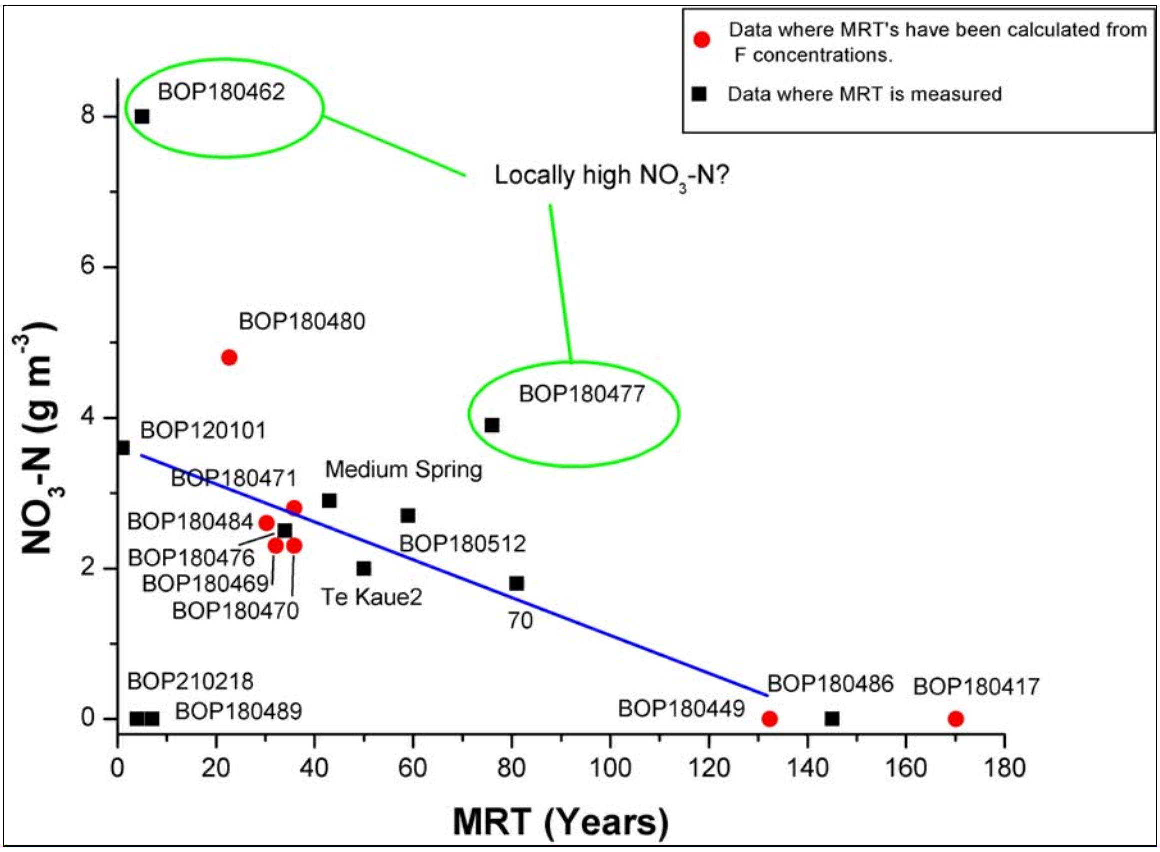


Figure 17 Plot of MRT versus NO_3-N. In addition to NO_3-N data with measured age data, data are shown for which age was not measured explicitly. Approximate MRTs were calculated using the correlation of F vs. MRT. These data are shown with circles. While their MRTs have high uncertainty, they do follow the general trend.

^{18}O and ^{2}H do not show a trend with water age. Also excess air and recharge temperature, as derived from Ar and N_2 concentrations in the water, do not show a trend with water age.

5.0 SUMMARY

Twenty one water samples were collected from bores, streams, springs and the lake from the Lake Rerewhakaaitu area. All water samples were analysed for major anions, major cations, nutrients, oxygen 18 and deuterium. Eleven samples were analysed for water dating isotopes (Tritium and/or CFCs). The results show:

- In general, the water quality of the groundwater in the Lake Rerewhakaaitu area is good relative to the NZ drinking water standards.
- Strong reducing conditions were found at 3 sites. These sites were characterised by elevated NH_4-N, Fe and Mn concentrations. All sites occur to the north/northwest of Lake Rerewhakaaitu and are suspected of containing a large proportion of water recharged by Lake Rerewhakaaitu.
- Oxygen 18 and Deuterium isotopes clearly demonstrate leakage of water from Lake Rerewhakaaitu on the north and western side of Lake Rerewhakaaitu. This is discussed in more detail in Reeves et al. (2007).

- Mean residence times (MRT) are between 1 and 145 years for water samples collected as part of this study. In general, increasing MRT is related to:
    - increasing depth
    - increasing ORP
    - decreasing pH
    - decreasing K
    - increasing DRP
    - increasing SiO2
    - increasing F
- NO_3-N concentrations are generally higher in younger waters suggesting an anthropogenic origin for the NO_3-N e.g., Site 180486 (MRT of 145 years) has a NO_3-N concentration of <0.002 gm^{-3} compared to Site 120101 (MRT of 1 year) having a NO_3-N concentration of 3.6 gm^{-3}. This is probably due to leaching of nitrogen into the groundwater from land use practices.
- One site has very high NH_4-N concentrations. The cause of this is unknown.

6.0 ACKNOWLEDGEMENTS

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APPENDIX 1 – WATER DATING METHODS

Methodology of Groundwater Age Dating
Text modified from Morgenstern (2006)

Tritium and the CFC Method

Tritium is produced naturally in the atmosphere by cosmic rays, but large amounts were also released into the atmosphere in the early 1960s during nuclear bomb tests, giving rain and surface water high tritium concentration at this time (Figure A1). Surface water becomes separated from the atmospheric tritium source when it infiltrates into the ground, and the tritium concentration in the groundwater then decreases over time due to radioactive decay. The tritium concentration in the groundwater is therefore a function of the time the water has been underground. Additionally, detection of superimposed bomb tritium can identify water recharged between 1960 and 1975. Groundwater dating using tritium is described in more detail in Cook & Herczeg (1999) and Stewart & Morgenstern (2001).

As a result of the superimposed atmospheric tritium "bomb" peak in the 1960s, ambiguous ages can occur with single tritium determinations in the age range 15-40 years (i.e. the tritium concentration can indicate any of several possible groundwater ages). This ambiguity can be overcome by using a second tritium determination after about 2-3 years, or combined age interpretation of tritium data and data from an independent dating method, for example CFCs or SF_6. CFC and SF_6 concentrations in the atmosphere have risen monotonously over that time and therefore can resolve tritium ambiguity if they are not altered in the aquifer.

Chlorofluorocarbons (CFCs) are entirely man-made contaminants. They were used for refrigeration and pressurising aerosol cans, and their concentrations in the atmosphere have gradually increased (Figure A1). CFCs are relatively long-lived and slightly soluble in water and therefore enter the groundwater systems with groundwater recharge. Their concentrations in groundwater record the atmospheric concentrations when the water was recharged, allowing determination of the recharge date of the water. CFCs are now being phased out of industrial use because of their destructive effects on the ozone layer. Thus rates of increase of atmospheric CFC concentrations slowed greatly in the 1990s, meaning that CFCs are not as effective for dating water recharged after 1990.

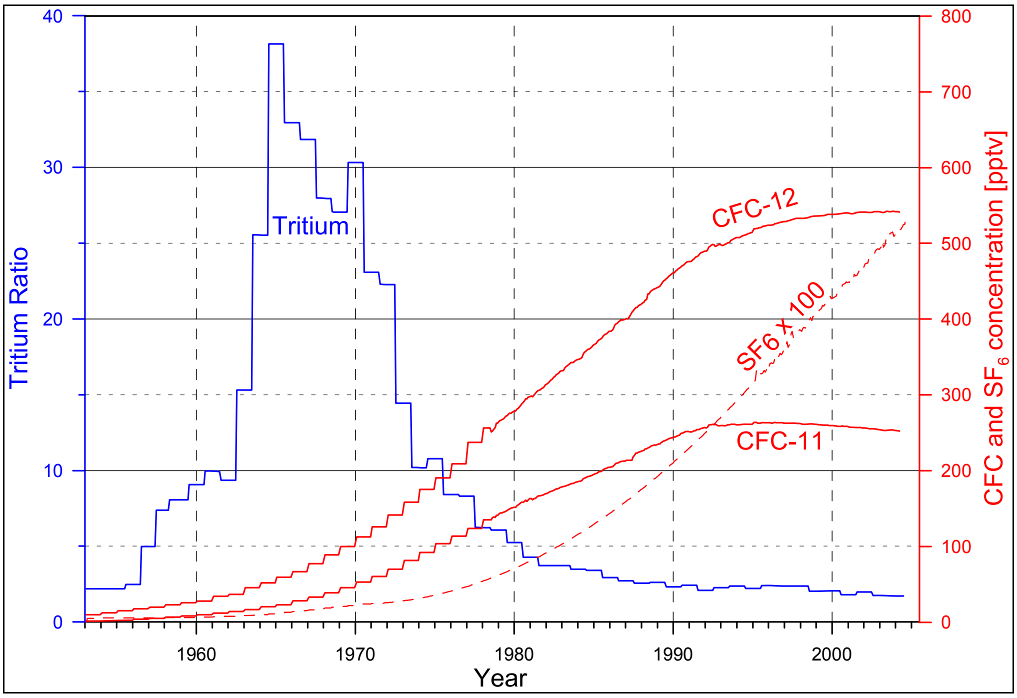

Figure A1 Tritium, CFC and SF_6 input for New Zealand rain. Tritium concentrations are in rain at Kaitoke, 40km north of Wellington (yearly averages), and CFC and SF_6 concentrations are for southern hemispheric air. TR=1 represents a 3H/1H ratio of 10-18, and 1 pptv is one part per trillion by volume of CFC or SF_6 in air, or 10^{-12}. Pre-1978 CFC data are reconstructed according to Plummer and Busenberg (1999), and scaled to southern hemisphere by factor 0.83 (CFC-11) and factor 0.9 (CFC-12). Post-1978 CFC data are from Tasmania. Pre-1970 SF_6 data are reconstructed (USGS Reston), 1970-1995 data are from Maiss and Brenninkmeijer (1998), and post-1995 data was measured in Tasmania.

Tritium is a conservative tracer in groundwater. It is not affected by chemical or microbial processes, or by reactions between the groundwater, soil sediment and aquifer material. Tritium is a component of the water molecule, and age information is therefore not distorted by any processes occurring underground. For CFCs, a number of factors can modify the concentrations in the aquifer, including microbial degradation of CFCs in anaerobic environments (CFC-11 is more susceptible then CFC-12), and CFC contamination from local anthropogenic sources (CFC-12 is more susceptible to this), Plummer and Busenburg (1999). CFC-11 has been found in New Zealand to be less susceptible to local contamination and age estimates agree better with tritium data. Note that CFC and SF_6 ages do not take into account travel time through unsaturated zones.

The tritium method is very sensitive to the flow model (distribution of residence times in the sample) due to the large pulse-shaped tritium input during 1965-1975. With a series of tritium measurements, and/or additional CFC and SF_6 measurements, age ambiguity can usually be resolved. In that case, both the mean groundwater age and the age distribution can be obtained.

Groundwater Mixing Models

Groundwater comprises a mixture of water of different ages due to mixing processes underground. Therefore, the groundwater doesn’t have a discrete age but has an age distribution or spectrum. Various mixing models with different age distributions describe different hydrogeological situations (Maloszewski and Zuber, 1982). The piston-flow model describes systems with little mixing (such as confined aquifers and river recharge), while the exponential model describes fully mixed systems (more like unconfined aquifers and local rain recharge). Real groundwater systems, which are partially mixed, lie between these two extremes. They can be described by a combination of the exponential and piston-flow models representing the recharge, flow and discharge parts of a groundwater system respectively. The output tracer concentration can be calculated by solving the convolution integral, and the mean residence time (MRT) can be obtained from the tracer output that gives the best match to the measured data. If the second parameter in the age distribution function, the fraction of mixed flow, cannot be estimated from hydrogeologic information, then two independent tracers (tritium and CFC/SF_6) or two tritium measurements over time are necessary.

Schematic groundwater flow situations are shown in Figure A2. The unconfined aquifer situation is described by the exponential model (EM). Flow lines of different length containing water of different age converge in the well or the stream, and the abstracted water has a wide range of ages with an exponential age distribution. The confined aquifer situation is described by the piston flow model (PM) with a narrow range of ages. The partly confined aquifer situation is described by the exponential-piston flow model (EPM). The free parameter is the fraction of exponential flow within the total flow volume (represented by E%PM, where the fraction is given in %), or the ratio η of the total flow volume to the volume of the exponential part. The water has a wide range of ages, but because part of the flow is piston flow, the age distribution has a minimum age (no water can be younger than the time necessary to pass through the piston flow part). The piston flow part can be represented by a partly confined flow with no vertical input of young water from the surface, or it can be represented by a significant unsaturated zone with vertical piston flow toward the water table and mixing of different ages below the water table.

As an example, the age distribution for the exponential-piston flow model for different fractions of mixed flow is shown in Figure A3 for water with a mean residence time of 50 years. Water with a high fraction of exponential flow of 90% has a wide range of ages, starting at 5 years and still significant contributions of old water with ages over 150 years. Despite the mean residence time of 50 years, the major part of the water is younger than 50 years. The water can therefore partly be contaminated before the mean residence time of 50 years has elapsed. About 2% of the water can already be contaminated after 5 years. With each further year, these young fractions accumulate, and increasingly contaminated water arrives at the spring or well. The total fraction of water within a certain age range can be obtained by integrating the age distribution over the specified age range. This is equal to the area below that part of the curve, with the total area below the whole curve being 100% water fraction. The fraction of water that is younger than a specified age is called the young water fraction (yf). The young water fraction younger than 55 years is about 80% in the example in Figure A3 (hatched area).

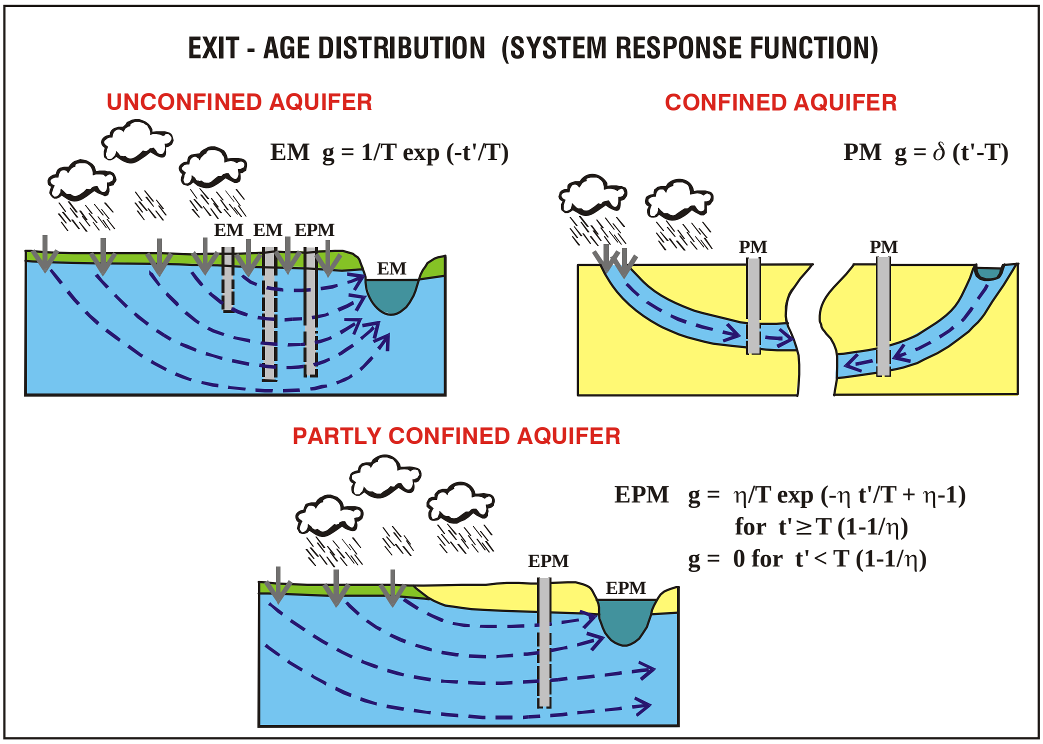

Figure A2 Schematic groundwater flow situations and corresponding age distribution functions (see Maloszewski and Zuber (1982) for theoretical background).

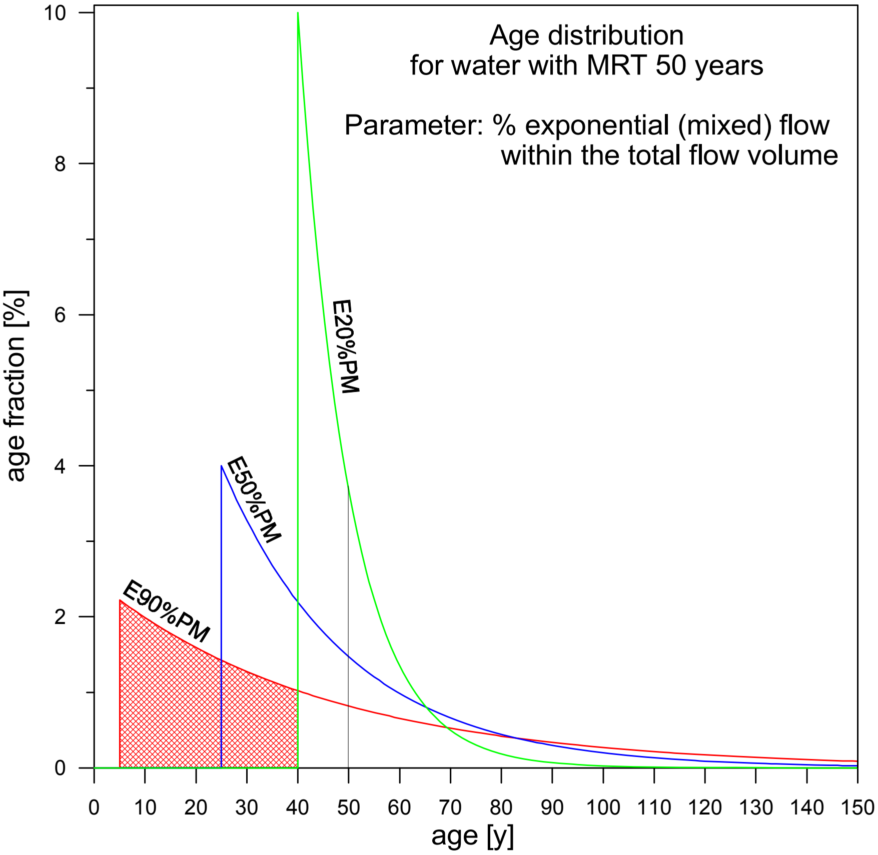

Figure A3 Age distribution for the exponential-piston flow model.

In a flow situation with less exponential flow, the age distribution of the water is less wide-spread. At 50% exponential flow, the minimum age is 25 years, and the water does not contain significant fractions older than 150 years. At only 20% exponential flow, the age distribution is relatively peaked around the mean residence time. The minimum age is 40 years, and there is an insignificant amount of water older than 100 years. This water would just start to show a contaminant introduced 40 years ago, but this contaminant would arrive in a relatively sharp front, with 10% contribution in the first year of arrival after 40 years time.

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