Water Resources of the Reporoa Basin

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Executive Summary

Over the past five years there has been an expansion of pasture irrigation in the Waikato Region, and in particular within the Reporoa Basin. Rivers and streams in the Reporoa Basin are fully allocated. With maximum allocation limits of 10-15% of the one in five year (Q_5) low flow, water users have started to target groundwater resources as an alternative water source. Through the development of groundwater and the perception that groundwater resources may become over exploited, community interest in current and future applications for pasture irrigation from groundwater is high.

This report describes the geology, groundwater chemistry, groundwater and surface water hydrology, groundwater age, water use and future groundwater allocation of the Reporoa Basin.

The geology comprises predominantly rhyolitic formations. The geology of the Basin edges is relatively simple with Taupo Ignimbrite overlying uplifted Rangitaiki Ignimbrite in the eastern Basin and Paeroa Ignimbrite in the western Basin. Rangitaiki Ignimbrite is welded and fractured. The central Basin is characterised by a complex sequence of pyroclastic Taupo and Oruanui Ignimbrites overlying lacustrine sediments of the Huka Formation. These in turn overly the ignimbritic Waiora Formation.

Groundwater flow in the Basin is consistent with topography although more subdued. There is a correlation between groundwater depth and well depth, indicating vertical groundwater recharge. Groundwater predominantly drains locally toward the streams within the Basin and ultimately the Waikato River. A large proportion of groundwater recharge from rainfall is intercepted by streams such as the Torepatutahi, Kaiwhitiwhiti and Waiotapu streams. Average groundwater flow velocities are estimated to range between 0.02 m d^{-1} to 0.16 m d^{-1}.

Groundwater quality was analysed to investigate land use impacts, particularly elevated nitrogen concentrations. General chemical character was also related to geology in order to improve the hydrogeological understanding of the Reporoa Basin. Groundwater was sampled from 32 sites. Groundwater is largely sodium bicarbonate dominated, which is a reflection of carbonic leaching of the rhyolitic formation. There is some evidence of land use impacts, with elevated nitrate-nitrogen concentrations in groundwater sourced from several bores. Sodium and chloride are generally elevated in groundwater at sites with high nitrate-nitrogen concentrations. They also appear to be higher where it is thought that groundwater is influenced by geothermal processes.

Elevated arsenic concentrations were found to occur in groundwater in 20% of wells and within most of the aquifer formations sampled. Possible factors influencing arsenic concentrations are reducing conditions and the influence of geothermal processes.

Age determination of groundwater at eight bore locations within recharge zones using tritium and CFCs, indicate that mean groundwater residence time in the aquifer is between 11 years to 73 years. A spring of the Torepatutahi Stream within a groundwater discharge zone sampled in 2001, was found to have a mean residence time of 150 years.

Water balance model estimates show that in many of the Reporoa Basin catchments, groundwater flow is predominantly intercepted by large springs. These commonly are the source of streams within the Basin. There is limited groundwater resource available for future abstraction in many catchments, particularly the Kaiwhitiwhiti, Torepatutahi and Waiotapu catchments. The inference of limited groundwater for abstraction is based on aquatic and ecologic requirements as well as water balance model estimates.

The reported investigation provides the basis for seeking future more detailed work not included in this report such as groundwater modelling, and also provides much needed

scientific information for the understanding and management of surface water and groundwater resources in the Reporoa Basin.

1 Introduction

1.1 Background

The need to manage water resources within the Reporoa Basin was recognised in 2001 when the effects of abstraction on river flow variation and water temperature in relation to trout was investigated in the Torepatutahi Stream (Speirs and Kusabs, 2001). Water abstraction for pasture irrigation occurs from a large number of streams and rivers in the Reporoa area. Demand for water is high and increasing at a steady rate.

Over the past five years there has been a steady expansion of pasture irrigation in the Waikato Region, and in particular within the Reporoa Basin. Prior to 2002, all applications to take water for irrigation in the Reporoa Basin were from surface water. With most streams and rivers in the Reporoa Basin reaching the maximum allocation limits of 10%-15% of the one in five year (Q_5) low flow, water users have started to target groundwater resources as an alternative source of water supply.

Groundwater resources in the Reporoa Basin are an important resource for many farms. Groundwater is used predominantly for stock watering and milk cooling systems in dairy sheds. Many farms rely solely on groundwater as no other water supplies are available. Community interest in current and future consent applications to take water for pasture irrigation from groundwater is high. This is due to the increasing use of groundwater and the perception that groundwater resources may become over exploited. Knowledge of the characteristics of the water resources of the Reporoa Basin is currently limited. This study seeks to investigate chemical and hydrologic characteristics of the water resources. Particular emphasis is on groundwater, to develop an information base for future water resource management in the Reporoa Basin.

1.2 Objectives

The aim of this Reporoa study is to investigate groundwater and surface water resources and their interaction in the Reporoa Basin to provide a technical basis for management.

Specific study objectives include:

i.   Estimation of the current water usage of the Reporoa Basin;
ii. Determination of the gross water balance including hydrological inputs and outputs;
iii. Description of surface water and groundwater interactions;
iv. Water availability estimation;
v.   Development of an information database.

2 Physical Setting

2.1 Location

The study area is located approximately mid-way between Taupo and Rotorua in the Rotorua and Taupo Districts (Figure 1). The area covers 718 km^2 and extends from Rainbow Mountain in the north to White Road in the south. The Paeroa Range forms the western boundary, and the eastern margin lies along Goudies Road. The area is also characterised by extensive active geothermal fields.
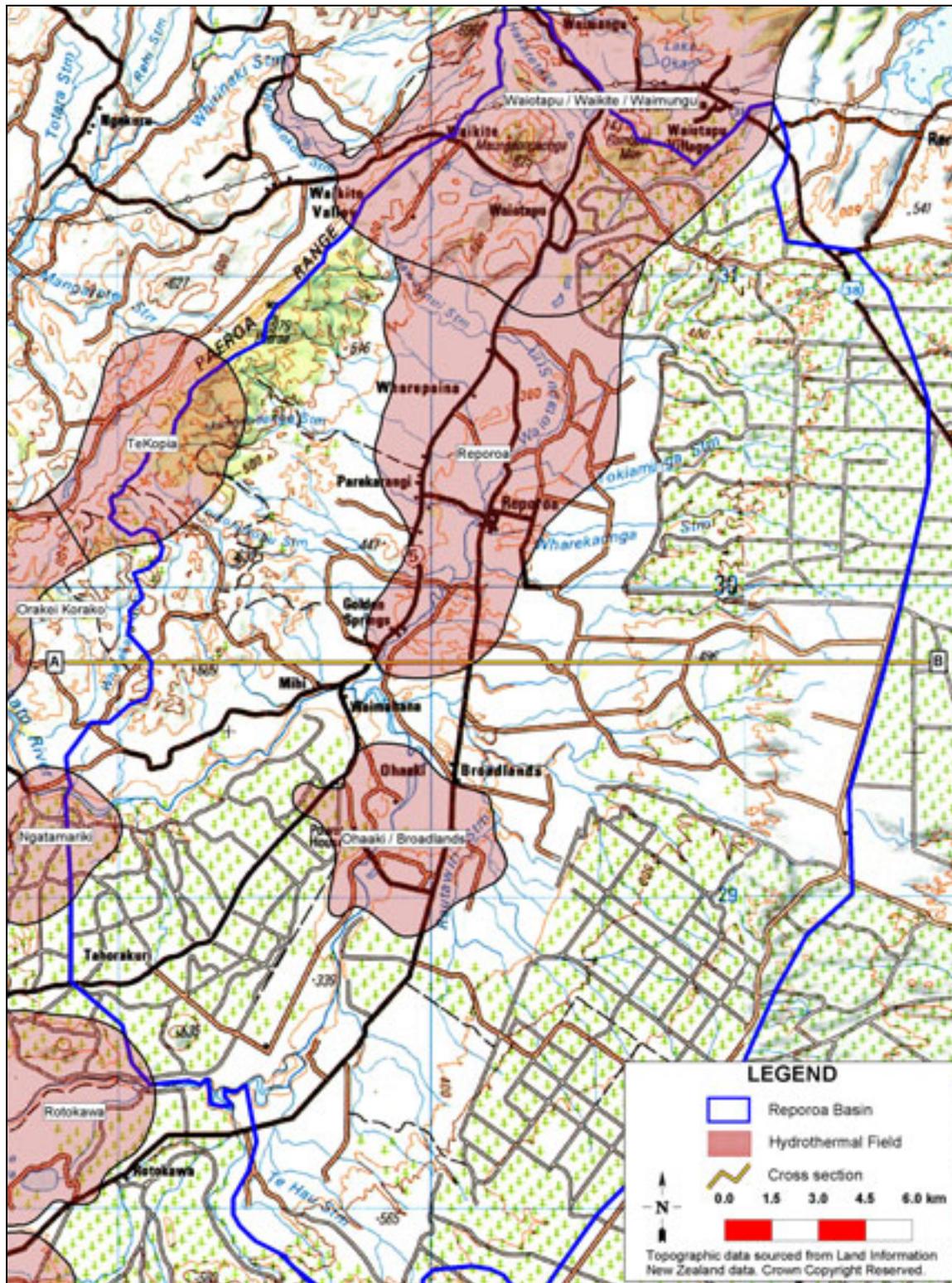
Figure 1: Reporoa Basin and features.

2.2   Soils

The dominant soils in the study area are classified as Pumice soils (Hewitt, 1998), largely derived from primary deposits of Taupo pumice and reworked Taupo pumice sediments. The most common soils are Kaingaroa, Taupo, Whenuaroa and Oruanui series. On the flats and undulating topography, Taupo and Whenuaroa series dominate (about 60% by area). Taupo and Oruanui series are the most common soils on the rolling country (about two thirds by area), with Oruanui increasing at higher elevations. The Kaingaroa series dominates the Kaingaroa Plateau, occupying just under a quarter of the study area (Newsome, 1992).

2.3   Rainfall

Rainfall data for the Reporoa Basin and surrounding region was obtained from the National Climate Database held at the National Institute of Water and Atmospheric Research, as well as data held by Environment Waikato (Figure 2).
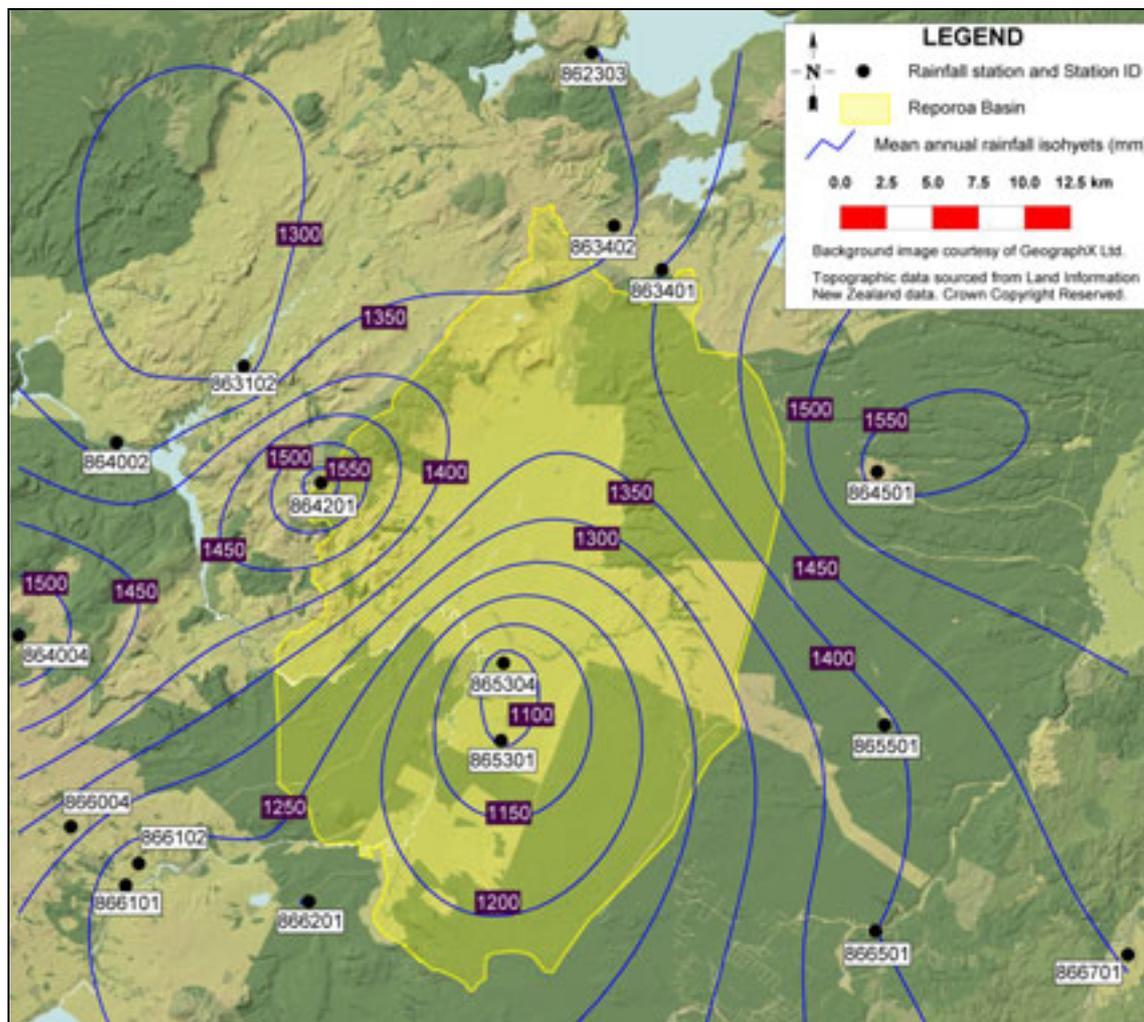
Figure 2:   Average annual rainfall for the period 1962 to 2002.

Typical mean annual rainfall for the study area is between 1100 mm and 1550 mm. Topography is the dominant influence on the rainfall distribution. Rainfall is highest along the western and northern flanks, with the lowest rainfall in the center of the Basin (Figure 2).

Rainfall for the Reporoa Basin shows considerable variation over the rainfall record used for the study. This is illustrated by the deviation from mean annual rainfall of 1278.46 mm at rainfall recorder site 863102 (Figure 3). Variations in the amount of rainfall directly influence the amount of groundwater recharge, which in turn controls the discharge of Reporoa Basin streams. The variability of rainfall in the Reporoa Basin is also illustrated by the seasonal pattern of rainfall for the period of the study (Figure 4). Figure 4 shows that there is a considerable difference between the average, minimum and maximum rainfall totals.
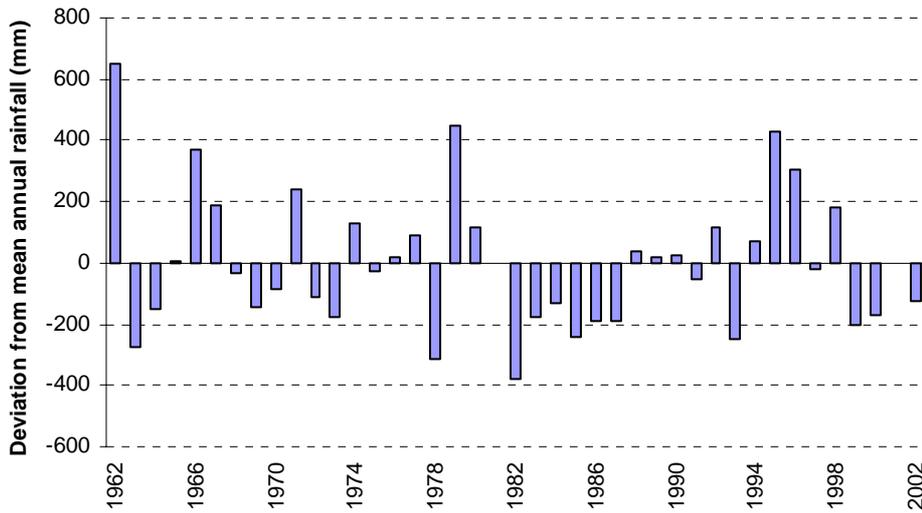
Figure 3: Rainfall deviation from the mean annual total at recorder site 863102 for the period 1962 to 2002.
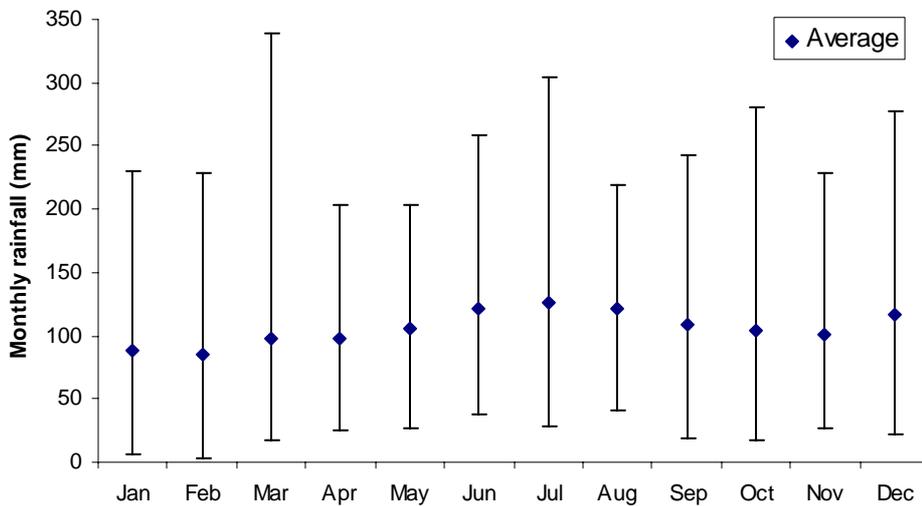
Figure 4: Minimum, average and maximum recorded rainfall at recorder site 863102 for the period 1962 to 2002.

2.4 Land Cover

Land cover in the Reporoa Basin area was determined from the 1996 New Zealand Land Cover Database (Copyright Terralink NZ Ltd). Land cover groups include pasture, indigenous forest, scrub, exotic forestry, wetlands and urban. Figure 5 shows the distribution of land cover in the area. Exotic forestry and pasture are the predominant land cover, accounting for 47.6% (341.8 km^2) and 46.3% (332.8 km^2) of the area respectively. Shrubland and indigenous forest account for 5.2% (37.1 km^2). The remaining 0.9% (6.7 km^2) of the Reporoa Basin comprises urban, wetland and surface waters.

Figure 5:   Land cover in the Reporoa Basin (Copyright Terralink NZ Ltd).

3   Geologic Setting

3.1   Geological history of the area

Reporoa Basin is a fault-angle depression between the Paeroa Block and the Kaingaroa Plateau (Figure 6). The Reporoa Basin is part of a caldera which was formed in association with the eruption of the c. 100 km^3 Kaingaroa Ignimbrites at 0.24 Ma (Nairn et al., 1994). The Reporoa Basin has been a depositional centre for at least 0.6 Ma, with the accumulation of a sequence of welded or brecciated rhyolitic pyroclastic units (Kaingaroa, Paeroa, Rangitaiki and Waiotapu Ignimbrites) and interbedded laustrine units (Huka Group, Wairoa Group) up to several kilometres in thickness (Healy, 1963; Bignall, 1990; Nairn et al., 1994).

Interbedded lacustrine silts, fluvial sands and gravels, and interbedded unwelded pyroclastic fall and flow units make up the upper 300 metres of material in the Reporoa Basin. The upper 3-12 metres of formation consists of pumiceous material derived from the Taupo 1.8 Ka eruption. Below this is a thick brownish palaeosol dated at 12,000 to 16,000 years before present. Below the palaeosol are reworked Oruanui pyroclastic units which overly the Oruanui pyroclastic sequence, dated at 26,000 years before present. The Oruanui pyroclastic unit is between 30 metres and 150 metres in thickness (Wilson, 1991). Beneath the Oruanui ignimbrite is the Huka Group formation made up of massive to laminated, pumiceous and diatomaceous silts several hundred metres thick. The Huka Formation is relatively impermeable, and has formed a cap to the geothermal fields at Wairakei and Ohaaki (Manville, 1999).

4   Hydrogeology

4.1   Taupo Formation (1.8 Ka)

Non-welded pyroclastic flow deposit erupted during the 1.8 Ka Taupo eruption. This material is characterised by a high primary permeability and a lack of jointing (Hadfield

et al., 2001). Permeability of the Taupo sequence is likely to be controlled by the coarse, loosely packed pumice/lithic gravel beds.

The Taupo formation constitutes is a shallow unconfined pumice and lapilli aquifer. Its saturated thickness is at least 10 metres. Recharge to the aquifer is from the infiltration rainfall and discharge from the Rangitaiki Ignimbrite aquifer (Cameron and Reeves, 2004).

4.2   Hinuera Formation (26 Ka)

The Hinuera Formation is a non-welded ignimbrite from the ~26 Ka Oruanui eruption. This unit is characterised by a high primary permeability and an almost complete lack of jointing. In comparison to the Taupo Ignimbrite, Oruanui Ignimbrite is finer grained and less permeable. It is suggested that the upper Oruanui Ignimbrite is likely to form the shallow regional aquifer of the Reporoa Basin (Wilson, *pers comm*). Thompson (2000) observed that the upper Oruanui sequence, identified from well cores, is silty and firmly packed, indicating relatively low permeability.

The Hinuera aquifer is located within a sand and gravel zone between approximately 90 and 110 metres below the ground surface. The aquifer is estimated to be approximately 20 metres thick. The material comprising the aquifer appears to change in composition, with formation material appearing finer and lower yielding on an east to west direction. The aquifer exhibits sub-artesian conditions similar to the Huka Formation aquifer.

4.3   Kaingaroa Formation (150 Ka)

A dark-grey, quartz-free, welded vitric tuff. The ignimbrite grades from a basal lenticulite, containing devitrified glassy lenticles, andesite and ignimbrite fragments, upwards into a compact dark-grey sandy tuff containing andesite, rhyolite and pumice inclusions (Grindley, 1961). The Kaingaroa Ignimbrite forms the northern portions of the Kaingaroa Plateau and is reported to consist of a welded top sheet, partially welded middle sheet, and an unwelded basal sheet consisting of ash and pumice braccia layers (Earthtech Consulting Ltd, 2000).

4.4   Huka Formation (~200 Ka)

Massive to laminated, pumiceous and diatomaceous silts several hundred metres thick that underlie the Oruanui ignimbrite. The Huka Group is relatively impermeable, and has formed a cap to the geothermal fields at Wairakei and Ohaaki (Manville, 1999). Primary permeability is likely to be highly variable but mostly low; jointing is sparsely present in the finer units, but not likely to contribute much to overall permeabilities (Hadfield *et al.*, 2001).

The Huka Formation aquifer is a pumice sand and gravel aquifer occurring approximately 150 metres below ground surface. Aquifer thickness is estimated to be between 15 to 20 metres thick. The Huka formation aquifer is confined by low permeability clay sediment and exhibits sub-artesian conditions.

4.5   Rangitaiki Formation (250 Ka)

A light-grey to buff, highly quartzose ignimbrite underlying the Kaingaroa Ignimbrite. Abundant phenocrysts of quartz, and biotite or hypersthene. Around the Waiotapu area, the Rangitaiki ignimbrite is interstratified with pumice breccias of the Huka Group at shallow depths (Grindley, 1961). The Rangitaiki Ignimbrite is an extensive unit located within the eastern margins of the Reporoa Basin. The ignimbrite consists of a series of sheets that are moderately welded and include unconsolidated pumice breccias between 100 metres to more than 200 metres in thickness (Earthtech Consulting Ltd, 2000).

The Rangitaiki Ignimbrite aquifer is estimated to be between 115 and 135 metres thick on the western margin of the Kaingaroa Plateau. Groundwater occurs within fractures in the welded ignimbrite and in the pore spaces of the non-welded ignimbrite (Cameron and Reeves, 2004). The aquifer is likely to be unconfined as the Rangitaiki ignimbrite and is exposed at the ground surface to the east of the Kaingaroa Plateau (Cameron and Reeves, 2004). No significant layers of low permeability are described by bore log data for bores utilizing the Rangitaiki Ignimbrite aquifer.

4.6   Hydraulic properties

Limited pumping test information is available for bores within the Reporoa Basin (Table 1). Records indicate only three in-depth pumping tests have been completed. For the remaining bores, the Logan Approximation Method for calculating transmissivities using the pumping rate, the duration of the pump test and the total drawdown was used. Transmissivity ranges from 2 to 1720 m^2 d^{-1}, with the majority of wells having transmissivities below 35 m^2 d^{-1}. Transmissivities are variable across and within the different aquifer formations. The heterogeneity of transmissivities within the same formation is likely to be associated with the spatial variability in the thickness, sorting and sequencing of the geology.

Table 1:   Summary of aquifer parameters.

Located ID	Formation	Map Reference	Conductivity m d^{-1}	Transmissivity m^2 d^{-1}	Storativity
66-90	Taupo Ignimbrite	U17:027-950	4.59		
66-91	Taupo Ignimbrite	U17:027-950	1.60		
66-93	Taupo Ignimbrite	U17:017-018	12.63		
68-626	Taupo Ignimbrite	U17:974-956		35	
68-853	Taupo Ignimbrite	U17:974-956		105	
66-35	Taupo Ignimbrite	U17:017-045		33	
66-20	Taupo Ignimbrite	U17:997-887		16	
72-122	Taupo Ignimbrite	U17:938-848		488	
68-634	Taupo Ignimbrite	U17:967-858		117	
66-58	Oruanui Ignimbrite	U17:048-996		73	
66-54	Oruanui Ignimbrite	U17:894-949		29	
66-16	Oruanui Ignimbrite	U17:914-943		24	
72-169	Oruanui Ignimbrite	U17:929-956		4	
72-170	Oruanui Ignimbrite	U17:929-956		638	
68-766	Oruanui Ignimbrite	U17:995-853		20	
68-767	Oruanui Ignimbrite	U17:991-871		26	
68-150	Oruanui Ignimbrite	U17:968-858		59	
68-426	Oruanui Ignimbrite	U17:967-858		10	
66-96	Oruanui Ignimbrite	U17:053-958		1720	0.00032
66-22	Rangitaiki Ignimbrite	V17:127-960		6	
66-40	Rangitaiki Ignimbrite	U17:048-985		30	
68-432	Rangitaiki Ignimbrite	V17:132-928		2	
68-229	Rangitaiki Ignimbrite	U17:995-865		16	
72-1583	Rangitaiki Ignimbrite	U17:941-819		17	
72-1882	Huka Formation	U17:033-959		924	0.00615

Porosity for the geological units of the Reporoa Basin is difficult to estimate. For some geological units such as Taupo and Oruanui ignimbrite, primary porosity is likely to range between 0.25-0.50 (Meinzer, 1923). Estimating porosity for other geological units such as the Kaingaroa and Rangitaiki ignimbrites is more complicated, due to the likelihood that the units have primary and secondary porosity. Porosity is likely to range between 0.01-0.50 based on descriptions by Meinzer (1923).
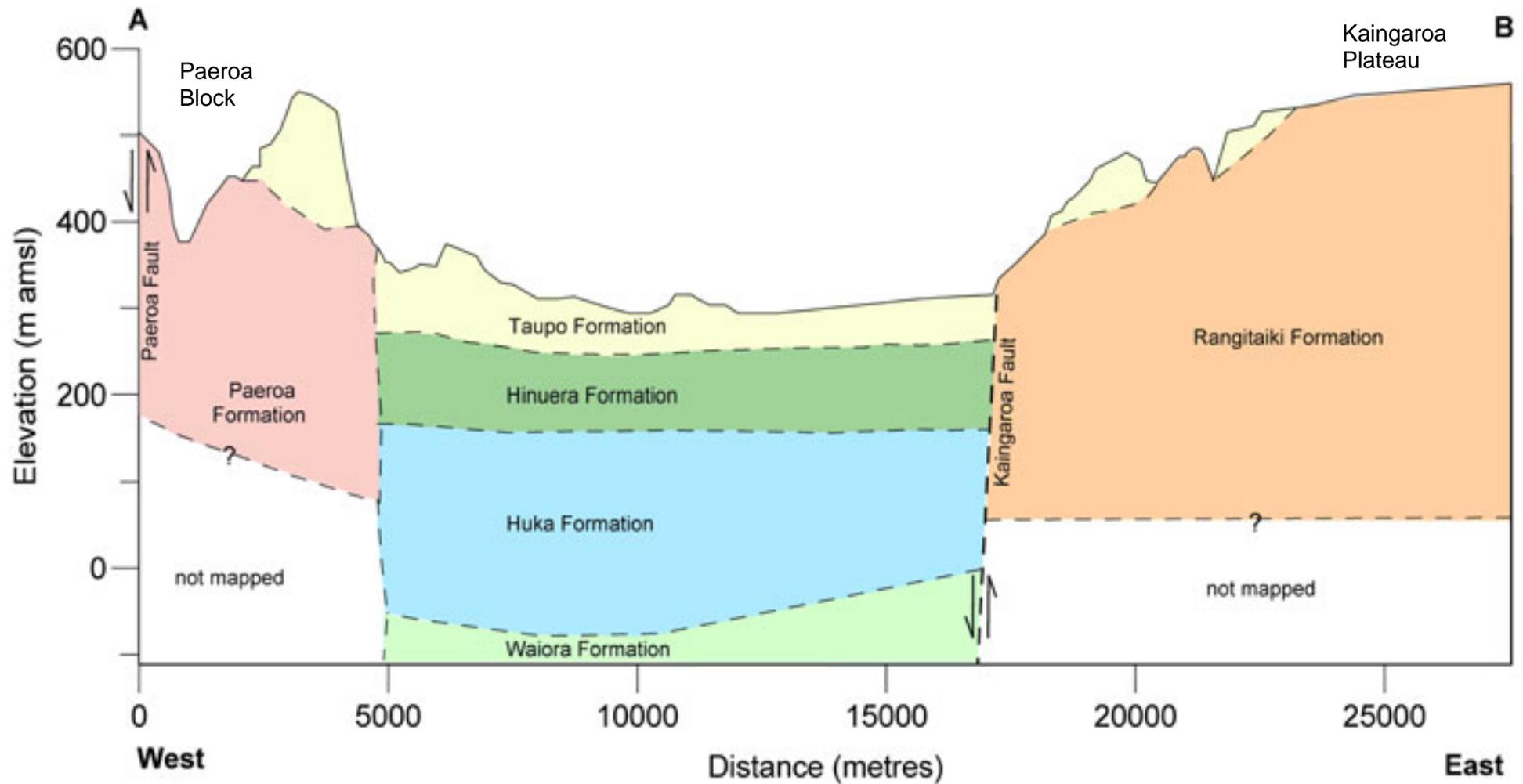
Figure 6: **Conceptual west to east hydrogeological cross-section of the Reporoa Basin.** (Located in Figure 1).

4.7   Piezometric surface

Static water levels were measured in 60 bores out of approximately 230 bores documented in the Reporoa Basin using electronic water level probes. The relative height of these was obtained by surveying a reference point for each well, usually the casing head flange, by global positioning (GPS) (Appendix IV).

Measured static water levels ranged from 1.64 metres to >100 metres below the ground surface. The deepest levels were found on the eastern boundaries of the basin on top of the Kaingaroa Plateau. The mean depth to static water level is just under 19 metres. The distribution is, however, skewed toward shallower levels with a median about 7 metres, which appears to be due to the spatial distribution of the 60 bores with most located in the lower Basin. Just over half (68%) the wells measured have static water levels less than 20 metres deep.

The piezometric surface illustrated in Figure 7 represents a composite of water levels from available wells. To show the water-table, wherever possible shallower wells were used in preference to deeper wells to better represent the water table as static water levels in deeper wells are generally lower than the water table (discussed further in section 4.8).

Groundwater contours closely follow the Basin topography (Figure 7). Along the western flank of the basin, groundwater flow is from west to east, flowing from the Paeroa Range towards the Waiotapu Stream. Along the southern end of the Paeroa Range, groundwater flow is towards the Waikato River. In the eastern basin, groundwater flow is from east to west, flowing from the Kaingaroa Plateau towards the Waikato River. Major sinks for groundwater flow discharge appear to be the main streams and rivers such as the Waiotapu Stream and Waikato River.
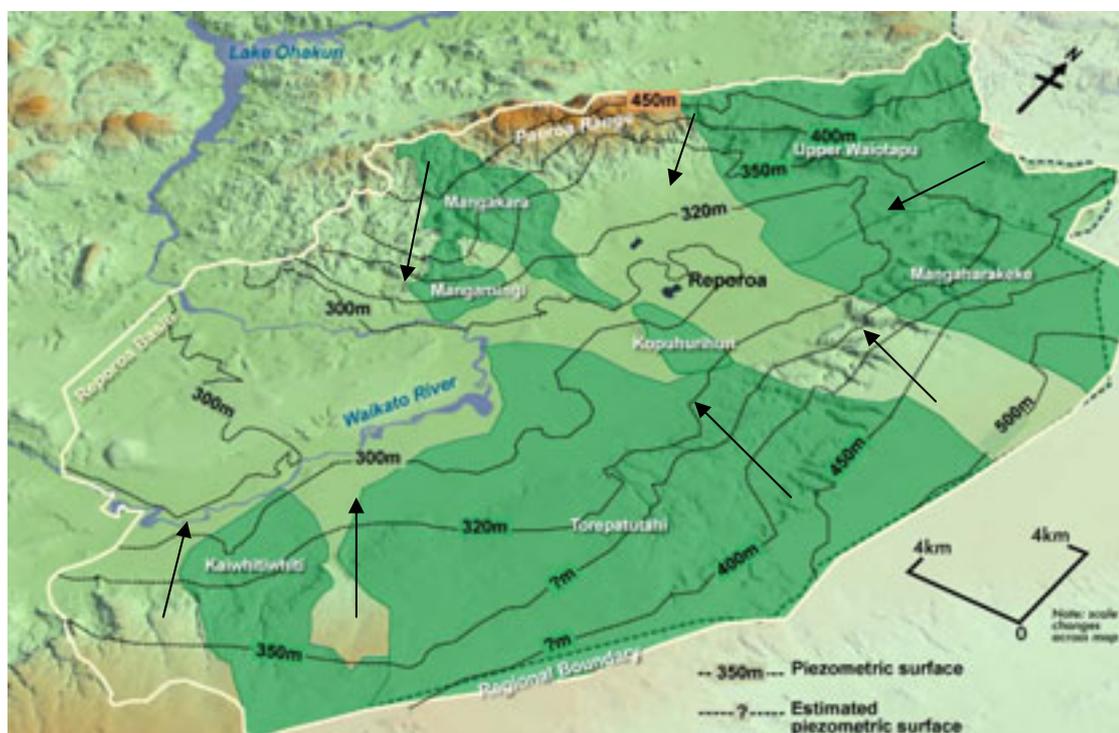
Figure 7:   Reporoa Basin piezometric surface and groundwater flow direction.

Hydraulic gradients range 0.014 at the northern area of the basin, to 0.037 at the southern end of the Paeroa Range. Hydraulic gradients are steeper toward the topographically high edges of the Basin where hydraulic head differences can be up to 200 metres from the high edges to the lower Basin. Lower hydraulic gradients exist in the lower Basin where the majority of groundwater users are located.

Average groundwater velocities estimated range between 0.02 to 0.16 m d^{-1} using a flow net, transmissivity, hydraulic gradient, porosity and conductivity. Estimates are very approximate as parameters such as aquifer thickness and conductivity are not well known.

4.8   Vertical gradients

Construction details for the majority of the bores in the Reporoa Basin are not available. Plotting the static water level versus total bore depth for the limited number of bores with this information that are spread throughout the Basin (Figure 8) illustrates there is a relationship between well depth and depth to static water level. This indicates a generally strong downward flow gradient exists. Figure 8, shows that depth to the static water level increases with drilling depth, with the exception of site 72.1565 which portrays sub-artesian characteristics.
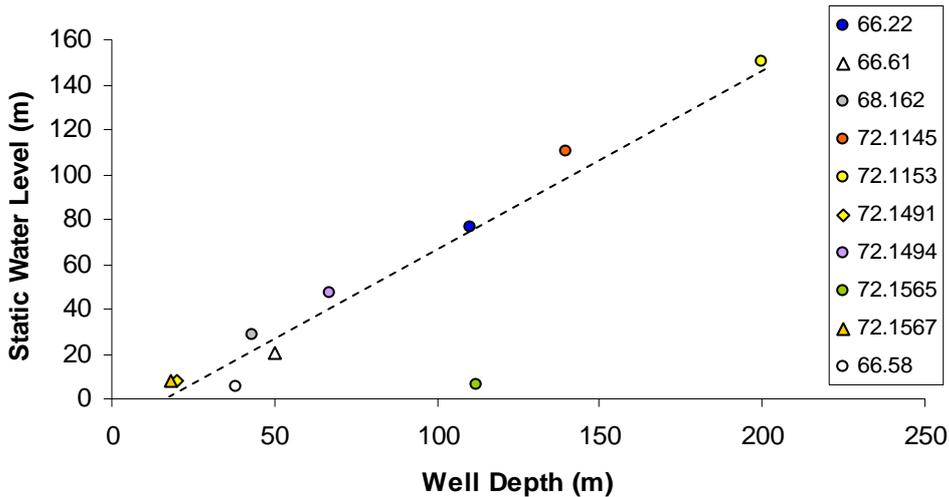
Figure 8:   Well depth versus depth to static water level.

5   Hydrology

5.1   Stream flow

Streams in the Reporoa Basin are predominantly characterised by springs at the head of the system. Some of the springs have flow discharge in excess of one cubic metre per second (Torepatutahi springs). The streams flowing from the eastern side of the basin are predominantly sourced from springs located at or near the base of large rhyolite bluffs, while the streams flowing from the western side of the basin are sourced from springs located in the Paeroa Range. The majority of the streams are perennial, although some streams draining from the Paeroa Range are ephemeral, flowing after rainfall events or when groundwater levels are high. Although mean flows are quite variable this relates largely to catchment size with specific discharge being fairly similar. Mean flows and specific discharges are listed in Table 2 for catchments shown in Figure 9.
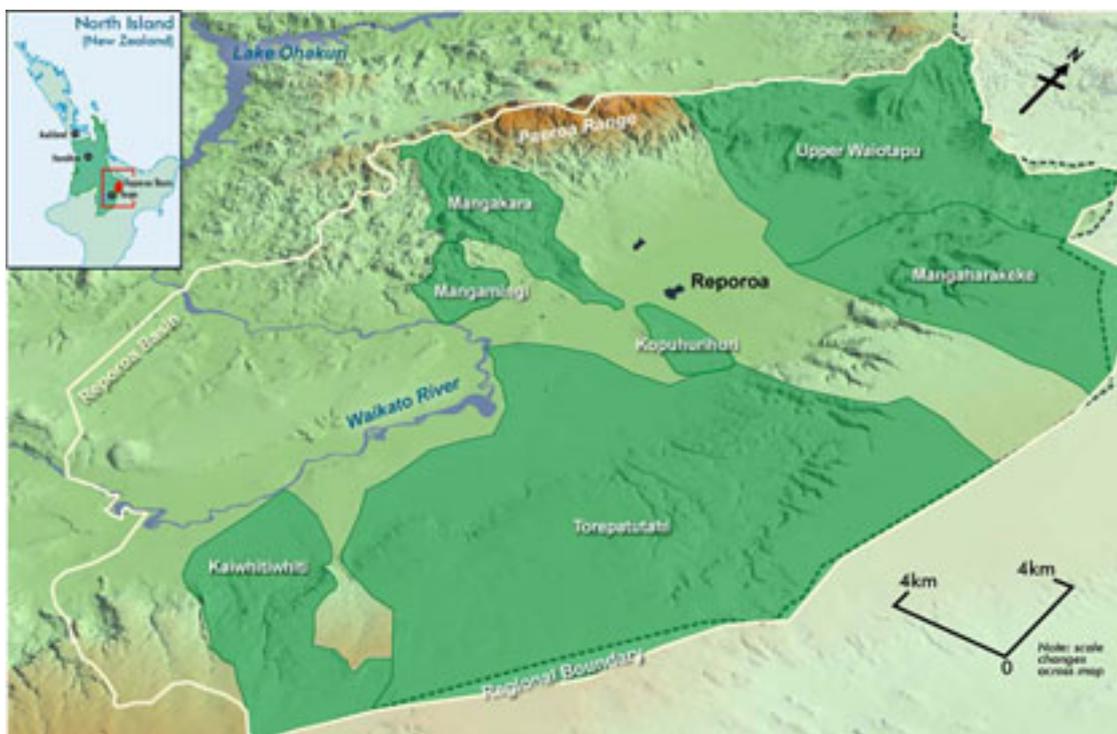
Figure 9: Reporoa Basin subcatchments.

Table 2: Mean flow and specific discharge for seven Reporoa Basin sub-catchments.

Catchment	Area (km^2)	Mean flow (m^{3}s^{-1})	Specific discharge (m^3 s^{-1} km^{-2})
Kaiwhitiwhiti	30.9	0.892	0.029
Torepatutahi	240	4.372	0.018
Kopuhurihuri	9.1	0.059	0.006
Mangaharakeke	56.8	0.688	0.012
Upper Waiotapu	98.4	1.879	0.019
Mangakara	22	0.374	0.017
Mangamingi	6.4	0.047	0.007

Several of the streams in the Basin are influenced by geothermal activity. The Waiotapu Stream receives geothermal water from the Waiotapu thermal area near the base of Rainbow Mountain as well as other localised areas. Most other streams influenced by geothermal activity are predominantly located at the base of the Paeroa Range or in the vicinity of Golden Springs (Figure 1).

Most of the streams in the basin are baseflow dominated. Flow duration curves for several automatic flow recorder sites are illustrated in Figure 10. Each curve is scaled by catchment area for the purpose of making comparisons between flow records. The slope of the flow duration curve, except at the low and high extremes, represents the typical flow range. Baseflow contribution was assessed using the ratio between the Q_{90} and Q_{50} percentiles (Crowcroft and Bowden, 2002). Baseflow separation from the hydrograph for several catchments was conducted with similar results to the ratio between the Q_{90} and Q_{50} percentiles. The ratios for each site are listed in Table 3, where it is evident that all of the streams are baseflow dominated, with the baseflow accounting for at least 59% of the total flow.
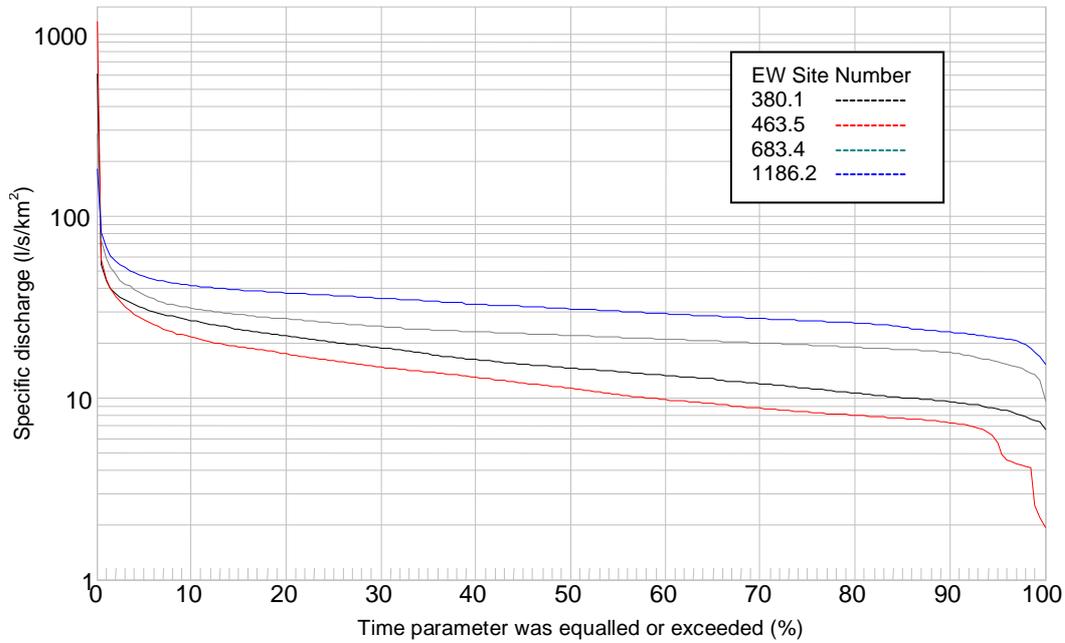
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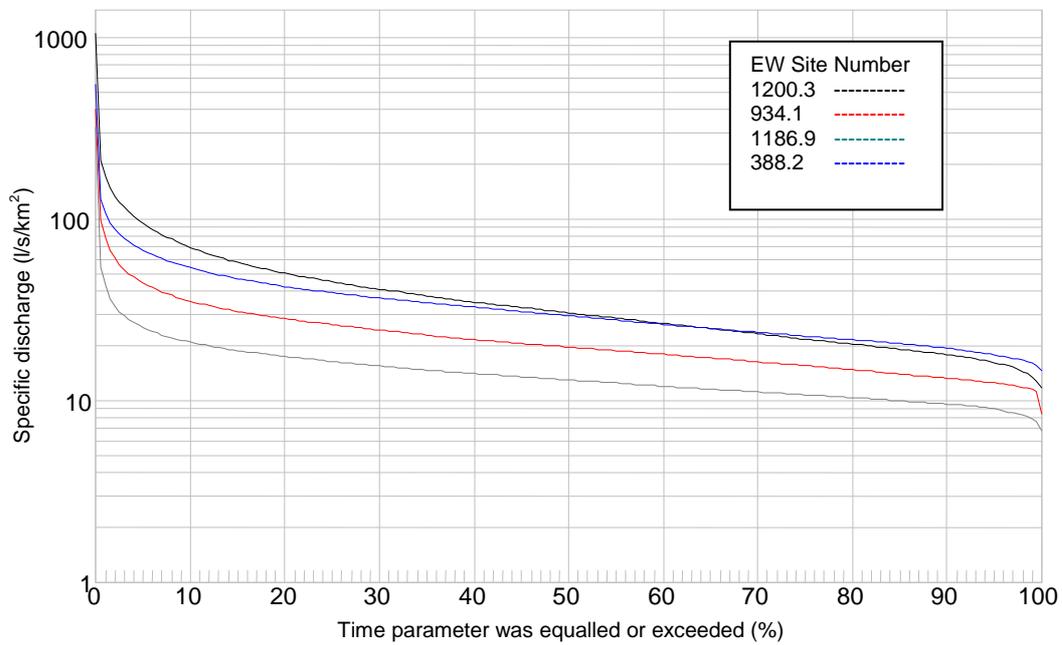
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Figure 10: Flow duration curves for Reporoa Basin surface water catchments.

Table 3:   Calculated Q$_{90}$, Q$_{50}$ flows and baseflow ratios.

Site	Catchment Name	Q$_{90}$ (m^{3}s^{-1})	Q$_{50}$ (m^{3}s^{-1})	Baseflow Ratio
380.1	Mangakara @ Hirsts	0.21	0.33	0.65
463.5	Mangatete Stm @ Te Weta Rd	0.22	0.27	0.83
683.4	Otamakokore @Hossack Rd	0.71	0.89	0.80
1186.2	Waiotapu @ Campbell Rd	1.10	1.48	0.74
1200.3	Waipapa @Ngaroma Rd	2.56	4.34	0.59
934.1	Tahunaatara @Ohakuri Rd	2.66	3.94	0.68
1186.9	Waiotapu @ Reporoa	2.39	3.25	0.73
388.2	Mangakino @ Dillon Rd	6.47	9.77	0.66

5.2   Flow interaction

Most streams in the Reporoa Basin are spring fed. A large part of the flow for many streams, however, is via influent groundwater flow via downstream through-bed discharge. The Torepatutahi Stream has large springs at the top of the system. It also accumulates significant flow from groundwater further down the catchment. There also appear to be several reaches where the stream loses water to the groundwater system. Overall approximately 74% of the total flow in the Torepatutahi Stream is generated from springs in the upper catchment. The remainder is from groundwater seepage to the channel between the upper springs and Waikato River confluence.

The Kaiwhitiwhiti, Kopuhurihuri and Mangaharakeke Streams as they drain similar geology in the east of the basin have similar characteristics to that of the Torepatutahi Stream.

6   Chemistry

6.1   Introduction and site selection

Groundwater chemistry can be influenced by several factors. These factors include precipitation chemistry, aquifer geology, soil type, geothermal influences and modifying factors such as climate and geomorphology (Hadfield *et al.*, 2001).

After recharge to the water table, groundwater migrates through a sequence of formations and mineral assemblages. The composition of these formations and the order in which water encounters these formations strongly influence the groundwater chemistry. Other subsurface factors that can influence the chemistry of groundwater are the length of flow paths and the velocities at which the water flows. Additional to these factors, reduction and oxidation reactions, cation exchange, mineral dissolution and precipitation can all affect groundwater chemistry (Freeze and Cherry, 1979).

Groundwater quality was sampled primarily to determine nitrogen concentrations, which is an indicator of land use. General chemistry was also characterised in relation to geology to improve hydrogeological understanding of the Reporoa Basin. Groundwater from a total of 32 wells were sampled in a single synoptic survey during January 2004. Sites were selected, where possible, to represent a broad range of hydrogeologic conditions and to provide a well-distributed network across the Reporoa Basin (Appendix V).

6.2   Sampling methods

Groundwater samples were collected from wells using the groundwater sampling protocol developed by the Institute of Geological and Nuclear Sciences (Rosen *et al.* 1999). The sampling protocol involved sampling as close as possible to the well-head before water passed through pipe networks, treatment systems and storage tanks. At least three annular volumes of water were pumped to purge the wells and piezometers prior to collecting a water analysis sample. Most wells had existing submersible pumps and occasional deep well cylinder pumps. Groundwater samples were cooled with ice to <4 degrees Celsius and sent promptly to the laboratory for analysis.

6.3   Analytical methods

Groundwater samples were analysed for nitrate, ammonia, arsenic and other 'routine' water quality analyses parameters. Routine water quality parameters consist of pH, conductivity, total dissolved solids, alkalinity, free carbon dioxide, calcium, magnesium, hardness, sodium, potassium, chloride, sulphate, boron, total iron, manganese, copper and zinc. Detection limits and analytical methods are listed in Table 4.

Table 4: Groundwater chemical parameters analysed, methods and detection limits.

Parameter	Method Used	Detection Limit
pH	pH meter APHA 4500-H+ B 20thed. 1998	0.01 pH units
Electrical Conductivity (EC)	Conductivity meter, 25oC APHA 2510 B 20thed. 1998	1 uS/cm
Approx Total Dissolved Salts	Calculation: from Electical Conductivity	2 g.m^{-3}
Alkalinity	Titration to pH 4.5 APHA 2320 B (Modified for alk <20) 20thed. 1998	1 g.m^{-3} as CaCO$_3$
Free carbon dioxide	Calculation: from alkalinity and pH APHA 4500-CO2 D 20thed. 1998	1 g.m^{-3}
Calcium	Boiling nitric acid digestion. ICP-OES	0.02 g.m^{-3}
Magnesium	Boiling nitric acid digestion. ICP-OES	0.005 g.m^{-3}
Total Hardness	Calculation: from Ca and Mg	1 g.m^{-3} as CaCO$_3$
Sodium	Boiling nitric acid digestion. ICP-OES	0.5 g.m^{-3}
Potassium	Boiling nitric acid digestion. ICP-OES	0.1 g.m^{-3}
Total Ammoniacal-N	Phenol/hypochlorite colorimetry. Flow injection analyser. (NH4-N =NH4+-N + NH3-N) APHA 4500-NH3 G 20thed. 1998	0.01 g.m^{-3}
Nitrate-N	Filtered sample. Ion Chromatography. APHA 4110 B 20thed. 1998	0.05 g.m^{-3}
Chloride	Filtered sample. Ion Chromatography. APHA 4110 B 20thed. 1998	0.5 g.m^{-3}
Sulphate	Filtered sample. Ion Chromatography. APHA 4110 B 20thed. 1998	0.5 g.m^{-3}
Boron	Boiling nitric acid digestion. ICP-OES	0.005 g.m^{-3}
Total Iron	Boiling nitric acid digestion. ICP-OES	0.01 g.m^{-3}
Total Manganese	Boiling nitric acid digestion. ICP-OES	0.005 g.m^{-3}
Total Copper	Boiling nitric acid digestion. ICP-OES	0.005 g.m^{-3}
Total Zinc	Boiling nitric acid digestion. ICP-OES	0.005 g.m^{-3}

6.4   Chemical characteristics

A Piper trilinear plot of ionic milli-equivalents for groundwater sampled from shallow wells (<30 metres total depth) is presented in Figure 11 and from deep wells (>30 metres total depth) in Figure 12. Overall both plots indicate a sodium and bicarbonate dominated chemistry found within a rhyolitic environment (Hounslow, 1995). From the Piper plot of shallow well chemistry, it can be seen that there is a large spread in the anion chemistry as well as the water type.

Groundwater samples from four shallow wells, which have high SO$_4$ and Cl. High SO$_4$ and Cl concentrations can be attributed to numerous sources. Under some conditions in groundwater considerable quantities of sulphate may be obtained from organic sulphur compounds such as geothermal waters (Hounslow, 1995). Common sources of chloride in groundwater are sea spray, brines and geothermal water (Hounslow, 1995), as well as various land uses (Rosen, 2001). The four sites where groundwater samples contain high SO$_4$ and Cl concentrations are clearly influenced by land use, as these sites all have high NO$_3$-N concentrations, although it is important to note that SO$_4$ and Cl concentrations could also be influenced by geothermal sources from the Ohaaki and Reporoa geothermal fields (Figure 1).
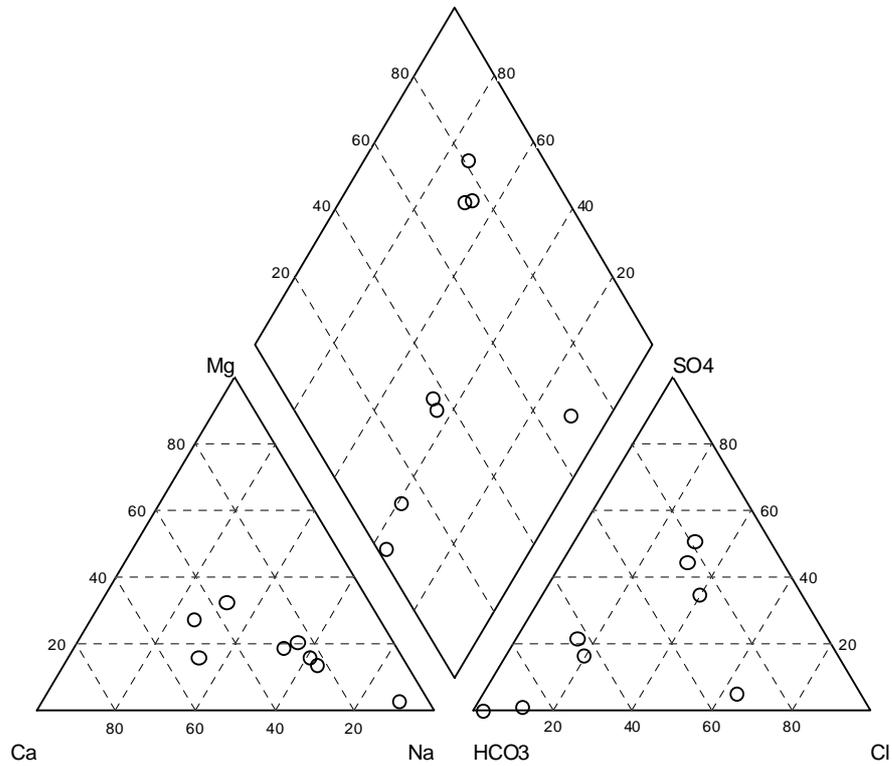
Figure 11: Piper trilinear plot of groundwater sample ionic chemistry for shallow wells. (units in % milli-equivalents L^{-1}).
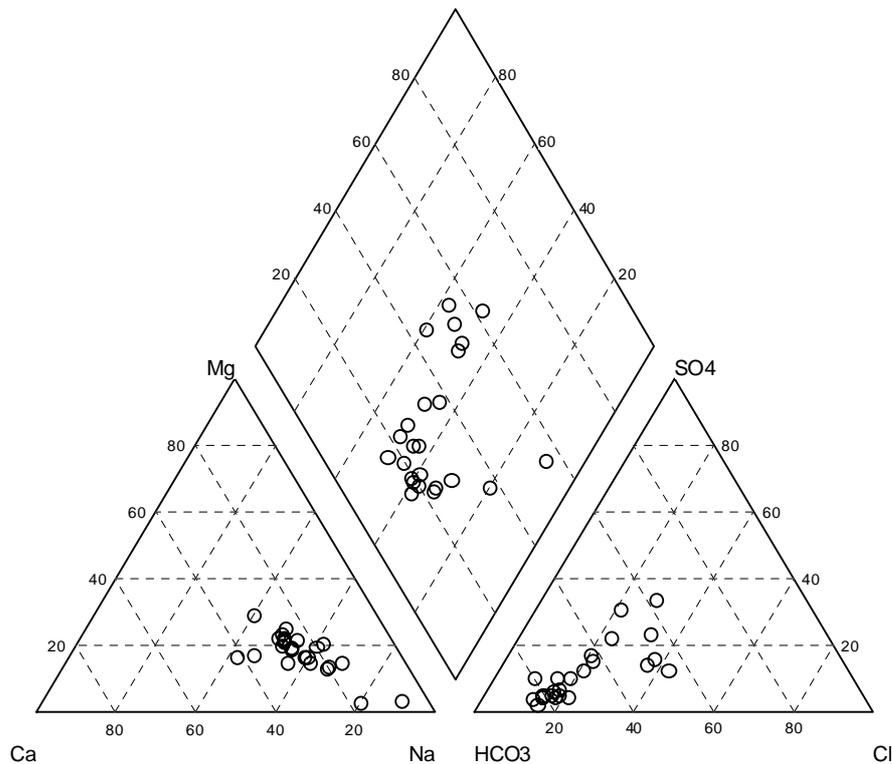
Figure 12: Piper trilinear plot of groundwater sample ionic chemistry for deep wells. (units in % milli-equivalents L^{-1}).

The Piper plot of groundwater from deep wells shown in Figure 12, illustrates that there is much less spread in both cation and anion chemistry compared to groundwater abstracted from the shallow wells. The deep aquifer chemistry is sodium bicarbonate dominated, which as mentioned above is typical of rhyolitic aquifer systems (Hounslow, 1995).

Additional to the piper plots in Figure 11 and Figure 12, water types were determined (Table 5). Water types can be determined using equivalents (a method that takes into account the molecular weight and ionic charge of each ion). Water types are calculated by first converting the milli-equivalents per litre of the major cations and anions to percentages. The water type expression is formed by listing the ions with concentrations greater than 10% in decreasing order with cations listed first (Rosen, 2001).

Table 5:   Water types in the Reporoa Basin.

Water Type	No. of sites	Water Type	No. of sites
Ca-Mg-Na-Cl-SO$_4$	1	Na-Fe-Ca-Cl	1
Ca-Mg-Na-SO$_4$-Cl	1	Na-Mg-Ca	1
Ca-Na-SO$_4$-Cl	1	Na-Ca-K-Cl	2
Fe-Na	1	Na-Ca-Mg-Cl-NO$_3$	2
Na-Ca-Cl	1	Na-Ca-Mg-Cl-SO$_4$	2
Na-Ca-Cl-NO$_3$	1	Na-Ca-Mg-SO$_4$	2
Na-Ca-K-Mg-Cl-SO$_4$	1	Na-Ca-Mg-SO$_4$-Cl	2
Na-Ca-Mg-K-Cl	1	Na-Mg-Ca-Cl	2
Na-Cl	1	Na-Ca-Mg	3
Na-Cl-SO$_4$	1	Na-Ca-Mg-Cl	5

Twenty different water types were determined with 12 water types unique to one site (Table 5). The most common single water type determined is a Na-Ca-Mg-Cl solution (5 sites), followed by Na-Ca-Mg (3 sites). All of the water types include sodium, making it the most abundant ion followed by calcium (17 water types). Chloride was the most abundant anion, present in 16 water types, with sulphate next (8 water types).

Sodium is the dominant cation (28 sites), followed by calcium (3 sites) and iron (1 site). Sodium is dominant in groundwater that is near the ocean or near geothermal area or affected by certain land uses (Rosen, 2001). The dominant anion was chloride (16 sites) followed by sulphate (6 sites). Three water types were dominated by cations. It was interesting to note that bicarbonate dominance did not exist in any of the shallow groundwater samples, as the interaction of dissolved atmospheric CO_2 with organic matter in the soil zone leaches HCO_3 into the groundwater (Rosen, 2001).

The mean concentrations of major ions for selected groundwater groupings are compared with rain water composition in Figure 13. The chemical composition of rain water in the Taupo area was measured by Timperley and Vigor-Brown (1986). The concentrations of major ions in rain water are flow-weighted mean annual averages from a site on the eastern side of Lake Taupo. The grouping of shallow and deep groundwater for the Schoeller plot was based predominantly on static water level data in substitute for total well depth. This was due to the limited construction details for the majority of the bores in the Reporoa Basin. The justification for using static water levels to determine the groundwater grouping was based on the good correlation between well depth and depth to static water level (Figure 8).

Nitrate-nitrogen (NO_3-N) was found to exceed the maximum acceptable value for New Zealand Drinking Water Standards (MoH, 2000) of 11.3 parts per million (ppm) (or 50 ppm as NO_3) at one sample site (66.90) (Figure 14). A further six sites had nitrate-nitrogen concentrations that exceeded half the drinking water standard. The mean and median nitrate-nitrogen concentrations of all results were 2.62 ppm and 0.765 ppm respectively (standard deviation of 3.78 ppm). Most sites have concentrations below 1 ppm, although there is a large concentrations range (Figure 15). Nitrate-nitrogen results indicate that land use within the catchment is having an effect on groundwater quality. Elevated nitrate-nitrogen concentrations reflect land use.
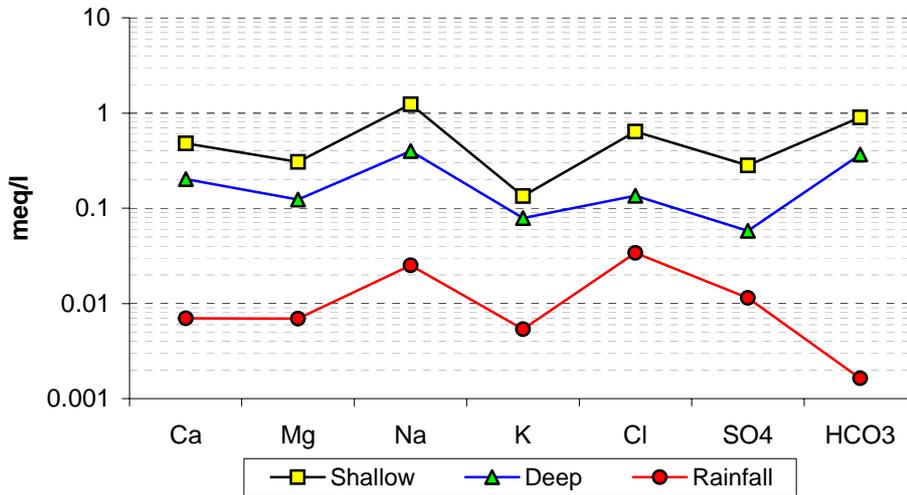
Figure 13: Schoeller plot of mean chemistry for groundwater groupings.
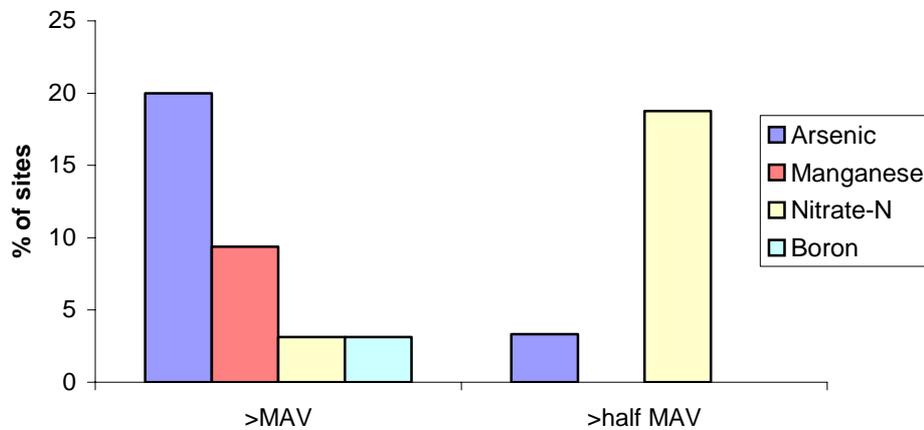
Figure 14: Percentage of samples exceeding NZ drinking water standards maximum acceptable values (MAV) for inorganic determinands of health significance.
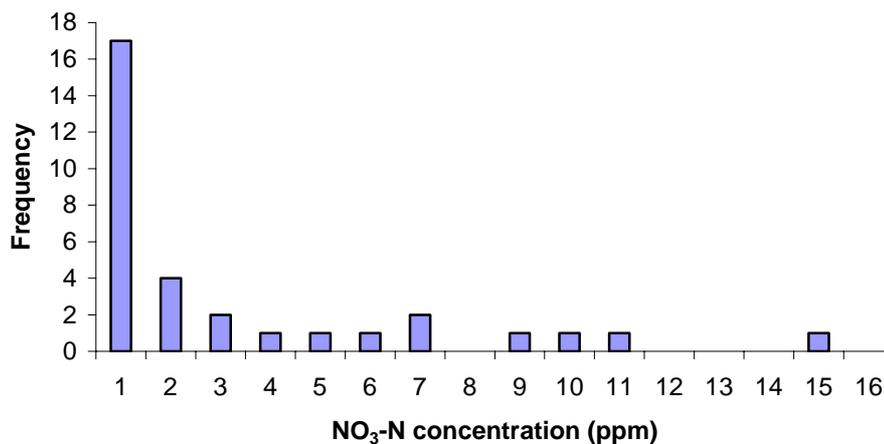
Figure 15: Histogram of NO$_3$-N concentrations.

Arsenic, manganese and boron were other water quality parameters that exceeded drinking water guidelines, as shown in Figure 14. Reduction and oxidation conditions are also inferred at several sites. Reducing conditions are inferred by high manganese, iron, ammonium-nitrogen and low nitrate-nitrogen. Of particular concern, is the elevated concentrations of arsenic in groundwater throughout the entire Reporoa

Basin. Elevated arsenic concentrations were found to occur within most of the aquifer formations sampled. Reducing conditions are known to affect the dissolution of arsenic in groundwater and could potentially be a contributing factor along with geothermal processes in the elevated arsenic concentrations exhibited.

The sub-parallel relationship exhibited in the Schoeller plot implies that the waters are of a generally similar character (Zaporozec, 1972). Analysis of variance, however, shows that there is a significant difference between the chemistry of shallow and deep groundwater ($n = 7$, p-value $= 0.03$). Shallow groundwater is more modified than deep groundwater when compared to the composition of rain water. The greatest differences between the two groundwater groupings are sulphate and chloride concentrations. Higher sulphate and chloride concentrations in groundwater imply several factors such as geothermal influence, salt water influence or land use influence. In this case it appears that shallow groundwater is influenced by land use more than deeper groundwater. The deeper groundwater is likely to be older and therefore the effects of land development is not yet apparent. The divergence in relative bicarbonate concentration between rain water and groundwater is a reflection of normal carbonic acid leaching of a rhyolitic formation (Hadfield *et al.*, 2001).

The effect of land use on groundwater quality at sites 66.90 and 66.91 is shown in Figure 16. Figure 16 shows temporal nitrate-nitrogen data in shallow groundwater under a dairy farm in the central Reporoa Basin. Nitrate-nitrogen concentrations are showing a consistent increase over time. This trend relates to land use intensification on the property though increased fertilizer and stocking rates.
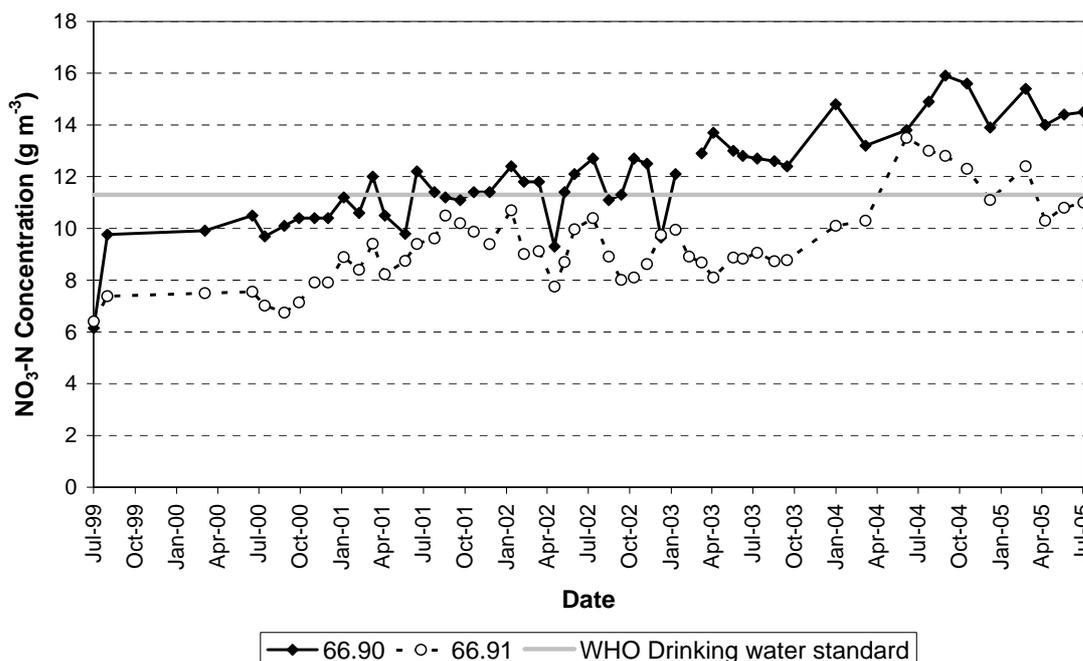
Figure 16: Long-term nitrate-nitrogen concentrations in the shallow Taupo Formation aquifer.

The increase in nitrate-nitrogen has pushed the concentrations over the MAV for the NZ drinking water standards at both bores (Figure 16). As other properties within the Reporoa Basin intensify farming activities through increased stocking and fertilizer rates, similar trends are likely to occur.

Nitrate-nitrogen concentrations are strongly related to groundwater mean residence times (time since recharge into the soil surface) (Figure 17). Older mean residence time groundwaters have lower nitrate concentrations compared to groundwater with young mean residence times.
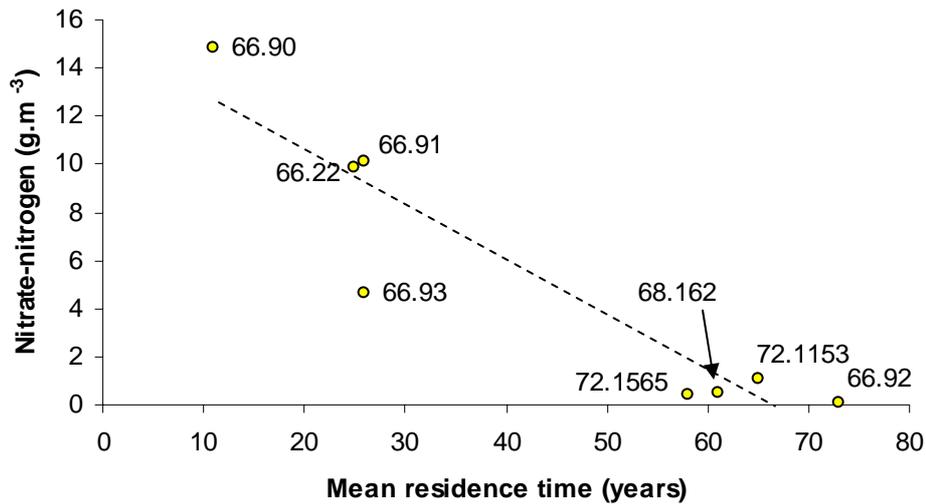
Figure 17: Relationship between groundwater mean residence time and nitrate-nitrogen concentrations.

6.5 Spatial distribution of chemical characteristics

Water chemistry changes with depth may reflect aquifer geology, reduction and oxidation conditions or land use impacts. There was, however, no correlation between any of the chemical parameters measured and well depth. There is nevertheless an apparent tendency for higher concentrations of nitrate-nitrogen, chloride and sulphate to occur at shallow depths (Figure 18). Each of these parameters is commonly influenced by land use.
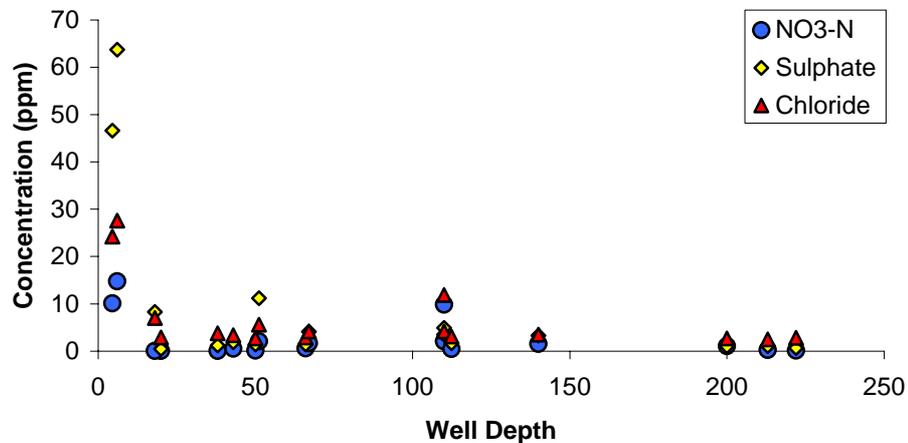
Figure 18: Variation of nitrate-nitrogen, sulphate and chloride concentrations with depth.

No lateral trends in chemistry are obvious from the variety of wells sampled across the Basin (Figure 19). In terms of sites where chemical concentrations of parameters are elevated, arsenic and manganese concentrations appear to be the highest in areas close to geothermal activity such as the Golden Springs and Ohaaki. These sites are in the central, west and southern regions of the Basin. Nitrate-nitrogen concentrations, and to a similar extent, sulphur concentrations, are elevated at sites dispersed in the center of the Basin along an east to west transect from the plateau to the base of the Paeroa Range.
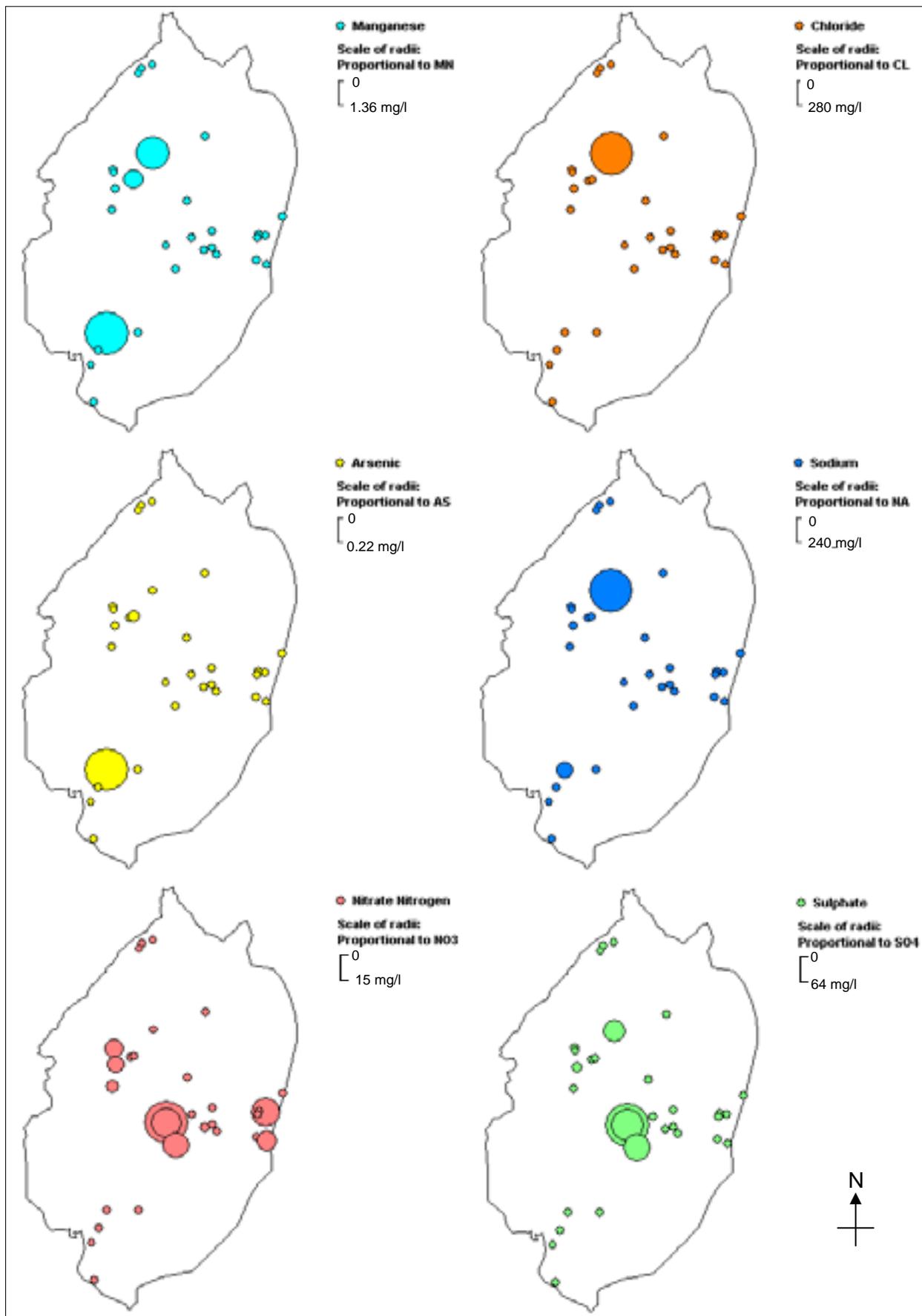
Figure 19: Lateral distribution of selected chemical parameters across the Reporoa Basin.

7 Groundwater Age Dating

7.1 Introduction

This section summarizes a report from the Institute of Geological and Nuclear Sciences Ltd on the analysis and interpretation of tritium and CFC dating[1] of groundwater from the study area. These data are the first indication of the age of groundwater in the Reporoa Basin area (Figure 20). The data are similar to other age dating results from similar pyroclastic geology in the Lake Taupo catchment (Hadfield *et al.*, 2001) inferring similar hydrological processes in the Taupo and Reporoa study areas.

Samples were collected for measurement of tritium (^3H) and chlorofluorocarbons (CFCs) concentrations. Sample information is given in Table 6. Samples for tritium analysis were collected in clean 1.1 litre Nalgene bottles. Samples for CFCs were collected in clean glass vials. Concentrations of tritium are reported as Tritium Ratios (TR) at the date of sample collection ± 1 standard measurement error, using the scale recommended by Taylor and Roether (1982). TR=1 corresponds to a Tritium/Hydrogen ratio of 10^{-18}. Water samples for CFC concentration measurements were collected in such a way as to prevent contact with the atmosphere or with plastic materials, either of which could contaminate the sample with CFCs.

Table 6: Sampling and bore data from Reporoa Basin groundwater.

Sample ID	Map Reference	Collection Date	Depth (m)	Screen depth (m)	Geology	Static water level (m bgl)
66.22	V17:127-960	10.3.04	110	65 – 110	Rangitaiki Ignimbrite	76.69
66.90	U17:027-950	18.3.04	6	1.5 – 4.5	Taupo Ignimbrite	2.79
66.91	U17:027-950	18.3.04	4.5	1 – 4.5	Taupo Ignimbrite	3.11
66.92	U17:017-018	10.3.04 (Tritium) 18.3.04 (CFCs)	48.5	17.2 – 19.2	Oruanui Ignimbrite	1.57
66.93	U17:017-018	18.3.04	8	2.1 – 8	Taupo Ignimbrite	2.17
68.162	U18:942-798	10.3.04	43	39 – 43	Rangitaiki Ignimbrite	28.6
72.1565	U17:052-958	10.3.04	112.4	91 – 112.4	Hinuera Formation	6.47
72.1153	V17:118-935	10.3.04	210	187 – 210	Rangitaiki Ignimbrite	155

7.2 Results and discussion

The results of the tritium and CFC analyses are given in Table 7. The objective of groundwater dating is to use the tritium and CFC concentrations to determine the mean and distribution of residence times of each sample. An exponential piston flow model (EPM) has been used to estimate the mean residence times of the samples. The EPM has been found to produce satisfactory fits for groundwater samples collected from the same bores that have a sequence of tritium analyses over many years (Stewart & Morgenstern, 2001). The mixing fraction used is indicated in Table 7; the mixing fraction is the fraction of the exponential volume to the total volume of the system. A mixing fraction of 0% means zero mixing (piston flow model) and a mixing fraction of 100% means the exponential model applies (i.e. water travelling through the aquifer via different flow paths combines at the outlet to give an exponential age distribution).

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[1] The results of this investigation were described in an unpublished report from the Institute of Geological and Nuclear Sciences Ltd (IGNS) to Environment Waikato in February 2005 (see Appendix II and EW DOCS #982737).
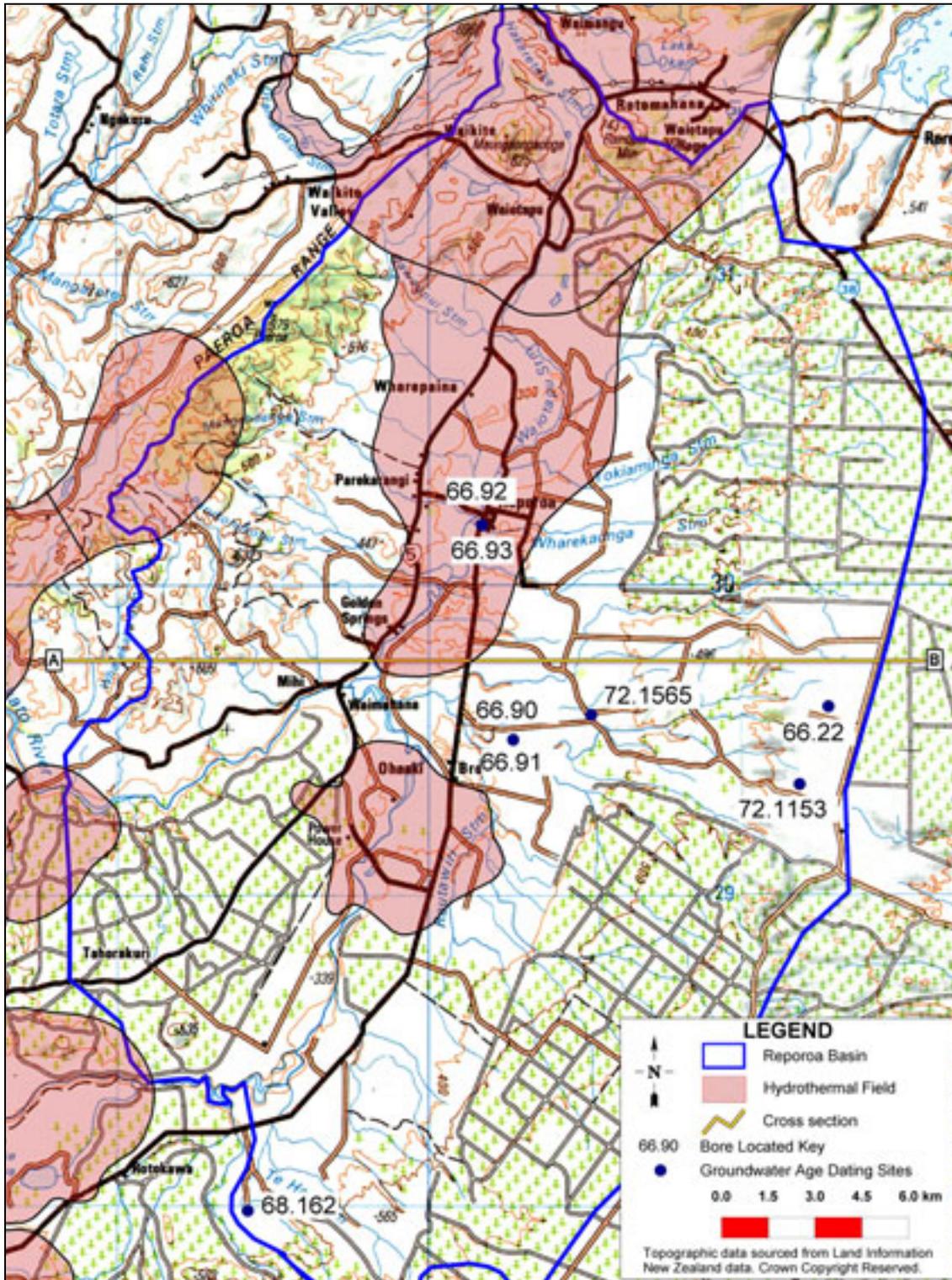
Figure 20: Bore locations where groundwater has been dated using tritium and CFC analysis.

Table 7: **Tritium concentrations, and age interpretation of the tritium and CFC concentrations using an exponential piston flow model with the indicated mixing fraction.**

Sample ID	Tritium Concentration TU	Mixing model fraction %	Mean age (in years) based on the EPM model shown			Recommended Age (years)
			Tritium	CFC-11	CFC-12	
66.22	1.71 ± 0.07	30	1, 28[1], 48	25	22	25
66.90	1.41 ± 0.03	90	5, 10[1], 16	13	9	11
66.91	1.45 ± 0.04	40	4, 25[1], 51	27	16	26
66.92	0.032 ± 0.021	40	80	65	73	73
66.93	1.66 ± 0.05	30	2, 27[1], 47[1]	49	25	26 or 48
68.162	0.602 ± 0.026	40	61	39	35	See below
72.1565	0.266 ± 0.025	40	65	55	54	58
72.1153	0.376 ± 0.023	40	65	35	28	See below

[1] Preferred tritium age

There is a general trend of deeper groundwater being characterised by older ages and shallow groundwater being characterised by young ages (Figure 21). Predominantly older groundwater is found in wells penetrating the Rangitaiki Ignimbrites of both the eastern plateau and lower Reporoa Basin (Figure 22). The exception to this is well 66.92, where geothermal waters appear to upwell into the Oruanui Ignimbrite aquifer within the Hinuera Formation.
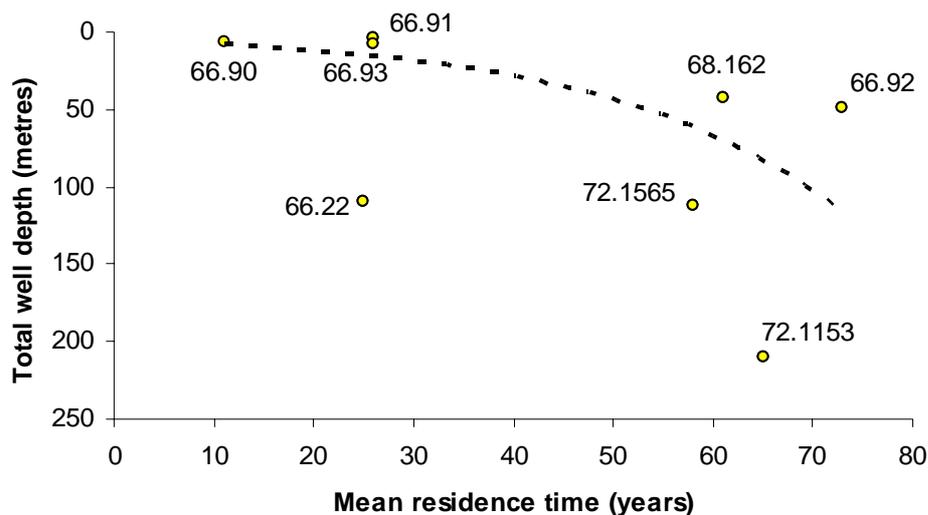
Figure 21: Mean groundwater residence time versus well depth.

The mean residence time at two of the sites 68.162 and 72.1153 are short relative to the total depth of the wells. This may result from ingress of younger groundwater down the side of the well casing or via multiple screening of different aquifers. Fracture flow between aquifers could also enhance mixing of groundwater in wells penetrating into Rangitaiki Ignimbrite. Site 66.22 (Figure 21) appears to be an outlier from the rest of the sites. Tritium and CFC results indicate consistently young groundwater mean residence times, which is different to that of well 72.1153 which is also located in the upper plateau Rangitaiki Ignimbrite.

Tritium dating of one of the main springs of the Torepatutahi Stream indicates a mean residence time of 130 years for groundwater contributing to discharge (Figure 22). The analysis and interpretation of the mean residence times for groundwater in wells up-gradient of the spring sampled infer that spring discharge is likely to be sourced from older groundwater found up-gradient in the Rangitaiki Formation.
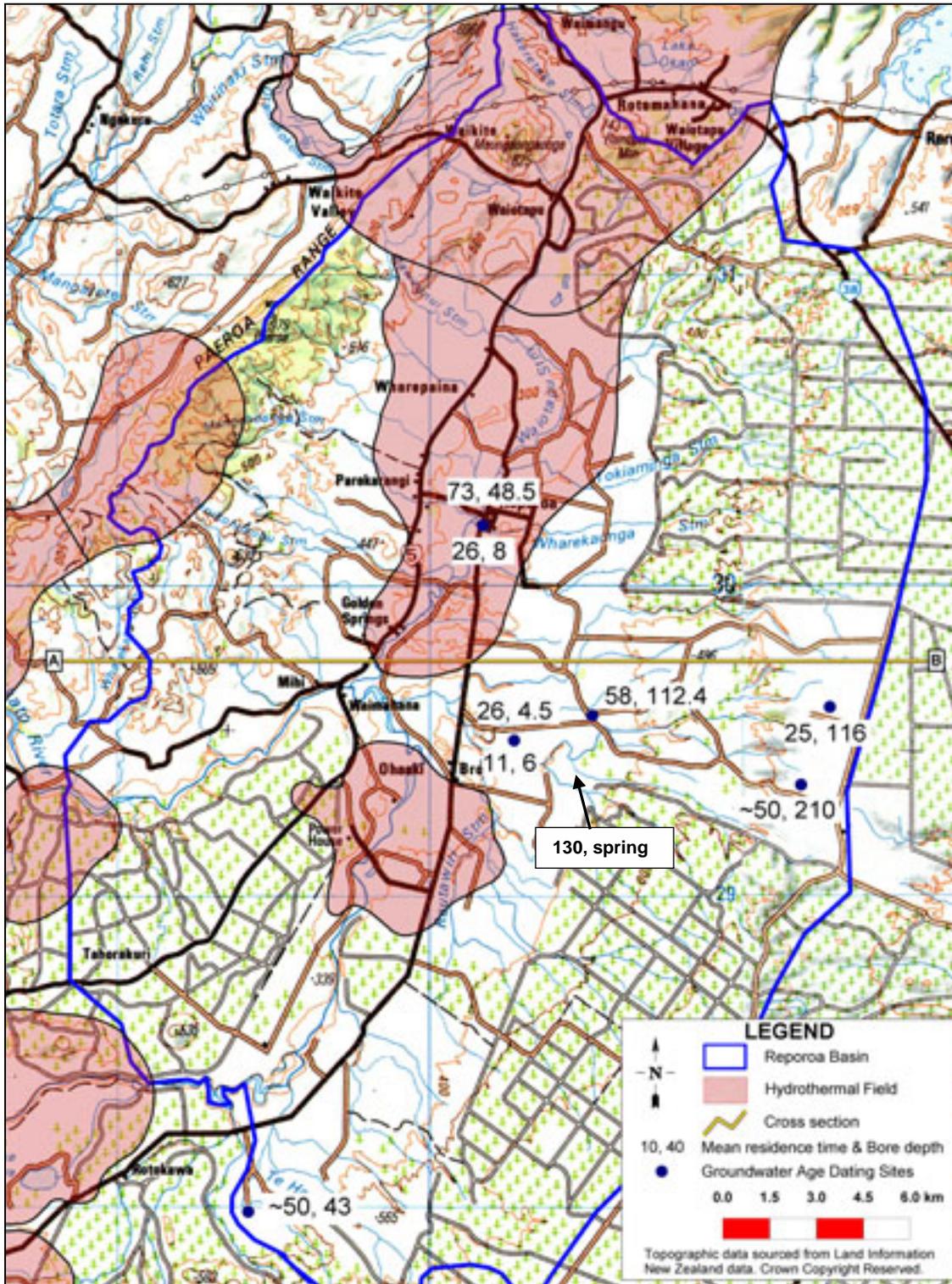
Figure 22: Groundwater mean residence times and bore depths.

The tritium and CFC data indicate that there is relatively rapid recharge to the shallow Taupo ignimbrite aquifers, and slow recharge to the deeper Oruanui and Rangitaiki Ignimbrite aquifers. The relationship between tritium data for ground and stream water also indicates that transmission of groundwater to streams is slow and predominantly from deep Rangitaiki Ignimbrite aquifers (Figure 23).

Figure 23, alternatively represents in vertical section groundwater flow along major flow paths from the upper infiltration zones of the Basin; recharge of the lower Basin aquifers and discharge to the stream springs.
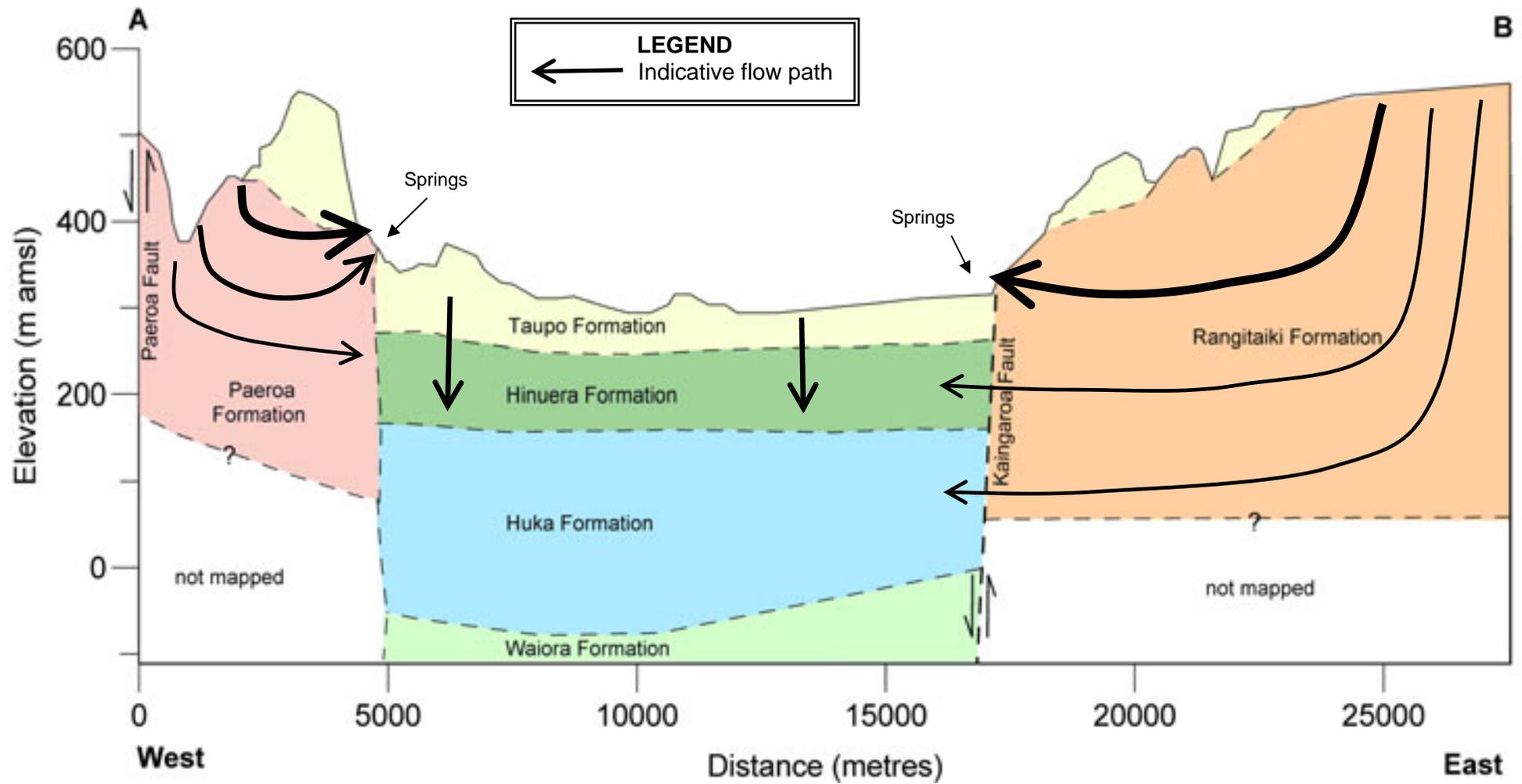
Figure 23: Schematic section of groundwater flow paths.

8 Water Balance

8.1 Introduction

A water balance is a quantitative statement of the water gains and losses of a catchment, for a period of time. The water balance considers all waters, surface and subsurface, entering and leaving or stored within a catchment (Walton, 1970).

For the Reporoa Basin precipitation is the source of water entering a catchment and is the only water gain considered in the water balance. Water leaving the catchment includes stream flow, evapotranspiration and subsurface flow. The main objective of the water balance is to estimate recharge to and discharge from shallow and deep aquifers.

8.2 Method

A standard water balance approach is used:

$$R = P - E - Q \tag{8.1}$$

where: R is annual net recharge;
P is annual precipitation;
E is annual evapotranspiration / actual evaporation;
Q is annual quick flow (storm flow)

The water balance is based on the conceptual relationships between surface water and groundwater. The water balance incorporates two distinct flow systems: a system dominated by discharges from shallow groundwater to the surface water; and a second system operating on a regional scale, in which leakage occurs from the shallow aquifers to recharge the deeper aquifers.

Average annual rainfall was used for the period 1962-2002, based on long-term records held by NIWA and Environment Waikato. Stream flow data was calculated using gauging, long-term flow recorder and site correlation data (Appendix 1). Evapotranspiration was estimated using guidelines of 500 mm and 800 mm for short and tall vegetation under New Zealand climatic conditions (Pearce and McKerchar, 1979; Pearce, 1980). The 1996 New Zealand LandCover database was used to identify and classify the land cover within each of the sub-catchments. Total evapotranspiration was estimated using the following;

$$\left(\frac{Q_t}{Z_t}\right) * V_t = E_t \tag{8.2}$$

where: Q_t = Land use area (m^2)
Z_t = Catchment area (m^2)
V_t = Annual evapotranspiration rate for land cover (m y^{-1})
E_t = Total evapotranspiration for land cover area (m^3 y^{-1})

Rainfall data from sites where the rainfall record is short in duration was correlated with annual rainfall at sites where there was a longer-term record. Records were extended from regression with sites of closest correlation.

The associated error of the water balance is not known, and in some cases could be significant. Water balance parameters used with confidence include rainfall, stream flow and storm flow, while there is some question about evapotranspiration (ET) rates,

as values are taken from literature and not actual measurements. Some catchments may not be hydrologically sealed, as found by Dons (1987) in the upper Mangakara catchment. Dons (1987) found identified that the upper Mangakara catchment may capture recharge from outside the topographically defined catchment boundary. It appears that this process could also occur in the Torepatutahi and Kaiwhitiwhiti stream catchments.

8.3 Model estimates

Water balance data for seven catchments investigated are presented in Table 8. For three of the catchments (Kaiwhitiwhiti, Torepatutahi and Upper Waiotapu), the water balance model indicates that aquifer recharge is very low. Resulting net recharge deficits are calculated for the Kaiwhitiwhiti and Torepatutahi catchments. There is a range of reasons for the recharge deficits such as incorrectly defined catchment boundaries and incorrect evapotranspiration rates. There is a very strong possibility that some of the flow to the Kaiwhitiwhiti and Torepatutahi streams originates from outside the topographical catchment boundary.

The water balance indicates that the majority of the remaining catchments have reasonably high aquifer recharge. It must be noted that this water balance considers the groundwater system as a whole and does not take into consideration the separate aquifer formations within each of the catchments. Between 12% to 42% of rainfall leaves the catchments as stream flow, 38% to 66% leaves as evapotranspiration, 5% to 18% leaves as storm flow, while 0% to 45% recharges aquifers.

8.3.1 Torepatutahi model estimate

The Torepatutahi Stream catchment is the most intensive groundwater use area in the Reporoa Basin. The catchment is divided into upper and lower zones on the basis of faulting and uplift (Figure 24). The two zones exhibit different hydrological characteristics, with the upper catchment acting as a recharge zone to springs discharging from the fault zone. The lower catchment is predominantly a discharge zone (Figure 23).
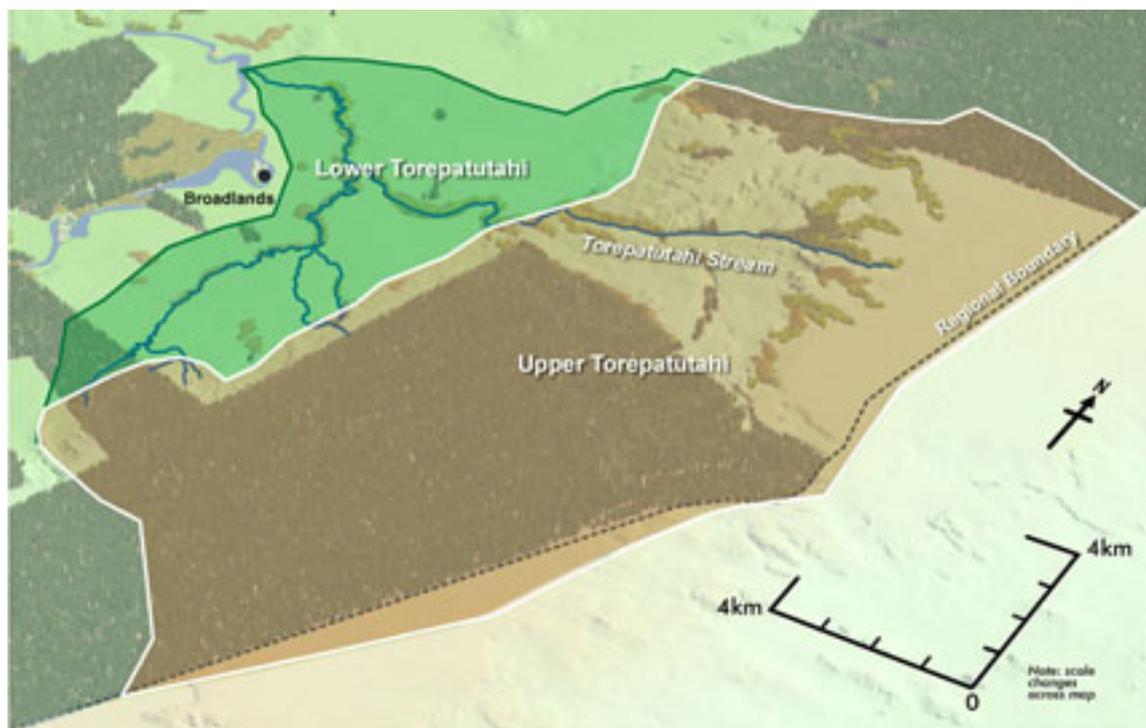
Figure 24: Upper and lower Torepatutahi catchment.

Table 8:   Water balance components for Reporoa Basin subcatchments.

Water balance parameters (mm yr^{-1})	Catchment							
	Kaiwhitiwhiti	Torepatutahi Option1	Torepatutahi Option2	Kopuhurihuri	Mangaharakeke	Upper Waiotapu	Mangakara	Mangamingi
Rainfall	1190	1209	1330	1267	1410	1374	1340	1319
ET	666	800	640	499	758	622	576	501
Storm flow	213	128	128	91	122	206	120	66
Recharge input	311	281	562	676	529	546	644	751
Stream flow	498	511	511	215	285	480	280	157
Aquifer recharge	-187	-230	51	461	244	66	364	595
Aquifer recharge as a % of rainfall	-16	-19	4	36	17	5	27	45

* Aquifer recharge may include groundwater discharge to the Waikato River and recharge to deeper aquifer systems

Table 9:   Aquifer recharge available for allocation.

Assume 50% of aquifer recharge available for allocation	Catchment							
	Kaiwhitiwhiti	Torepatutahi Option1	Torepatutahi Option2	Kopuhurihuri	Mangaharakeke	Upper Waiotapu	Mangakara	Mangamingi
mm yr^{-1}	-93	-115	25	231	122	33	182	297
m^3 d^{-1}	-10123	-66923	14693	3822	17849	7822	11397	5411

Two water balance options are given for the Torepatutahi catchment (Table 8). The option 1 water balance model calculated a groundwater deficit. The recharge deficit calculated by the option 1 model used mean annual rainfall calculated from climate records, baseflow of 3.44 $m^3 s^{-1}$ calculated from flow duration curves and baseflow ratios, and storm flow equal to 20% of the mean annual stream flow calculated from flow duration curves. The model was revised (option 2) using 10% higher rainfall and 62% of mean annual stream flow based on low flow values. The storm flow value was modeled on values used by Dons (1987) in the upper Mangakara catchment. The option 2 water balance model relates well to recharge estimates obtained by Dons (1987).

The water balance in Table 8 for both options 1 and 2 both indicate that the Torepatutahi catchment has limited aquifer recharge. Examining the water balance further by upper and lower catchment indicates that the aquifer recharge characteristics may be quite different. Spring discharge from the upper Torepatutahi catchment is 2.7 $m^3 s^{-1}$, which is equivalent to 519 mm yr^{-1} over the 164 km^2 catchment. Average rainfall is 1229 mm. Groundwater recharge less storm runoff (64 mm yr^{-1}), is about 2% of annual rainfall or about 29 mm annually.

For the management of an unknown groundwater resource it is conservative to assume that 50% of aquifer recharge can be allocated (Lowry *et al.*, 2001) (Table 9). Potentially 24 mm annually (2,369,944 $m^3 yr^{-1}$ or 6492 $m^3 d^{-1}$) is available for allocation. Of the groundwater recharge, there is the possibility that groundwater is recharging geothermal systems and deeper groundwater flow towards the lower catchment and Waikato River.

8.3.2 Kaiwhitiwhiti model estimate

In the Kaiwhitiwhiti catchment, a comparison between rainfall and stream flow measurements indicate that the majority of the measurements were obtained during a wet period. This possibly equates to the average stream flow shown skewed towards higher flow values. Small changes in model variables in the Kaiwhitiwhiti catchment lead to quite large changes which illustrate the sensitivity of the model.

9 Water Use and Availability

An initial survey of properties with groundwater or surface water takes using GIS, identified a number of properties as not being clearly associated with either a groundwater or surface water take. A large number of these properties were found to be within the reticulated water supply areas of Reporoa and Mihi. The water source for approximately 70 properties could not be identified due to no data being held on the type of water sources used.

9.1 Groundwater use

Database, ground and phone surveys of properties, identified approximately 220 groundwater bores exist in the Reporoa Basin (Figure 25). An initial database query identified 100 bores spread throughout the Basin. A field survey identified an additional 100 bores spread throughout the entire Basin. Approximately 70 properties not covered by any of the water supply schemes of Reporoa, Mihi, East Road and River Road (Figure 26) were not visited in the field. A phone survey of these 70 properties identified 20 of these had groundwater bores. The other 50 properties were either connected to small water supplies such as the River Road Scheme, had small private surface water takes, or were collecting rainwater.

Groundwater use in the Reporoa Basin was calculated using consented (abstraction over 15 $m^3 d^{-1}$)[2], permitted (abstraction up to 15 $m^3 d^{-1}$) (Table 10) and modelled water use (Appendix III).
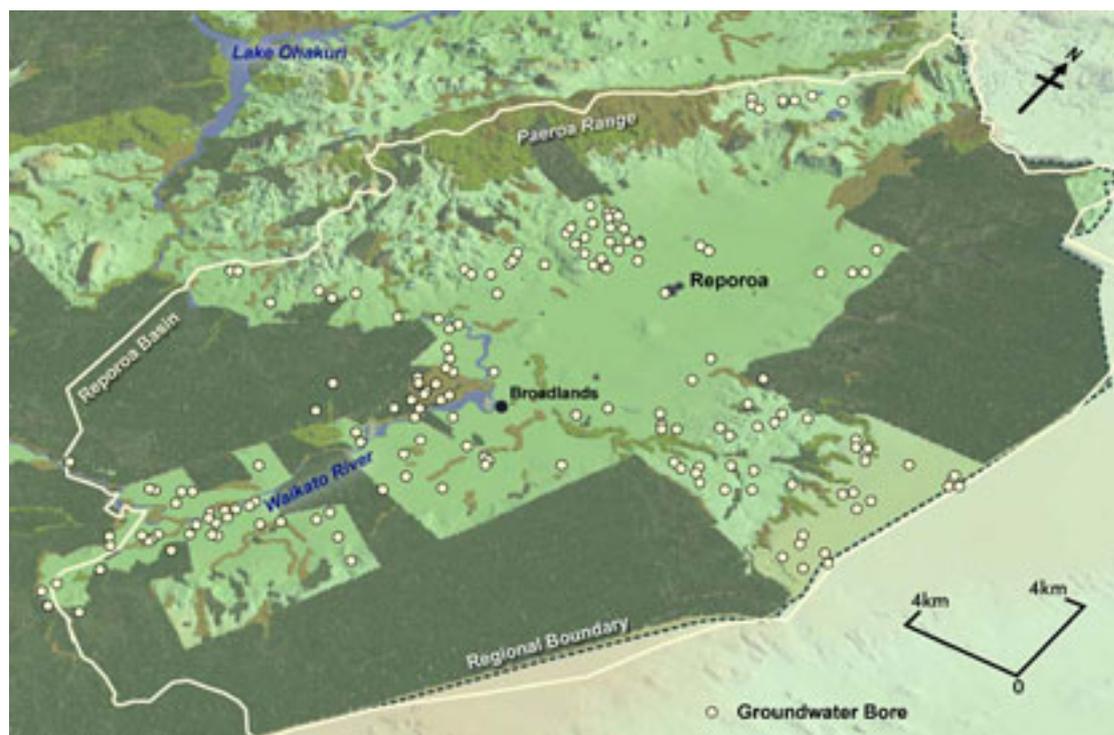
Figure 25: Location of groundwater bores in the Reporoa Basin.

9.2 Surface water use

Surface water usage was calculated using two categories; consented (takes above 15 $m^3 d^{-1}$ from surface waters excluding the Waikato River) and permitted activities (surface water takes up to 15 $m^3 d^{-1}$) (Table 10). There is no definitive data on how many permitted surface water takes are present within the Reporoa Basin. Under Rule 3.3.4.6 of Environment Waikato's Regional Plan, the maximum amount of water that can be taken from surface waters, excluding the Waikato River, in the Reporoa Basin under a permitted activity is 15 $m^3 d^{-1}$. Under Rule 3.3.4.7 of the Regional Plan, a permitted surface water take of 30 $m^3 d^{-1}$ is allowed from the Waikato River.

It has been assumed that properties have permitted takes of up to 15 $m^3 d^{-1}$ from surface waters with exception of up to 30 $m^3 d^{-1}$ from the Waikato River.

Table 10: Estimate of water usage for the Reporoa Basin ($m^3 d^{-1}$).

	Surface Water	Surface Water	Groundwater	Groundwater
Consented	246346	246346	9516	9516
Permitted	1500[a]	3000[b]	3300[c]	6600[d]
Total	**247846**	**249346**	**12816**	**16116**

[a] Permitted Surface water usage based on 94 properties taking a maximum of 15 $m^3 d^{-1}$
[b] Permitted Surface water usage based on 94 properties taking a maximum of 30 $m^3 d^{-1}$
[c] Permitted Groundwater usage based on 220 properties taking a maximum 15 $m^3 d^{-1}$
[d] Permitted Groundwater usage based on 220 properties taking a maximum 30 $m^3 d^{-1}$
[e] The estimate of permitted surface and ground water use is proposed to be an under-estimate of actual usage.

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[2] Under Rule 3.3.4.8 of the Transitional Waikato Regional Plan up to 15 $m^3 d^{-1}$ of groundwater can be abstracted as a permitted activity. Under Rule 3.3.4.8 of the proposed Waikato Regional Plan up to 30 $m^3 d^{-1}$ of groundwater can be abstracted as a permitted activity.
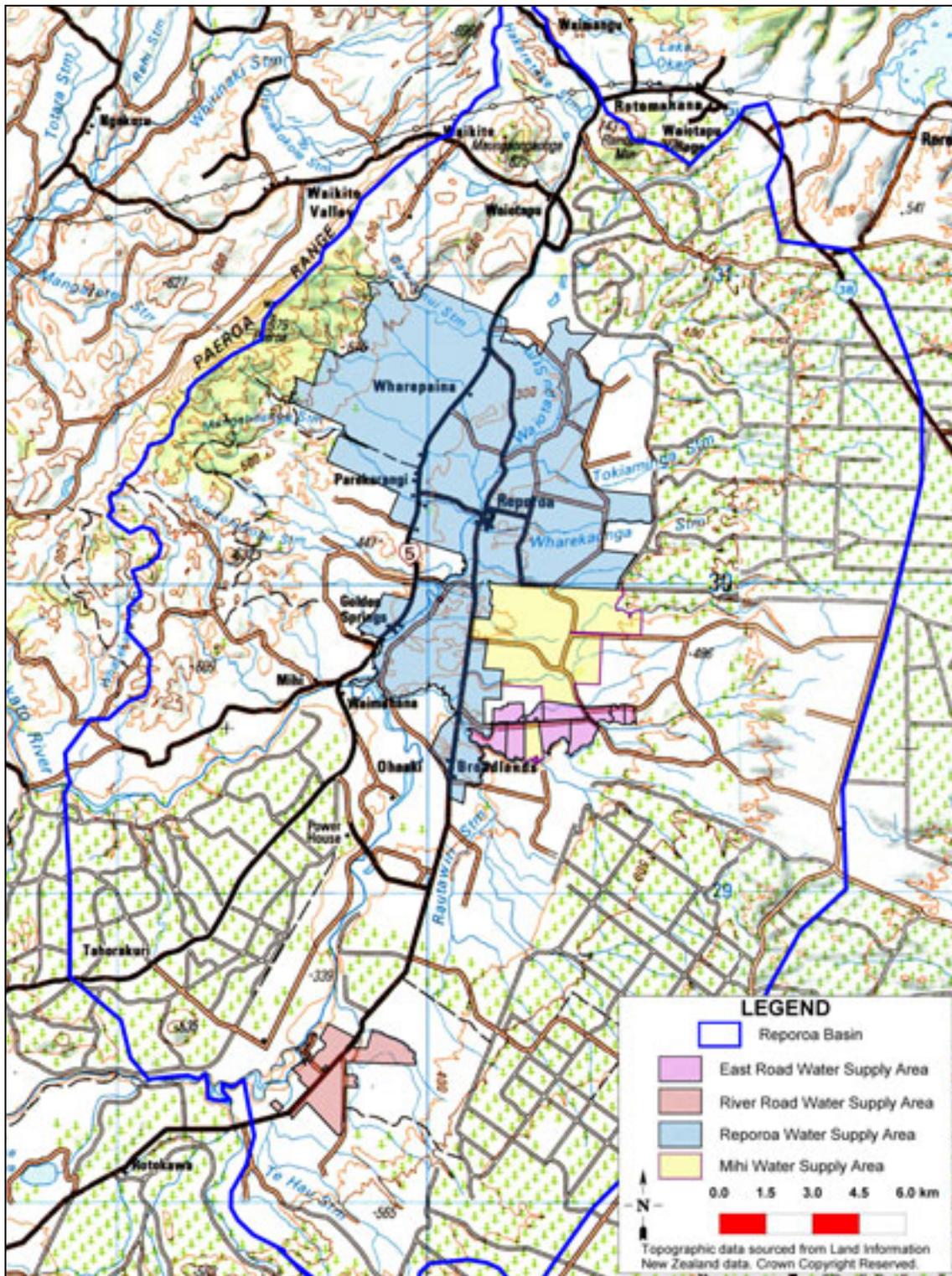
Figure 26: Community water supply schemes. (Water supply areas supplied by Rotorua and Taupo District Councils).

9.3   Refinement of permitted use model

Water use was estimated for each sub-catchment based on the 2001 AgriBase farm database (AgriQuality New Zealand Ltd, 2001). AgriBase provides an estimate of total farm properties in the catchment, total stock numbers and species, number of dairy farms, and number of residential dwellings. Guidelines (Table 11) taken from Maggs (1987), Flemming (1996) and the Transitional Waikato Regional Plan (2001) provide the basis for water use estimates in Appendix III.

Table 11: Water use guidelines.

Water use	$m^3\ d^{-1}$
Dairy Shed wash down per animal	0.07
Household use (4 people)	0.74
Dairy[1]	0.1
Beef[1]	0.0625
Deer[1]	0.0385
Sheep[1]	0.0055

[1]Water use per animal.

From the initial database query of bores and permitted usage, the water usage from groundwater resources was estimated at 1500 $m^3\ d^{-1}$. After the field survey identified an additional 100 bores, the estimated water usage increased to 3000 $m^3\ d^{-1}$. The estimated water usage after the phone survey increased to 3300 $m^3\ d^{-1}$. Permitted use (based on 15 $m^3\ d^{-1}$) along with consented groundwater use in the Basin is estimated at 12,816 $m^3\ d^{-1}$ (Table 10). It must be noted not all groundwater bores in the basin have been identified by this study and water use may exceed 15 $m^3\ d^{-1}$, consequently water usage in this study may be under estimated.

To quantify the usefulness and accuracy of estimating property water use based on the Agribase and permitted use scenarios, water use records from the Rotorua District Council Reporoa/Mihi water supply scheme were compared to the estimates of total use for corresponding properties. Comparison of the water use estimated based on Agribase and permitted use models with the actual water use from the Reporoa/Mihi supply schemes, it has been identified that the Agribase model provides an over-estimation of water use, while the permitted use model compares favourably to actual use. Based on the average actual daily water use for properties within the Kopuhurihuri and Upper Waiotapu catchments, actual use is between 39% - 44% less than the Agribase modelled use. The difference between the actual and Agribase estimated water use is most likely attributed to error associated with reporting stock numbers. Stock water use accounts for between 57% - 63% of total use within the Agribase estimates.

Surface water in the Reporoa Basin is fully allocated based on meeting aquatic limitations (Spiers and Kusabs, 2001). Further indirect abstraction of surface water via groundwater would be of concern environmentally. Long term sustainability of the groundwater resource also needs consideration when managing allowable abstraction.

In the Torepatutahi catchment, the water balance model identified the importance of the groundwater capture zone within the upper catchment to the springs of the Torepatutahi Stream. The water balance model indicates that there is very little groundwater available for future groundwater abstraction. This scenario is similar in the Kaiwhitiwhiti and Upper Waiotapu catchments where the water balance model also indicates little available groundwater for allocation.

Overall, the availability of groundwater in many of the catchments in the Reporoa Basin is limited based on this initial investigation. Once existing groundwater use is taken into consideration, there maybe no water available for allocation in some catchments based on flow protection for instream requirements.

This investigation has provided important information on the availability of groundwater in the Reporoa Basin. It has been highlighted that variability of several parameters such as spring discharge, rainfall and recharge can affect the amount of groundwater available for use. To substantiate the scenarios discussed, further work is needed such as modelling the interaction between surface water and groundwater, as well as the relationship between rainfall and aquifer recharge and discharge.

10 Summary

This investigation has provided a first insight into the hydrogeological system in the Reporoa Basin. It is focused on the geological setting, flow regime, groundwater quality, age and water balance in the Basin.

The geology comprises predominantly rhyolitic formations. Stratigraphy of the eastern Basin comprises Taupo Ignimbrite overlying the uplifted Rangitaiki Ignimbrite. The stratigraphy of the western Basin is characterised by Taupo Ignimbrite overlying the Paeroa Formation. In the north-eastern side of the Basin, Taupo Ignimbrite overlies Kaingaroa Ignimbrite. The stratigraphic sequence in the central Basin is more complex with pyroclastic Taupo and Oruanui Ignimbrites overlying lacustrine sediments of the Huka Formation. These in turn overly the ignimbritic Waiora Formation.

Groundwater flow in the Basin is consistent with topography although more subdued. There is a relationship between depth to groundwater and well depth, indicating vertical groundwater recharge. Groundwater predominantly drains locally toward the streams within the Basin and ultimately the Waikato River. A large proportion of groundwater recharge from rainfall is intercepted by streams such as the Torepatutahi, Kaiwhitiwhiti and Waiotapu streams. Aquifer transmissivity ranges between $2 \text{ m}^2 \text{ d}^{-1}$ to $1720 \text{ m}^2 \text{ d}^{-1}$ and average groundwater flow velocities are estimated to range between 0.02 m d^{-1} to 0.16 m d^{-1}.

Groundwater quality samples were collected from wells across the Reporoa Basin that penetrated a range of different geologic formations (Taupo, Hinuera and Rangitaiki Formations). The chemical character of groundwaters is largely sodium bicarbonate dominated. Sodium bicarbonate dominance is typical of groundwater abstracted from normal weathering of rhyolitic formations. There is some evidence of land use impacts with elevated nitrate-nitrogen concentrations in groundwater samples from several bores. Sodium and chloride concentrations are generally also elevated in groundwater at sites with high nitrate-nitrogen concentrations, and where it is thought that the aquifer is geothermally influenced.

Reducing conditions are indicated at several sites. Reducing conditions are inferred by high manganese, iron, ammonium-nitrogen and low nitrate-nitrogen. Of particular concern, is the elevated concentrations of arsenic in groundwater throughout the entire Reporoa Basin. Elevated arsenic concentrations were found to occur within groundwater samples from most of the aquifer formations. Possible factors influencing arsenic concentrations are reducing conditions and to a smaller extent, geothermal influence.

Age determination of groundwater at eight bore locations using tritium and CFCs indicate that mean groundwater residence time is between 11 years and 73 years. A spring of the Torepatutahi Stream sampled in 2001 was found to have a mean residence time of 150 years. The mean residence time of groundwater in relation to nitrate-nitrogen concentrations shows that nitrate-nitrogen concentrations are higher in young groundwater and low in old groundwater.

Water balance model estimations show that in many of the Reporoa Basin catchments, groundwater flow is predominantly intercepted by large springs. These commonly are the source of streams within the Basin. There is very little allocatable groundwater available for future abstraction in many catchments, particularly the Kaiwhitiwhiti, Torepatutahi and Waiotapu catchments. This is based on water balance estimates and aquatic and ecologic requirements of a minimum of 85% to 90% of a 1 in 5 year low flow (Q_5) in surface water systems.

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Appendix I: Calculation of mean annual flow

Mean flows were estimated for the eight sub-catchments of the Reporoa Basin on the True Right Bank of the Waikato River as provided. The order of regions is from the Downstream Mangamingi catchment to the Kaiwhitiwhiti catchment. Map References are approximate downstream limits of the catchment regions.

Mean flows were estimated for 3 long-term recorder sites (Table I) in the basin and these were then used in other estimation methods.

Flow characteristics of three long-term recorder sites

	Waiotapu at Campbell Rd	Waiotapu at Reporoa	Mangakara at Hirsts
EW HYDROL Number	1186.2	1186.9	380.1
Map Reference (NZ 260 series)	U17:024-082	U17:016-022	U17:988-006
Mean Flow m^3s^{-1}	1.445	3.733	0.374
Catchment Area km^2	47.6	228.0	22.0
Specific Discharge $ls^{-1} km^{-2}$	30.3	16.4	17.0

Methods used included:-
- correlation – where sufficient gaugings were done at a location, gauged flows were correlated against the corresponding flows at the recorders
- ratio – relationship of mean flow at recorder site to the flow at the time of the gauging used to factor the gauged flow to mean flow conditions.
  Mean Flow = gauged flow x recorder Mean Flow/Recorder Flow at time of gauging
- Gauged during mean flow conditions
- Mean Gauged flow – mean of all gaugings at predominantly spring fed streams with 30 or more gaugings.

Mangamingi Catchment

Mean flow was calculated for one site in the catchment using gauged flows.

Flow sites in the Mangamingi catchment

Stream	Location	Hydrol Site Number	Map Reference	No. of Gaugings
Mangamingi	Tutukau Road	1470.1	U17:965-968	1

Mangamingi catchment mean flow

Stream	Catchment Area km^2	Mean Flow $m^3 s^{-1}$	Calculation method used
Mangamingi	6.4	0.047	Ratio with Mangakara at Hirsts

Mangakara Catchment

Mean flow was calculated for one site in the catchment using gauged flows.

Flow sites in the Mangakara catchment

Stream	Location	Hydrol Site Number	Map Reference	No. of Gaugings
Mangakara	Hirsts	380.1	U17:988-006	(7)

Mangakara catchment mean flow

Stream	Catchment Area km^2	Mean Flow m^3 s^{-1}	Calculation method used
Mangakara	22.0	0.374	Recorder site

Upper Waiotapu Catchment

Mean flow was calculated for four sites in the catchment using gauged flows.

Flow sites in the Upper Waiotapu catchment

Stream	Location	Hydrol Site Number	Map Reference	No. of Gaugings
Waiotapu	Campbell Rd	1186.2	U17:024-082	158
Kawaunui	End of Ngapouri Rd	240.1	U16:987-111	9
Waiotapu Tributary	Campbell Rd (B3)	1187.1	U17:031-082	10
Waiotapu Tributary	Campbell Rd	1187.5	U17:035-078	18

The contribution of the remaining catchment was estimated using the mean specific discharge for the Kawaunui and Waiotapu Tributary (B3) and the associated catchment area.

Mean flow in Upper Waiotapu catchment = mean flow Waiotapu at Campbell Rd + mean Kawaunui at End of Ngapouri Rd + mean flow Waiotapu Tributaries at Campbell Rd (2) + mean flow in remaining catchment.

Upper Waiotapu catchment mean flow

Stream	Catchment Area km^2	Mean Flow m^3 s^{-1}	Calculation method used
Waiotapu	63.5	1.445	Recorder site
Kawaunui	21.1	0.146	Correlation with Mangakara at Hirsts
Waiotapu Tributary	0.8	0.015	Correlation with Waiotapu at Reporoa
Waiotapu Tributary	6.0	0.184	Correlation with Waiotapu at Reporoa
Other Catchment	7.0	0.090	CA and mean Specific Discharge
Total Catchment	98.4	1.879	

Mangaharakeke Catchment

Mean flow was calculated for one site in the catchment using gauged flows.

Flow sites in the Mangaharakeke catchment

Stream	Location	Hydrol Site Number	Map Reference	No. of Gaugings
Mangaharakeke	Campbell Rd	361.1	U17:042-053	19

There is no significant contribution from the remaining catchment.

Mean flow in Mangaharakeke catchment = mean flow Mangaharakeke at Campbell Rd

Mangaharakeke catchment mean flow

Stream	Catchment Area km^2	Mean Flow m^3 s^{-1}	Calculation method used
Mangaharakeke	56.8	0.688	Correlation with Mangakara at Hirsts
Other Catchment	0.0	0.000	No significant flow
Total Catchment	56.8	0.688	

Kopuhurihuri Catchment

Mean flow was calculated for one site in the catchment using gauged flows.

Flow sites in the Kopuhurihuri catchment

Stream	Location	Hydrol Site Number	Map Reference	No. of Gaugings
Kopuhurihuri	Settlers Rd	265.1	U17:015-007	3

Kopuhurihuri catchment mean flow

Stream	Catchment Area km^2	Mean Flow $m^3 s^{-1}$	Calculation method used
Kopuhurihuri	9.7	0.059	Ratio with Mangakara at Hirsts

Torepatutahi Catchment

Mean flow was calculated for one site in the catchment using gauged flows.

Flow sites in the Torepatutahi catchment

Stream	Location	Hydrol Site Number	Map Reference	No. of Gaugings
Torepatutahi	Vaile Rd	1057.6	U17:985-965	40

There is no significant contribution from the remaining catchment.

Mean flow in Torepatutahi catchment = mean flow Torepatutahi at Vaile Rd.

Torepatutahi catchment mean flow

Stream	Catchment Area km^2	Mean Flow $m^3 s^{-1}$	Calculation method used
Torepatutahi	240	4.372	Mean of gaugings
Other Catchment	0	0.000	No significant flow
Total Catchment	240	4.372	

Kaiwhitiwhiti Catchment

Mean flow was calculated for one site in the catchment using gauged flows.

Flow sites in the Kaiwhitiwhiti catchment

Stream	Location	Hydrol Site Number	Map Reference	No. of Gaugings
Kaiwhitiwhiti	Broadlands Rd	218.1	U17:978-856	35

Kaiwhitiwhiti catchment mean flow

Stream	Catchment Area km^2	Mean Flow $m^3 s^{-1}$	Calculation method used
Kaiwhitiwhiti	30.9	0.892	Mean of gaugings

Appendix II: Age dating of groundwater in the Reporoa Basin

Report on tritium and CFC analysis and interpretation The report from IGNS is reproduced below (see EW DOCS #982737).

Mike Stewart
18 February 2005

Introduction

Water allocation has become a topical community issue in the Reporoa Basin, since large quantities of groundwater have been taken for irrigation (Piper and Brown, 2004). Most streams are at maximum allocation, so groundwater is being exploited for irrigation. CFC and tritium measurements were carried out to determine groundwater ages. Many of the samples were from the Torepatutahi Catchment, where approximately 74% of the headwater streamflow is from springs.

Age-dating using tritium is based on radioactive decay of tritium after rainwater penetrates the ground during recharge. The half-life of tritium decay is 12.3 years. Figure 27 shows the variation of the tritium concentration in rainfall in time; the peak in tritium concentration is due to nuclear weapons testing during the 1960s and early 1970s (Stewart and Morgenstern, 2001). Age-dating using dissolved gases is possible due to the steady increase in atmospheric SF_6 and CFC concentrations since their production began in the 1940s (Figure 27). The measured concentrations in groundwater are used to calculate the corresponding atmospheric concentrations using Henry's Law and the recharge temperature, and the age is determined by comparing these with the atmospheric record.
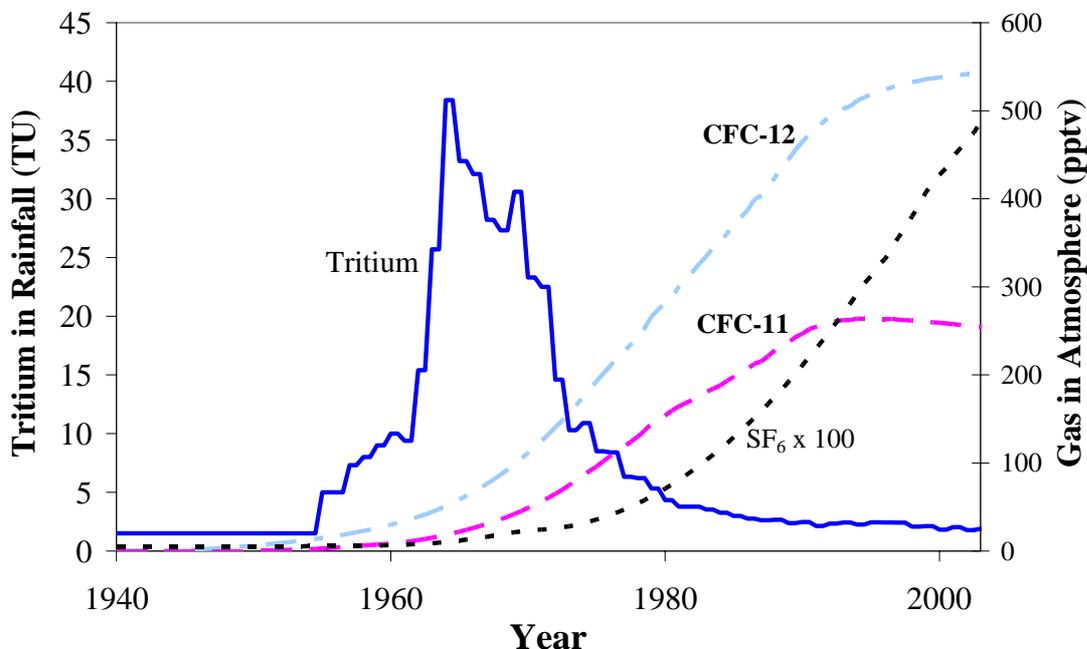
Figure 27: Tritium concentration in rainfall at Kaitoke, New Zealand, and SF_6 and CFC concentrations in the Southern Hemisphere atmosphere.

Sampling

Samples were collected for measurement of tritium and CFC concentrations. Sample information is given in Table 12. Samples for tritium analysis were collected in clean 1.1 litre Nalgene bottles. Concentrations of ^{3}H are reported as Tritium Ratios (TR) at the date of sample collection ± 1 standard measurement error, using the scale recommended by Taylor and Roether (1982). TR = 1 corresponds to a T/H ratio of 10^{-18}. Water samples for CFC concentration measurements were collected in such a way as to prevent contact with the atmosphere or with plastic materials, either of which could contaminate the sample with CFCs.

Table 12: Sampling and bore data from Reporoa Basin groundwater

Sample ID	Map Reference	Collection Date	Depth (m)	Screen depth (m)	Geology	Static water level (m bgl)
66.22	V17:127-960	10.3.04	110	65 – 110	Rangitaiki Ignimbrite	76.69
66.90	U17:027-950	18.3.04	6	1.5 – 4.5	Taupo Ignimbrite	2.79
66.91	U17:027-950	18.3.04	4.5	1 – 4.5	Taupo Ignimbrite	3.11
66.92	U17:017-018	10.3.04 (Trit) 18.3.04 (CFC)	48.5	17.2 – 19.2	Hinuera Formation	1.57
66.93	U17:017-018	18.3.04	8	2.1 – 8	Taupo Ignimbrite	2.17
68.162	U18:942-798	10.3.04	43	39 – 43	Rangitaiki Ignimbrite	28.6
72.1565	U17:052-958	10.3.04	112.4	91 – 112.4	Rangitaiki Ignimbrite	6.47
72.1153	V17:118-935	10.3.04	210	187 – 210	Hinuera Formation	155

The recharge temperatures have been determined by measuring the argon and nitrogen concentrations in the samples (see Figure 28). Solution of these gases in water decreases with increasing temperature. The figure also shows the effect of excess air in the sample (excess air is air in excess of the equilibrium soluble amount at the given temperature). The grid in the figure allows the recharge temperature and excess air concentration of the sample to be determined.
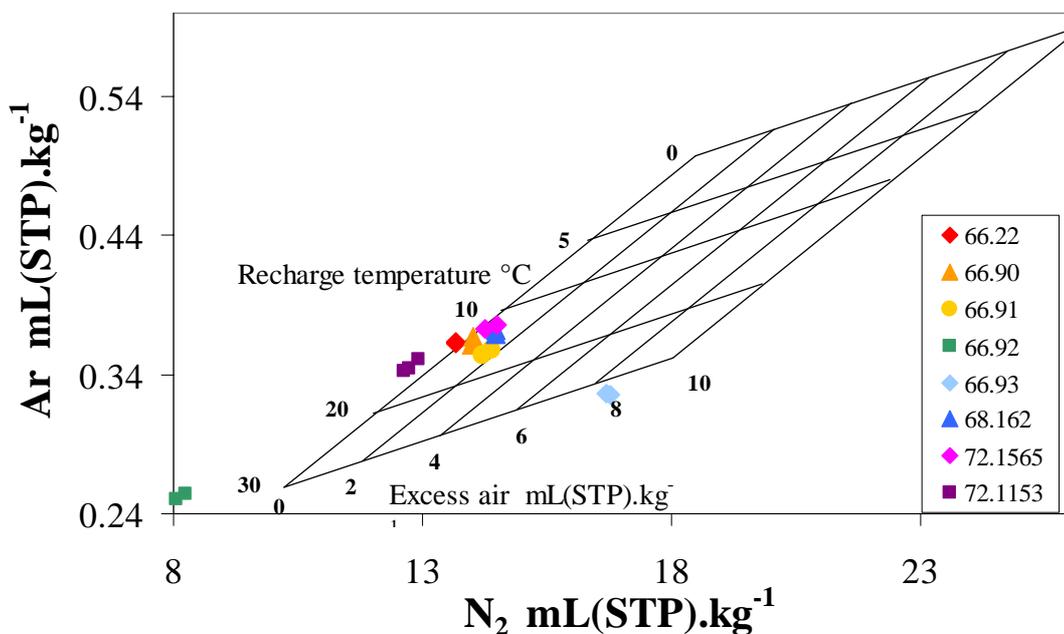
Figure 28: Plot of nitrogen versus argon concentrations. The positions of the samples within the grid indicate their recharge temperatures and excess air concentrations.

Results

Samples 66.22, 66.90, 66.91, 68.162, 72.1565 and 72.1153 plot close to the equilibrium line, showing that the samples have very little excess air (Figure 28). Their recharge temperatures are all close to 11°C, which is about the mean soil temperature in the region. The duplicate samples agree very well; these are excellent samples. In contrast, sample 66.92 has lower concentrations of argon and nitrogen. The position of this sample in the plot shows that gas has been lost from the water, consequently the water is undersaturated with air. This sample has been affected by geothermal heating. Sample 66.93 also plots in an odd position in Figure 28. This water looks as if it has gained gas from geothermal sources; the indicated temperature in the plot (32°C) shows that this is not excess air at normal temperature.

The recharge temperature and excess air concentration results are given in Table 13. (Results for samples 66.92 and 66.93 have been adjusted − 66.92 is corrected for outgassing and 66.93 is treated as if the temperature and excess air content are normal, since any gas added to this sample would not have been expected to contain CFCs.) These have been used to calculate the atmospheric concentrations of CFCs at the time of recharge. 'Piston flow' ages have been determined from these concentrations by comparing them with the atmospheric record given in Figure 27. However, such ages implicitly assume that all of the water in the sample has the same age. In reality, every sample has a distribution of ages resulting from collection of water following different flow paths through the aquifer. Consequently, we need to consider possible 'mixing' models in interpreting the CFC (and tritium) concentrations as ages.

Table 13: Recharge temperatures and excess air concentrations, calculated atmospheric CFC concentrations during recharge, and piston flow ages of CFC samples.

Sample ID	CFC No.	Calculated from Ar & N_2[1]		Calculated atmospheric partial pressure (pptv)[2]		Piston flow age[3] (yrs)	
		Temp °C	Excess air	CFC-11	CFC-12	CFC-11	CFC-12
66.22	FWK33	11.1	-0.1	144.6 ± 0.1	330.6 ± 1.3	25.0	21.5
66.90	FWK34	11.6	0.5	224.2 ± 1.2	488.9 ± 4.6	16.5	12.7
66.91	FWK35	14.1	1.8	139.3 ± 0.9	434.3 ± 0.9	26.0	16.0
66.92	FWK36	11.5	-3.8	3.4 ± 0.1	5.4 ± 0.0	48.2	54.0
66.93	FWK37	11.5	0.0	14.6 ± 0.1	279.5 ± 1.8	41.0	24.2
68.162	FWK38	11.4	1.0	62.5 ± 0.1	160.2 ± 0.6	32.5	31.0
72.1565	FWK39	10.4	0.6	13.3 ± 0.2	37.6 ± 0.6	41.5	42.0
72.1153	FWK40	12.3	-0.8	81.0 ± 1.4	246.5 ± 4.0	30.8	26.5

[1] See Figure 29. Excess air is given in mL(STP)/kg.
[2] Pptv is parts per trillion by volume (pptv), and 1 pptv signifies a ratio of $1×10^{-12}$.
[3] Piston flow ages are calculated assuming that all of the water in the sample has the same age (i.e. there is no mixing).

Nevertheless, the piston flow ages are useful for comparing the CFC-11 and CFC-12 results. Samples 66.22, 66.90, 66.92, 68.162, 72.1565 and 72.1153 all have quite close agreement between the CFC-11 and CFC-12 piston flow ages. There is a consistent pattern in which the CFC-11 ages are older in the youngest samples, and CFC-12 ages are older in the oldest samples. This suggests that there may be some miscalibration of the historical atmospheric concentrations (Figure 27). (If the atmospheric concentrations were adjusted we might be able to get almost identical ages from the CFC-11 and CFC-12 concentrations.) Samples 66.91 and 66.93 show

larger differences between the CFC-11 and CFC-12 piston flow ages, with CFC-11 ages being much older. These could result from slight contamination of the CFC-12 concentrations, or degradation of the CFC-11 concentrations in reducing conditions underground.

Tritium concentrations were also determined for these samples. The results are given in Table 14. The objective is to use the tritium and CFC concentrations to determine the mean and distribution of residence times in each sample. An exponential piston flow model (EPM) has been used to estimate the mean residence times of the samples. The EPM has been found to produce satisfactory fits for bores that have a sequence of tritium measurements over many years (Stewart & Morgenstern 2001). The mixing fraction used is indicated in Table 14; the mixing fraction is the fraction of the exponential volume to the total volume of the system. A mixing fraction of 0% means zero mixing (i.e. a pure piston flow model as used in Table 13), and a mixing fraction of 100% means the exponential model applies (i.e. water travelling through the aquifer via different flowpaths combines at the outlet to give an exponential age distribution). Both of these extremes are to some extent unrealistic.

Table 14: Tritium concentrations, and age interpretation of the tritium and CFC concentrations using an exponential piston flow model with the indicated mixing fraction.

Sample ID	Tritium Concentration TU	Mixing model fraction %	Mean age (in years) based on the EPM model shown			Recommended Age (years)
			Tritium	CFC-11	CFC-12	
66.22	1.71 ± 0.07	30	1, 28[1], 48	25	22	25
66.90	1.41 ± 0.03	90	5, 10[1], 16	13	9	11
66.91	1.45 ± 0.04	40	4, 25[1], 51	27	16	26
66.92	0.032 ± 0.021	40	80	65	73	73
66.93	1.66 ± 0.05	30	2, 27[1], 47[1]	49	25	26 or 48
68.162	0.602 ± 0.026	40	61	39	35	See below
72.1565	0.266 ± 0.025	40	65	55	54	58
72.1153	0.376 ± 0.023	40	65	35	28	See below

[1] Preferred tritium age

Sample 66.22 has well-defined CFC ages of 25 and 22 years, which are almost independent of the mixing fraction. The tritium concentration does not give a unique age, but the middle of the three possible ages with 30% mixing (28 years) is close to the CFC ages. The tritium concentration shows that the mixing fraction cannot be greater than 40%, because if it was the only possible tritium age would be 1 year, and this is ruled out by the CFC ages. Sample 66.90 has CFC concentrations indicating a consistent young age (11 years). A mixing fraction of 90% produces the closest tritium age match; younger and older tritium ages are possible, but are ruled out by the CFC ages.

Sample 66.91 does not have such a well defined CFC age, and either CFC-11 could be partially degraded or CFC-12 could be slightly contaminated. However, the mean age in the range 26-16 years is accurate enough to show that the mixing fraction cannot be greater than 50%, because then the tritium concentration could not be simulated. With mixing fraction in the range 0-50%, the middle of three possible ages is 24-29 years and the other possible ages are ruled out by the CFC ages. The CFC-12 age is considerably younger than the preferred tritium age and the CFC-11 age, and has been discarded (highlighted in blue in Table 14). Sample 66.92 has low concentrations of tritium, CFC-11 and CFC-12 and therefore is old (73 years with a mixing fraction of 40%). The tritium age interpretation is unique, but using a higher mixing fraction would give a greater age (for the CFCs as well as for tritium). There is no way with the present data to determine which mixing fraction should be applied. (A mixing fraction of 70% would give a mean age of 128 years.)

Sample 66.93 shows a considerable difference between the CFC-11 and CFC-12 ages. As with sample 66.91, either could be correct. However, tritium could not be used in this case to determine which is more likely to be correct, because possible tritium ages match both CFC ages. Sample 68.162 shows a considerable discrepancy between the (unique) tritium age and the CFC ages, and this discrepancy remains regardless of the mixing fraction used. This discrepancy shows that two types of water are being tapped by this bore (see Figure 29 and Figure 30 below).

Sample 72.1565 has consistent low tritium and CFC concentrations which give a mean residence time of 58 years assuming a mixing model with 40% mixing, and 97 years with 70% mixing. Sample 72.1153 shows the same discrepancy between the tritium and CFC ages as sample 68.162, for the same reason.

The reasons for the agreement or disagreement between the tritium age and the CFC ages can be seen more clearly if the tritium concentration is plotted against the CFC concentrations (Figure 29 and Figure 30). In these plots, the tritium concentrations have been reduced by radioactive decay from the time of deposition to the present. Samples that plot on or near the solid curve have tritium and CFC-11 or CFC-12 concentrations that are consistent with one water 'type' (i.e. water with a mean age and fixed distribution of ages about the mean). These samples show agreement between the ages determined from the different measurements. These diagrams illustrate why
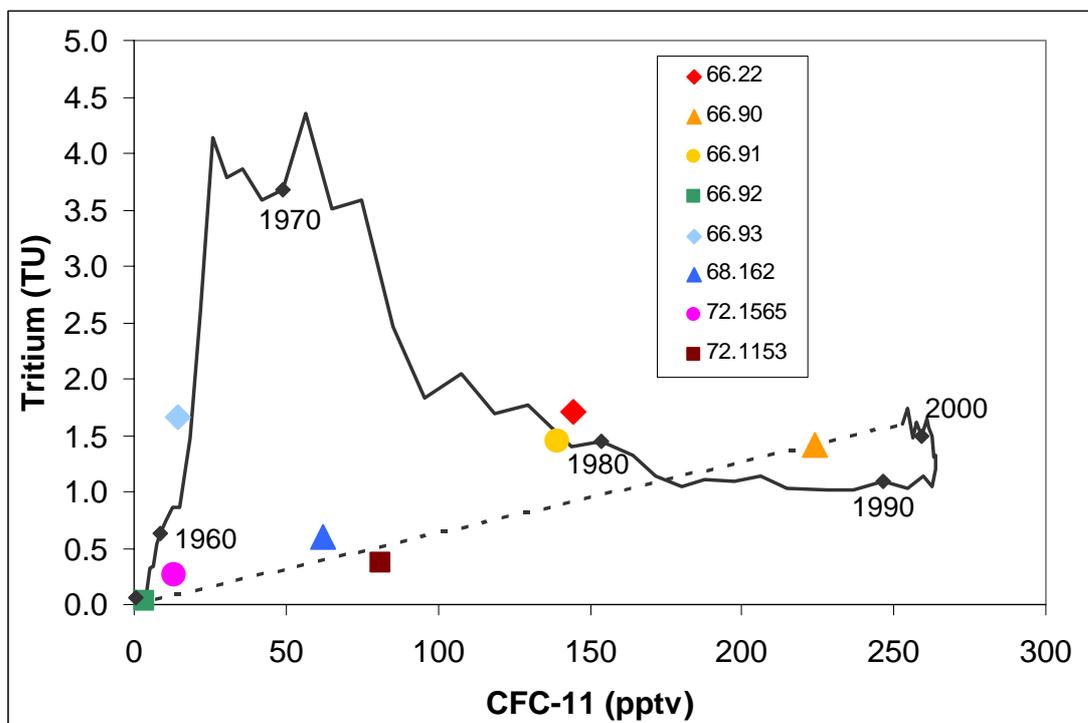
Figure 29: Plot of tritium versus CFC-11 concentrations in Reporoa Basin groundwaters.

certain tritium concentrations can yield three possible ages (e.g. 1.5 TU), whereas others give only one age (<1.0 TU). Most of the Reporoa samples plot near the solid curve and thus give consistent tritium and CFC ages. Sample 66.91 plots in different places in Figure 29 and Figure 30; it plots on the curve in Figure 29 and the tritium and CFC-11 ages agree, but off the curve in Figure 30 and tritium and CFC-12 ages disagree. Sample 66.93 also plots in different places in Figure 29 and Figure 30, but in this case both points coincide with the solid curve, so both CFC-11 and CFC-12 ages agree with tritium ages (but different ones).
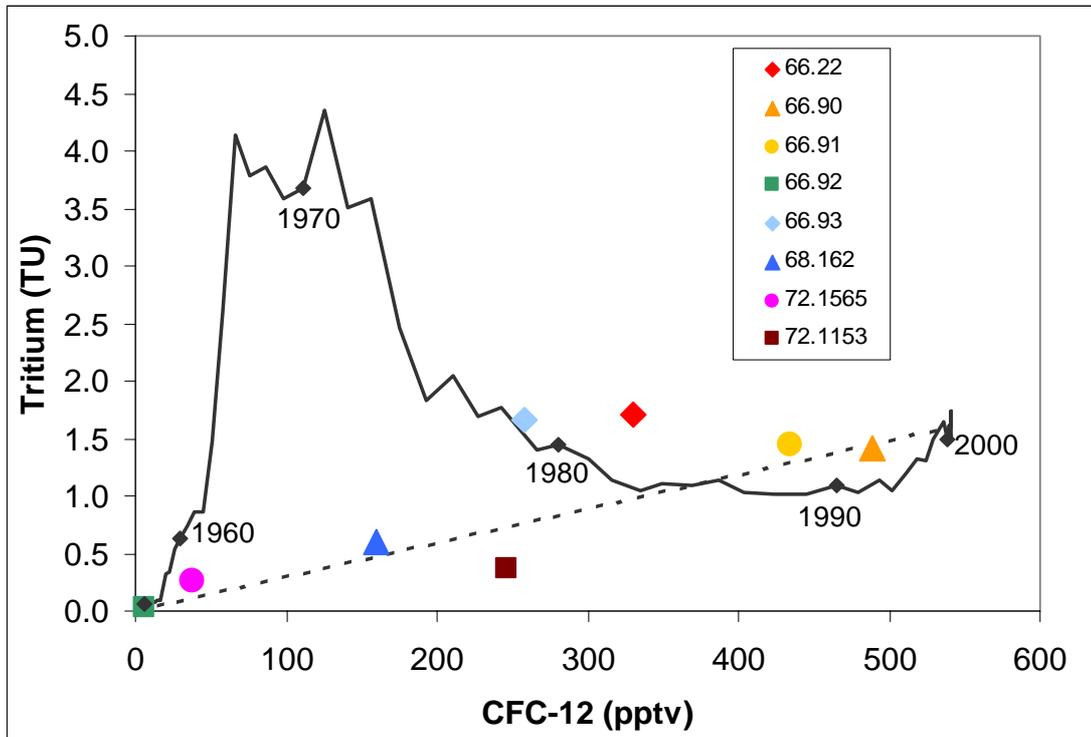
Figure 30: Plot of tritium versus CFC-12 concentrations in Reporoa Basin groundwaters.

However, two samples do not lie close to the solid curve (68.162 and 72.1153) on either Figure 29 or Figure 30. These lie on the dotted straight line which represents mixing of two water types (in this case, deep old water (with zero tritium and CFC-11) and very young water (with ambient tritium and CFC-11). (Because the dotted line crosses the solid curve, the mixtures could either involve old and very young water, or old and early 1980s water. In the present case, the former has been assumed.) The position of these points on the line (Figure 29) show that 68.162 has 75% old water and 25% young water, and 72.1153 has 70% old water and 30% young water.

Input of two types of water implies that the bores have two screens or there is leakage of young water down the outside of the bore, or some such exceptional circumstance, although such bores are probably not rare. The chemical composition of the water would be expected to reflect input of two water types, if their chemistries are different. And there is a possibility that bacteria could be present in apparently old groundwater if there is an input of very young water.

Appendix III: Catchment water use estimates

Table 15: Torepatutahi catchment Agribase water use

Torepatutahi catchment	Numbers	Water Use $m^3 d^{-1}$
Number of properties	169	125
Number of dairy farms	118	
Dairy shed washdown per animal	41028	2872
Beef numbers	6667	417
Dairy numbers	41028	4103
Deer numbers	632	24
Sheep numbers	12297	68
Consented groundwater takes	2	9500
Water use m^3 day		7608
Water use m^3 year		2777093
Total stock usage $m^3 d^{-1}$		4611
% of total daily usage		61

Table 16: Upper Torepatutahi catchment Agribase water use

Upper Torepatutahi catchment	Numbers	Water Use $m^3 d^{-1}$
Number of properties	78	58
Number of dairy farms	44	
Dairy shed washdown per animal	19863	1390
Beef numbers	4497	281
Dairy numbers	19863	1986
Deer numbers	527	20
Sheep numbers	12297	68
Consented groundwater takes	0	0
Water use m^3 day		3803
Water use m^3 year		1388247
Total stock usage $m^3 d^{-1}$		2355
% of total daily usage		62

Table 17: Kaiwhitiwhiti catchment Agribase water use

Kaiwhitiwhiti catchment	Numbers	Water Use $m^3 d^{-1}$
Number of properties	31	23
Number of dairy farms	9	
Dairy shed washdown per animal	6380	447
Beef numbers	270	17
Dairy numbers	6380	638
Deer numbers	0	0
Sheep numbers	2098	12
Consented groundwater takes	1	16
Water use m^3 day		1136
Water use m^3 year		414623
Total stock usage $m^3 d^{-1}$		666
% of total daily usage		59

Table 18: Upper Waiotapu catchment Agribase water use

Upper Waiotapu catchment	Numbers	Water Use $m^3 d^{-1}$
Number of properties	83	61
Number of dairy farms	59	
Dairy shed washdown per animal	18471	1293
Beef numbers	4833	302
Dairy numbers	18471	1847
Deer numbers	0	0
Sheep numbers	34125	188
Consented groundwater takes	0	0
Water use m^3 day		3691
Water use m^3 year		1347303
Total stock usage $m^3 d^{-1}$		2337
% of total daily usage		63

Table 19: Mangaharakeke catchment Agribase water use

Mangaharakeke catchment	Numbers	Water Use $m^3 d^{-1}$
Number of properties	19	14
Number of dairy farms	19	
Dairy shed washdown per animal	3550	249
Beef numbers	0	0
Dairy numbers	3550	355
Deer numbers	0	0
Sheep numbers	0	0
Consented groundwater takes	0	0
Water use m^3 day		618
Water use m^3 year		225409
Total stock usage $m^3 d^{-1}$		355
% of total daily usage		57

Table 20: Mangamingi catchment Agribase water use

Mangamingi catchment	Numbers	Water Use $m^3 d^{-1}$
Number of properties	20	15
Number of dairy farms	14	
Dairy shed washdown per animal	3586	251
Beef numbers	150	9
Dairy numbers	3586	359
Deer numbers	741	29
Sheep numbers	1806	10
Consented groundwater takes	0	0
Water use m^3 day		672
Water use m^3 year		245374
Total stock usage $m^3 d^{-1}$		406
% of total daily usage		60

Table 21: Mangakara catchment Agribase water use

Mangakara catchment	Numbers	Water Use $m^3 d^{-1}$
Number of properties	24	18
Number of dairy farms	15	
Dairy shed washdown per animal	4797	336
Beef numbers	1693	106
Dairy numbers	4797	480
Deer numbers	214	8
Sheep numbers	5500	30
Consented groundwater takes	0	0
Water use m^3 day		978
Water use m^3 year		356806
Total stock usage $m^3 d^{-1}$		624
% of total daily usage		64

Table 22: Kopuhurihuri catchment Agribase water use

Kopuhurihuri catchment	Numbers	Water Use $m^3 d^{-1}$
Number of properties	18	13
Number of dairy farms	18	
Dairy shed washdown per animal	4084	286
Beef numbers	50	3
Dairy numbers	4084	408
Deer numbers	0	0
Sheep numbers	0	0
Consented groundwater takes	0	0
Water use m^3 day		711
Water use m^3 year		259415
Total stock usage $m^3 d^{-1}$		412
% of total daily usage		58

Appendix IV: Site details

EW Located Database Number	Easting	Northing	RL (m)
72.1569	2805728	6296095	337.9
72.1565	2805330	6295819	318.54
66.96	2805343	6295823	318.81
72.2724	2805343	6295823	321.22
72.1570	2804868	6296474	
72.1566	2803665	6292659	308.71
72.1579	2807488	6294430	
72.1580	2806984	6294508	
72.1144	2807382	6294809	
72.1143	2806596	6294547	
72.1145	2807816	6294124	
72.613	2813168	6292770	
72.614	2813170	6292776	
68.432	2813162	6292773	553.25
72.1577	2812891	6293171	552.01
72.1154	2812907	6293124	551.31
72.1578	2812717	6292282	
66.22	2812791	6296065	545.37
72.1155	2812642	6295552	543.62
72.1882	2803000	6298000	306.7
72.1427	2803345	6295899	306.49
72.1140	2808295	6297845	481.2
72.1156	2811929	6295863	538.37
72.1572	2811950	6295864	538.76
72.1142	2812083	6296201	412.87
72.1576	2801176	6289710	307.6
68.229	2799836	6286050	333.75
72.2394	2800824	6285303	362.08
68.253	2798753	6286415	319.03
72.2395	2798979	6286870	317.56
68.767	2798976	6286869	317.56
68.766	2799500	6285300	
72.1568	2796690	6286048	297.85
72.1585	2796393	6285430	298.72
72.1586	2795827	6284185	303.39
72.1587	2795884	6282815	314.95
72.1582	2793935	6279676	327.39
72.1581	2793937	6279676	327.29
68.162	2795346	6278893	375.04
72.1583	2794160	6281987	313.71
72.1567	2795095	6282756	307.69
72.1571	2795098	6282745	307.28
72.1584	2795097	6282865	298.75
72.1512	2797445	6285314	
72.1594	2794539	6285179	307.64
66.54	2789419	6294941	
72.1574	2789561	6295050	
72.1605	2793408	6296188	
72.1611	2794710	6284691	
72.1575	2812083	6293088	
72.1589	2808892	6295594	
72.1150	2808713	6294292	
66.3	2800660	6291818	297.95

EW Located Database Number	Easting	Northing	RL (m)
66.18	2807390	6296540	
72.1153	2811871	6293569	555.17
72.1152	2809300	6294700	
66.90	2802700	6295000	297.07
66.91	2802700	6295000	296.38
66.23	2801600	6291600	
66.72	2801700	6291400	
66.36	2801500	6291700	
66.37	2801700	6291400	
66.9	2799900	6289600	
66.20	2799700	6288700	
66.5	2799700	6288700	
68.414	2797900	6285700	
68.150	2796800	6285800	
68.426	2796700	6285800	
68.634	2796700	6285800	
68.684	2796200	6285200	
68.665	2795900	6284800	
68.302	2796000	6284600	
68.686	2796300	6284600	
68.806	2796500	6284100	
68.266	2795100	6283200	
68.819	2794700	6282900	
68.363	2790800	6284400	
72.14	2793600	6284800	
72.20	2793600	6284800	
72.122	2793800	6284800	
68.724	2794500	6285200	
68.870	2794800	6285400	
67.577	2795800	6287500	
68.641	2797800	6290200	
68.35	2797400	6290500	293.79
68.97	2795800	6290600	
68.103	2797700	6292100	
68.2	2798500	6292200	
68.1	2798770	6293630	
66.2	2799248	6291267	
68.98	2795400	6292000	
68.96	2798100	6293900	
68.3	2797600	6293600	
68.569	2797500	6293800	
68.71	2797800	6295200	307.49
72.1516	2798240	6294724	297.42
72.1515	2798010	6294708	
68.626	2797400	6295600	295.66
68.853	2797400	6295600	
66.13	2799500	6292800	
66.1	2799229	6290407	
72.1481	2801311	6313685	491.03
66.43	2799217	6311769	
72.1477	2799613	6312541	
72.1478	2799611	6312551	
72.1479	2798938	6311724	
68.8	2798700	6312069	
66.4	2800250	6313325	496.38
72.1482	2801370	6304546	297.84

EW Located Database Number	Easting	Northing	RL (m)
72.1475	2799710	6312431	
72.1474	2799704	6312429	
72.1476	2799924	6312821	492.23
66.61	2806629	6306282	335.68
72.1483	2806248	6305990	
72.1484	2806251	6305993	
72.1485	2806257	6306046	
72.1486	2805348	6305444	
66.35	2801700	6304500	
66.51	2799600	6303500	
66.52	2799600	6303500	
NZMP	2799200	6303500	
NZMP	2799200	6303500	
NZMP	2799200	6303500	
NZMP	2799200	6303500	
NZMP	2799200	6303500	
NZMP	2799200	6303500	
NZMP	2799200	6303500	
NZMP	2799200	6303500	
66.92	2801700	6301800	
66.93	2801700	6301800	
72.796	2796700	6300400	
66.39	2796500	6299500	
72.169	2732400	6344000	
72.170	2792900	6295600	
66.11	2799300	6295400	
66.58	2804800	6299600	322.61
66.40	2804800	6298500	
72.1149	2806811	6299496	
72.1139	2807047	6298224	
72.1148	2808270	6298321	
72.1140	2808220	6297931	
72.1141	2807900	6297400	
72.1505	2809053	6298470	
72.1504	2811022	6298182	
72.1147	2811022	6298182	
72.151	2811440	6298166	
72.1511	2811441	6298070	
72.1512	2811683	6297753	
72.1513	2811676	6297763	
66.32	2810911	6298395	
72.1514	2812910	6298230	
72.1138	2814360	6298381	
72.1508	2814379	6298486	
72.1509	2814372	6298586	
72.1507	2814463	6298039	545.76
66.60	2814460	6298021	546
66.16	2791400	6294300	
72.1487	2799049	6301715	
72.1489	2799052	6302106	336.77
72.1488	2798502	6302031	349.6
72.1491	2799428	6301852	315.09
72.1492	2799341	6301834	
72.1492	2797947	6302279	350.24
72.1493	2797981	6302799	
72.1494	2797302	6302927	357.46

EW Located Database Number	Easting	Northing	RL (m)
72.1495	2797397	6302589	357.53
72.1497	2796635	6300812	360.36
72.1496	2796635	6300814	360.39
72.1499	2796676	6300319	360.23
72.1500	2796678	6300320	360.57
72.1498	2797578	6300937	322.3
72.1501	2797189	6298746	
72.1502	2797208	6298766	
72.1503	2797210	6298768	331.09
72.1519	2798638	6293313	
72.1517	2798088	6293376	
72.1506	2798097	6293383	
72.1518	2798118	6293273	
72.1521	2798415	6292621	
72.1520	2797975	6292775	
66.83	2797750	6303667	336.602
66.84	2798007	6304201	337.475
66.85	2798395	6303718	320.635
66.86	2798788	6303818	327.289
66.87	2798800	6303042	312.51
66.88	2799240	6302892	308.263
BH8	2800073	6302744	303.176
72.1524	2797239	6304269	352.755
72.1525	2797736	6303638	334.706
72.1526	2797927	6304312	339.355
72.1527	2797978	6304173	337.47
72.1528	2798006	6304204	337.548
72.1529	2798097	6304399	338.426
72.1530	2798095	6304122	335.716
72.1531	2798114	6304154	336.22
72.1532	2798203	6304341	337.107
72.1533	2800079	6302748	303.128
72.1534	2798093	6304117	335.415
72.1535	2798099	6304398	338.519
72.1536	2797926	6304310	339.259
72.1590	2806300	6307400	
72.1612	2796400	6296700	
72.1591	2806900	6296800	
72.1592	2808100	6295400	
72.1593	2808100	6295400	
72.1595	2811900	6292300	
72.1596	2795200	6296000	
72.1597	2810300	6295500	
72.1598	2796300	6296700	
72.1599	2797000	6296800	
72.1600	2795700	6299100	
72.1601	2796000	6299100	
72.1602	2793800	6279100	
72.1603	2794400	6278600	
72.1604	2795900	6283700	
72.1606	2794600	6280900	
72.1607	2793900	6282300	
72.1608	2796600	6284200	
72.1609	2796900	6296500	
72.1610	2796400	6285000	

Appendix V: Water quality results

Located Number	Alkalinity g.m⁻³ as CaCO₃	As g.m⁻³	B g.m⁻³	Ca g.m⁻³	Cl g.m⁻³	Cond uS/cm	Cu g.m⁻³	Fe g.m⁻³	CO2 g.m⁻³	Hardness g.m⁻³ as CaCO₃	K g.m⁻³	Mg g.m⁻³	Mn g.m⁻³	Na g.m⁻³	NH₄ g.m⁻³	NO₃-N g.m⁻³	pH pH Units	SO₄ g.m⁻³	TDS g.m⁻³	Zn g.m⁻³
66.18	24	0.001	0.005	2.63	2.5	6.2	0.005	0.01	6	11	2.1	1.13	0.005	7.6	0.01	0.3	6.9	1.1	42	0.013
66.22	22	0.001	0.005	11.7	11.9	18.3	0.005	0.01	12	41	6.8	2.85	0.005	13.7	0.01	9.87	6.6	4.9	122	0.005
66.4	23	0.001	0.008	3.35	4.4	8.7	0.005	0.01	20	15	5.1	1.5	0.005	8	0.01	1.19	6.4	5	58	0.005
66.58	23	-	0.009	2.55	3.8	6	0.005	3.76	28	10	2.7	0.788	0.096	5.5	-	0.05	6.2	1.2	40	0.005
66.60	28	0.001	0.007	2.74	2.8	6.9	0.005	0.01	6	11	3.1	1.07	0.005	8.1	0.01	0.16	6.9	0.7	46	0.005
66.61	26	0.002	0.007	2.87	2.7	6.7	0.005	0.01	4	14	1.6	1.61	0.005	7.6	0.01	0.12	7.1	1.4	45	0.005
66.90	30	0.001	0.038	32.9	27.6	42	0.005	0.02	39	131	11.2	11.9	0.005	21	0.01	14.8	6.2	63.7	281	0.017
66.91	32	0.001	0.036	29.7	24.2	34.4	0.005	0.01	45	97	9.8	5.63	0.005	21.8	0.01	10.1	6.2	46.6	230	0.005
66.96	21	-	0.007	1.86	2.6	5	0.005	0.01	7	9	1.3	1.13	0.005	6.5	-	0.05	6.8	1.1	33	0.005
68.162	28	0.001	0.006	3.52	3.4	7.9	0.005	0.01	8	18	2.2	2.2	0.005	8.1	0.01	0.53	6.9	1.9	53	0.005
68.766	34	0.001	0.006	4.06	2.9	8.7	0.005	0.01	10	19	3.2	2.19	0.005	8.7	0.01	0.64	6.8	1.4	59	0.01
72.1142	25	0.001	0.006	2.69	2.6	6.5	0.005	0.01	7	11	2.6	1.12	0.005	7.4	0.01	0.38	6.9	1.1	43	0.005
72.1143	26	0.001	0.011	6.45	6.3	12.4	0.005	0.01	14	31	3.5	3.72	0.005	9.7	0.01	3.32	6.6	8.4	83	0.005
72.1144	23	0.001	0.007	3.89	4.2	8.9	0.005	0.01	8	18	2.8	2.01	0.005	8.5	0.01	2.09	6.7	3.5	59	0.005
72.1145	29	0.001	0.007	4.37	3.5	9.1	0.005	0.03	11	20	3.1	2.1	0.005	8.9	0.01	1.54	6.7	3.3	61	0.007
72.1153	19	0.001	0.009	1.98	2.7	6.1	0.005	0.01	7	8	2.9	0.765	0.005	7.3	0.01	1.09	6.8	1	41	0.266
72.1154	23	0.001	0.006	9.09	10.5	15.7	0.005	0.01	12	33	6	2.56	0.005	13.1	0.01	6.87	6.6	6.2	105	0.031
72.1476	22	0.01	0.007	1.69	3.4	6.5	0.005	0.13	19	8	2.9	0.946	0.022	8.3	0.01	0.21	6.4	2.5	44	0.223
72.1481	38	0.012	0.008	3.03	2.7	9.2	0.005	2.36	14	16	0.8	2.13	0.123	12.1	0.03	0.05	6.7	3.8	62	0.005
72.1482	235	0.014	4.65	16.5	276	138	0.019	33.2	275	60	27.3	4.44	1.04	240	1.6	0.05	6.2	32.2	923	15.2
72.1487	22	0.022	0.008	4.9	5.6	10.9	0.005	0.01	11	22	3.1	2.43	0.005	10.6	0.01	2.07	6.6	11.2	73	0.005
72.1491	38	0.058	0.009	3.43	2.9	8.6	0.005	18	6	15	1.9	1.46	0.587	10.3	0.73	0.05	7.1	0.5	57	4.85
72.1494	21	0.004	0.005	2.3	4.2	8	0.005	0.03	5	7	1.4	0.267	0.005	12.4	0.01	1.68	6.9	4.1	53	0.005
72.1495	20	0.001	0.005	5.93	8.4	13.2	0.005	0.01	13	26	3.5	2.6	0.005	12.4	0.01	6.18	6.5	4.6	88	0.005
72.1498	21	0.003	0.005	6.61	9.3	15.7	0.005	0.02	15	30	5.4	3.16	0.132	14.4	0.01	5.73	6.4	14.9	105	0.008
72.1501	19	0.021	0.006	1.3	8.1	12.3	0.005	0.04	9	5	2.4	0.405	0.005	20.2	0.01	4.29	6.6	7.9	82	0.005
72.1565	23	0.001	0.005	2.9	3.1	6.6	0.005	0.01	3	12	2.4	1.25	0.005	6.8	0.01	0.45	7.2	1.7	44	0.006
72.1566	37	0.005	0.02	20.6	32.3	34.3	0.005	0.03	34	99	8.9	11.4	0.007	20.7	0.02	8.9	6.3	39.5	230	0.006
72.1567	40	0.001	0.037	5.1	7	12.5	0.005	2.45	13	24	2.6	2.63	0.116	13.4	0.15	0.05	6.8	8.3	84	0.354
72.1568	311	0.219	0.069	27.5	3.8	59.7	0.005	4.42	27	110	2.1	10.1	1.36	89	0.78	0.05	7.4	0.5	400	0.005
72.1572	18	0.001	0.009	1.6	2.4	4.9	0.005	0.01	5	7	2.4	0.661	0.005	6.1	0.01	0.21	6.8	0.9	33	0.005
72.1586	31	0.002	0.022	5.19	4.3	10.6	0.005	0.02	6	22	3	2.08	0.005	11	0.01	0.89	7	8.4	71	0.005