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# Regional conceptual and numerical modelling of the Wairarapa groundwater basin

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# Contents

**1. Introduction 1**

**2. Previous work 1**

**3. Geological overview 2**
3.1 Regional geological setting 2
3.2 Basin-fill Deposits 4
3.3 Formations bounding and underlying the Wairarapa Basin 8
3.4 Groundwater basin structure 8
3.4.1 Major faults 8
3.4.2 Long-valley structures 9
3.5 Uplift across the Lower Wairarapa Valley 10
3.6 Lake Wairarapa 11

**4. Conceptual groundwater model for the Wairarapa Valley 12**
4.1 Overview 12
4.2 Regional basin geometry and groundwater flow controls 13
4.2.1 Masterton Fault (Section lines A and B) 16
4.2.2 Te Ore Ore Basin (Section line A) 16
4.2.3 Carterton Fault (Section line B) 17
4.2.4 Tiffen Hill – Parkvale Basin (Section line C) 17
4.2.5 Te Maire Ridge (Section line D) 17
4.2.6 Lower Valley Basin (Section lines E, F, G) 17
4.2.7 Lake Onoke/Narrows ‘Rise’ (Section line G) 18
4.3 Summary of 3-D regional groundwater basin conceptual model 26

**5. Hydrogeology 29**
5.1 Hydrostratigraphic units 29
5.1.1 Unit 1: Alluvial fans/outwash gravels 29
5.1.2 Unit 2: Q1 Holocene gravels 30
5.1.3 Unit 3: Reworked gravels 30
5.1.4 Unit 4: Lower Valley Transition Zone – intercalation of distal fan sediments with estuarine/ lacustrine deposits 31
5.1.5 Unit 5: Uplifted low-permeability ‘blocks’ 31
5.1.6 Unit 6: Low permeability lacustrine and estuarine deposits 31
5.2 Regional groundwater flow patterns 32
5.3 Identification of sub-regional flow systems 34
5.4 Hydraulic properties 36
5.5 Recharge 39
5.5.1 Approaches to recharge assessment 40
5.5.2 Direct recharge: soil moisture balance modelling 40
5.5.3 Indirect recharge 43
5.5.4 Groundwater chemistry 44
5.6 Sub-basin hydrogeology 44
5.6.1 Te Ore Ore sub-basin (Masterton sub-regional flow system) 45
5.6.2 Parkvale sub-basin (Carterton sub-regional flow system) 45
5.6.3 Lower valley sub-basin (Lower valley sub-regional flow system) 46

**6. Groundwater-surface water interconnection 47**
6.1 Introduction 47
6.2 River – aquifer transfer flows 47
6.2.1 Tauherenikau 48
6.2.2 Waingawa 48
6.2.3 Waipoua 48
6.2.4 Ruamahanga 49
6.3 Spring flows 49
6.4 Lake Wairarapa 51
6.5 Conceptual water balance 52

**7. Groundwater Flow Model for the Wairarapa Groundwater Basin 54**
7.1 Approach 54
7.2 Model code 54
7.3 Finite difference grid design 55
7.4 Boundaries 56
7.4.1 Specified flow boundaries 56
7.4.2 Specified head boundaries 56
7.4.3 Head-dependent flow boundaries 56
7.5 Steady state model calibration 58
7.5.1 Calibration targets 58
7.5.2 Input parameter zones 59
7.6 Steady state model calibration results 60
7.6.1 Parameter estimation 61
7.7 Modeled heads 62
7.7.1 Regional and sub regional steady state water balances 63
7.8 Simulation of groundwater abstraction 65

**8. Summary and conclusions 68**

**9. Recommendations 71**
9.1 Further work objectives 71
9.2 Proposed physical investigations 71
9.2.1 Fieldwork Theme 1: Understanding groundwater – surface water interconnection 71
9.2.2 Fieldwork Theme 2: Hydrogeological investigations 73
9.2.3 Theme 3: Monitoring review 75
9.3 Stage two technical analysis 75
9.3.1 Transient flow modeling 75
9.3.2 Abstraction scenario analysis 76
9.3.3 Recharge investigations 76
9.3.4 Coupled surface water-groundwater model 76
9.3.5 Satellite imagery analysis 77
9.3.6 Development of groundwater resource management objectives 77

**10. References 78**

**Appendix 1 – Begg et al (2005). 81**

**Appendix 2 – 1985 piezometric survey wells 83**

**Appendix 3 – Concurrent gauging results** **89**

**Appendix 4 – Wairarapa River bed profiles** **93**

**Appendix 5 – pumping wells simulated in the model** **99**

**Appendix 6 – Morgenstern (2005).** **105**

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Andrew and Mark

# 1. Introduction

Groundwater is an important water source in the Wairarapa for public water supply, domestic use, stock water and irrigation. Furthermore, there are a number of groundwater dependent ecosystems in springs and wetlands throughout the valley. The demand for groundwater has increased markedly in the last ten years (Jones and Baker, 2005) and a third of Wairarapa groundwater zones, as defined in the Regional Freshwater Plan (Wellington Regional Council, 1999), are at allocation levels greater than 60% of their allocation limits. In three of these zones: Parkvale, Kahutara and Martinborough Terraces, Greater Wellington is advocating no additional allocation of groundwater because groundwater pumping may be causing a long-term decline in groundwater levels.

This increase in demand, and groundwater level decline, has brought into question the validity of the allocation limits specified in the Freshwater Plan. Consequently, a comprehensive review of the Wairarapa groundwater system was necessary to provide a sound scientific platform for the review of groundwater allocation limits and appropriate management objectives.

This report describes a regional-scale revision of the geology and conceptual hydrogeology of the Wairarapa groundwater system. This revision has provided a context for local-scale information and identified information gaps. Furthermore, this report describes preliminary steady-state modelling that has been undertaken to test the conceptualisation and to provide an indication of the regional water balance.

The conceptual and numerical modelling exercise has resulted in a number of recommendations for further work that we consider is necessary to ensure sustainable use and management of the Wairarapa groundwater resource.

# 2. Previous work

A report to the Wairarapa Catchment Board in 1980 (Scientific Advisory Group, 1980), concluded that comprehensive investigations were required to adequately determine the extent and availability of the Wairarapa groundwater resource. This report prompted an eight-year investigation programme that included: drilling, geophysical surveys, chemical and isotopic analysis of groundwater samples, water level monitoring and a large number of aquifer tests. A summary of these investigations was produced in 1989 (Wairarapa Catchment Board, 1989) but a comprehensive analysis and interpretation was never published.

Since the study in the 1980s, a number of groundwater investigations have been undertaken and reported. The majority of these reports are at a local-scale, but one report defines safe yield estimates for all identified aquifers in the Wairarapa Valley (Butcher, 1996). It is this report that formed the basis for the allocation limits specified in the Regional Freshwater Plan. This report has since been supplemented by further assessments of the Te Ore Ore Plains, Martinborough Terraces, Huangarua, Battersea, Rathkeale and Parkvale zones (Butcher, 1997, 2000, 2001a, 2001b, 2001c, 2004). These assessments have refined the original safe yield estimates in these areas, however, there remain a large number of zones whose allocation limits are being approached without additional investigation work having been done to ensure those limits are realistic.

# 3. Geological overview

A review of the geology of the Wairarapa has been undertaken by the Institute of Geological and Nuclear Sciences to assist development of a conceptual hydrogeological model for the Wairarapa Region.

The review focuses on the hydrostratigraphy of the Wairarapa groundwater basin, as well as the principal geological structures (such as active faults and folding), and depositional processes that influence the hydrogeology of the basin. The work highlights the complexity of the geological and groundwater environment due to the combined effects of major active faulting, folding and subsidence, as well as sea level changes in response to glacial cycles.

The geological review is presented in a separate report entitled '*A review of Wairarapa geology- with a groundwater bias*' (Begg et. al., 2005). That report is included here as Appendix 1 and is summarised below.

## 3.1 Regional geological setting

The Wairarapa Valley groundwater basin occupies a structural depression orientated NE-SW, some 110km long with a maximum width of 15km (Fig.1). The basin is enclosed by the basement rock greywacke (Torlesse) formations of the fringing Tararua Ranges to the north and west, and the Aorangi Mountains and hills formed by Early Pleistocene/Late Tertiary marine strata to the east. The NW margin is controlled by the regionally important Wairarapa Fault. Numerous other major faults and folds cross-cut, and are parallel to, the basin axis creating a complex hydrogeological environment.

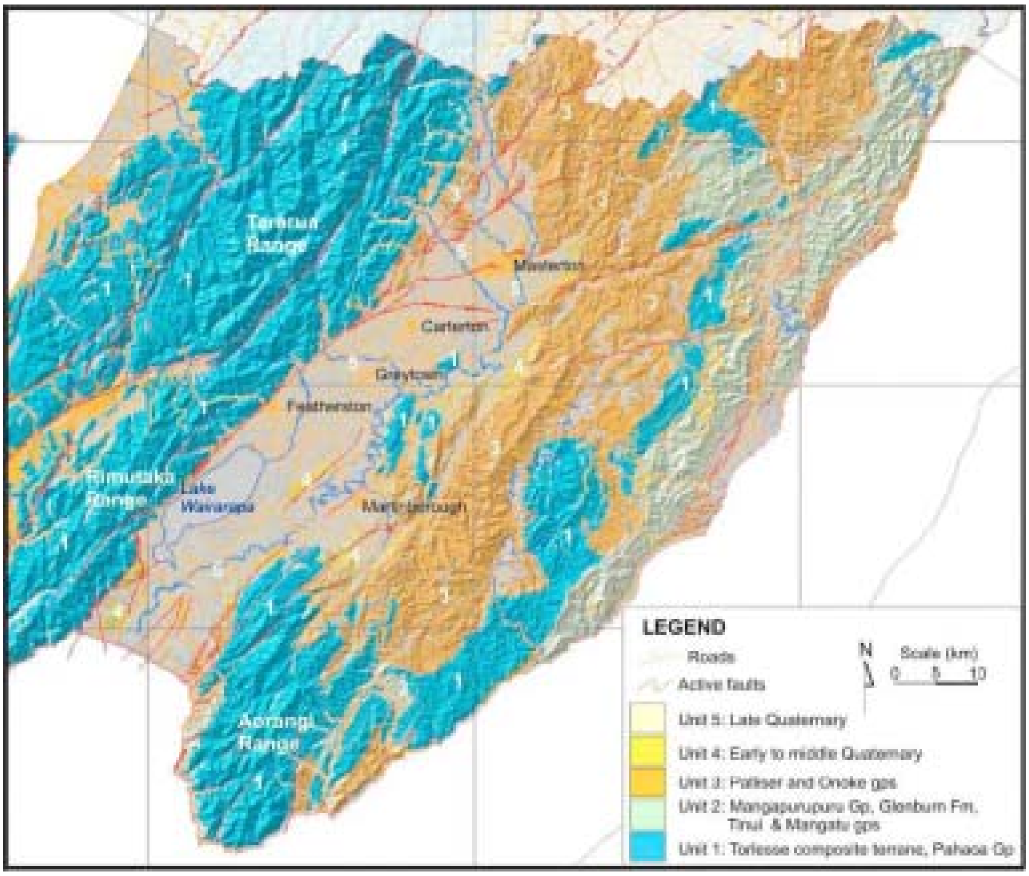


**Figure 1: Wairarapa Basin and regional geology, from Begg et al (2005).**

The structural depression and associated internal deformation are a reflection of active plate margin tectonism in the region. The Wairarapa coast is located about 65-125 km northwest of the Hikurangi Trough, the boundary between the Australian Plate to the west and the Pacific Plate to the east. The strain associated with the plate boundary is expressed by broad geomorphic zones: the axial (Tararua) ranges, the Wairarapa Valley and the Wairarapa hill country (Fig. 2). Some of the strain is transferred up through the over-riding Australian Plate to the ground surface in the form of active faults and folds. This deformation, both the broad regional strain and deformation associated with faults and folds, strongly influences the hydrogeological environment.

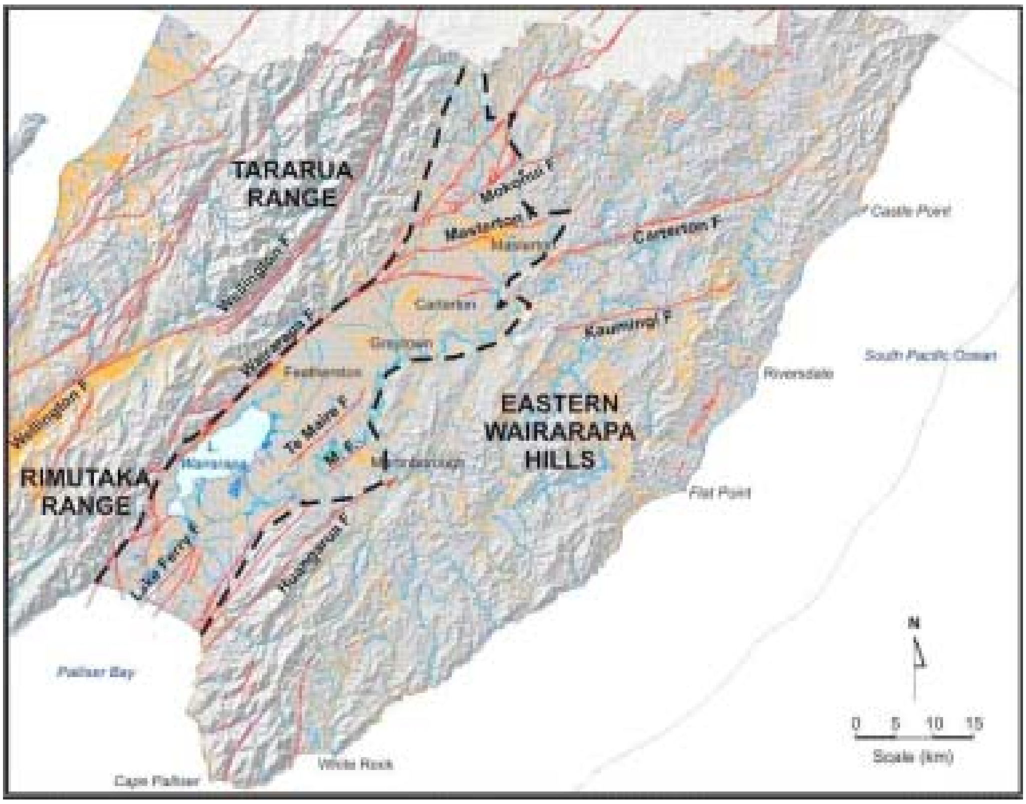


**Figure 2: Wairarapa Basin geomorphic zones, from Begg et al (2005).**

## 3.2 Basin-fill Deposits

The basin is filled with Quaternary fluvial gravels, and possibly older deposits at depth. The younger, Late Quaternary deposits (of oxygen isotope Q1 to Q6 age) comprise greywacke-sourced gravel and sand derived from erosion of the Tararua Range and deposited by southeast flowing rivers. These deposits host the ‘dynamic’ groundwater system of interest to this study. The depositional environments of the Late Quaternary sequence have been strongly influenced by subsidence, uplift and sea level changes. The deposits are also frequently disrupted by uplifted blocks of greywacke basement and older Quaternary and Tertiary sediments associated with faulting and folding.

Table 1 shows the young Q1 - Q6 stratigraphic sequence of hydrogeological significance above the mQa (middle Quaternary) surface. This sequence occupies the upper 100m or so of the Wairarapa Valley.

### Table 1: Wairarapa Valley – Stratigraphic Sequence

(yellow shading indicates units that are considered to contain the dynamic Wairarapa Valley groundwater system)

| Relative age | Material | Name | Depositional environment | Map Symbol[1] | Absolute age (ka) |
|---|---|---|---|---|---|
| Holocene | Mud & silt | | Estuarine, lacustrine | Q1m<br>Q1s | 0-7 |
| Holocene | Gravel & sand | | Alluvial | Q1a | 0-10 |
| Late Quaternary<br>Late Otiran | Gravel & sand | Waiohine. Equivalent to **Waiwhetu Gravel** in L.Hutt Basin | Alluvial | Q2a | 10-25 |
| Late Quaternary<br>Middle Otiran | Gravel & sand | Ramsley | Alluvial | Q3a | 50-25 |
| Late Quaternary<br>Early Otiran | Gravel & sand | Waipoua | Alluvial | Q4a | 70-50 |
| Late Quaternary<br>Kaihinu Interglacial | Mud, silt, sand & minor gravel | Francis Line | Swamp, lacustrine | Q5m | 125-70 |
| Late Quaternary<br>Kaihinu Interglacial | Sand, some gravel | Eparaima | Marginal marine | Q5b | 125-70 |
| Middle Quaternary<br>Waimea Glacial | Gravel & sand | Equivalent to **Moera Gravel** in L.Hutt Basin | Alluvial | Q6a | 186-125 |
| Middle Quaternary | Gravel, sand, silt, loess, tephra | Ahiaruhe | Alluvial, swamp | mQa | >500-186 |
| Early Quaternary | Gravel, sand, silt, loess, tephra | Te Muna | Alluvial, swamp | eQa | c. 1000-500 |

1. GNS QMap (1:250 000) of Wellington and Wairarapa areas (Begg and Johnston, 2000; Lee and Begg 2002).

The Late Quaternary deposits are dominated by aggradational alluvial and glacial outwash gravels laid down by major rivers draining the Tararua Range. The gravels represent high energy, poorly sorted alluvial fan environments interdigitated with fine-grained over-bank, swamp or lacustrine deposits. Alluvial gravels are commonly clast-supported, and rich in sand and silt, with sandier and siltier horizons being common. As such, they generally represent poor aquifers except where they are reworked. Broad areas of re-worked, high yielding gravels are recognisable in the vicinity of former and modern drainage courses and in distal fan areas.

On the eastern margin of the Wairarapa Valley, deposits of Late Quaternary age may be substantially more matrix-rich than in the central and western valley because many of the clasts within gravel deposits are derived from the fine-grained marine sediments of the eastern hill country and break down rapidly upon weathering.

The units shown in Table 1 have been mapped on the valley floor (Figs. 3 and 4). The figures also show areas where sub-basins have formed and been infilled: Te Ore Ore, Parkvale and the Lower Valley. The ages of terrace surfaces have been estimated by examining the coverbed sequences (loess, paleosol and tephra horizons). Degradational gravel surfaces of low elevation that are not overlain by loess units are considered to be Holocene in age (Q1a). Aggradational gravels at a level higher than these, with cobbles sitting at the surface and a straw-coloured loess are late last glacial (14,000-18,000 yrs) in age (Q2a). Higher gravels with a coverbed sequence of a single loess unit (Ohakea loess), and tephra (Kawakawa Tephra) are Ratan (Q3a) in age. Gravels at higher elevation again that are overlain by a red loess (Rata loess) as well as the Ohakea loess are Porewan in age (Q4a). Weathered gravels at higher elevations again have a cover of three loesses. Loess and coverbed stratigraphy is not well developed or is poorly preserved in the Ruamahanga River valley north of Masterton, possibly due to wind stripping.

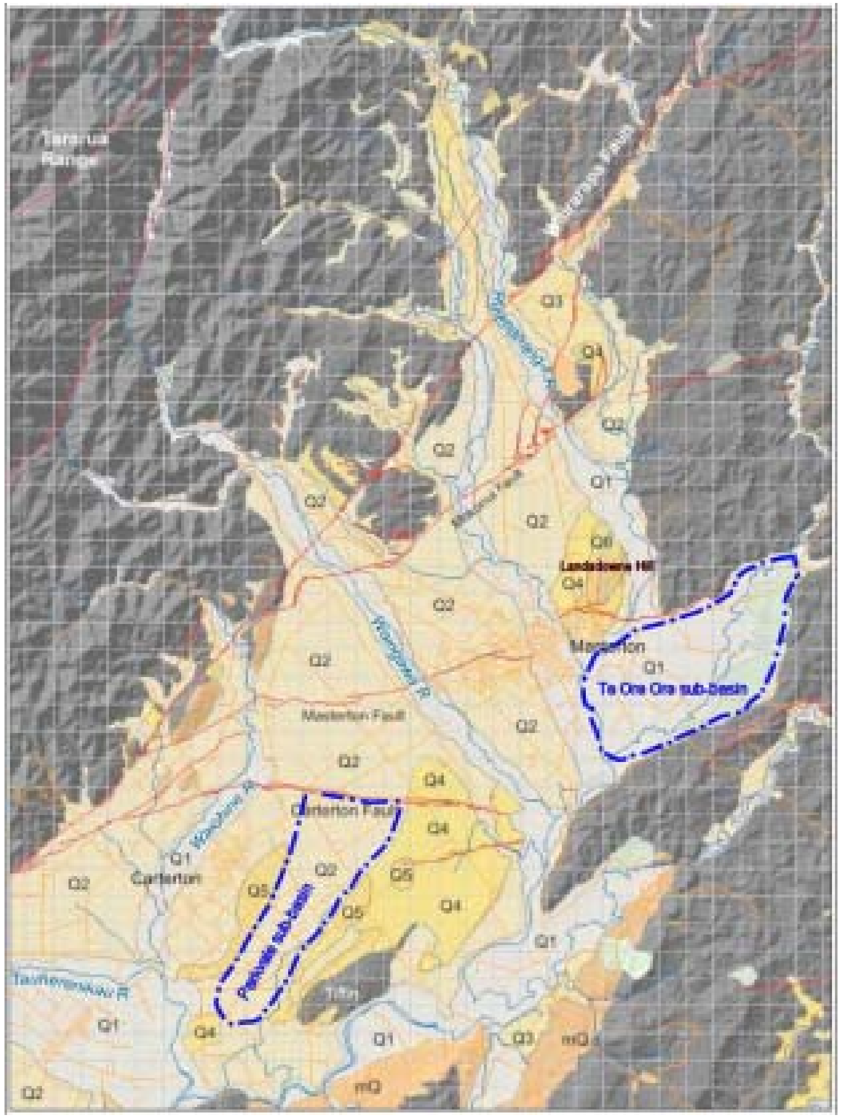


Figure 3: Upper Wairarapa Valley Quaternary sediments, from Begg et al (2005).

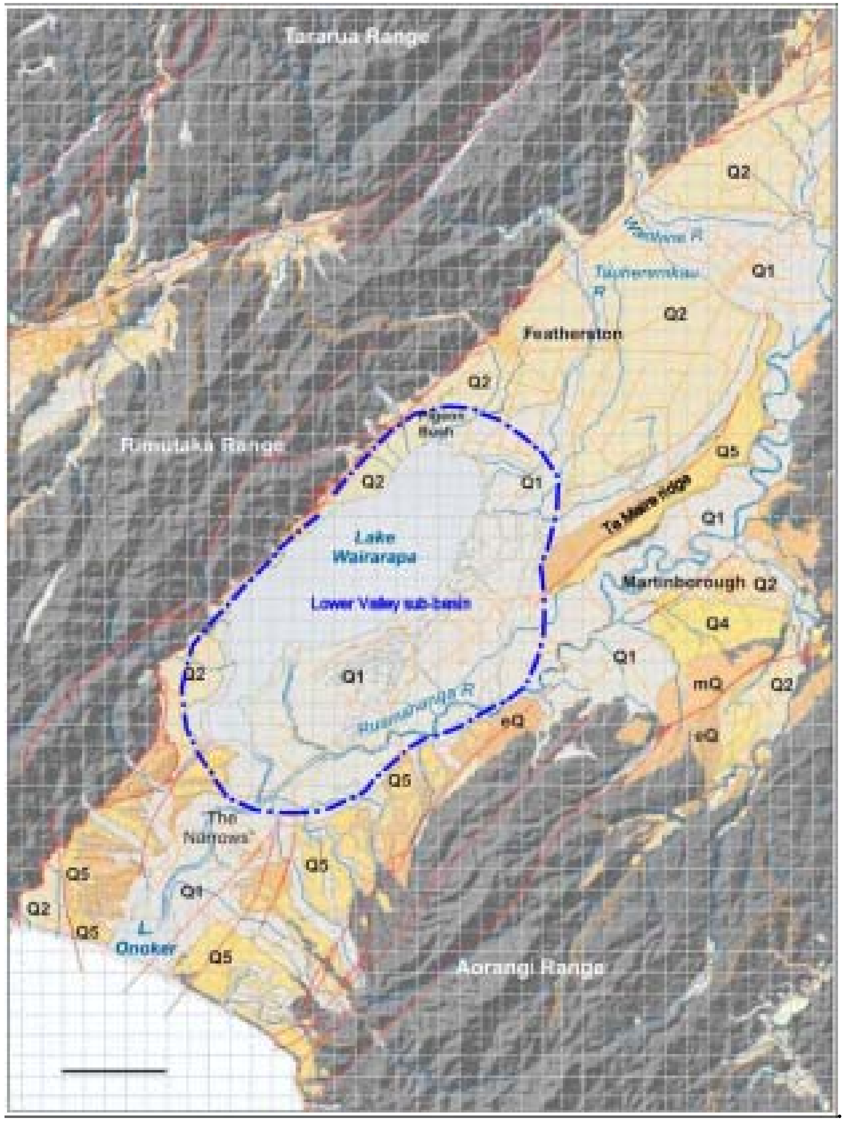


Figure 4: Lower Wairarapa Valley Quaternary sediments, from Begg et al (2005).

## 3.3 Formations bounding and underlying the Wairarapa Basin

Hard greywacke rock comprising sandstone and interbedded mudstone of the Tararua, Rimutaka and Aorangi Ranges bound the Wairarapa basin and are faulted against the western margin of the basin by the Wairarapa Fault. These rocks belong to the Torlesse and Pahaoa Groups (230-120Ma) and represent ‘basement’. They are indurated and have no primary porosity or permeability, but locally exhibit a secondary permeability along joint and fracture zones. On a regional scale, the greywacke is regarded to be impermeable.

The eastern hills comprise the Palliser and Onoke groups (25-2.3Ma), which consist of marine sandstones, siltstones, mudstones and limestone. These deposits probably also underlie younger deposits within the Wairarapa basin. Regionally, these deposits are not an important groundwater resource and tend to exhibit a low hydraulic conductivity, although locally, aquifers may be developed and yield low quantities of water.

Early to Middle Quaternary (2.3Ma-125ka) alluvial sands, gravels and swamp deposits extend to the start of oxygen isotope stage 5 (Table 1). These sediments underlie the groundwater basin and have poor groundwater potential due to their silt and clay rich matrix; swamp, silt and loess interbeds; and structure. These sediments also outcrop along the eastern margin of the valley with some isolated outcrops on the western side. Waimea Glacial gravels (Q6a) probably form a viable aquifer and are included as part of the dynamic groundwater system (Table 1).

## 3.4 Groundwater basin structure

Major complex tectonic structures have influenced the Late Quaternary depositional environments and therefore control the distribution of aquifer deposits in the Wairarapa Valley. An appreciation of the structural evolution of the basin and associated influence on the sedimentological environment is therefore necessary to develop a sound conceptual groundwater model for the Wairarapa Valley.

The structure of the Wairarapa Valley is intimately associated with the subduction interface between the Pacific and Australian plates. Strain associated with the relative motion of the two plates is released periodically as large earthquakes. Also, broad (long wavelength) patterns of deformation at the earth’s surface are the result of plate convergence over a long time, notably: uplift of the Wairarapa coastal ranges, development of the Wairarapa-Pahiatua basins and uplift of the Tararua and Rimutaka ranges. Active uplift is demonstrated by the presence of uplifted marine benches along the Wairarapa coastline.

### 3.4.1 Major faults

The **Wairarapa Fault** (Fig. 2) is believed to penetrate the full thickness of the Australian Plate and is one of a series of long sub-parallel active faults in the southern North Island that carry most of the shear associated with the plate boundary. The western side of the Wairarapa Valley groundwater basin is delimited by the Wairarapa Fault, with up-thrown greywacke basement rocks lying to the northwest of the fault.

Three major cross-valley active faults branch eastwards from the Wairarapa Fault in the upper valley area and compartmentalise the regional groundwater system (Figs. 2 and 3). These are the Mokonui, Masterton and Carterton faults. Each cuts across the rivers (and their terrace gravels) flowing into the northern end of the valley. The faults form flow barriers, principally as a result of tilting and deformation, as shown by the common emergence of springs along the fault traces.

The **Mokonui Fault** is the northernmost of the cross-valley faults, branching from the Wairarapa Fault at Tea Creek (Fig. 3). The surface trace splays and curves around an elevated Miocene-Pliocene block near Twin Bridges. Back-tilting on Quaternary terrace gravels indicate that the block between the Wairarapa and Mokonui faults, at least at the northeast end, is tilting to the northwest. This tilting has lifted Miocene-Pliocene mudstone to the surface on the up-thrown northwest side of the fault, thereby restricting groundwater movement in the terraces to the northwest.

A similar structural arrangement occurs at the north-eastern end of the **Masterton Fault**. This fault splays from the Wairarapa Fault near the southern end of Carterton Bush, can be traced across the Waiohine surface, across the Waingawa River and through Masterton. It raises Miocene-Pliocene mudstone to the surface at Lansdowne and in the Ruamahanga River, and may curve northwards up the Ruamahanga River. Terrace gravels on the north-western side of the fault at Lansdowne are back-tilted to the northwest. The Ruamahanga and Waingawa rivers and their terraces are likely to be affected by the fault, and restriction of the groundwater movement probably occurs north of Masterton as indicated by spring emergence along the fault.

The **Carterton Fault** is the southernmost of the three cross-valley faults, splaying from the Wairarapa Fault near Papaitonga Stream, and cutting across the Waiohine surface behind Carterton. Gravel units to the northeast of this fault are not as clearly back-tilted as observed along the two faults further to the north, and its influence on groundwater movement is therefore less apparent.

### 3.4.2 Long-valley structures

A number of long-valley faults are known to exist in the Wairarapa Valley, particularly on the eastern side (Fig. 2). Profiles along the last interglacial marine bench across the southern end of the valley suggest the presence of a fault with significant vertical displacement (down to the west) through the gap at Lake Onoke.

The Turanganui Fault and some others on the eastern side of Lake Onoke appear to displace the last interglacial marine bench, although there are no large scarps. The Martinborough Fault displaces (down to the SE) Waiohine gravel at Martinborough. Last interglacial deposits are displaced (down to the SE) on Te Maire Ridge by the Te Maire Fault. The presence of greywacke bedrock near the Ruamahanga River on the eastern flank of Te Maire Ridge and at Glenmorven suggests there is unlikely to be a substantial deep groundwater resource in that part of the valley.

The Huangarua Fault lies to the east of Martinborough and is associated with a broad anticlinal fold that forms the Harris Ridge. The fault has significant vertical displacement (down to the east), and effectively separates the Huangarua Valley groundwater system from the Lower Wairarapa Valley because mudstone is uplifted on the west side of the fault above the elevation of the floor of the Huangarua River.

The presence of greywacke, last interglacial deposits (Francis Line Formation), and early (Waipoua Gravel) and middle last glacial gravel (Ramsley gravel) near Tiffen (Fig. 3) suggest the presence of a fault or anticline. To the northwest of this feature, there is a channel of Waiohine gravel that has been interpreted as having a synclinal structure, the Taratahi Syncline. This syncline is bounded on the northwest, close to Carterton, by surficial deposits of the last interglacial Francis Line Formation. Francis Line Formation consists of mud, of swamp or lacustrine origin, and may act as an aquitard, limiting groundwater exchange between overlying units and those below.

## 3.5 Uplift across the Lower Wairarapa Valley

Whilst the Rimutaka and Tararua ranges are sliding northwards with respect to the Wairarapa Valley, the south-eastern part of the Rimutaka Range is also thrusting south-eastwards across the mouth of the Wairarapa Valley. Evidence for this active deformation is exhibited by marine benches at the mouth of the valley, which rise up to 130 m above sea level. These benches were cut during the last interglacial period when the sea was within a few metres of its current level (Fig. 5). On the western side of the valley, the marine benches dip to the southeast. On the eastern side of the valley, east of Lake Ferry, they dip to the northwest but rather more gently than on the other side of the valley.

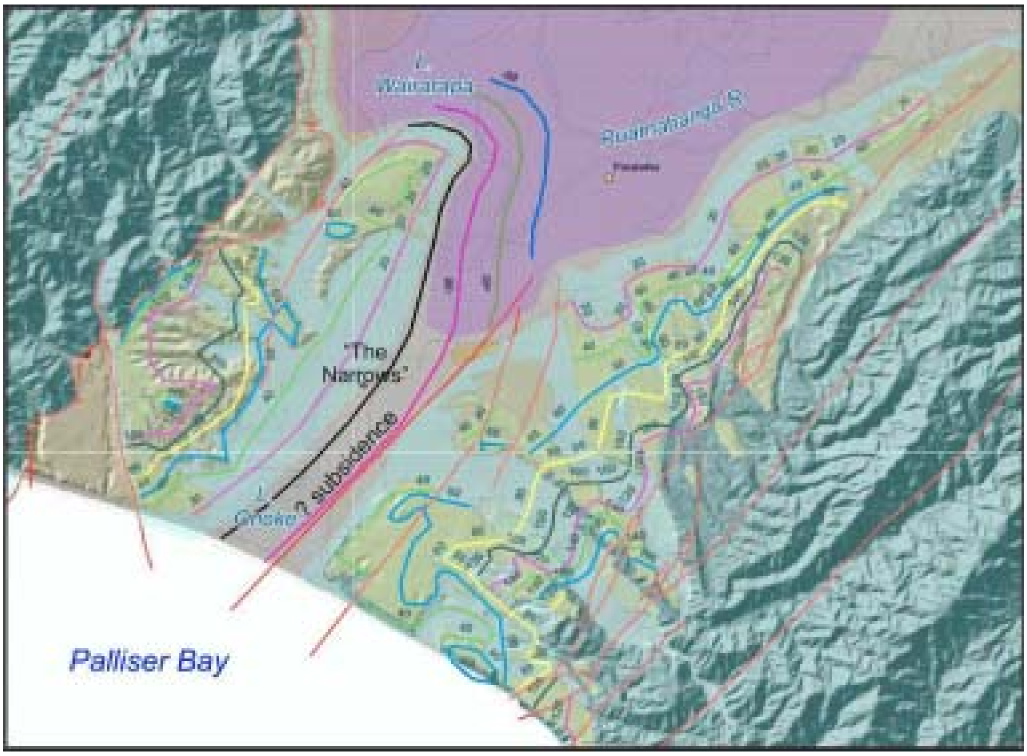


**Figure 5: relative uplift across the Lower Wairarapa Valley. Areas with a blue colour are actively uplifting, while those with a purple colour are subsiding. Red lines are active faults. Coloured lines are structural contours on the Last Interglacial marine bench. From Begg et al (2005).**

The uplift across the southern end of the Wairarapa Valley has particular significance to the groundwater system because it has uplifted the Miocene-Pliocene 'groundwater basement' above sea level in the Lake Ferry - Palliser Bay area. At the western end of Palliser Bay, Early to Middle Quaternary mud, and some silt-bound gravel, are exposed in cliffs behind the bay. These uplifted and relatively impermeable rocks constrain the southern end of the Wairarapa Valley groundwater system. The Ruamahanga River, despite having a very low gradient, must continue to cut downwards through the rising rocks to maintain egress to the sea. The river enters the sea through Lake Onoke, which lies in a restricted opening ('The Narrows') between the uplifted hills. Permeable sediments must be present through this gap, but they are unlikely to be particularly thick because of the uplift since the last interglacial.

## 3.6 Lake Wairarapa

Lake Wairarapa lies in a shallow elongate depression, which has historically been a focus for the main drainage systems in the valley. Rapid subsidence is occurring beneath the lake; well log data around the lake south of Kahutara through to the Palliser Bay coast, show that the area is underlain by a substantial thickness (20-40 m) of postglacial estuarine mud, commonly with shells. These marine sediments are a product of deposition during the sea level rise at the end of the last glaciation (Otiran, 14 000 yrs BP) until 6500 yrs BP when the present level was attained.

A Holocene maximum inland shoreline is indicated by well logs recording shells, and surface features such as sand dunes, near the inland margin of Lake Wairarapa. It is probable that the sea did not extend into the Wairarapa Valley until the present sea level was attained 6500 years ago, and that rapid subsidence and infilling has occurred beneath the lake. As sea level rose, the last glacial Wairarapa Valley longitudinal river system would have adjusted to the shortening of its course (as the coastline transgressed landwards) by degrading into its existing floodplain deposits progressively further up valley.

A series of distinct, thin gravel layers occur at depth within the lower valley sequence beneath the lake, representing distal Holocene fans of rivers prograding into the subsiding basin. A thicker aquifer at the base of the mud may represent the Waiohine gravel (Q2a).

# 4. Conceptual groundwater model for the Wairarapa Valley

## 4.1 Overview

The Wairarapa Valley is a structurally controlled basin containing an accumulation of alluvial fan sequences built up by the Ruamahanga River and its main tributaries: the Waingawa, Waiohine, Waipoua and Tauherenikau. In the subsiding lower valley beneath Lake Wairarapa, substantial thicknesses of Holocene marine and estuarine deposits have also accumulated.

Late Quaternary sediments fill the upper levels of the basin to depths of between <10m and about 100m; the average thickness being about 50m. These sediments host a dynamic groundwater flow system that exhibits a strong inter-relationship with the surface water environment.

The top of the Middle Quaternary deposits (mQa) is assumed to be the base of the groundwater flow system (Table 1). Formations beneath the top of mQa are regarded to be largely isolated from the shallow actively recharged system since they are more compact, and because of their general lithological nature, are likely to be of significantly lower permeability. However, it should be appreciated that groundwater can occur where conditions are favourable within mQa and older formations and reasonable yields may be encountered locally.

The sediments within the active groundwater system, although connected, are highly heterogeneous and exhibit large variations in hydraulic conductivity. These variations are the result of differing lithological characteristics, specifically: grain size, gravel matrix composition, degree of sediment sorting/reworking, and degree of compaction.

Broad patterns of hydraulic conductivity are recognisable on a regional scale that relate to depositional environments. Enhanced formation transmissivities due to better sediment sorting and reworking occur around the modern-day channels of major drainage systems and in distal fan and basin areas. These highly conductive sediments support the large-volume groundwater abstractions in the Wairarapa.

The groundwater basin is internally structurally complex as a result of extensive (and active) faulting and folding, which has strongly influenced the drainage pattern and hence the depositional environment of the Late Quaternary aquifers. Geological structures have also caused blocks of older less permeable sediments and basement greywacke to be upthrown and displaced against younger water-bearing strata in some areas (eg. Te Marie Ridge, Tiffen Hill, Lansdowne Hill). This juxtapositioning is responsible for the creation of localised sub-basins where aquifer sequences are thicker, and where the more productive groundwater resources are encountered.

On a regional scale, the Wairarapa Valley basin contains an unconfined to leaky-confined aquifer system with greater degrees of confinement occurring at depth within the sub-basins. The regional aquifer system is internally compartmentalised by geological structures that have facilitated the development of flow barriers and sub-basins.

## 4.2 Regional basin geometry and groundwater flow controls

The development of a conceptual model for the structure and geometry of the Wairarapa basin is fundamental for the characterisation of the regional groundwater environment, analysis of the regional flow system, and the identification of discrete sub-domains within the regional flow system.

The basin geometry is dominated by the major intra-basin cross-cutting faults, which have tilted and folded older less permeable sediment sequences (‘groundwater basement’) towards the surface, thus impeding or blocking the flow of groundwater some areas. Uplift and subsidence processes have also created groundwater sub-basins such as Te Ore Ore, Parkvale, and the rapidly subsiding lower valley basin beneath Lake Wairarapa (Figs. 3 and 4). Uplift of the coastal area has largely isolated the groundwater basin from the sea. Figure 6 illustrates these features.

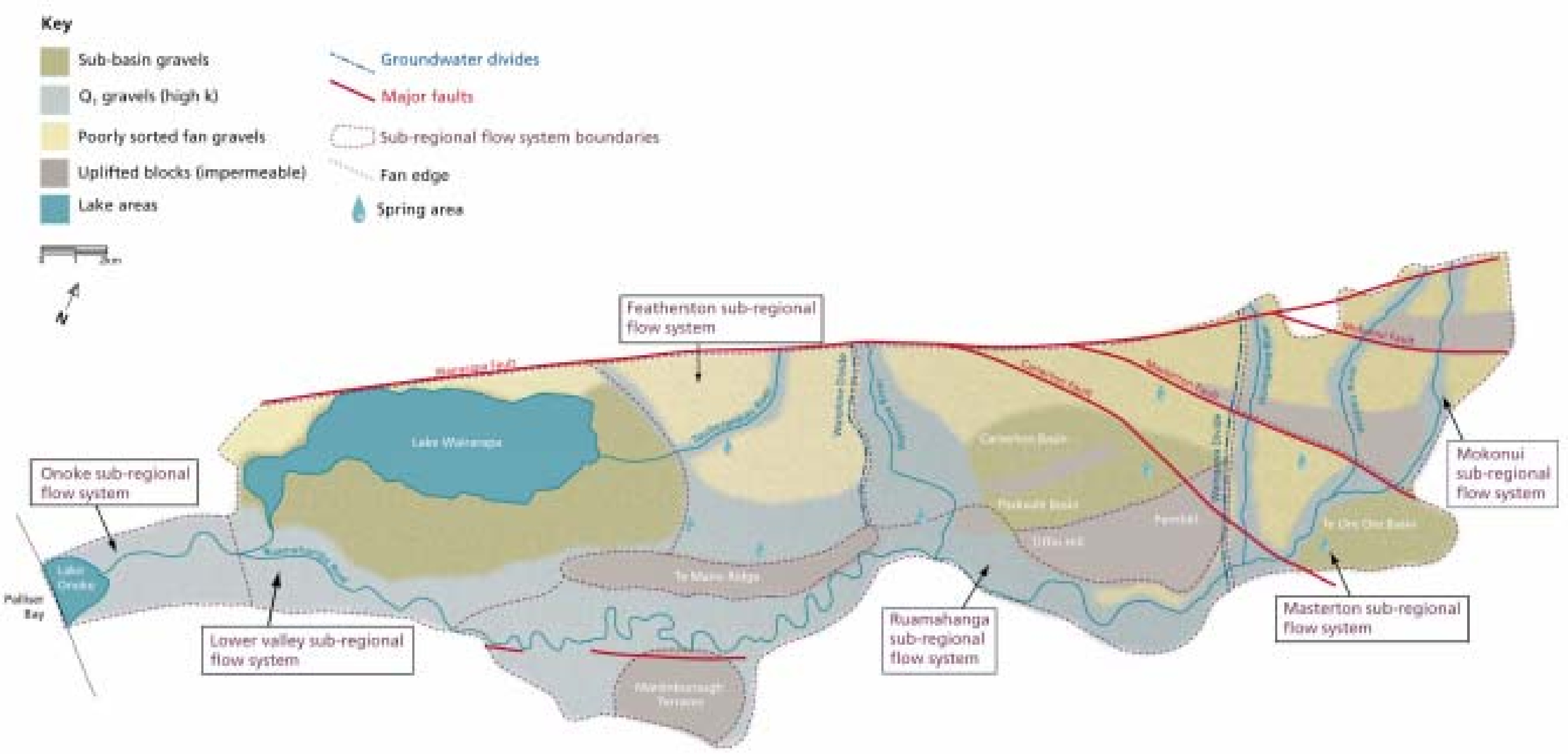


Figure 6: conceptualisation of the Wairarapa groundwater system.

Well log data have been used to construct a suite of geological cross-sections to help build a three-dimensional basin geometry model and understand the regional flow system. Figure 7 shows the locations of seven cross-sections constructed using well log data. Reliable geological well log data is available for a large number of sites throughout the valley as shown in Figure 8.

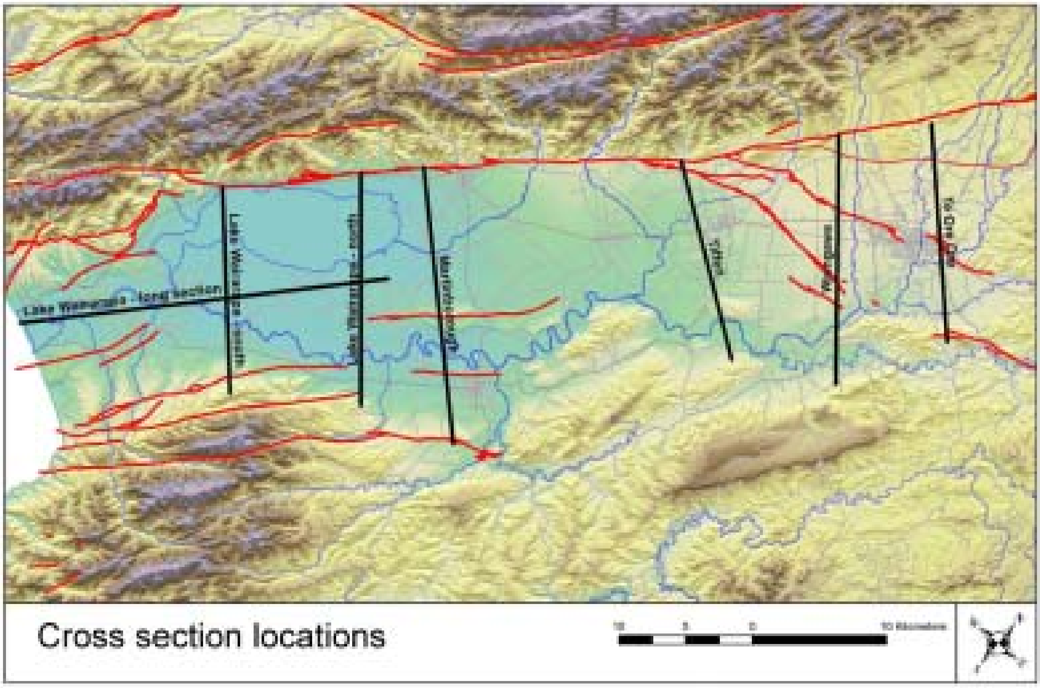


**Figure 7: cross section locations.**

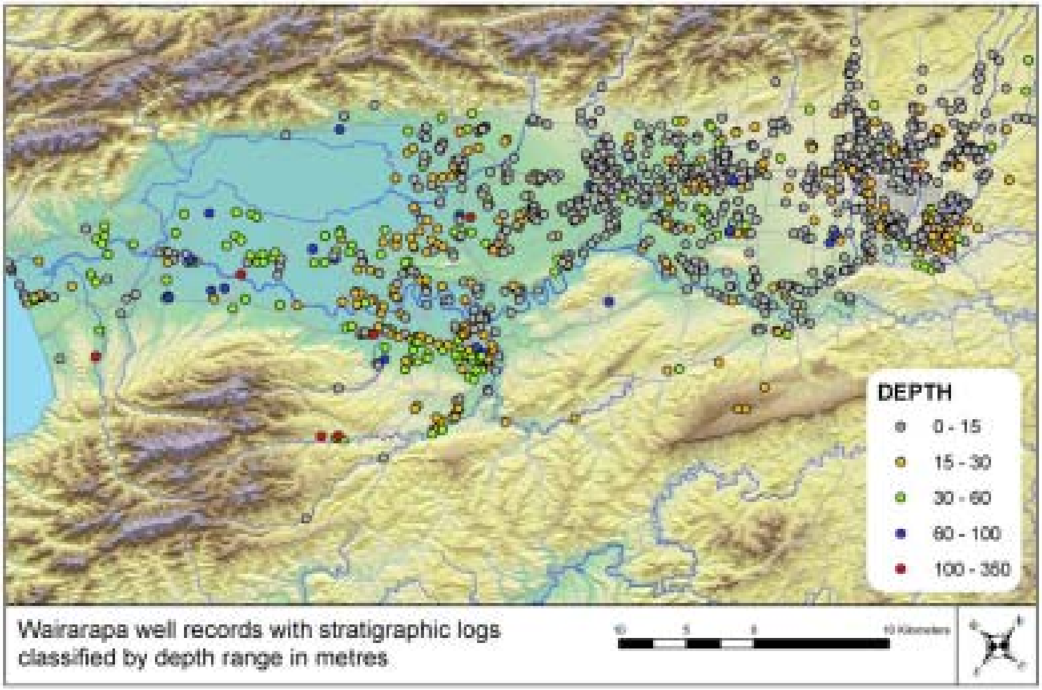


**Figure 8: location of wells with stratigraphic logs**

Table 2 lists the cross sections which are shown in Figures 9 - 15; all are cross valley sections orientated NW-SE except for Section G which is along-valley from the coast to the inland edge of Lake Wairarapa. The base of the sections represents the mQa surface, except where specified.

**Table 2: Geological Cross Sections**

| Section Line | Figure No. | Section Name |
|---|---|---|
| **A** | 9 | Te Ore Ore |
| **B** | 10 | Waingawa |
| **C** | 11 | Tiffen |
| **D** | 12 | Martinborough |
| **E** | 13 | L. Wairarapa North |
| **F** | 14 | L. Wairarapa South |
| **G** | 15 | L. Wairarapa long section |

The cross sections show that the following features exert an important control on groundwater flow and occurrence within the Wairarapa regional groundwater system:

### 4.2.1 Masterton Fault (Section lines A and B)

The Masterton Fault raises Miocene-Pliocene mudstone to the surface at Lansdowne Hill and in the Ruamahanga River, and early to middle Quaternary impermeable sediments to near surface in the Masterton area. Terrace gravels on the north-western side of the fault are back-tilted to the northwest. As a result of the back tilting, the aquifer thickness on the north-west side of the fault is considerably reduced as older formations rise up towards the surface thus restricting groundwater movement across the fault and forcing groundwater to the surface. Prolific spring flows north of Masterton along the fault line, and the gaining nature of the Ruamahanga and Waipoua rivers upstream of the fault, are expressions of forced groundwater discharge associated with the Masterton Fault.

The area to the northwest of the Masterton Fault is therefore considered to be an isolated aquifer compartment filled with rapidly deposited, poorly sorted, alluvial fan material of low permeability. Groundwater from the compartment discharges as springs and river baseflow along, or immediately upstream, of the fault line.

The Mokonui Fault further subdivides this compartment in a similar manner (section A).

### 4.2.2 Te Ore Ore Basin (Section line A)

The Te Ore Ore Basin is a syncline structure aligned with the Whangaehu Valley. The basin is filled with Late Quaternary sandy and silty gravels with minor silt/clay horizons. It is bounded to the north by the Tertiary hill country and to the west by the toe of the alluvial fans formed by the Waingawa and Waipoua rivers (Butcher, 1997). Geophysical surveying indicates that the basin has a very steep south-eastern side and is at least 100m deep (to the top of underlying Tertiary mudstone and limestone).

### 4.2.3 Carterton Fault (Section line B)

The back-tilting of terrace formations to the northeast of this fault, and the offset across the fault, do not appear to be as extreme as the Masterton and Mokonui faults. Therefore, its influence on groundwater movement is expected to less significant.

### 4.2.4 Tiffen Hill – Parkvale Basin (Section line C)

Tiffen Hill is an up-faulted block of greywacke bedrock that effectively marks the edge of the regional groundwater basin. The Ruamahanga River has eroded a shallow channel to the east of Tiffen where the aquifer depth is probably less than 15m. North of Tiffen, raised older terrace deposits (Fernhill) provide an effective continuation of this impermeable block (Fig. 6).

To the west of Tiffen Hill another groundwater sub-basin occupies a synclinal structure - the 'Taratahi Syncline'. This syncline is the Parkvale sub-basin, which is delimited on its western side by a steep, possibly fault-bound, anticlinal structure, the 'Brickworks' Anticline. Last interglacial (Q5m, Francis Line Formation swamp deposits), and last glacial gravels (Q3a and Q4a) are exposed on this anticline, which probably hydraulically separates the Parkvale sub-basin from the adjacent Carterton sub-basin (Section C). Geophysical surveying indicates that Late Quaternary sediments may extend to 200m depth within the sub-basin, decreasing in thickness to the north and south (Butcher, 2004).

### 4.2.5 Te Maire Ridge (Section line D)

Greywacke bedrock and early-mid Quaternary terrace deposits are exposed on Te Maire ridge – a narrow NE-SW aligned fault-controlled ridge about 7km long and up to 1km wide. The Ruamahanga River flows down the eastern side of the ridge, which separates the groundwater system of the Featherston-Greytown area (Tauherenikau alluvial fan) from the Ruamahanga – Martinborough terrace systems. Last interglacial deposits are displaced (down to the SE) on Te Maire Ridge by the Te Maire Fault. The presence of greywacke bedrock near the Ruamahanga River on the eastern flank of Te Maire Ridge and at Glenmorven suggests there is unlikely to be a substantial groundwater resource in this part of the valley.

### 4.2.6 Lower Valley Basin (Section lines E, F, G)

Te Maire ridge plunges southwards into the lower valley and probably creates a flow barrier within the deeper flow system (Section E). Beneath Lake Wairarapa, a deep basin has developed as a result of rapid subsidence. The total thickness of basin fill sediment could be in excess of 1000m.

Beneath the lake there is a substantial thickness (c. 30-40 m) of postglacial (Q1) estuarine mud deposited during the sea level rise at the end of the last glaciation (14 000 yrs BP until 6500 yrs BP). A series of distinct thin gravel layers occur within the predominantly fine-grained sequence to at least 60m depth. These layers appear to represent distal alluvial fans of rivers prograding into the subsiding basin. Gravels occurring on the surface up-valley (e.g. the Waiohine Q2a gravels) are expected to occur at a depth of 20-30m in the lower valley basin due to subsidence.  These gravel deposits probably fine out and disappear further into the basin and are therefore regarded to be 'blind' in terms of groundwater flow.

### 4.2.7 Lake Onoke/Narrows 'Rise' (Section line G)

There is good evidence that uplift of the Miocene-Pliocene 'groundwater basement' above sea level has occurred across the southern end of the Wairarapa Valley. Early to middle Quaternary mud, and some silt-bound gravel are exposed in cliffs behind the bay. These uplifted and relatively impermeable rocks probably constrain the southern end of the Wairarapa Valley groundwater system. The Ruamahanga River enters the sea through Lake Onoke, which lies in a restricted opening between the uplifted hills – 'The Narrows'. Permeable sediments must be present through this gap, but they are unlikely to be particularly thick, because of the uplift since the last interglacial.

If the inferences made here are true, that along the coastline there is uplift, but subsidence in the Lake Wairarapa area, it is likely that the Wairarapa Valley groundwater system is largely isolated from the sea.

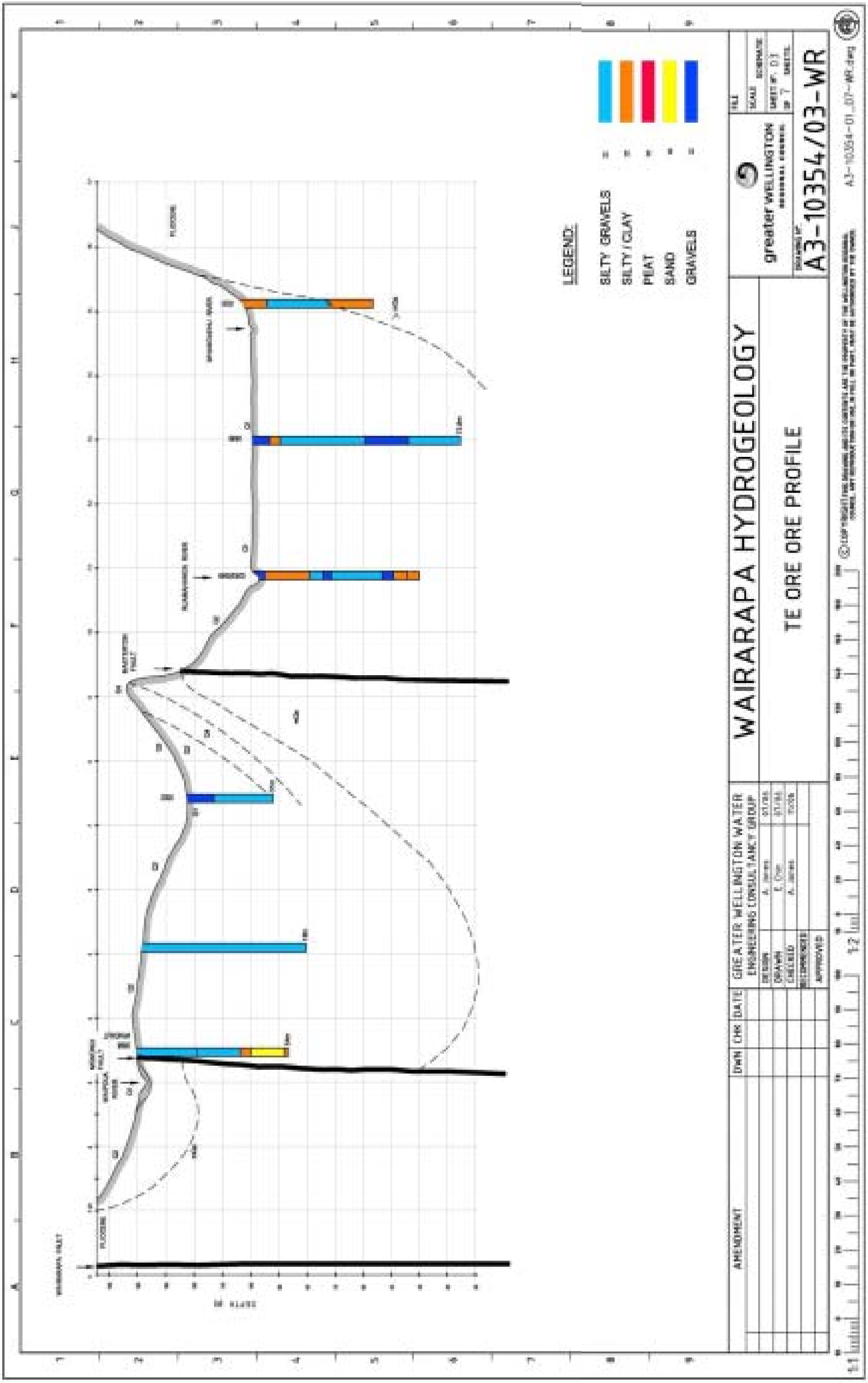


Figure 9: section A, Te Ore Ore

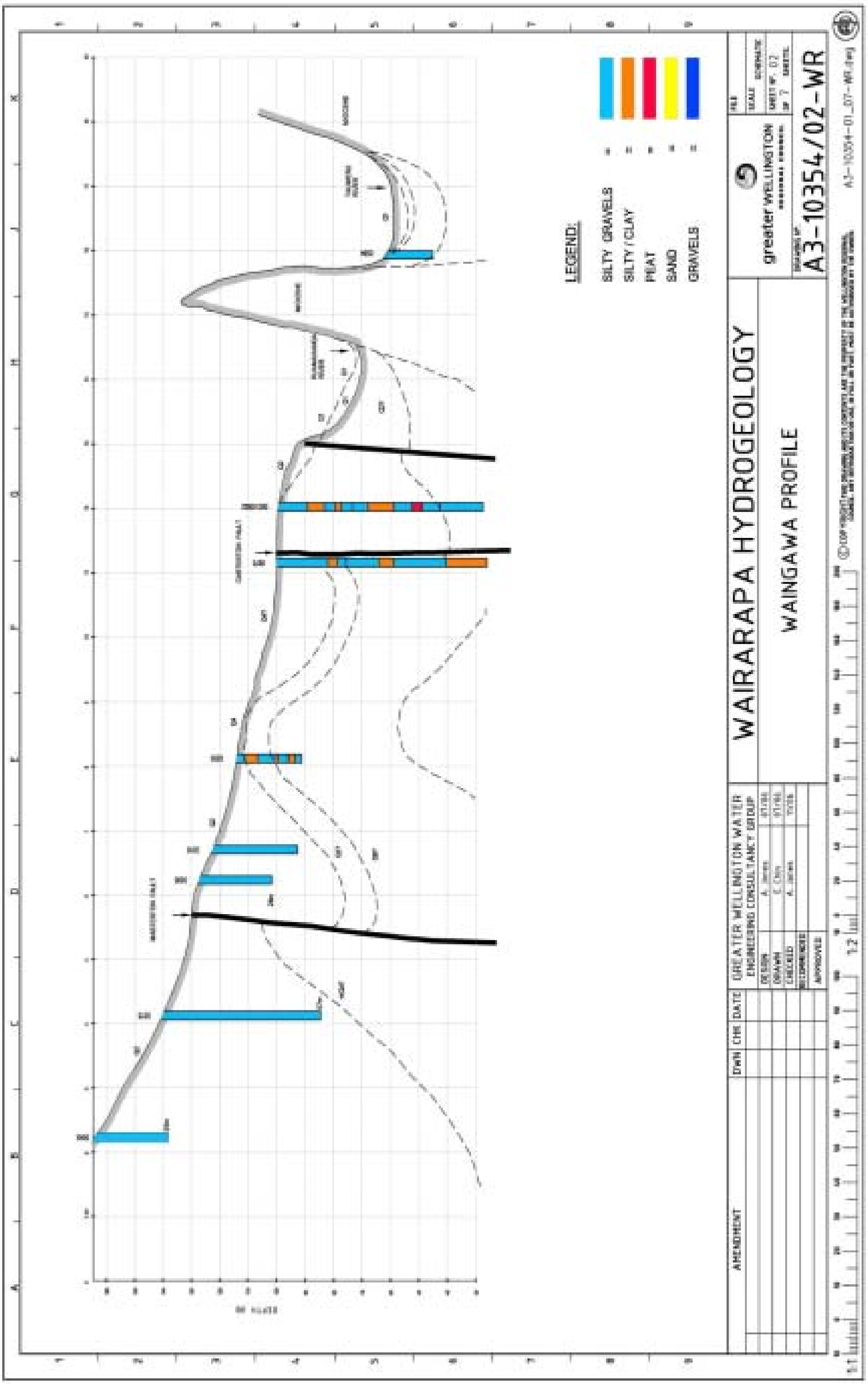


Figure 10: section B, Waingawa

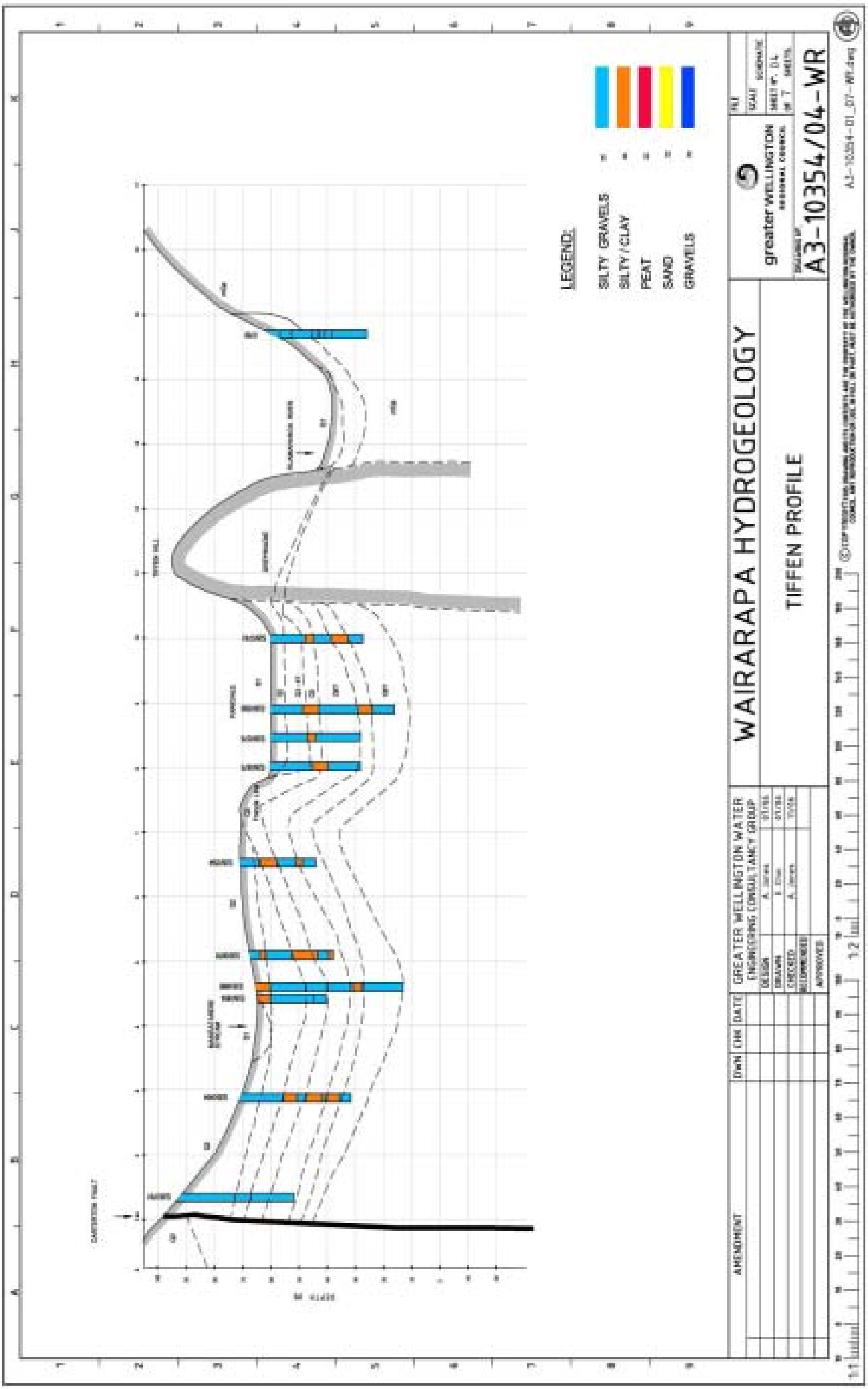


Figure 11: section C, Tiffen

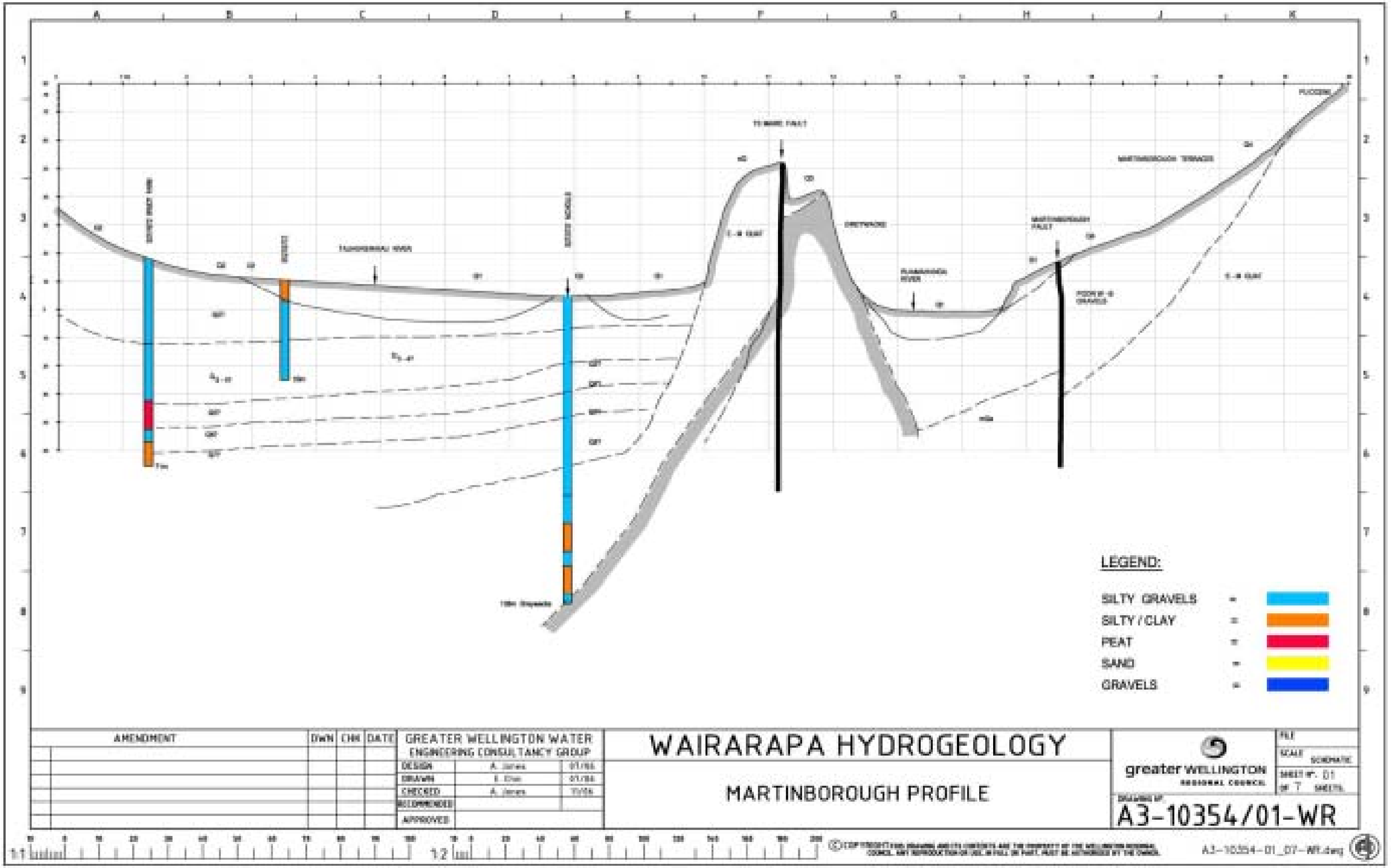


Figure 12: section D, Martinborough

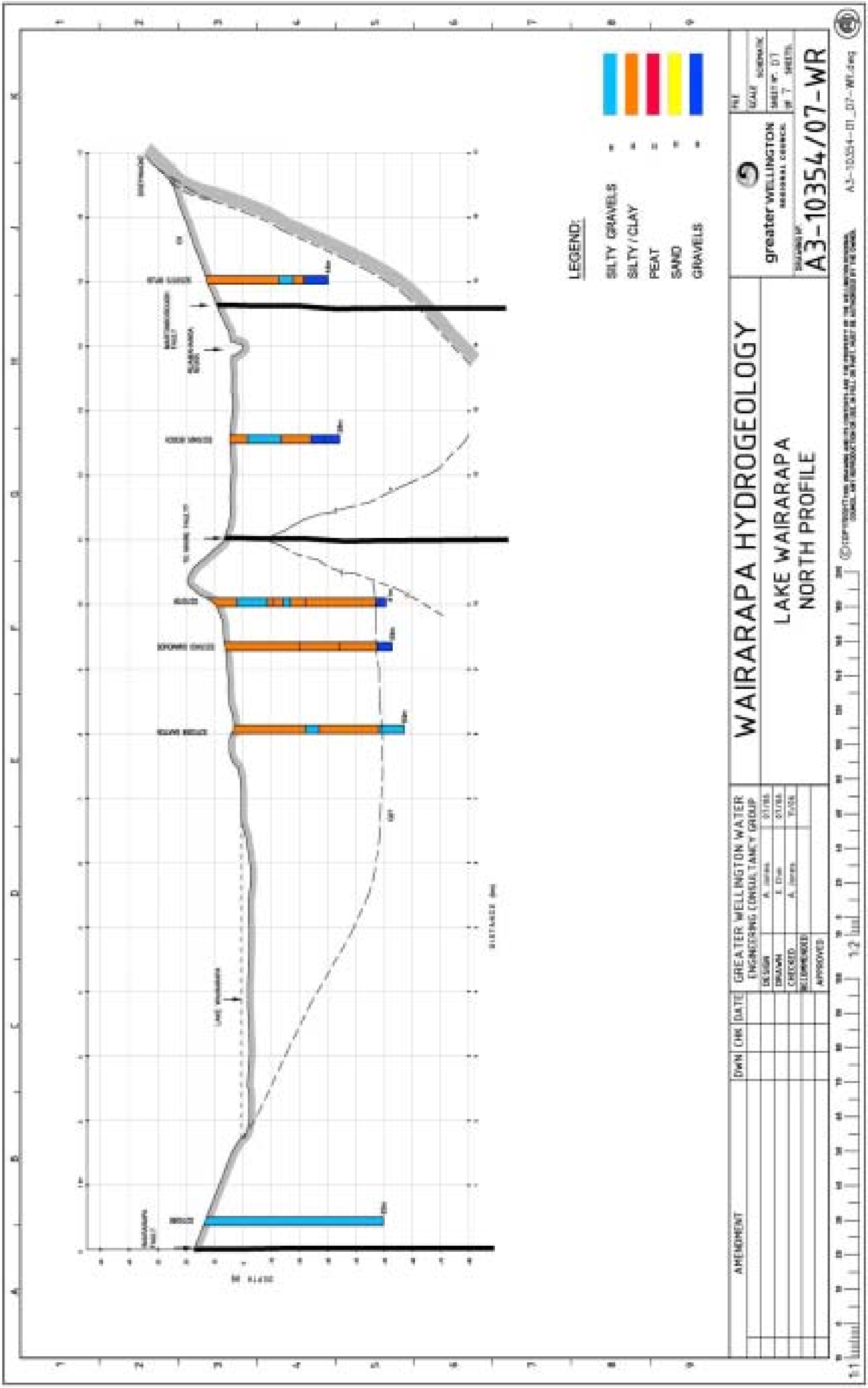


Figure 13: section E, Lake Wairarapa - north

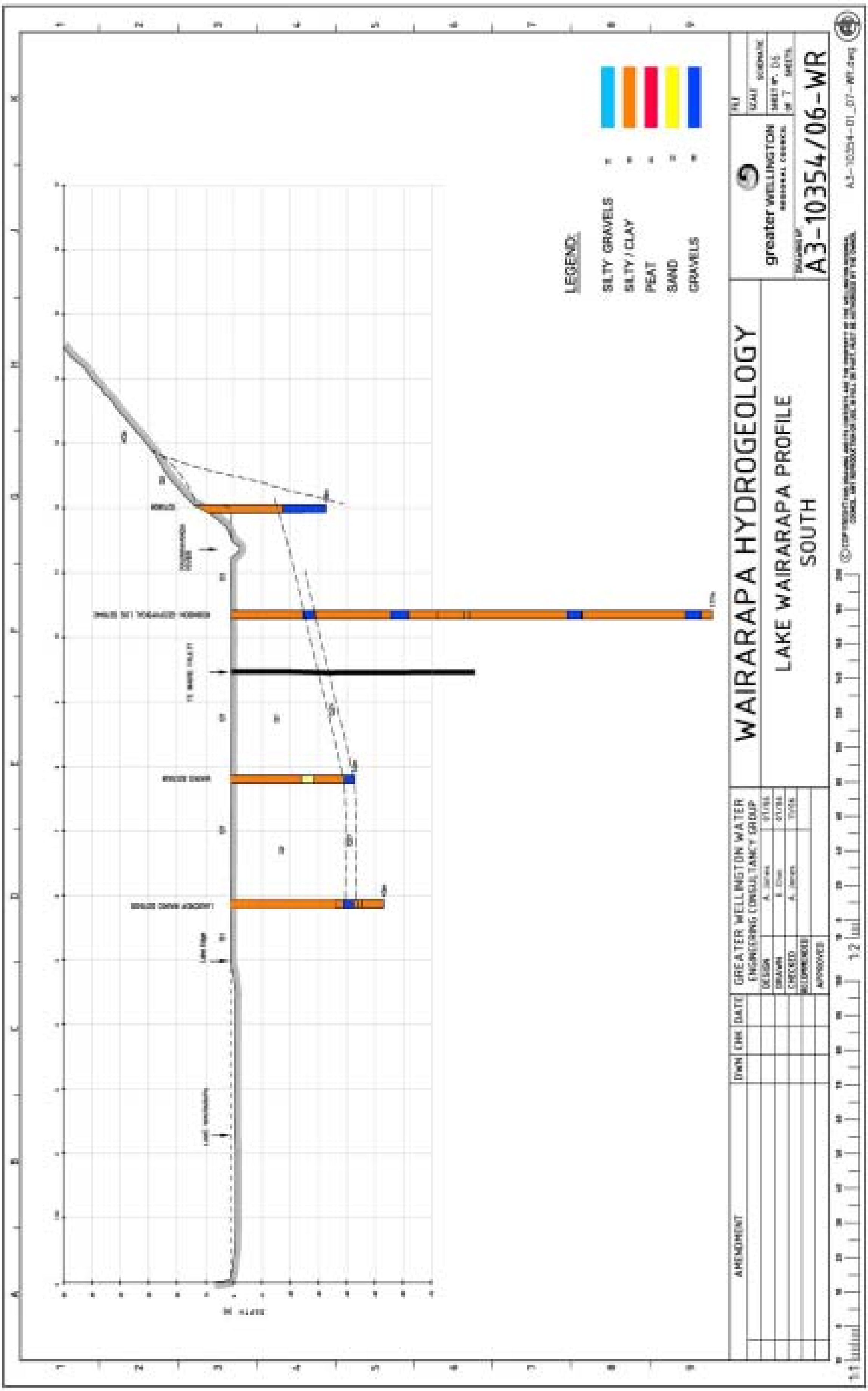


Figure 14: section F, Lake Wairarapa - south

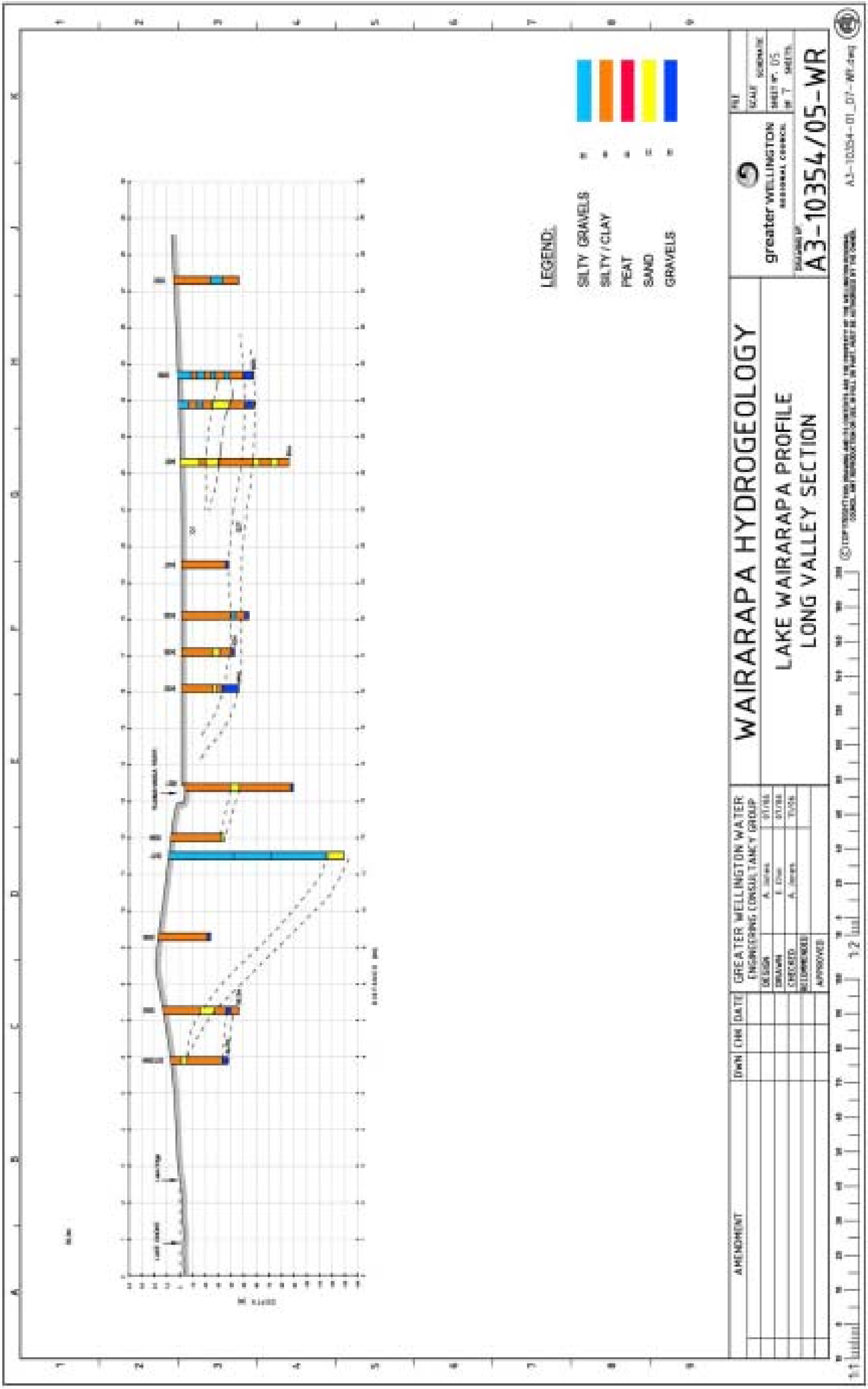


Figure 15: section G, Lake Wairarapa - long section

## 4.3 Summary of 3-D regional groundwater basin conceptual model

The three-dimensional nature of the Wairarapa Groundwater Basin is illustrated in Figure 16. The ‘groundwater basement’ is taken to be the top of the mQa unit, which coincides with the base of unit Q6 (Waimea Glacial gravels). The large offset across the Masterton Fault and the uplifted basement blocks at Tiffen and Te Maire are particularly clear. Also indicated are the three sub-basins, Te Ore Ore, Parkvale and the Lower Valley – the base of the latter is unverified and may actually be considerably deeper than shown. The ground surface is shown in Figure 17 with a highly exaggerated vertical scale to illustrate the locations of the main topographical features such as the alluvial fan systems and the lower valley basin.

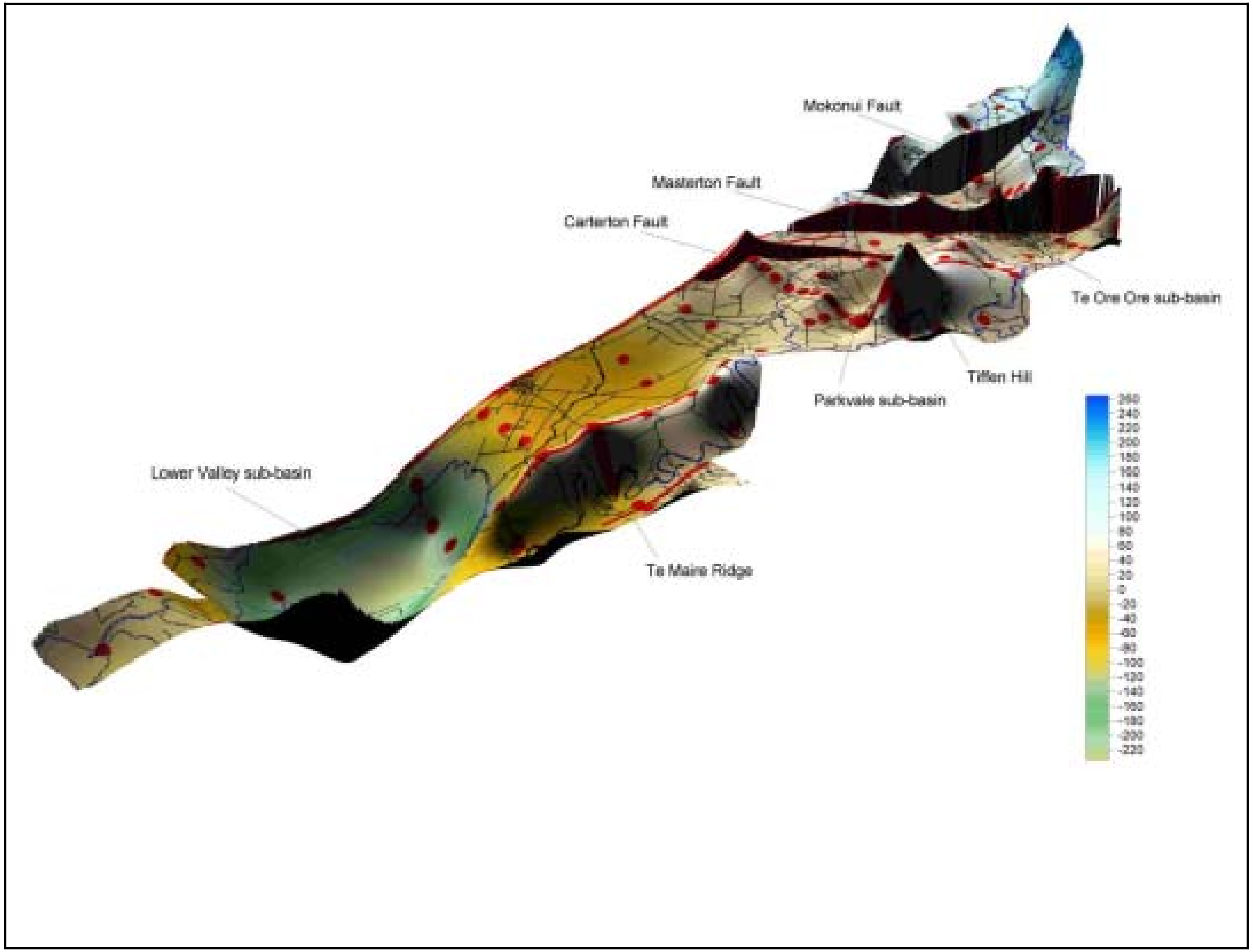


Figure 16: three dimensional model of groundwater basement geometry. Elevation units are metres above mean sea level.

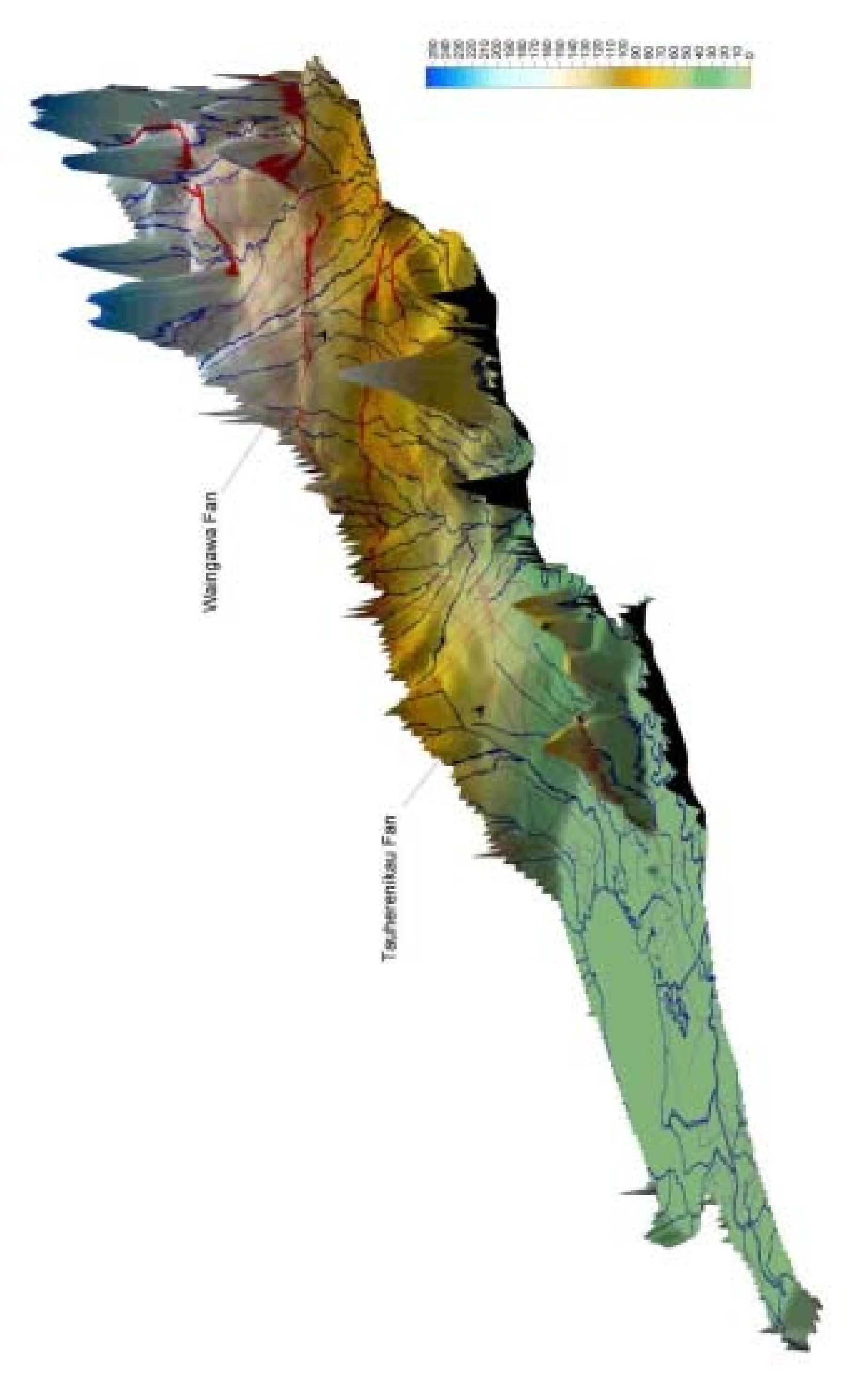


**Figure 17: Wairarapa Valley ground elevation model. Elevation units are metres above mean sea level.**

# 5. Hydrogeology

## 5.1 Hydrostratigraphic units

Six broad hydrostratigraphic units can be identified within the Wairarapa Groundwater Basin on the basis of formation lithology, well yields, and measured aquifer properties. Table 3 lists the units, their spatial distribution and the general nature of their hydraulic properties.

**Table 3: Principal Hydrostratigraphic Units of the Wairarapa Groundwater Basin**

| Unit | Name | General hydraulic nature | Distribution |
|---|---|---|---|
| 1 | Alluvial fans/outwash gravels | low k, poor yields | Major fan systems on western valley side of Tauherenikau, Waiohine, Waingawa, Waipoua rivers. |
| 2 | Q1 Holocene gravels | High k, reworked, strong connection with rivers | Main river channels, Waiohine floodplain, Ruamahanga floodplain, Lower Valley. |
| 3 | Reworked Gravels | medium to high k, generally thin localised zones. | Distal environment – lower valley, eastern side of valley, sub-basins (Parkvale, Te Ore Ore). |
| 4 | Lower Valley Transition Zone | med. to high k, intercalated permeable gravels and low k lacustrine/estuarine sediments. | Lower Valley: lower Tauherenikau fan – northern lake area; Huangarua area. |
| 5 | Uplifted Blocks | very low or low k. Low bore yields. Form flow barriers. | Lansdowne, Tiffen, Fernhill, Te Maire ridge, Martinborough terraces. |
| 6 | Lower Valley Sub-basin estuarine and lacustrine deposits | very low k; occasional thin high k gravel layers. | Lower Valley, Lake Wairarapa. |

### 5.1.1 Unit 1: Alluvial fans/outwash gravels

Accretions of a successively younger fluvio-glacial outwash fans fill the Wairarapa Basin and are thickest along the Wairarapa Fault. These fans represent rapid deposition of coarse, matrix rich material during glacial periods by the major river systems draining the Tararua Ranges. The fans prograde south-east or east towards the eastern hills, and are responsible for pushing the Ruamahanga River over to the eastern margin of the valley.

The fans are clearly identifiable on the topographic surface (Fig. 17) and are mapped at the surface as last glacial deposits (Q2). The main fan systems are the Tauherenikau fan in the mid-valley, and the coalescing Waingawa, Waipoua and Ruamahanga fans in the north. In the north, the fan sequences have been deformed and fill subsiding basins controlled by the major cross-valley faults and the Wairarapa Fault. The Carterton/Parkvale areas lie in a depression between the major fans.

Considerably smaller and older fan systems are associated with the eastern hills; these include the Martinborough and Pirinoa Terraces.

Where they have not been reworked, the fan deposits are generally poorly sorted and matrix supported, and often become very compact with depth. The fan sediments do not form good aquifers as they tend to have a very low hydraulic conductivity. Few, low yielding wells are located in this unit.

### 5.1.2 Unit 2: Q1 Holocene gravels

Postglacial Holocene gravels often have a strong hydraulic connection to the present river channels and generally form high yielding, shallow aquifers less than about 20m deep. They are largely derived from the degradation and transport of the extensive poorly sorted glacial fan gravels eroded from the Tararua Range. The reworked gravels occur around present-day river channels and immediate flood plains, but also form a very extensive cover on the Te Ore Ore Plains and in the Greytown area on the Waiohine River plain (Fig. 3).

### 5.1.3 Unit 3: Reworked gravels

The geological logs for many wells at the edge of the major alluvial fan systems and within sub-basins record thin permeable aquifers of predominantly matrix-rich gravels. These gravels can sustain high well yields and are a product of sorting after deposition, and the removal of the fine silt and sand matrix.

Sediment reworking and sorting is likely to have occurred during interglacial periods. During interglacial periods, ice and snow cover retreat, and vegetation regeneration on the Tararua Range resulted in rivers emerging onto the Wairarapa Valley with reduced sediment loads, and with sufficient energy to entrench into glacial floodplain deposits. This process reworked gravels along drainage courses and at the base of the main alluvial fan systems, and towards the lower valley area.

A result of sediment reworking by sorting and lateral spreading is that strata and aquifers can be more easily identified and correlated between wells, particularly within subsiding areas away from the massive glacial outwash fan deposits - such as in the Parkvale and the Lower Valley sub-basins. Reworked, well-sorted and clean gravel aquifers are inter-bedded with silt-bound gravel, sand and silt strata that form distinct laterally continuous confining layers.

This cycle of depositional events, controlled by climate change from glacial to interglacial periods, has been repeated many times throughout the Quaternary creating a series of thin gravel aquifers in downstream depositional environments. The exact number of depositional cycles represented by the sediments underlying the Wairarapa Valley is unknown.

### 5.1.4 Unit 4: Lower Valley Transition Zone – intercalation of distal fan sediments with estuarine/ lacustrine deposits

This unit represents the complex hydrogeological environment between the base of the Tauherenikau fan and the Lower Valley Sub-basin. Re-worked alluvial deposits prograding into the large subsiding lower valley basin interdigitate with thick fine-grained postglacial estuarine and lacustrine deposits. The result is a very thick succession of predominantly silts with intercalated gravels that become progressively segregated towards the centre of the Lower Valley sub-basin. Because of the rapid subsidence rates in the Lower Valley Sub-basin, gravel aquifers occurring at or near the surface to the north of the lake quickly descend into the basin and become increasingly confined by overlying lake and estuary sediments.

The modern day gravel fan of the Tauherenikau River spreads out into the Lower Valley Sub-basin and is in direct hydraulic connection with the lake.

Deep gravel layers are assumed to be ‘blind’ and discharge via slow vertical leakage into the lake. As such, most groundwater flowing southwards into the lower valley is forced upwards to discharge as surface water (springs or river baseflow) prior to entering the deepening basin.

### 5.1.5 Unit 5: Uplifted low-permeability ‘blocks’

A number of discreet low-permeability ‘blocks’ of older terrace sediments punctuate the regional groundwater basin. These blocks consist of Q4 or older age deposits that have been uplifted and tilted by associated folds and faults, and generally restrict the regional flow of groundwater – although low-yielding minor aquifers occur within them. Principal blocks are:

- Tiffen Hill/Fernhill
- Lansdowne Hill (Masterton Fault)
- ‘Brickworks’ anticline (between Parkvale and Carterton)
- Te Maire Ridge
- Martinborough Terraces

The Martinborough Terraces are an area of uplifted (Q4) terraces associated with the Harris Anticline and bounded to the west by Martinborough Fault. The Martinborough Terrace deposits yield limited quantities of groundwater from about 15-35m depth, which is typically used for vineyard irrigation. Individual bore yields are generally only 1-2 L/sec.

### 5.1.6 Unit 6: Low permeability lacustrine and estuarine deposits

In the central part of the lower valley, a thick sequence of low permeability silts and clays has accumulated within the subsiding Lower Valley Sub-basin. The thickness of these sediments exceeds 200m, although no wells have penetrated deeper than 178m in this area. This unit merges with the transitional Unit 5, but may still contain thin gravel horizons that extend up-valley to recharge areas north of the lake.

## 5.2 Regional groundwater flow patterns

Characterisation of regional groundwater flow patterns in the Wairarapa Groundwater Basin has relied upon the analysis of groundwater level measurements taken over the past two decades in a number of surveyed monitoring wells. Figure 18 shows the piezometric surfaces for the regional flow system for November 1985 (based upon survey data contained in Appendix 2). The exaggerated 3-dimensional representation of the ground surface shown in Figure 17 has been used to assist in the analysis of the regional groundwater flow regime.

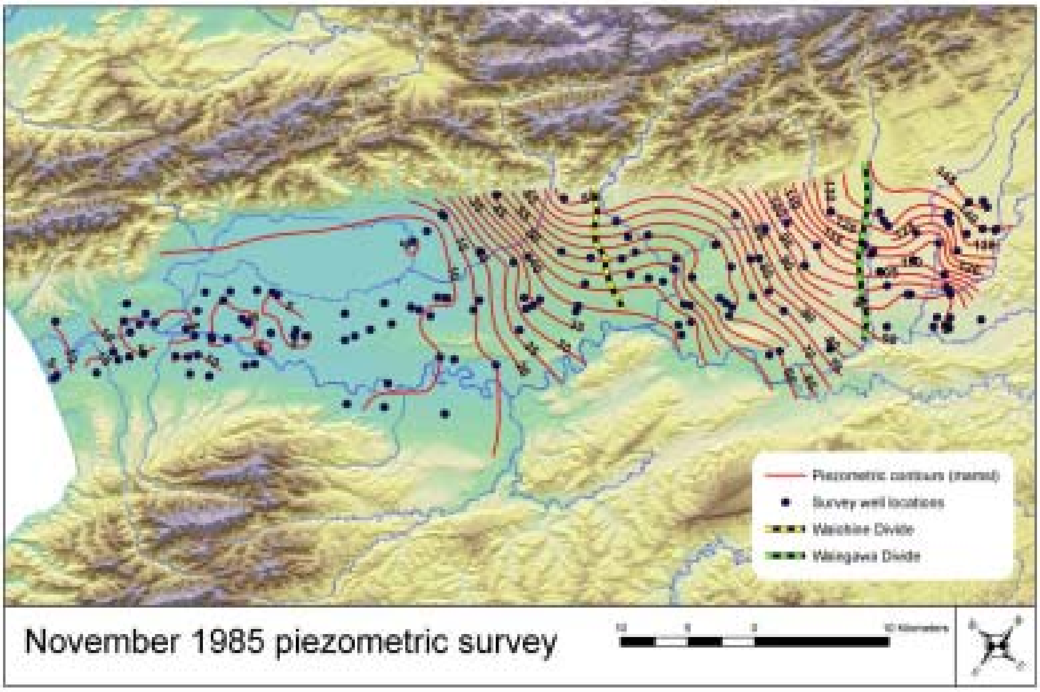


**Figure 18: 1985 piezometric survey contours.**

Although water levels have been measured in bores of different depths, a consistent regional groundwater flow pattern emerges when the data from all monitoring wells are contoured together, as shown in Figure 18. It is only within the deep lower valley sub-basin that significant increases in head are observed with depth. Within the other sub-basins (Parkvale, Carterton and Te Ore Ore) small changes in groundwater level occur with depth, but these are not significant enough to disrupt regional flow patterns when used to map the flow system. Discussion of the detailed sub-basin flow dynamics is contained in Section 5.6.

The general regional flow regime, as revealed by the groundwater level surveys, closely reflects topography. North of the Waingawa River, groundwater flows in a south-easterly direction off the outwash fan areas towards the Ruamahanga River and the Te Ore Ore Plains.

Down-valley, the regional flow vector swings to a more southerly direction parallel to the edge of the Tiffen Hill/Fernhill block and the axis of the Parkvale and Carterton Basins. A groundwater and surface water divide is evident on the southern side of the Waingawa River in the vicinity of Fernhill. This divide has been named the *Waingawa Divide* and is shown in Figure 18.

The regional flow direction then swings back towards the Ruamahanga River along the Waiohine floodplain through the ‘gap’ between Tiffen Hill and Te Maire Ridge. The Q1 Waiohine gravels represent a highly active shallow groundwater system that discharges across-valley to the Ruamahanga River upstream of Te Maire Ridge. The wider-spaced flow contours in this area reflect the more transmissive nature of the Q1 gravels. Similarly, the lower flow gradients through the Parkvale and Carterton areas reflect a thicker aquifer sequence and the presence of more permeable re-worked gravel aquifers.

There is another more prominent regional groundwater and surface water divide - the *Waiohine Divide* - along the south-western edge of the Q1 Waiohine gravels as highlighted on Figures 17 and 18.

The main ‘discharge point’ for regional groundwater flow at the Waingawa and Waiohine divides is the narrow Ruamahanga River channel (and the shallow underlying alluvium) where it flows behind the Fernhill Block and Te Maire Ridge respectively.

South of the Waiohine Divide, groundwater flow occurs off the Tauherenikau fan and then southwards, parallel to Te Maire Ridge, which acts as a flow barrier. More permeable, reworked gravels occur against the ridge, probably a result of the former drainage courses of the Ruamahanga or Waiohine rivers (the channel shown clearly on the topographic map in Figure 17). The southern edge of the Tauherenikau fan is a prominent break in slope where major spring discharges occur.

The Ruamahanga River controls regional groundwater discharge and it is probable that the river receives baseflow from groundwater downstream of the Waingawa confluence and to the end of Te Maire Ridge where it occupies a shallow alluvium filled course between the uplifted blocks and the eastern hills. The channel segment behind the uplifted ridges is regarded to be a distinct shallow, surface water-groundwater coupled flow system.

In the lower valley area, around Lake Wairarapa and downstream of the Tauherenikau fan, a flattening of the piezometric gradient is evident. The groundwater level contours appear to show that regional flow is focused on the area beneath the lake and that the lower valley system is a ‘closed basin’. This concept is supported by groundwater chemistry data that indicate old (>100 years) anaerobic water with elevated conductivity within deeper aquifers in the lower valley sub-basin (Morgenstern, 2005 – Appendix 6). The basin can only discharge by leakage through large thickness of low permeability lake sediment. Although the contours indicate flow to the lake area, we expect the rate of flow to be very small given the large thickness of lacustrine sediments.

## 5.3 Identification of sub-regional flow systems

The conceptual hydrogeological model and the observed regional groundwater flow patterns, provide information for the existence of distinct groundwater flow sub-regions. The boundaries between the sub-regional flow systems are either physical (such as faults and uplifted impermeable material), or hydraulic (groundwater divides). Table 4 contains a list of eight sub-regional flow systems identified in the Wairarapa Groundwater Basin.

**Table 4: Sub-Regional Flow Systems**

| Sub Regional Flow System Name | Boundaries | Hydrogeological Summary |
|---|---|---|
| Mokonui | south-east - Masterton Fault;<br>north-west - Wairarapa Fault;<br>north - older Tertiary sediments. Mokonui Fault. sub-divides system. | Mostly poorly sorted clay-bound fan gravels to large thickness; resource potential generally poor.<br>Q1 gravels in vicinity of Ruamahanga and Waipoua rivers are high k – locally good well yields and aquifer interaction with surface water. |
| Masterton | north-west - Masterton Fault.;<br>east - Tertiary sediment contact;<br>south - Waipoua gw and sw divide. | Large areas of shallow, high k, Q1 gravels.<br>Te Ore Ore sub-basin contains important gw resource to 60-70m depth.<br>Prolific spring discharges along Masterton F., in Masterton and Te Ore Ore Plains.<br>Flow system discharges to Ruamahanga River around Waingawa confluence. |
| Carterton | west - Wairarapa Fault.;<br>east - Tiffen Hill and Fernhill uplifted blocks;<br>north - Waipoua groundwater divide;<br>south Waiohine groundwater divide. | Poorly sorted clay-bound fan gravels to large thickness in western and northern parts with low throughflows and poor resource potential.<br>Carterton and Parkvale sub-basins contain large thickness of alluvial sediments with intermittent high k gravel aquifers.<br>Extensive areas of shallow high k Q1 gravel with good |

| | | |
|---|---|---|
| | | resource potential. Large spring discharges within Q1 gravel into Papawai spring system.<br>Flow system discharges to Ruamahanga River near upstream tip of Te Maire Ridge. |
| Ruamahanga | east – eastern hills (Tertiary sediments; low k).<br>west – uplifted blocks (Fernhill; Tiffen and Te Marie. | Shallow high k Q1 groundwater system.<br>Interacts closely with surface water.<br>Very good groundwater potential.<br>Large number of high-volume irrigation takes, |
| Featherston | west - Wairarapa F.;<br>east - Te Maire Ridge<br>north - Waiohine gw divide<br>south - Tauherenikau fan edge (break of slope) | Poorly sorted clay-bound Tauherenikau fan gravels to large thickness occupy most of the area.<br>Reworked gravels occur against Te Marie Ridge – slightly higher k and resource potential.<br>Shallow high k Q1 gravels along Tauherenikau River – local high resource potential.<br>Numerous topographically-controlled springs at fan edge (break of slope) and along edge of Te Marie Ridge; Otukura spring system. |
| Martinborough | uplifted block<br>west – Ruamahanga terrace<br>east – tertiary sediments | Compact gravel terrace deposits. Generally low k; low bore yields. |
| Lower Valley | north – Tauherenikau delta and fan edge<br>west – Wairarapa Fault.<br>east – eastern hills and uplifted terraces. | Large thickness on lacustrine and estuarine silts and clays in a subsiding basin.<br>Intercalated reworked gravels becoming more segregated towards the central part of the sub-basin.<br>Tauherenikau flats are a transition zone between distal |

| | | |
|---|---|---|
| | | alluvial gravels and lake sediments. Gravels plunge into basin, thin out and disappear.<br>The lower valley sub-basin groundwater system is 'blind' – slow leakage of groundwater occurs into lake. Bores do not show a tidal response indicating that aquifers are not connected to the sea.<br>There is a shallow unconfined aquifer within the surficial dune sands surrounding the lake. This does not appear to be connected with the deeper groundwater system. |
| Onoke | south – coastline<br>north – start of 'narrows'<br>west/east – uplifted older terraces (mQa and older) | Shallow 'channel' deposits (<20m??) incised through uplifted older sediments in coastal area.<br>Relatively high k, reworked alluvial deposits.<br>Wells show a response to tidal fluctuations and are probably connected to the sea.<br>Local aquifers encountered in older terrace sediments. |

## 5.4 Hydraulic properties

The hydraulic properties of the various aquifer formations within the Wairarapa Groundwater Basin have been assessed using aquifer test analyses from some 255 wells (stored on the Greater Wellington Regional Council 'Wells' database). These wells are classified as having reliable test data which has been analysed using appropriate methods (termed: '*Type 1*' pumping tests). No attempt has been made to re-analyse any of the test data, or to undertake any quality-control evaluation of the analyses.

Table 5 shows a summary of the data, which have been grouped into three classes:

- water table – wells screened within unconfined aquifers. These are generally bores shallower than 10m located within Unit 2 (permeable Q1 Holocene gravels).

- semi-confined – wells within shallow, stratified aquifers of Units 2, 3 or 4 to a depth of about 20-30m.

- confined aquifers (flowing artesian and artesian categories in the GW database) in Units 3 or 4; generally within deeper aquifers in sub-basins.

**Table 5: Summary of Transmissivity and Hydraulic Conductivity Data for the Wairarapa Valley (all wells)**

| | Water Table (Unit 2 Q1 gravels) | | Semi-confined (Units 2, 3 or 4 reworked gravels) | | Confined (Units 3 or 4; sub basin aquifers; distal fan deposits) | |
|---|---|---|---|---|---|---|
| | T m²/day | K m/day | T m²/day | K m/day | T m²/day | K m/day |
| | | | | | | |
| Mean | 2400 | 300 | 2000 | 230 | 1500 | 170 |
| GeoMean | 1250 | 160 | 600 | 70 | 750 | 85 |
| Min | 5 | 1 | 20 | 2 | 6 | 1 |
| Max | 8430 | 940 | 13000 | 1450 | 10500 | 1200 |
| Standard deviation | 2170 | 260 | 3100 | 360 | 1900 | 200 |
| | | | | | | |
| Mean depth | 10 | | 20 | | 28 | |
| Geomean Depth | 9 | | 18 | | 24 | |
| Min Depth | 2 | | 5 | | 6 | |
| Max Depth | 24 | | 40 | | 91 | |
| Standard deviation Depth | 5 | | 10 | | 15 | |

The geometric mean, unlike the arithmetic mean, tends to dampen the effects of very high or very low values that would tend to skew the mean. It is particularly useful for data sets such as this, which display a high standard deviation.

Figures 19 and 20 shows the spatial distribution of the hydraulic conductivity data, with the addition of 'Type 2 ' test data – these are basic yield tests from which transmissivity has been derived using a simple yield-drawdown calculation. These data supplement the Type 1 tests and are generally consistent with the spatial patterns exhibited by them.

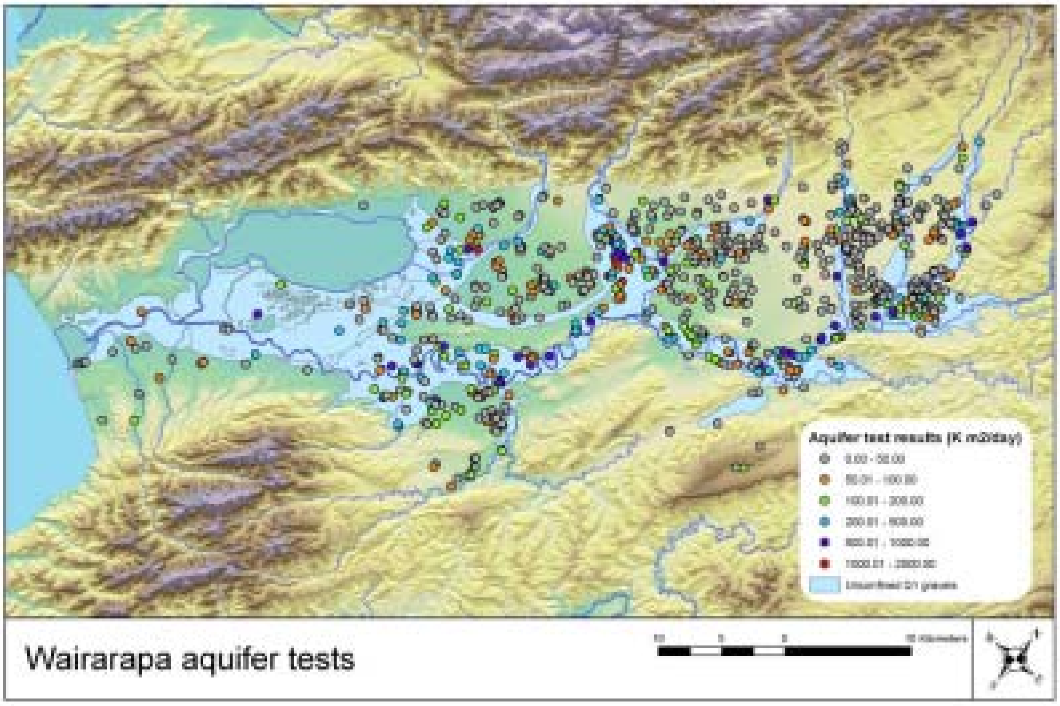


Figure 19: location of aquifer tests

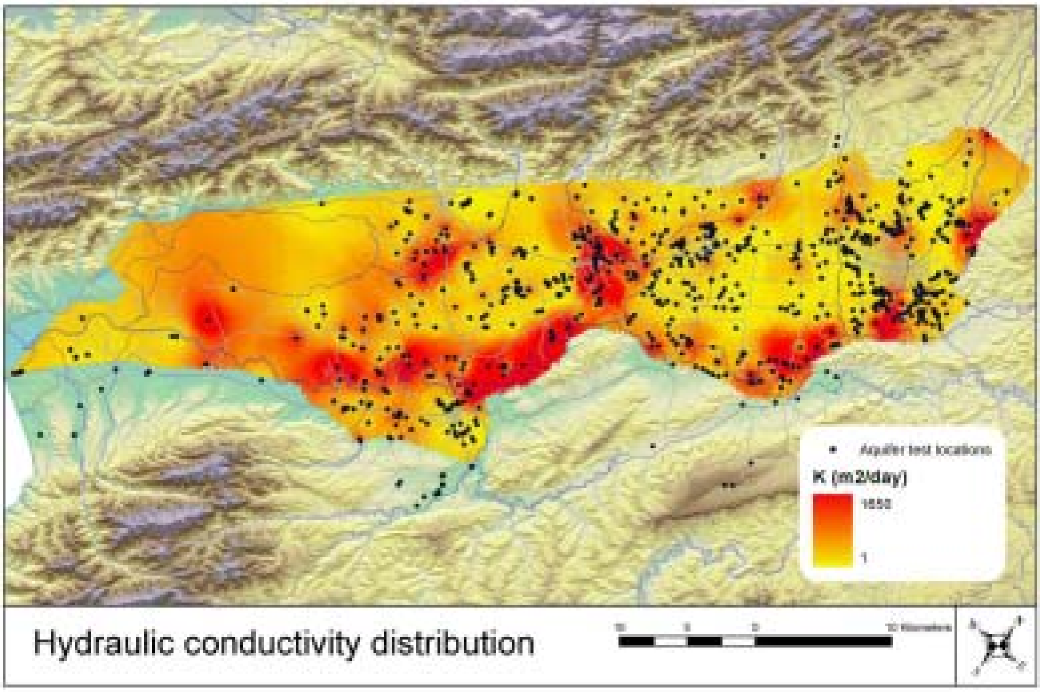


Figure 20: distribution of hydraulic conductivity inferred from existing aquifer test data.

Figures 19 and 20 show a clear pattern in hydraulic conductivity distribution, which reflects the hydrostratigraphy and basin geometry. In particular, the low hydraulic conductivity of the major fan deposits (Unit 1) and the contrasting highly transmissive shallow Q1 gravels located along the major drainage courses are apparent. Table 6 provides a summary of the hydraulic conductivity ranges for each hydrostratigraphic unit.

**Table 6: Representative Hydraulic Conductivity Ranges for Hydrostratigraphic Units**

| Unit | Description | Hydraulic conductivity m/day |
|---|---|---|
| 1 | Outwash fan deposits | 0-20 |
| 2 | Q1 Gravels | 100-300 |
| 3 | Reworked gravels | 50-200 |
| 4 | Lower Valley Transition zone | 50-100 |
| 5 | Uplifted blocks | <1 |
| 6 | Lake sediments | <10 |

Figure 21 relates measured hydraulic conductivity to aquifer depth and shows that higher values tend to occur only within the shallow aquifers less than 20m deep.

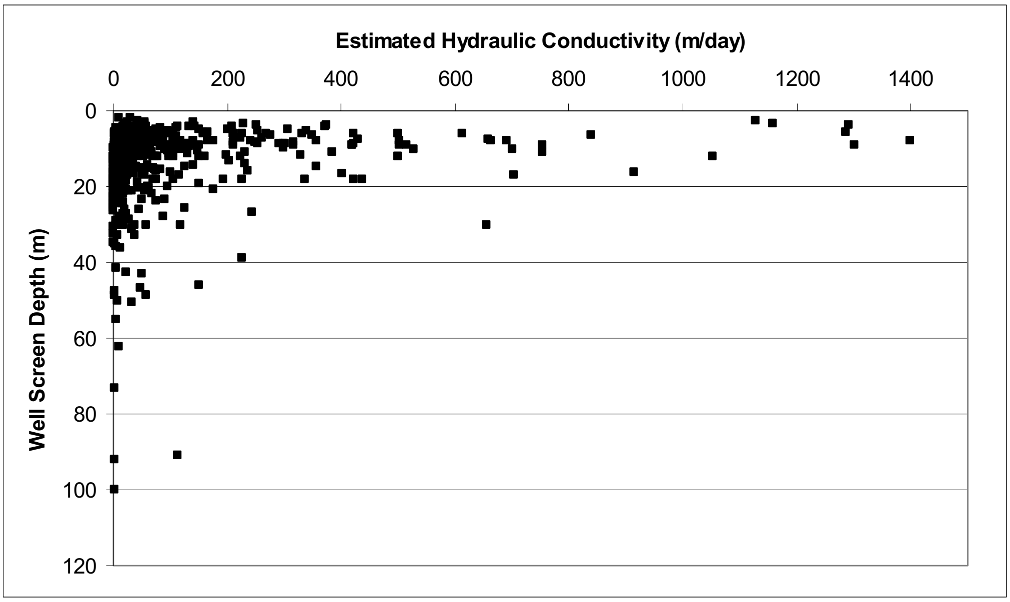


**Figure 21: hydraulic conductivity plotted against well screen depth.**

## 5.5 Recharge

Reliable estimates of groundwater recharge are needed to quantify the sustainable groundwater resource. There are two main types of recharge: direct (vertical infiltration of precipitation where it falls on the ground), and indirect (infiltration following runoff such as river bed leakage). There is a continuum between these two types of recharge process where rainfall flows overland via a ‘micro-drainage’ system before it reaches the main rivers, streams and drains.

Factors which influence the amount and type of recharge are:

- precipitation (volume, intensity, duration)
- topography (runoff)

- vegetation cover (cropping pattern, rooting depth) and evapotranspiration
- soil and subsoil types
- soil storage properties
- flow mechanisms in the unsaturated zone
- underlying geology
- presence and nature of influent rivers

### 5.5.1 Approaches to recharge assessment

Recharge is difficult to quantify reliably, and more than one method is generally employed to develop both a conceptual understanding of the dominant processes in operation, and a quantification of aquifer inflows. The suitability of methods depends upon the conceptualisation of the flow system and the level of accuracy required.

There are several approaches for estimating groundwater recharge, which can be grouped as follows:

a) Inflow estimation (soil moisture budgets, unsaturated zone modeling, direct measurement i.e. lysimeters).

b) Aquifer response analysis (analysis of groundwater level hydrographs; throughflow analysis).

c) Outflow estimation (baseflow analysis from suitable located gauging stations; concurrent flow gaugings).

d) Catchment water balance (groundwater flow modeling).

e) Groundwater chemistry trends.

This regional study warrants a broad approach, which could be based on simple soil moisture budget modeling, baseflow analysis and a more holistic overall catchment water balance through numerical modeling. Groundwater chemistry is also valuable in terms of understanding the recharge processing and locations. From a regional perspective, the catchment water balance tends to provide the most reliable estimate, particularly when recharge is a principal model calibration parameter.

In the Wairarapa, soil moisture balance modelling has been carried out in some areas, although baseflow analysis and regional scale water balances (the objective of the present study) have not been undertaken to date.

### 5.5.2 Direct recharge: soil moisture balance modelling

Soil moisture budgets involve the calculation of soil moisture surpluses and deficits, and hence actual evapotranspiration, from precipitation and potential evapotranspiration (usually Penman) data. The Grindley method is often used and the calculations are normally performed on a catchment or sub-catchment scale.

The method tends to be very sensitive to the time step used in the calculations, with shorter time steps being preferable. As well as being sensitive to the length of time step, the calculations can also be strongly influenced by the assumed root constant (RC) and wilting point (WP) values.

The rainfall distribution pattern in the Wairarapa Valley is shown by the rainfall isohyet map in Figure 22. There is a steep topographically controlled rainfall gradient across the valley from the Tararua Ranges, where the average annual rainfall is 1400-1600mm, to the eastern side of the valley where the average annual rainfall drops to less than 800mm.

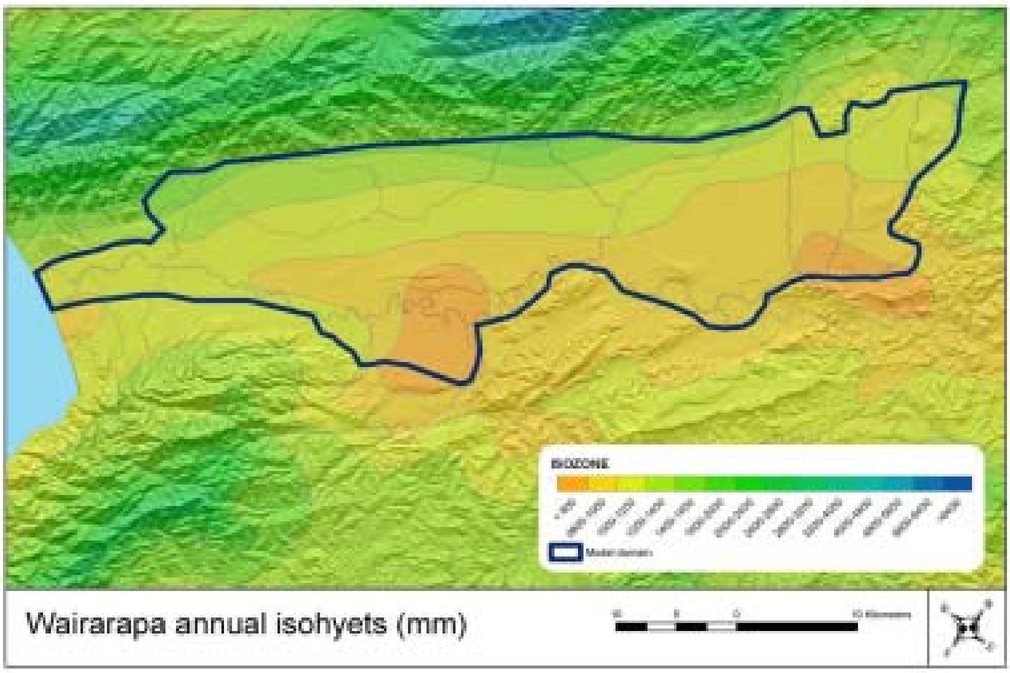


**Figure 22: Wairarapa Valley annual rainfall distribution.**

Direct rainfall recharge is a function of rainfall, actual evapotranspiration and soil moisture deficit conditions. Recharge to groundwater is often calculated using the following simple budget:

Recharge = rainfall – actual evapotranspiration – soil moisture deficit

Although a good starting point for the estimation of recharge, the soil moisture budget calculation may over estimate actual recharge for the following reasons:

- runoff may be a significant component of the budget on sloping land with low permeability soils (particularly when the water table is high). Soil moisture balance calculations that do not take this factor into account may overestimate recharge.

- simple soil moisture balance calculations assume that following substantial rainfall when the soil moisture deficit (SMD) is greater than the readily available water (RAW), on the day the rainfall occurs the evapotranspiration (ET) is at the potential rate and excess water is used to reduce the SMD or provide recharge if the SMD is zero. However, in reality, the heavy rain leads to an increase in the soil moisture in the upper part of the soil profile, which may be sufficient for evapotranspiration to continue for the following days at the potential rate. This phenomenon is known as 'near surface soil storage' (Rushton, 2003) and is an important factor in estimating ET when the soil moisture deficit is greater than RAW, particularly in low permeability soils. Recharge may be overestimated if the near surface soil storage effects are significant and not accounted for.

Simple soil moisture balance calculations based upon soil moisture deficit calculations and assumed root constants have been carried out in several areas in the Wairarapa Valley (Butcher, 1996) to provide an approximation of direct rainfall recharge; these are summarised in Table 7.

**Table 7: Annual Average Direct Rainfall Recharge Calculated from Soil Moisture Balance Modelling**

| Groundwater Sub-Region (this study) | Previous Groundwater Zone Name | Mean annual rainfall (mm) | Calculated mean annual recharge (mm) | Recharge as % of mean rainfall |
|---|---|---|---|---|
| Lower Valley/Lake | Lower Valley | 943-1096 | 392-394 | 36-42 |
| Featherston | Battersea | 947 | 419 | 44 |
| Masterton | Te Ore Ore | 900 | 309 | 34 |
| Ruamahanga | Ruamahanga | 760 | 250 | 33 |
| Martinborough | Martinborough | 720-760 | 207-236 | 29-31 |
| Lower Valley/Lake | Huangarua | 816 | 290 | 36 |
| Carterton | Parkvale | 970 | 350 | 37 |

Table 7 is representative of the groundwater basin within the 800-1000mm rainfall isohyet and shows that, on average, 35% of rainfall contributes to groundwater recharge on an annual basis. This proportion equates to a range in annual mean recharge of about 250-400mm. As discussed above, the soil moisture balance assessment may over-estimate rainfall recharge but the calculations nevertheless serve to provide a reasonable provisional estimate of rainfall recharge.

The soil moisture balance calculations generally show highly seasonal rainfall recharge between May and September. Rainfall recharge between October and April is fairly uncommon due to high soil moisture deficits and low rainfall.

The rainfall recharge processes in the Wairarapa Valley – both direct rainfall infiltration and indirect runoff recharge, require further investigation.

### 5.5.3 Indirect recharge

Indirect recharge, or runoff recharge, refers to the infiltration of runoff water through the beds of river and stream channels. Many of the rivers in the Wairarapa lose significant proportions of their flow to groundwater generally along their higher reaches on the alluvial fans, and tend to gain flow along lower reaches. Some of the flow lost to groundwater probably remains close to the river channel and flows within permeable shallow reworked gravels (Q1) and then re-joins the river in lower reaches. However, groundwater isotope chemistry (Morgenstern, 2005) indicates that some of the flow infiltrating the river beds recharges deeper groundwater flow systems.

Concurrent flow gaugings have been used to identify the river reaches that recharge the groundwater system, and to quantify the amount of loss from the river beds. Section 6.2 contains a description of the concurrent gauging work carried out to date in the Wairarapa showing that losses from rivers accounts for a significant proportion of the total recharge to the groundwater system. The concurrent gauging surveys were carried out in February and March 2006 for the present study (Appendix 3). Historical data are also available for April and December 1974 (Appendix 3) and November 1979 (Wairarapa Catchment Board, 1980). Table 8 provides a summary of the river reaches identified as losing flow to groundwater during the 1979 and 2006 gauging runs. The data are also shown on Figure 23.

**Table 8: Recharging River Reaches Identified from Concurrent Flow Gaugings – Nov. 1979 and Feb. 2006**

(a negative loss indicates flow gain)

| River | Re charging reaches | Gauged loss L/sec (1979/2006) |
|---|---|---|
| Waipoua | Mikimiki – Matahiwi/Lahores<br>Akura Road – Ruamahanga confluence. | -160/-515<br>-100/-150 |
| Waingawa | Gorge – Skeets Rd.<br>Masterton Fault – Ruamahanga confluence | 100/350<br>-200/470 |
| Waiohine | Wairarapa Fault – SH2 | 1000-1800/ --- |
| Tauherenikau | Gorge - Underhill Road<br>SH2 – SH53 | 320/430<br>480/680 |
| Ruamahanga River | Mokonui Fault – Kopuaranga confluence | 430/350-500 |

Table 8 shows that the two flow gaugings in 1979 and 2006 show similar flows between groundwater and the river. However, the 1979 gauging sites were fewer in number and the additional sites in 2006 have allowed better characterisation of flow, particularly on the Waipoua River. On that river, a series of gaining and losing reaches have been identified. Further concurrent gauging data and flow analyses are required to confidently characterise the groundwater-surface water flow dynamics of all the major tributaries to the Ruamahanga. The interaction between surface water and groundwater is discussed in further detail in section 6.

### 5.5.4 Groundwater chemistry

Hydrochemistry trends and spatial patterns have been used to help understand the groundwater flow patterns, natural hydrochemistry evolution processes, and recharge processes in the Wairarapa Groundwater Basin.

By studying groundwater chemistry, including $^{18}O$ isotope, nitrate and excess air indicators, Morgenstern (2005) was able to show that both direct and indirect recharge processes are important in the Wairarapa valley. The stable isotopes of water ($^{18}O$ and $^{2}H$) can indicate the source of recharge (river or local rainfall) assuming river water originates from higher altitude rain, compared to rain over the plains. However, the assumptions do not always hold and local natural variabilities can occur.

The isotopic data indicate that the majority of samples from the 'upper valley' (north of Lake Wairarapa) have a mixed river and rain recharge source, with only a few samples near the eastern hills showing a pure rainfall recharge. Few samples showed a pure river recharge source.

In the Lower Valley Sub-regional Flow System, most samples on the eastern side indicate rainfall recharge from the eastern hills and no contribution from the Ruamahanga River. In the central part of the lower valley basin, the majority of water samples from deep wells indicate a mixed river/rainfall source.

Generally, the groundwater age data indicate that residence time increases with depth. Shallow groundwaters contain mostly young (c. 2 years) aerobic water. Deeper wells in the Lower Valley Sub-regional Flow System were discovered to contain old (>100 years) anaerobic water indicating that deep aquifers in this area are essentially stagnant. Deep wells in the upper valley were also shown to contain old (>100 years) groundwater. Younger groundwaters are observed in deep wells along the south-eastern edge of the Lower Valley Sub-regional Flow System (45-80 years) indicating recharge from the eastern hills. Appendix 6 contains the Morgenstern (2005) report.

## 5.6 Sub-basin hydrogeology

The main groundwater sub-basins in the Wairarapa Valley groundwater zone tend to represent locally important groundwater resources that are heavily utilised for irrigation purposes. The three main basins are: Te Ore Ore, Parkvale (including Carterton), and the large Lower Valley sub-basin (refer to Fig. 6 for locations). A summary description of each of these areas is provided below based upon previous work (as referenced).

### 5.6.1 Te Ore Ore sub-basin (Masterton sub-regional flow system)

The hydrogeology of the Te Ore Ore Basin is described in detail by Butcher (1997). The basin is a locally important groundwater resource for irrigation supply and is exploited by numerous wells between just a few metres to over 50m depth. The basin is a synclinal structure aligned with the Whangaehu Valley and is filled with Late Quaternary sandy and silty gravels with minor silt/clay horizons. The basin is bounded to the north by the Tertiary hill country and to the west by the toe of the alluvial fans formed by the Waingawa and Waipoua rivers. The Ruamahanga River is roughly coincident with the latter boundary. Geophysical surveying indicates that the basin has a very steep south-eastern side and is at least 100m deep (to the top of underlying Tertiary mudstone and limestone).

Aquifers in the sub-basin are highly stratified and groundwater occurs in thin (0.5-2.0m thick) reworked gravel layers of moderate to high transmissivity. Two aquifer levels appear to be present in the Te Ore Ore sub-basin: an unconfined system between about 15-20m depth; and a deeper, semi-confined aquifer to depths in excess of 50m beneath a silt aquiclude developed in the central part of the basin. The top 20-30m of the lower aquifer layer produces the best well yields.

Groundwater levels in the shallow unconfined and deeper semi-confined aquifer are identical, suggesting common recharge and discharge mechanisms. This similarity indicates that the basin contains a single unconfined – leaky aquifer system flowing to the south-southwest. Discharge from the basin occurs as springflow into the Poterau Stream, and into the Ruamahanga River. Recharge occurs principally from leakage through the bed of the Ruamahanga River and also from rainfall recharge over the plains. A rainfall recharge component is confirmed by elevated nitrate levels in the central Te Ore Ore Plains (Morgenstern, 2005).

### 5.6.2 Parkvale sub-basin (Carterton sub-regional flow system)

The Parkvale sub-basin, to the west of Tiffen Hill, occupies a synclinal structure called the ‘Taratahi Syncline’. The sub-basin is bounded on its western side by a steep, possibly fault-bound, anticline (the ‘Brickworks’ anticline). Last interglacial (Q5m, Francis Line Formation swamp deposits), and last glacial gravels (Q3a + Q4a) are exposed on the anticline, which is regarded to hydraulically separate the Parkvale sub-basin from the adjacent Carterton ‘sub-basin’. Geophysical surveying indicates that Late Quaternary sediments may extend to 200m depth within the Parkvale Sub-basin, decreasing in thickness to the north and south.

Four aquifers have been identified in the sub-basin (Butcher, 2004): a shallow unconfined aquifer to 10-15m depth, and a series of leaky-confined aquifers between about 20-30m, 35-50m and 50-60m depth. Deeper wells are flowing artesian although poor water quality and isotope dates in deeper aquifers reported by Morgenstern (2005) suggests they may be blind (cf. Denbee S26/0568 and Wither S26/0793 bores).

The basin is perceived to rise to the north towards the Carterton Fault and to the south in the vicinity of the Waiohine River into which it discharges. Downwards flow gradients at the northern end indicate recharge, whilst near the Waiohine River at the southern end of the basin upward flow gradients and flowing artesian wells indicate that the Parkvale sub-basin discharges in this area.

Parkvale represents the first occurrence down-valley of a distinctly segregated aquifer-aquitard sequence. The aquitard sequence represents interglacial swamp deposits caused by raised sea levels and the establishment of stable swamp/lacustrine conditions in the centre of the subsiding basin. Rivers periodically flowed through the basin during glacial events depositing a series of gravel units, which exhibit higher transmissivities than the alluvial fan sequence to the west.

### 5.6.3 Lower valley sub-basin (Lower valley sub-regional flow system)

A growing syncline or fault-angle depression occurs beneath the lower valley and Lake Wairarapa. This groundwater sub-basin contains a considerable thickness of predominantly lacustrine, estuarine and marine sediments. Lake Wairarapa has developed as a result of the subsidence and has historically been a focus for the main drainage systems in the valley.

The basin contains at least 40-50m of postglacial (Q1) estuarine mud which is a product of marine deposition during the sea level rise at the end of the last glaciation (14 000 yrs BP). Beneath this deposit, a series of at least six (Butcher, 1996) thin artesian gravel layers occur within a predominantly lacustrine sequence to more than 200m depth. These layers are thought to have been deposited during warmer periods by prograding alluvial fans (Butcher, op. cit.). The segregated gravel aquifers observed in the sub-basin centre probably coalesce to the north where they may connect to gravel aquifers lying near the surface and where recharge may occur.

Wells are screened within four principal aquifers between about 20 and 120m depth, which dip down-valley toward the sub-basin centre, but most are located in the top two gravel aquifers to a depth of about 60m. Aquifer transmissivity in the shallowest aquifer appears to increase on the eastern side of the basin where the Ruamahanga River may have reworked the deposits.

In the Lower Valley Sub-regional flow system, static water levels increase with depth, which implies an upward discharge of groundwater between aquifers and through aquitards within the layered aquifer system. Large constraints on groundwater flow are imposed by: down valley thinning of the gravel deposits forming the aquifers, the upward warping and lateral constriction of the last interglacial and older Quaternary sediments at the Wairarapa Valley coast, and the distinct likelihood that at least the deeper aquifers in these warped deposits do not continue through to the coast and out into Palliser Bay. The Lower Valley Sub-basin is therefore perceived as being ‘blind’, and that groundwater escapes from the deeper gravel aquifers only through slow vertical leakage to shallow aquifers or to the surface. Groundwater chemistry data provides strong support for this assertion, as discussed in Section 5.5.4.

# 6. Groundwater-surface water interconnection

## 6.1 Introduction

Significant interactions occur between groundwater and surface water in the Wairarapa Valley. As such, it is difficult to consider groundwater and surface water as two separate resources as they are complexly interconnected. Under favourable conditions, exploitation of groundwater will induce impacts in the surface water environment and other groundwater dependent ecosystems such as springs or wetlands. These depletion effects can be significant, particularly during low flow periods. Figure 34 illustrates the concentration of large shallow abstractions (<15m deep; green circles) located within unconfined Q1 gravels adjacent to major drainage systems, particularly along the Ruamahanga and Waiohine rivers. Many of these abstractions will source water through the depletion of surface water flows.

Natural outflows from aquifers in the Wairarapa Groundwater Basin occur as springflow, river baseflow, and seepage into lakes and wetlands. Conversely, the higher reaches of many of the Wairarapa rivers are groundwater recharge sources as they are observed to lose large quantities of flow to aquifers. Surface water ecosystems are therefore linked in many ways to the recharge-discharge dynamics of the regional groundwater system. Thorough understanding of nature and degree of connectedness is extremely important for the sustainable management of both surface water and groundwater use.

Little work has been carried out to investigate the detailed interaction between aquifers and rivers, springs or wetlands in the Wairarapa. At the present time, only limited concurrent gauging data are available to characterise the basic regional interconnection between surface water and groundwater.

## 6.2 River – aquifer transfer flows

A comprehensive concurrent gauging survey of the major Wairarapa rivers was undertaken in 2006 to characterise the transfer of flows between surface water and groundwater. This survey was designed to repeat and extend surveys completed in the 1970s. The Scientific Advisory Group (1980) provides a summary of a large concurrent gauging run undertaken in November 1979. Two concurrent gauging runs were also undertaken on the Waiohine in 1974 (Appendix 3).

The survey undertaken for this study largely repeated the 1979 effort, with the addition of extra sites to capture significant tributaries and to assess the effect on flow caused by the Mokonui and Masterton faults.

The survey was undertaken on 21 and 22 February 2006 and the results are tabled in Appendix 3. Unfortunately, a small fresh occurred in the Waiohine on the 22nd that made data collected that day for the Waiohine and Ruamahanga Rivers unusable. A repeat run of the Ruamahanga River was undertaken on 16 March and the results of that survey are also tabled in Appendix 3.

The results of the 2006 survey are illustrated in Figure 23, where river reaches are classified as losing, gaining or neutral; the classification is from the river's point of view. Reaches were classified as neutral when the measured flow loss or gain was less than the margin of error of the flow measurement. For this study, the margin of error on all flow gaugings was assumed to be +/- 10%. The classification for the Upper Waiohine River is based on the 1974 and 1979 surveys.

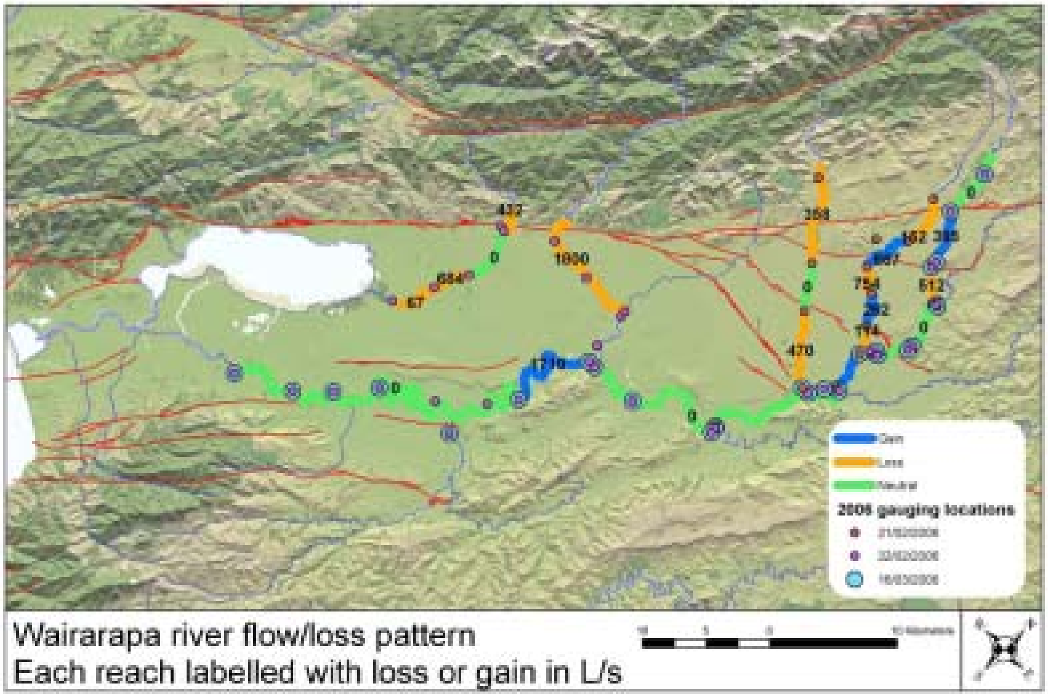


**Figure 23: concurrent gauging survey results for the principal Wairarapa rivers.**

### 6.2.1 Tauherenikau

This river appears to have three different reaches. From the Gorge to Underhill Road the river loses to groundwater. Below Underhill Road, the river crosses the fan and appears to neither lose nor gain water until SH2. Between SH2 and SH53 the river loses about 60% of its flow to groundwater. And below SH53, the river continues to lose water, but at a much lower rate.

### 6.2.2 Waingawa

Three reaches were identified on this river. The river loses water from the Gorge to Skeets Road, which is just below the Mokonui Fault trace. Flow is then steady until the river crosses the Masterton fault, at which point it begins to lose water and continues to do so until the confluence with the Ruamahanga River.

### 6.2.3 Waipoua

This river has a complex pattern of losing and gaining reaches that appear to be controlled by the Mokonui and Masterton faults. The river gains water upstream of the faults and after crossing the fault traces water is lost to groundwater.

### 6.2.4 Ruamahanga

Similarly to the Waipoua, flow in the upper Ruamahanga is influenced by the effect of the fault lines on groundwater flow, although the pattern is less clear. The pattern may be less clear because the river runs along the northern margin of the groundwater basin at this point and water bearing sediments are expected to be thin.

Further downstream, a 25% increase in flow was observed adjacent to, and below, Te Ore Ore. It is assumed that this increase in flow reflects discharge from the Te Ore Ore sub-basin.

Below Te Ore Ore, flow is steady until a short reach below the confluence with the Waiohine River, where a 1700L/s increase was observed. This increase must represent discharge from the Greytown springs and associated shallow groundwater flow.

Below Morrison’s Bush, flow in the river remains steady, however the relatively high flow in this reach compared with the upper river means the error on the flow measurements is high. This error means that significant groundwater-surface water interaction may be undetected. Conceptually, we expect there to be a high degree of connection between the river and the shallow near-river Q1 gravels.

## 6.3 Spring flows

The Wairarapa Valley contains a large number of springs associated either with major active cross-valley fault lines, and/or with topographic features. These springs represent an important groundwater discharge process in the Wairarapa Valley.

Figure 24 shows the locations and estimated baseflows from the principal springs. Lines of springs occur on the Masterton and Carterton faults and flows from these springs appear to be greater towards the eastern ends of the faults. Large springs occur in Masterton and emanate in the vicinity of the Masterton Fault.

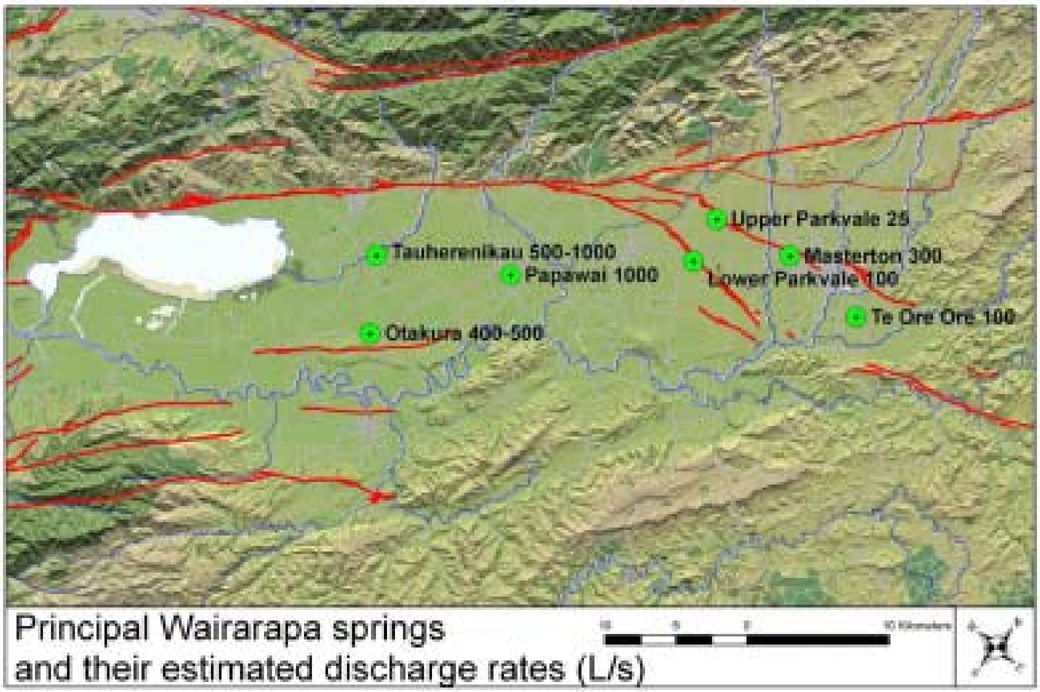


**Figure 24: principal spring locations in the Wairarapa Valley.**

The mechanism of spring discharge along the faults relates to uplift and tilting of older less permeable geological formations on their northern sides, with displacement being more pronounced towards the east. The uplift and displacement forces groundwater to the surface in the vicinity of the faults – into springs and into the rivers as shown by the general pattern of river flow gains above the faults.

Other springs, such as the Greytown/Papawai springs, and the Otukura springs, are surface expressions of the shallow groundwater flowing through very permeable Q1 gravels.

Although ecologically important, there is very sparse information on the seasonal flow regimes of most springs and their sensitivity to climatic changes and groundwater abstractions. There have been sporadic gaugings of some, mostly in the early 1980's, and only one – the Otukura Spring – has a permanent flow recorder (installed in 1998). Table 9 presents a summary of the estimated flows from the principal spring systems – based upon summer gauging data, or an estimation based upon visual observations of the system over a number of years. Large numbers of smaller springs are not included, which could cumulatively account for a significant additional aquifer discharge.

**Table 9: Principal Spring Systems in the Wairarapa Groundwater Basin and Estimated Summer Baseflows**

| Spring System | Estimated Average Baseflow (L/sec) |
|---|---|
| Masterton Springs | 300 |
| Te Ore Ore Springs | 110 |
| Parkvale Springs | 100* |
| Greytown/Papawai springs | 1,000 |
| Otukura/Battersea system | 4-500 |
| Tauherenikau Springs | 500? |
| Total | 2,500 L/sec (216 ML/day) |

(* - no gauging data available, visual estimate)

Figure 25 shows the flow record for the Otukura Stream from 1998 to 2006. The spring system includes the extensive Otukura and Battersea drain network and extends along the base of the Tauherenikau fan. The flow record shows a strongly seasonal flow, with a very low mid-summer baseflow of about 1-200 L/sec, rising to 6-700 L/sec in the winter. Peak runoff discharge from the drainage system frequently exceeds 2 $m^3$/sec.

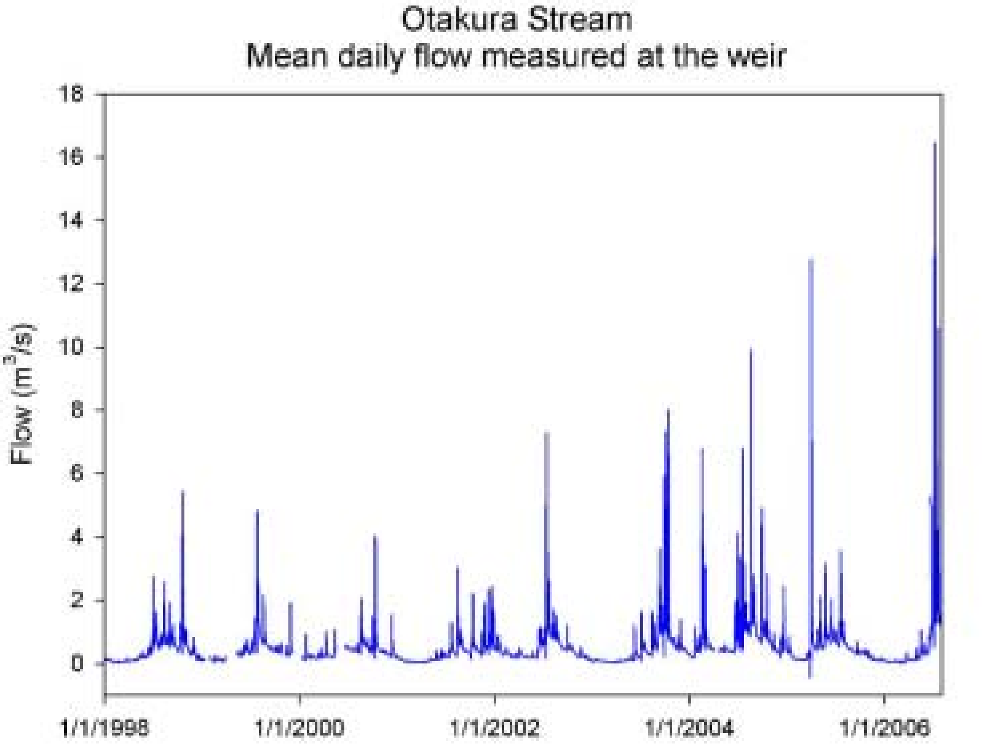


**Figure 25: flow record for the Otukura Stream.**

## 6.4 Lake Wairarapa

Lake Wairarapa is a very large shallow lake of approximately 76 $km^2$ in area, occupying a topographic depression over the centre of the subsiding lower valley sub basin. The lake has historically been the focus for all surface water draining the Wairarapa Plains. The piezometric map (Fig. 18) also indicates that it may also be the focus for regional groundwater flow.

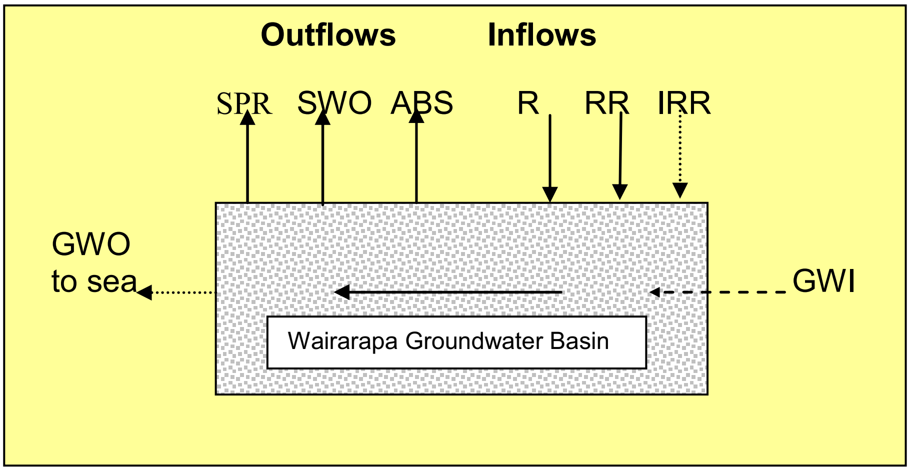
The principal inflow to Lake Wairarapa is the Tauherenikau River. The lake also receives significant inflow of shallow groundwater from the wide Tauherenikau fan gravels (Q1) along the northern shoreline. It may also receive groundwater seepage (in the form of springs around the shoreline or through the bed) from deeper confined aquifers as suggested by the piezometric contours beneath the lake and the strong upward vertical flow gradients.

The lake is underlain by considerable thickness of fine-grained lacustrine and estuarine sediment that fill the subsiding basin. Thin, blind gravel and sand aquifer units occur below about 40m depth, although the modern-day gravel fan on the Tauherenikau River extends into the lake near the surface and the gravels associated with this river probably interdigitate with the fine grained lake and estuary sediments around the northern lake edge, with older gravels becoming progressively deeper towards the centre of the lake/sub-basin. (Figure 15, cross section G). In terms of groundwater flow in the deeper confined aquifers, there is likely to be only a very small aquifer throughflow and a very slow vertical discharge through the fine grained sediments into the lake. Vertical seepage rates from deeper aquifers may be more rapid in the Tauherenikau fan area.

Calculation of a water balance to assess the magnitude of groundwater inflows to the lake is currently not possible due to the absence of surface water inflow and outflow monitoring data.

## 6.5 Conceptual water balance

A conceptual water balance for the Wairarapa Groundwater Basin is schematically represented in Figure 26. The diagram shows the principal components of the regional water balance - the inputs are rainfall recharge and runoff recharge, and the main output is discharge into the surface water environment (rivers, springs and the lake).



**Key:**

*Principal inflows:*

| | |
|---|---|
| RR | Runoff recharge - surface water inflow from rivers/streams |
| R | Rainfall recharge |

*Principal outflows*:

| | |
|---|---|
| SWO | Surface water outflow to rivers, streams and drains and L. Wairarapa |
| SPR | Springflow |

*Minor flow components:*

| | |
|---|---|
| GWI | Groundwater inflow from adjacent older glacial sequences |
| GWO | Groundwater outflow into the sea |
| IRR | Irrigation returns |
| ABS | Abstractions |

**Figure 26: conceptual water balance for the Wairarapa Groundwater Basin.**

# 7. Groundwater Flow Model for the Wairarapa Groundwater Basin

## 7.1 Approach

The hydrogeological conceptualisation of the Wairarapa Groundwater Basin presented in sections 2 – 4 provides the basis for the construction of a numerical groundwater flow model.

The numerical model serves the primary purposes of ‘testing’ the conceptual interpretation of the regional groundwater system, and providing regional and sub-regional water balances. Modelling also provides important insights to the functioning of the groundwater system, the principal controlling processes operating within it, and their sensitivity to induced stresses such as groundwater abstractions.

The approach adopted in this modelling investigation has been to develop an initial, ‘first-cut’, three-dimensional steady state (‘time-instant’) simulation for the Wairarapa Groundwater Basin. This approach has entailed transforming the conceptual model, including the interpreted basin geometry (Section 4), boundary conditions, and the hydrostratigraphic units into a multi-layered numerical model grid. Accurate representation of the surface water environment – rivers, streams, springs and Lake Wairarapa has also been a prime focus, since it is evident that the recharge-discharge dynamics of the groundwater basin are controlled by groundwater-surface flow transfers.

Calibration of the model has been undertaken using both manual and automatic optimisation methods using regional groundwater levels and observed flows to and from rivers, as also spring discharge data. The calibration was then tested through a sensitivity analysis.

Following steady state calibration, a preliminary assessment of the impacts of current groundwater abstraction has been attempted by comparing the calibrated, no-pumping modelled water balance to a pumping scenario that represents current consented abstractions.

A very important outcome of the initial modelling study has been the identification of information gaps and additional data needs required to facilitate a detailed assessment of groundwater resource sustainability. Recommendations for further investigations required to develop and refine knowledge of the Wairarapa Groundwater Basin are presented in Section 9.

## 7.2 Model code

The USGS finite difference numerical code MODFLOW (McDonald and Harbaugh, 1988) was used to model the Wairarapa Groundwater Basin. The ‘Visual Modflow’ graphical data processing interface (Version 4.1, Waterloo Hydrogeologic, 2006) was used to build the model, prepare the input files and process the output data.

## 7.3 Finite difference grid design

MODFLOW uses a finite difference solution method that requires the use of a rectilinear, block-centered spatial grid and one or more layers. The Wairarapa groundwater model grid covers an area of 80,000m x 21,000m and has an even grid spacing of 500m as shown in Figure 27.

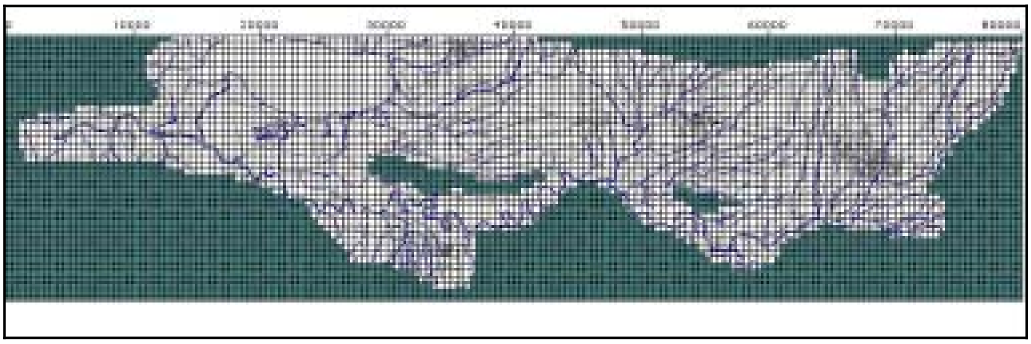


**Figure 27: model grid with inactive cells shown in green.**

The finite difference grid has been rotated and aligned with the Wairarapa Fault, which forms the western boundary to the basin. Rotating the grid this way also means that the principal regional groundwater flow vectors are aligned with the grid axes.

The model has been constructed simplistically with two layers to represent the stratified nature of the aquifer sequence with progressively more confined conditions developing in the sub-basins. The location of the layer boundary is not explicitly intended to represent an actual geological horizon except in the lower valley and Parkvale sub-basins where the layer boundary corresponds to an identified confined aquifer layer about 5-10m thick. This aquifer layer was subsequently modelled as a third layer of this thickness to facilitate the simulation of abstraction bores in the lower valley sub basin within a thick sequence of low permeability material. However, because of the very thin thickness of this third layer the model should essentially be regarded as a two-layer simulation.

Figure 28 shows a section along the length of the model to illustrate the layer structure and thickness of the modelled flow system. The base of the model represents the mQa surface as shown in the geological cross sections in (Figures 9-15) and Figure 16. The Lower Valley Sub-basin represents the deepest part of the model where the aquifer thickness is about 230m. Further up the valley, the aquifer thickness reduces to between 50 and 100m – with major changes in thickness occurring across the main faults as described in section 3.

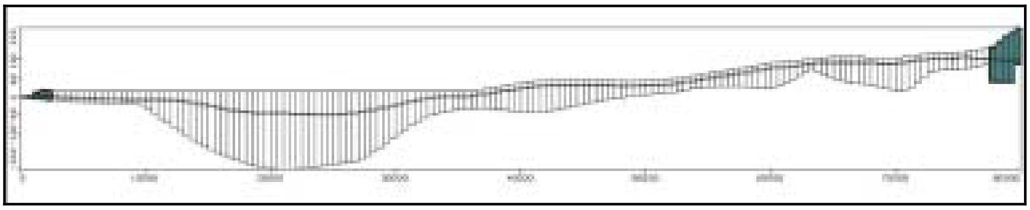


**Figure 28: longitudinal section through the model grid.**

## 7.4 Boundaries

Boundary conditions are mathematical statements specifying head or flux dependent conditions at boundaries within the aquifer system, and also within the active model domain. In steady state simulations, the boundaries largely determine the flow pattern and therefore correct selection of boundary conditions is critical to the success of the model.

Physical boundaries are formed by the physical presence of, for example, an impermeable body of rock, or the presence of a body of surface water such as a lake or river. There are also non-physical (hydraulic) boundaries such as groundwater divides and flowlines – these are transitory and are generally controlled by topography.

The steady state model constructed for the Wairarapa uses the following physical boundary conditions:

### 7.4.1 Specified flow boundaries

No-flow (impermeable) boundaries are present when the flux of groundwater across the boundary is zero. The Wairarapa groundwater basin boundaries are modelled as a no-flow condition and simulated by the placement of inactive model cells outside the basin boundaries (Figure 27). The western margin of the basin is constrained by 'impermeable' greywacke bedrock along the Wairarapa Fault. The remaining groundwater basin boundaries represent the contact between the 'active groundwater system' defined by younger Quaternary and Holocene sediments, and the much older, relatively impermeable eastern hills.

Two internal impermeable blocks are also simulated with no-flow conditions – Te Marie Ridge and Tiffen Hill. These have been represented as blocks of inactive cells, increasing in width with depth.

### 7.4.2 Specified head boundaries

A specified head boundary (or constant head boundary) has been used at the coastline to represent the ocean. Constant head values of 0m have been assigned to a row of cells at the southern extremity of the model some 2km offshore to simulate the head control of the ocean on aquifer levels in the Onoke Sub-Regional Flow System.

### 7.4.3 Head-dependent flow boundaries

Flow across this type of boundary is calculated using the difference between a specified head on one side of the boundary, and the model-calculated head on the other. Leakage to or from a river, lake, or spring is simulated using this type of boundary.

*Lake Boundary (RIV):* Lake Wairarapa has been simulated using the River Package (RIV). The lake level has been fixed at 0.5m amsl and the conductance (CRIV) of the lake bed has been set at a nominal 100$m^2$/day. The bed conductance relates to the 500m x 500m model cell size and is equivalent to a vertical hydraulic conductivity of the lake bed of 4 x $10^{-4}$ m/day to represent the accumulation of low permeability lacustrine sediments.

*River Boundaries (STR1):* River Boundaries have been simulated using the MODFLOW STR1 Package. The bed profiles of each of the main rivers – Ruamahanga, Waipoua, Waingawa, Mangatarere, Waiohine, and Tauherenikau, were plotted using detailed bed survey data undertaken between 2002 and 2004. The river profiles were then divided into reaches based the bed slope. The heads in the stream cells were fixed at an approximation of the average depth of water in the channels following consultation with GW field staff. Appendix 4 contains the bed profiles for each of the rivers.

Bed conductance is a parameter used by MODFLOW to control the flow of water to and from the underlying aquifer. This parameter is not easily measurable and is usually derived through trail and error in the calibration process. Bed conductance is calculated using the length of the river in each river cell (L), the width of the river (W) in the cell, the thickness of the river bed (M), and the hydraulic conductivity of the river bed material (K). The stream bed conductance, C, is described as:

$$C = K L W / M$$

The river width varies between about 10m 30m based upon the estimated average river widths for each reach. Streambed vertical hydraulic conductivity values were originally set at 20m/day for all rivers, which appeared to allow the correct (observed) flows between groundwater and the rivers. The vertical conductivity value equates to the streambed conductance of about 30-40,000$m^2$/day per 100m reach of river, depending upon channel width. These values were derived during model calibration against the concurrent flow gauging data (Appendix 3).

*Spring Boundaries (DRN):* All the major spring systems listed in Table 9 have been simulated using MODFLOW's Drain (DRN) package. This type of boundary will only permit water to be taken out of the aquifer when the water table is modeled above the base of the drain cell (the spring elevation). When the water table drops below the base of the drain cell, flow into the spring ceases. Flow from the aquifer to the drain cells (springflow) is controlled by the value used for the drain bed conductance and the drain bed elevation. The drain bed elevations were estimated from topographic maps, and the bed conductance values were derived through a trial and error process during calibration. Table 10 shows the bed conductance values adopted.

**Table 10: Calibrated Drain Conductance Values for Spring Systems**

| Spring System | Bed vertical hydraulic conductivity (m/day) | Bed conductance ($m^2$/day) |
|---|---|---|
| Masterton Springs | 0.04 | 10,000 |
| Te Ore Ore Springs | 0.002 | 500 |
| Parkvale Springs | 0.08 | 20,000 |
| Greytown/Papawai springs | 0.02 | 5,000 |
| Otukura/Battersea system | 0.04 | 10,000 |
| Tauherenikau Springs | 0.04 | 10,000 |

## 7.5 Steady state model calibration

Calibration of the steady state model has a dual purpose. The first is to provide an initial test of the conceptual groundwater model developed for the Wairarapa Valley groundwater basin and assess its limitations and assumptions. The second purpose of the calibration is to provide a basic water balance, both on a regional scale, and a sub-regional scale as a basis for estimating the sustainable groundwater resource.

Calibration of the steady-state Wairarapa groundwater model has involved the iteration of several stages of parameter estimation and calibration testing:

- Initial estimation of aquifer parameters and recharge within the ranges identified from field measurements and calculations, and manual (forward) steady-state calibration.

- Modification of parameters and manual calibration (forward) against steady-state groundwater levels in monitoring wells, and to water balance estimations (river losses and gains).

- Optimisation of parameters using the model-independent parameter estimator – PEST (Doherty, 1998). PEST also performs a sensitivity analysis to assess parameter uncertainty.

### 7.5.1 Calibration targets

Steady state calibration was initially performed using average groundwater level data. Few concurrent groundwater level monitoring datasets are available upon which to base a representative piezometric map for the whole valley. Assessment of the available data concluded that concurrent groundwater level measurements made in November 1985 would provide a good representation of ‘average’ aquifer conditions. This dataset is not influenced by significant groundwater abstractions. Such early summer data are assumed to portray a ‘pseudo’ steady-state condition suitable for model calibration purposes.

Figure 18 shows the contoured groundwater level data for November 1985 after filtering out very deep bores in the lower valley with high artesian heads.

In general, although there are small vertical gradients in most areas, when plotted together the data provide a consistent flow pattern across the basin. Further discussion of the regional flow regime is provided in Section 5.2.

Measured flow losses and gains in the rivers from concurrent gauging work (Appendix 3), and springflow measurements (Table 9) were also used as ‘loose’ calibration targets. These data provide guidance on the location and magnitude of flows between the groundwater system and rivers to check that the model simulates losing and gaining reaches. Because there are so few gaugings, no attempt was made to calibrate the model exactly to this information. Similarly, since there are even fewer sporadic flow gaugings and visual flow estimates for the spring systems, this information has been used to guide model calibration only.

### 7.5.2 Input parameter zones

*Hydraulic conductivity*

The range of hydraulic property values for the different hydrostratigraphic units is provided in Table 3. Seven hydraulic conductivity zones were used to represent the principal hydrostratigraphic units and gradational units between some of them. Table 11 shows the values of horizontal (x,y) and vertical (z) hydraulic conductivity derived from model calibration. Figures 29 and 30 show the spatial distribution of the zones for model layers 1 and 3.

**Table 11: Hydraulic conductivity zones (calibrated values)**

| Hydrostratigraphic Unit | MODFLOW Zone No. | Horiz. hydraulic conductivity m/day | Vertical hydraulic conductivity m/day |
|---|---|---|---|
| Outwash fan deposits | 11 | 24 | 0.2 |
| Q1 Gravels | 2 | 232 | 50 |
| Reworked gravels (west of Te Maire Ridge) | 7 | 60 | 0.04 |
| Lower Valley Transition zone (1) | 8+9 | 50 | 2 |
| Lower Valley Transition zone (2) / Parkvale | 4 | 60 | 0.005 |
| Martinborough Terraces | 6 | 1 | 0.01 |
| Lake sediments | 3 | 4 | 0.04 |

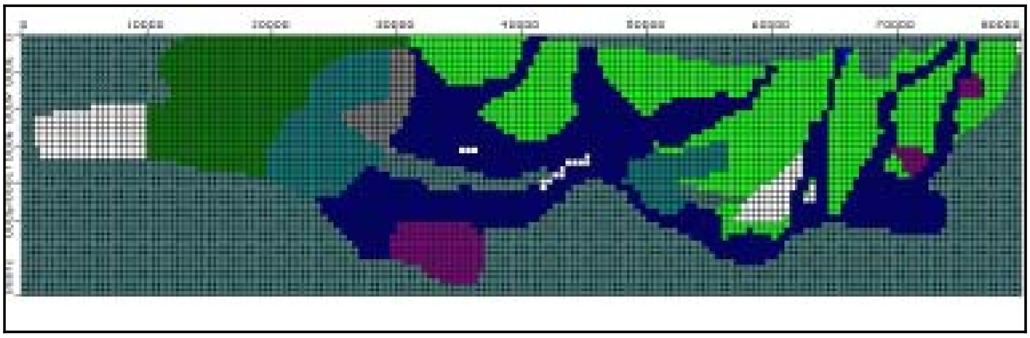


Figure 29: hydraulic conductivity zones for Layer 1.

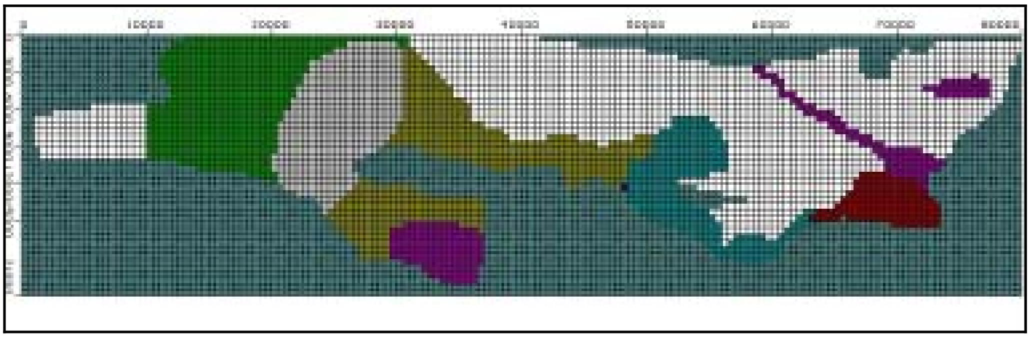


Figure 30: hydraulic conductivity zones for Layer 3.

*Recharge*

Figure 31 shows the four recharge zones used in the steady state model. These correlate to the rainfall isohyets (Figure 22) and to perceived soil/shallow geology conditions. The rates assigned to each zone range from 200 to 270mm/year – at the lower end of the range suggested by the soil moisture balance calculations (Section 5.5; Table 7).

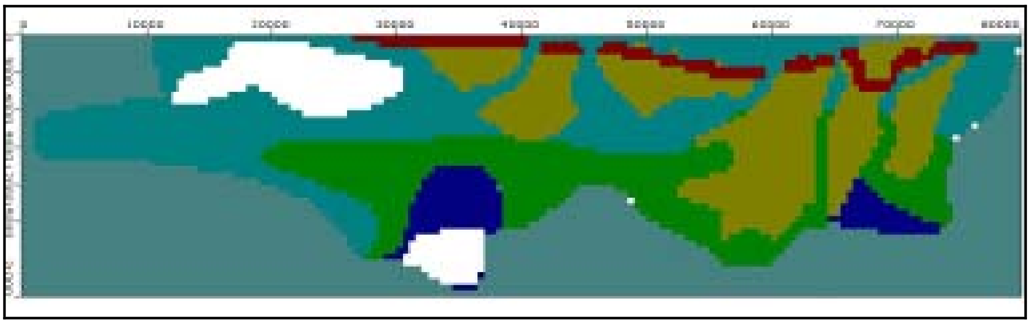


Figure 31: recharge zones.

## 7.6 Steady state model calibration results

The first model run using initial starting conditions for aquifer parameters and boundary conditions immediately provided a reasonable calibration to observed groundwater levels. Refinement of the calibration subsequently involved a number of model runs to attain an improved match between observed and modeled groundwater heads, and to water balance targets (river losses/gains and springflow). This refinement was a trial and error process involving adjustment of model parameters – hydraulic conductivity, recharge and bed conductance values (streams and drains).

### 7.6.1 Parameter estimation

The parameter estimation model, PEST, was used to further refine the model calibration and to assess the sensitivity of some of the parameters and the level of uncertainty inherent in the simulation. PEST automatically adjusts parameters within a specified range until the fit between the model outputs and the observed data (groundwater heads) is optimized. PEST was only run to optimize hydraulic conductivity values for all zones (vertical and horizontal).

PEST also calculates a relative sensitivity, which is a measure of the sensitivity of all model outputs to a particular parameter. If a parameter has a low relative sensitivity, it will be poorly estimated. Table 12 shows the outputs from PEST and the sensitivity analysis.

**Table 12: Parameter Optimisation and Sensitivity Analysis**

| Hydraulic conductivity zone | Relative Sensitivity (unitless) | Optimized Value |
|---|---|---|
| kx 11 | 0.17 | 24 |
| kz 11 | 0.001 | 0.2 |
| kx 2 | 0.3 | 232 |
| kz 2 | 0.0003 | 50 |
| kx 3 | 0.1 | 4 |
| kz 3 | 0.11 | 0.04 |
| kx 4 | 0.52 | 60 |
| kz 4 | 0.02 | 0.005 |
| kx 7 | 0.23 | 60 |
| kz 7 | 0.05 | 0.04 |
| kx 8 | 0.04 | 30 |
| kz 8 | 0.04 | 0.02 |
| kx 9 | 0.05 | 50 |
| kz 9 | 0.0001 | 2 |

Table 12 shows several hydraulic conductivity zones in which parameters are poorly estimated, principally due to the cross-correlation between estimated parameters. These are generally the vertical hydraulic conductivity values for zones 2, 9 and 11, which are relatively insensitive to change. Transient model calibration would tend to improve the estimation of these parameters.

## 7.7 Modeled heads

A good initial steady state calibration to regional head patterns was achieved relatively easily. This result indicates that the conceptual model developed for the groundwater basin is valid, and that the regional simplifications and placement of boundary conditions simulate the essential principal features of the flow system.

Figure 32 shows the modeled heads at the end of the manual calibration process and Figure 33 shows a comparison between the observed and modeled groundwater heads with calibration statistics. The absolute mean calibration residual is 3.4m – which is the difference between the calculated results and the observed results and indicates a good calibration given the heterogeneity of the system and the simplified nature of the model layers. The root mean square (RMS) error is also a good measure of the calibration fit. The model shows an RMS of 4.7% indicating a good fit between calculated and observed values.

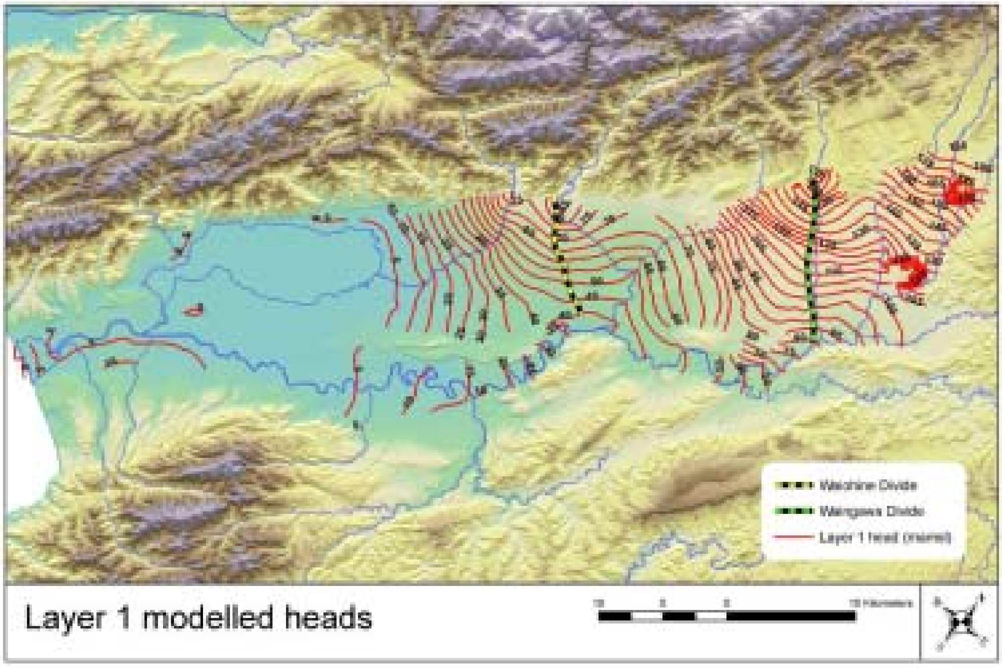


**Figure 32: modeled steady state heads for Layer 1.**

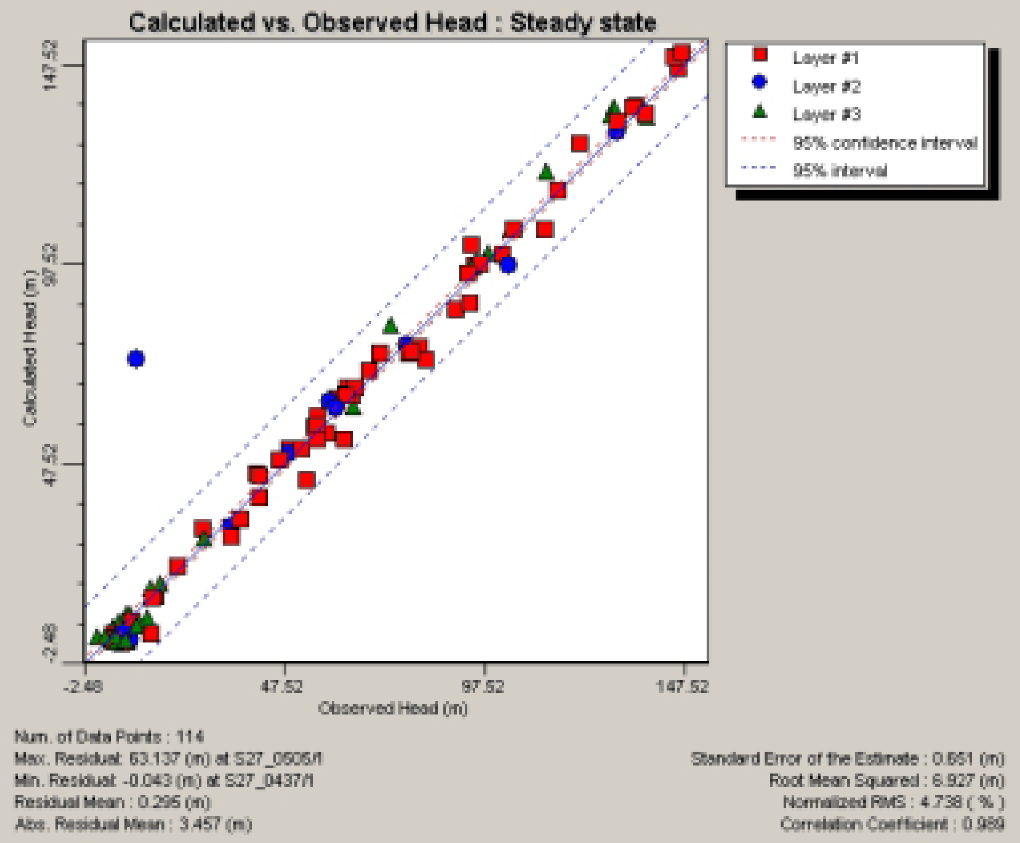


**Figure 33: comparison between observed and modeled groundwater heads.**

### 7.7.1 Regional and sub regional steady state water balances

The steady state regional water balance for the Wairarapa Plains groundwater basin is shown in Table 14. The balance indicates that most of the recharge from rainfall and river bed leakage discharges back into the rivers and springs down-gradient. A negligible amount of water flows to the sea at the coast. Lake Wairarapa is also shown to receive a significant inflow from groundwater, about 1.5 m$^3$/sec. Much of this water is derived from shallow Tauherenikau fan gravels where they enter the lake.

**Table 14: Steady State Water Balance**

| | Inflow (m$^3$/day) | Outflow (m$^3$/day) |
|---|---|---|
| Rainfall recharge | 547,220 | |
| River Leakage | 1,061,516 | 1,301,593 |
| Into sea (constant head) | | 4,494 |
| Into Lake Wairarapa | | 122,300 |
| Into Springs | | 180,350 |
| Totals | 1,608,736 | 1,608,737 |

Table 15 provides estimated water balances for the aquifer sub-regions to indicate the quantities of water entering and leaving each one. The discharges leaving the flow sub-regions represent groundwater outflows, which may discharge into the Ruamahanga River in the case of the Masterton and Carterton sub-regions, or flow as groundwater into the downstream sub-region. The water balances do not however take into account surface water flows entering and leaving the sub-regions, they show only the net flows from surface water to groundwater, or vice versa.

**Table 15: Sub-regional steady state water balances with and without consented groundwater abstraction**
(Figures in brackets show water balances with abstraction occurring at consented rate. Only wells consented to abstract more than 10 L/sec are included)

| Sub-Region | Inflow (x 1000 $m^3$/day) | Outflow (x 1000 $m^3$/day) |
|---|---|---|
| **Mokonui** | | |
| Wells | | 0 (2.9) |
| Rainfall recharge | 68 | |
| River Leakage | 248 (250) | 163 (162) |
| Springs | | 3 |
| GW Discharge from Sub-region to Masterton SR | | 90 |
| **Masterton** | | |
| Wells | | 0 (29.6) |
| GW Flow into SR from Mokonui SR | 90 | |
| Rainfall recharge | 44 | |
| River Leakage | 113 (120) | 195 (175.5) |
| Springs | | 46 (43.5) |
| GW discharge from Sub-region to Ruamahanga SR | | 6 |
| **Carterton** | | |
| Wells | | 0 (50.1) |
| Rainfall recharge | 121 | |
| River Leakage | 125 (139) | 142 (118) |
| Springs | | 65.6 (59) |
| GW flow out of Sub-region to Ruamahanga SR | | 38.5 (33) |
| **Featherston** | | |
| Wells | | 0 (26.6) |
| Rainfall recharge | 84 | |

| | | |
|---|---|---|
| River Leakage | 180 (184) | 87 (75.6) |
| Springs | | 25 (20.8) |
| GW flow out of Sub-region to Ruamahanga | | 15 |
| GW flow out of Sub-region to Lake SR | | 137 (129) |
| **Lake** | | |
| Wells | | 0 (50) |
| GW inflow from Featherston RS | 137 | |
| GW inflow from Ruamahanga SR | 3 | |
| Rainfall recharge | 111.5 | |
| River Leakage | 1.5 (3.9) | 93 (66.4) |
| Springs | | 37 (30.7) |
| Into Lake | | 122 (106) |
| GW Flow out of Sub-region to Onoke SR | | 0 |
| **Martinborough** | | |
| Wells | | 0 (3.3) |
| Rainfall recharge | 17 | |
| GW Flow out of Sub-region to Ruamahanga SR | | 17 |

## 7.8 Simulation of groundwater abstraction

Consented groundwater allocations account for a significant proportion of the water balance for the Wairarapa Valley, particularly during the summer months. The total allocated volume for all consents greater than 10 L/sec is 358,000 $m^3$/day. When all consents and permitted takes are considered, the total allocated volume is likely to be close to the estimated rainfall recharge on a regional basis (Table 14). Metering investigations conducted by Greater Wellington Regional Council indicate that consent holders generally use less than 30% of the allocated volume, even in particularly dry years (Jones and Baker, 2005). The total volume of groundwater actually abstracted is therefore likely to be less than 200,000 $m^3$/day, although further research is required to provide a more accurate assessment and sub-regional analysis.

Figure 34 shows the locations of groundwater consents (>10 L/sec) and the relative sizes of abstraction. To identify those bores likely to have a significant interaction with surface water, the map distinguishes shallow wells screened at less than 15m depth, and those greater than 15m depth. All shallower wells are located above the lower valley sub-basin within Q1 gravels near to rivers. The total allocated volume for these wells is 155,228 $m^3$/day. A large concentration of shallow groundwater abstraction is notable in the Greytown area around the

Waiohine River and Papawai springs. Also of note on Figure 34 is the concentration of larger abstractions close to the Ruamahanga River.

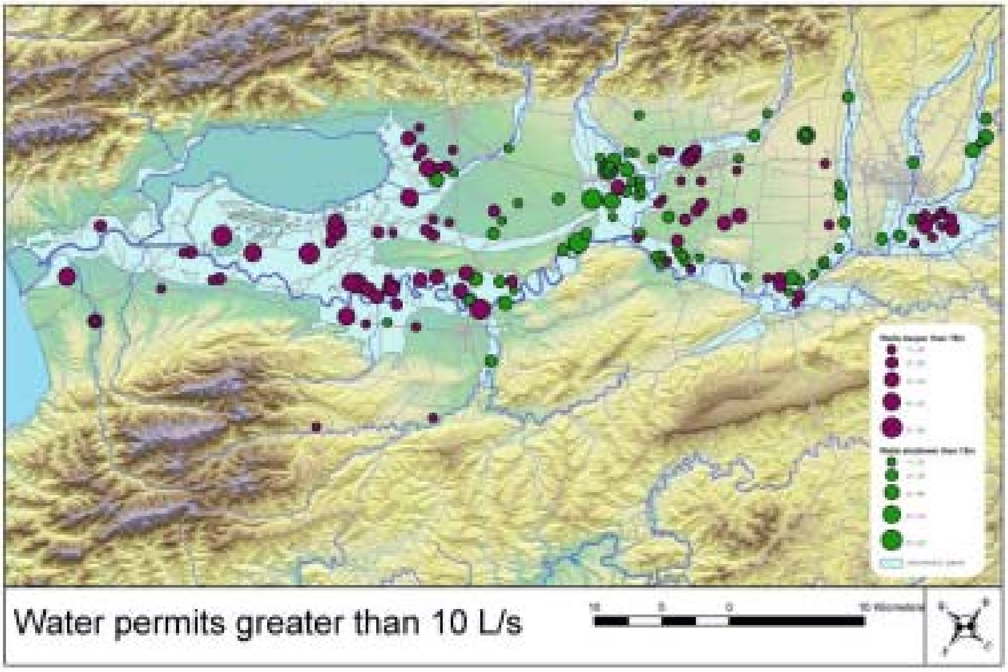


Figure 34: location of wells abstracting more than 10L/s.

Simulation of wells consented to take over 10 L/sec using the steady state model indicates the scale of potential abstraction impacts on the regional and sub-regional steady state water balances. Since most of the abstraction is seasonal, the steady state simulation will tend to over-estimate the effects of abstraction by assuming that pumping continues until the system reaches a new equilibrium. The abstraction simulation nevertheless provides an initial broad perspective of the scale of abstraction in the context of the sub-regional water balances, as well as an indication of the magnitude of potential effects on the recharge-discharge dynamics of the system.

Further work, through transient flow modeling is necessary to fully investigate the effects of abstractions on the surface water environment.

Table 15 includes the sub-regional water balances when the consented bores are simulated. Table 16 provides a more detailed water balance in terms of the effects that abstraction will theoretically have in rivers and springs by comparing the modeled non-pumping and pumping scenarios. The pumping scenarios incorporate the full consented volume (for takes over 10 L/sec) but contain only 75% of the consented wells due to lack of information on the screen locations for the remaining 25%. The total abstraction volume in the pumping simulation is therefore only 260,000 $m^3$/day, and therefore closer to the estimated actual volume abstracted.

**Table 16: Modeled effects of consented groundwater abstractions (>10 L/sec) on rivers and springs (using 100% consented volume, and 75% of consented bores)**

| Sub regional flow system | Total consented abstraction for takes >10 L/sec ($m^3$/day) | Total River flow depletion ($m^3$/day) | Total spring flow depletion ($m^3$/day) and % depletion of flow |
|---|---|---|---|
| Mokonui | 2,898 | 3,000 | 0 |
| Masterton | 29,594 | 26,500 | 2,500 (5%) |
| Carterton | 50,076 | 38,000 | 6,500 (10%) |
| Featherstone | 26,650 | 11,400 | 4,200 (17%) |
| Lower Valley | 48,953 | 29,000 | 6,300 (17%)<br>+<br>Lake inflow depletion 16,000 (13%) |
| Martinborough | 3,283 | - | - |

Tables 16 and 17 show that groundwater abstractions are a sizeable component of the water balance for the regional groundwater system, and that the model predicts significant changes to the groundwater recharge and discharge flow components. Table 16 shows that the Carterton and Lower Valley sub-regional flow systems are the most heavily utilized at about 50 ML/day each. The largest river flow depletions – caused by induced recharge and reduced baseflow, occur in the Carterton system, probably because this sub-regional flow system contains two large tributaries: the Waiohine and the Mangatarere rivers, and also has a large number of large takes in the shallow Q1 aquifers around Greytown. The Masterton and Lower Valley flow systems also show comparable depletions in river flow.

Table 16 also indicates that significant reductions in spring flows result from groundwater abstraction, and that the depletion effects increase down-valley. The steady state model suggests that up to 17% (as an average over the sub-region) of the spring flow may be depleted by groundwater abstraction during the summer months at present. Localised depletions may be significantly larger than this amount.

The steady state model provides a broad approximation on a sub-regional scale of the effects of abstraction on the groundwater balance. It also assumes that the irrigation abstraction continues for long enough so that the groundwater system reaches equilibrium. The latter would probably never occur. More detailed transient modeling focused upon particular areas perceived to be under stress from abstraction is therefore needed.

# 8. Summary and conclusions

**A.** Greater Wellington Regional Council has embarked upon a major review of the geology and conceptual hydrogeology of the Wairarapa Groundwater Basin to help sustainably manage the use of a major regional water resource.

**B.** The study provides a review of the geology and basin tectonics of the Wairarapa Valley as a basis for developing a coherent regional conceptual groundwater model. The review has highlighted the complexity of the geological and groundwater environment resulting from the combined effects of major active faulting, folding and subsidence, as well as sea level changes in response to glacial cycles. A large amount of bore log and monitoring information, and number of separate sub-regional studies, have been relied upon to formulate the conceptual model.

**C.** The Wairarapa Groundwater Basin contains a series of tectonically controlled sub-basins and regional flow controls relating to displacement along major intra-basin cross-cutting faults and uplifted basement blocks at Tiffen and Te Maire. The main sub-basins represent locally important groundwater resources that are utilised for irrigation purposes, basins are: Te Ore Ore, Parkvale (including Carterton) and the large Lower Valley sub-basin. The latter, beneath Lake Wairarapa, is a dominant regional feature, which continues to subside at a high rate. Uplift of the coastal area has largely isolated the groundwater basin from the sea.

**D.** A number of coalescing alluvial and glacial outwash fans fill the Wairarapa Basin, with the distribution of higher-yielding aquifer zones being influenced by depositional environment and sediment reworking. Six hydrostratigraphic units have been recognised on the basis of lithology, bore yields and aquifer properties. The most productive unit is the shallow Holocene (Q1) Gravels that exhibit high transmissivity and a strong connection with the surface water environment and locally re-worked gravels within sub-basins. The majority of large irrigation wells are screened within these gravels. The groundwater basement, defined by the top of the mQa unit that coincides with the base of Q6 (Waimea Glacial gravels), has an average depth of 50m but ranges from <10m to over 200m beneath Lake Wairarapa.

**E**. The conceptual groundwater model recognises a strongly interconnected groundwater-surface water environment. Thorough understanding of the nature of this interaction is extremely important for the sustainable management of both surface water and groundwater resources. Little work has been carried out to investigate the detailed interaction between aquifers and rivers, springs or wetlands in the Wairarapa.

**F.** Natural outflows from aquifers in the Wairarapa Groundwater Basin occur as springflow, river baseflow, and seepage into lakes and wetlands. Conversely, the higher reaches of many of the Wairarapa rivers are important groundwater recharge sources as they are observed to lose large quantities of flow to aquifers. Surface water ecosystems are therefore linked in many ways to the recharge-discharge dynamics of the regional groundwater system. The impacts of abstracting groundwater in the vicinity of groundwater dependent ecosystems such as rivers, springs or wetlands can be significant, particularly during low flow periods.

**G.** The Wairarapa Valley contains a large number of springs associated with major active cross-valley fault lines or with topographic features. Although ecologically important, there is very sparse information on the seasonal flow regimes of most springs and their sensitivity to climatic changes and groundwater abstractions. Average spring discharge is estimated to be about 2,500 L/sec (216 ML/day).

**H.** The conceptual hydrogeological model, and the observed regional groundwater flow patterns, provide information for the existence of distinct groundwater flow sub-regions. The boundaries between the sub-regional flow systems are either physical (such as faults and uplifted impermeable material), or hydraulic (groundwater divides). Eight sub-regional flow systems have been identified in the Wairarapa Groundwater Basin: the Mokonui, Masterton, Carterton, Ruamahanga, Featherston, Martinborough, Lower Valley and Onoke ‘Sub-regional Flow Systems’.

**I.** The hydrogeological conceptualisation of the Wairarapa Groundwater Basin has provided the basis for the construction of a numerical groundwater flow model. The numerical model serves the primary purposes of ‘testing’ the conceptual interpretation of the regional groundwater system, and provides regional and sub-regional water balances. Modelling has also provided important insights to the functioning of the groundwater system, the principal controlling processes operating within it, and their sensitivity to induced stresses such as groundwater abstractions.

**J.** Preliminary steady-state numerical modelling has provided confidence in the conceptualisation of the system and has also helped confirm the sub-regional flow systems. The steady state regional water balance for the Wairarapa Plains groundwater basin indicates that recharge from river bed leakage (1M $m^3$/day) is almost double rainfall recharge. The dominant aquifer discharge process is leakage back into rivers (1.3M $m^3$/day), with relatively minor quantities discharging as spring flow (0.2M $m^3$/day), and into Lake Wairarapa (0.1M $m^3$/day). A negligible amount of water flows to the sea at the coast. Lake Wairarapa is also shown to receive a significant inflow from groundwater, about 1.5 $m^3$/sec. Much of this inflow is derived from shallow Tauherenikau fan gravels where they enter the lake.

**K**. Groundwater abstractions are a sizeable component of the water balance for the regional groundwater system. The total allocated volume for all consents greater than 10 L/sec is 358,000 $m^3$/day. When all consents and permitted takes are considered, the total allocated volume appears to be close to the estimated rainfall recharge on a regional basis. However, metering investigations indicate that consent holders in reality use less than 30% of the allocated volume, even in particularly dry years. The total volume of groundwater actually abstracted is therefore likely to be less than 200,000 $m^3$/day, although further analysis and metering information is required to confirm this assertion. Due to the lack of widespread metering of large takes, the volume of groundwater currently used is unknown. This limitation greatly hinders assessment of the sustainable groundwater resource. The Carterton and Lower Valley sub-regional flow systems appear to be the most heavily utilised at about 50,000 $m^3$/day each (consented allocations). Most large irrigation wells are located within Q1 gravels near to rivers and a large concentration of shallow groundwater abstraction is notable in the Greytown area around the Waiohine River and Papawai springs, and close to the Ruamahanga River.

**L.** The model predicts significant changes to the groundwater recharge and discharge flow dynamics of most sub regions as a result of abstraction. The biggest river flow depletions occur in the Carterton system, probably because this sub-regional flow system contains two large tributaries (the Waiohine and the Mangatarere rivers), and also has a large number of large takes in the shallow Q1 aquifers around Greytown. The Masterton and Lower Valley flow systems also show comparable depletions in river flow as a result of groundwater abstraction.

**M.** Significant reductions in spring flow result from groundwater abstraction. The steady state model predicts that up to 17% (as an average over the sub-region) of the spring flow may be depleted by groundwater abstraction during the summer months. Localised depletions may be significantly larger than this value.

# 9. Recommendations

## 9.1 Further work objectives

It is recommended that a second stage of advanced investigation is implemented to build upon the geological and hydrogeological models developed to date. The 'Stage 2' investigation phase would have the following purpose:

***To provide a sound technical foundation for the practical and effective sustainable allocation of groundwater resources in the Wairarapa Valley.***

The objectives of the advanced work are to:

- Refine the conceptual and numerical groundwater models by addressing critical information gaps by undertaking field investigations and further analysis of existing information.
- Construct a transient numerical model capable of accurately simulating the temporal behaviour of the groundwater system and its responses to stresses such as abstraction and climate change.
- Develop selected local-scale detailed numerical models in areas identified as being heavily utilised with ecosystems vulnerable to groundwater abstraction.
- Improve the understanding of groundwater-surface water interconnections by completing selected detailed case studies in high-priority areas.
- Define groundwater management objectives focused upon protecting the environmental values of freshwater ecosystems. These objectives should be based upon the ecological values, sensitivity and functioning of freshwater ecosystems (springs, streams, wetlands).
- Develop a proposal for groundwater resource allocation and quantify sub-regional allocation limits.
- Review Greater Wellington's groundwater and surface water monitoring network to ensure it is consistent with the conceptual model.
- To achieve the project objectives, a number of fieldwork activities and enhanced data analysis stages are recommended.

## 9.2 Proposed physical investigations

### 9.2.1 Fieldwork Theme 1: Understanding groundwater – surface water interconnection

The investigation outcomes presented in this report identify the importance of groundwater and surface water interconnection. Current understanding of the nature of this interconnection, and its sensitivity to both groundwater and surface water abstractions, as well as climatic change is very limited. The steady state numerical model, sparse concurrent gauging data, and the high concentration of large abstraction wells close to river and spring systems, highlights the importance of understanding surface water and groundwater interconnections in the Wairarapa Valley.

An important work theme is therefore focused on improving understanding of how surface waters and groundwater interact, and how groundwater abstractions impact on surface freshwater ecosystems

The following fieldwork activities are recommended:

*Concurrent gauging surveys*

At least two concurrent gauging runs should be undertaken in the next year for all major tributaries to the Ruamahanga River. These surveys should be designed and rationalised on the basis of currently available information. The aim of this work will be to characterise the temporal nature of groundwater – surface water interaction.

*Sub-catchment case studies*

It would be valuable to select example river reaches, or ‘type localities’, and undertake detailed case studies to investigate the nature of groundwater-surface water interconnection, and the sensitivity of the interrelationship to groundwater abstraction.

The case studies could involve low-flow gauging of rivers and springs, surveying, drilling of shallow piezometers, and establishment of level and flow monitoring sites, installation of monitoring equipment, localised geophysical surveys, and water quality studies. Controlled testing of existing wells close to rivers could be conducted to assess stream/river depletion effects. Case studies need to be consistent with the Council’s existing work program for assessing in-stream flow requirements of surface water bodies.

Suggested example reaches include:

- The Waiohine – Papawai system in the Greytown area (Q1 gravels, gaining/losing river reaches, large spring discharges, large shallow groundwater takes, and has high ecosystem value)

- Tauherenikau River and associated spring systems (high abstraction area, strong interconnection between groundwater and surface water, potential recharge area for the Lower Valley sub-basin aquifers and intervening Kahutara area).

- Ruamahanga River – middle reach between the Waiohine confluence and Kahutara-Dyerville (large concentration of large, generally shallow irrigation abstractions, unknown nature of interaction between groundwater and surface water, high ecological value).

Outcomes of the case study investigations would be the characterisation of groundwater-surface interconnection, and improved understanding of surface water depletion effects. This information could lead to the formulation of guidelines for the Wairarapa Plains, and for the specific sub-catchments studied, for the assessment of depletion effects.

Another important outcome of the case studies would be the provision of information to improve the regional, and sub-regional simulation of groundwater-surface water interconnections. Improved confidence in the models would enable them to be used more effectively for resource management purposes.

*Spring surveys*

Little information is currently available on the Wairarapa spring systems: their spatial distribution, flow regimes, source areas and water quality.

A field survey and mapping of Wairarapa springs and spring-fed wetlands, including assessments of their ecological/cultural/economic significance is required. It is important to develop an inventory of regionally important groundwater dependent ecosystems.

The spring survey would entail identification of all large spring systems, their characteristics, flow regimes, source areas, water quality, ecology, utilisation and catchment characteristics. Principal springs would be visited regularly for gauging and sampling. Consideration should also be given to the establishment of permanent flow monitoring sites on principal spring systems.

### 9.2.2 Fieldwork Theme 2: Hydrogeological investigations

Important information gaps in the hydrogeological characterisation and analysis of the Wairarapa groundwater basin exist. Data needs include:

- Concurrent piezometric surveys
- Improved geological knowledge in some areas
- Additional water chemistry/isotope data.
- Improved groundwater abstraction (actual vs. consented) and water demand information

*Piezometric surveys*

In light of the conceptual groundwater model presented in this study, the first stage of this activity should be a thorough review of the spatial distribution of monitoring sites, followed by recommendations for additional sites and deletion of obsolete sites.

Concurrent surveys of all groundwater level monitoring sites should be programmed prior to the next irrigation season (Nov/Dec 2006) and again in late March 2007.

### *Exploration drilling*

A drilling programme, whilst desirable, would be considerably expensive. We consider that the project budget could be used more productively on other components of the recommended work programme.

Should it become feasible to drill an exploration well, it should be sited where there is a critical information shortage and where there is a compelling need to understand the local groundwater flow system due to a high demand on the resource. Drill holes should be carefully logged and sampled in order to obtain a detailed stratigraphic log. The log can then be compared to the logs for other bores in the area to develop a more detailed understanding of the local groundwater system.

A potential target drilling site is:

- lower valley/Kahutara area – the transition zone with the lower valley basin, which is poorly understood and where there is a significant irrigation demand. Drilling and testing of a well in this area would help to understand the aquifer sequence, the connectivity between aquifers and recharge sources.

Drilling should be followed by a carefully designed aquifer testing programme using existing bores as observation sites. Alternatively, testing using existing wells could be feasible.

### *Water quality sampling*

Age dating, in combination with hydrochemistry and stable isotope analyses, allows for valuable insights into the Wairarapa groundwater basin, which help support and build the conceptual model for the system. Morgenstern (2005) analysed available information using dating results derived from a few key sites since 1983, as well as new data from additional sites sampled in 2005. There is clear scope and value in building on this work and tailoring the sampling program to the new conceptual model to test assumptions and refine the model.

### *Water demand and abstraction analysis*

Evaluation of the actual and potential effects of abstraction is hindered by a lack of knowledge about the quantity of water actually taken by consent holders, and the potential future irrigation demand. Further modeling will require this information to assess the sustainability of the resource, and the potential effects of abstractions on the regional and sub-regional water balances. We recommend that a comprehensive metering program be implemented, and that a study be conducted to enable the actual irrigation take to be evaluated more robustly, possibly using a combination of metering data, physical variables (such as climate, soil and crop data), and experience from elsewhere in New Zealand.

Evaluation of the maximum and expected irrigation demands and spatial distribution of the future demand is also required. This evaluation can be carried out using potential crop water demand analysis and assessment of the suitability of land for irrigation based on soil types, topography, and availability of groundwater.

### 9.2.3 Theme 3: Monitoring review

*Low-flow surface water monitoring review*

Surface water monitoring in the Wairarapa Basin has historically focused upon high-flow characterisation and flood warning. In recent years, additional sites have been installed that focus on low-flow conditions. We believe that conjunctive management of groundwater and surface water resources is necessary to sustainably manage the area's water resource given the high degree of interconnection between surface water and groundwater. Reviewing, and perhaps expanding, the Council's existing low-flow gauging schedule is therefore necessary. Low flow gauging sites would be focused upon protecting minimum flows in the major river, stream and spring systems, and would be a critical component of a prospective groundwater management strategy for the region. The location, design and low-flow rating of sites should be undertaken by GW hydrology staff.

The identification of the groundwater sub-regions suggests that some, such as the Masterton and Carterton systems, have distinct 'discharge points' into the Ruamahanga River (or associated shallow groundwater), and that the discharge from these sub regions could be monitored at specific locations on the river. If there is agreement with this conceptualisation, thought may be given to establishing permanent monitoring sites on the Ruamahanga near to these locations. Such sites would enable the water balances for these sub-regions to be monitored, as well as the assessment of abstraction-related stresses in the upstream sub-regions.

## 9.3 Stage two technical analysis

### 9.3.1 Transient flow modeling

Development of the steady state MODFLOW model has been successfully achieved and has helped to refine and understand the conceptual flow system. It has also been a necessary first step in developing a tool to assist with the sustainable management of the groundwater resource. However, this model is limited to the simulation of steady-state flow conditions – it does not simulate seasonal or transient flow conditions or transient system stresses such as recharge or abstraction. It also focused upon a regional ('bulk') representation of the groundwater basin and as such cannot accurately simulate local flow conditions.

It is clear, from our experience with the steady state model, the capabilities of the finite difference MODFLOW model are limited in terms of simulating the complex hydrogeology, layering structure, and interactions between surface water and groundwater. It is also difficult in MODFLOW to create sub models within the regional model, for areas that require more detailed examination.

We recommend the finite element code FEFLOW for the advanced (Phase 2) modeling phase. This code is regarded to be more suitable for the complex Wairarapa hydrogeological environment and facilitates the creation of detailed sub models.

Phase 2 modeling would include the following objectives:

- Construction and transient calibration of a transient finite element model incorporating the outcomes of additional fieldwork.
- Simulation of current and projected water demands.
- Development of ‘local’ models of selected sub-regions, or sub-basins, to simulate in detail, including the modeling of sub-catchment case study areas.
- Identification of areas vulnerable to groundwater abstraction.
- Development of sustainable abstraction limits for sub-regions based upon environmental objectives (such as minimum flow conditions in rivers and springs)
- Development of guidelines for the protection of surface waters from the effects of groundwater abstractions.

### 9.3.2 Abstraction scenario analysis

A major component of Phase 2 modeling would be the simulation of current abstractions. At present, this variable is unknown and presents a major hindrance to the evaluation of the sustainable groundwater resource. A comprehensive metering program should provide enough information to calculate or project annual abstraction quantities. Projected irrigation water demands may be available, but should be assessed if they are not (refer to Theme 1: Proposed Physical Investigations – Water Demand and Abstraction Analysis).

### 9.3.3 Recharge investigations

Basic soil moisture balance modeling has been done for some areas of the plains. The current model uses a very broad regional steady state approximation that should be developed further, and in more detail. More sophisticated models take into account runoff, for example the HortResearch model, SPASMO. The outputs from such a model can be applied to the groundwater model.

### 9.3.4 Coupled surface water-groundwater model

FEFLOW has the capacity to interface with the Mike11 surface water model thereby creating a more sophisticated coupled groundwater-surface water model. It may be possible to construct a basic Mike11 (low-flow) simulation for the Wairarapa Rivers.

### 9.3.5 Satellite imagery analysis

Satellite imagery can be useful in understanding recharge processes, locating discharge areas, identifying structures and shallow geology/soil conditions. Expert assistance would be required to help select the best images and interpret them.

### 9.3.6 Development of groundwater resource management objectives

Modeling of sustainable groundwater yields needs to be guided by a set of well-formulated and agreed sustainability criteria, such as: the environmental impacts of abstractions on rivers, springs, lakes and wetlands; and interference effects on other users. This activity ties in with the in-stream work on selected Wairarapa rivers currently being carried out by GW.

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# A review of Wairarapa geology
# - With a groundwater bias

Confidential

by J.G. Begg, L.J. Brown, M. Gyopari & A. Jones

Client Report
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The data presented in this Report are
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# CONTENTS

## SECTION A - GEOLOGY

**1.0 INTRODUCTION .......... 4**

- 1.1 Regional Geological Setting .......... 5

**2.0 PHYSIOGRAPHY .......... 5**

**3.0 MAJOR ROCK GROUPS .......... 6**

- 3.1 Unit 1—Torlesse composite terrane and Pahaoa Group (230 - 120 Ma) .......... 6
  - 3.1.1 Rock types .......... 6
  - 3.1.2 Relationship with underlying rocks .......... 6
  - 3.1.3 Distribution .......... 6
  - 3.1.4 Hydrogeology .......... 6
- 3.2 Unit 2—Mangapurupuru Group, Glenburn Formation, Tinui Group, Mangatu Group (100 - 25 Ma) .......... 7
  - 3.2.1 Rock types .......... 7
  - 3.2.2 Distribution .......... 7
  - 3.2.3 Relationship with underlying rocks .......... 7
  - 3.2.4 Hydrogeology .......... 7
- 3.3 Unit 3—Palliser Group, Onoke Group (25 - 2.3 Ma) .......... 7
  - 3.3.1 Rock types .......... 7
  - 3.3.2 Distribution .......... 8
  - 3.3.3 Relationship with underlying rocks .......... 8
  - 3.3.4 Hydrogeology .......... 8
- 3.4 Unit 4—Early to middle Quaternary (2.3 Ma - 128 ka) .......... 8
  - 3.4.1 Rock types .......... 8
  - 3.4.2 Distribution .......... 9
  - 3.4.3 Relationship with underlying rocks .......... 9
  - 3.4.4 Hydrogeology .......... 9
- 3.5 Unit 5—Late Quaternary (<128 ka) .......... 9
  - 3.5.1 Rock types .......... 9
  - 3.5.2 Distribution .......... 12
  - 3.5.3 Relationship with underlying rocks .......... 12
  - 3.5.4 Hydrogeology .......... 12

**4.0 A GEOLOGICAL HISTORY .......... 12**

**5.0 STRUCTURE .......... 13**

- 5.1 Subduction interface .......... 13
- 5.2 Wairarapa Valley .......... 14
- 5.3 Wairarapa and Wharekauhau faults .......... 14
- 5.4 Uplift across the Lower Wairarapa Valley .......... 15
- 5.5 Subsidence at Lake Wairarapa .......... 15
- 5.6 Mokonui and Masterton faults .......... 16
- 5.7 Carterton Fault .......... 17
- 5.8 Brickworks Anticline and Taratahi Syncline .......... 17
- 5.9 Huangarua Fault and Harris Ridge Anticline .......... 17
- 5.10 Te Maire, Turanganui, Martinborough and other long valley faults .......... 17

## SECTION B - HYDROGEOLOGY

**6.0 INTRODUCTION .......... 18**
- 6.1 Holocene depositional processes .......... 19
- 6.2 Holocene deposits and tectonics in the Lower Wairarapa Valley .......... 19
- 6.3 Unconfined aquifers .......... 21
- 6.4 Deeper aquifers .......... 21
- 6.5 Structure of deeper aquifers .......... 22
- 6.6 The Taieri Plains – a structural analogue .......... 22
- 6.7 Water level, isotopes and hydrochemistry .......... 23

**7.0 CONCLUSIONS .......... 25**

**8.0 RECOMMENDATIONS .......... 26**

**9.0 ACKNOWLEDGMENTS .......... 27**

**10.0 REFERENCES .......... 27**

# EXECUTIVE SUMMARY

This review of the geology of the Wairarapa (with emphasis on the Wairarapa Valley) was undertaken to aid Greater Wellington Regional Council better understand the groundwater resources of the region, and will contribute to development of a defendable model for groundwater resource allocation, and management of water quality.

The rock types and their distributions in the Wairarapa are outlined in the report. The western side of the Wairarapa Valley is defined by the Wairarapa Fault, with upthrown greywacke basement rocks to the northwest, and Neogene and Early Quaternary marine deposits (largely impermeable) and Quaternary non-marine valley-fill deposits (commonly permeable) to the southeast. On the eastern side of the valley, Late Cretaceous to Early Quaternary deposits of marine origin are faulted against, or unconformably overlie various greywacke basement units. Within the Valley, Middle to Holocene non-marine and marginal marine deposits dominate, faulted against or overlying scattered areas of Neogene and basement deposits. The younger two of the five geological units differentiated here are the most significant for groundwater resources.

The southern part of the valley, from Carterton to Lake Ferry is apparently without crosscutting active faults, but hosts a series of long-valley faults on the southeastern side. While the full significance of these faults is uncertain, vertical offset of the Last Interglacial marine bench across The Narrows requires the presence of a significant active long-valley fault. This fault, and/or splays separate the Huangarua River and that part of the Ruamahanga River east of Te Maire ridge from the western part of the valley. Actively growing folds associated with faults have uplifted impermeable rocks of Late Neogene or Early Quaternary age to close to the surface on each side of The Narrows. Permeable deposits in the southernmost valley are restricted to The Narrows, and are unlikely to be thick.

Inland from this uplift, the presence of mid-late Holocene estuarine shells in a drillhole near the northern end of The Narrows indicates a likelihood that this area is actively subsiding. Lake Wairarapa is likely to be an actively subsiding local basin. The Taieri Basin is discussed as an analogue.

A number of active faults (the Carterton, Masterton, Mokonui and Wairarapa faults) cut across the axis of the Valley in the northern third of its extent, from Carterton to Mikimiki. The surface traces of these faults are associated with lines of springs and ponds. The faults influence thickness and dip of Quaternary deposits, and therefore groundwater storage and flow. Potential is identified to rationalise existing groundwater zones currently employed in the Wairarapa Valley through defining the likely three dimensional structure of Quaternary deposits that host known aquifers.

The review of geology of the Wairarapa Valley highlights the effect of active tectonics, sea level and climate change on hydrogeology of this area, and provides a basis on which to model the groundwater systems and rationalise groundwater management tools.

# SECTION A - GEOLOGY

## 1.0 INTRODUCTION

This geological report has been commissioned by Greater Wellington Regional Council to assist in a comprehensive review of the groundwater resources of the Wairarapa region. The groundwater resources of a third of the 29 designated groundwater zones (Butcher 1996 – Table 1a) of the Wairarapa Valley could be stressed, as indicated by a long term decline in groundwater levels. Also, allocation levels are >60% of the estimated safe yield. As a result moratoria on issuing additional water permits have been imposed for the zones where groundwater resources could be stressed.

The purpose of the groundwater review is to provide a robust regional-scale conceptual model for effective management achieving sustainable use of the groundwater resource under increasing demand. Writing of this report follows completion of a successful three day workshop at the Masterton Office of Greater Wellington in early June.

Compilation of this geological report is aided by the recent completion of 1:250,000 scale geological mapping of the region (Begg & Mazengarb 1996, Begg & Johnston 2000, Lee & Begg 2002), providing a reliable basis for understanding the surface geology, and allowing reasonable extrapolation to limited depth. For ease of reading the citation of references in this report is limited, but an extended list can be found in the references sections of Begg & Johnston (2000) and Lee & Begg (2002). Drillhole logs are used to constrain the subsurface distribution of the geological units identified at the surface. A summary is provided of the geology of the Wairarapa, with emphasis on the major rock groups, geological structure, river and marine depositional processes, and geological features such as active faults and folding that influence the occurrence and continuity of aquifers and aquicludes. The report outlines a geological context in which to place existing groundwater information, so that ultimately resource management decisions may be based on the best possible information on the spatial distribution of groundwater aquifers and their capacity to supply groundwater, to ensure that abstraction does not exceed recharge.

The report is divided into two subsections. The first describes the geology and structure of the Wairarapa Valley and the second summarises hydrogeological information. Following a summary of the regional geological setting and physiography, the first subsection describes the lithologies and distributions of five major geological units in the Wairarapa. This is followed by an outline of the geological history and identification of active structures.

The second subsection deals with various aspects of hydrogeology of the Wairarapa Valley and introduces the Taieri Basin as a possible analogue. This is followed by a series of conclusions.

## 1.1 Regional Geological Setting

The Wairarapa coast is about 65-125 km northwest of the Hikurangi Trough, the boundary between the Australian Plate (to the west) and the Pacific Plate (to the east) (Fig. 1). The Hikurangi Trough is a major break in the earth's crustal structure separating the two converging crustal plates. Their rate of convergence amounts to about 40 mm/year, and results in the thicker Australian Plate (made of lighter silica-rich continental crust) over-riding the thinner, denser Pacific Plate (made of dense basaltic rocks). Much of the strain associated with this collision is transferred to the crust that immediately underlies the Wairarapa and Wellington regions. Thus, the broad geomorphic zones of the axial (Tararua) ranges, the Wairarapa Valley and the Wairarapa hill country are expressions of the strain associated with the plate boundary. The top of the down-going Pacific Plate dips ever deeper to the northwest of the Hikurangi Trough, and can be found at depth (~10 km beneath the Wairarapa coast, and ~20 km beneath the eastern Tararua Range) beneath the Wairarapa landscape. Some of the strain associated with the boundary between the Pacific and Australian plates is transferred up through the over-riding Australian Plate to the ground surface in the form of active faults and folds. This deformation, both the broad regional strain and more local deformation associated with faults and folds influences the hydrogeological environment.

## 2.0 PHYSIOGRAPHY

The physiography of the Wairarapa Region is a result of the tectonic environment, the physical properties of the rock bodies that underlie it, and geomorphic processes. The region is topographically diverse, and is bounded on the northwest by mountains of the Tararua Range (Fig. 2) that reach an elevation of 1571 m. This mountainous area has steep, forested slopes, with fast flowing streams and rivers deeply incised into hard greywacke bedrock. The Wairarapa Valley to the southeast of the range is characterised by gentle slopes, mostly deforested and intensively farmed, braided channel streams and rivers bounded by terraces, that downstream form extensive floodplains, and lakes, lagoons and the beach at the Palliser Bay coast. Southeast of the valley, the Wairarapa hill country (Eastern Uplands; see Kamp 1992, Lee & Begg 2002) consists largely of steep hills, commonly cleared of forest and farmed, and streams and rivers incised into soft sandstone and mudstone. The Aorangi and Waewaepa ranges are exceptions with forest clad hill country of hard greywacke bedrock.

The physiography of the area impacts on the distribution of rainfall, with the Tararua Range receiving abundant rainfall throughout the year due to its elevation and location in the path of the west wind. The Eastern Uplands receive heavy rain from the relatively rare easterly weather systems, with limited rainfall from the westerly winds. Between these two areas of elevated land, the Wairarapa Valley occupies a rain shadow zone (although southerly winds bring rain). River and stream systems, fed largely by rainfall within the Tararua Range flow down the Wairarapa Valley. These include the Ruamahanga, Waingawa, Waiohine, Tauherenikau and Waiorongomai rivers. Less significant water contributors to the valley are streams derived from rain on the Eastern Uplands, the largest of which is the Huangarua River.

## 3.0 MAJOR ROCK GROUPS

The major rocks comprising the Wairarapa region are discussed in 5 aggregated units. This grouping is based on rock relationships (and hence geological history) and properties, with emphasis on application to the hydrogeology of the region (Fig. 3).

## 3.1 Unit 1—Torlesse composite terrane and Pahaoa Group (230 - 120 Ma)

### 3.1.1 Rock types

This unit of combines several recognised lithostratigraphic and tectonostratigraphic bodies making up the old, hard greywacke rocks of the Tararua mountain range and parts of the Eastern Uplands. The predominant rock type in this group is hard quartzofeldspathic sandstone, and interbedded mudstone. They commonly have mineralised cement, thus lack or have very little intergranular void space. Rare fossil occurrences within the unit show it ranges in age from Permian to Early Cretaceous. Some rocks in this group have been so thoroughly disrupted by ancient shearing that they consist of mixtures of blocks floating within a sheared mudstone matrix. These are known as melange and they commonly contain blocks of other rock types including basalt, chert and limestone. The rocks of the entire group are commonly deformed, often showing several generations of folding and faulting (including bedding plane shear) and are now usually steeply dipping.

### 3.1.2 Relationship with underlying rocks

In the South Island these rocks grade laterally into schist. Nowhere in the Wairarapa region is any relationship with underlying rocks exposed, and they are usually referred to as basement.

### 3.1.3 Distribution

These rocks make up the Tararua, Aorangi and Waewaepa ranges and a strip of land between White Rock and Tinui (Fig. 3).

### 3.1.4 Hydrogeology

Joints and non-mineralised shear and fault planes provide these rocks with some capacity to store groundwater. This forms the source of sporadic perennial springs. River and stream beds within the ranges are commonly incised within bedrock and thus have limited capability of hosting significant groundwater resources. However, rock eroded by the river systems in the ranges is the source of the gravel (rounded pebbles, cobbles and boulders) deposited where the gradients of the streams and rivers reduces, on the floodplains of the Wairarapa Valley. These alluvial gravel deposits of the floodplains contain the principal groundwater aquifers of the Wairarapa region.

## 3.2 Unit 2—Mangapurupuru Group, Glenburn Formation, Tinui Group, Mangatu Group (100 - 25 Ma)

### 3.2.1 Rock types

Conglomerate and breccia-conglomerate with a muddy matrix is exposed in places at the base and is overlain by mudstone. In the eastern Wairarapa, the alternating sandstone and mudstone of the Glenburn Formation and overlying Whangai siltstone, limestone (particularly in the east; e.g. Kaiwhata Limestone) and bentonitic mudstone (Wanstead Formation) dominates the unit. In the northeast, Weber Formation, mainly calcareous mudstone and limestone, overlies Wanstead Formation bentonitic mudstone. Marine fossils indicate a depositional age between about 100-25 million years ago.

### 3.2.2 Distribution

This unit occurs at the eastern margin of the Wairarapa area, but small outliers are found in the inland Awhea River catchment and between Te Humenga Point and the Turanganui River (Fig. 3).

### 3.2.3 Relationship with underlying rocks

Mangapurupuru Group conglomerate and mudstone unconformably overlie the Pahaoa Group basement rocks in places. In other places higher units appear to unconformably overlie basement rocks, but in the east, there are no known rocks underlying the Glenburn Formation.

### 3.2.4 Hydrogeology

Most of the formations within this unit are dominated by mudstone and siltstone, and have little or no capacity for water storage. In eastern Wairarapa Whangai Formation siltstone, where highly fractured, may have sufficient permeability to store water, and provide low volume but reliable springs. Bentonitic rocks of the Wanstead Formation have some ability to absorb water, and flow, as landslides.

## 3.3 Unit 3—Palliser Group, Onoke Group (25 - 2.3 Ma)

### 3.3.1 Rock types

These deposits consist of minor conglomerate, sandstone, siltstone, mudstone and limestone and are largely marine in origin. Thin alluvial conglomerate occupying a basal position in some areas is overlain by thick marine sandstone, siltstone, mudstone and limestone. As a general rule, the rocks of the unit become finer grained going up through the Palliser Group, but then coarser from near the base of the Onoke Group to the top. The unit can be typified as basinal marine deposits, and sequences differ locally. The Whakataki Formation in the east consists of a thick sequence of alternating sandstone and mudstone beds typical of a deep marine turbidite basin. Marine fossils are common within these rocks and show a depositional age range from about 24-2.3 million years ago (Ma).

### 3.3.2 Distribution

Palliser and Onoke groups and the partially coeval Whakataki Formation rocks underlie a belt between the Wairarapa Valley and older rocks in the east. Whakataki Formation rocks also underlie a coastal strip between Flat Point and the Mataikona River. They probably also underlie the younger deposits of the Wairarapa Valley.

### 3.3.3 Relationship with underlying rocks

Figure 18 in Lee & Begg (2002) illustrates local stratigraphy and stratigraphic relations around the Wairarapa.

### 3.3.4 Hydrogeology

The basal alluvial conglomerate beds, where present, are potential aquifers, although they are rarely thick. Thick sandstone formations within this unit could contain groundwater in intergrain pore space, but their structure, confining beds above and below and topography will determine their potential as an aquifer.

## 3.4 Unit 4—Early to middle Quaternary (2.3 Ma - 128 ka)

### 3.4.1 Rock types

Early to Middle Quaternary is here defined as the period of time between the start of the Quaternary (2.3-1.8 million years) to the start of oxygen isotope stage 5, 128,000 years ago. These deposits consist mainly of alluvial gravel and sand with minor silt and swamp deposits. These were deposited in response to tectonic uplift of the Eastern Uplands and the Tararua Range during a period of fluctuating climatic conditions. In places, rhyolitic volcanic ash (tephra) and loess horizons may be preserved. In particular, tephra allies to the Pakihikura Tephra (c. 1.6 million years old) are found in the Te Muna Formation, and Rangitawa Tephra (345 thousand years ago (ka)) is found within Ahiaruhe Formation. Gravel clasts in these units are typically rounded, of basement greywacke, and may be clast- or matrix- supported. Some of these gravel deposits have high porosities, but many are clay-bound and have relatively low permeabilities. Roundstone gravels are commonly interbedded with sand, silt, volcanic ash and loess strata of varying thicknesses. Although Early Quaternary beds in the north of the Wairarapa area may be partially estuarine, Wairarapa equivalents are alluvial or lacustrine in origin. Although geologically young, they may be tilted, folded and faulted, reflecting the active tectonic environment.

### 3.4.2 Distribution

Early to middle Quaternary rocks crop out in a belt along the western margin of the Palliser/Onoke group rocks on the eastern side of the Wairarapa Valley. Some more isolated areas crop out along the western side of the valley.

### 3.4.3 Relationship with underlying rocks

North of the area being considered here, Early Quaternary deposits are conformable on the marine Pliocene (Onoke Group) sequence, but this relationship is nowhere demonstrable within the Wairarapa area. Te Muna Formation alluvial deposits unconformably overlie the Pliocene beds or basement greywacke where the contact is exposed, but the time gap may not be great. Where contacts are exposed, Middle Quaternary Ahiaruhe Formation alluvial gravel unconformably overlies the Te Muna Formation or other older units.

### 3.4.4 Hydrogeology

Theoretically the Early and Middle Quaternary alluvial gravels should include aquifers in the Wairarapa area, but their value may be limited by their silt and clay-rich matrix, swamp, silt and loess interbeds, and structure.

## 3.5 Unit 5—Late Quaternary (<128 ka)

### 3.5.1 Rock types

Unit 5 is likely to be the most significant of the groundwater units of the Wairarapa region, so more attention is paid here to description (Fig. 4). The unit can be subdivided, and divisions mapped with some confidence at the surface. The three dimensional distribution of the units is more difficult to define on the basis of surface mapping, but normal stratigraphic principals constrain possibilities at depth. Some subunits within Unit 4 are likely to act as aquifers and are discussed below with those of Unit 5.

Useful subunits of Units 4 and 5 are (in stratigraphic order, from youngest to oldest) are shown in Table 1.

**Table 1** Useful subunits of Units 4 and 5, arranged in stratigraphic order, from youngest to oldest.

| Unit | Relative age | Material | Name | Depositional environment | Symbol | Absolute age (ka) |
|---|---|---|---|---|---|---|
| **5** | Holocene | Mud & silt | | Estuarine, lacustrine | Q1m<br>Q1s | 0-7 |
| **5** | Holocene | Gravel & sand | | Alluvial | Q1a | 0-10 |
| **5** | Late Otiran | Gravel & sand | Waiohine | Alluvial | Q2a | 10-25 |
| **5** | Middle Otiran | Gravel & sand | Ramsley | Alluvial | Q3a | 50-25 |
| **5** | Early Otiran | Gravel & sand | Waipoua | Alluvial | Q4a | 70-50 |
| **5** | Kaihinu Interglacial | Mud, silt, sand & minor gravel | Francis Line | Swamp, lacustrine | Q5m | 125-70 |
| **5** | Kaihinu Interglacial | Sand, some gravel | Eparaima | Marginal marine | Q5b | 125-70 |
| **4** | Waimea Glacial | Gravel & sand | | Alluvial | Q6a | 186-125 |
| **4** | Middle Quaternary | Gravel, sand, silt, loess, tephra | Ahiaruhe | Alluvial, swamp | mQa | >500-186 |
| **4** | Early Quaternary | Gravel, sand, silt, loess, tephra | Te Muna | Alluvial, swamp | eQa | c. 1000-500 |

Late Quaternary is here defined as the period between 128,000 years ago and the present day. Deposits of Late Quaternary age in the area are dominated by alluvial gravel deposited by the major rivers draining the Tararua Range. Some gravel deposits are clay-bound and interdigitated with fine grained overbank, swamp or lacustrine deposits. These alluvial gravels are commonly clast-supported, although sand and silt are components, and sandier and siltier horizons within, are common. Last interglacial swamp deposits have been mapped (Vucetich et al. 1996; Warnes 1992) in the Carterton area. Deposits of Late Quaternary age on the eastern margin of the Wairarapa Valley may be substantially more matrix-rich than in the central and western valley because many of the clasts within deposits there are derived from Unit 2, and break down relatively rapidly upon saturation and/or weathering. Some loess and volcanic ash horizons may be present.

In many cases, the ages of terrace surfaces can be estimated by looking at the coverbed sequence sitting on top of the underlying alluvial gravel. In practise, coverbed stratigraphy is commonly done through a combination of counting back loess and paleosol units and by recognition of the typical characteristics of individual loess, paleosol and tephra horizons. It is important to note that all outcrops/auger holes do not yield a complete coverbed sequence. The age of a surface is constrained by the most complete sequence that can be found covering gravels.

Alluvial gravel depositional ages can be determined by coverbed sequences as illustrated in Table 2.

**Table 2** Idealised table illustrating possible coverbed sequences on terraces of increasing age (from right to left). Age and age range of terrace abandonment by alluvial deposition is indicated at the top of each column.

| Holocene (Q1a) -<br>late Last Glacial (Q2a)<br><10,000-14,000 yr | Ramsley (Q3a)<br>30,000-<br>50,000 | Waipoua (Q4a)<br>80,000-<br>60,000 | Waimea Glacial (Q6a)<br>130,000-<br>190,000 |
|---|---|---|---|
| +/- topsoil | Topsoil<br>Ohakea loess | Topsoil<br>Ohakea loess<br>Paleosol<br>Rata loess | topsoil<br>Ohakea loess<br>paleosol<br>Rata loess<br>Chocolate paleosol<br>Porewa loess<br>Brown paleosol |
| ***GRAVEL*** | ***GRAVEL*** | ***GRAVEL*** | ***GRAVEL*** |

Degradational gravel surfaces that are of low elevation and are not overlain by loess units can be considered Holocene in age (Q1a). Aggradational gravels at a level higher than these, with cobbles sitting at the surface and, at best minimal development of commonly straw-coloured loess are late last glacial (14,000-18,000 yrs) in age (Q2a). Higher gravels with a coverbed sequence consisting of a single straw-coloured loess unit (Ohakea loess), commonly with a sandy-textured tephra (Kawakawa Tephra) near its basal third are Ratan (Q3a) in age. Gravels at higher elevation again are overlain by a commonly red friable loess (Rata loess; often with a paleosol developed in the upper third) as well as the straw-coloured Ohakea loess are Porewan in age (Q4a). Weathered gravels at higher elevations again have three loesses: a basal, commonly chocolate brown coloured Porewa loess with an overlying paleosol, the Rata loess with overlying paleosol, the Ohakea loess with tephra, sometimes with paleosol and topsoil. The paleosol developed at the top of the Porewa loess is commonly chocolate brown in colour and contains residues of fine-grained andesitic ash representing the c. 60,000 year "Middle Tongariro tephras". Loess and coverbed stratigraphy is not as well developed or is poorly preserved in the Ruamahanga River valley north of Masterton, possibly due to wind stripping.

Radiocarbon ages are a tool that may also be used to constrain the age of Late Quaternary deposits up to ages of about 30,000 to 40,000 years. For example, a radiocarbon age of >30 000 years (NZ 6118) was obtained for small branches (S26/f10) from a depth of 29.5 m in a well (WRC well no. 4H/1/45) near Carterton. The flowing artesian well is located on a surface mapped as the Waiohine surface by Warnes (1992) and Begg and Johnston (2000). The strata dated may represent Francis Line Formation swamp deposits of last interglacial age and the underlying confined aquifer penultimate glacial (Waimea Glacial) alluvial gravel.

### 3.5.2 Distribution

Most of the Late Quaternary deposits in the area occupy the central belt of the Wairarapa Valley (Fig. 3). Isolated valley floors with alluvial and marginal marine deposits of Late Quaternary age are scattered through eastern Wairarapa.

### 3.5.3 Relationship with underlying rocks

Most of the Late Quaternary gravel units comprise alluvial deposits that unconformably overlie all older rock units. They lap onto each of the units described above.

### 3.5.4 Hydrogeology

The younger components of this unit in the Wairarapa Valley form by far the most productive aquifer in the Wairarapa region. The large rivers draining the Tararua Range spill out into the Wairarapa Valley, depositing alluvial gravels as their course gradient declines. Water from these rivers recharges the permeable gravel aquifers of the valley.

## 4.0 A GEOLOGICAL HISTORY

Sand and mud of the various units of the Torlesse composite terrane were deposited in deep marine basins along the eastern margin of Gondwanaland in a compressional or transpressional setting during the Late Paleozoic to Early Cretaceous (Bradshaw 1989). Evidence suggests that deformation of these deposits (commonly involving bedding plane shear) commenced soon after they were deposited and continued until near the end of the Early Cretaceous. At this time, about 100 million years ago, a major, abrupt tectonic event marks the termination of deposition, with significant and widespread tilting, folding and faulting. One possible interpretation is that this tectonic event reflects the amalgamation of the various terranes of the Torlesse composite terrane (Begg & Johnston 2000). The Rakaia, Pahau, Waioeka terranes and probably the Pahaoa Group, all represented in the Tararua Range and Wairarapa, were amalgamated. The amalgamation event was probably the origin of at least some of the melange units found throughout the Torlesse composite terrane, including Esk Head terrane.

In eastern Wairarapa, Pahaoa Group (of Torlesse composite terrane) of late Early Cretaceous age is unconformably overlain by Mangapurupuru Group, also of late Early Cretaceous age. This unconformity is known widely throughout eastern New Zealand as the intra-Motuan unconformity (Moore & Speden 1984; Crampton 1997). It marks a significant change in rock hardness, metamorphism and structural complexity, which probably represents this tectonic event, interpreted as the cessation (or near-cessation) of Mesozoic active margin compressional tectonics.

Rocks representing the time between this fundamental change in the eastern New Zealand tectonic environment (about 100 million years) to about 25 million years, are those of Unit 2, the Glenburn Formation, and the Mangapurupuru, Tinui and Makatu groups. These rocks are characterised by marine deposition in subsiding basins with a generally decreasing supply of clastic material. The region must have been low-lying or submarine through this period of time, and the tectonic conditions that existed prior to deposition had been supplanted by a tectonically quiescent state. While the Tasman Sea opened during this period, the eastern continental margin was passive.

About 25-20 million years ago, a sudden change in depositional signature occurred across the Wairarapa region, from deposition of fine-grained sediments, to an influx of submarine landslides and sand deposition. Stratigraphy of marine units across the Wairarapa becomes less consistent and it is likely that local basins were developing. These changes are believed to result from re-activation of a compressional or transpressional tectonic regime with subduction at the Hikurangi margin. Emergence of the Wairarapa region proceeded through the Late Miocene and Pliocene, perhaps with emergence and westward tilting of the eastern coastal ranges before the slow retreat of the sea from the Wairarapa Basin. During low sea level stands local bioclastic limestone units reflect areas where the sea shallowed to suitable depths. By the start of the Early Quaternary, the shoreline had retreated almost as far as the southern Wairarapa coastline and the Wairarapa Basin was now a valley occupied by Tararua Range sourced rivers.

Emergence of the area coincided with the initiation of reverse faulting on the large regional faults still active to the present day. Hills and mountains grew from uplift associated with the faults, supplying the developing catchment systems with large volumes of greywacke cobbles. These gravels and associated sequences have been deformed by the active faults since deposition, and are now in some areas significantly deformed. Some time in the last 1 million years, the largely reverse faulting evolved into the dominantly strike-slip regime of today.

## 5.0 STRUCTURE

The intention of this section is to describe structures in the Wairarapa Valley that modify the distribution of late Quaternary deposits. The geological structure of the deposits in the valley outlined below has a significant influence on the distribution of groundwater units and may help understand confinement and flow between units.

### 5.1 Subduction interface

The subduction interface is a term given to the shallow-dipping fault that separates crustal plates at a convergent plate boundary, here the Pacific Plate and the Australian Plate (Fig 1). It lies at a depth of about 15 km depth beneath the Wairarapa coast and 30 km beneath the Tararua Range. Deposits on top of the Pacific Plate to the east are being scraped off on the leading edge of the Australian Plate, and underplated (thrust under) beneath the east coast of the Wairarapa. While the plates slide easily, one across the other to the east of the Wairarapa coast, they are locked from about beneath the Wairarapa coast to beneath the west Wellington coast. Strain associated with the relative motion of the two plates accumulates in the locked portion of the subduction fault and is released periodically as large earthquakes. Deformation at the surface associated with plate convergence over a long period of time has resulted in broad (long wavelength) patterns of deformation at the earth's surface, notably uplift of the Wairarapa coastal ranges, development of the Wairarapa-Pahiatua basins and uplift of the Tararua and Rimutaka ranges. Active uplift is demonstrated by the presence of uplifted marine benches along the Wairarapa coastline.

## 5.2 Wairarapa Valley

Uplift of the Tararua Range during the last c.1.5 million years has enhanced rainfall from the prevailing westerly winds, much of which drains eastwards into the Wairarapa Valley. Rainfall and runoff from the range is supplemented by local rainfall, and together comprise the inflow for the Wairarapa Valley groundwater resource (Gunn et al. 1987). Discussion below is focussed on the geological structures thought likely to influence groundwater, and little attention is paid to other areas of the Wairarapa because groundwater systems are small elsewhere and usage is only local.

## 5.3 Wairarapa and Wharekauhau faults

The Wairarapa Fault is one of a series of long subparallel active faults in the southern North Island that carry most of the shear associated with the plate boundary. The fault is believed to penetrate the full thickness of the Australian Plate, being rooted on the subduction interface.

On January 23rd 1855, the Wairarapa Fault ruptured, resulting in New Zealand's largest historic earthquake, estimated at M8.1. Rupture at Pigeon Bush, a classical fault trace site near the northwest end of Lake Wairarapa (Fig. 5), was associated with dextral (right-lateral) slip of 15-20 m in a near horizontal plane and about 3 m vertically. Lateral displacement in 1855 is the greatest single event displacement ever recorded on a strike-slip fault throughout the world. A prior very large (slightly smaller) surface rupture displacement at the same site is revealed by detailed surveying.

At the southern end of Lake Wairarapa, the fault splits into two, with one splay entering the Rimutaka Range, and crossing the northern end of the Orongorongo catchment (Fig. 5). This is straight in form, and truncates spurs on the valley wall in a similar sense to the fault at Pigeon Bush. The other splay occupies a position at the eastern foot of the Rimutaka Range, and has the characteristic lobate shape of a thrust fault. An exposure of the fault in Wharekauhau Creek clearly shows its thrust character, with greywacke rock of the range thrust over marginal marine deposits of last interglacial age. Further south, uplift at Turakirae

Head locally amounted to >6 m in 1855, and a series of uplifted beach ridges and marine cut terraces records a history of similar events during the last c. 10 ka and the last 300 ka respectively, in response to uplift on the Wharekauhau Thrust

### 5.4 Uplift across the Lower Wairarapa Valley

While the Rimutaka and Tararua ranges are sliding northwards with respect to the Wairarapa Valley, the southeastern part of the Rimutaka Range is also thrusting southeastwards across the mouth of the Wairarapa Valley. This active deformation can be corroborated by recent geological features additional to the faults themselves. Near the mouth of the valley, extensive surfaces rising to 130 m above sea level are marine benches cut during the last interglacial period, when the sea was within a few metres of its current level (Fig. 5, Fig. 6). On the western side of the valley, they dip to the southeast. On the eastern side of the valley east of Lake Ferry, they dip to the northwest, but rather more gently than on the other side of the valley. At the southwest end of Lake Wairarapa the bench is offset vertically across a fault with uplift on the east (Fig. 5). This is probably a backthrust, responding to the compression generated at the Wharekauhau Thrust.

The uplift across the southern end of the Wairarapa Valley has particular significance to the groundwater system because it has uplifted the Miocene-Pliocene groundwater basement above sea level at Lake Ferry at Palliser Bay. At the western end of Palliser Bay, Early to Middle Quaternary mud and some silt-bound gravel are exposed in cliffs behind the bay. These uplifted and relatively impermeable rocks could constrain the southern end of the Wairarapa Valley groundwater system. On the hill above Lake Ferry, the last interglacial marine bench is channelled and overlain by (?) early last glacial alluvial gravel. Cobbles are relatively large and well-rounded, and this must represent a paleo-Ruamahanga deposit that has since been uplifted. The present river, despite having a very low gradient, must continue to cut downwards through the rising rocks to maintain egress to the sea. The Ruamahanga River enters the bay through Lake Onoke, which lies in a relatively restricted opening (The Narrows) between the uplifted hills. Permeable sediments must be present through this gap, but they are unlikely to be particularly thick, because of the uplift since the last interglacial. The slopes and elevations of the last interglacial bench on each side of Lake Ferry provide evidence for a fault through Lake Ferry, although this has not been substantiated.

### 5.5 Subsidence at Lake Wairarapa

Lake Wairarapa is shallow and elongate, and lies just northeast of the point where the Wharekauhau Fault splays from the Wairarapa Fault (Fig. 5, Fig. 6). The lake is confined to the south by the uplifted hills discussed above, and to the northeast by another active tectonic structure, the Te Maire Fault and ridge. The Ruamahanga River gradient is very low from Kahutara to the sea, and struggles to occupy a channel. Drillhole data from holes around the lake show that it is underlain by a substantial thickness (20-40 m) of estuarine mud, commonly with shells. Shells from a drillhole at Pouawha have been dated from 4 levels in this mud unit, yielding ages of 4-5000 years. The lowest was from 35 m below sea level. Because all the shells are of estuarine origin, there is a clear indication that the area is subsiding during the Holocene. Thin gravel aquifers within the mud sampled in drillholes on the eastern side of the lake are likely to represent Holocene fans from Turanganui and Tauanui rivers. A thicker aquifer at the base of the mud may represent the Waiohine gravel.

If the inference made here is true, that in the lower valley there is uplift but subsidence in the Lake Wairarapa area, it is likely that the groundwater system of the Wairarapa Valley is largely isolated from the sea.

## 5.6 Mokonui and Masterton faults

Three cross-valley faults, branching eastwards from the Wairarapa Fault in the upper valley area are likely to influence groundwater systems (Fig. 4). Each cuts across the rivers (and their terrace gravels) flowing into the northern end of the valley. The Mokonui Fault is the northernmost of these, branching from the Wairarapa Fault at Tea Creek (Fig. 2, Fig. 4). The fault was trenched at Viewfield in 2004, demonstrating a history of Holocene ruptures. The surface trace splays and curves around an elevated Miocene-Pliocene block near Twin Bridges, and back-tilting on Quaternary terrace gravels indicate that the block between the Wairarapa and Mokonui faults, at least at the northeast end, is tilting to the northwest. This tilting has lifted Miocene-Pliocene mudstone to the surface on the upthrown northwest side of the fault, and must restrict groundwater in the terraces to the northwest.

A similar structural arrangement occurs at the northeastern end of the Masterton Fault. This fault splays from the Wairarapa Fault near the southern end of Carterton Bush, can be traced across the Waiohine surface to behind Renall’s timber yard (where it was trenched in 2001), across the Waingawa River and through Masterton. It raises Miocene-Pliocene mudstone to the surface at Lansdown and in the Ruamahanga River, and may curve northwards up the Ruamahanga River. Terrace gravels on the northwestern side of the fault at Lansdown are back-tilted to the northwest. The Ruamahanga and Waingawa rivers and their terraces are likely to be affected by the fault, and restriction of the groundwater must occur at least north of Masterton. At the Te Ore Ore bridge over the Ruamahanga River, Masterton, tree trunks in position of growth buried by gravel and silt (N158/f954 – 955) occur on both sides of the river. The radiocarbon age is 760 ± 80 years BP (NZ 1810) and may record a change of river course and depositional processes as a result of activity associated with the nearby Masterton Fault. A seismic profile across the Wairarapa Valley south of Masterton (Cape et al. 1990) provides information on deformational style.

## 5.7 Carterton Fault

The Carterton Fault is the southernmost of these three cross-valley faults, splaying from the Wairarapa Fault near Papaitonga Stream, and cutting across the Waiohine gravel behind Carterton, and across to the Masterton District sewerage ponds (Fig. 2, Fig. 4). Gravel units to the northeast of this fault are not clearly and unambiguously back-tilted as in the two faults further to the north, and its influence on the groundwater is less clearly understood.

## 5.8 Brickworks Anticline and Taratahi Syncline

The presence of greywacke and last interglacial (Francis Line Formation), and early (Waipoua Gravel) and middle last glacial gravel (Ramsley gravel) near Tiffen (Fig. 4) suggest the presence of a fault or anticline. To the northwest of this feature, there is a channel of Waiohine gravel that has been interpreted as having a synclinal structure, the Taratahi Syncline. This is bounded on the northwest, close to Carterton, by surficial deposits of the last interglacial Francis Line Formation. Francis Line Formation at least in part consists of mud of swamp or lacustrine origin, and may act as an aquitard, limiting groundwater exchange between overlying units from those below.

## 5.9 Huangarua Fault and Harris Ridge Anticline

The Huangarua Fault (Fig. 2) lies to the east of Martinborough and is associated with a broad anticlinal fold that makes up the Harris Ridge (Collen & Vella in prep, Nicol et al. 2002). The fault has significant vertical displacement (down to the east), and effectively separates the Huangarua Valley groundwater system from the lower Wairarapa Valley because mudstone is uplifted on the west side of the fault above the elevation of the floor of the Huangarua River.

## 5.10 Te Maire, Turanganui, Martinborough and other long valley faults

A number of long-valley faults are known to exist in the Wairarapa Valley, particularly on the eastern side (Fig. 2). Profiles along the last interglacial marine bench across the southern end of the valley suggest the presence of a fault with significant vertical displacement (down to the west) through the gap at Lake Onoke.

The Turanganui Fault and some others on the eastern side of Lake Onoke appear to displace the last interglacial marine bench, although there are no large scarps. The Martinborough Fault displaces (down to the SE) Waiohine gravel at Martinborough (Van Dissen et al. 1998). Last interglacial deposits are displaced (down to the SE) on Te Maire Ridge by the Te Maire Fault. The presence of greywacke bedrock near the Ruamahanga River on the eastern flank of Te Maire Ridge and at Glenmorven suggests there is unlikely to be a substantial deep groundwater resource in that part of the valley.

## SECTION B - HYDROGEOLOGY

## 6.0 INTRODUCTION

This section is designed to provide a general guide to groundwater in the Wairarapa Valley, in the context of the geology discussed above. Following discussion of the unconfined and deeper confined aquifers, the structure of the deeper aquifers and Holocene deposits is presented. Holocene depositional processes are compared with those in a structural analogue, the Taieri Plains. Finally, the section finishes with some discussion of water level, isotopes and hydrochemistry.

The most important groundwater resource in the Wairarapa region occurs in the greywacke-sourced gravel and sand aquifers in the Wairarapa Valley, derived from erosion of the Tararua Range. These were deposited by southeast flowing rivers and occur within the sediments of major rock group units 4 and 5, Early to Middle Quaternary and Late Quaternary. Groundwater is present in water table, confined and flowing artesian aquifers. The total thickness of gravels beneath the valley is unknown. Geophysical surveys (Hicks & Woodward 1978) place some constraints on the shape of the greywacke basement, and indicate deep troughs near Masterton and southwest of Carterton. The greatest thickness of gravel deposits is likely to be in these troughs and other tectonic induced structures such as the fault angle depression adjacent to the Wairarapa Fault and the area of (at least) Late Quaternary subsidence occupied by Lake Wairarapa. In the sector of the valley inland of Carterton exploration and production wells have encountered gravel aquifers within explored depths of 50 m. The deepest known water well (WRC well no. 7C/7/178) in the Wairarapa Valley is 178 m deep, located near Kahutara in the Lower Wairarapa Valley and reported to provide good quality water.

Down plain southwest of Martinborough and towards Lake Wairarapa well logs show that the fluvial deposits are better sorted and gravel aquifers are interbedded with silt-bound gravel, sand and silt strata that form confining layers (aquitards and aquicludes). This is attributable largely to the upstream degradation and downstream aggradation by rivers, producing progressively better sorted deposits downstream. Ice and snow cover retreat and vegetation regeneration on the Tararua Range occurred with climate change from glacial to temperate interglacial conditions, resulting in rivers with catchments in the ranges emerging onto the Wairarapa Valley with reduced sediment loads, and with sufficient energy to entrench into glacial floodplain deposits. This reworking process resulted in development of fans spreading laterally across the low gradient plain surface. A result of this better sorting and lateral spread of deposits is that strata and aquifers can be more easily identified and correlated between wells. This cycle of depositional events controlled by climate change from glacial to interglacial periods has repeated many times throughout the Quaternary. The exact number of depositional cycles represented by the sediments underlying the Wairapapa Valley is unknown.

## 6.1 Holocene depositional processes

Marine and estuarine silt, peat and shelly sand are common in the postglacial sediments penetrated by wells south of Kahutara through to the Palliser Bay coast. These marine sediments are a product of deposition during the sea level rise at the end of the last (Otiran) glaciation. As ice caps melted and glaciers receded, sea level rose from about 14 000 yrs BP until 6500 yrs BP when the present level was attained. This sea level rise and the resultant depositional processes had important hydrogeological implications for the aquifers underlying many New Zealand coastal floodplain aquifer systems, including the Wairarapa Valley. During the last glaciation at about 18 000 yrs BP, sea level was about 130 m below that of the present, and the Wairarapa Valley coastline was offshore in Palliser Bay at the edge of the continental shelf. A land bridge connecting the western Marlborough Sounds to the Kapiti Coast may have formed a southeast facing “Cook Strait” embayment (Te Punga 1953), an extension of Palliser Bay. A last glacial Wairarapa Valley river system may have transported and deposited gravel out to the coast at the edge of the continental shelf. As sea level rose, the last glacial Wairarapa Valley longitudinal river system would have adjusted to the shortening of its course (as the coastline transgressed landwards) by degrading into its existing floodplain deposits progressively further up valley. This would have occurred unless a proto-Lake Wairarapa was large enough and deep enough to provide an intermediate depositional base level

Studies of Holocene coastal processes at Cloudy Bay, Marlborough, on the other side of Cook Strait have identified a similar depositional environment to Palliser Bay with a major river valley (Wairau Plain) in a fault angle depression exposed to southerly storms. At Cloudy Bay the rising postglacial sea reached the present Wairau Plain coast about 9000 yrs BP. This age is established by radiocarbon ages for the deepest shells penetrated by a groundwater testbore at the coast (Ota et al. 1995). Other postglacial coastal plains, including the Canterbury Plains at Christchurch and the Heretaunga Plains, Hawke’s Bay, replicate this 9000 yr age. For the Wairau Plain and other New Zealand postglacial coastal plains the maximum inland extent of the postglacial marine transgression occurred about 6500 yrs BP when sea level first reached an elevation similar to present level (Gibb 1986). Once sea level stabilised the coast began to prograde. The Wairarapa Valley does not seem to conform to this standard Holocene sea level process trend. The reason for this will be discussed in detail as it provides important insight into the sediment transport regime of Wairarapa Valley rivers, the occurrence of gravel aquifers and groundwater flow.

## 6.2 Holocene deposits and tectonics in the Lower Wairarapa Valley

In the Wairarapa Valley a Holocene maximum inland shoreline is indicated by well logs recording shells and surface features such as sand dunes, near the inland margin of Lake Wairarapa. Limited age control for the establishment of this shoreline is provided by radiocarbon ages on estuarine shells from excavations at Kumenga and Birchwood (Leach &

Anderson 1974) and a groundwater testbore at Pouawha (Brown unpublished data) on the east or coastal margin of Lake Wairarapa. In the Pouawha testbore (WRC well no. 8C/6/44(88)) the two deepest shell strata were from a depth of 26.0 m below ground level (24.3m below mean sea level; Fossil Record Number S27/f397) with Austrovenus stutchburyii dated at 5700 ± 100 yrs BP (NZ), and shells from a depth of 35.0 m below ground level (33.3 m below mean sea level; Fossil Record Number S27/f398) with Austrovenus stutchburyii dated at 4920 ± 90 yrs BP (NZ). In the Pouawha testbore the uppermost shell strata at a depth of 1.5 m below ground level (0.3 m below mean sea level; Fossil Record Number S27/f386) with Cyclomactra tristis dated at 3240 ± 90 yrs BP (NZ). For the Kumenga excavation Leach & Anderson (1974) report ages of 3470 ± 50 yrs BP (NZ1634) from a depth of 2.0 m below ground level and 4120 ± 50 yrs BP (NZ 1635) from a depth of 2.1 m below ground level – both these samples are close to mean sea level.

This limited Wairarapa Valley sea level radiocarbon age data suggests two Holocene depositional factors (that could be related) that are relevant to the hydrogeology:

- The maximum age for Holocene shells of 6000 years suggests the sea did not extend into the Wairarapa Valley until the present sea level was attained 6500 years ago.
- A range of ages 4500 to 6000 years for 5 samples in the Pouawha testbore in a depth range 9.1 to 33.3 m below mean sea level suggests rapid subsidence and infilling.

These two factors suggest the following postglacial depositional processes and environment at the coastal Wairarapa Valley:

- Continuing Holocene tectonic subsidence of the coastal valley in combination with coastal erosion by the sea during postglacial sea level rise (and subsequently after sea level stabilised 6500 years ago) may have allowed the sea to enter the valley along the course of the Ruamahanga River through a channel flanked by the uplifted Te Muna Formation (western Palliser Bay coast; Early Quaternary) and Pliocene siltstone capped by last interglacial marginal marine benches (eastern Palliser coast; see Structure above). This constriction, caused by uplift near the present day Wairarapa coast, may be associated with the southeast thrusting from the west.
- The present channel, known as “The Narrows”, connecting Lake Wairarapa to Lake Onoke is about 5 km wide. The macrofaunal assemblages as determined for samples from the Pouawha testbore (S27/f386 – f398 – Beu pers. comm.), and from the Kumenga and Birchwood excavations (Leach & Anderson 1974), are entirely estuarine and low saline species with some freshwater species. The Pouawha testbore is located about 1 km inland of The Narrows channel (Fig. 6). The testbore log records marine deposits to a depth of 37.9 m, reworked gravel forming a flowing artesian aquifer to 44.0 m, sand and silt with some vegetation to 87.0 m unconformably overlying tight poorly sorted gravel, sand and silt (?)last glacial (Otiran) deposits. The base of Holocene deposition is 85 m below sea level compared with the Cloudy Bay coast where the base of Holocene marine deposition is 38 m below sea level. This contrast is a result of ongoing subsidence. Leach &

Anderson (1974) on the basis of macrofauna, sediment and two radiocarbon dates, postulate a change occurred from estuarine to lacustrine environment about 3500 yrs BP. This change was a result of progradation, possibly following or accompanied by warping and tilting, which progressively narrowed the seaward end of the Lake Wairarapa area. Continuing progradation and development of bay bars in The Narrows area constricted the sea entrance until a sufficiently severe episode of freshwater flooding, sedimentation, and bar development, was able to close The Narrows, transforming conditions from estuarine to lacustrine.

### 6.3 Unconfined aquifers

The water table aquifer is located throughout most of the Wairarapa Valley with groundwater occurring in shallow gravel strata (mostly units 4 and 5). The groundwater is derived from local rain and river infiltration. In general, water yields from this aquifer are highest in the eastern part of the valley near the Ruamahanga River and the other main rivers, where the adjacent river is the groundwater recharge source. These high yielding water table aquifers are former river channel gravel deposits that remain in hydraulic contact with the river. They will provide conduits through which groundwater will flow to deeper interconnected gravel strata.

### 6.4 Deeper aquifers

Logs for exploration wells at Te Ore Ore, Masterton and Waingawa record predominantly gravel with aquifers occurring in poorly defined layers. Sporadic layers of fine sediments and peat, wood and vegetation occur, but aquifers cannot be correlated between wells with any certainty. Within the almost continuous gravel deposit sequence penetrated by wells in the inland or northern Wairarapa Valley the seemingly sporadic aquifers are related to the permeability of the gravel deposits. The degree of permeability is a product of the sorting of the gravel during deposition and the removal of the fine silt and sand sediments that would form the matrix in which the gravel clasts are imbedded. This is more likely to occur wherever the fluvial gravel, sand and silt sediments are subjected to long occupation with reworking and sorting by the transporting river. Postglacial gravel aquifers often with near surface hydraulic connection to the present river channels and deeper interglacial gravels are thus more likely to contain high yielding aquifers, being in large part derived from degradation and transport of the extensive poorly sorted cold glacial climate gravels eroded from the Tararua Range. Permeability will be anisotropic, with highest permeability in the direction of flow of the depositing rivers and lower permeability in a lateral and vertical direction.

In the lower valley adjacent to Lake Wairarapa, well logs of the few deep wells drilled provide no definite evidence such as shells to suggest marine strata underlie the aquifer and last glaciation gravels. While this may be interpreted as suggesting that the sea never occupied the lower valley during the last interglacial period, the presence of a marine bench in the

Pirinoa and Pounui areas indicate that it did. Silt strata logged may be estuarine (and lacking in shells), or lacustrine in origin. If the latter is the case, it indicates the presence of a last interglacial Lake Wairarapa.

A very early radiocarbon date on wood from a depth of 150 ft below sea level (c. 46 m) in a drillhole near Kahutara (AA962, NZ 14; location about S27/034961) yielded an age of >37,000 years (Fig. 6).

### 6.5 Structure of deeper aquifers

The well logs of the exploration wells in the Wairarapa Valley also indicate that the static water level at each well tends to fall as drilling depth increases. This shows that the wells are in an area of groundwater recharge, where groundwater moves downward as well as down plain. Departures from this trend are the two zones of springs, one to the north and one to the south of Masterton. These springs are immediately adjacent to the fault traces of the Masterton and Carterton faults suggesting that they are a result of fault dislocation of aquifers causing groundwater to flow at the ground surface.

In the Lower Wairarapa Valley, static water levels measured as wells were drilled show increasing or higher water levels with increasing depth of well or aquifer. This implies upward flow of groundwater between aquifers through hydraulic connections and aquitards within the layered aquifer system. Constraints on groundwater flow are imposed by down valley thinning of the gravel deposits forming the aquifers, the upward warping and lateral constriction of the last interglacial and older Quaternary sediments at the Wairarapa Valley coast, and the distinct likelihood that at least the deeper aquifers in these warped deposits may not continue through to the coast and out into Palliser Bay. At Lake Ferry wells about 50 m deep have water levels above sea level and include a flowing artesian well (WRC well no. 8B/6/44). At the coast, well water levels are reported to fluctuate with tidal change, indicating an aquifer extension or connection out into Palliser Bay. Wells located inland of The Narrows show no response to tidal fluctuations. The few logs available for Lake Ferry wells (WRC well no's 8B/6/44 and 8B/5/52(80)) record interbedded fluvial and beach deposits including vegetation, shells, silt, sand and gravel. Limited available data precludes correlation with strata penetrated by wells located further inland.

### 6.6 The Taieri Plains – a structural analogue

The Lower Taieri Plain, Otago provides a good New Zealand analogue for postglacial depositional processes with the coastal Wairarapa Valley. This is because the Lower Taieri Plain lies in a near coast tectonic depression (Taieri Basin) separated from the sea by a range of hills uplifted by reverse faults, a geological environment similar to the coastal Wairarapa Valley (Litchfield et al. 2002). The Taieri River maintains a 10 km long course in a gorge cut through this range of hills. Freshwater Lakes Waihola and Waipori at the southern end of the basin adjacent to the gorge are remnants of a formerly more extensive water body (Barrell et al. 1999) that was for a time sufficiently saline to support estuarine macrofauna species such as Austrovenus stutchburyii and crabs (Irricon Consultants 1994) and marine forams and rare ostracods (Dickinson et al. 2000). Postglacial sea level rise resulted in marine incursion up the Taieri River through the gorge into the Taieri Basin. Exactly when the postglacial sea entered the basin is not constrained only by three radiocarbon dates. A radiocarbon date of 8538 +-71 yrs BP (NZA10137) (Dickinson et al. 2000) for shell hash from a depth of 19.8 m in a testbore (Waipori 99-1 Victoria Link Ltd) near Henley is the oldest date. In the same testbore shell (?Mactra discors) from a depth of 3.6 m has been dated at 4389 +- 59 yrs BP (NZ10162) (Dickinson et al. 2000). Shells from a drain near the Sinclair Wetlands information centre near Lake Waipori radiocarbon dated at about 4000 yrs BP (M. Schallenberg pers. comm.). Thus the Lower Taieri Plain demonstrates how the postglacial sea level rise promoted marine incursion through a gorge into a basin containing a lake. After sea level stabilised, marine sediments were overlain by late Holocene fluvial deposits of the Taieri and Waipori rivers. This is similar to the model proposed for the postglacial marine incursion into Lake Wairarapa and the Lower Wairarapa Valley based on available geological and groundwater knowledge.

## 6.7 Water level, isotopes and hydrochemistry

Overall the recharge source, groundwater flow direction and groundwater age, support the Wairarapa Valley groundwater aquifer model established from the hydrogeological data.

Besides spot water levels other information relevant to groundwater flow is provided by groundwater contours, piezometric surfaces and groundwater isotope and chemical data. Well water level measurements provide broad groundwater contours covering most of the Wairarapa Valley (O'Dea et. al. 1980). For the upper Wairarapa Valley the contours show that groundwater flow is to the southeast down across the fans of right bank tributaries of the Ruamahanga River. In the vicinity of the Ruamahanga River the direction of groundwater flow swings to the south towards and parallel with the river. In the area upstream of Martinborough where the Ruamahanga River course is between the Te Maire ridge in the west and the block of greywacke that forms south Jury and Morrison Peaks in the east, the groundwater flow for the upper Wairarapa Valley is also channelled through the constriction.

Gunn et al. (1987) and Morgenstern (2005) discuss isotope analyses from Wairarapa Valley groundwater, river and rain samples – deuterium/oxygen 18 for identifying the possible source of the groundwater and tritium (H3) for groundwater age. Groundwaters are grouped into three source types – river recharge, rain recharge and combined rainfall/river recharge – river recharge is derived from the Tararua Range catchment rivers.

In the upper Wairarapa Valley predominantly river-derived groundwater occurs in the vicinity of the Waiohine River and the Waingawa River to the west of Masterton. Rain-derived groundwater occurs south of Carterton and close to the Waiohine River. Rainfall/river recharge type groundwater predominates in the upper Wairarapa Valley. In the area between the Waingawa River and Carterton the extensive river sourced water race network is likely to leak and contribute water to the underlying groundwater aquifers. In the upper Wairarapa Valley all the groundwater analysed for tritium is relatively young apart from a sample from a 45 m deep well (WRC well no. 4H/1/45) near Carterton tapping a (?)Last Interglacial flowing artesian aquifer (see Major Rock Groups – Late Quaternary).

For the Lower Wairarapa Valley piezometric contours indicate a groundwater trough centred on Lake Wairarapa and the Te Opai Lagoon area to the southeast of the lake, into which groundwater flows from the north, west and east (O'Dea et. al. 1980). There are insufficient wells or water level measurements to establish piezometric contours for the sector through The Narrows from the south end of Lake Wairarapa to Palliser Bay. Groundwater isotope analyses (Gunn et al. 1987) shows that most of the Lower Wairarapa Valley groundwater is rain derived suggesting that side valley recharge is sufficient to eliminate the river recharge groundwater signature associated with Upper Wairarapa Plain groundwater. Tritium analyses (13 samples) show all groundwater to be more than 30 years old except for 2 samples. One from a 91 m deep well (WRC well no. 8C/2/91) in a side valley to the south of the Ruamahanga River and the other from a 60 m deep well (WRC well no. 9A/2/60) at Lake Ferry. The age of the groundwater suggests relatively slow outflow from the Lake Wairarapa trough to the Palliser Bay coast. The low tritium content of the 60 m deep well at Lake Ferry indicates some outflow of Wairarapa Valley groundwater at the coast.

Groundwater chemistry also provides information relevant to groundwater flow path and groundwater age. Aquifer water chemistry is influenced by composition of subsurface sediments and their organic content and infiltration through soil, and by landuse procedures. The Wairarapa Valley gravel aquifers and interbedded sediments are mainly derived from the chemically inert greywacke rock of the Tararua Range. However, local conditions such as proximity to limestone, or interbedding with swamp and buried organic material (peat, vegetation and wood), and marine sourced sediments and associated shells, determine groundwater chemistry. Generally the older the groundwater the higher the content of dissolved chemicals. As a result in the Wairarapa Valley, groundwater from wells located in the Lower Wairarapa Valley typically contains more dissolved chemicals than wells further inland. There are zones where particular chemical parameters are high (e.g. iron, because of anaerobic environment) but the precise reason for this is not known. If Wairarapa Valley groundwater is to be dated using the radiocarbon (carbon 14) method, existing chemical data will need to be looked at in detail and further analyses for relevant parameters carried out to provide background information for meaningful age interpretation.

A more extensive sampling and analyses programme of Wairarapa Valley groundwater has been completed – Morgenstern (2005). This utilised chlorofluorocarbon (CFCs) and sulphur hexafluoride (SF6) analyses, additional tritium analyses including repeats of samples included in Gunn et al. (1987), nine new stable isotope (deuterium/oxygen 18) analyses and a time/spatial hydrochemistry evaluation of Wairarapa groundwater chemistry parameters. As a result a better understanding of groundwater source, flow path and age is available.

Gunn et al. (1987) concluded that predominantly river recharged Wairarapa Valley groundwater will be less negative than -6.3‰ in 18O and rain recharge less negative than -6.8‰. Morgenstern (2005) revised the river recharge boundary to -5.9‰ but retained the -6.8‰ boundary for rain recharge. These new criteria were used to re-evaluate groundwater recharge origin. Only three groundwater samples from the upper Wairarapa Valley show strong evidence for river recharge. Two of these samples were from wells located on the Waiohine River postglacial floodplain and the other on the Waingawa River postglacial floodplain. The majority of samples from wells in the upper Wairarapa Valley were mixed river/rain recharge, with only a few on the south-eastern hills being classed as pure rainfall recharge. In the Lower Wairarapa Valley, the majority of the samples adjacent to the southeastern hills were rain recharge while in the centre of the valley adjacent to Lake Wairarapa a mixed river/rain recharge source was indicated.

Age dating, in combination with hydrochemistry and stable isotopes shows groundwater in the upper Wairarapa Valley contain mostly young (about 2 years) aerobic water, while deep wells and the central Lower Wairarapa Valley contain old (>100 years) anaerobic water. This part of the aquifer system is nearly stagnant. Intermediate mean residence times (MRT about 40 years) occur in the Martinborough and south of Greytown areas. The groundwater along the southeast margin of the Lower Wairarapa Valley have MRT of 45 to 80 years, contain small amounts of tritium and indicate recharge from the southeast hills.

Hydrochemistry time trends show consistent patterns with increasing age of the groundwater. Consistent trends in hydrochemistry and consistent trends in water residence time indicate a continuous groundwater system in the Wairarapa. Time trends in hydrochemistry also allow for identification of landuse activities on groundwater quality with elevated levels of nitrate, sulphate and possibly lead related to landuse.

## 7.0 CONCLUSIONS

- A broad geological history derived from the distribution and composition of the five major rock groups in the Wairarapa Region is presented, with relevant discussion of their hydrogeologic properties. The Quaternary or youngest two units are identified as the most significant for groundwater resources.
- The existence of the Wairarapa Valley is attributable to active tectonic processes

associated with the subduction of the Pacific Plate beneath the Australian Plate.

- A detailed Late Quaternary geological history including comparisons with the postglacial marine transgression for the Wairau Plain, Marlborough and Lower Taieri Plain, Otago, provide a basis for a hydrogeological model of the Lower Wairarapa Valley.
- Because the Wairarapa Valley lies in a tectonically active zone, active deformation and tectonic structures play an influential role in the distribution of aquifers, with warping, tilting and fault dislocation becoming more pronounced with increasing depth.
- During the late mid- to Late Quaternary, tectonic upwarping at The Narrows channel (connecting Lake Wairarapa to Lake Onoke) has constricted and controlled fluvial sediment deposition and transport. This has resulted in the deeper gravel aquifers being restricted to inland of The Narrows with only the postglacial gravel aquifers possibly providing a groundwater flow path to Palliser Bay.
- Tectonically controlled subsidence has resulted in the deepest sequence of Late Quaternary deposits and interbedded aquifers occurring beneath the Lake Wairarapa area.
- The response of fluvial depositional processes to climate change results in increasing down-valley sorting of sediments with layers of gravel channel deposits (including aquifers) increasingly interbedded with sand, silt and clay deposits.
- Postglacial estuarine and lacustrine deposits cap and confine underlying gravel aquifers from the inland margin of Lake Wairarapa coastwards to Palliser Bay.
- Isotope analyses show rain on the plain is the dominate recharge source of Wairarapa Valley groundwater. Tararua Range catchment rivers provide a source of “top up” groundwater recharge operating independently of plain rain.
- Groundwater tritium analyses show “old” groundwater (>100 years) in deep (?Last interglacial) aquifers in the Upper Wairarapa Valley and in the confined aquifers in the Lower Wairarapa Valley. This suggests restricted outflow and connection through to Palliser Bay and corroborates conclusions reached independently in this report.
- For groundwater management purposes the aquifers underlying the Wairarapa Valley have been divided into 29 groundwater management zones (Butcher 1996). A variety of hydrological, physiographical, geological and geographical criteria were used to establish these zones. Some of these criteria are relevant to hydrogeology, and the boundaries established occur at the margin of an aquifer system or where aquifers have been dislocated by faulting or warped by folding. However, other boundaries and the zones they define are invalid and only serve to subdivide a continuous aquifer system.
- This review of geological constraints on groundwater provides a basis on which to reduce the number and boundaries of zones in the Wairarapa Valley.

## 8.0 RECOMMENDATIONS

- Drillhole logs should be correlated using surface geology as a guideline, and where applicable, structure contours on depositional surfaces.
- Groundwater level, groundwater geochemistry (including isotopic information) and pump

test data should be rationalised against drillhole logs.

- Modelling the groundwater system should be attempted, involving dialogue and with review by specialists in each discipline (perhaps involving another workshop).
- Following that, any problem(s) with the initial model can be rectified.

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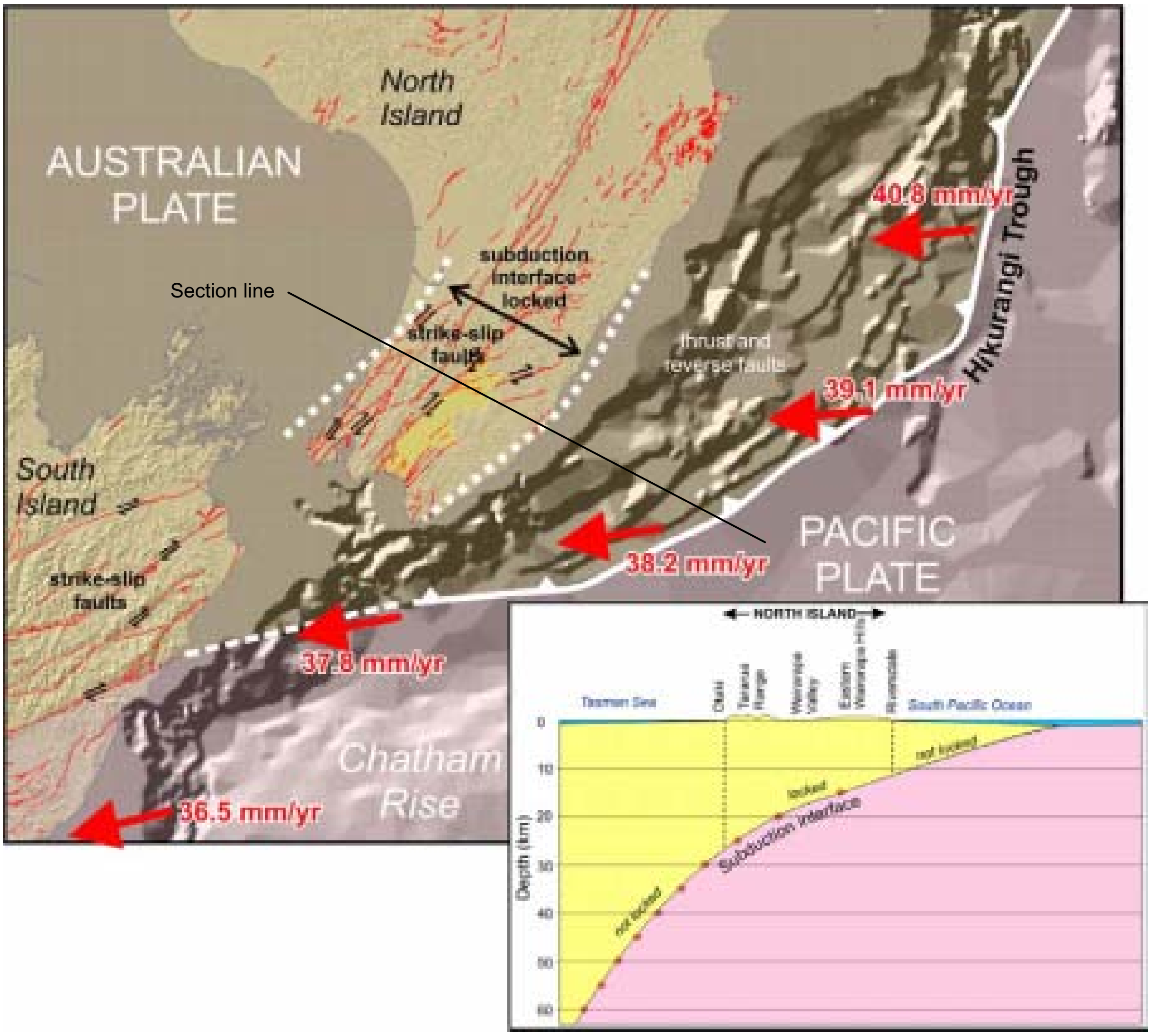

**Figure 1**: The Wairarapa region lies close to the boundary between the Pacific (here coloured pink) and Australian (yellow) tectonic plates. The plates are moving across the surface of the globe at differing rates and the relative difference is represented here by specific convergence rates at specific places at along boundary (red arrows and numbers). The Wairarapa region sits on the outer edge of the Australian Plate in a zone above the locked west-dipping plate interface (see inset cross section). Locking of the plate interface, and the relative convergence rates and vectors contribute to the upward bulge in the Australian Plate that is the landmass of the southern North Island. The offshore DTM is derived from bathymetric contours.

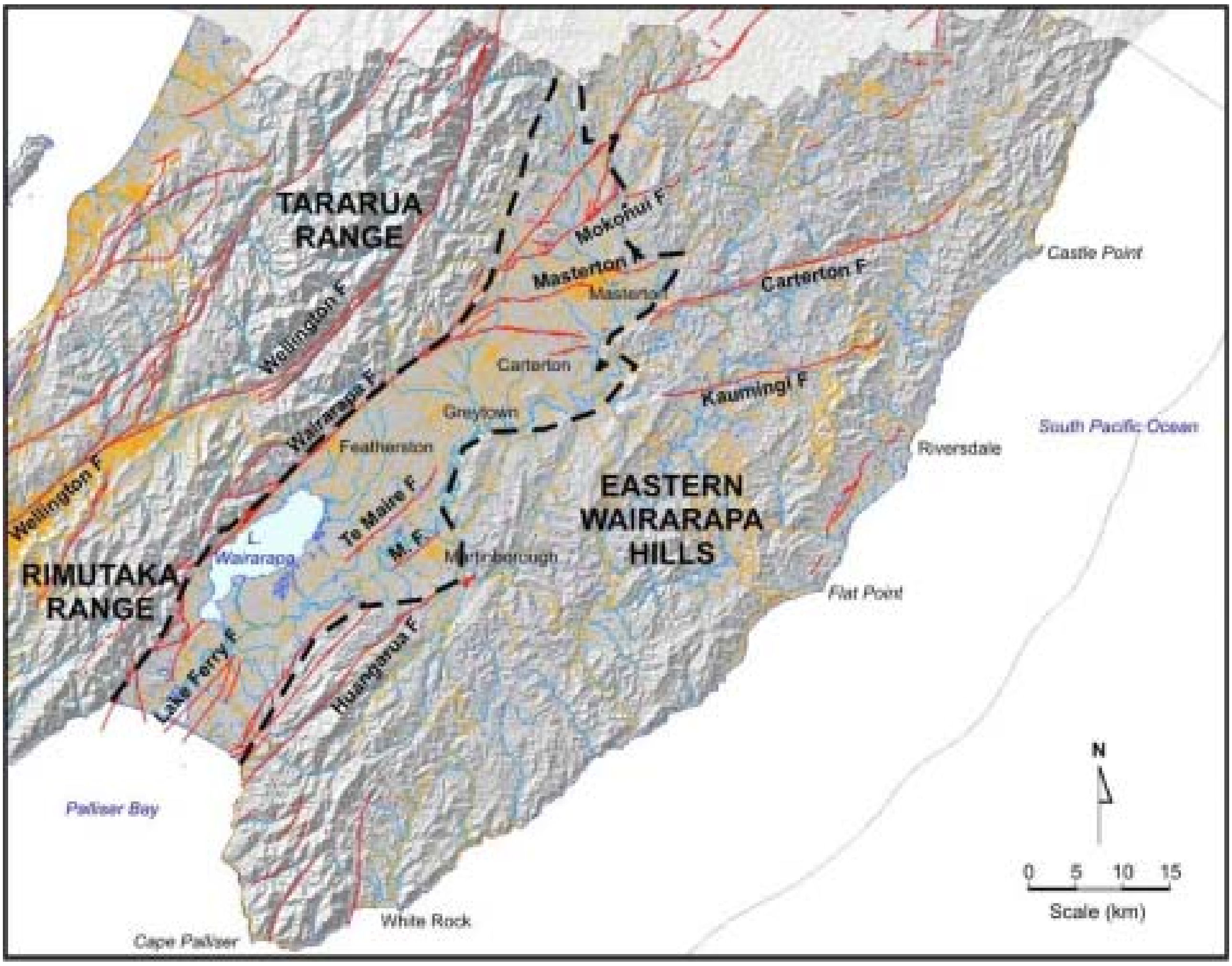

**Figure 2**: The Wairarapa can be separated into three main areas on physiographical grounds, the Eastern Uplands (east Wairarapa hill country), a central lowland basin (the Wairarapa Valley) and western ranges (including the Tararua and Rimutaka ranges). There is a predominant NE-SW grain to the country, both at the scale of the units themselves, and in the detail of features within each unit. This grain, and the orientation of active faults reflects the broader tectonic environment of the region, Tectonism, both past and modern, clearly heavily influences existing geomorphology. Note however, that the Kaumingi, Carterton and Masterton faults crosscut this tectonic grain, and also that the northern extent of the Wairarapa lowlands cuts across the Wairarapa Fault and extends northward subparallel to the Wellington Fault.M. F. = Martinborough Fault.

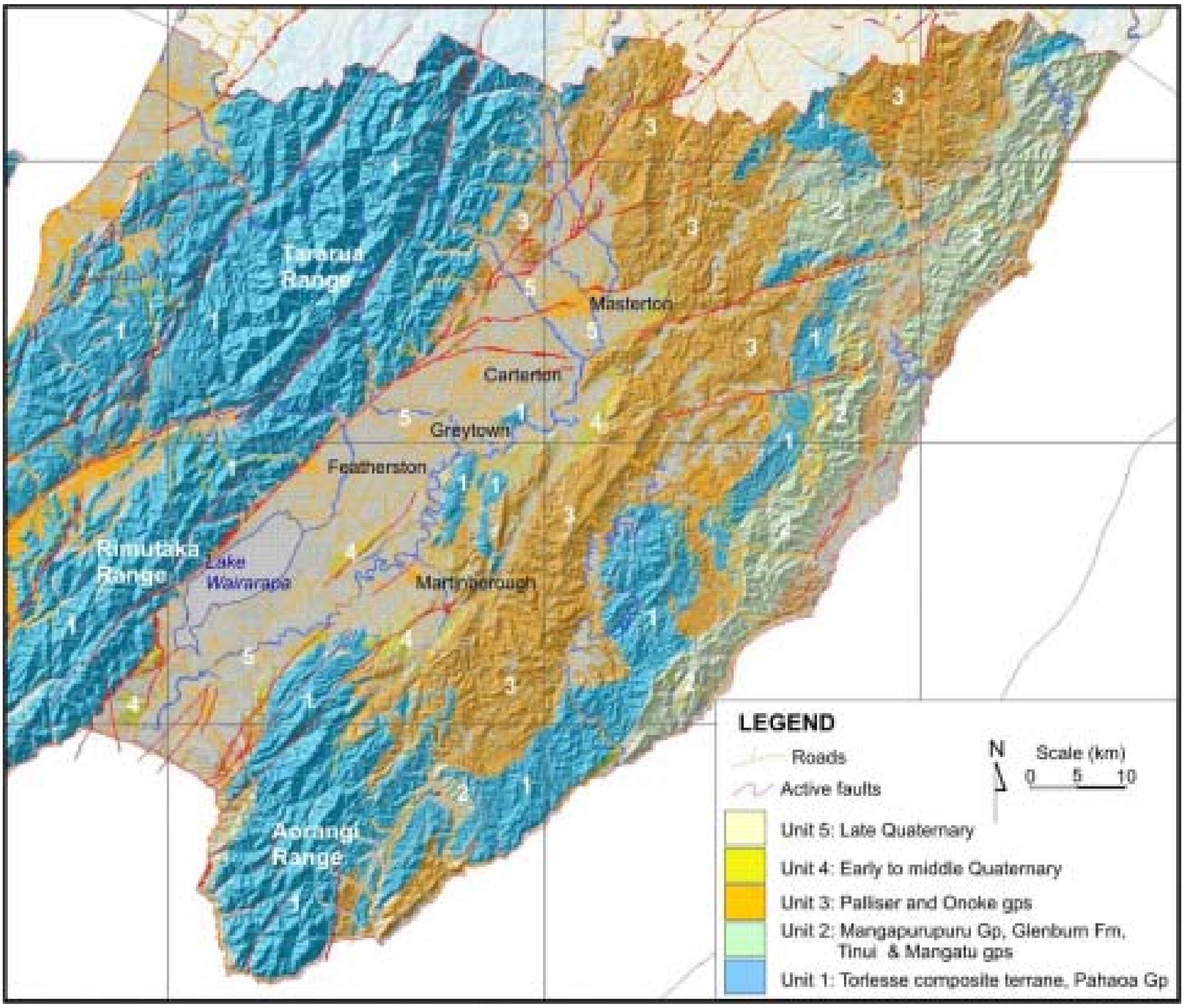

**Figure 3**: Geology of the Wairarapa region, illustrating the spatial distribution of the rock units defined in the text of this report. Note the western and eastern belts of Unit 1, the eastern belt of Unit 2, the central and eastern belts of Unit 3, and the dominantly central belt of Quaternary deposits of units 4 and 5. The latter are the deposits that are of most significance to groundwater management in the Wairarapa. Active deformation greatly influences the structure and distribution of these deposits.

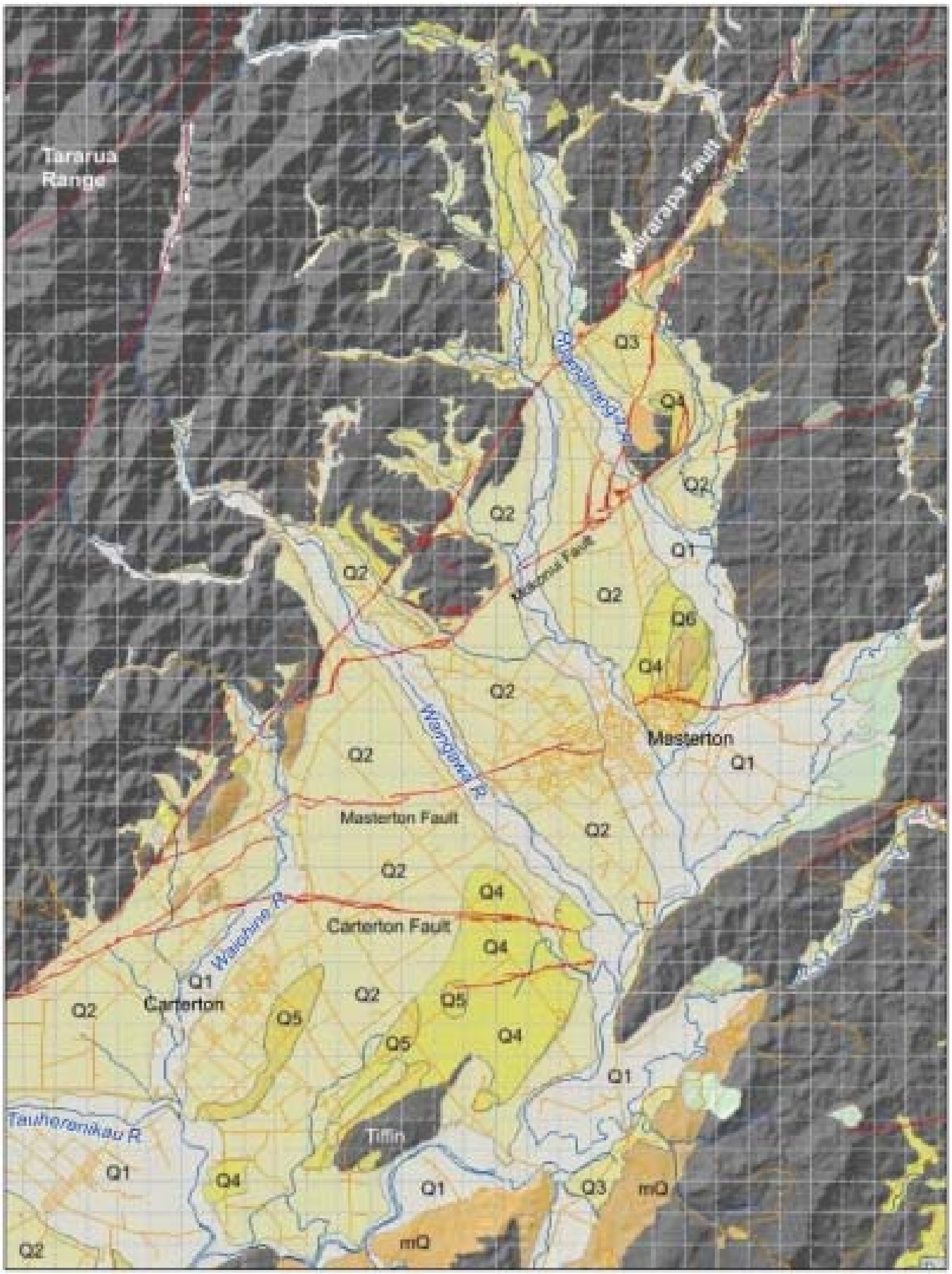

**Figure 4**: Geological constraints in the upper Wairarapa Valley on hydrogeology discussed in the text are summarised in this map. This part of the Wairarapa Valley is characterised by the cross-cutting of the valley by a series of active faults, the Carterton, Masterton, Mokonui and Wairarapa faults. Slip on the first three of these include a dip slip vector that has resulted in uplift and northwest tilting of terrace gravels on the northwest side of each fault. Gravels probably increase in thickness and depth northwest of each fault to the next fault upvalley. Other faults that have little surface expression may be present (e.g. the Kaumingi and Huangarua faults). Quaternary geology is here superimposed on a DTM. Grey areas are underlain by greywacke rock, or largely impermeable Neogene siltstone and mudstone.

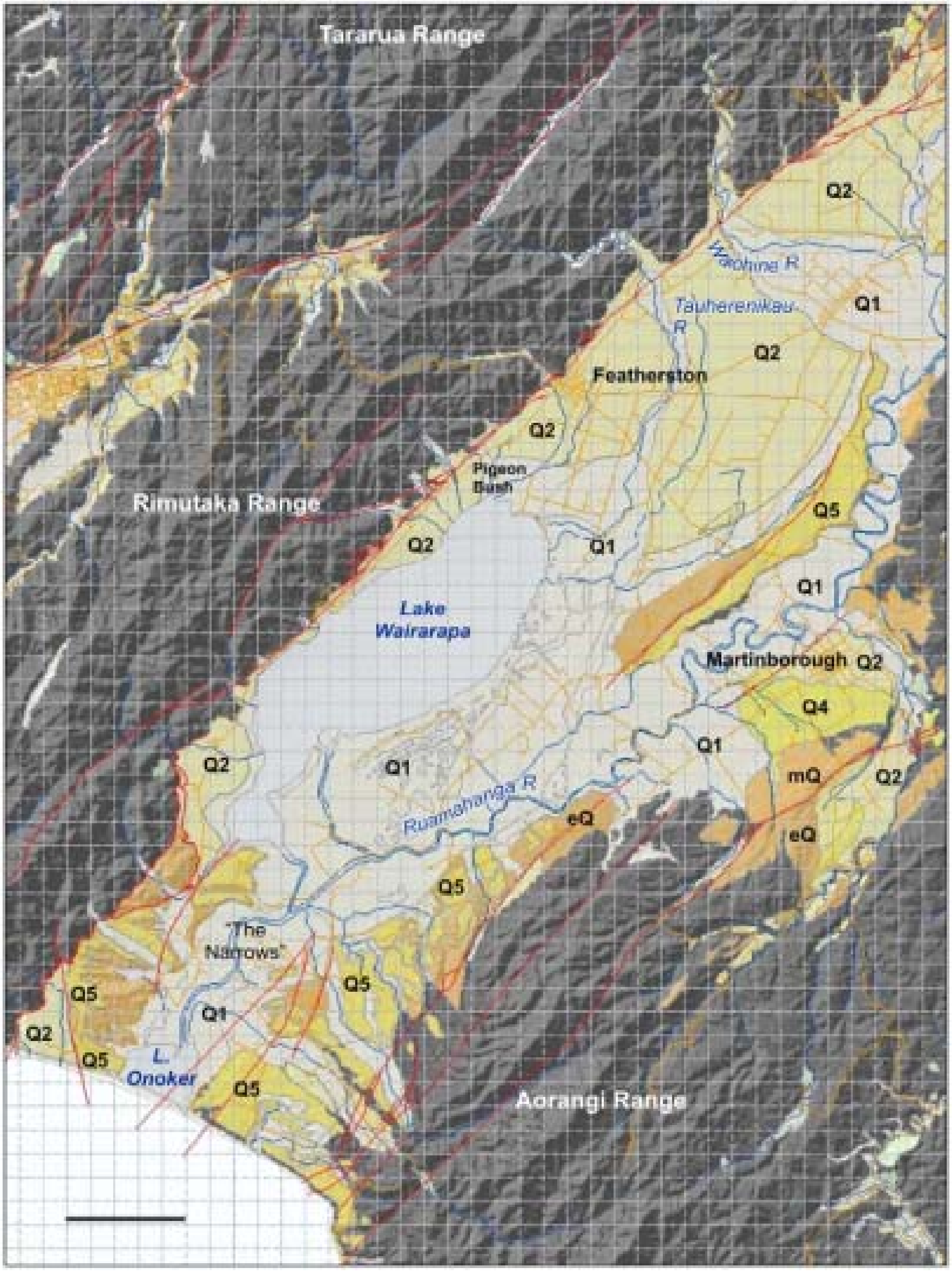

**Figure 5**: Geological constraints in the lower Wairarapa Valley, as summarised in the text, are illustrated in this map. This part of the valley is characterised by long-valley faults, an area of subsidence around Lake Wairarapa and an area of uplift at the southern end of the valley. The Waiohine Gravel dips down beneath Holocene valley fill deposits south of Featherston. Older Quaternary deposits south of Lake Wairarapa have no overlying last glacial gravel cover, indicating that river egress from the basin has been restricted since at least last interglacial times. The presence of Pliocene and Early Quaternary deposits in the coastal cliff on the eastern side of Lake Onoke, and uplifted Early and middle Quaternary sediments on the western side, indicate that thickness of younger Quaternary deposits across the Lake Onoke corridor are unlikely to be thick. In addition, uplift of last interglacial marine benches confirms substantial uplift at the southern end of the valley.

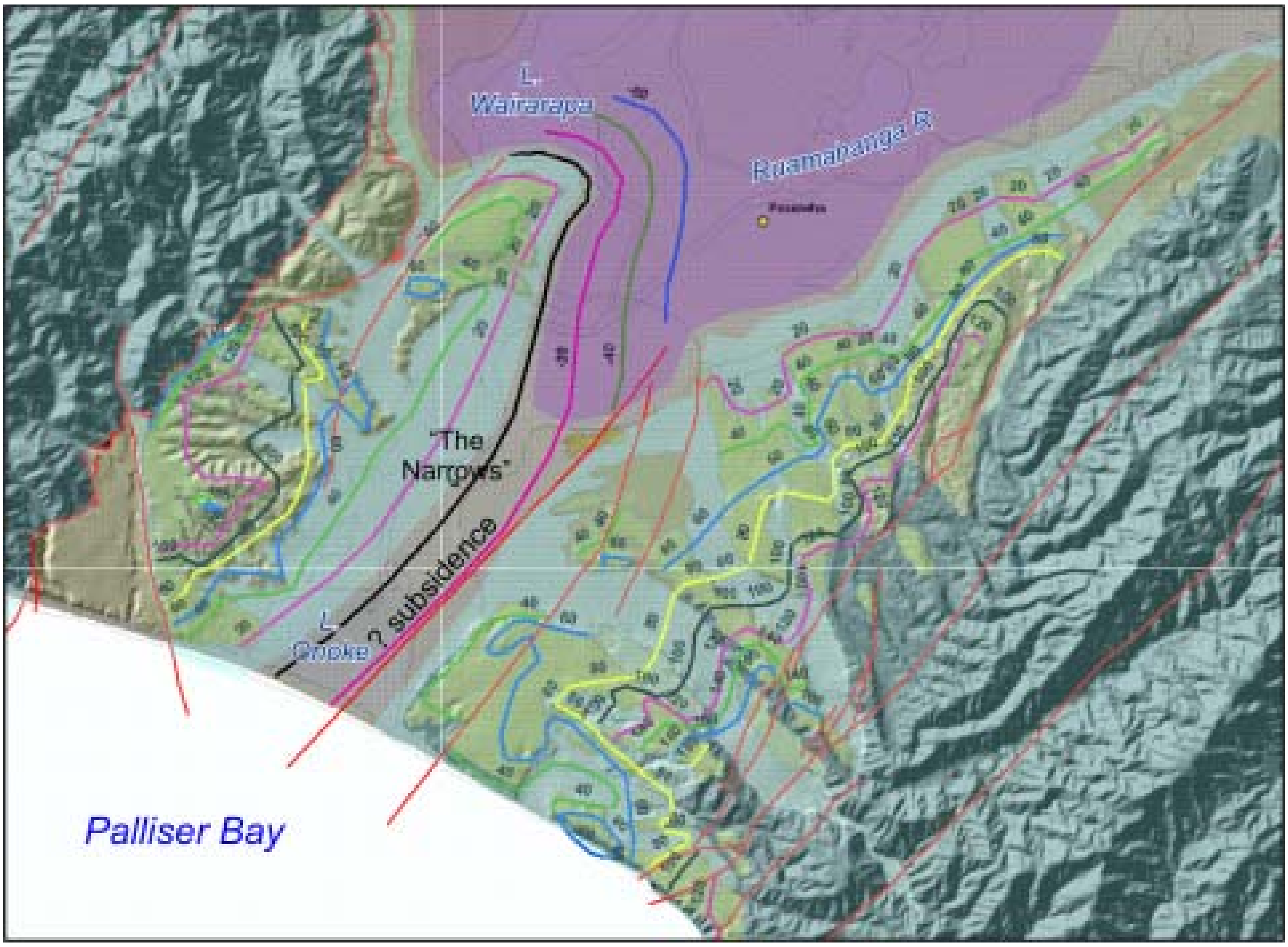

**Figure 6**: Map illustrating the location of relative uplift and subsidence in the Lower Wairarapa Valley. Areas with a blue hue are characterised by active uplift, and those with a purple hue, subsidence. Red lines are active faults from the GNS active faults database. Coloured lines represent structure contours on the Last Interglacial marine bench (or benches; see Ghani (1978). Only a very narrow corridor through The Narrows can conceivably be subsiding, this associated with an inferred active fault, with substantial vertical throw (down to the west). The location of the Pouawha drillhole, the place where the case for Lower Wairarapa subsidence is strongest, is shown.

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# Appendix 2 – 1985 piezometric survey wells

| Wells_No | East | North | Well Depth | Top Screen | Bottom Screen | MP_RL (mamsl) | WL_DATA (mmBRL) | DATE | Screen_RL (mamsl) | Water_level_RL (mamsl) |
|---|---|---|---|---|---|---|---|---|---|---|
| T26/0232 | 2735953 | 6025169 | 30.6 | 28.6 | 30.6 | 104.778 | -6453 | 12/11/85 | 74.178 | 98.325 |
| T26/0489 | 2737640 | 6023590 | 54 | 48 | 54 | 100.97 | -5325 | 12/11/85 | 46.97 | 95.645 |
| T26/0487 | 2736864 | 6022996 | 33 | 0 | 0 | 96.18 | -2162 | 12/11/85 | 63.18 | 94.018 |
| T26/0547 | 2737100 | 6022300 | 5 | 0 | 0 | 94.84 | -1623 | 12/11/85 | 89.84 | 93.217 |
| T26/0508 | 2738050 | 6022980 | 5 | 0 | 0 | 99.145 | -2913 | 12/11/85 | 94.145 | 96.232 |
| T26/0503 | 2739500 | 6024974 | 10.6 | 9.3 | 10.3 | 105.635 |  |  | 95.035 |  |
| T26/0504 | 2739500 | 6024972 | 6 | 0 | 0 | 105.595 |  |  | 99.595 |  |
| T26/0507 | 2736530 | 6024960 | 6 | 0 | 0 | 99.145 | -4920 | 12/11/85 | 93.145 | 94.225 |
| T26/0230 | 2735200 | 6025800 | 11 | 0 | 0 | 116.115 | -3485 | 11/11/85 | 105.115 | 112.63 |
| T26/0165 | 2734800 | 6027750 | 6 | 0 | 0 | 135.507 | -3070 | 11/11/85 | 129.507 | 132.437 |
| T26/0204 | 2734520 | 6029200 | 14.71 | 11.71 | 14.71 | 137.844 | -295 | 12/11/85 | 123.134 | 137.549 |
| T26/0170 | 2734392 | 6031719 | 15.33 | 0 | 0 | 150 | -5393 | 11/11/85 | 134.67 | 144.607 |
| T26/0211 | 2733900 | 6031900 | 7.6 | 0 | 0 | 152.097 | -5375 | 11/11/85 | 144.497 | 146.722 |
| T26/0160 | 2733142 | 6031152 | 13.2 | 12.2 | 13.2 | 149.673 | -3652 | 11/11/85 | 136.473 | 146.021 |
| T26/0206 | 2732580 | 6029520 | 28.7 | 22.3 | 28.7 | 138.77 | -9120 | 12/11/85 | 110.07 | 129.65 |
| T26/0201 | 2732550 | 6029530 | 18.3 | 15.2 | 18.3 | 139.33 | -4807 | 12/11/85 | 121.03 | 134.523 |
| T26/0207 | 2732590 | 6029241 | 53 | 20.94 | 53.02 | 136.6 | -7490 | 12/11/85 | 83.6 | 129.11 |
| T26/0208 | 2733062 | 6029067 | 17.6 | 0 | 0 | 135.84 | -5323 | 11/11/85 | 118.24 | 130.517 |
| T26/0233 | 2736000 | 6030750 | 3 | 0 | 0 | 139.96 |  |  | 136.96 |  |
| T26/0235 | 2735210 | 6030260 | 5.8 | 0 | 0 | 139.24 |  |  | 133.44 |  |
| T26/0192 | 2731600 | 6026820 | 9 | 0 | 0 | 127.337 | -6395 | 11/11/85 | 118.337 | 120.942 |
| S26/0032 | 2729110 | 6025990 | 6.25 | 0 | 0 | 140.675 | -5492 | 11/11/85 | 134.425 | 135.183 |
| S26/0031 | 2729620 | 6025870 | 5.4 | 0 | 0 | 136.94 | -4747 | 11/11/85 | 131.54 | 132.193 |
| S26/0030 | 2729680 | 6025905 | 38 | 0 | 0 | 137.715 | 129.885 | 11/11/85 | 99.715 | 137.8449 |
| T26/0052 | 2733400 | 6027300 | 24 | 4 | 8.5 | 117.036 | -4262 | 11/11/85 | 93.036 | 112.774 |
| T26/0209 | 2732725 | 6025154 | 4.9 | 0 | 0 | 115.864 | -3153 | 11/11/85 | 110.964 | 112.711 |
| S26/0033 | 2728508 | 6026282 | 12 | 9.22 | 12 | 145.167 |  |  | 133.167 |  |
| T26/0412 | 2730042 | 6023468 | 8.6 | 0 | 0 | 118.537 | -2935 | 11/11/85 | 109.937 | 115.602 |
| T26/0431 | 2731400 | 6022860 | 0 | 0 | 0 | 109.836 | -3105 | 11/11/85 | 109.836 | 106.731 |
| T26/0359 | 2732500 | 6022400 | 4 | 0 | 0 | 102.716 | -2628 | 11/11/85 | 98.716 | 100.088 |
| T26/0411 | 2734445 | 6020045 | 6.09 | 0 | 0 | 94.381 | -752 | 11/11/85 | 88.291 | 93.629 |
| T26/0420 | 2734250 | 6023040 | 9 | 0 | 0 | 96.834 | -1900 | 11/11/85 | 87.834 | 94.934 |
| T26/0416 | 2734050 | 6022881 | 26 | 22.34 | 25.64 | 96.594 | -2915 | 11/11/85 | 70.594 | 93.679 |
| T26/0248 | 2736000 | 6030920 | 6.5 | 0 | 0 | 141.04 |  |  | 134.54 |  |
| T26/0243 | 2736240 | 6025100 | 47.5 | 40.7 | 42.3 | 105.655 |  |  | 58.155 |  |

| Wells_No | East | North | Well Depth | Top Screen | Bottom Screen | MP_RL (mamsl) | WL_DATA (mmBRL) | DATE | Screen_RL (mamsl) | Water_level_RL (mamsl) |
|---|---|---|---|---|---|---|---|---|---|---|
| T26/0243 | 2736240 | 6025100 | 47.5 | 40.7 | 42.3 | 105.583 | | | 58.083 | |
| T26/0429 | 2730037 | 6023706 | 13 | 0 | 0 | 120.106 | | | 107.106 | |
| T26/0535 | 2737743 | 6022898 | 5.85 | 0 | 0 | 98.45 | | | 92.6 | |
| S26/0308 | 2729228 | 6023435 | 5.5 | 0 | 0 | 122.397 | | | 116.897 | |
| S26/0298 | 2729240 | 6023650 | 7 | 1.6 | 7 | 123.61 | | | 116.61 | |
| S26/0122 | 2720400 | 6019200 | 17 | 0 | 0 | 86.428 | -8265 | 851113 | 69.428 | 78.163 |
| S26/0155 | 2723845 | 6017830 | 13.4 | 10.31 | 13.41 | 83.434 | -2460 | 851114 | 70.034 | 80.974 |
| S26/0166 | 2722800 | 6019800 | 12.4 | 0 | 0 | 93.370 | -3371 | 851111 | 80.970 | 89.999 |
| S26/0140 | 2723700 | 6021200 | 12 | 0 | 0 | 106.873 | -5115 | 851111 | 94.873 | 101.758 |
| S26/0229 | 2726562 | 6021309 | 23.8 | 0 | 0 | 110.298 | -6464 | 851111 | 86.498 | 103.834 |
| S26/0230 | 2725700 | 6023930 | 21 | 0 | 0 | 136.732 | -6028 | 851111 | 115.732 | 130.704 |
| S26/0231 | 2725670 | 6023980 | 11 | 0 | 0 | 137.347 | | | 126.347 | |
| S26/0239 | 2726829 | 6019622 | 21.3 | 0 | 0 | 98.765 | 4530 | 851114 | 77.465 | 103.295 |
| S26/0242 | 2726569 | 6021323 | 7.5 | 0 | 0 | 110.613 | -6076 | 851111 | 103.113 | 104.537 |
| S26/0243 | 2726780 | 6019600 | 2 | 0 | 0 | 98.617 | -1000 | 851114 | 96.617 | 97.617 |
| S26/0320 | 2709800 | 6011900 | 9 | 0 | 0 | 87.283 | -4560 | 851112 | 78.283 | 82.723 |
| S26/0326 | 2713900 | 6013100 | 3 | 0 | 0 | 72.120 | -981 | 851112 | 69.120 | 71.139 |
| S26/0500 | 2717265 | 6010718 | 3.4 | 0 | 0 | 50.657 | -2207 | 851112 | 47.257 | 48.45 |
| S26/0520 | 2716450 | 6012250 | 7 | 0 | 0 | 60.304 | -4561 | 851113 | 53.304 | 55.743 |
| S26/0529 | 2716000 | 6011200 | 7 | 0 | 0 | 57.606 | -2827 | 851112 | 50.606 | 54.779 |
| S26/0539 | 2715295 | 6012772 | 3.7 | 0 | 0 | 66.614 | | | 62.914 | |
| S26/0540 | 2715297 | 6012774 | 6.8 | 0 | 0 | 66.782 | -3615 | 851112 | 59.982 | 63.167 |
| S26/0545 | 2719501 | 6013110 | 18 | 0 | 0 | 51.029 | -2665 | 851112 | 33.029 | 48.364 |
| S26/0547 | 2719471 | 6011895 | 4 | 0 | 0 | 47.127 | -1035 | 851112 | 43.127 | 46.092 |
| S26/0553 | 2719100 | 6013800 | 4 | 0 | 0 | 52.599 | | | 48.599 | |
| S26/0387 | 2716350 | 6013830 | 6 | 0 | 0 | 62.700 | -2275 | 851113 | 56.700 | 60.425 |
| S26/0397 | 2718480 | 6011380 | 4 | 0 | 0 | 48.893 | | | 44.893 | |
| S26/0568 | 2723504 | 6013642 | 45 | 40.9 | 43.9 | 57.661 | 6800 | 851114 | 12.661 | 64.461 |
| S26/0580 | 2720900 | 6013500 | 15 | 0 | 0 | 58.323 | 3930 | 851114 | 43.323 | 62.253 |
| S26/0591 | 2724067 | 6013676 | 18 | 0 | 0 | 59.956 | -1384 | 851114 | 41.956 | 58.572 |
| S26/0622 | 2723000 | 6010900 | 46 | 0 | 0 | 44.305 | -3163 | 851111 | -1.695 | 41.142 |
| S26/0629 | 2722200 | 6011800 | 6 | 0 | 0 | 51.717 | -110 | 851111 | 45.717 | 51.607 |
| S26/0632 | 2724644 | 6013731 | 14.3 | 0 | 0 | 62.880 | 1430 | 851114 | 48.580 | 64.31 |
| S26/0642 | 2721762 | 6011581 | 16.5 | 0 | 0 | 54.700 | | | 38.200 | |
| S26/0644 | 2720700 | 6016550 | 4 | 0 | 0 | 65.591 | -2773 | 851112 | 61.591 | 62.818 |
| S26/0649 | 2722630 | 6016010 | 18 | 0 | 0 | 75.378 | -10515 | 851114 | 57.378 | 64.863 |
| S26/0656 | 2723379 | 6017372 | 78.05 | 0 | 0 | 79.347 | | | 1.297 | |

| Wells_No | East | North | Well Depth | Top Screen | Bottom Screen | MP_RL (mamsl) | WL_DATA (mmBRL) | DATE | Screen_RL (mamsl) | Water_level_RL (mamsl) |
|---|---|---|---|---|---|---|---|---|---|---|
| S26/0657 | 2724881 | 6013103 | 62 | 0 | 0 | 64.935 | 1760 | 851115 | 2.935 | 66.695 |
| S26/0658 | 2720650 | 6016480 | 8 | 0 | 0 | 65.561 | -2945 | 851111 | 57.561 | 62.616 |
| S26/0659 | 2722460 | 6010120 | 6 | 0 | 0 | 42.723 | -2280 | 851112 | 36.723 | 40.443 |
| S26/0779 | 2726000 | 6016400 | 3 | 0 | 0 | 79.492 | -1075 | 851111 | 76.492 | 78.417 |
| S26/0780 | 2729500 | 6013500 | 10 | 0 | 0 | 65.115 | -4750 | 851111 | 55.115 | 60.365 |
| S26/0781 | 2729100 | 6012800 | 9 | 0 | 0 | 63.440 | -5458 | 851111 | 54.440 | 57.982 |
| S26/0730 | 2727800 | 6016000 | 33 | 0 | 0 | 90.540 | -16470 | 851113 | 57.540 | 74.07 |
| S26/0738 | 2725320 | 6015300 | 5.4 | 0 | 0 | 72.112 | -3490 | 851111 | 66.712 | 68.622 |
| T26/0619 | 2732257 | 6016018 | 3 | 0 | 0 | 80.470 | -1450 | 851111 | 77.470 | 79.02 |
| S27/0025 | 2705800 | 6008870 | 19 | 0 | 0 | 59.718 | -6746 | 851112 | 40.718 | 52.972 |
| S27/0031 | 2710000 | 6005850 | 8 | 0 | 0 | 31.201 | -4419 | 851102 | 23.201 | 26.782 |
| S27/0035 | 2707527 | 6004826 | 6.5 | 0 | 0 | 24.938 | -4084 | 851112 | 18.438 | 20.854 |
| S27/0126 | 2714160 | 6009760 | 10 | 0 | 0 | 59.460 | -3990 | 851112 | 49.460 | 55.47 |
| S27/0148 | 2712220 | 6008740 | 8.77 | 0 | 0 | 60.577 | -5102 | 851112 | 51.807 | 55.475 |
| S27/0096 | 2710550 | 6006850 | 10 | 0 | 0 | 45.217 | -4260 | 851112 | 35.217 | 40.957 |
| S27/0099 | 2713190 | 6004230 | 16.76 | 0 | 0 | 34.650 | -444 | 851112 | 17.890 | 34.206 |
| S27/0102 | 2712330 | 6004300 | 6 | 0 | 0 | 34.620 | -670 | 851112 | 28.620 | 33.95 |
| S27/0106 | 2713274 | 6004926 | 11 | 0 | 0 | 37.455 | -946 | 851112 | 26.455 | 36.509 |
| S27/0108 | 2712900 | 6003750 | 11.3 | 8.3 | 11.3 | 32.862 | | | 21.562 | |
| S27/0171 | 2715117 | 6008003 | 7 | 0 | 0 | 48.770 | | | 41.770 | |
| S27/0173 | 2715800 | 6006400 | 5 | 0 | 0 | 42.995 | | | 37.995 | |
| S27/0183 | 2715948 | 6005982 | 37 | 0 | 0 | 42.288 | | | 5.288 | |
| S27/0248 | 2723076 | 6009725 | 7.9 | 0 | 0 | 42.733 | -1540 | 851111 | 34.833 | 41.193 |
| S27/0374 | 2713600 | 6002200 | 18.56 | 0 | 0 | 29.005 | -1700 | 851128 | 10.445 | 27.305 |
| S27/0006 | 2703562 | 6005165 | 12 | | | 19.026 | -3658 | 851115 | 7.026 | 15.368 |
| S27/0011 | 2703561 | 6003444 | 24 | | | 6.127 | 170 | 851115 | -17.873 | 6.297 |
| S27/0012 | 2703799 | 6005119 | 66 | | | 18.331 | -4190 | 851115 | -47.669 | 14.141 |
| S27/0261 | 2704550 | 5997300 | 41 | | | 2.133 | 5990 | 851119 | -38.867 | 8.123 |
| S27/0263 | 2703229 | 6002232 | 19 | | | 3.382 | 1360 | 851115 | -15.618 | 4.742 |
| S27/0271 | 2707818 | 5998780 | 30 | | | | 12490 | 851115 | -30 | 12.49 |
| S27/0282 | 2707818 | 6000462 | 22 | | | 8.423 | 550 | 851115 | -13.577 | 8.973 |
| S27/0293 | 2709850 | 6002000 | 22 | | | 16.825 | -305 | 851112 | -5.175 | 16.52 |
| S27/0304 | 2705050 | 5995050 | 52 | | | 4.458 | 1195 | 581120 | -47.542 | 5.653 |
| S27/0326 | 2705989 | 5996434 | 30 | | | 4.82 | 3415 | 851119 | -25.18 | 8.235 |
| S27/0274 | 2706884 | 5998568 | 30 | | | 4.04 | 4135 | 851119 | -25.96 | 8.175 |
| S27/0275 | 2706298 | 5998329 | 28 | | | 3.95 | 3870 | 851119 | -24.05 | 7.82 |
| S27/0277 | 2707310 | 6000149 | 28 | | | 8.11 | 920 | 851115 | -19.89 | 9.03 |

| Wells_No | East | North | Well Depth | Top Screen | Bottom Screen | MP_RL (mamsl) | WL_DATA (mmBRL) | DATE | Screen_RL (mamsl) | Water_level_RL (mamsl) |
|---|---|---|---|---|---|---|---|---|---|---|
| S27/0278 | 2707920 | 6000558 | 15 | | | 8.27 | | | -6.73 | 8.27 |
| S27/0340 | 2710009 | 6001182 | 45 | | | 18.051 | -4195 | 851128 | -26.949 | 13.856 |
| S27/0351 | 2710350 | 5996800 | 17 | | | 11.837 | -2460 | 851115 | -5.163 | 9.377 |
| S27/0362 | 2713933 | 5999049 | 9 | | | 17.339 | -2765 | 851118 | 8.339 | 14.574 |
| S27/0376 | 2711275 | 5997390 | 35 | | | 13.25 | | | -21.75 | 13.25 |
| S27/0425 | 2693800 | 5989300 | 49 | | | 3.11 | 4030 | 851121 | -45.89 | 7.14 |
| S27/0426 | 2694224 | 5987842 | 48 | | | 4.497 | 1230 | 851121 | -43.503 | 5.727 |
| S27/0427 | 2695199 | 5990534 | 79 | | | 3.78 | 4390 | 851121 | -75.22 | 8.17 |
| S27/0437 | 2695200 | 5989700 | 42 | | | 3.18 | 1360 | 851121 | -38.82 | 4.54 |
| S27/0438 | 2697300 | 5987700 | 39 | | | 3.08 | 1640 | 851121 | -35.92 | 4.72 |
| S27/0439 | 2697201 | 5989561 | 28 | | | 2.05 | 2630 | 851121 | -25.95 | 4.68 |
| S27/0440 | 2698076 | 5992640 | 38 | | | 3.337 | 1790 | 851119 | -34.663 | 5.127 |
| S27/0441 | 2696682 | 5991896 | 40 | | | 4.2 | 1360 | 851119 | -35.8 | 5.56 |
| S27/0442 | 2699915 | 5988602 | 178 | | | 4.545 | | | -173.455 | 4.545 |
| S27/0443 | 2699510 | 5990105 | 33 | | | 2.93 | 2760 | 851119 | -30.07 | 5.69 |
| S27/0428 | 2697641 | 5992527 | 44 | | | | 4971 | 851119 | -44 | 4.971 |
| S27/0429 | 2697781 | 5989573 | 39 | | | 1.83 | 3060 | 851121 | -37.17 | 4.89 |
| S27/0461 | 2701693 | 5991624 | 24 | | | 4.26 | 645 | 851120 | -19.74 | 4.905 |
| S27/0463 | 2700076 | 5987525 | 64 | | | 3.96 | 3615 | 851119 | -60.04 | 7.575 |
| S27/0464 | 2700955 | 5991084 | 40 | | | 3.5 | 1230 | 851120 | -36.5 | 4.73 |
| S27/0465 | 2704079 | 5993248 | 39 | | | 5.48 | -150 | 851120 | -33.52 | 5.33 |
| S27/0466 | 2702813 | 5994787 | 59 | | | 3.525 | 5225 | 851120 | -55.475 | 8.75 |
| S27/0446 | 2704505 | 5993956 | 60 | | | 5 | 645 | 851120 | -55 | 5.645 |
| S27/0447 | 2700830 | 5991478 | 37 | | | 4.02 | 100 | 851119 | -32.98 | 4.12 |
| S27/0478 | 2707277 | 5989676 | 24 | | | 10.915 | -4375 | 851118 | -13.085 | 6.54 |
| S27/0502 | 2708650 | 5992850 | 30 | | | 8.088 | -620 | 851115 | -21.912 | 7.468 |
| S27/0503 | 2709567 | 5991285 | 14 | | | 18.072 | -3897 | 851118 | 4.072 | 14.175 |
| S27/0505 | 2713364 | 5993828 | 15 | | | 19.475 | -9000 | 851118 | 4.475 | 10.475 |
| R27/0004 | 2689858 | 5984857 | 27 | | | 7.67 | | | -19.33 | 7.67 |
| R27/0006 | 2686615 | 5980432 | 11 | | | 8.73 | 1870 | 851120 | -2.27 | 10.6 |
| S27/0576 | 2691443 | 5985224 | 56 | | | 2.607 | 3250 | 851120 | -53.393 | 5.857 |
| S27/0593 | 2692050 | 5981240 | 52 | | | 13.885 | -5395 | 851118 | -38.115 | 8.49 |
| S27/0594 | 2691376 | 5981438 | 44 | | | 4.675 | 7930 | 851118 | -39.325 | 12.605 |
| S27/0595 | 2692391 | 5985142 | 41 | | | 3.51 | 1695 | 851120 | -37.49 | 5.205 |
| S27/0596 | 2690550 | 5983750 | 46 | | | 2.22 | 3150 | 851120 | -43.78 | 5.37 |
| S27/0597 | 2693209 | 5982818 | 30 | | | 7.24 | -2272 | 851118 | -22.76 | 4.968 |
| S27/0577 | 2694500 | 5986310 | 137 | | | 3.584 | 1390 | 851121 | -133.416 | 4.974 |

| Wells_No | East | North | Well Depth | Top Screen | Bottom Screen | MP_RL (mamsl) | WL_DATA (mmBRL) | DATE | Screen_RL (mamsl) | Water_level_RL (mamsl) |
|---|---|---|---|---|---|---|---|---|---|---|
| S27/0579 | 2694490 | 5986290 | 50 | | | 3.264 | -2740 | 851121 | -46.736 | 0.524 |
| S27/0581 | 2692570 | 5981940 | 15 | | | 6.5 | | | -8.5 | 6.5 |
| S27/0583 | 2691430 | 5983400 | 58 | | | | | | -58 | 0 |
| S27/0584 | 2691597 | 5984311 | 49 | | | 1.6 | 3070 | 850514 | -47.4 | 4.67 |
| S27/0609 | 2696850 | 5983880 | 91 | | | 15.23 | | | -75.77 | 15.23 |
| S27/0609 | 2696850 | 5983880 | 91 | | | | >12400 agl | 851118 | -91 | |
| S27/0618 | 2695193 | 5984189 | 47 | | | 9.013 | | | -37.987 | 9.013 |
| S27/0619 | 2696371 | 5985322 | 69 | | | 3.2 | 7130 | 851118 | -65.8 | 10.33 |
| S27/0621 | 2696450 | 5986950 | 42 | | | 2.554 | 40 | 851119 | -39.446 | 2.594 |
| S27/0599 | 2695300 | 5986300 | 41 | | | 3.136 | 1845 | 851119 | -37.864 | 4.981 |
| S27/0600 | 2696300 | 5987010 | 90 | | | 3.39 | 2115 | 851118 | -86.61 | 5.505 |
| S27/0601 | 2698061 | 5984656 | 31 | | | 9.74 | 2920 | 851118 | -21.26 | 12.66 |
| S27/0602 | 2699650 | 5987020 | 61 | | | 3.155 | 4430 | 851119 | -57.845 | 7.585 |
| S27/0603 | 2695950 | 5984750 | 58 | | | 4.658 | 6340 | 851119 | -53.342 | 10.998 |
| R28/0001 | 2689304 | 5977073 | 28 | | | 8.31 | -5860 | 851118 | -19.69 | 2.45 |
| R28/0012 | 2689319 | 5977396 | 60 | | | 3.96 | -145 | 851118 | -56.04 | 3.815 |
| S28/0003 | 2691450 | 5979450 | 18 | | | 19.63 | | | 1.63 | 19.63 |

# Appendix 3 – Concurrent gauging results

| Gauging site | Site type | Easting | Northing | Date | Flow L/s | Error +/- L/s | Raw difference | Adjusted difference |
|---|---|---|---|---|---|---|---|---|
| Mt Bruce | Ruamahanga |  |  |  | 2100 | 210 |  |  |
| Dunvegan | Ruamahanga | 2732169 | 6041075 | 16/03/2006 | 2015 | 202 | -85 | 0 |
| Ruamahanga opposite Mikimiki Rd. | Ruamahanga | 2732331 | 6037083 | 16/03/2006 | 1905 | 191 | -110 | 0 |
| Opaki W/R Diversion control Structure u/s of intake | Abstraction | 2734376 | 6032953 | 16/03/2006 | 67 | 7 |  |  |
| Double bridges | Ruamahanga | 2734362 | 6033495 | 16/03/2006 | 2233 | 223 | 395 | 395 |
| Above Kopuaranga confluence | Ruamahanga | 2736719 | 6031119 | 16/03/2006 | 1721 | 172 | -512 | -512 |
| Kopuaranga at Ruamahanga confluence | Input | 2736891 | 6031095 | 16/03/2006 | 530 | 53 |  |  |
| Carrolls | Ruamahanga | 2737677 | 6027518 | 16/03/2006 | 2165 | 217 | -86 | 0 |
| Te Ore Ore W/R d/s of intake | Abstraction | 2737649 | 6027020 | 16/03/2006 | 210 | 21 |  |  |
| Henley Lake Intake | Abstraction | 2735981 | 6025206 | 16/03/2006 | 15 | 2 |  |  |
| Te Ore Ore Bridge | Ruamahanga | 2736285 | 6025035 | 16/03/2006 | 2089 | 209 | 149 | 0 |
| Henley Lake Intake | Abstraction | 2735981 | 6025206 | 16/03/2006 | 175 | 18 |  |  |
| Waipoua at Ruamahanga Confluence | Input | 2735196 | 6024148 | 16/03/2006 | 167 | 17 |  |  |
| 300m u/s of Whangaehu | Ruamahanga | 2735900 | 6020900 | 16/03/2006 | 2574 | 257 | 493 | 493 |
| Whangaehu at Ruamahanga Confluence | Input | 2736152 | 6020924 | 16/03/2006 | 237 | 24 |  |  |
| Makoura Sewerage Ponds | Input | 2735200 | 6020200 | 16/03/2006 | 242 | 24 |  |  |
| Kuripuni Ruamahanga Confluence | Input | 2734559 | 6019072 | 16/03/2006 | 136 | 14 |  |  |
| Waingawa at Ruamahanga Confluence | Input | 2733895 | 6019022 | 16/03/2006 | 1625 | 163 |  |  |
| Ruamahanga u/s Taueru confluence | Ruamahanga | 2731223 | 6012056 | 16/03/2006 | 4960 | 496 | 146 | 0 |
| Taueru at Ruamahanga Confluence | Input | 2731272 | 6011993 | 16/03/2006 | 542 | 54 |  |  |
| Makahakaha Western Culvert | Input | 2731315 | 6011490 | 16/03/2006 | 89 | 9 |  |  |
| Kokotau Bridge | Ruamahanga | 2725213 | 6008885 | 16/03/2006 | 5821 | 582 | 230 | 0 |
| Ruamahanga u/s Waiohine | Ruamahanga | 2721220 | 6008667 | 16/03/2006 | 5985 | 599 | 164 | 0 |
| Waiohine at Ruamahanga Confluence | Input | 2720589 | 6008649 | 16/03/2006 | 5222 | 522 |  |  |
| Morrisons Bush | Ruamahanga | 2718795 | 6002639 | 16/03/2006 | 12917 | 1292 | 1710 | 1710 |
| Huangarua at Ponatahi | Input | 2716832 | 5996891 | 16/03/2006 | 258 | 26 |  |  |
| Walls | Ruamahanga | 2710408 | 5995552 | 16/03/2006 | 13064 | 1306 | -111 | 0 |
| Pukio | Ruamahanga | 2708048 | 5992739 | 16/03/2006 | 13646 | 1365 | 582 | 0 |

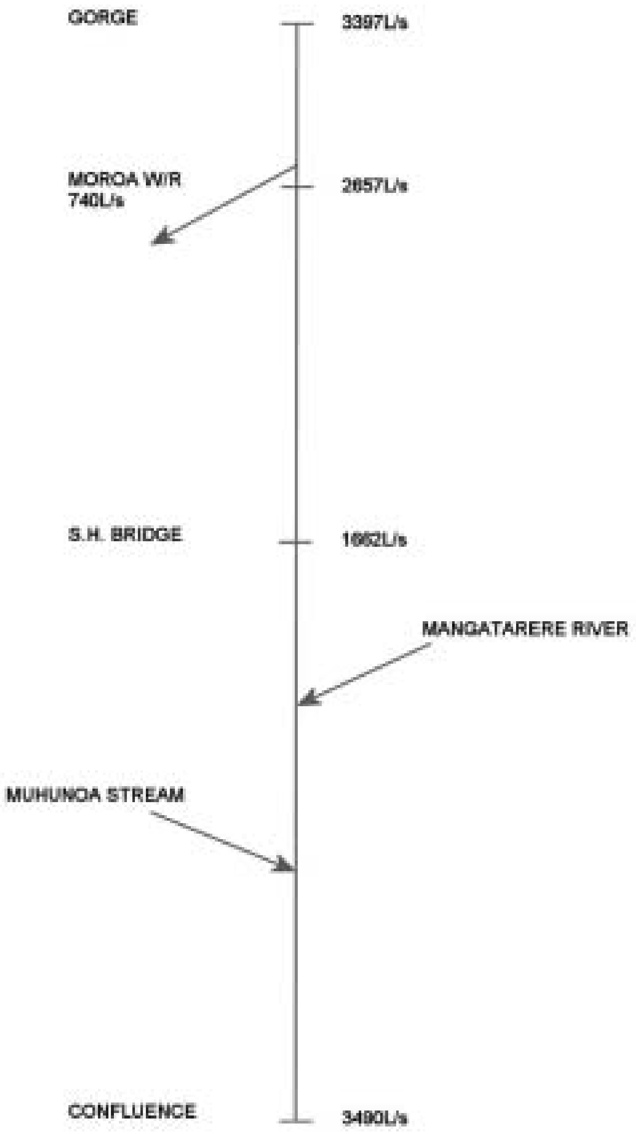
| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Awaroa Sill | Ruamahanga | 2705781 | 5990561 | 16/03/2006 | 13359 | 1336 | -287 | 0 |
| Otaraia | Ruamahanga | 2701538 | 5988303 | 16/03/2006 | 13265 | 1327 | -94 | 0 |

| Gauging site | Site type | Easting | Northing | Date | Flow L/s | Error +/- L/s | Raw difference | Adjusted difference |
|---|---|---|---|---|---|---|---|---|
| Gorge | Tauherenikau | 2708109 | 6012776 | 22/02/2006 | 1660 | 166 | | |
| Longwood Water Race at Underhill Rd | Abstraction | 2708157 | 6011287 | 22/02/2006 | 66 | 7 | | |
| Underhill Rd | Tauherenikau | 2708615 | 6011184 | 22/02/2006 | 1162 | 116 | -432 | -432 |
| SH2 | Tauherenikau | 2709130 | 6006787 | 22/02/2006 | 1104 | 110 | -58 | 0 |
| SH53 | Tauherenikau | 2707892 | 6004178 | 22/02/2006 | 420 | 42 | -684 | -684 |
| Donalds Road | Tauherenikau | 2706300 | 6001100 | 22/02/2006 | 353 | 35 | -67 | -67 |

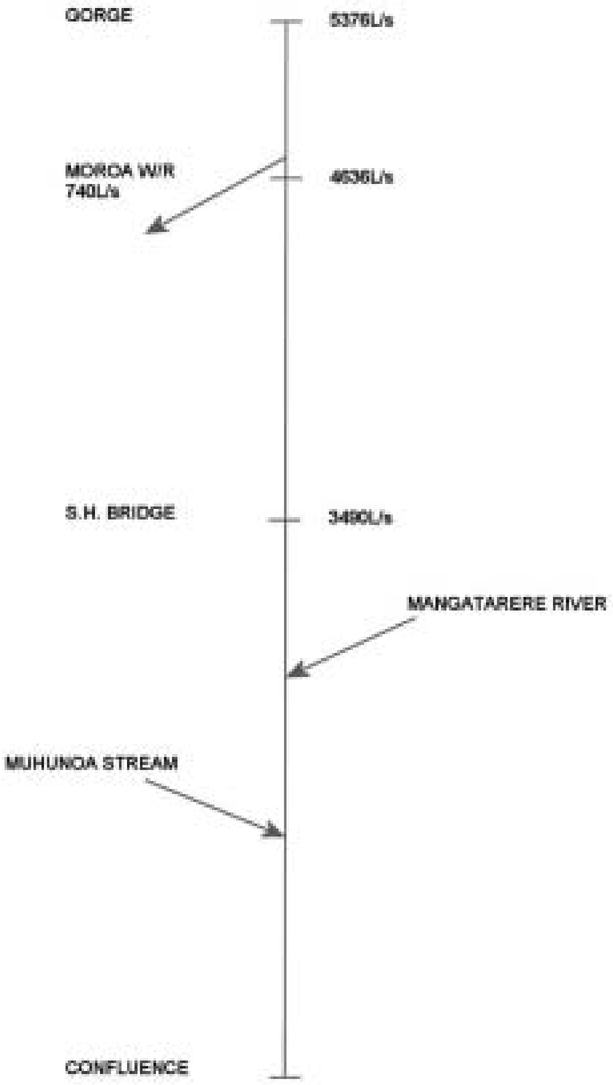
| Gauging site | Site type | Easting | Northing | Date | Flow L/s | Error +/- L/s | Raw difference | Adjusted difference |
|---|---|---|---|---|---|---|---|---|
| Mikimiki | Waipoua | 2730680 | 6036835 | 21/02/2006 | 380 | 38 | | |
| Lahores | Waipoua | 2731634 | 6033075 | 21/02/2006 | 228 | 23 | -152 | -152 |
| Whites | Input | 2729765 | 6031408 | 21/02/2006 | 40 | 4 | | |
| Holmes | Waipoua | 2730788 | 6029382 | 21/02/2006 | 935 | 94 | 667 | 667 |
| Akura Rd Bridge | Waipoua | 2732499 | 6028173 | 21/02/2006 | 181 | 18 | -754 | -754 |
| Railway Crescent | Waipoua | 2734035 | 6026075 | 21/02/2006 | 443 | 44 | 262 | 262 |
| At Ruamahanga Confluence | Waipoua | 2735192 | 6024144 | 21/02/2006 | 329 | 33 | -114 | -114 |

| Gauging site | Site type | Easting | Northing | Date | Flow L/s | Error +/- L/s | Raw difference | Adjusted difference |
|---|---|---|---|---|---|---|---|---|
| Kaituna | Waingawa | 2722600 | 6032400 | 21/02/2006 | 1873 | 187 | | |
| Norfolk Rd Bridge | Input | 2723100 | 6031600 | 21/02/2006 | 117 | 12 | | |
| Skeets Rd | Waingawa | 2727519 | 6026511 | 21/02/2006 | 1632 | 163 | -358 | -358 |
| SH2 | Waingawa | 2729742 | 6023425 | 21/02/2006 | 1499 | 150 | -133 | 0 |
| Above Ruamahanga Confluence | Waingawa | 2733895 | 6019022 | 21/02/2006 | 1029 | 103 | -470 | -470 |

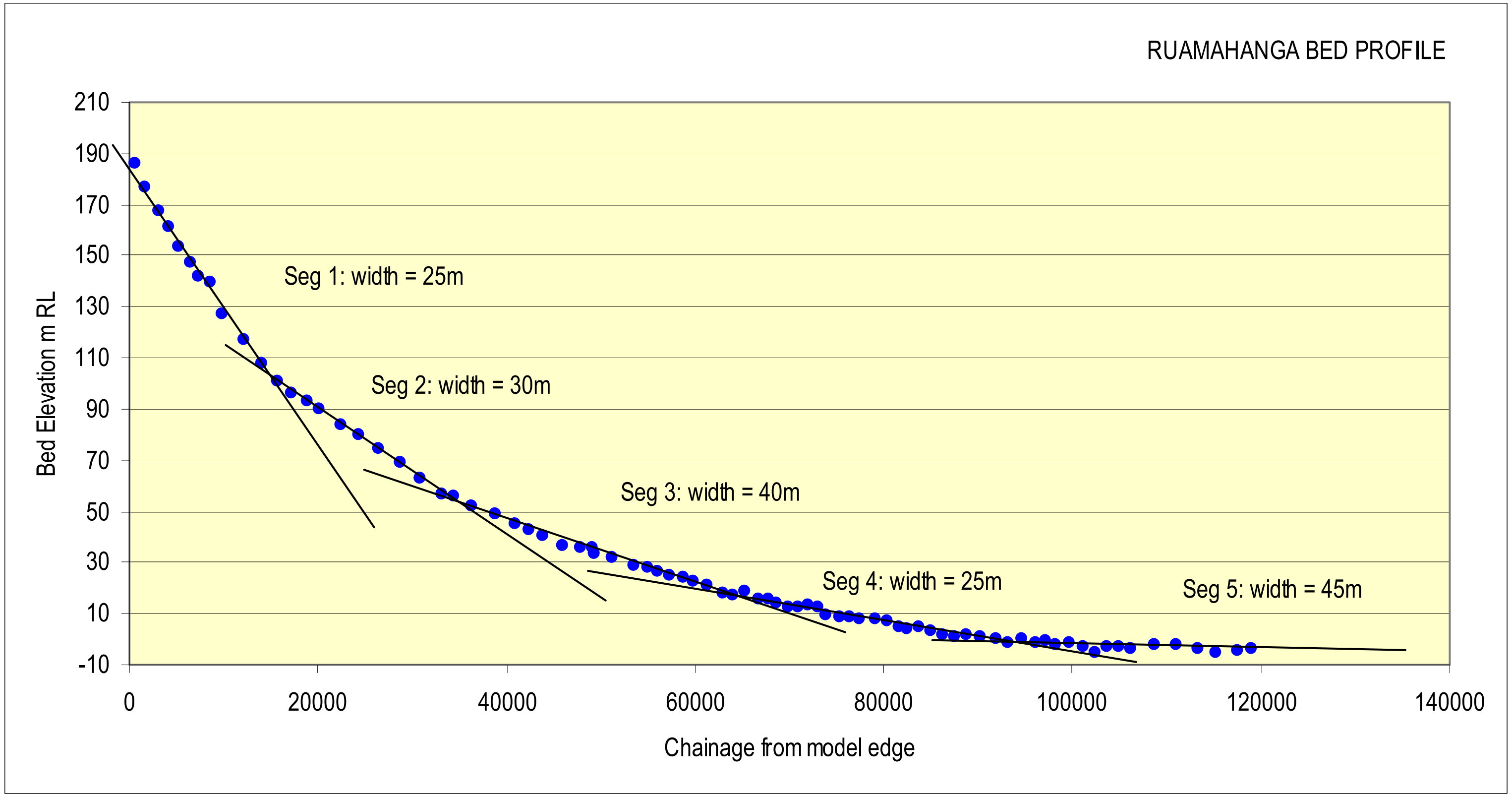
Waiohine River: 3 April 1974

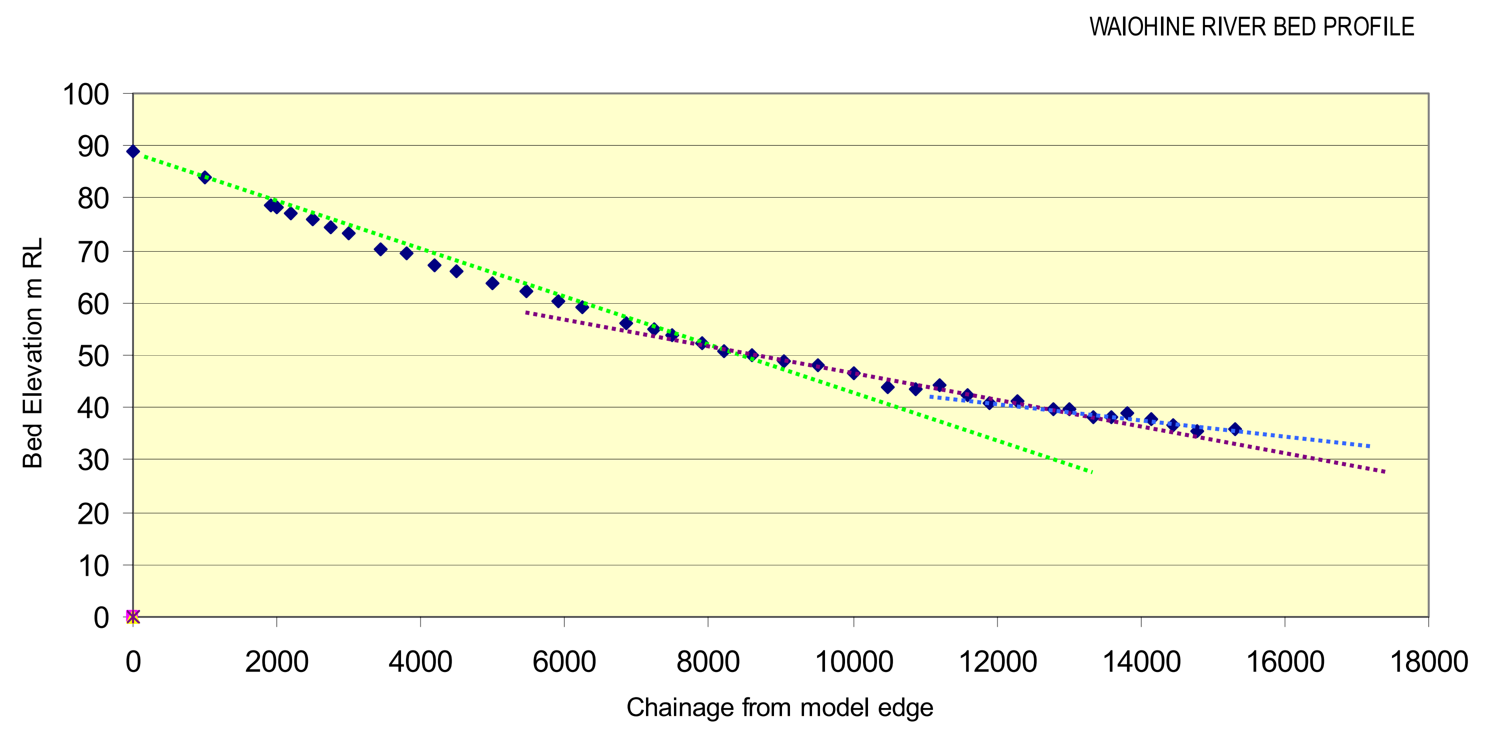


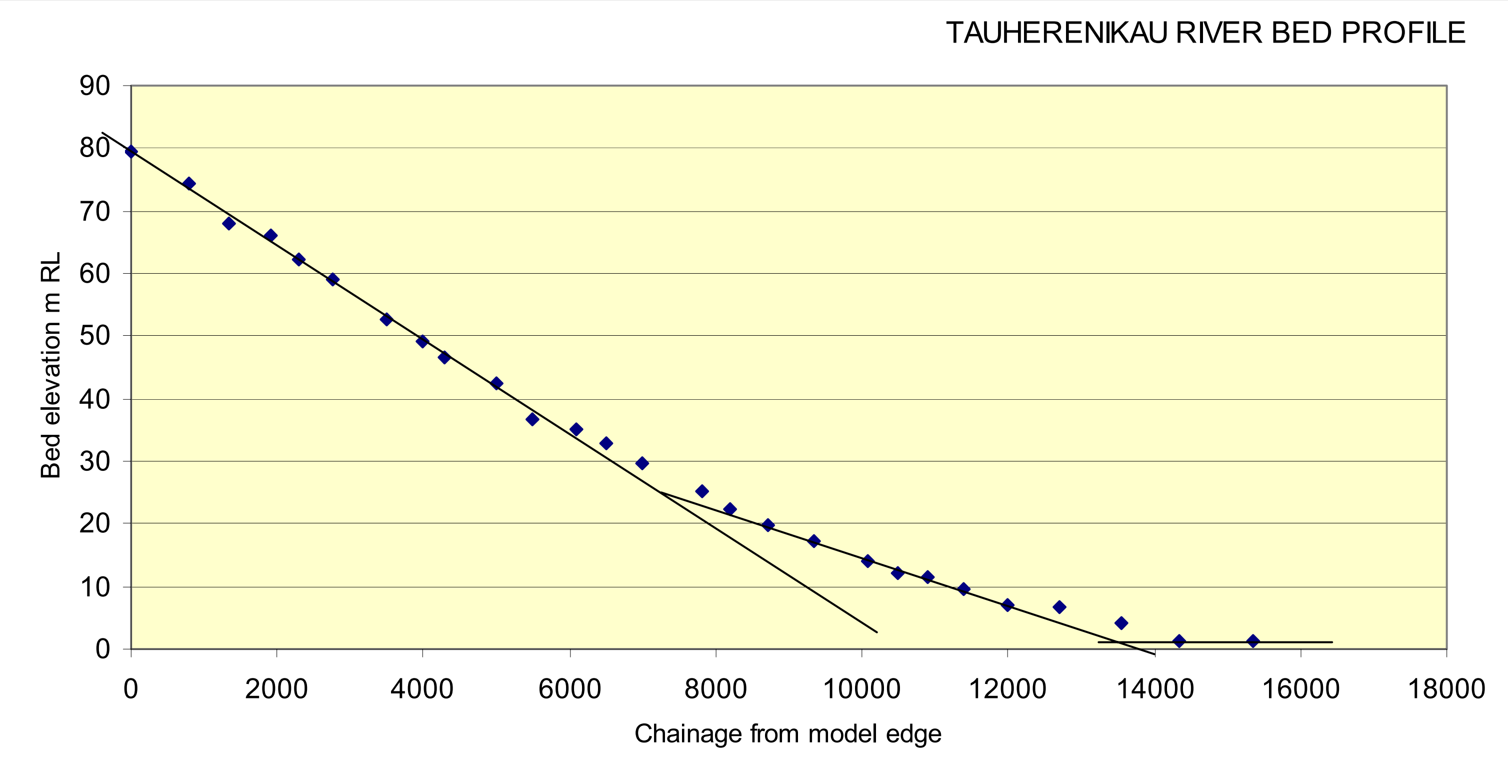
Waiohine River: 18 December 1974

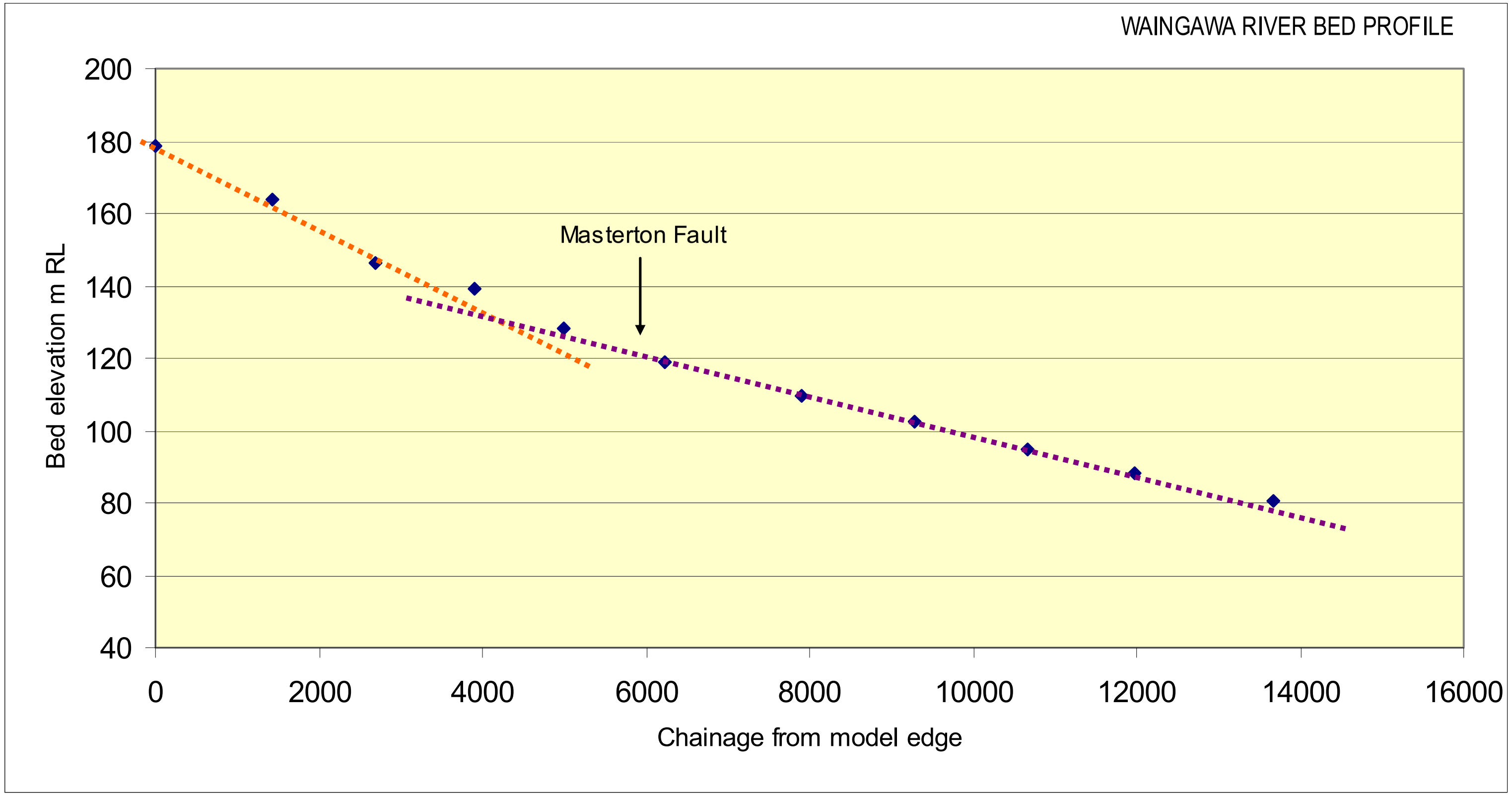


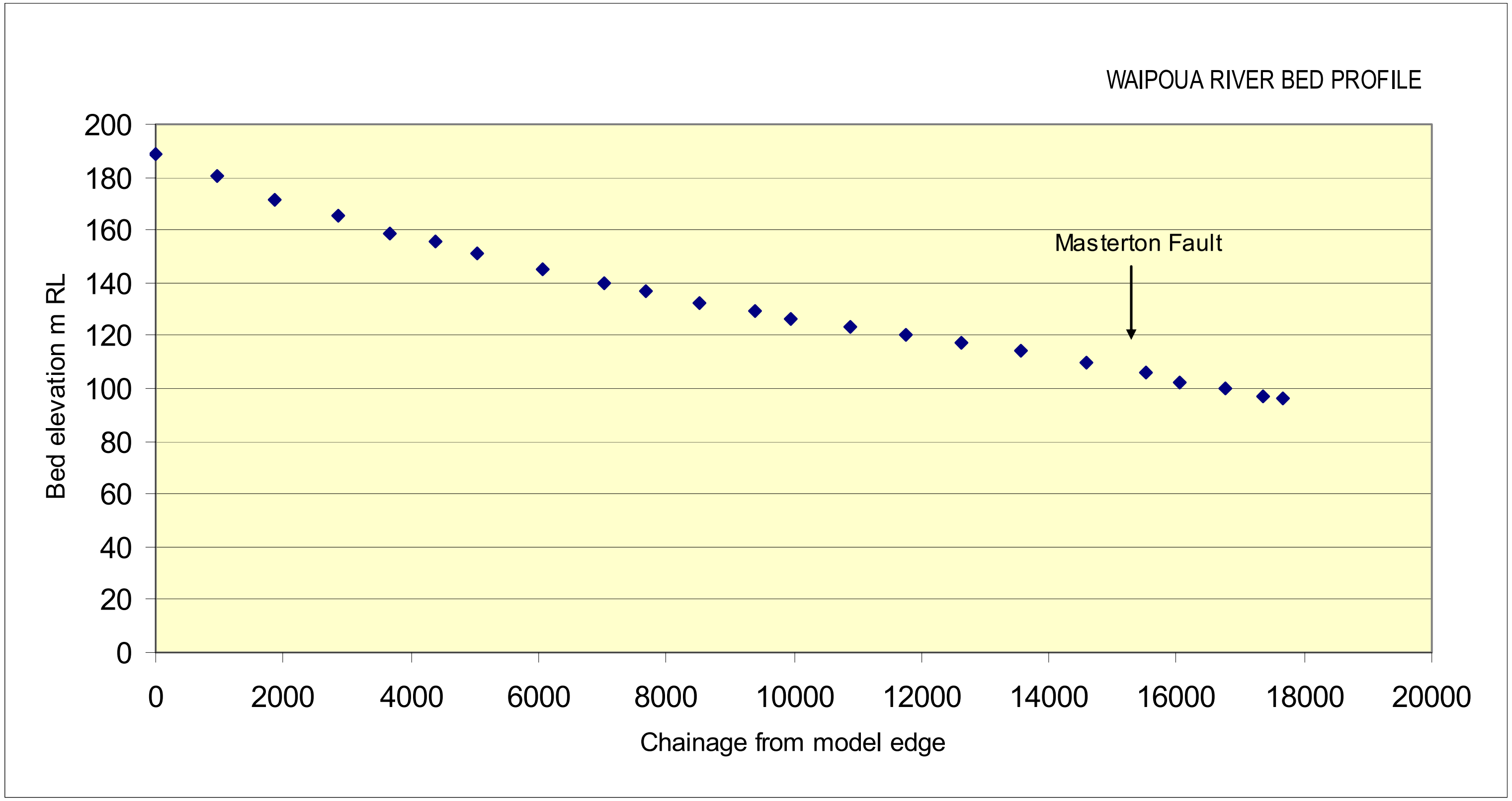
# Appendix 4 – Wairarapa River bed profiles



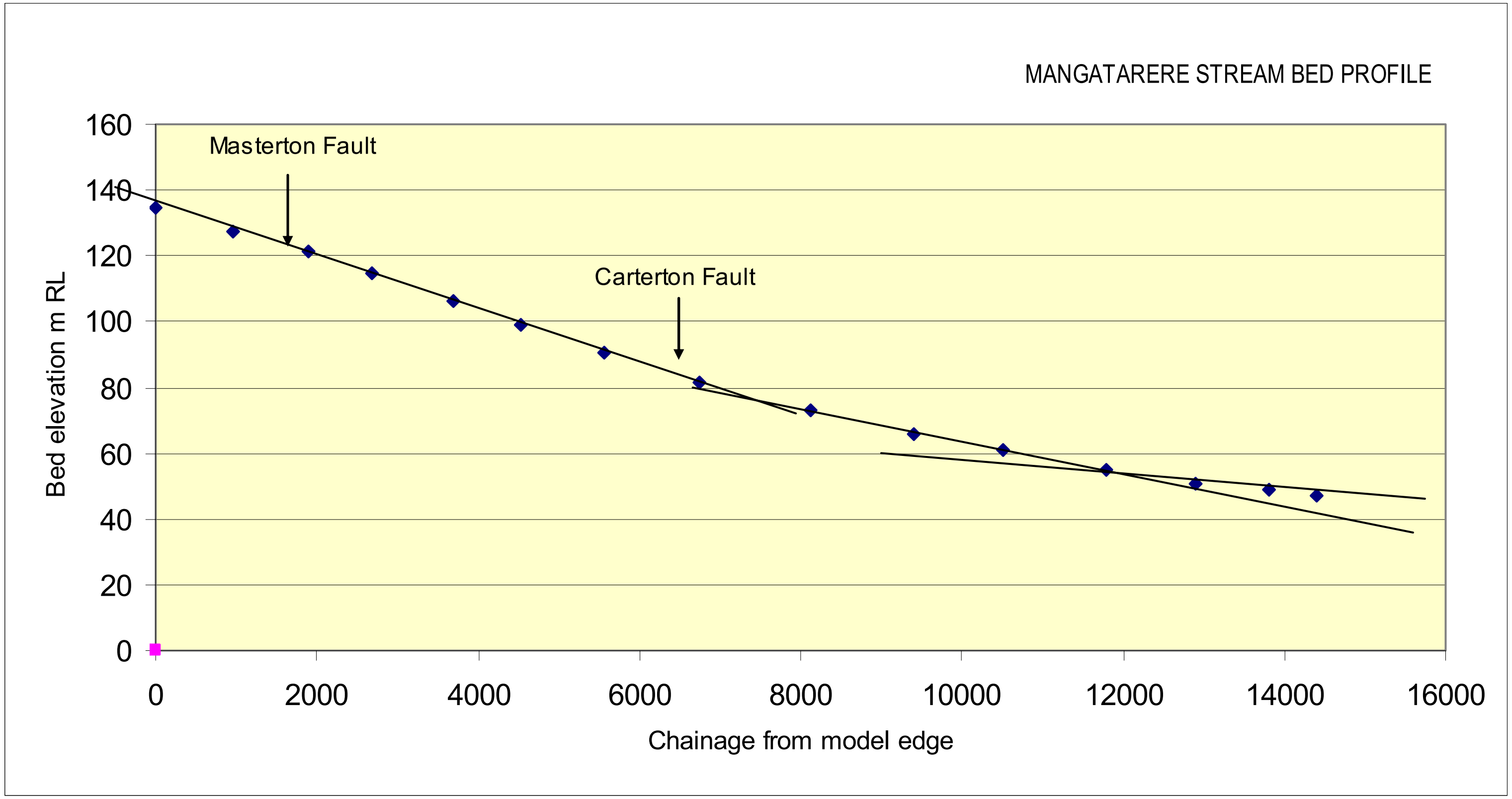

WAIOHINE RIVER BED PROFILE
Bed Elevation m RL
100
90
80
70
60
50
40
30
20
10
0
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
Chainage from model edge


TAUHERENIKAU RIVER BED PROFILE
Bed elevation m RL
90
80
70
60
50
40
30
20
10
0
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
Chainage from model edge


WAINGAWA RIVER BED PROFILE
Bed elevation m RL
200
180
160
140
120
100
80
60
40
0
2000
4000
6000
8000
10000
12000
14000
16000
Chainage from model edge
Masterton Fault



WAIPOUA RIVER BED PROFILE


MANGATARERE STREAM BED PROFILE
Masterton Fault
Carterton Fault
Bed elevation m RL
160
140
120
100
80
60
40
20
0
0
2000
4000
6000
8000
10000
12000
14000
16000
Chainage from model edge

# Appendix 5 – pumping wells simulated in the model

| Permit | Name | Take L/s | Take m$^3$/yr | Well number | Depth (m) | Well elevation (mamsl) | Screen base (mamsl) | Screen top (mamsl) | Easting | Northing |
|---|---|---|---|---|---|---|---|---|---|---|
| WAR 000380 | Wadham N H & B A | 23 | 308910 | S26/0046 | 5 | 165.00 | 160 | 161 | 2726700 | 6027300 |
| WAR 050141 | Stuart G J | 30 | 544320 | T26/0034 | 6 | 160.00 | 154 | 155 | 2735541 | 6032627 |
| WAR 010371 | Reid N & E E | 13 | 397488 | S26/0169 | 8 | 140.00 | 132 | 133 | 2722884 | 6022504 |
| WAR 050122 | McLachlan S J & J | 36 | 566093 | T26/0286 | 5 | 140.00 | 135 | 136 | 2736302 | 6030185 |
| WAR 050077 | Stuart D R & K L | 35 | 649152 | T26/0267 | 5 | 140.00 | 135 | 136 | 2736414 | 6031597 |
| WAR 050143 | Rathkeale College | 13 | 47320 | T26/0278 | 0 | 140.00 | 140 | 141 | 2736400 | 6031020 |
| WAR 010351 | Stolte Dairy Ltd | 25 | 453600 | S26/0226 | 4 | 140.00 | 136 | 137 | 2726115 | 6023127 |
| WAR 050169 | Stolte Dairy Ltd | 15 | 272160 | S26/0855 | 5 | 140.00 | 135 | 136 | 2726005 | 6023147 |
| WAR 050067 | Stolte Dairy Ltd | 50 | 907200 | S26/0226 | 4 | 140.00 | 136 | 137 | 2726115 | 6023127 |
| WAR 980170 | Busby Family Trust | 11 | 190134 | S26/0218 | 41 | 120.00 | 79 | 80 | 2728550 | 6022410 |
| WAR 000298 | Smith D G & A B | 27 | 491501 | S26/0190 | 4 | 120.00 | 116 | 117 | 2723160 | 6020620 |
| WAR 000383 | Baily-Gibson T J | 13 | 88452 | T26/0270 | 31 | 120.00 | 89 | 90 | 2737510 | 6025290 |
| WAR 990088 | Bosch A & J | 13 | 140400 | T26/0488 | 34 | 120.00 | 86 | 87 | 2737500 | 6025000 |
| WAR 010261 | Hurrell C J & D C | 11 | 40027 | T26/0532 | 24 | 120.00 | 96 | 97 | 2736620 | 6024310 |
| WAR 990231 | McKenzie J B | 17 | 290360 | T26/0539 | 25 | 120.00 | 95 | 96 | 2738160 | 6024370 |
| WAR 000314 | McKinstry J F | 15 | 272160 | T26/0474 | 27 | 120.00 | 93 | 94 | 2737370 | 6024500 |
| WAR 030143 | Percy JF & CA | 17 | 176256 | T26/0668 | 27 | 120.00 | 93 | 94 | 2738180 | 6023318 |
| WAR 030147 | Percy JF & CA | 40 | 414720 | T26/0667 | 32 | 120.00 | 88 | 89 | 2737226 | 6023591 |
| WAR 040128 | Stuart C & L | 30 | 129600 | T26/0677 | 27 | 120.00 | 93 | 94 | 2738310 | 6025259 |
| WAR 000350 | Daniell M E | 25 | 310464 | T26/0093 | 4 | 120.00 | 116 | 117 | 2733510 | 6026680 |
| WAR 990258 | Dean R E | 15 | 90720 | T26/0331 | 3 | 120.00 | 117 | 118 | 2730370 | 6021860 |
| WAR 010297 | G H & L E Tulloch | 25 | 453600 | T26/0363 | 3 | 120.00 | 117 | 118 | 2730950 | 6021375 |
| WAR 010333 | Tulloch G H | 18 | 326592 | T26/0364 | 38 | 100.00 | 62 | 63 | 2731655 | 6019130 |
| WAR 030167 | Smith P I | 12 | 199584 | S26/0459 | 5 | 100.00 | 95 | 96 | 2715670 | 6016300 |
| WAR 000304 | Somerville Family | 17 | 259532 | S26/0171 | 5 | 100.00 | 95 | 96 | 2723380 | 6018590 |
| WAR 050118 | TSM Farms (Tulloch | 15 | 272160 | S26/0167 | 12 | 100.00 | 88 | 89 | 2723885 | 6017850 |
| WAR 050105 | TSM Farms (Tulloch | 15 | 199584 | S26/0198 | 41 | 100.00 | 59 | 60 | 2723897 | 6017834 |
| WAR 990306 | Homebush Dairy Co | 25 | 453600 | T26/0472 | 8 | 100.00 | 92 | 93 | 2735365 | 6020876 |
| WAR 030141 | Little Avondale St | 26 | 550368 | T26/0484 | 6 | 100.00 | 94 | 95 | 2736255 | 6023492 |
| WAR 990289 | Percy J F & C A | 30 | 544320 | T26/0471 | 11 | 100.00 | 89 | 90 | 2736280 | 6021860 |
| WAR 010355 | Percy J F & C A | 11 | 199584 | T26/0475 | 30 | 100.00 | 70 | 71 | 2737432 | 6022141 |
| WAR 990060 | Tulloch DJ & FB | 11 | 133056 | T26/0567 | 18 | 100.00 | 82 | 83 | 2736577 | 6023767 |

| Permit | Name | Take L/s | Take m$^3$/yr | Well number | Depth (m) | Well elevation (mamsl) | Screen base (mamsl) | Screen top (mamsl) | Easting | Northing |
|---|---|---|---|---|---|---|---|---|---|---|
| WAR 030135 | Tulloch G H | 28 | 508032 | T26/0669 | 4 | 100.00 | 96 | 97 | 2732432 | 6019980 |
| WAR 990132 | Booth J B | 33 | 453222 | T26/0577 | 9 | 80.00 | 71 | 72 | 2732121 | 6014331 |
| WAR 060088 | Cliffs Trust | 25 | 357000 | T26/0607 | 10 | 80.00 | 70 | 71 | 2733210 | 6016692 |
| WAR 990012 | Johner & Schubert | 20 | 362880 | T26/0590 | 8 | 80.00 | 72 | 73 | 2733190 | 6015590 |
| WAR 000361 | Mebus Estate | 13 | 78624 | T26/0581 | 6 | 80.00 | 74 | 75 | 2732765 | 6014545 |
| WAR 990018 | Patrick B B & C M | 15 | 208656 | T26/0591 | 6 | 80.00 | 74 | 75 | 2731880 | 6013320 |
| WAR 060054 | Patrick B B & C M | 11 | 153014 | T26/0628 | 8 | 80.00 | 72 | 73 | 2732634 | 6013399 |
| WAR 990018 | Patrick B B & C M | 25 | 347760 | T26/0592 | 20 | 80.00 | 60 | 61 | 2731809 | 6013321 |
| WAR 060053 | Patrick B | 32 | 445133 | T26/0611 | 23 | 80.00 | 57 | 58 | 2731518 | 6013657 |
| WAR 050116 | Patrick B | 22 | 306029 | T26/0703 | 18 | 80.00 | 62 | 63 | 2733380 | 6013722 |
| WAR 030177 | Southey CT | 20 | 207360 | T26/0644 | 5 | 80.00 | 75 | 76 | 2733375 | 6018275 |
| WAR 030093 | Urlar Farms Ltd | 15 | 308448 | T26/0659 | 10 | 80.00 | 70 | 71 | 2733166 | 6016858 |
| WAR 010230 | Booth BJ | 17 | 181440 | T26/0612 | 24 | 80.00 | 56 | 57 | 2730738 | 6013188 |
| WAR 970258 | Pa Puke Farm Ltd | 15 | 226044 | T26/0589 | 32 | 80.00 | 48 | 49 | 2733500 | 6013090 |
| WAR 050156 | Toledo Dreamcatche | 28 | 48384 | S26/0620 | 18 | 80.00 | 62 | 63 | 2720557 | 6016490 |
| WAR 950050 | Carterton District | 40 | 532224 | S26/0824 | 21 | 80.00 | 59 | 60 | 2720564 | 6016101 |
| WAR 000374 | Terry N R | 11 | 198240 | S26/0594 | 27 | 80.00 | 53 | 54 | 2722319 | 6015504 |
| WAR 020049 | Wilmshurst L E | 15 | 272160 | S26/0784 | 18 | 80.00 | 62 | 63 | 2721164 | 6014553 |
| WAR 050111 | Toledo Dreamcatche | 50 | 648000 | S26/0885 | 34 | 80.00 | 46 | 47 | 2720566 | 6016481 |
| WAR 010233 | Slater B & J | 18 | 32076 | S26/0461 | 9 | 80.00 | 71 | 72 | 2715470 | 6012010 |
| WAR 050176 | Smallwood Family T | 36 | 466560 | S26/0915 | 10 | 80.00 | 70 | 71 | 2716394 | 6012567 |
| WAR 040058 | Fisher Family Trus | 25 | 453600 | S26/0854 | 24 | 80.00 | 56 | 57 | 2720550 | 6017003 |
| WAR 010235 | Brazendale W E & E | 15 | 181440 | S26/0382 | 4 | 80.00 | 76 | 77 | 2716800 | 6013700 |
| WAR 050065 | Sage K & A | 33 | 420790 | S26/0768 | 47 | 80.00 | 33 | 34 | 2726180 | 6015400 |
| WAR 050023 | Wither I R & M A | 40 | 532224 | S26/0744 | 33 | 80.00 | 47 | 48 | 2725645 | 6014231 |
| WAR 010234 | Slater B & J | 18 | 26244 | S26/0475 | 9 | 60.00 | 51 | 52 | 2719139 | 6012183 |
| WAR 010172 | Slater C J | 21 | 166725 | S26/0399 | 10 | 60.00 | 50 | 51 | 2718570 | 6011343 |
| WAR 020018 | Berwick Holdings L | 40 | 725760 | S26/0454 | 12 | 60.00 | 48 | 49 | 2717570 | 6012640 |
| WAR 010091 | Wong Donald | 17 | 100800 | S26/0393 | 7 | 60.00 | 53 | 54 | 2719510 | 6012060 |
| WAR 010258 | Van Der Put M | 12 | 108864 | S26/0389 | 9 | 60.00 | 51 | 52 | 2718438 | 6012150 |
| WAR 010071 | Wong Les | 25 | 96904 | S26/0561 | 9 | 60.00 | 51 | 52 | 2718800 | 6012500 |
| WAR 010198 | Wright A N | 23 | 70560 | S26/0398 | 10 | 60.00 | 50 | 51 | 2719488 | 6011761 |
| WAR 030120 | Druzianic W T | 40 | 725760 | S26/0846 | 39 | 60.00 | 21 | 22 | 2717921 | 6011212 |
| WAR 990249 | Bicknell J A | 13 | 235872 | S27/0197 | 5 | 60.00 | 55 | 56 | 2719040 | 6009260 |

| Permit | Name | Take L/s | Take m$^3$/yr | Well number | Depth (m) | Well elevation (mamsl) | Screen base (mamsl) | Screen top (mamsl) | Easting | Northing |
|---|---|---|---|---|---|---|---|---|---|---|
| WAR 030132 | Hammond And Co | 80 | 1451520 | S27/0224 | 8 | 60.00 | 52 | 53 | 2717004 | 6009287 |
| WAR 010163 | Pinehaven Orchards | 11 | 150797 | S26/0469 | 11 | 60.00 | 49 | 50 | 2716410 | 6012050 |
| WAR 040115 | Scott R I & C V | 45 | 583200 | S26/0871 | 10 | 60.00 | 50 | 51 | 2718204 | 6010097 |
| WAR 040067 | South Wairarapa Di | 60 | 155520 | S26/0880 | 11 | 60.00 | 49 | 50 | 2716483 | 6011738 |
| WAR 040067 | South Wairarapa Di | 40 | 314496 | S26/0880 | 11 | 60.00 | 49 | 50 | 2716483 | 6011738 |
| WAR 010111 | Price W & A | 15 | 265650 | S26/0405 | 5 | 60.00 | 55 | 56 | 2717212 | 6013907 |
| WAR 960250 | Fitzgerald D P & P | 15 | 260820 | S26/0400 | 16 | 60.00 | 44 | 45 | 2718695 | 6015416 |
| WAR 010145 | Fitzgerald D P & P | 20 | 241920 | S26/0472 | 18 | 60.00 | 42 | 43 | 2719173 | 6015684 |
| WAR 010169 | McLennan H L & L M | 20 | 347760 | S26/0823 | 13 | 60.00 | 47 | 48 | 2718480 | 6014440 |
| WAR 040102 | Knowles R J | 16 | 165888 | S26/0880 | 11 | 60.00 | 49 | 50 | 2716483 | 6011738 |
| WAR 060039 | Budd & Watters Par | 16 | 267960 | S27/0252 | 10 | 60.00 | 50 | 51 | 2723330 | 6009090 |
| WAR 060040 | Budd & Watters Par | 28 | 332640 | S27/0245 | 12 | 60.00 | 48 | 49 | 2723906 | 6009014 |
| WAR 960239 | Westbourne Farms L | 12 | 146300 | S26/0755 | 13 | 60.00 | 47 | 48 | 2729480 | 6012210 |
| WAR 010279 | Herrick M B & H F | 28 | 508032 | S27/0244 | 14 | 60.00 | 46 | 47 | 2721376 | 6009566 |
| WAR 960137 | Saywell J | 16 | 230630 | S26/0761 | 12 | 60.00 | 48 | 49 | 2725890 | 6011070 |
| WAR 060050 | Stevenson R J & C | 25 | 434700 | S26/0745 | 11 | 60.00 | 49 | 50 | 2725190 | 6010260 |
| WAR 060051 | Stevenson R J & C | 24 | 417312 | S26/0604 | 13 | 60.00 | 47 | 48 | 2724750 | 6010360 |
| WAR 060057 | Taylor S M & J D | 17 | 294630 | S27/0249 | 13 | 60.00 | 47 | 48 | 2723620 | 6009420 |
| WAR 990275 | Westbourne Farms L | 13 | 176904 | S26/0608 | 6 | 60.00 | 54 | 55 | 2724250 | 6010500 |
| WAR 060038 | Budd & Watters Par | 18 | 318780 | S27/0251 | 24 | 60.00 | 36 | 37 | 2724230 | 6009350 |
| WAR 060049 | Stevenson R J & C | 13 | 196742 | S26/0756 | 19 | 60.00 | 41 | 42 | 2725937 | 6010018 |
| WAR 000296 | Westbourne Farms L | 25 | 434700 | S26/0588 | 29 | 60.00 | 31 | 32 | 2723820 | 6011000 |
| WAR 010301 | Field Brothers | 23 | 179088 | S27/0200 | 6 | 60.00 | 54 | 55 | 2715102 | 6007721 |
| WAR 040163 | Engel C G & J R (R | 27 | 212212 | S26/0677 | 14 | 60.00 | 46 | 47 | 2722180 | 6011930 |
| WAR 050020 | Engel C G & J R | 15 | 199584 | S26/0614 | 35 | 60.00 | 25 | 26 | 2721000 | 6012643 |
| WAR 050036 | Parkvale Dairy Ltd | 23 | 229522 | S26/0576 | 31 | 60.00 | 29 | 30 | 2723479 | 6014255 |
| WAR 050100 | Westbourne Farms | 25 | 332640 | S26/0621 | 20 | 60.00 | 40 | 41 | 2723280 | 6012560 |
| WAR 050046 | Kilmory Farms Ltd | 25 | 332640 | S26/0568 | 45 | 60.00 | 15 | 16 | 2723504 | 6013642 |
| WAR 050021 | Engel C G & J R | 13 | 158558 | S26/0573 | 49 | 60.00 | 11 | 12 | 2720970 | 6012190 |
| WAR 010084 | Feast J K | 20 | 362880 | S27/0088 | 5 | 60.00 | 55 | 56 | 2709856 | 6008212 |
| WAR 020010 | Bolton M I H & S M | 15 | 272160 | S27/0153 | 10 | 60.00 | 50 | 51 | 2712986 | 6005531 |
| WAR 990227 | Craggy Range Viney | 18 | 326592 | S27/0554 | 47 | 80.00 | 33 | 34 | 2718406 | 5989283 |
| WAR 010364 | Bidwill A J C | 30 | 544320 | S27/0334 | 29 | 20.00 | -9 | -8 | 2706420 | 5997193 |
| WAR 020158 | Osborne A L | 15 | 228137 | S27/0283 | 19 | 20.00 | 1 | 2 | 2707298 | 5997888 |

| Permit | Name | Take L/s | Take m$^3$/yr | Well number | Depth (m) | Well elevation (mamsl) | Screen base (mamsl) | Screen top (mamsl) | Easting | Northing |
|---|---|---|---|---|---|---|---|---|---|---|
| WAR 010249 | Roto Farm Trust (R | 60 | 544320 | S27/0262 | 30 | 20.00 | -10 | -9 | 2703955 | 5995366 |
| WAR 020111 | Caldwell Trust | 25 | 453600 | S27/0642 | 26 | 20.00 | -6 | -5 | 2704174 | 5994436 |
| WAR 020093 | Thurston A W | 20 | 362880 | S27/0284 | 29 | 20.00 | -9 | -8 | 2708932 | 6000550 |
| WAR 020095 | McCreary, TR & HM | 22 | 291200 | S27/0585 | 42 | 20.00 | -22 | -21 | 2690345 | 5984315 |
| WAR 020145 | Finlayson K & S | 19 | 239085 | S27/0607 | 38 | 20.00 | -18 | -17 | 2696313 | 5986755 |
| WAR 020115 | Finlayson K & S | 23 | 348600 | S27/0608 | 50 | 20.00 | -30 | -29 | 2696750 | 5987150 |
| WAR 010072 | Bosch AA & HM | 59 | 535248 | S27/0492 | 30 | 20.00 | -10 | -9 | 2707669 | 5993278 |
| WAR 010073 | Bosch BF & J | 48 | 798336 | S27/0495 | 38 | 20.00 | -18 | -17 | 2707250 | 5993050 |
| WAR 960165 | Loch Ness Farm | 40 | 602784 | S27/0494 | 29 | 20.00 | -9 | -8 | 2708625 | 5993484 |
| WAR 990222 | Maori Education Fo | 80 | 1451520 | S27/0433 | 45 | 20.00 | -25 | -24 | 2697716 | 5989557 |
| WAR 010300 | Te Pare Farm Partn | 68 | 1398298 | S27/0457 | 34 | 20.00 | -14 | -13 | 2703512 | 5992715 |
| WAR 010350 | Warren R | 45 | 816480 | S28/0008 | 30 | 20.00 | -10 | -9 | 2690876 | 5979863 |
| WAR 020105 | Lakeview Trust Par | 18 | 326592 | S27/0614 | 36 | 20.00 | -16 | -15 | 2696803 | 5983642 |
| WAR 020054 | Oporua Dairy Farm | 50 | 907200 | S27/0460 | 38 | 20.00 | -18 | -17 | 2700263 | 5990055 |
| WAR 020156 | Windy Farm Ltd | 35 | 635040 | S27/0664 | 24 | 20.00 | -4 | -3 | 2703674 | 6003973 |
| WAR 020100 | Rotopai Trust | 25 | 380926 | S27/0602 | 61 | 20.00 | -41 | -40 | 2699650 | 5987020 |
| WAR 020101 | Rotopai Trust | 20 | 301392 | S27/0611 | 55 | 20.00 | -35 | -34 | 2699300 | 5986590 |
| WAR 020155 | Barton S | 33 | 573804 | S27/0268 | 58 | 20.00 | -38 | -37 | 2703475 | 5995774 |
| WAR 020110 | Caldwell Trust | 25 | 520244 | S27/0450 | 59 | 20.00 | -39 | -38 | 2704170 | 5994450 |
| WAR 020092 | Thurston A W | 22 | 399000 | S27/0295 | 25 | 20.00 | -5 | -4 | 2709080 | 5999610 |
| WAR 000231 | Fuge D F & E A | 20 | 302400 | S27/0366 | 81 | 20.00 | -61 | -60 | 2710000 | 6001150 |
| WAR 040126 | D B Osborne Trust | 30 | 544320 | S27/0336 | 29 | 20.00 | -9 | -8 | 2709693 | 5999686 |
| WAR 040171 | Vista Trust (SJ Ca | 50 | 829080 | S27/0770 | 44 | 20.00 | -24 | -23 | 2708646 | 5990929 |
| WAR 020022 | Totara Grove Farm | 25 | 453600 | S27/0010 | 24 | 20.00 | -4 | -3 | 2704960 | 6003980 |
| WAR 030014 | Dondertman A J | 18 | 312984 | S27/0012 | 71 | 20.00 | -51 | -50 | 2703799 | 6005119 |
| WAR 050096 | Scott KF & AF Esta | 12 | 217770 | S27/0772 | 33 | 20.00 | -13 | -12 | 2705064 | 6003416 |
| WAR 000390 | Rylib Dairies Ltd | 32 | 580608 | S27/0331 | 15 | 20.00 | 5 | 6 | 2707769 | 6002182 |
| WAR 990002 | Diversion Partners | 25 | 453600 | S27/0325 | 14 | 20.00 | 6 | 7 | 2706836 | 6000595 |
| WAR 990010 | Johnson M S & G | 44 | 698544 | S27/0299 | 17 | 20.00 | 3 | 4 | 2706525 | 6000655 |
| WAR 010265 | Cates M E | 36 | 625968 | S27/0067 | 12 | 20.00 | 8 | 9 | 2707220 | 6002950 |
| WAR 010286 | Clarke C A Estate | 23 | 382536 | S27/0047 | 15 | 20.00 | 5 | 6 | 2706472 | 6002723 |
| WAR 010285 | Clarke C A Estate | 15 | 260820 | S27/0051 | 24 | 20.00 | -4 | -3 | 2706740 | 6003760 |
| WAR 010304 | Farrier P G | 30 | 417312 | S27/0065 | 21 | 20.00 | -1 | 0 | 2707180 | 6004190 |
| WAR 990238 | Wairarapa Aggregat | 15 | 99000 | S27/0076 | 4 | 20.00 | 16 | 17 | 2707870 | 6004200 |

| Permit | Name | Take L/s | Take m$^3$/yr | Well number | Depth (m) | Well elevation (mamsl) | Screen base (mamsl) | Screen top (mamsl) | Easting | Northing |
|---|---|---|---|---|---|---|---|---|---|---|
| WAR 020094 | Presbyterian Chuch | 44 | 620928 | S27/0638 | 18 | 20.00 | 2 | 3 | 2706188 | 6003233 |
| WAR 980229 | Barton A J | 40 | 695520 | S27/0357 | 18 | 20.00 | 2 | 3 | 2711898 | 5997476 |
| WAR 020142 | Butcher O L & P J | 39 | 500526 | S27/0480 | 27 | 20.00 | -7 | -6 | 2709450 | 5993490 |
| WAR 020154 | Osborne R | 45 | 816480 | S27/0355 | 15 | 20.00 | 5 | 6 | 2712930 | 5998750 |
| WAR 020037 | Vollebregt C L J & | 32 | 541901 | S27/0479 | 23 | 20.00 | -3 | -2 | 2709908 | 5994650 |
| WAR 030117 | George B L | 38 | 571200 | S27/0344 | 16 | 20.00 | 4 | 5 | 2713369 | 5999061 |
| WAR 020160 | Melton Farms | 27 | 347116 | S27/0380 | 12 | 20.00 | 8 | 9 | 2715705 | 5997707 |
| WAR 020159 | Melton Farms | 27 | 338261 | S27/0354 | 10 | 20.00 | 10 | 11 | 2714850 | 5997720 |
| WAR 990019 | Osborne A L | 35 | 635040 | S27/0360 | 19 | 20.00 | 1 | 2 | 2713882 | 5997803 |
| WAR 030131 | Barton A J | 43 | 702173 | S27/0650 | 15 | 20.00 | 5 | 6 | 2710630 | 5997045 |
| WAR 020104 | Scadden RL & RE | 32 | 559860 | S27/0352 | 20 | 20.00 | 0 | 1 | 2711120 | 5996500 |
| WAR 020112 | Simmonds S A R | 19 | 284815 | S27/0641 | 17 | 20.00 | 3 | 4 | 2709234 | 5995075 |
| WAR 020128 | Smithfield Farm | 38 | 563040 | S27/0345 | 14 | 20.00 | 6 | 7 | 2714170 | 5999220 |
| WAR 990001 | South Wairarapa Di | 90 | 2231712 | S27/0396 | 17 | 20.00 | 3 | 4 | 2715880 | 5997683 |
| WAR 010352 | Sutherland T | 30 | 544320 | S27/0537 | 21 | 20.00 | -1 | 0 | 2710909 | 5993967 |
| WAR 020153 | Vollebregt C L J & | 45 | 703296 | S27/0475 | 21 | 20.00 | -1 | 0 | 2709803 | 5994668 |
| WAR 020108 | Harvey A & L | 15 | 178673 | S27/0108 | 11 | 40.00 | 29 | 30 | 2712900 | 6003750 |
| WAR 980213 | Harvey A & L | 25 | 453600 | S27/0141 | 13 | 40.00 | 27 | 28 | 2713020 | 6002620 |
| WAR 990241 | Harvey A & L | 22 | 399168 | S27/0144 | 18 | 40.00 | 22 | 23 | 2712000 | 6003950 |
| WAR 030170 | Thomson I | 15 | 272160 | S27/0721 | 36 | 40.00 | 4 | 5 | 2710114 | 5991410 |
| WAR 050158 | Beveridge Simon | 15 | 142500 | S27/0774 | 0 | 40.00 | 40 | 41 | 2711248 | 5992514 |
| WAR 060085 | L & AJ Trust, C/- | 15 | 129600 | S27/0814 | 24 | 40.00 | 16 | 17 | 2713069 | 5993649 |
| WAR 010280 | Herrick M B & H F | 20 | 362880 | S27/0699 | 21 | 40.00 | 19 | 20 | 2721469 | 6009226 |
| WAR 990140 | Didsbury A C | 22 | 260064 | S27/0196 | 11 | 40.00 | 29 | 30 | 2718330 | 6007020 |
| WAR 990117 | Kershaw Partnershi | 13 | 196560 | S27/0398 | 11 | 40.00 | 29 | 30 | 2716910 | 6000380 |
| WAR 010127 | Tucker B T | 30 | 335720 | S27/0184 | 10 | 40.00 | 30 | 31 | 2717773 | 6005018 |
| WAR 020083 | Guscott P | 64 | 1161216 | S27/0636 | 15 | 40.00 | 25 | 26 | 2718024 | 6004637 |
| WAR 020099 | Kershaw R | 30 | 155520 | S27/0639 | 17 | 40.00 | 23 | 24 | 2716378 | 6000809 |
| WAR 020117 | Tucker B T | 52 | 943488 | S27/0643 | 12 | 40.00 | 28 | 29 | 2718269 | 6006110 |
| WAR 030096 | A S Phelps Family | 25 | 156000 | S27/0668 | 13 | 40.00 | 27 | 28 | 2715701 | 6000199 |
| WAR 030128 | Morison N | 28 | 508032 | S27/0681 | 5 | 40.00 | 35 | 36 | 2718974 | 5995264 |
| WAR 040056 | Cresswell C | 40 | 170000 | S27/0728 | 11 | 40.00 | 29 | 30 | 2717039 | 5999255 |
| WAR 030095 | A S Phelps Family | 25 | 156000 | S27/0668 | 13 | 40.00 | 27 | 28 | 2715701 | 6000199 |
| WAR 960206 | J M Newton & B J M | 20 | 241920 | S27/0059 | 53 | 40.00 | -13 | -12 | 2706739 | 6005452 |

| Permit | Name | Take L/s | Take m$^3$/yr | Well number | Depth (m) | Well elevation (mamsl) | Screen base (mamsl) | Screen top (mamsl) | Easting | Northing |
|---|---|---|---|---|---|---|---|---|---|---|
| WAR 020004 | Te Kairanga Wines | 20 | 163296 | S27/0632 | 104 | 180.00 | 76 | 77 | 2712210 | 5983199 |
| WAR 980192 | Coveney J | 36 | 653184 | S28/0006 | 16 | 60.00 | 44 | 45 | 2694590 | 5978660 |
| WAR 980192 | Coveney J | 20 | 362880 | S28/0007 | 42 | 60.00 | 18 | 19 | 2694570 | 5978660 |

## Appendix 6 – Morgenstern (2005).

# Wairarapa Valley Groundwater – Residence time, flow pattern, and hydrochemistry trends

Science Report

2005/33

September 2005

by Uwe Morgenstern

# Wairarapa Valley Groundwater
# Residence time, flow pattern, and hydrochemistry trends

by

**Uwe Morgenstern**

**Institute of Geological & Nuclear Sciences science report 2005/33**

**Institute of Geological & Nuclear Sciences Limited**
**Lower Hutt, New Zealand**

**September, 2005**

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# CONTENTS

SUMMARY .......... III

KEYWORDS .......... IV

1.0 INTRODUCTION .......... 1

2.0 SAMPLE LOCATION AND BORE DATA .......... 1

3.0 RESULTS .......... 3

4.0 DISCUSSION .......... 7

4.1 GEOGRAPHIC DISTRIBUTIONS .......... 7

4.2 DEPTH VERSUS RESIDENCE TIME .......... 11

4.3 RECHARGE SOURCE .......... 12

4.4 TIME TRENDS IN HYDROCHEMISTRY .......... 14

5.0 CONCLUSIONS .......... 27

6.0 ACKNOWLEDGEMENTS .......... 27

7.0 ADDITION .......... 27

8.0 REFERENCES .......... 28

# FIGURES

Figure 1 Geographic distribution of sampling points .......... 8

Figure 2 Geographic distribution of well depth .......... 8

Figure 3 Geographic distribution of Dissolved Oxygen and Iron .......... 9

Figure 4 Geographic distribution of groundwater conductivity .......... 9

Figure 5 Geographic distribution of the fraction of exponential (mixed) flow .......... 10

Figure 6 Geographic distribution of mean residence times .......... 10

Figure 7 Geographic distribution of tritium concentration .......... 11

Figure 8 Mean residence time vs. well depth .......... 11

Figure 9 Excess air and nitrate vs. $^{18}O$. .......... 13

Figure 10 Geographic distribution of samples with river and rain recharge .......... 13

Figure 11 Recharge and discharge temperature, and pH vs. mean residence time .......... 14

Figure 12 Manganese, iron, dissolved oxygen, and boron vs. mean residence time .......... 15

Figure 13 Total ion concentrations vs. mean residence time .......... 16

Figure 14 Sodium, chloride, and conductivity vs. mean residence time .......... 17

Figure 15 Silicon, magnesium, calcium, and total hardness vs. mean residence time .......... 18

Figure 16 Mg vs. Na .......... 18

Figure 17 Si vs. Na .......... 19

**Figure 18** **Trace and heavy metal concentration vs. mean residence time ... 20**
**Figure 19** **Br vs. Cl ... 21**
**Figure 20** **Bicarbonate, total organic carbon, free $CO_2$, and total alkalinity vs. mean residence time ... 22**
**Figure 21** **Equivalent of Ca vs. $HCO_3$ ... 22**
**Figure 22** **Nitrogen species vs. mean residence time ... 23**
**Figure 23** **Nutrients vs. mean residence time ... 24**
**Figure 24** **K versus Mg ... 25**
**Figure 25** **Sulphate vs. nitrate ... 26**
**Figure 26** **Sulphate vs. magnesium ... 26**
**Figure 27** **Tritium, CFC and $SF_6$ input for New Zealand rain ... 29**
**Figure 28** **Schematic groundwater flow situations ... 31**
**Figure 29** **Age distribution for the exponential-piston flow model ... 32**
**Figure 30** **Ar vs. $N_2$ ... 34**

## APPENDICES

**Appendix 1** **Methodology of groundwater Age Dating ... 29**
**Appendix 2** **CFC and $SF_6$ raw data ... 33**
**Appendix 3** **Stable Isotope Results ... 35**
**Appendix 4** **CFC and $SF_6$ contamination ... 36**

# SUMMARY

The Wairarapa groundwater system has a complex hydrogeological setting as it has evolved from sea level changes, tectonic activity, and geomorphic processes. Due to increasing groundwater demand a better understanding of the groundwater resources is required to help achieve effective management and sustainable use. We use age dating of groundwater for understanding the flow pattern, and for understanding the natural hydrochemistry evolution processes in the groundwater system. Thus, spatial patterns of hydrochemistry become obvious and provide an additional tool for understanding the groundwater flow. The groundwater age also allows for identification of anthropogenic influences on groundwater quality.

The shallow groundwaters in the Upper Valley contain mostly young (~2yrs) aerobic water, while the deep wells and the central Lower Valley contain old (>100yrs) anaerobic water. This part of the aquifer is nearly stagnant. Intermediate mean residence times (~40yrs) occur in the area between. The waters along the south-eastern side of the Lower Valley are younger (45-80yrs), they contain small amounts of tritium and indicate recharge from the south-eastern hills. The deep wells in the Upper Valley also contain old (>100yrs) groundwater.

Generally, with increasing depth the residence time also increases. But three wells are older for their shallow depth compared to the general trend. This may indicate that the wells are in an area of uprising old deep groundwater.

Hydrochemistry time trends show consistent patterns with increasing age of the water:

- Increasing **pH** due to evolving hydrochemistry of the groundwater**.**
- Increasing **sodium** and **chloride** (much elevated compared to rain water) originating from remanent (connate) seawater.
- Similar increases for **calcium** and **magnesium**, with the source being mainly connate seawater and to some extent leaching by water-rock interaction. Saturation concentration is reached after 50-70 years.
- Increasing **silicon** due to water-rock interaction, with more then 100 years required to reach saturation.
- Increasing **fluoride**, **bromide**, and **zinc** indicate geogenic origin due to evolving water-rock interaction.
- Increasing **bicarbonate**, originating from calcite dissolution and from soil organic matter for the anaerobic waters.
- Increasing **potassium** indicating geogenic origin due to water-rock interaction, and unusually high and low potassium in the older (>100 yrs) anaerobic waters indicating excessive leaching of potassium from soils with high content of organic matter, and also potassium removal by absorption.
- A slight increase of **dissolved reactive phosphate** indicating that there is leachable geogenic phosphate in the Wairarapa aquifer.

- Increase in **sulphate** and correlation with magnesium shows the major source of sulphate is connate seawater. Low sulphate in the old anaerobic waters shows that in the anaerobic waters sulphate is being removed by reduction.

Anthropogenic influences on groundwater quality can be identified using the time trends in hydrochemistry:

- **Nitrate** shows a cluster of young contaminated groundwaters, and also a cluster of young uncontaminated groundwaters. The uncontaminated groundwaters are likely to originate from uncontaminated recharge (absence of nitrate in the recharge area). All groundwaters classified as river-recharge are uncontaminated. The old anaerobic groundwaters do not contain nitrate.
- High **sulphate** concentrations in the young waters are dominated by anthropogenic sources, while moderate sulphate concentrations are due to connate seawater.
- Elevated **lead** concentrations in younger waters indicate that anthropogenic lead may find its way into the groundwater.
- While certain chemicals are introduced by humans and have the potential to affect groundwater quality, we found **no anthropogenic influence** (no elevated level in young waters) in the Wairarapa data set for the following chemistry parameters: potassium (fertiliser, waste), fluoride, calcium (lime), magnesium (fertilisers), dissolved reactive phosphate (fertiliser).

Only nitrate and sulphate show anthropogenic influence, and possibly lead.

Consistent trends in hydrochemistry and water residence time indicate a continuous groundwater system in the Wairarapa.

To identify the recharge source, we use the indicators $^{18}O$, nitrate and excess air. Only three of the investigated groundwaters in the Upper Valley show strong evidence for pure river recharge. The majority of the samples in the Upper Valley indicate mixed river and rain recharge, with only a few on the south-eastern hills as pure rainfall recharge. In the Lower Valley, the majority of the samples adjacent to the south-eastern hills indicate rainfall recharge from the south-eastern hills without contribution from Ruamahanga River. In the central lower valley, consistent to the upper valley, the majority of the samples indicate a mixture of rain/river recharge, with the river contribution likely to be through the coalescising fans from the western tributaries of the Ruamahanga River.

## KEYWORDS

Groundwater dating, tritium, CFCs, $SF_6$, groundwater flow, groundwater recharge source, hydrochemistry evolution, nitrate contamination, anthropogenic influence on groundwater quality.

## 1.0 INTRODUCTION

The Wairarapa groundwater system has a complicated hydrogeological setting as it evolved from sea level changes, tectonic activity, and geomorphic processes [Begg et al. 2005]. Due to increasing groundwater demand a better understanding of the groundwater resources is required to help achieve effective management and sustainable use. In addition to previous ‘classical’ hydrogeology studies [O’Dea et al. 1980, Gunn et al. 1987, Annear et al. 1989, Butcher 1996, Jones and Baker 2005], this report represents the first stage of a comprehensive approach using age dating and chemistry time trends for understanding the Wairarapa groundwater system.

The methodology of groundwater age dating and mixing models is described in Appendix 1. Historic tritium data were evaluated, and combined with new tritium and CFC/$SF_6$ data to allow for robust age dating.

## 2.0 SAMPLE LOCATION AND BORE DATA

Geographic and bore data are summarized in Table 1. Sample locations are shown in Figure 1. The classification on confinement of the aquifer for the various groundwater samples (made by Tim Baker, GWRC) is based on bore log data showing impermeable clay layers, static water level, and screen settings. For some bores it is questionable if a bore log shows impermeable clay layers, and these may not be uniform throughout the surrounding area. Questionable data are highlighted. These bores show some degree of impermeable layers in their logs, and static water levels above the screen setting, but the strata surrounding these sites are often different.

Table 1: Bore data, provided by Tim Baker, Greater Wellington Regional Council. Decision on aquifer confinement is based on bore log data (see text), with uncertain data highlighted in grey. In the column 'well depth', grey highlight indicates slightly different location at the time of re-sampling.

| # | Name | Wairarapa_ID | Well_ID | East | North | well depth [m] | water level (m) | Top Screen [m] | Bottom Screen [m] | confined? (bore log) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Candy | 2I/3/7/DS | S26/0032 | 2729110 | 6025990 | 7 | | | | N |
| 2 | Van der Put | 2I/31/9.5(14)/I | S26/0043 | 2729310 | 6026190 | 9.5 | -6.04 | | | N |
| 3 | Porter | 2J/77/47 | T26/0199 | 2730200 | 6025500 | 47 | | | | Y |
| 4 | Tulloch | 3H/5/13/I | S26/0155 | 2723845 | 6017830 | 13 | | 10.31 | 13.41 | N |
| 5 | Tulloch | 3H/5/13/I | S26/0155 | 2723845 | 6017830 | 13 | -1.85 | 10.31 | 13.41 | N |
| 6 | Waingawa Spring | 3I/27/0/N | S26/0244 | 2727780 | 6023410 | | | | | N |
| 7 | Waingawa Spring | 3I/27/0/N | S26/0244 | 2727780 | 6023410 | | | | | N |
| 8 | Transport | 3J/73/13/N | T26/0429 | 2730037 | 6023706 | 13 | | | | N |
| 9 | Trout Hatchery Spring | 3J/74/0/S | T26/0430 | 2732160 | 6024730 | | | | | N |
| 10 | Trout Hatchery Spring | 3J/74/0/S | T26/0430 | 2732160 | 6024730 | | | | | N |
| 11 | Duffy (deep) | 3K/24/54(74) | T26/0489 | 2737640 | 6023590 | 54 | | 48 | 54 | Y |
| 12 | Duffy (deep) | 3K/24/54(74) | T26/0489 | 2737640 | 6023590 | 54 | -5.4 | 48 | 54 | Y |
| 13 | Duffy (shallow) | 3K/5/5/I | T26/0517 | 2737500 | 6023500 | 5 | | | | N |
| 14 | Duffy (shallow) | 3K/5/5/I | T26/0517 | 2737500 | 6023500 | 5 | -4.55 | | | N |
| 15 | White | 3K/8/5/D | T26/0547 | 2737100 | 6022300 | 5 | | | | N |
| 16 | Papawai Spring | 4G/139/0/N | S26/0395 | 2717500 | 6010730 | | | | | N |
| 17 | Papawai Spring | 4G/139/0/N | S26/0395 | 2717500 | 6010730 | | | | | N |
| 18 | Smith's Orchard | 4G/29/6(8)/DI | S26/0487 | 2717700 | 6012300 | 6 | | | | N |
| 19 | GP Orchard | 4G/237/9/DI | S26/0911 | 2717612 | 6012423 | 9 | -3.02 | | | N |
| 20 | Denbee | 4H/1/45/I | S26/0568 | 2723504 | 6013642 | 45 | | 40.9 | 43.9 | Y |
| 21 | Denbee | 4H/1/45/I | S26/0568 | 2723504 | 6013642 | 45 | | 40.9 | 43.9 | Y |
| 22 | Simmonds deep | 6E/1/30/SI | S27/0271 | 2707818 | 5998780 | 30 | | | slotted casing last 1m | Y |
| 23 | Simmonds deep | 6E/1/30/SI | S27/0271 | 2707818 | 5998780 | 30 | | | slotted casing last 1m | Y |
| 24 | Simmonds deep | 6E/1/30/I | S27/0271 | 2704810 | 5995502 | 30 | | | slotted casing last 1m | Y |
| 25 | Simmonds shallow | 6E/51/18/I | S27/0317 | 2707821 | 5998803 | 18 | | | | Y |
| 26 | Stout | 6E/4/42 | S27/0303 | 2705620 | 6000360 | 42 | | | | Y |
| 27 | Stout | 6E/4/42 | S27/0303 | 2705620 | 6000360 | 42 | | | | Y |
| 28 | Stout | 6E/4/52/S | S27/0303 | 2705050 | 5995050 | 52 | | | | Y |
| 29 | Burt | 6E/63/20/I | S27/0330 | 2707788 | 6002140 | 20 | | 16 | 20 | N |
| 30 | Burt | 6E/63/20/I | S27/0330 | 2707788 | 6002140 | 20 | -2.18 | 16 | 20 | N |
| 31 | Nichols | 6F/43/46/I | S27/0669 | 2710998 | 6001967 | 46 | | 40 | 46 | Y |
| 32 | Wall | 6G/6/27/D | S27/0419 | 2716200 | 5995250 | 27 | | | | Y |
| 33 | Colton | 7C/1/79/S | S27/0427 | 2695300 | 5990500 | 79 | | | | Y |
| 34 | Colton | 7C/1/79/S | S27/0427 | 2695300 | 5990500 | 79 | | | | Y |
| 35 | Colton | 7C/1/79/S | S27/0427 | 2695300 | 5990500 | 79 | | | | Y |
| 36 | Wairio Windmill | 7C/12/40/S | S27/0430 | 2697579 | 5992197 | 40 | | | | Y |
| 37 | Wairio | 7C/5/38/S | S27/0440 | 2698076 | 5992640 | 38 | | | slotted casing last 1m | Y |
| 38 | Wairio | 7C/17/44/S | S27/0435 | 2697614 | 5992527 | 44 | 4.14 | | | Y |
| 39 | Robinson | 7C/7/178/DS | S27/0442 | 2699915 | 5988602 | 178 | | | | Y |
| 40 | Green | 7D/9/30/I | S27/0467 | 2702842 | 5994784 | 30 | | 27.1 | 30.1 | Y |
| 41 | Ness | 7E/7/31/D | S27/0502 | 2708650 | 5992850 | 31 | | | | Y |
| 42 | Holmes Warren | 8B/6/44/IR | S27/0594 | 2691376 | 5981438 | 44 | | 40.8 | 44.09 | Y |
| 43 | Holmes Warren | 8B/6/44/IR | S27/0594 | 2691376 | 5981438 | 44 | 7.93 | | | Y |
| 44 | Pouawha Co | 8C/10/41/D | S27/0599 | 2695300 | 5986300 | 41 | | | slotted casing last 1m | Y |
| 46 | Westherstone | 8C/13/61/I | S27/0602 | 2699650 | 5987020 | 61 | | | | Y |
| | Westherstone | | | | | | | | | |
| 47 | Anne Sinclair | 8C/2/91/DS | S27/0609 | 2696850 | 5983880 | 91 | | | | Y |
| 48 | Anne Sinclair | 8C/2/91/DS | S27/0609 | 2696850 | 5983880 | 91 | 1.3 | | | Y |
| 49 | Pouawha | 8C/6/42(88)/DS | S27/0621 | 2696450 | 5986950 | 42 | | 38.7 | 42.03 | Y |
| 45 | Pouawha | 8C/6/42(88)/DS | S27/0621 | 2696450 | 5986950 | 42 | | | | Y |
| 50 | Lake Ferry Motorcamp | 9A/2/30.5/D | R28/0012 | 2689300 | 5977370 | 30.5 | | | | Y |
| 51 | Lake Ferry Motorcamp | 9A/2/30.5/D | R28/0012 | 2689300 | 5977370 | 30.5 | c. +1000 | | | Y |
| 52 | Martinborough golf club | 7G/5/32/I | S27/0571 | 2717180 | 5994736 | 32 | -22.03 | 31 | 32 | Y |
| 53 | Dimittina | 6G/20/18/I | S27/0389 | 2717227 | 5995514 | 18 | -6.38 | 17.4 | 17.85 | N |
| 54 | Te Kairanga | 6G/47/69/I | S27/0640 | 2718144 | 5995373 | 69 | -4.13 | 62 | 68 | Y |
| 55 | George | 6F/13/16.5/I | S27/0344 | 2713369 | 5999061 | 16.5 | -2.31 | 13 | 16 | Y |
| 56 | Basett | 6G/55/80/I | S27/0717 | 2717493 | 5995706 | 80 | -12.89 | 78.1 | 80.1 | Y |
| 57 | Martinborough WaterSupplyBore#1 | 6G/27/17/P | S27/0396 | 2715880 | 5997683 | 17 | | 15 | 17 | ? |
| 58 | Sugrue | 5F/49/20/DI | S27/0136 | 2712259 | 6008074 | 20 | -5.5 | 17.1 | 20.4 | N |
| 59 | Findlayson | 8C/18/38/I | S27/0607 | 2696313 | 5986755 | 38 | ~ +400 | 35 | 38 | Y |
| 60 | CDC South | 4H/90/27/P | S26/0705 | 2720489 | 6016012 | 27 | | 25.9 | 27.4 | Y |
| 61 | CDC North | 4H/66/21/P | S26/0824 | 2720512 | 6016098 | 21 | | 15.7 | 16.6 | Y |
| 62 | Wither | 4I/68/75(100)/I | S26/0793 | 2725595 | 6014321 | 75 | -6.12 | 64.6 | 73.2 | Y |
| 63 | McCreary | 8B/8/45/S | S27/0596 | 2690550 | 5983750 | | | | | Y |

## 3.0 RESULTS

Table 2 provides a summary of the field parameters, and results of tritium, $SF_6$ and CFC, and $^{18}O$ analyses, together with the age interpretation. The original analysis reports for CFCs, $SF_6$, and $^{18}O$ are in Appendix 2 and 3.

Field parameters were measured during sampling by GWRC using a YSI 556 meter. None of the samples show tritium or $SF_6$ concentrations above their expected natural occurrence. Parts of the aquifers are, however, clearly CFC contaminated. This is probably in many cases due to pesticide use in horticultural areas. Extremely high contamination was observed at the CDC wells. It is unlikely that a sampling error has caused this contamination because the contamination pattern is different - CDC South has extremely high CFC12 contamination, while CDC North is contaminated in both, CFC11 and CFC12. Burt was CFC12 contaminated in 2003. Re-sampling in 2005 reproduced this contamination.

For age interpretation, it was in all cases possible, despite CFC contamination, to resolve age ambiguity with the remaining information. Several springs and wells with long-term tritium data (Papawai, Trout Hatchery, Anne Sinclair, Duffy shallow, Lake Ferry, Holmes Warren) resulted in good model matches of the tritium data. This indicates steady state flow conditions in the aquifers and suggests that the applied exponential-piston-flow model can describe the age distribution in these waters, as has been found in many other aquifers throughout New Zealand. Some samples (Candy, Tulloch, Waingawa, Duffy deep, Smith’s) do not show a good model match to tritium long-term data, with increased tritium concentrations in 1983. This may indicate non-steady state condition in these parts of the aquifer (e.g. a shift to younger water since 1983, Candy/Van der Put has a clear drop in water level), or it may simply be caused by the fact that the re-sampling could not be done exactly at the same part of the aquifer (Waingawa, Smith’s, Van der Put), or the exponential-piston-flow model cannot describe the age distribution in these parts of the aquifer.

Disagreement between the robust ages from time series tritium and the ages from the gas methods indicates occurrence of gas exchange and/or CFC/$SF_6$ contamination in unconfined conditions. The CFC and $SF_6$ ages therefore represent only a minimum age estimate (see Appendix 4).

The chemistry data, provided by GWRC, are listed in Tables 3a and 3b.

Table 2: Field parameters (measured by GWRC), and water dating results with age interpretation. New $^{18}$O results are included. Red highlight of the dissolved oxygen field indicates anaerobic condition (a cut-off of <0.4mg/L was used), yellow highlight slightly anaerobic (0.4-0.5 mg\L). For CFCs, red highlight indicates high contamination above natural occurance (Fig. 27), yellow highlight indicates slight contamination, and grey highlight indicates likelihood that CFCs are degraded. For age interpretation, the Exponential Piston Flow model was used (see Appendix 1). E%PM is the fraction of mixed flow within the total flow volume. MRT is the mean residence time. For ambiguous results, the more likely result is in bold. SigTR is 1-sigma standard deviation.

| **#** | **Name** | **Date** | **Temp** | **DO** | **Cond** | **pH** | **TR** | **sigTR** | **SF6** | **CFC11** | **CFC12** | **18O** | **E%PM** | **MRT** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  | **Sampl.** | **°C** | **mg/l** | **uS/cm** |  | 2005scale |  |  | **pptv** |  | **‰** | **%** | **[y]** |
| 1 | Candy | 12/04/1983 |  |  |  |  | 4.3 | 0.22 |  |  |  |  | 70 | 1 |
| 2 | Van der Put | 3/05/2005 | 13.7 | 7.6 | 92 | 5.9 | 1.92 | 0.04 | 5.94 | 272 | 595 | -5.49 | 70 | 1 |
| 3 | Porter | 12/04/1983 |  |  |  |  | 3.68 | 0.2 |  |  |  |  | 70 | **40** / 1.5 |
| 4 | Tulloch | 12/04/1983 |  |  |  |  | 4.65 | 0.22 |  |  |  |  | 90 | 1.5 |
| 5 | Tulloch | 3/05/2005 | 15.3 | 6.22 | 147 | 5.81 | 1.74 | 0.06 | 5.24 | 442 | 2263 |  | 90 | 1.5 |
| 6 | Waingawa Spring | 2/06/1983 |  |  |  |  | 4.21 | 0.2 |  |  |  |  | 70 | 1 |
| 7 | Waingawa Spring | 3/05/2005 | 15.4 | 8.22 | 105 | 5.54 | 1.91 | 0.05 | 6.18 | 3121 | 772 |  | 70 | 1 |
| 8 | Transport | 12/04/1983 |  |  |  |  | no result |  |  |  |  |  |  |  |
| 9 | Trout Hatchery Spring | 12/04/1983 |  |  |  |  | 3.84 | 0.21 |  |  |  |  | **90** | 1.5 |
| 10 | Trout Hatchery Spring | 3/05/2005 | 14.7 | 6.04 | 110 | 6.05 | 1.72 | 0.04 | 5.39 | 237 | 565 |  | **90** | 1.5 |
| 11 | Duffy (deep) | 28/04/1983 |  |  |  |  | 5.11 | 0.26 |  |  |  |  | 76 | 40 |
| 12 | Duffy (deep) | 3/05/2005 | 13 | 2.83 | 249 | 6.22 | 1.08 | 0.03 | 1.45 | 5.3 | 253 |  | 76 | 40 |
| 13 | Duffy (shallow) | 7/06/1983 |  |  |  |  | 4.53 | 0.22 |  |  |  |  | 80 | 32 |
| 14 | Duffy (shallow) | 3/05/2005 | 15.3 | 7.24 | 288 | 5.98 | 1.63 | 0.06 | 6.31 | 203 | 562 |  | 80 | 32 |
| 15 | White | 2/06/1983 |  |  |  |  | 3.95 | 0.23 |  |  |  |  | 80 | **2** / 40 |
| 16 | Papawai Spring | 2/06/1983 |  |  |  |  | 3.92 | 0.22 |  |  |  |  | **84** | 2 |
| 17 | Papawai Spring | 3/05/2005 | 13.3 | 6.73 | 88 | 6.03 | 1.81 | 0.05 | 6.37 | 1431 | 917 |  | **84** | 2 |
| 18 | Smith's Orchard | 2/06/1983 |  |  |  |  | 5.09 | 0.24 |  |  |  |  | 70 | 1 |
| 19 | GP Orchard | 3/05/2005 | 13 | 2.19 | 83 | 6.07 | 1.85 | 0.05 | 5.93 | 259 | 716 | -5.55 | 70 | 1 |
| 20 | Denbee | 1/04/1983 |  |  |  |  | 0.05 | 0.1 |  |  |  |  | 70 | >110 |
| 21 | Denbee | 1/09/1990 |  |  |  |  | 0.09 | 0.07 |  |  |  |  | 70 | >110 |
| 22 | Simmonds deep | 1/04/1983 |  |  |  |  | -0.14 | 0.12 |  |  |  |  | 70 | >150 |
| 23 | Simmonds deep | 1/09/1990 |  |  |  |  | 0.13 | 0.06 |  |  |  |  | 70 | >150 |
| 24 | Simmonds deep | 18/09/2003 | 13.7 | 0.05 | 291 |  | 0.007 | 0.018 |  |  |  |  | 70 | >150 |
| 25 | Simmonds shallow | 18/09/2003 | 13.9 | 0.06 | 235 |  | 0.371 | 0.026 | 0 | 0.56 | 0 |  | 70 | 110 |
| 26 | Stout | 1/04/1983 |  |  |  |  | 0.11 | 0.09 |  |  |  |  | 70 | >145 |
| 27 | Stout | 1/09/1990 |  |  |  |  | 0.06 | 0.06 |  |  |  |  | 70 | >145 |
| 28 | Stout | 16/09/2003 | 13.9 | 0.07 | 513 |  | 0.015 | 0.02 |  |  |  |  | 70 | >145 |
| 29 | Burt | 18/09/2003 | 13.9 | 2.55 | 79 |  | 1.88 | 0.05 | 4.65 | 134 | 972 |  | **39** | 40 |
| 30 | Burt | 5/05/2005 | 12.8 | 2.94 | 88 | 6.63 |  |  | na | 136 | 645 |  | **39** | 40 |
| 31 | Nichols | 21/08/2003 | 13.4 | 0.02 | 217 |  | 0.043 | 0.021 | 0.23 | 0.72 | 1.2 |  | 70 | 150 |
| 32 | Wall | 3/06/1983 |  |  |  |  | 0.19 | 0.11 |  |  |  |  | 80 | 80 |
| 33 | Colton | 1/04/1983 |  |  |  |  | 0.4 | 0.14 |  |  |  |  | 70 | >140 |
| 34 | Colton | 1/09/1990 |  |  |  |  | 0.01 | 0.06 |  |  |  |  | 70 | >140 |
| 35 | Colton | 1/03/2005 | 14.3 | 0.37 | 627 | 6.66 | .027 | 0.018 |  |  |  |  | 70 | >140 |
| 36 | Wairio Windmill | 12/04/1983 |  |  |  |  | 0.19 | 0.12 |  |  |  |  | 70 | 140 |
| 37 | Wairio | 1/09/1990 |  |  |  |  | 0.19 | 0.05 |  |  |  |  | 70 | 140 |
| 38 | Wairio | 28/02/2005 | 14 | 0.14 | 329 | 6.72 | 0.047 | 0.018 |  |  |  |  | 70 | 140 |
| 39 | Robinson | 12/04/1983 |  |  |  |  | -0.04 | 0.14 |  |  |  |  | 70 | >150 |
| 40 | Green | 15/09/2003 | 13.5 | 1.84 | 791 |  | -0.01 | 0.02 | 0 | 1.1 | 2.5 |  | 70 | >150 |
| 41 | Ness | 3/06/1983 |  |  |  |  | 0.18 | 0.12 |  |  |  |  | 70 | 80 |
| 42 | Holmes Warren | 12/04/1983 |  |  |  |  | 0.27 | 0.11 |  |  |  |  | **90** | 180 |
| 43 | Holmes Warren | 28/02/2005 | 13.6 | 0.07 | 475 | 7.36 | 0.279 | 0.023 |  |  |  |  | **90** | 180 |
| 44 | Pouawha Co | 12/04/1983 |  |  |  |  | 0.06 | 0.11 |  |  |  |  | 70 | >150 |
| 46 | Westherstone | 12/04/1983 |  |  |  |  | 0.12 | 0.11 |  |  |  |  | 70 | >140 |
|  | Westherstone | 1/09/1990 |  |  |  |  |  |  |  |  |  |  |  |  |
| 47 | Anne Sinclair | 12/04/1983 |  |  |  |  | 2.52 | 0.15 |  |  |  |  | **68** | 45 |
| 48 | Anne Sinclair | 5/05/2005 | 13.7 | ? | 246 | 7.04 | 1.05 | 0.04 | 0.08 | 0.2 | 2.6 |  | **68** | 45 |
| 49 | Pouawha | 12/04/1983 |  |  |  |  | 0.21 | 0.11 |  |  |  |  | 70 | >140 |
| 45 | Pouawha | 1/03/2005 | 13.8 | 0.06 | 1040 | 6.81 | 0.012 | 0.021 |  |  |  |  | 70 | >140 |
| 50 | Lake Ferry Motorcamp | 12/04/1983 |  |  |  |  | 1.22 | 0.14 |  |  |  |  | **82** | 81 |
| 51 | Lake Ferry Motorcamp | 28/02/2005 | 14.8 | 3.38 | 815 | 7.37 | 0.720 | 0.030 |  |  |  |  | **82** | 81 |
| 52 | Martinborough golf club | 4/05/2005 | 14 | 0.51 | 230 | 6.48 | 0.984 | 0.033 | 0.74 | 3.6 | 88 |  | 68 | 60 |
| 53 | Dimittina | 4/05/2005 | 14.4 | 0.21 | 188 | 6.97 | 0.192 | 0.021 | 0.31 | 13.6 | 231 |  | 80 | 180 |
| 54 | Te Kairanga | 4/05/2005 | 14.3 | 0.16 | 820 | 7.44 | 0.036 | 0.022 | 0 | 1.3 | 29.2 |  | 70 | 150 |
| 55 | George | 4/05/2005 | 13.7 | 0.13 | 247 | 6.4 | 1.22 | 0.04 | 1.24 | 0.4 | 1.4 | -6.19 | 50 | 55 |
| 56 | Basett | 4/05/2005 | 14.3 | 0.24 | 359 | 7.33 | 0.019 | 0.018 | 0 | 1.5 | 0.2 | -7.36 | 70 | >150 |
| 57 | Martinborough WaterSupplyBore#1 | 4/05/2005 | 14.8 | 0.42 | 507 | 6.96 | 1.65 | 0.04 | 5.02 | 1.2 | 165 |  | 33 | 50 |
| 58 | Sugrue | 4/05/2005 | 14.7 | 7.34 | 146 | 5.8 | 1.83 | 0.06 | 5.06 | 204 | 550 | -6.23 | 30 | 40 |
| 59 | Findlayson | 5/05/2005 | 14.2 | 0.13 | 1342 | 6.89 | -0.005 | 0.021 | 0.38 | 2.1 | 4.1 | -7.31 | 70 | >150 |
| 60 | CDC South | 12/05/2005 | 13.6 | 1.84 | 165 | 5.9 | 1.41 | 0.06 | 2.71 | 112 | 20000 | -6.08 | 50 | 40 |
| 61 | CDC North | 12/05/2005 | 13.72 | 2.85 | 175 | 5.75 | 1.74 | 0.04 | 3.86 | 1050 | 6200 | -6.07 | 35 | 40 |
| 62 | Wither | 12/05/2005 | 14.1 | 0.27 | 5260 | 6.84 | -0.015 | 0.019 | 0 | 7.5 | 24.6 | -6.3 | 70 | >150 |
| 63 | McCreary | 1/09/1990 |  |  |  |  | -0.01 | 0.05 |  |  |  |  | 70 | >160 |

Table 3a: Chemistry parameters (provided by GWRC). Data represent single analysis results.

| # | **Tot Alkalinity** mg/L as CaCO3 | **Free CO2** mg/L at 25C | **HCO3** mg/L | **TDS** mg/L | **Ca** mg/L | **Mg** mg/L | **Tot Hardness** mg/L as CaCO3 | **Na** mg/L | **K** mg/L | **NH4-N** mg/L | **TON** mg/L | **NO3-N** mg/L | **NO2-N** mg/L | **DRP** mg/L | **Cl** mg/L |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | | | | | | | 1.4 | | | 6 |
| 2 | 23 | 29 | 28 | 77 | 8.92 | 1.73 | 29 | 5.82 | 1.2 | < 0.01 | 1.79 | 1.79 | < 0.002 | 0.016 | 7.9 |
| 3 | | | | | | | | | | | | 3.6 | | | 9 |
| 4 | | | | | | | | | | | | 6.2 | | | 11 |
| 5 | 18 | 40 | 22 | | 9.75 | 4.32 | 42 | 11.8 | 1.43 | < 0.01 | | 6.78 | < 0.002 | 0.022 | 18 |
| 6 | | | | | | | | | | | | 4.5 | | | 8 |
| 7 | 9 | 23 | 11 | 101 | 6.54 | 2.34 | 26 | 8.06 | 1.27 | < 0.01 | 4.27 | 4.27 | < 0.002 | 0.017 | 10.7 |
| 8 | | | | | | | | | | | | 5.2 | | | |
| 9 | | | | | | | | | | | | 1 | | | 5 |
| 10 | 31 | 22 | 38 | 76 | 9.12 | 2.27 | 32 | 8.11 | 1.36 | 0.01 | 1.28 | 1.28 | < 0.002 | 0.02 | 7.1 |
| 11 | | | | | | | | | | | | 6.6 | | | 12 |
| 12 | 45 | 25 | 55 | 212 | 24.7 | 4.28 | 79 | 18.1 | 1.47 | < 0.01 | 10.6 | 10.6 | < 0.002 | 0.024 | 23.6 |
| 13 | | | | | | | | | | | | 6.2 | | | 12 |
| 14 | 49 | 61 | 59 | 247 | 30.9 | 5.77 | 101 | 17.9 | 2.84 | < 0.01 | 10.9 | 10.8 | 0.04 | 0.018 | 23.3 |
| 15 | | | | | | | | | | | | 3.6 | | | 11 |
| 16 | | | | | | | | | | | | 0.72 | | | 8 |
| 17 | 27 | 27 | 33 | 66 | 8.38 | 1.75 | 28 | 6.18 | 1.09 | < 0.01 | 0.7 | 0.699 | < 0.002 | 0.014 | 7 |
| 18 | | | | | | | | | | | | 0.33 | | | 7 |
| 19 | 22 | 22 | 27 | 63 | 7.79 | 1.61 | 26 | 5.55 | 1.06 | < 0.01 | 1.15 | 1.15 | < 0.002 | 0.006 | 7.3 |
| 20 | | | | | | | | | | | | 0.05 | | | 10 |
| 21 | | | | | | | | | | | | | | | |
| 22 | | | | | | | | | | | | 0.05 | | | 34 |
| 23 | | | | | | | | | | | | | | | |
| 24 | | | | | | | | | | | | | | | |
| 25 | | | | | | | | | | | | | | | |
| 26 | | | | | | | | | | | | | | | 100 |
| 27 | | | | | | | | | | | | | | | |
| 28 | | | | | | | | | | | | ? | | | |
| 29 | | | | | | | | | | | | | | | |
| 30 | 25 | 16 | 30 | 70 | 6.83 | 2.05 | 25 | 7.19 | 0.79 | < 0.01 | 0.464 | 0.463 | < 0.002 | 0.018 | 8.6 |
| 31 | | | | | | | | | | | | | | | |
| 32 | | | | | | | | | | | | | | | |
| 33 | | | | | | | | | | | | 1.25 | | | 38 |
| 34 | | | | | | | | | | | | | | | |
| 35 | 282 | 49 | 343 | 355 | 41.2 | 21.8 | 193 | 50.2 | 9.8 | 11.2 | 0.012 | 0.011 | < 0.002 | 0.016 | 30.8 |
| 36 | | | | | | | | | | | | 0.03 | | | 23 |
| 37 | | | | | | | | | | | | | | | |
| 38 | 112 | 47 | 136 | 220 | 14.9 | 5.84 | 61 | 34.6 | 4.57 | 7.79 | 0.003 | 0.003 | < 0.002 | 3.35 | 34.3 |
| 39 | | | | | | | | | | | | | | | 100 |
| 40 | | | | | | | | | | | | | | | |
| 41 | | | | | | | | | | | | | | | 56 |
| 42 | | | | | | | | | | | | 0.05 | | | 80 |
| 43 | 134 | 18 | 163 | 295 | 35.6 | 10.7 | 133 | 57.7 | 2.84 | 0.73 | 0.009 | 0.008 | < 0.002 | 0.217 | 82.4 |
| 44 | | | | | | | | | | | | | | | 692 |
| 46 | | | | | | | | | | | | | | | |
| 47 | | | | | | | | | | | | | | | |
| 48 | 40 | 16 | 48 | 190 | 8.81 | 4.37 | 40 | 32.9 | 1.7 | 0.12 | 0.007 | < 0.002 | 0.009 | 0.021 | 39.8 |
| 49 | | | | | | | | | | | | 0.5 | | | 298 |
| 45 | 211 | 51 | 257 | 577 | 39.5 | 15.2 | 161 | 163 | 6.4 | 8.69 | 0.023 | 0.021 | 0.002 | 0.024 | 229 |
| 50 | | | | | | | | | | | | | | | 172 |
| 51 | 160 | | 195 | | 45 | 17 | 180 | 110 | 3.1 | 0.02 | | 1.6 | 0.005 | 0.03 | 180 |
| 52 | 36 | 15 | 43 | 170 | 13.3 | 5.99 | 58 | 28.3 | 1.68 | < 0.01 | 9.25 | 9.25 | < 0.002 | 0.028 | 29.1 |
| 53 | 54 | 7 | 65 | 131 | 7.65 | 4.57 | 38 | 26 | 1.19 | 0.15 | 0.002 | < 0.002 | < 0.002 | 0.88 | 23.5 |
| 54 | 107 | 7 | 130 | 458 | 13 | 9.9 | 73 | 137 | 6.46 | 1.78 | < 0.002 | < 0.002 | < 0.002 | 0.912 | 208 |
| 55 | 56 | 20 | 69 | 194 | 15.7 | 7.01 | 68 | 32.6 | 1.61 | 0.08 | 0.003 | < 0.002 | < 0.002 | 0.019 | 50.9 |
| 56 | 134 | 13 | 163 | 254 | 13.4 | 9.07 | 71 | 52.9 | 1.06 | 0.78 | 0.004 | 0.003 | < 0.002 | 2.31 | 35.5 |
| 57 | 182 | 25 | 221 | 326 | 74.2 | 9.41 | 224 | 30.8 | 2.59 | < 0.01 | 0.73 | 0.729 | < 0.002 | 0.018 | 43.4 |
| 58 | 11 | 22 | 13 | 107 | 7.97 | 3.47 | 34 | 10.4 | 1.25 | 0.01 | 6.11 | 6.1 | < 0.002 | 0.014 | 11.3 |
| 59 | 179 | 31 | 218 | 676 | 42.8 | 19.9 | 189 | 170 | 7.58 | 9.06 | 0.017 | 0.008 | 0.009 | 0.057 | 331 |
| 60 | 32 | 20 | 39 | 120 | 8.4 | 3.89 | 37 | 15.8 | 1.02 | < 0.01 | 5.02 | 5.02 | < 0.002 | 0.032 | 12.4 |
| 61 | 31 | 12 | 38 | 130 | 8.83 | 4.14 | 39 | 17.5 | 1.1 | 0.02 | 5.3 | 5.3 | < 0.002 | 0.029 | 13.4 |
| 62 | 217 | 15 | 264 | | 146 | 48.8 | 564 | 944 | 9.3 | 3.1 | | 0.004 | < 0.002 | 0.008 | 1690 |
| 63 | | | | | | | | | | | | | | | |

Table 3b: Chemistry parameters (provided by GWRC). Data represent single analysis results.

| # | **Br** | **F** | **SO4** | **B** | **SiO2** | **TOC** | **Fe** | **Mn** | **Pb** | **Zn** | **Tot. Anion** | **Tot. Cation** | **Diff. An-Cat** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mEquiv/L | mEquiv/L | [%] |
| 1 | | | | | | | | | | | | | |
| 2 | < 0.05 | < 0.05 | 4.5 | 0.018 | 9.1 | 0.12 | < 0.02 | 0.001 | 0.0001 | 0.009 | 0.9 | 0.87 | 1.6 |
| 3 | | | | | | | | | | | | | |
| 4 | | | | | | | | | | | | | |
| 5 | | | 15 | 0.016 | | | < 0.02 | 0.0006 | 0.0012 | | 1.67 | 1.39 | 9.15 |
| 6 | | | | | | | | | | | | | |
| 7 | < 0.05 | < 0.05 | 9.4 | 0.015 | 12.2 | 0.98 | < 0.02 | 0.0038 | 0.0011 | 0.008 | 0.98 | 0.9 | 4.3 |
| 8 | | | | | | | | | | | | | |
| 9 | | | | | | | | | | | | | |
| 10 | < 0.05 | 0.08 | 5.5 | 0.02 | 12.5 | 2.32 | < 0.02 | 0.0015 | < 0.0001 | 0.006 | 1.03 | 1.03 | 0.2 |
| 11 | | | | | | | | | | | | | |
| 12 | < 0.05 | 0.11 | 9.9 | 0.02 | 32.3 | 2.18 | < 0.02 | 0.0019 | 0.0003 | 0.013 | 2.53 | 2.41 | 2.5 |
| 13 | | | | | | | | | | | | | |
| 14 | < 0.05 | 0.12 | 33 | 0.021 | 17.4 | 3.27 | < 0.02 | 0.0007 | 0.0001 | 0.007 | 3.09 | 2.86 | 3.7 |
| 15 | | | | | | | | | | | | | |
| 16 | | | | | | | | | | | | | |
| 17 | < 0.05 | 0.11 | 4.9 | 0.017 | 10.4 | 0.48 | < 0.02 | 0.0016 | 0.0005 | 0.005 | 0.89 | 0.86 | 2 |
| 18 | | | | | | | | | | | | | |
| 19 | < 0.05 | 0.11 | 5 | 0.015 | 8.2 | 0.51 | 0.12 | 0.0095 | 0.0003 | 0.003 | 0.83 | 0.79 | 2 |
| 20 | | | | | | | | | | | | | |
| 21 | | | | | | | | | | | | | |
| 22 | | | | | | | | | | | | | |
| 23 | | | | | | | | | | | | | |
| 24 | | | | | | | | | | | | | |
| 25 | | | | | | | | | | | | | |
| 26 | | | | | | | | | | | | | |
| 27 | | | | | | | | | | | | | |
| 28 | | | | | | | | | | | | | |
| 29 | | | | | | | | | | | | | |
| 30 | < 0.05 | 0.13 | 4.1 | 0.02 | 11.5 | 0.43 | 0.57 | 0.0692 | < 0.0001 | 0.001 | 0.86 | 0.87 | 0.3 |
| 31 | | | | | | | | | | | | | |
| 32 | | | | | | | | | | | | | |
| 33 | | | | | | | | | | | | | |
| 34 | | | | | | | | | | | | | |
| 35 | 0.34 | 0.08 | < 0.5 | 0.081 | 48.4 | 12.3 | 7.49 | 1.18 | 0.0001 | 0.01 | 6.5 | 7.39 | 6.4 |
| 36 | | | | | | | | | | | | | |
| 37 | | | | | | | | | | | | | |
| 38 | 0.24 | 0.32 | < 0.5 | 0.094 | 39.1 | 4.08 | 5.97 | 0.49 | 0.0003 | 0.016 | 3.2 | 3.63 | 6.4 |
| 39 | | | | | | | | | | | | | |
| 40 | | | | | | | | | | | | | |
| 41 | | | | | | | | | | | | | |
| 42 | | | | | | | | | | | | | |
| 43 | 0.38 | 0.28 | < 0.5 | 0.09 | 26.1 | 1.77 | 1.63 | 0.256 | 0.0001 | 0.002 | 5 | 5.36 | 3.5 |
| 44 | | | | | | | | | | | | | |
| 46 | | | | | | | | | | | | | |
| 47 | | | | | | | | | | | | | |
| 48 | 0.12 | 0.29 | 26 | 0.026 | 30.4 | 0.16 | 2.73 | 0.124 | < 0.0001 | 0.018 | 2.46 | 2.38 | 1.5 |
| 49 | | | | | | | | | | | | | |
| 45 | 0.96 | 0.15 | < 0.5 | 0.181 | 38 | 10.3 | 12.2 | 1.06 | < 0.0001 | 0.001 | 10.7 | 11.6 | 4.1 |
| 50 | | | | | | | | | | | | | |
| 51 | 0.65 | 0.34 | 32 | <0.2 | 18 | | 0.03 | 0.01 | <0.05 | 0.08 | | | |
| 52 | 0.44 | 0.32 | 7.5 | 0.026 | 28.5 | 1.53 | < 0.02 | 0.0063 | 0.0004 | 0.038 | 2.35 | 2.43 | 1.8 |
| 53 | 0.11 | 0.57 | 6.1 | 0.046 | 36.5 | 1.37 | 0.12 | 0.451 | < 0.0001 | 0.008 | 1.86 | 1.95 | 2.4 |
| 54 | 0.73 | 0.28 | < 0.5 | 0.203 | 32.1 | 2.78 | 0.17 | 0.274 | 0.0004 | 0.066 | 7.98 | 7.73 | 1.6 |
| 55 | 0.2 | 0.19 | 10.9 | 0.04 | 23.9 | 2.85 | 0.74 | 0.44 | < 0.0001 | 0.028 | 2.79 | 2.87 | 1.5 |
| 56 | 0.08 | 0.52 | < 0.5 | 0.118 | 26.8 | 1.8 | 1.26 | 0.794 | < 0.0001 | 0.002 | 3.68 | 3.87 | 2.5 |
| 57 | 0.36 | 0.14 | 33.4 | 0.042 | 11 | 3.74 | 0.1 | 0.0267 | 0.0004 | 0.009 | 5.6 | 5.89 | 2.5 |
| 58 | < 0.05 | 0.07 | 10.4 | 0.015 | 14.3 | 0.64 | < 0.02 | 0.0191 | 0.0007 | 0.008 | 1.19 | 1.17 | 0.8 |
| 59 | 1.2 | 0.37 | < 0.5 | 0.178 | 39.2 | 9.03 | 12.5 | 1.14 | < 0.0001 | 0.005 | 12.9 | 12.5 | 1.6 |
| 60 | 0.07 | 0.18 | 10.3 | 0.029 | 28 | < 0.05 | < 0.02 | 0.0013 | 0.0007 | 0.03 | 1.56 | 1.45 | 3.5 |
| 61 | < 0.05 | 0.19 | 9.6 | 0.037 | 26.6 | 2.09 | < 0.02 | 0.0011 | 0.001 | 0.071 | 1.58 | 1.57 | < 0.1 |
| 62 | | | < 0.5 | 4.57 | | | < 0.1 | 3.42 | < 0.0005 | | 51.8 | 52.6 | 0.77 |
| 63 | | | | | | | | | | | | | |

## 4.0 DISCUSSION

### 4.1. Geographic distributions

The geographic distribution of the sampling points is shown in Fig.1, and well depths in Fig.2. The Upper Plain is on the top right, and the Lower Valley on the bottom left.

Fig. 3 shows the geographic distribution of dissolved oxygen and iron. The Upper Valley (with the exception of deep well #62 Wither) contains aerobic groundwaters, with mostly high (>60% of saturation) levels of oxygen and no dissolved iron. The deep wells in the Lower Valley contain anaerobic water, with no remaining oxygen (<5% saturation) and elevated iron (>0.1 mg/L) levels in the water. The area between these contains water of intermediate aerobic-anaerobic condition.

Fig. 4 shows the geographic distribution of groundwater conductivity, with elevated values in the Lower Valley (including Martinborough), and an extremely high level at Wither (#62).

Fig. 5 shows the fraction of exponential (mixed) flow within the total flow volume (see Appendix 1 for explanation). Most wells show high fractions of mixed flow. In comparison, the river recharged confined aquifers of the Hutt Valley and Hawkes Bay show higher fractions of piston flow (20-60%), particularly in the upper part of the aquifer. However, the Wairarapa data are too sparse and in the Upper Valley are only from local springs, therefore these data do not allow for a conclusive decision on the spatial distribution of the flow model over the whole area. If the local springs are not taken into consideration, the data then show a trend of low fractions of mixed flow (high fractions of piston flow) in the Upper Valley, increasing down-valley.

Fig. 6 shows the mean residence times, with mostly young (MRT~2yrs) groundwater in the Upper Valley, and old (MRT>100yrs) groundwater in the central Lower Valley. Intermediate ages (MRT~40yrs) occur in the area between. The deep wells in the Upper Valley also contain old (MRT>100yrs) groundwater.

Most groundwaters in the central part of the Lower Valley do not contain tritium as shown in Fig. 7, therefore these mean residence times are minimum values only, with the possibility that the actual residence times are much greater. This part of the aquifer is nearly stagnant. The waters along the south-eastern side of the Lower Valley contain small amounts of tritium (MRT 45-80yrs), indicating recharge from the south-eastern hills.

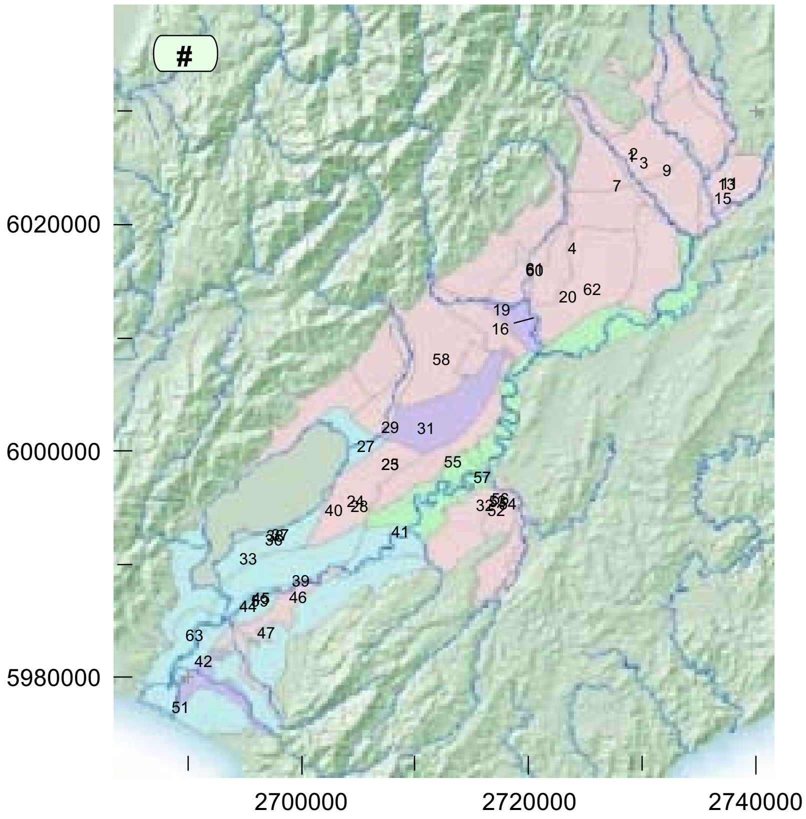


Figure 1: Geographic distribution of sampling points. Sample codes are given in Tab. 1.

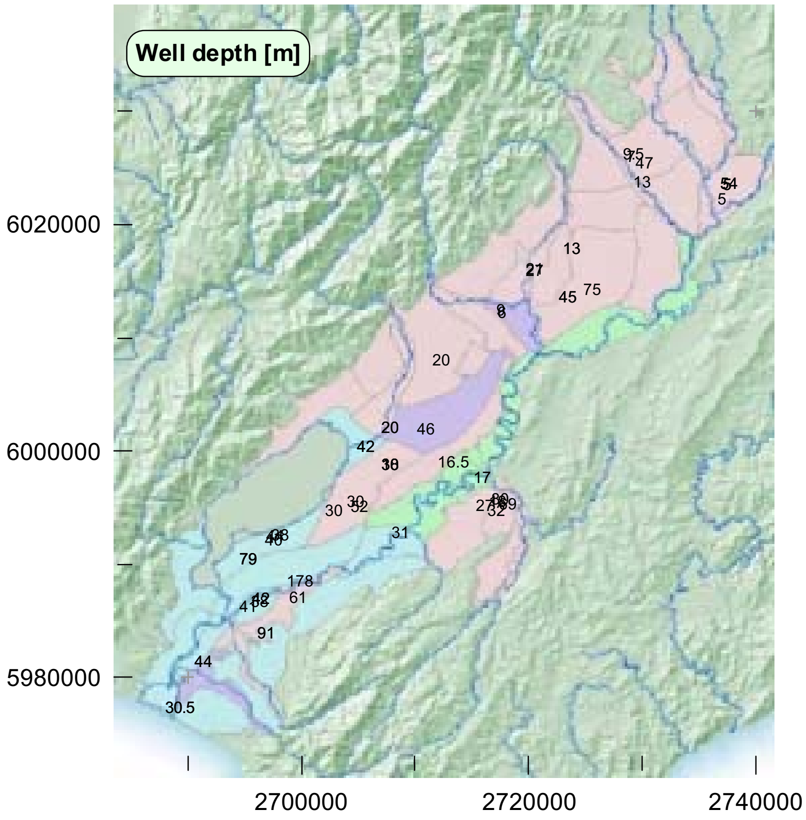


Figure 2: Geographic distribution of well depth.

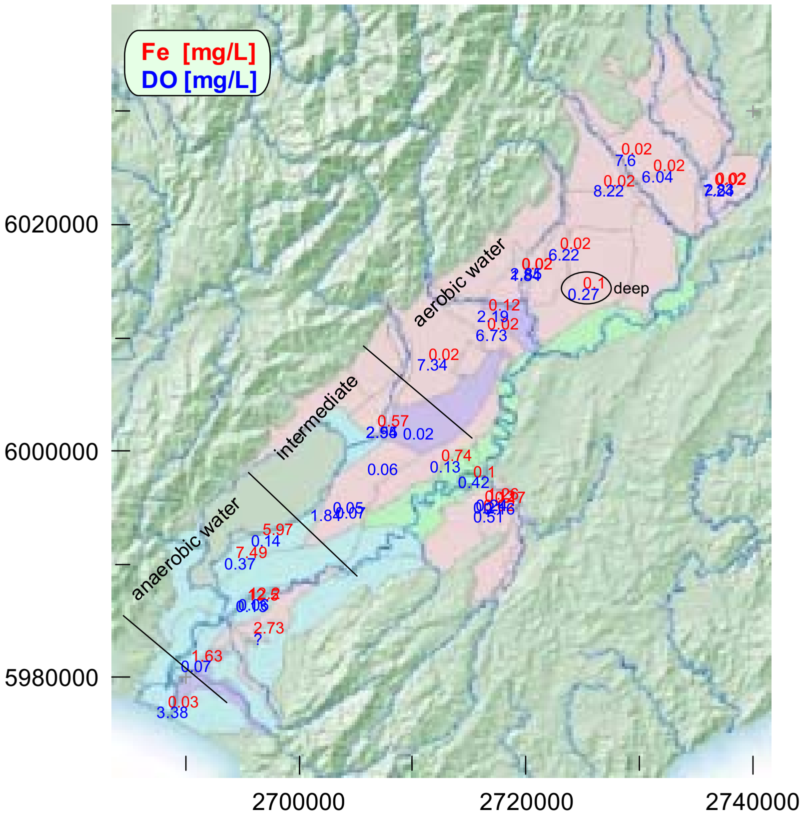


Figure 3: Geographic distribution of Dissolved Oxygen and Iron.

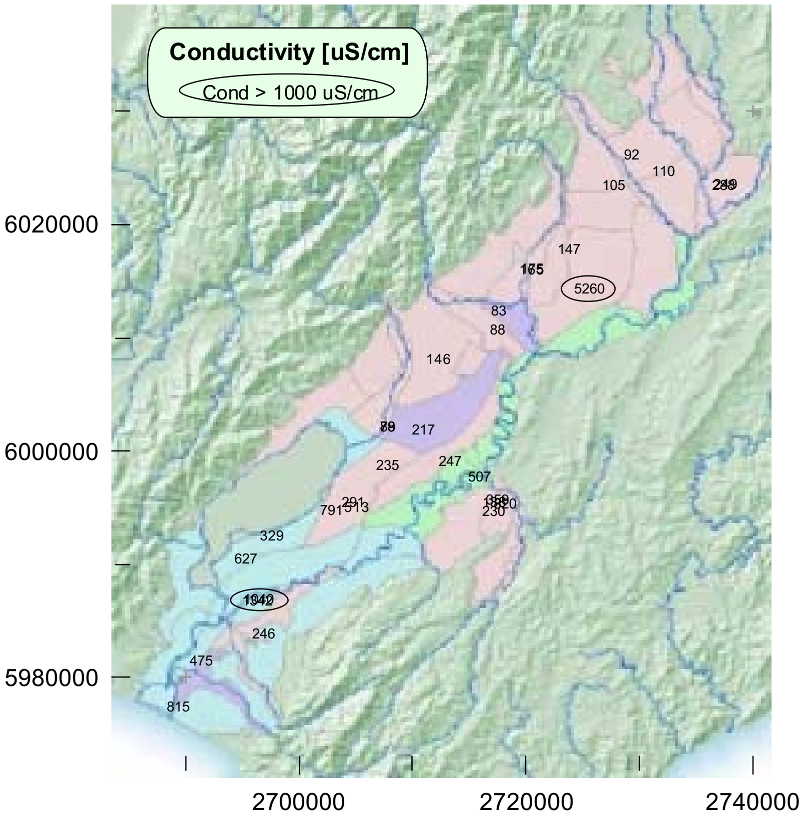


Figure 4: Geographic distribution of groundwater conductivity.

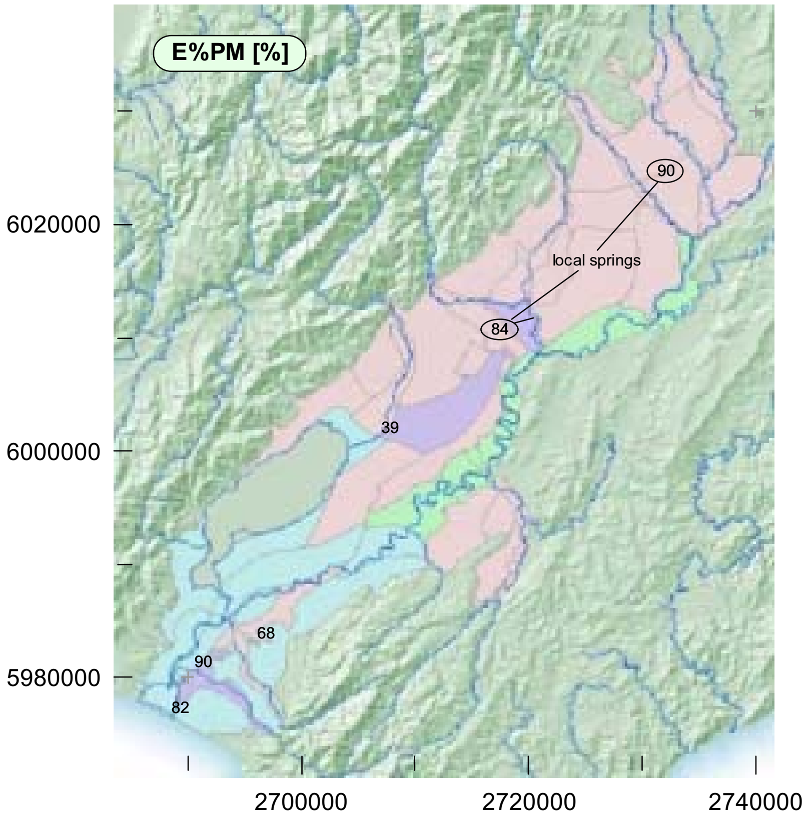


Figure 5: Geographic distribution of the fraction of exponential (mixed) flow within the total flow volume.

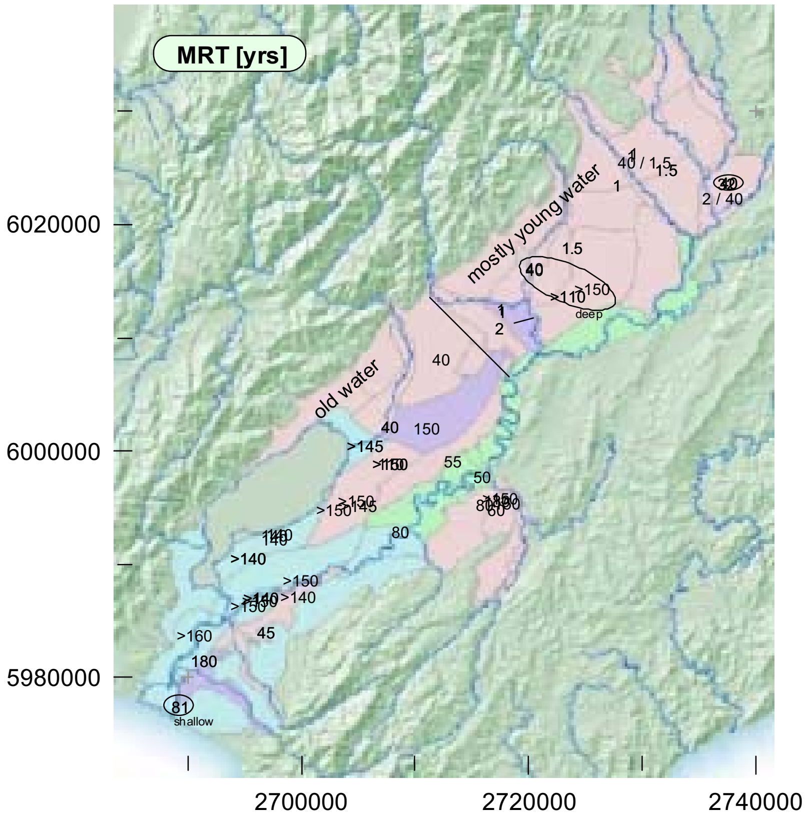


Figure 6: Geographic distribution of mean residence times.

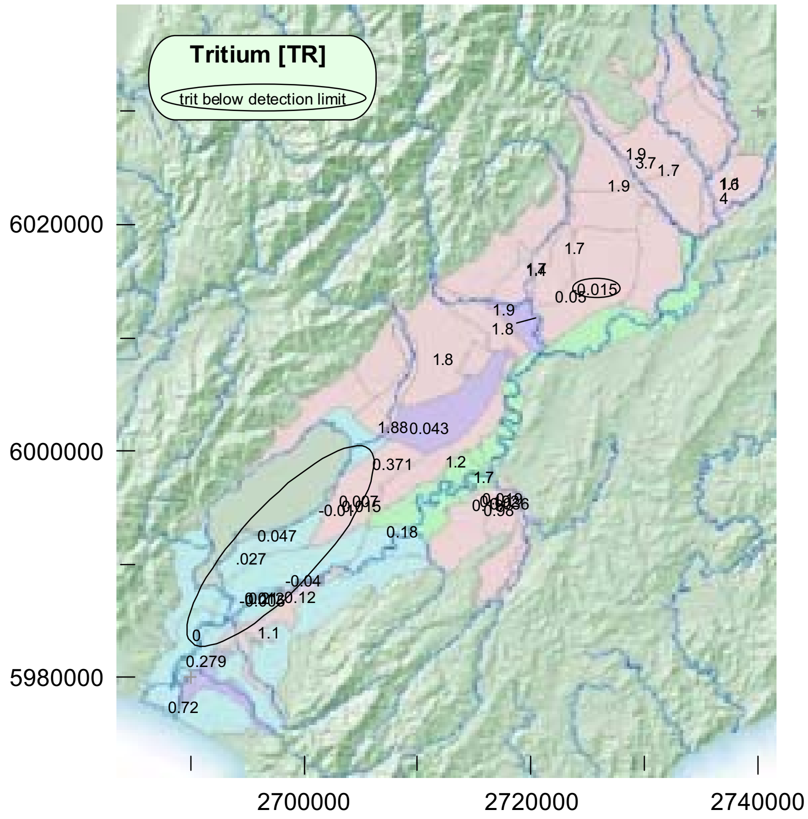


Figure 7: Geographic distribution of tritium concentration.

## 4.2. Depth versus residence time

Fig. 8 shows the plot of depth vs. mean residence time. Most of the groundwaters plot in a narrow linear range.

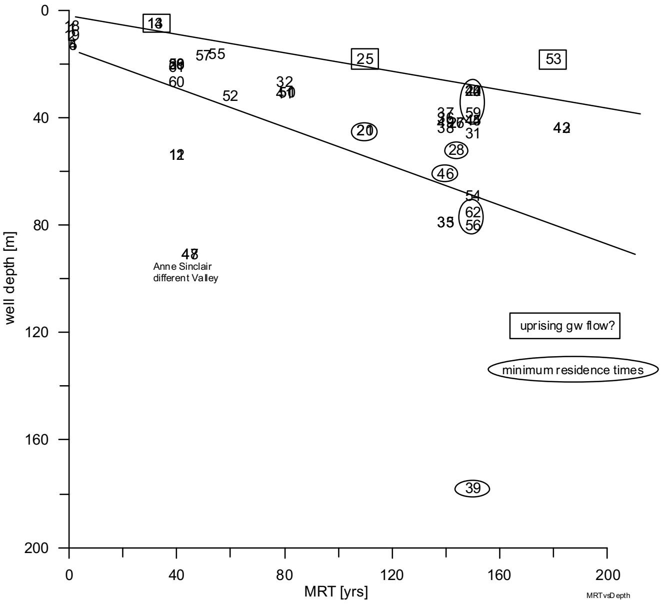


Figure 8: Mean residence time versus well depth. Label numbers refer to Tab. 1. Labels in ellipses are minimum MRTs only, these residence times could be much higher.

Generally, with increasing depth the residence time also increases (Fig. 8). An exception is the Anne Sinclair well, situated at the foot of the Whangaehu valley which is on the eastern side of the Wairarapa valley. The water there may reach greater depth more quickly. On the other hand, Dimittina (#53) is older for its shallow depth compared to the general trend. This may indicate that the well is in an area of uprising old deep groundwater (or is very slowly recharged). Duffy shallow and Simmonds shallow are also old compared to the general trend. The theory of uprising old groundwater is supported by the fact that Duffy shallow is only slightly younger than Duffy deep, and it has a very similar chemical composition to Duffy deep.

## 4.3. Recharge source

The stable isotopes of the water ($^{18}O$ and $^{2}H$) can indicate the source of recharge (river or local rain). River water normally originates from higher altitude rain compared to local rain in the plains, with a difference in isotopic composition of the water. However, this method is not absolutely conclusive due to natural variability. Available data in the Wairarapa are too sparse for sufficient understanding of stable isotope levels in the rain of the various parts of the catchment. In an earlier study (Gunn et al. 1987) it was concluded that predominantly river recharged groundwater will be less negative than -6.3‰ in $^{18}O$.

To improve the reliability in identifying the recharge source, an attempt follows that includes other indicators for the recharge source such as nitrate and excess air. Rivers from less intensively farmed higher altitude catchments usually have little nitrate compared to rainfall recharge in the plains, and river recharged groundwaters are expected to recharge in equilibrium with air while rain recharged groundwater can have significant excess air due to air trapping at the water table.

Fig. 9 shows excess air and nitrate versus $^{18}O$. From the above reasons, river recharged groundwaters are expected to plot into the lower left corner of Fig. 9. Three groundwaters, Candy/Van der Put, Papawai spring, and Smith's Orchard/GP Orchard indicate river recharge in all three parameters. The result is very consistent because the replacement wells for Candy and Smith's Orchard, which represent a similar part of the aquifer, also plot into the river recharge cluster. Groundwaters more negative than -6‰ contain significant nitrate and/or excess air. Therefore, classification of groundwater less negative than -6.3‰ as river recharge is not warranted. From Fig. 9 we conclude a boundary of less negative than -5.9‰ for river recharge. The boundary for rain recharge from Gunn et al. 1987 of less negative than -6.8‰ matches the pattern in Fig. 9. This boundary is being kept in this study.

The above criteria were used to re-evaluate the samples for their recharge origin, and the result is shown in Figure 10. Only three of the investigated groundwaters in the Upper Valley show strong evidence for river recharge. The majority of the samples in the Upper Valley fall into the cluster of mixed river and rain recharge, with only a few on the south-eastern hills being classed as pure rainfall recharge. In the Lower Valley, the majority of the samples adjacent to the south-eastern hills fall into the cluster of rainfall recharge indicating recharge from the south eastern hills without contribution from Ruamahanga River. In the central lower valley, consistent to the upper valley, the majority of the samples indicate a mixture of rain/river recharge, with the river contribution likely to be through the coalescising fans from the western tributaries of the Ruamahanga River.

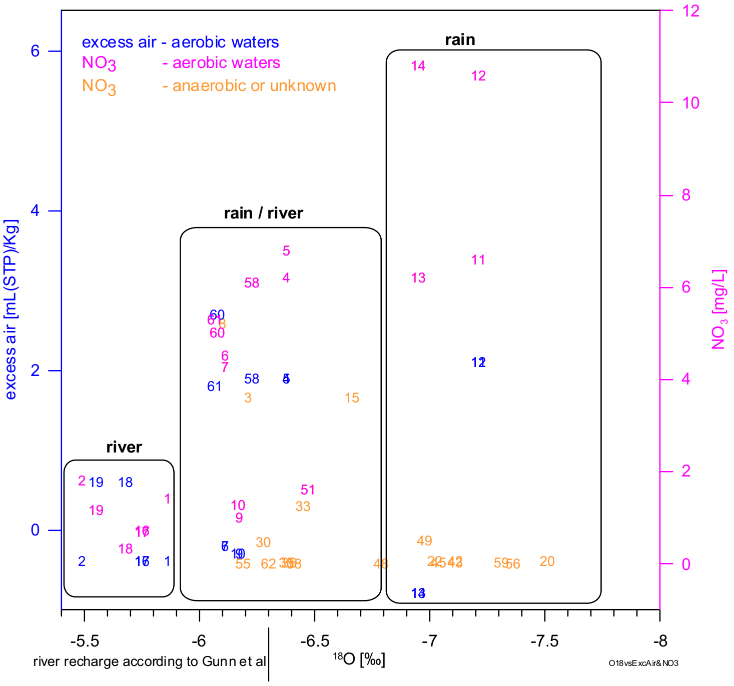


Figure 9: Excess air and nitrate versus $^{18}$O (old data from Gunn et al. 1987). Nitrate and excess air are subject to alteration within the aquifer at anaerobic conditions, therefore only aerobic waters are plotted in blue and magenta. Nitrate for anaerobic waters is added in orange for comparison.

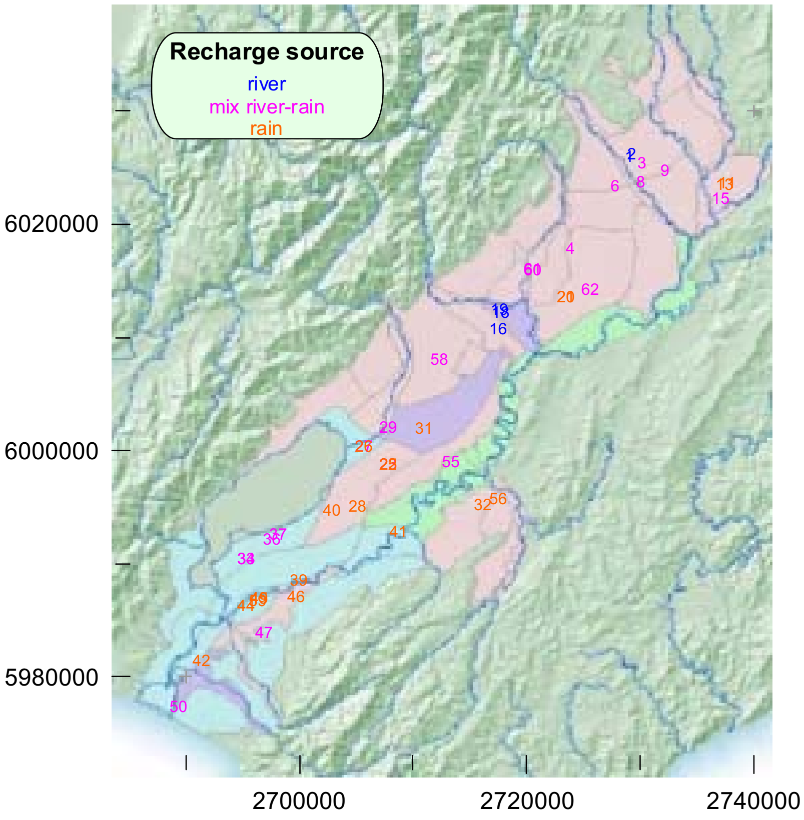


Figure 10: Geographic distribution of samples with predominantly river recharge, rain recharge, and a mixture of the two.

## 4.4. Time trends in hydrochemistry

In the following section, chemical and field parameters are plotted against the mean residence times to

- obtain information on the natural hydrochemistry evolution processes in the Wairarapa groundwater system to enable their use in understanding the groundwater flow pattern, and
- identify anthropogenic influences on groundwater quality.

The figures are colour coded to distinguish between aerobic and anaerobic waters because this affects the chemical composition of the water. Plotting the different groundwaters against their mean residence times is not strictly correct because mean residence times have different meanings for different mixing models. However, the applied models only vary within a small range, so the time trends are not distorted significantly.

Fig. 11 shows the measured discharge temperature, calculated recharge temperature, and pH of the groundwaters.

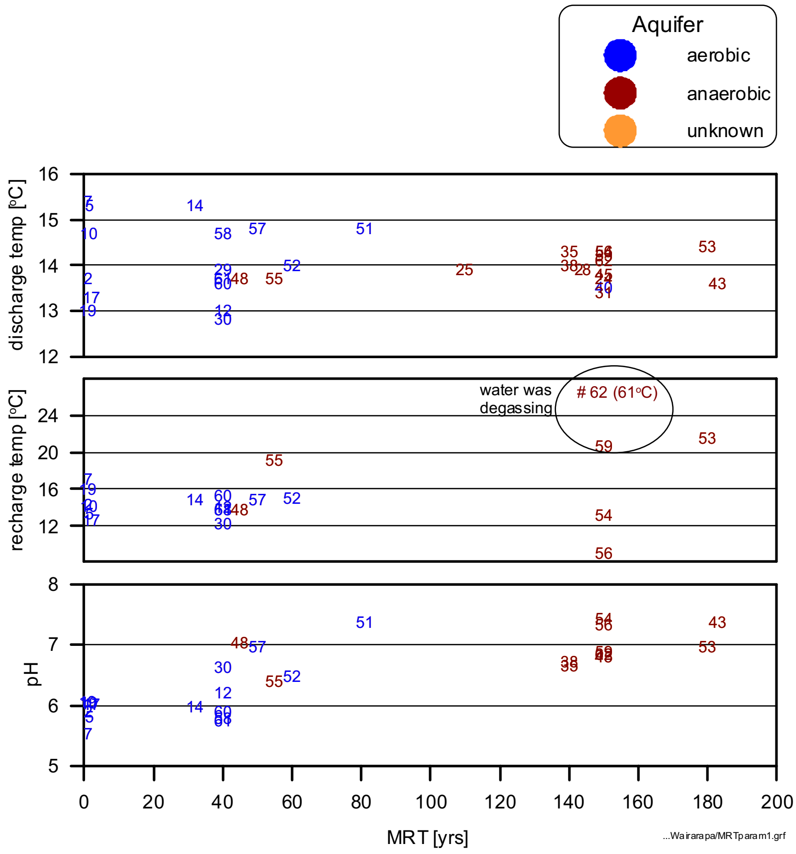


Figure 11: Recharge and discharge temperature, and pH versus mean residence time.

The **discharge temperature** for the older (deeper) groundwaters is relatively constant but has higher variability for the young groundwaters. Higher variability for the shallower water is expected. The average discharge temperature of 14.0 °C is in good agreement with the mean annual air temperature of 12.7 °C (Masterton). The slightly elevated water temperature after passage of the groundwater system may reflect slight pickup of geogenic heat.

The **recharge temperature**, calculated from Ar and $N_2$ concentrations of the water, is relatively constant for the aerobic groundwaters and demonstrates reliability of the recharge temperature measurement for correction of CFC and $SF_6$ equilibrium concentrations. The average recharge temperature of 14.4°C (instrumental error due to solubility constants ±0.5°C) is in good agreement with the mean annual air temperature of 12.7 °C (Masterton). Using Ar and $N_2$ for recharge temperature reconstruction is inaccurate for anaerobic waters because the gas concentrations are being altered by denitrification processes in the aquifer, and by degassing.

The plot of **pH** versus mean residence time indicates increasing pH with increasing chemical evolution of the groundwater, independently of the aerobic/anaerobic condition. Young groundwaters have pH of about 6, increasing to a saturation value of about 7.

Dissolved oxygen, iron, and manganese as indicators for aerobic/anaerobic aquifer conditions are shown in Fig. 12. Boron is added as a possible indicator of geothermal/faultline influence.

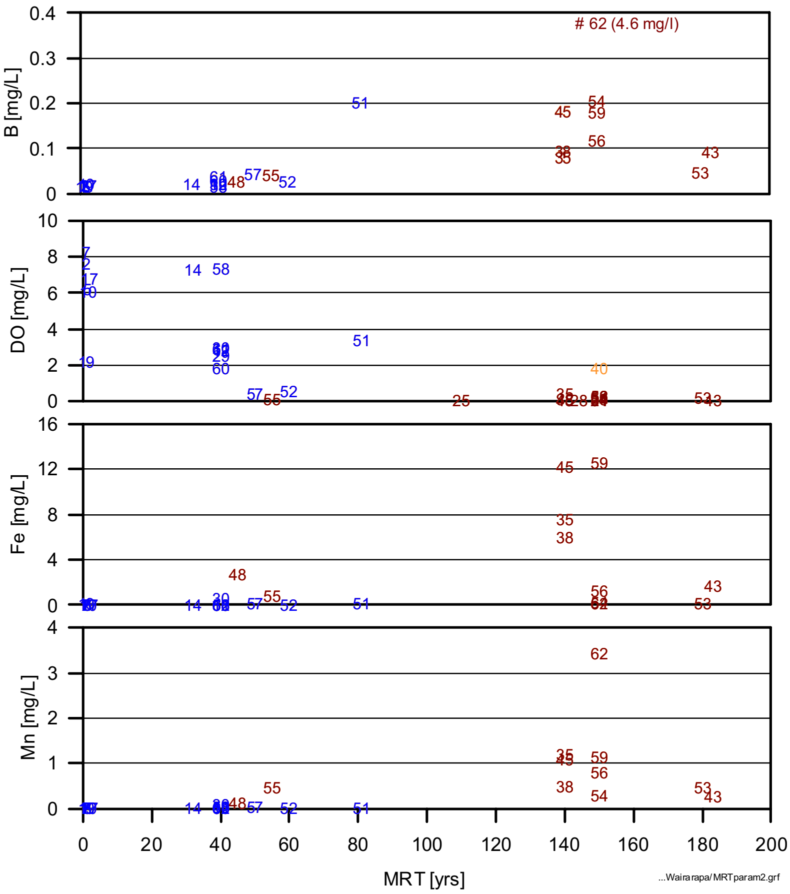


Figure 12: Manganese (Mn), iron (Fe), dissolved oxygen (DO), and boron (B) versus mean residence time. #40 was sampled with a bailer. Therefore, non-zero DO is likely to be due to contamination from air.

In slowly moving aquifers that still contain organic matter, utilization of **dissolved oxygen** along the flow path leads to reducing conditions that mobilize iron and manganese. Therefore, absence of oxygen and presence of Mn and/or Fe were used to classify the groundwaters into aerobic and anaerobic (see Tab. 2 and colour code in Figs. 11-23).

Most of the deep old groundwaters in the Lower Valley are anaerobic (see also Fig.3), indicating the presence of organic matter in this aquifer. On the other hand, aerobic waters with mean residence times up to 80 years in other parts of the Wairarapa indicate absence of organic matter, or organic matter not readily available for complete utilization of dissolved oxygen (confirmed by bore logs?).

The **boron** concentration (Fig. 12) increases slightly with time, independent on aerobic/anaerobic conditions. This gradual increase indicates geogenic origin of the boron due to evolving water-rock interaction. Well Wither (#62), however, has extremely high boron concentration of 4.6 mg/L, indicating faultline influence. Also other chemical parameters are unusually high for this water sample (total alkalinity, $HCO_3$, Na, Cl, Ca, Mg, total hardness, $NH_4$, see below).

The **total ion concentrations** are shown in Fig. 13. They increase with time due to evolving water-rock interaction. Well Wither (#62) has unusual high ion concentrations compared to the other waters.

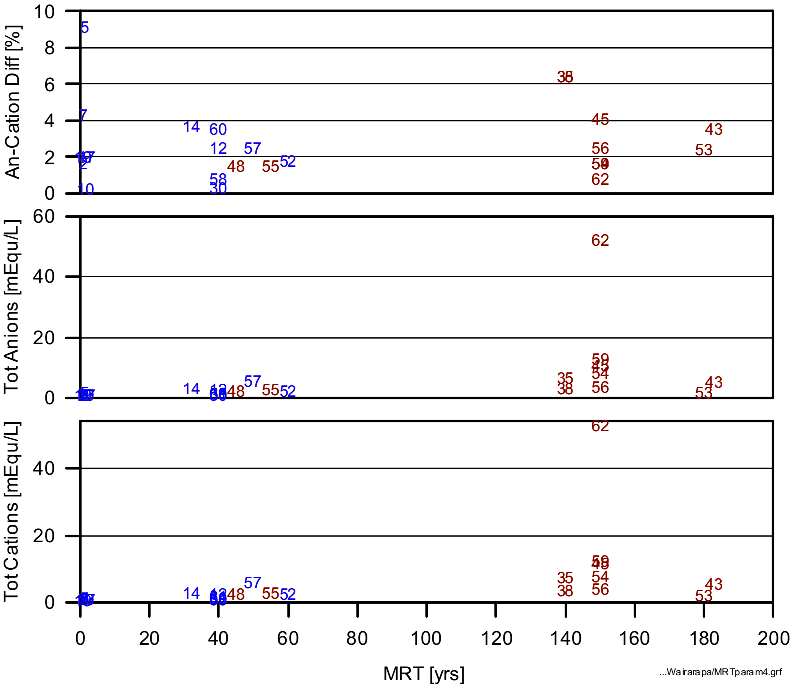


Figure 13: Total ion concentrations versus mean residence time.

Sodium, chloride, and conductivity are shown in Fig. 14. **Sodium** and **chloride** are much elevated compared to rain water, and this is likely to be due to remanent seawater (connate seawater or seawater intrusions from interglacial and postglacial high sea level periods) in the deeper aquifer. The Na concentration increases with age, but this cannot be explained by progressive leaching of Na from the rock matrix because Cl also is increasing in about the same ratio. Cl is generally a conservative tracer, not contained in most rock matrixes. Therefore, in the absence of sea salt in the aquifer, Cl is expected to be constant at about the level of coastal rain (10mg/L). The nearly constant Na/Cl ratio therefore indicates connate seawater as the origin of the NaCl. The correlation between NaCl and age indicates that the deeper aquifers are less flushed and therefore connate seawater (and organic matter producing anaerobic conditions) is still present in this aquifer due to nearly stagnant flow condition. The Na/Cl ratio in rain water is approximately 0.6, therefore the elevated ratios indicate some degree of Na leaching from the aquifer.

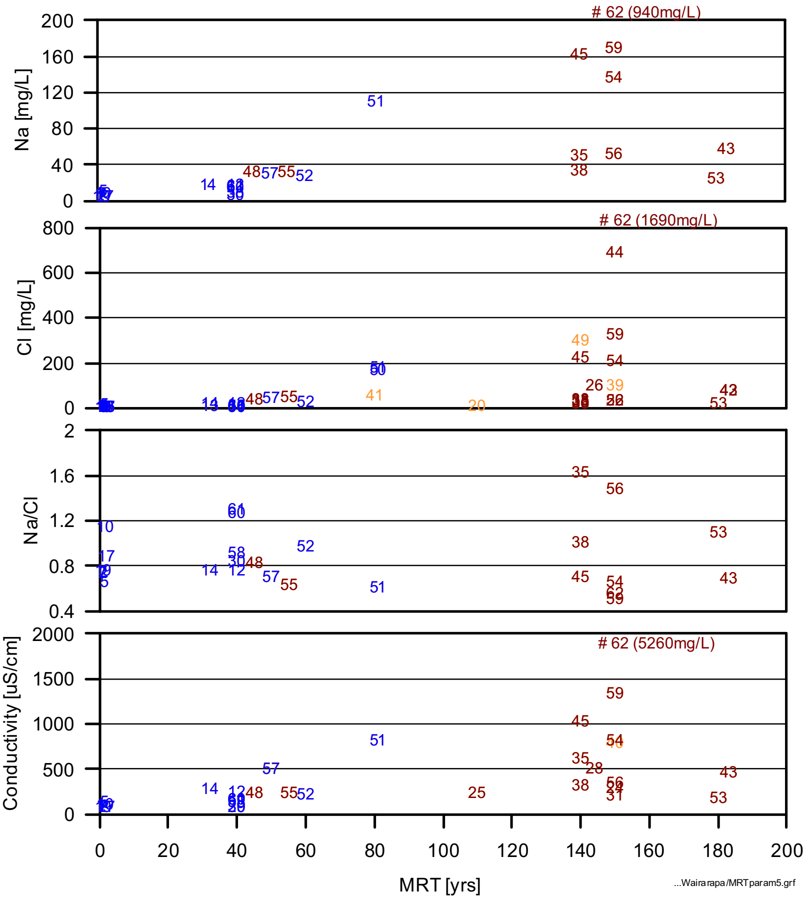


Figure 14: Sodium (Na), chloride (Cl), and conductivity versus mean residence time.

Fig. 15 shows **total hardness**, **calcium, magnesium** and silica concentrations versus mean residence time. Total hardness reflects the calcium and magnesium concentrations. Because all these parameters show identical patterns in the plot versus mean residence time, the reactions controlling their concentrations in the water have the same time constants, and are probably identical. In agricultural areas large amounts of CaO (lime) may be added to pastures to adjust soil pH, and Mg may be added with fertilisers. However, the data set shows no evidence of elevated Ca and Mg concentration for young anthropogenically influenced waters. The concentration increases with the age of the water, and the correlation with Na (see Mg versus Na in Fig. 16) reflects similar sources, mainly connate seawater, and to some extent leaching by rock-water interaction. The increasing trend is similar for both, aerobic and anaerobic water, and equilibrium concentration is reached after about 50-70 years.

**Silica** in Fig. 15 shows a similar trend. It requires more than 100 years for saturation.

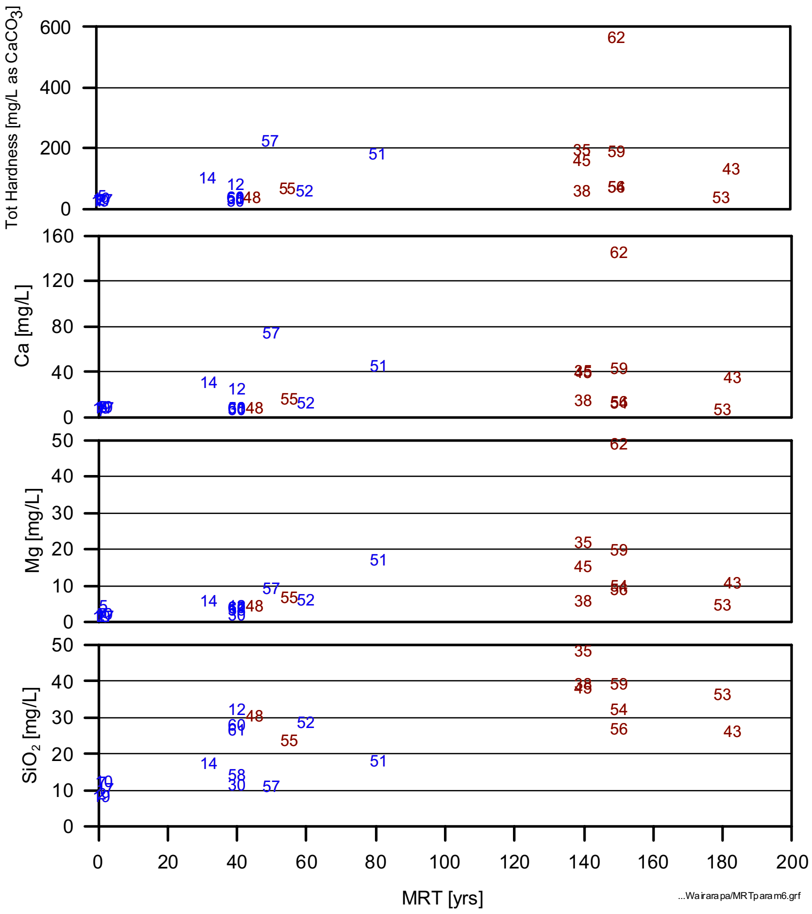
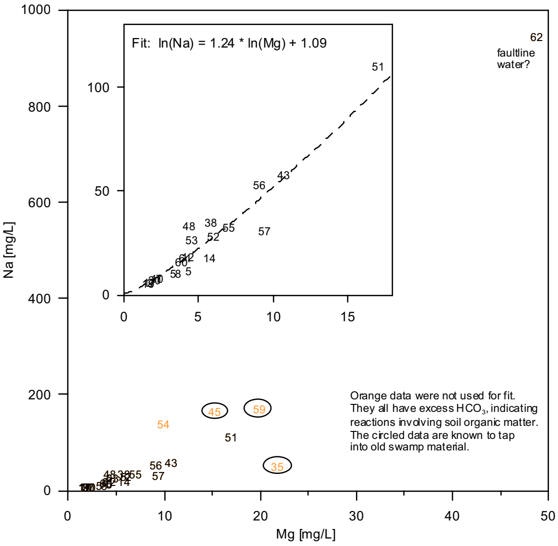


Figure 15: Silica ($SiO_2$), magnesium (Mg), calcium (Ca), and total hardness versus mean residence time.



Orange data were not used for fit. They all have excess $HCO_3$, indicating reactions involving soil organic matter. The circled data are known to tap into old swamp material.

Figure 16: Mg versus Na. The insert shows the lower concentrations with higher resolution.

Na and Si in NZ aquifers usually correlate well at low concentrations (Rosen 2001). This also applies to the Wairarapa data set (Fig. 17), with the exception of #57 Martinborough Water Supply well 1 which has unusually high Na relative to Si (and also Ca and $SO_4$).

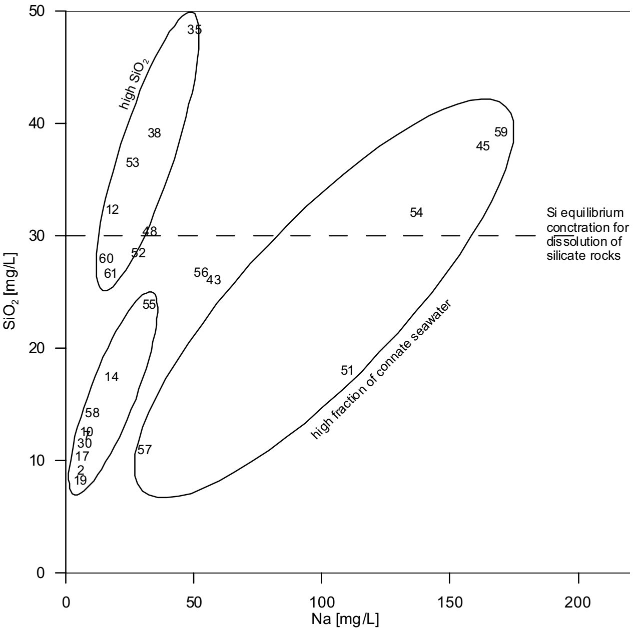


Figure 17: Si versus Na concentration. The dashed line represents Si equilibrium concentration for dissolution of silicate rocks (Rosen 2001). Si concentrations much greater then that usually indicate dissolution of volcanic glass.

Some wells (#51, 54, 45, 59) with higher Si concentration also have unproportional high Na concentration relative to Si, indicating a higher fraction of Na comes from connate seawater (as opposed to dissolution of rock). This occurs predominantly on the south eastern margin of the Lower Valley. On the other hand, waters with unproportional high $SiO_2$ concentration occur predominantly in the central valley.

Trace and heavy metals are shown in Fig. 18. The increase of **fluoride** with time indicates geogenic origin due to evolving water-rock interaction. **Bromide** also increases with mean residence time, but the good correlation with Cl (most values plot near the seawater concentration dilution line, Fig. 19) indicates the same origin of Br and Cl (i.e. from old connate seawater that is still present in the aquifer with old water due to the nearly stagnant flow condition). Only Martinborough wells (golf club #52 and water supply #57) and Colton (#35) have elevated Br compared to seawater origin. The water from Colton well is too old for Br to be anthropogenic, indicating the likelihood of elevated Br of a geogenic origin in certain geological formations.

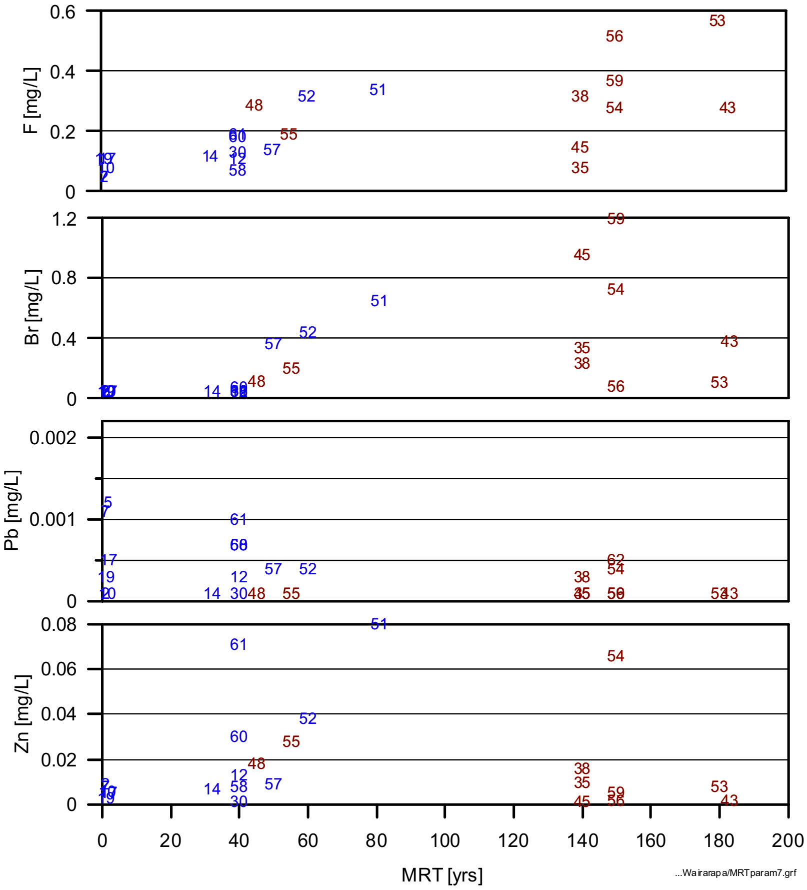


Figure 18: Trace and heavy metal concentration versus mean residence time. Zinc – Zn, lead – Pb, bromide – Br, Fluoride – F.

Elevated **lead** concentrations in younger waters indicate Pb finds its way into the groundwater. Measured concentrations are similar to other NZ groundwaters (Rosen 2001). The origin may be anthropogenic (leaded petrol) because elevated Pb occurs preferably in younger groundwaters. However, it cannot be excluded that the origin is geogenic with low concentrations in old waters due to Pb precipitation as sulphides in anaerobic conditions.

**Zinc** shows a trend of increasing concentration with residence time. However, most of the very old anaerobic waters have low Zn concentrations which may be caused by absorption or precipitation with sulphides in anaerobic conditions (elevated Zn in #54 is an outlier, could it be caused by brass in the piping system?). Aerobic water from Lake Ferry (#51) and CDC North (#61) show the highest concentrations of Zn. CDC North shows elevated concentration in Pb and Zn, and high contamination with CFCs. The same pattern to a lesser extend is observed at CDC South. This indicates that the water at the CDC wells may be affected by old landfills.

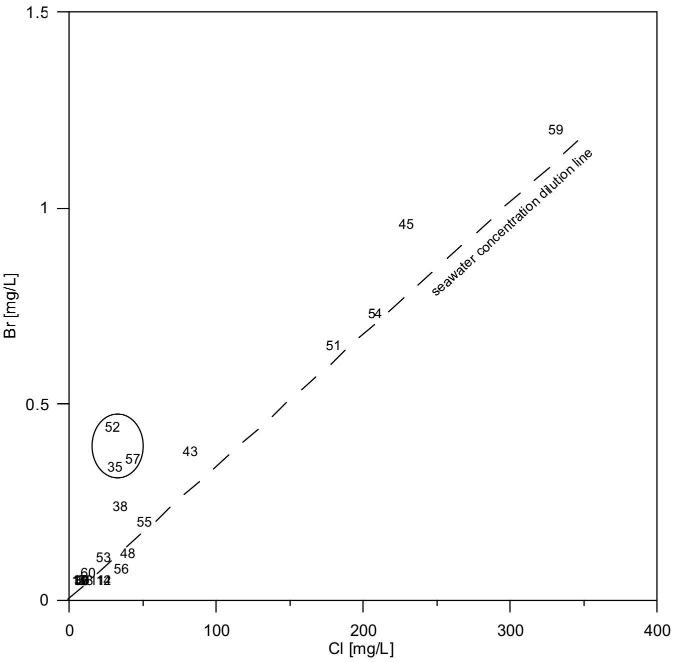


Figure 19: Br versus Cl concentration.

Bicarbonate (and total alkalinity), total organic carbon and free $CO_2$ are shown in Fig. 20 versus mean residence time. With increasing residence time, **bicarbonate** is increasing. The majority of the data plot near the trend of calcite dissolution (Fig. 21), therefore, calcite dissolution is likely to be the main origin of $HCO_3$. Excellent agreement to calcite dissolution is observed for well #57 Martinborough water supply which originates from a limestone area.

However, the anaerobic waters show mostly excess $HCO_3$ compared to calcite dissolution. The most likely reason is $HCO_3$ derived from reactions involving soil organic matter. Samples #35, 45, and 59 are known to tap into old swamp material. Influence by soil organic matter is also indicated by methane in #45 (and by electro-corrosion problems of #35 in the tritium enrichment which is often caused by organic matter). TOC is also high for #35, 45, and 59. Excess $HCO_3$ occurs on the southern margin of Lake Wairarapa (#35, 38, 45, 59). Also the deep wells near Martinborough (#54, 56) that tap old (>150yrs) water contain excess $HCO_3$ but not related to high TOC.

Apart from the 3 wells in the old swamp, the trend of **total organic carbon** versus time is very low concentrations for the very young aerobic waters (MRT<2yrs), and a slight increase with equilibrium reached after several years.

The time trend of **free $CO_2$** is 20-40 mg/L for the very young aerobic waters, decrease to 20 mg/L at MRT 40-60 years, and 10 mg/L at MRT>140 years. This suggests free $CO_2$ is getting used up for calcite dissolution. Exceptions with higher concentrations are the samples from the old swamp, and #14 Duffy shallow.

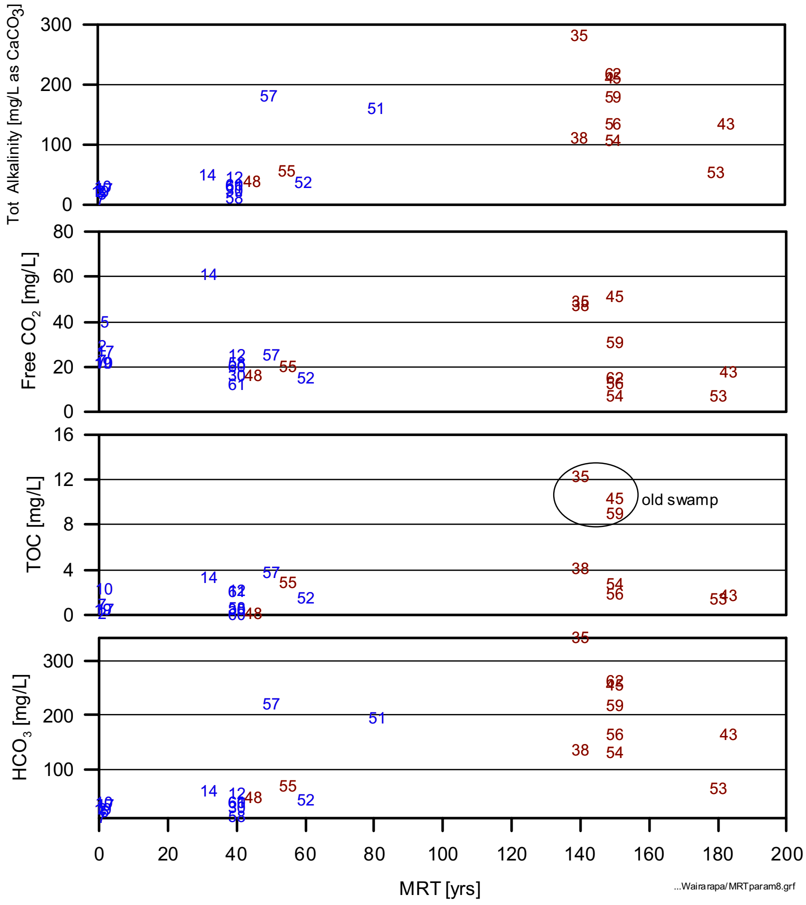


Figure 20: Bicarbonate ($HCO_3$), total organic carbon (TOC), free $CO_2$, and total alkalinity versus mean residence time.

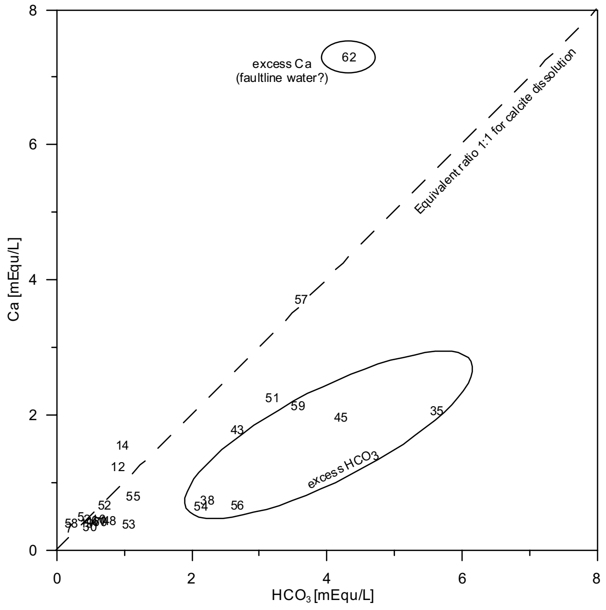


Figure 21: Equivalent of Ca versus $HCO_3$. The equivalent is the molar concentration multiplied with the ionic charge. Dissolution of calcite would result in a 1:1 ratio for Ca and $HCO_3$ (Rosen 2001).

Nitrogen species are shown in Fig. 22. **Nitrate** shows a cluster of young contaminated groundwaters, and also a cluster of young uncontaminated groundwaters. The uncontaminated aerobic groundwaters are likely to originate from uncontaminated recharge (absence of nitrate in the recharge area) as opposed to de-nitrification processes in the aquifer because de-nitrification is highly unlikely in aerobic water. The two young anaerobic waters may also originate from uncontaminated recharge because they do not contain ammonia (see below). In good agreement, all groundwaters which are likely to originate from river-recharge (see 4.3) fall into the uncontaminated cluster. The old groundwaters all have low nitrate concentrations. These waters are too old for anthropogenic nitrate influence.

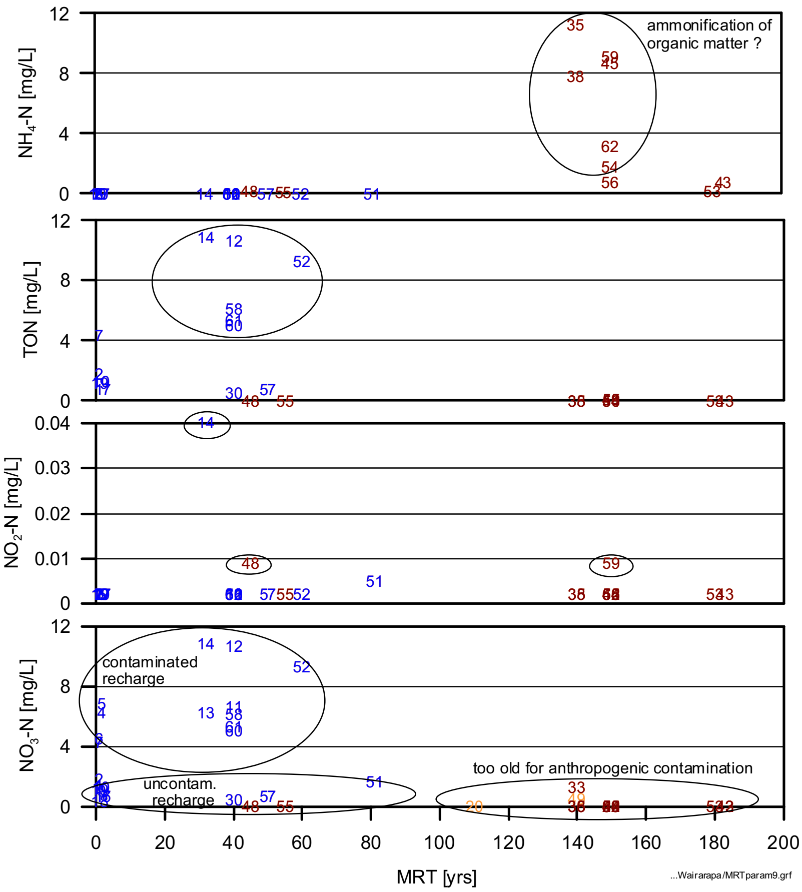


Figure 22: Nitrogen species versus mean residence time. $NO_3$ – nitrate, $NO_2$ – nitrite, TON – total oxidised nitrogen ($NO_3$ + $NO_2$), $NH_4$ – ammonia.

Absence of **ammonium** in the younger aerobic waters is an additional indicator that de-nitrification processes in these waters are unlikely. Elevated ammonium can be a product of de-nitrification processes in anaerobic aquifers and in the presence of nitrate. While there is also some possibility for de-nitrification without ammonia production, absence of ammonium in the young anaerobic waters makes it more likely that de-nitrification has not occurred. Ammonium is present in the old anaerobic water. However, these waters are too old to have contained high levels of anthropogenic nitrate. Therefore, the ammonium in the old anaerobic waters is probably not caused by de-nitrification, and is assumed to originate from ammonification processes of organic matter in the organic-rich soil.

For **nitrite**, only sample Duffy shallow (#14) shows an elevated value, and samples Anne Sinclair (#48) and Findlayson (#59) slightly elevated values. **Total oxidised nitrogen** basically reflects $NO_3$.

Fig. 23 shows nutrient related species versus mean residence time. There is no anthropogenic influence on groundwater quality for potassium and dissolved reactive phosphate, but sulphate and nitrate do show anthropogenic influence on groundwater quality.

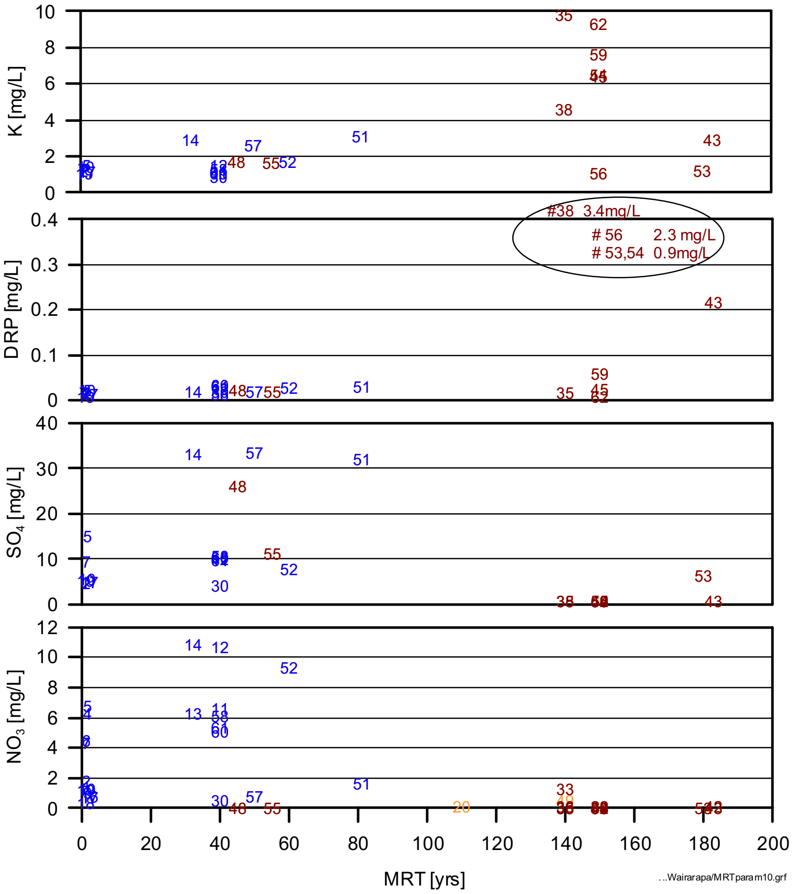


Figure 23: Nutrients versus mean residence time. K – potassium, DRP - dissolved reactive phosphate, $SO_4$ – sulphate, $NO_3$ – nitrate.

Common anthropogenic sources of **potassium** include fertilisers and human and animal waste. However, plants utilize fertiliser K effectively, and reactions with clay minerals can take up remaining K. Nevertheless, K was detected in elevated concentrations in the Rotorua Lakes area in young groundwater indicating that anthropogenic K can find its way into the groundwater. The Wairarapa data set shows clearly the opposite trend, low potassium in young groundwater, and rising concentrations with age (independent of aerobic/anaerobic conditions). The increase of K with time indicates geogenic origin due to water-rock interaction, and the correlation of K with Mg (Fig. 24) indicates similar geochemical reactions for the control of K and Mg in the water. The old anaerobic waters show a wide range in K concentration, with very high concentration for the wells in the old swamp (#35 Colton and #59 Findlayson), and the well that possibly taps faultline water (#62, Wither).

The trend of K versus time in the younger (<100 years) Wairarapa groundwaters indicates that, (i) whether or not K gets applied by human activities or fertilisers, it doesn't find its way into the deeper groundwater, and (ii) the geogenic K is not effectively absorbed by reactions with clay. Unusually high and low K values in the older (>100 years) anaerobic Wairarapa groundwaters indicate that excessive leaching of K can occur from soils with high content of organic matter, and also K removal by absorption may be possible.

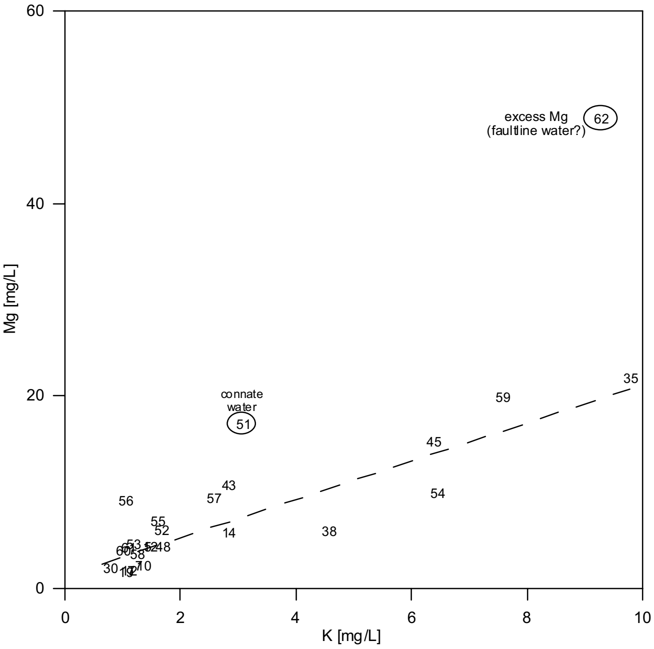


Figure 24: K versus Mg. The correlation indicates that similar geochemical reactions control K and Mg in the groundwater.

**Dissolved reactive phosphate** is low in all groundwaters younger than MRT 100 yrs (Fig. 23), but significant amounts of DRP occur in some of the old anaerobic waters. These are locally very restricted to Martinborough (#53, 54, 56) and Wairio, indicating local phosphorite deposits in the aquifer.

Phosphorus as an essential plant nutrient is applied as fertiliser in agriculture areas. However, it is taken up by organic matter in the top soil, and absorbed in the unsaturated zone. Therefore, P usually doesn't find its way into the groundwater. Low DRP values in the youngest waters clearly demonstrate that no anthropogenic DRP finds its way into the groundwater in the Wairarapa. The slight increase of DRP with time, however, indicates that there is leachable phosphate in the Wairarapa aquifer as has been found in rhyolitic pumice in Taupo and Rotorua.

Unusually high **sulphate** concentrations are observed in young groundwaters of MRT<100yrs (Fig 23). The trend is similar to nitrate which has been added to Fig. 23 again for comparison. Wells with high nitrate and high $SO_4$ are not necessarily identical (Fig. 25). A relatively good correlation between $NO_3$ and $SO_4$ for most of the aerobic groundwaters indicates an anthropogenic source of $SO_4$ (added as gypsum to fertilisers). However, the major source of $SO_4$ is geogenic. Fig. 26 shows $SO_4$ versus Mg. Apart from the old anaerobic waters most of the groundwater samples plot near the seawater concentration dilution line, indicating that as for Mg, the majority of $SO_4$ originates from connate seawater. Most of the wells with the highest $SO_4$ (#14, 48, 57), however, also show a large $SO_4$ excess to connate seawater and indicate additional anthropogenic sources of $SO_4$ (~20mg/L). Only at Lake Ferry (#51) does the large amount of $SO_4$ originate from connate seawater.

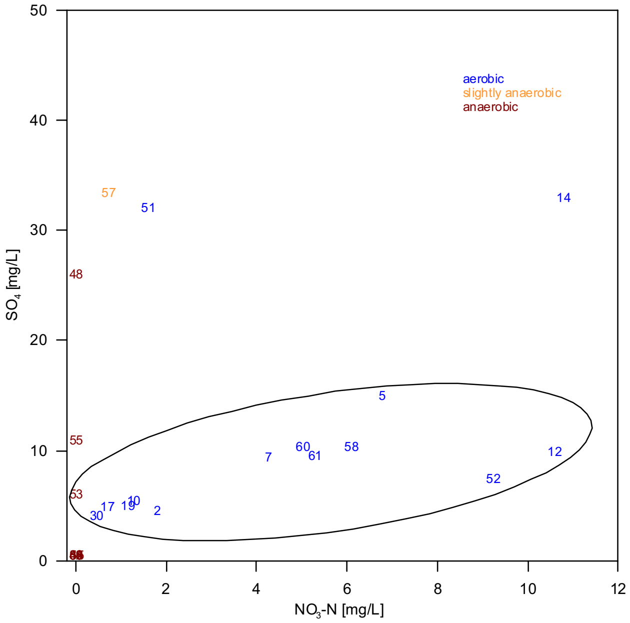


Figure 25: Sulphate versus nitrate. The good correlation for most of the aerobic waters indicates a similar source.

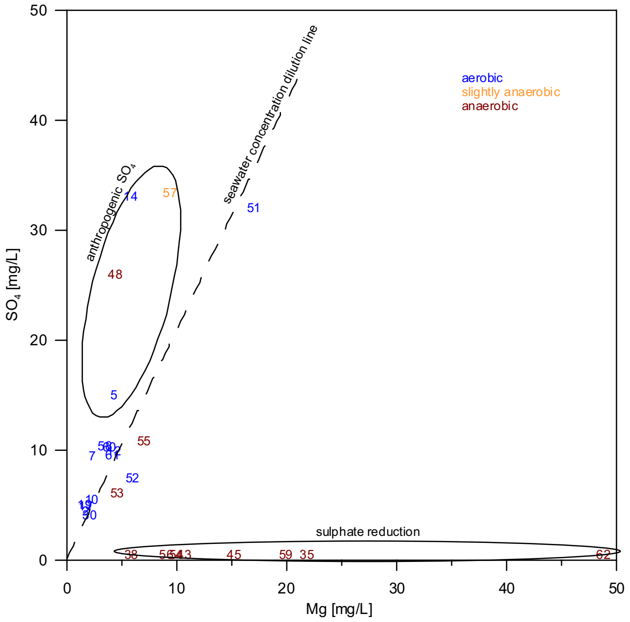


Figure 26: Sulphate versus magnesium. Dashed line is the seawater concentration dilution line (Rosen 2001).

Most old anaerobic waters have low $SO_4$. This is most likely because of reduction of $SO_4$ to sulphide. The anaerobic shallow wells near Martinborough (#53, 55) plot near the seawater concentration line indicating that $SO_4$ reduction does not occur in this part of the aquifer. Note that these waters also have no elevated $HCO_3$ and TOC. The deeper anaerobic waters in this area contain excess $HCO_3$ but not related to high TOC.

In summary, very high $SO_4$ in the young waters is dominated by anthropogenic sources, while moderate $SO_4$ levels are due to connate seawater. In the old anaerobic waters $SO_4$ is being removed by reduction.

## 5.0 CONCLUSIONS

Age dating, in combination with hydrochemistry and stable isotopes, allows for new insights into the Wairarapa groundwater system. Water dating results show mostly young (~2yrs) waters in the Upper Valley. In the central Lower Valley the waters are significantly older (>100yrs), and along the south-eastern side of the Lower Valley small amounts of tritium indicate recharge from the south-eastern hills.

We used $^{18}O$, nitrate and excess air as indicators to identify the recharge source. The results are consistent. Only three of the investigated groundwaters in the Upper Valley show strong evidence for river recharge. The majority of the samples in the Upper Valley indicate mixed river and rain recharge, with only a few on the south-eastern hills as pure rainfall recharge. In the Lower Valley, the majority of the samples adjacent to the south-eastern hills indicate rainfall recharge from the south-eastern hills with very little contribution from Ruamahanga River. In the central lower valley, consistent to the upper valley, the majority of the samples indicate a mixture of rain/river recharge, with the river contribution likely to be through the coalescising fans from the western tributaries of the Ruamahanga River.

Hydrochemistry time trends show consistent patterns with increasing age of the water. This allows for understanding the natural hydrochemistry evolution, and for identifying spatial hydrochemistry patterns to understand groundwater flow paths.

Consistent trends in hydrochemistry and consistent trends in water residence time indicate a continuous groundwater system in the Wairarapa.

Time trends in hydrochemistry also allow for identification of anthropogenic influences on groundwater quality. Only nitrate, sulphate, and possibly lead show anthropogenic influence.

## 6.0 ACKNOWLEDGEMENTS

Rob van der Raaij and Mike Stewart are thanked for development of the CFC and $SF_6$ measurement systems at GNS. Additional, Rob van der Raaij is thanked for performing the analyses. Chris Daughney and Mike Stewart have provided useful review comments. Tim Baker is thanked for excellent preparation of the sampling campaign in May 05, and together with Lindsay Annear and Brent King, for excellent help during sampling. The GIS background of the Wairarapa in figures 1-7 and 10 was provided by Tim Watson (GWRC).

## 7.0 ADDITION

After finalising the report it was detected that sample #45 was wrongly attributed to Pouwawha Co instead of Pouawha. This error was corrected in the result tables but not in the figures. The impact of this mistake is insignificant.

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## Appendix 1: Methodology of groundwater Age dating

### *Tritium, CFC and $SF_6$ method*

**Tritium** is produced naturally in the atmosphere by cosmic rays, but large amounts were also released into the atmosphere in the early 1960s during nuclear bomb tests, giving rain and surface water high tritium concentration at this time (Figure 27). Surface water becomes separated from the atmospheric tritium source when it infiltrates into the ground, and the tritium concentration in the groundwater then decreases over time due to radioactive decay. The tritium concentration in the groundwater is therefore a function of the time the water has been underground. Additionally, detection of superimposed bomb tritium can identify water recharged between 1960 and 1975. Groundwater dating using tritium is described in more detail in Cook & Herczeg (1999) and Stewart & Morgenstern (2001).

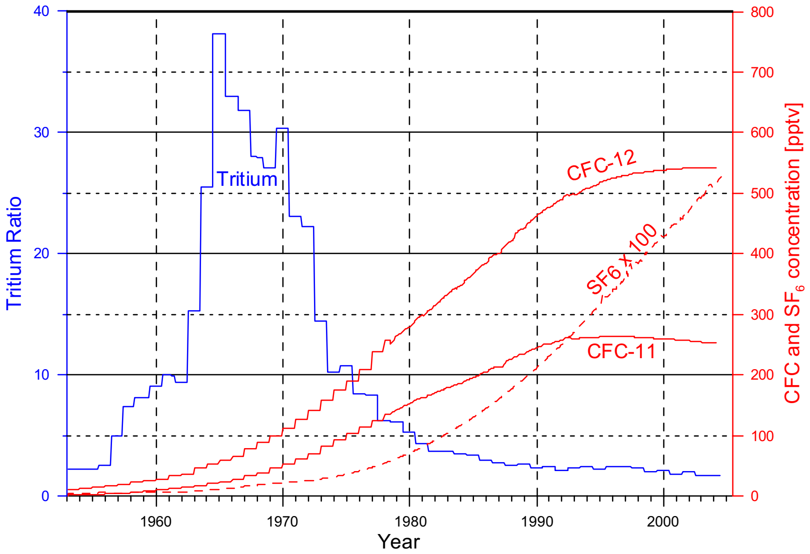

Figure 27: Tritium, CFC and $SF_6$ input for New Zealand rain. Tritium concentrations are in rain at Kaitoke, 40km north of Wellington (yearly averages), and CFC and $SF_6$ concentrations are for southern hemispheric air. TR=1 represents a $^3H/^1H$ ratio of $10^{-18}$, and 1 pptv is one part per trillion by volume of CFC or $SF_6$ in air, or $10^{-12}$. Pre-1978 CFC data are reconstructed according to Plummer and Busenberg (1999), and scaled to southern hemisphere by factor 0.83 (CFC-11) and factor 0.9 (CFC-12). Post-1978 CFC data are from Tasmania. Pre-1970 $SF_6$ data are reconstructed (USGS Reston), 1970-1995 data are from Maiss and Brenninkmeijer (1998), and post-1995 data was measured in Tasmania.

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

**Chlorofluorocarbons (CFCs)** are entirely man-made contaminants. They were used for refrigeration and pressurising aerosol cans, and their concentrations in the atmosphere have gradually increased (Fig. 27). CFCs are relatively long-lived and slightly soluble in water and therefore enter the groundwater systems with groundwater recharge. Their concentrations in groundwater record the atmospheric concentrations when the water was recharged, allowing determination of the recharge date of the water. CFCs are now being phased out of industrial use because of their destructive effects on the ozone layer. Thus rates of increase of atmospheric CFC concentrations slowed greatly in the 1990s, meaning that CFCs are not as effective for dating water recharged after 1990.

**Sulphur hexafluoride ($SF_6$)** is primarily anthropogenic in origin, but can also occur in some volcanic and igneous fluids. Significant production of $SF_6$ began in the 1960s for use in high-voltage electrical switches, leading to increasing atmospheric concentrations (Fig. 27). The residence time of $SF_6$ in the atmosphere is extremely long (800-3200 years). It holds considerable promise as a dating tool for post-1990s groundwater because, unlike CFCs, atmospheric concentrations of $SF_6$ are expected to continue increasing for some time (Busenberg and Plummer, 1997).

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

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

### *Groundwater mixing models*

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

Schematic groundwater flow situations are shown in Fig. 28. The unconfined aquifer situation is described by the exponential model (EM). Flow lines of different length containing water of different age converge in the well or the stream, and the abstracted water has a wide range of ages with an exponential age distribution. The confined aquifer situation is described by the piston flow model (PM) with a narrow range of ages. The partly confined aquifer situation is described by the exponential-piston flow model (EPM). The free parameter is the fraction of exponential flow within the total flow volume (represented by E%PM, where the fraction is given in %), or the ratio ? of the total flow volume to the volume of the exponential part. The water has a wide range of ages, but because part of the flow is piston flow, the age distribution has a minimum age (no water can be younger than the time necessary to pass through the piston flow part). The piston flow part can be represented by a partly confined flow with no vertical input of young water from the surface, or it can be represented by a significant unsaturated zone with vertical piston flow toward the water table and mixing of different ages below the water table.

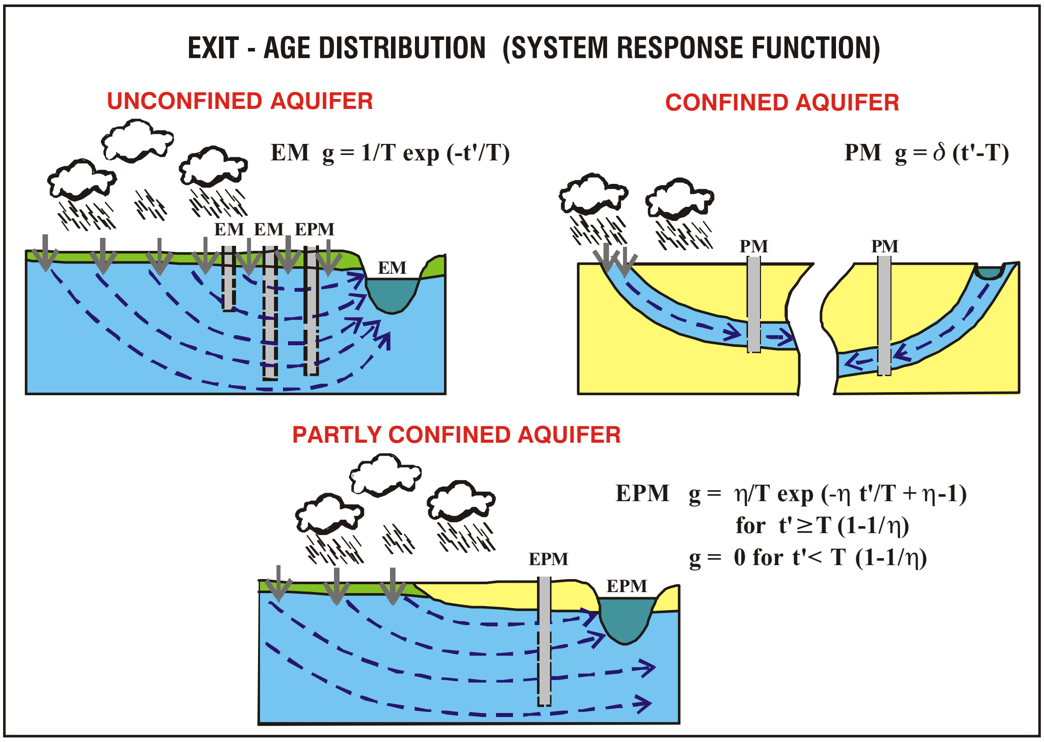

Figure 28: Schematic groundwater flow situations and corresponding age distribution functions (see Maloszewski and Zuber (1982) for theoretical background).

As an example, the age distribution for the exponential-piston flow model for different fractions of mixed flow is shown in Fig. 29 for water with a mean residence time of 50 years. Water with a high fraction of exponential flow of 90% has a wide range of ages, starting at 5 years and still significant contributions of old water with ages over 150 years. Despite the mean residence time of 50 years, the major part of the water is younger than 50 years. The water can therefore partly be contaminated before the mean residence time of 50 years has elapsed. About 2% of the water can already be contaminated after 5 years. With each further year, these young fractions accumulate, and increasingly contaminated water arrives at the spring or well. The total fraction of water within a certain age range can be obtained by integrating the age distribution over the specified age range. This is equal to the area below that part of the curve, with the total area below the whole curve being 100% water fraction. The fraction of water that is younger than a specified age is called the young water fraction (yf). The young water fraction younger than 55 years is about 80% in the example in Fig. 29 (hatched area).

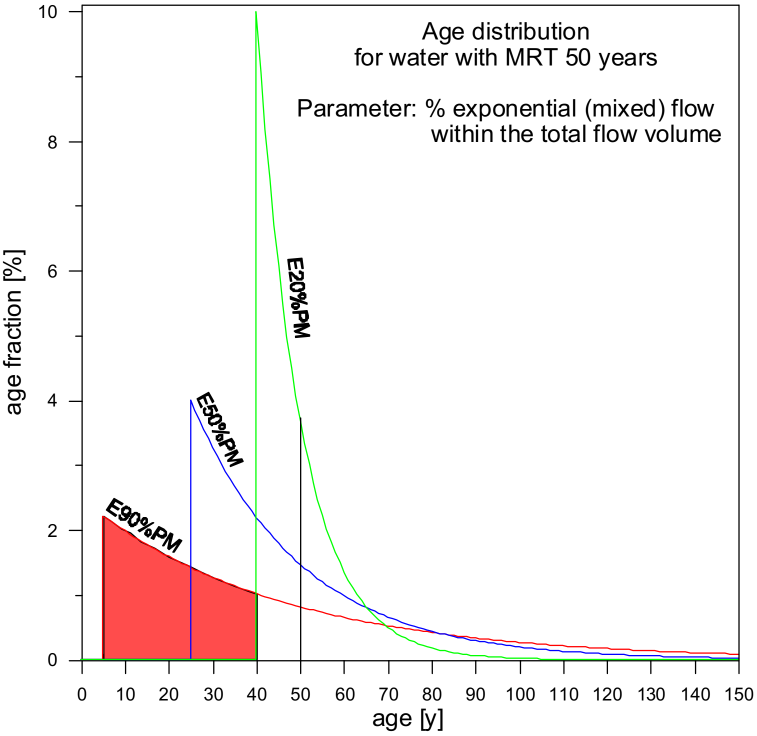

Figure 29: Age distribution for the exponential-piston flow model.

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

# Appendix 2: CFC and SF$_6$ raw data

Table 4a: Raw data of CFC and SF$_6$ results. See appendix 1 for explanation.

| | | | | Measured concentration in solution | | | | | | Calculated Atmospheric Partial Pressure in pptv | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CFC No. | SF6 No. | Sample Details | Sampling Date | fmol/kg SF6 | ± | pmol/kg CFC-11 | ± | pmol/kg CFC-12 | ± | SF6 | ± | CFC-11 | ± | CFC-12 | ± |
| FWA11 | SWA5 | Duffy shallow | 38475 | 1.86 | 0.12 | 3.25 | 0.01 | 2.39 | 0.00 | 6.31 | 0.41 | 202.64 | 2.73 | 562.20 | 6.93 |
| FWA12 | SWA6 | Duffy deep | 38475 | 0.63 | 0.01 | 0.09 | 0.00 | 1.16 | 0.02 | 1.45 | 0.02 | 5.29 | 0.11 | 252.70 | 4.42 |
| FWA13 | SWA7 | Trout Hatchery spring | 38475 | 1.76 | 0.01 | 3.97 | 0.00 | 2.50 | 0.01 | 5.39 | 0.04 | 237.45 | 1.79 | 565.27 | 1.35 |
| FWA14 | SWA8 | Van der Put | 38475 | 1.92 | 0.06 | 4.50 | 0.01 | 2.62 | 0.01 | 5.94 | 0.18 | 271.47 | 0.47 | 595 | 0.20 |
| FWA15 | SWA9 | Tulloch | 38475 | 2.29 | 0.07 | 7.74 | 0.01 | 10.64 | 0.06 | 5.24 | 0.17 | 442 | 2.87 | 2263 | 21.35 |
| FWA16 | SWA10 | Smith's Orchard | 38475 | 2.04 | -- | 3.94 | 0.00 | 2.94 | 0.01 | 5.93 | -- | 258.67 | 2.88 | 716 | 3.92 |
| FWA17 | SWA11 | Papawai Spring | 38475 | 2.18 | -- | 25.76 | 0.01 | 4.34 | 0.01 | 6.37 | -- | 1431 | 5.73 | 917 | 5.27 |
| FWA18 | SWA12 | Waingawa Spring | 38475 | 1.82 | -- | 45.04 | 0.16 | 3.00 | 0.01 | 6.18 | -- | 3121 | 32.99 | 772 | 6.19 |
| FWA19 | SWA13 | Martinborough Golf Club | 38476 | 0.50 | -- | 0.06 | 0.02 | 0.41 | 0.00 | 0.74 | -- | 3.62 | 1.37 | 87.86 | 0.97 |
| FWA20 | SWA14 | Dimmittina | 38476 | 0.20 | -- | 0.16 | 0.00 | 0.83 | 0.01 | 0.31 | -- | 13.59 | 0.02 | 230.85 | 3.73 |
| FWA21 | SWA15 | Te Kairanga | 38476 | 0.00 | -- | 0.02 | 0.00 | 0.14 | 0.00 | 0.00 | -- | 1.34 | 0.26 | 29.17 | 0.92 |
| FWA22 | SWA16 | George | 38476 | 0.66 | -- | 0.01 | 0.01 | 0.00 | 0.01 | 1.24 | -- | 0.42 | 0.59 | 1.39 | 1.97 |
| FWA23 | SWA17 | Bassett | 38476 | 0.00 | -- | 0.03 | 0.00 | 0.00 | 0.00 | 0.00 | -- | 1.49 | 0.05 | 0.21 | 0.30 |
| FWA24 | SWA18 | Martinborough Water Supply | 38476 | 2.13 | -- | 0.02 | 0.00 | 0.72 | 0.01 | 5.02 | -- | 1.21 | 0.02 | 165.17 | 2.51 |
| FWA25 | SWA19 | Sugrue | 38476 | 2.17 | 0.01 | 3.51 | 0.29 | 2.54 | 0.04 | 5.06 | 0.02 | 204.24 | 1.19 | 549.79 | 24.51 |
| FWA26 | SWA20 | Findlayson | 38477 | 0.05 | -- | 0.03 | 0.00 | 0.01 | 0.01 | 0.38 | -- | 2.08 | 0.30 | 4.08 | 1.83 |
| FWA27 | SWA21 | Anne Sinclair | 38477 | 0.06 | -- | 0.00 | 0.00 | 0.01 | 0.00 | 0.08 | -- | 0.22 | 0.11 | 2.62 | 0.02 |
| FWA28 | -- | Burt | 38477 | -- | -- | 2.52 | 0.02 | 3.12 | 0.01 | -- | -- | 136.40 | 0.51 | 645 | 1.27 |
| FWA29 | SWA22 | CDC South | 38484 | 1.21 | -- | 1.78 | 0.00 | 86.66 | 0.85 | 2.71 | -- | 112.04 | 0.07 | 19963 | 134.69 |
| FWA30 | SWA23 | CDC North | 38484 | 1.65 | -- | 18.00 | -- | 28.54 | -- | 3.86 | -- | 1051 | -- | 6204 | -- |
| FWA31 | SWA24 | Wither | 38484 | 0.00 | -- | 0.02 | -- | 0.02 | -- | 0.00 | -- | 7.52 | -- | 24.56 | -- |

Table 4b: Raw data of CFC and SF$_6$ results. See appendix 1 for explanation.

| | Piston Flow Model Recharge Dates | | | Concentration in solution | | | | calculated variables | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| CFC No. | SF6 | CFC-11 | CFC-12 | mL(STP)/kg Ar | ± | N2 | ± | temp °C | ± | excess air mL(STP)/kg | ± |
| FWA11 | Contam. (>5%) | 1985.5 | Modern | 0.339 | 0.001 | 12.56 | 0.03 | 14.9 | 0.3 | -0.8 | 0.2 |
| FWA12 | 1986 | 1957.5 | 1978 | 0.373 | 0.001 | 15.10 | 0.14 | 14.0 | 0.1 | 2.1 | 0.2 |
| FWA13 | 2004.5 | 1989 | Modern | 0.349 | 0.001 | 13.16 | 0.10 | 14.2 | 0.1 | -0.3 | 0.2 |
| FWA14 | Modern | 1994-1997 | Contam. (>5%) | 0.348 | 0.000 | 13.08 | 0.03 | 14.3 | 0.1 | -0.4 | 0.1 |
| FWA15 | 2004.5 | Hi Cont. (>25%) | Hi Cont. (>25%) | 0.377 | 0.000 | 15.11 | 0.05 | 13.3 | 0.1 | 1.9 | 0.1 |
| FWA16 | Modern | 1991.5 / 2001 - 2002 | Hi Cont. (>25%) | 0.344 | 0.001 | 13.38 | 0.02 | 16.0 | 0.2 | 0.6 | 0.0 |
| FWA17 | Contam. (>5%) | Hi Cont. (>25%) | Hi Cont. (>25%) | 0.360 | 0.001 | 13.48 | 0.07 | 12.7 | 0.1 | -0.4 | 0.1 |
| FWA18 | Contam. (>5%) | Hi Cont. (>25%) | Hi Cont. (>25%) | 0.329 | 0.000 | 12.48 | 0.03 | 17.1 | 0.2 | -0.2 | 0.1 |
| FWA19 | 1980 | 1956 | 1968 | 0.418 | 0.002 | 19.25 | 0.15 | 15.0 | 0.1 | 7.8 | 0.2 |
| FWA20 | 1973.5 | 1962.5 | 1976.5 | 0.379 | 0.001 | 18.08 | 0.01 | 21.5 | 0.2 | 8.2 | 0.1 |
| FWA21 | <1952.5 | 1953 | 1960 | 0.407 | 0.001 | 17.62 | 0.05 | 13.2 | 0.1 | 5.1 | 0.0 |
| FWA22 | 1984.5 | 1950.5 | 1945.5 | 0.369 | 0.004 | 16.50 | 0.43 | 19.1 | 0.4 | 5.5 | 0.7 |
| FWA23 | <1952.5 | 1953 | 1939.5 | 0.457 | 0.005 | 20.04 | 0.30 | 9.0 | 0.2 | 6.6 | 0.3 |
| FWA24 | 2003 | 1952.5 | 1973.5 | 0.366 | 0.000 | 14.84 | 0.05 | 14.9 | 0.1 | 2.1 | 0.1 |
| FWA25 | 2003 | 1985.5 | Modern | 0.373 | 0.006 | 14.97 | 0.08 | 13.7 | 1.5 | 1.9 | 0.6 |
| FWA26 | 1975 | 1954 | 1949 | 0.277 | 0.002 | 9.29 | 0.17 | 20.7 | 0.1 | -3.3 | 0.2 |
| FWA27 | 1962.5 | 1949 | 1947.5 | 0.441 | 0.001 | 20.76 | 0.01 | 13.8 | 0.3 | 9.3 | 0.1 |
| FWA28 | -- | 1978 | Contam. (>5%) | 0.364 | 0.001 | 13.67 | 0.08 | 12.3 | 0.0 | -0.3 | 0.1 |
| FWA29 | 1993 | 1976 | Hi Cont. (>25%) | 0.369 | 0.003 | 15.23 | 0.23 | 15.3 | 0.0 | 2.7 | 0.3 |
| FWA30 | 1997.5 | Hi Cont. (>25%) | Hi Cont. (>25%) | 0.372 | -- | 14.93 | -- | 13.8 | -- | 1.8 | -- |
| FWA31 | <1952.5 | 1959 | 1958.5 | 0.113 | -- | 2.93 | -- | 60.6 | -- | -5.2 | -- |

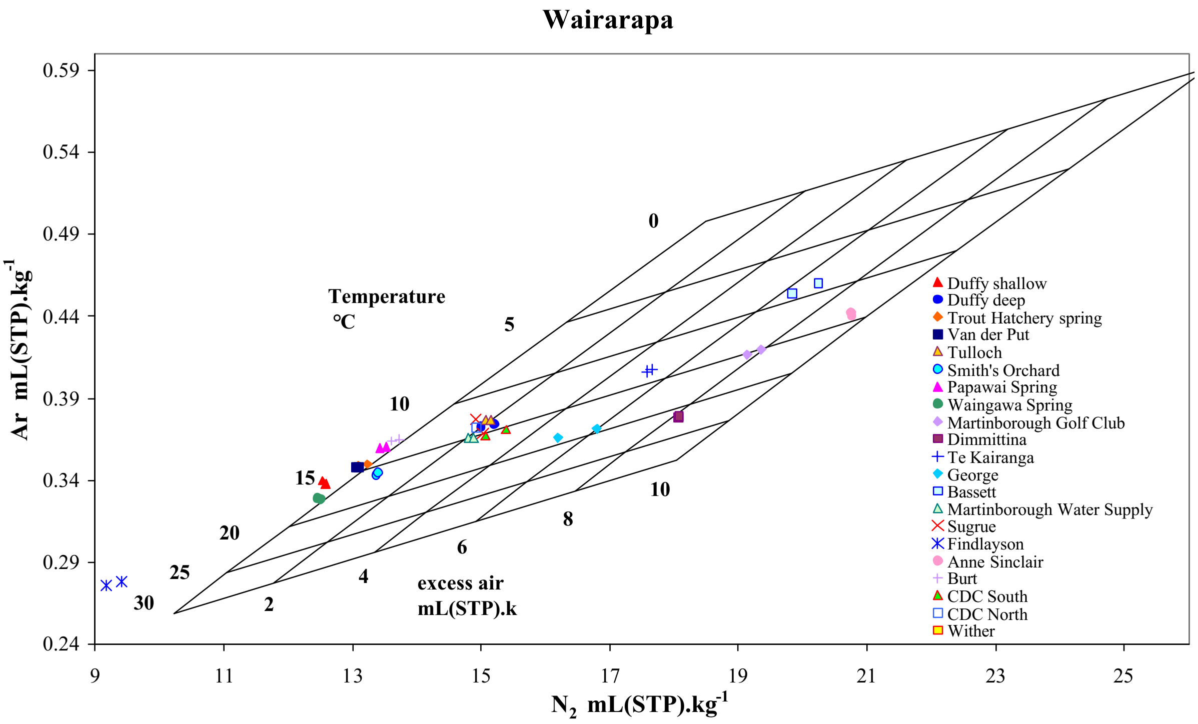

Figure 30: Ar versus $N_2$. Note that values for Wither are outside the axes, and the unusual results for Wither and Findlayson are due to degassing.

## Appendix 3: Stable isotope results

# *Stable Isotope Laboratory*

**Water Isotope Report**

Institute of
GEOLOGICAL
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SCIENCES
Limited

***Client:*** *Tririum and Water Dating Laboratory, GNS Science*
***Attn:*** *Uwe Morgenstern*
***Client Reference:***
***SIL Order No: 3251***

| ***SIL Number*** | ***Sample Name*** | ***$\delta^{18}O$ (‰)*** | ***$\delta^{2}H$ (‰)*** |
|---|---|---|---|
| 40064 | 1330 | -5.49 | |
| 40065 | TW1332 | -5.55 | |
| 40066 | 1338 | -6.19 | |
| 40067 | 1339 | -7.36 | |
| 40068 | 1341 | -6.23 | |
| 40069 | 1342 | -7.31 | |
| 40070 | 1344 | -6.08 | |
| 40071 | 1345 | -6.07 | |
| 40072 | 1346 | -6.30 | |

Total: 9 Samples

All measurements are with respect to VSMOW, and have uncertainties of ±1.0‰ for $\delta^{2}$H and ±0.1 ‰ for $\delta^{18}$O.
Samples will be kept for 3 months from the date of this report and then discarded unless otherwise notified.

Results approved for release by Valerie Claymore. (rafterisotopes@gns.cri.nz) 31/8/2005

## Appendix 4: CFC and $SF_6$ contamination

Several of the water samples have unambiguous old tritium ages, and in most cases the CFC and $SF_6$ concentrations are too high for water of such old age. This indicates a small contamination or possible gas exchange processes in the unconfined aquifers or in the unsaturated zone.

Gas exchange does occur during travel of the water through the unsaturated zone. However, groundwater travel through the unsaturated zone cannot completely explain the large age differences even though unsaturated zone is very thick in some cases. These large age differences may indicate that there is additional gas exchange at semi- or unconfined aquifer conditions after passage through the unsaturated zone between the soil air and the water table. Further indication for this is that the wells with the largest age discrepancy (Duffy shallow/deep, Burt, Dimittina, Martinborough bore1, Sugrue) are all classified as unconfined or questionable confinement.

If gas exchange between the groundwater and soil air occurs, the CFC and $SF_6$ clock is partially reset toward zero, and CFC and $SF_6$ therefore indicate only a minimum mean residence time. This was also found in other areas throughout New Zealand.

Tritium is an ideal conservative tracer for groundwater flow, and for age interpretation highest emphasis was given to the tritium results with unique age solution (which in most cases gave pre-bomb recharge) for the following reasons:

- Several of the tritium age interpretations are based on tritium time series data that show good agreement with the decay- and mixing model,
- The gas results were inconsistent between one another (potential gas exchange),
- CFCs are prone to contamination (which was observed excessively in several cases),
- Tritium is inert to chemical alterations,
- Tritium is also not affected by gas exchange process in the unsaturated zone,
- No tritium contamination has ever been observed in New Zealand because there are no nearby nuclear facilities, and

The unique tritium mean residence times were used, and for the ambiguous tritium results, CFCs and $SF_6$ could be used to resolve the ambiguity despite the differences between the tritium and gas methods.