

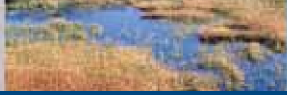

Wairarapa Valley groundwater resource investigation

Middle Valley catchment hydrogeology and modelling

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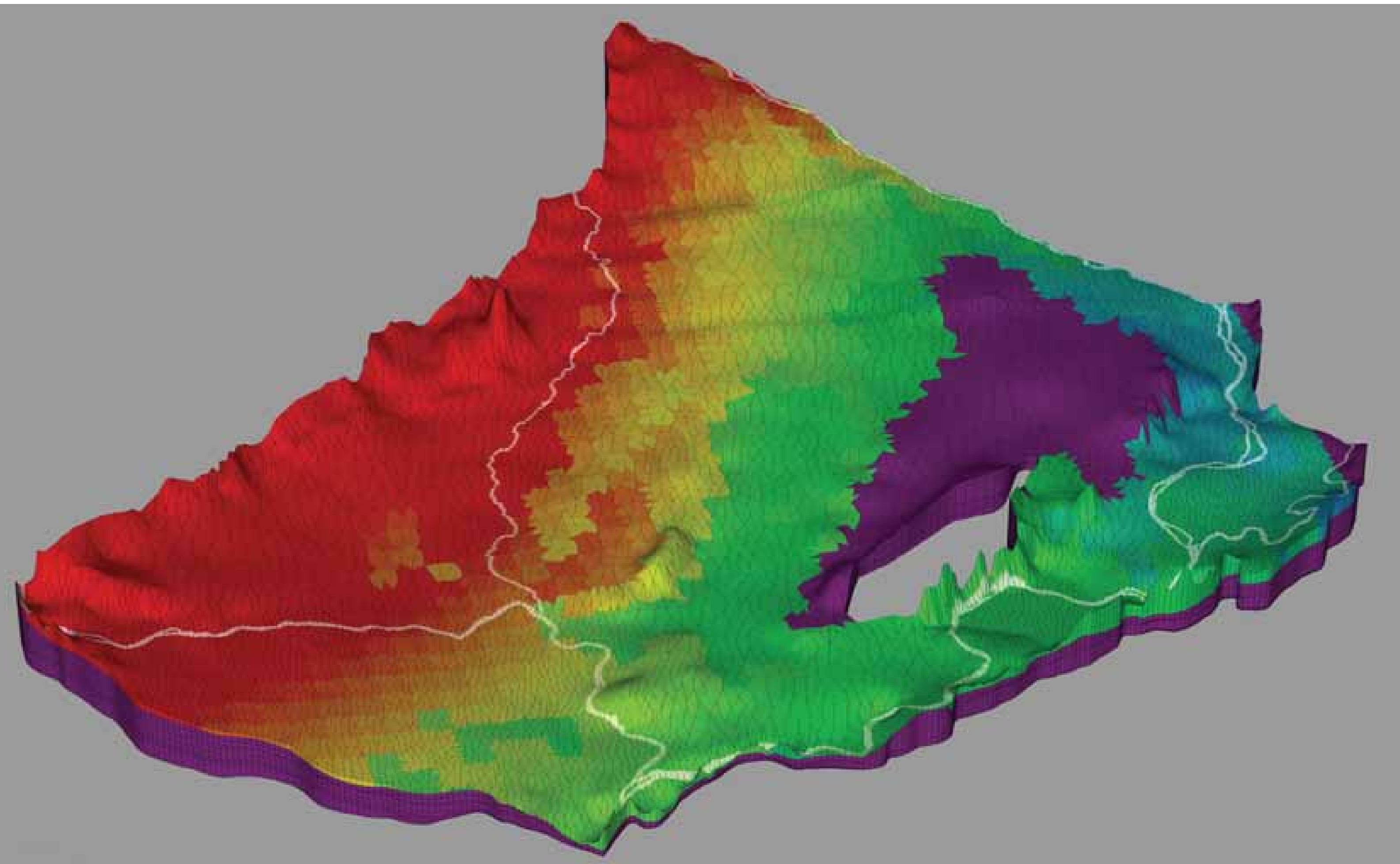

Wairarapa Valley groundwater resource investigation

Middle Valley catchment hydrogeology and modelling

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Executive summary

Greater Wellington Regional Council (Greater Wellington) has undertaken a comprehensive investigation of groundwater in the Wairarapa Valley to re-assess the sustainable yields of aquifers in the valley. Phase 2 of the investigation, reported here, provides a technical analysis of the groundwater environments of the Wairarapa Valley and presents three sub-regional numerical groundwater flow models. These models will be used in the third phase of the investigation to evaluate aquifer sustainable yields and assist in a review of Greater Wellington's existing groundwater allocation policy for the Wairarapa Valley.

This report documents the results and outcomes of the Phase 2 hydrogeological and groundwater modelling investigation for one of three sub-regions of the Wairarapa Valley – the Middle Valley catchment. This 270 km^2 catchment encompasses the plains area between the Waingawa River in the north to the Waiohine plains south of Greytown. The Ruamahanga River and its tributaries – the Waingawa and Waiohine rivers – are the principal surface water systems in the catchment. There are a number of smaller waterways in the catchment such as the Mangatarere Stream and also major spring discharge areas.

The Phase 2 investigation entailed the development of a geological framework followed by a hydrogeological analysis from which conceptual and numerical groundwater models were formulated. A field investigation programme designed to address critical information gaps included drilling of monitoring bores, seismic surveying, river and spring flow gaugings, a water metering study, piezometric surveying and hydrochemical sampling.

Core research themes of the investigation were:

- Geological and structural characterisation of the catchment
- Analysis of temporal and spatial groundwater levels and regional flow patterns
- Rainfall recharge quantification
- Groundwater–surface water interaction characterisation
- Groundwater abstraction analysis and modelling, and
- Hydrochemical investigations and statistical modelling.

Formulation of a three-dimensional geological framework helped to characterise the Middle Valley groundwater environment. A heterogeneous succession of late Quaternary and Holocene unconsolidated sediments comprise the dynamic groundwater environment of the catchment. Variable degrees of sediment sorting, reworking, compaction and deformation by faulting and folding have resulted in a complex aquifer system. Major structures such as the Masterton and Carterton faults have dislocated and folded the sediment sequence and created the Parkvale sub-basin. Five broad hydrostratigraphic units were identified – the most important, in terms of groundwater resource potential, is highly permeable recent (Holocene, Q1 age) alluvium connected to major river systems.

The groundwater head distribution shows that the Middle Valley groundwater environment behaves as a hydraulic continuum with variable degrees of impedance across major structural features (such as the Masterton and Carterton faults) where groundwater is forced to discharge. The groundwater flow pattern reflects a hydrogeological system in which rivers interact closely with adjacent shallow aquifers – groundwater and surface water are indistinguishable in such areas.

Temporal variability in groundwater level and flow dynamics in the groundwater system is attributable to a combination of natural climatic variability and rapidly developing abstraction stresses. Inter-seasonal variability in recharge reflects temporal rainfall patterns driven by the Pacific El Nino Southern Oscillation. Areas such as the Parkvale sub-basin show clear evidence of abstraction-related seasonal declines in groundwater level.

Rainfall recharge, modelled using a soil moisture balance technique on a 500 m^2 grid, was based on detailed spatial climate modelling and soil property mapping. Average annual recharge rates were modelled at 600-700 mm (30-40% of rainfall) in the northern, down to less than 100 mm (<10% of rainfall) on the southern side of the catchment. The average recharge volume over a 15-year period between 1992 and 2007 was 68.2×10^6 m^3/year (190,000 m^3/day).

Fluxes between shallow groundwater and surface water dominate the groundwater balance for the Middle Valley catchment. Natural groundwater discharges occur as river base flow, spring flow and diffuse seepage into wetlands. Some reaches of the main river channels recharge groundwater by losing part, or sometimes all, of their flow into underlying aquifers. Concurrent river gauging surveys show that the three principal river systems – the Ruamahanga, Waiohine and the Waingawa rivers – exhibit complex patterns of flow gain and loss with respect to underlying shallow aquifers.

Groundwater abstractions in the catchment have more than doubled over the past 10 years primarily due to demand for seasonal pasture irrigation. At the time of initial groundwater model development in 2007, there were 126 consented bores with a combined allocation of about 155,000 m^3/day and 28×10^6 m^3/year. Annual meter readings show that water users do not normally exceed 50% of their annual allocation (10-30% being the norm). A metering study showed that resource consent holders tend to abstract between 50-70% of their consented daily rate. Historical groundwater abstraction for the catchment has been modelled using soil moisture deficit in conjunction with available annual meter records to estimate demand periods.

Multivariate statistical analysis of groundwater and surface water data, in conjunction with mean residence time and stable isotope data, supported the conceptual hydrogeological model development. In particular, water chemistry helped with stratigraphic correlation work and the identification of aquifer flow paths.

Conceptually, the Middle Valley groundwater catchment is characterised as a ‘closed’ groundwater basin in which the dominant water balance components are rainfall recharge and fluxes between surface water and groundwater. Rainfall infiltration and river bed leakage are both important for recharge. The most important hydrogeological characteristic of the catchment is the strong interdependence of surface water and groundwater.

Groundwater abstraction constitutes more than about 15% of the catchment water balance during the summer months. A shallow unconfined dynamic aquifer is of particular significance since it is freely connected to the surface water environment (rivers, springs and wetlands).

The conceptual hydrogeological model for the Middle Valley catchment was verified and transformed into a numerical transient flow model using FEFLOW finite element code. The model was qualitatively and quantitatively calibrated to field measurements of groundwater level and fluxes to and from surface water environments. The calibration process followed procedures that minimise non-uniqueness and predictive uncertainty.

Calibration robustness was achieved for the principal aquifers – the shallow unconfined Holocene aquifer of the Waiohine, Ruamahanga, Mangatarere and Waingawa floodplains; and the semi-confined aquifers in the Parkvale sub-basin.

Simulated water balances show that groundwater provides base flow to rivers and springs in the catchment year-round and is critically important during summer when the base flow to rivers and springs dominates the catchment water balance. Simulated spring discharges show a long-term decline probably as a result of increased groundwater abstraction.

Model limitations include the bulking (or averaging) assumption used to represent a very heterogeneous environment, limited surface water gauging data and assumptions made in the recharge model. Despite these limitations the model has been assessed as being a reliable ‘aquifer simulator’. It is suited for use as a dependable predictive tool at a sub-regional scale for the development of policy for sustainable groundwater allocation in the Middle Valley catchment.

Contents

1. Introduction

Groundwater is an integral component of freshwater ecosystems in the Wairarapa Valley. It is intrinsically connected to many river and stream systems and supports numerous groundwater dependent ecosystems such as springs and wetlands. Groundwater is also an important source for public water supply and is relied upon for domestic, stock water, irrigation and industry uses.

Demand for groundwater in the Wairarapa region has increased substantially over the last decade with total allocation more than doubling over this period. A large proportion of the increase in demand for groundwater has resulted from land use intensification and farm conversions to irrigated dairy pasture. Heavy reliance is increasingly being placed on the groundwater resource – as opposed to the surface water resource which is approaching full allocation in many areas.

Nearly half[1] of Wairarapa groundwater management zones, as defined in the Regional Freshwater Plan (Wellington Regional Council 1999), are allocated at more than 60% of their calculated 'safe yields' (Figure 1.1). Heavily allocated zones contain the most productive aquifers in the Wairarapa Valley; however, some exhibit long-term declining water levels even though abstraction volumes are considerably lower than assessed 'safe yields'.

The considerable increase in demand for water and the observed decline in groundwater levels in some areas have raised concern regarding the potential adverse impacts of abstraction on groundwater dependent ecosystems. Greater Wellington Regional Council (Greater Wellington) consequently initiated a comprehensive groundwater investigation to re-assess the sustainable yields of Wairarapa Valley aquifers.

1.1 Wairarapa Valley groundwater resource investigation

The overall purpose of the Wairarapa Valley groundwater resource investigation is to provide a robust technical foundation for the review of groundwater allocation policy for the Wairarapa Valley.

The investigation involves three phases, with this report (being the first of three publications[2]) documenting the outputs of Phase 2. Information used in this phase was current up until the end of 2008. The three phases of the investigation are outlined below.

Phase 1 – Regional conceptual and numerical modelling of the Wairarapa Valley groundwater basin: This preliminary phase of the investigation, reported by Jones and Gyopari (2006), provided a general regional evaluation of the entire Wairarapa Valley and consolidated existing knowledge of Wairarapa hydrogeology. The investigation was based upon existing information sources and resulted in a revised geological model. Phase 1 culminated with the production of a regional conceptual model and 'bulked'

[1] As of June 2008 46% of Wairarapa Groundwater Zones as defined in the RFP were at or above 60% allocation.

[2] See Gyopari and McAlister (2010a and b) for reports on the Upper and Lower valley catchments respectively.

steady state numerical model to test the conceptualisation and to identify any additional information needed. Phase 1 also identified three sub-catchments (Upper, Middle and Lower Valley, Figure 1.2) that essentially set the scene for the comprehensive Phase 2 investigations.

Phase 2 – Detailed sub-regional resource analysis and modelling (this report)**:** The purpose of the Phase 2 investigation was to provide robust technical analysis of the groundwater environments of the Wairarapa Valley leading to the development of transient groundwater flow models for the Upper, Middle and Lower Valley sub-catchments suitable for evaluating the allocation of the Wairarapa's groundwater and surface water resources.

The Upper, Middle and Lower Valley sub-catchments have been freshly researched in terms of their geological characteristics and hydrogeological functioning. Therefore some of the quantitative outputs from the 2006 Phase 1 study (e.g. the sub-regional water balances) have been revised following more comprehensive analysis and numerical modelling. The sub-catchment studies are documented in three separate reports (see also Gyopari and McAlister 2010a, 2010b).

Phase 2 also included a field investigation programme to address critical information gaps identified during Phase 1. In addition, the analysis and quantification of rainfall recharge processes, groundwater abstraction and hydrochemistry have been core themes of Phase 2.

Phase 3 – Groundwater resource sustainability assessment: The third and final phase of the project, undertaken during 2010, will propose a water allocation framework consistent with the conceptual understanding developed for the groundwater systems during Phase 2. The numerical models developed in Phase 2 will be used to investigate aquifer sustainable yields and assist in a review of Greater Wellington's existing water allocation policy for the Wairarapa Valley.

1.2 Report structure

This report documents the results and outcomes of the Phase 2 sub-regional hydrogeological and groundwater modelling investigation for one of the three identified sub-catchments, the Middle Valley. It comprises the following sections:

- Section 2 – Physical setting: Briefly describes the Middle Valley environment and climate.
- Section 3 – Surface water: Describes the surface water systems in the study area that are referred to in subsequent sections of this report.
- Section 4 – Previous work: Summarises previous Wairarapa groundwater investigations, including key historical work.
- Section 5 – Field work: Describes the field data collected as part of this investigation.

- Section 6 – Geology and Hydrostratigraphy: Describes the geology of the Middle Valley catchment with a hydrogeological focus and presents a conceptual geological interpretation of the catchment with the aid of cross sections.

- Section 7 – Hydrogeology: Reviews the hydrogeological functioning of the Middle Valley catchment, flow system characteristics, surface water-groundwater interactions, system fluxes, recharge and aquifer properties.

- Section 8 – Hydrochemistry: Presents groundwater and surface water hydrochemical data and outlines their use in supporting the development of the conceptual hydrogeological model.

- Section 9 – Conceptual hydrogeological model: Consolidates the information presented in previous sections to formulate a hydrogeological framework as a basis for numerical modelling.

- Section 10 – Numerical groundwater model: Documents the development and calibration of a transient numerical groundwater flow model for the Middle Valley catchment using FEFLOW.

- Section 11 – Model calibration: Details the calibration process, automated parameter estimation, calibration evaluation, sensitivity analysis and model limitations.

- Section 12 – Summary and conclusions.

2. Middle Valley environment and climate

2.1 Physical setting and landuse

The Middle Valley catchment (Figure 2.1 covers an area of 270 km^2. It is bounded to the northeast by the Waingawa River and to the northwest by the Tararua Range. The south-eastern boundary of the catchment is at the foot of the eastern hill country. The south-western boundary runs through the Waiohine alluvial fan at the base of the Tararua Range to the Ruamahanga River near Papawai. The towns of Greytown and Carterton lie within the area.

The catchment is generally of low relief (Figure 2.2. and photo below) sloping gently in a south-easterly direction. Tiffen Hill to the south east of Carterton represents the one area of higher relief in the catchment.

The Ruamahanga River and its tributaries – the Waingawa and Waiohine rivers – are the principal surface water systems. The Mangatarere Stream is a smaller tributary of the Waiohine River. Numerous smaller streams and spring systems occur on the fans and alluvial plains. Important spring discharge areas occur on the Greytown-Waiohine plains, in the Parkvale basin, and along major fault lines further to the north.

Agriculture is the dominant land use in the catchment. Dairy farming is the dominant agricultural activity (40% of the catchment area), followed by sheep (19%), beef (17%) and sheep and beef (5%) farming. Arable cropping and urban land use make up 5% and 3% of the catchment area respectively (Figure 2.3).

Looking nothwest from Tiffen Hill across the Parkvale basin towards Carterton and the Tararua Range in the distance

2.2 Soils

The distribution of soil groups in the Middle Valley catchment is shown in Figure 2.4. There are five principal soils groups in the catchment – Brown Soils, Recent Poorly Drained Soils, Recent Well Drained Soils, Gley Soils and Pallic Soils.

Brown Soils dominate the older alluvial fan surfaces over the northern part of the catchment to the west of Fernhill. These are mainly yellow-brown shallow silt loams on a gravel substrate which are well, to excessively, drained.

Recent Well Drained Soils occur on the recent alluvial floodplains of the Waipoua and Ruamahanga rivers, and also the Mangatarere Stream. Extensive areas of this soil group also occur around Greytown. This soil group comprises stony sands that are well, to excessively, drained.

Recent Poorly Drained Soils are silt loams that occur on river floodplains where they represent overbank deposits. They occur extensively along the Ruamahanga River valley and are also present on the Waiohine floodplain and around the lower reaches of the Mangatarere Stream.

Gley Soils are organic rich, poorly drained and very poorly drained soils generally occurring where the water table is high. In their undrained state oxygen is limited and reducing conditions occur. These soils are widespread on the Parkvale plain and to the south of Carterton – areas which, before widespread drainage, were formerly swampy.

Pallic Soils occur only on the Fernhill area and attest the older, geologically distinct nature of this area. They are well, to excessively, drained yellow grey earths and are characteristic of seasonally dry areas.

2.3 Climate

2.3.1 General climatic conditions in the Wairarapa Valley

Sheltered by the Tararua Range, the Wairarapa plains experience a dry, warm climate. Typical maximum summer daytime temperatures range between 20 and 28°C and sometimes rise above 30°C. High summer temperatures may be accompanied by strong dry 'foehn' winds from the northwest. Winters are generally mild in the north of the region and cooler in the south where frosts are common. Typical maximum winter temperatures range from 10 to 15°C.

The range shelters the plains from the predominant westerly winds resulting in warm temperatures and a very steep rainfall gradient from west to east as shown by the annual average rainfall map in Figure 2.5. Highest annual rainfall of 1,600-1,700 mm occurs close to the range, reducing to 800-900 mm on the eastern side of the valley. However, in southerly and easterly airflow conditions, rainfall can be significant across the entire Wairarapa Valley as moist air masses travelling towards the Tararua Range are forced to rise. Rainfall on the plains can be particularly heavy and persistent (e.g., lasting 2-3 days) if associated with slow moving easterly frontal systems (Thompson 1982).

2.3.2 Climate variations and trends

Variations in climate occur from year to year and also over longer periods of decades, centuries or millennia. The El Niño Southern Oscillation (ENSO) is the primary driver of natural climate variability that affects New Zealand's precipitation on a two to seven year timescale (Salinger et al. 2004). El Niño is defined by sustained differences in Pacific Ocean surface temperatures when compared with the average value. The accepted definition is a warming or cooling of at least 0.5°C averaged over the east-central tropical Pacific Ocean. When this happens for five months or longer, it is called an El Niño or La Niña episode. Typically, the episodes occur at irregular intervals of 2–7 years and may last from nine months to two years.

El Nino (the ENSO warm phase) is associated with more frequent west or southwest airflows over New Zealand. This leads to cooler conditions than normal, more rain in western areas, and can cause drought in eastern areas such as the Wairarapa. Conversely, La Nina (the ENSO cool phase) conditions lead to more frequent northeast winds. This can cause drought on the Wairarapa plains due to the sheltering effect of the eastern hill country.

Although both La Nina and El Nino can cause low seasonal rainfall in the Wairarapa, overall El Niño has a greater influence due to the enhancement of westerly conditions. In general, in the Wairarapa an El Niño episode increases the chance of low *summer* rainfall; conversely, if a La Nina episode occurs, the chance of low *autumn* rainfall increases (Harkness 2000). Some of the most severe droughts of the last few decades in the Wairarapa (e.g. 2002/03, 1997/98, 1977/78) occurred during El Nino episodes, although there have also been notable droughts during La Nina (e.g. 2007/08, 2000/01).

The 'Interdecadal Pacific Oscillation' (IPO) is an oscillation in the ocean-atmosphere system that affects decadal climate variability by modulating the frequency of El Nino and La Nina. Three phases of the IPO were identified during the 20th century:

- A positive phase from 1922-1944 during which time there were more frequent southwest airflows over New Zealand and a long-lived El Niño episode (1939-42);
- A negative phase from 1947-1977 during which time there was an increase in airflow from the east and northeast and prominent La Niña events in the 1970s; and
- A positive phase from 1978 to about 1998 which again saw an increased occurrence of west to southwest flows over New Zealand and more frequent and intense El Niño events compared to in the previous phase (Mullan et al. 2001).

The period since 1998 appears to have been variable, with no clear pattern yet evolving, although there is a tendency toward a negative phase.

To determine long-term climatic trends in the Wairapapa Valley, rainfall records from several sites distributed across the valley were obtained from NIWA's National Climate Database and Greater Wellington's hydrological database. Figure 2.6 shows the locations of the rain gauges. Unfortunately, there are no long-term daily rainfall records for the Tararua Range or the foothills along the western side of the Wairarapa Valley. The longest rainfall record for the range is from Greater Wellington's Angle Knob site (starting in 1974), although the first eight years of that data are storage gauge readings (approximately six weekly totals). The site at Waiorongomai gives an indication of long-term trends on the western side of the valley, although data are only available until the end of 2007.

Table 2.1 lists the record lengths and mean annual rainfall for six long-term sites in or near the Wairarapa Valley (Figure 2.6).

Table 2.1: Mean annual rainfall statistics for long-term monitoring sites in or near the Wairarapa. Note annual rainfalls were computed for a July to June year.

Site	Records begin	Mean annual rainfall (entire record) (mm)
Putara	1974	3,357
Angle Knob	1975	6,934
Bagshot	1924	1,076
Bannockburn	1937	923
Mahaki	1958	764
Waiorongomai*	1929	1,575

*Does not include data for 2008.

Figure 2.7 shows cumulative deviation from the mean monthly rainfall (cusum) plots for the Bagshot, Bannockburn and Mahaki rainfall sites. The cusum plots are most useful for the detection of trends, changes in gradient (not magnitude) and inflection points being significant. The cusum plot is continuously built by summing the deviation from the record mean. In this way, positive and negative deviations will tend to cancel each other out and the plot will run horizontally when the system is stable (monthly rainfall is close to the long-term mean). If the monthly rainfall average begins to change, the plot will move increasingly upwards or downwards. The differences between the sites either relates to the different record lengths, or real differences in climate trend specific to the gauge location. The cusum plot for the Mahaki gauge (near Martinborough) is significantly different to the other two sites and this may in fact relate to the shorter monitoring record for this site.

Figure 2.7 shows six prominent inflection points over the past 40 years in 1974, 1982, 1992, 1997, 2003 and 2007. These trends are important when interpreting long-term groundwater level hydrographs (Section 7.2).

3. Surface water environment

Groundwater in the Wairarapa interacts dynamically with surface water. Surface water and groundwater resources therefore can not be analysed or managed independently of one another. This section provides a characterisation of the surface water environment in the Middle Valley catchment incorporating the main rivers, springs, wetlands and water race systems.

3.1 Rivers

3.1.1 Channel systems and flow characteristics

The Middle Valley catchment contains the Waingawa and Waiohine rivers – both are tributaries of the Ruamahanga River which flows along the south-eastern edge of the catchment (Figure 3.1). Longitudinal bed profiles of the main rivers and streams in the study area are shown in Figure 3.2 (derived from the MIKE 11 surface water model, see Section 10.5.3).

(a) Waingawa River

The Waingawa River forms the northern boundary of the Middle Valley catchment. It rises in the Tararua Range between Mt Arete and Mt Girdlestone and is approximately 36 km in length. The catchment has a total area of 146 km^2, of which 119 km^2 is in the Tararua Range. In the foothills, the river is joined by a major tributary – the Atiwhakatu Stream – it then crosses the Wairarapa plains in an easterly direction for 16 km to its confluence with the Ruamahanga River. The mean flow of the Waingawa River (measured at Kaituna in the foothills before the river emerges onto the plains) is 10.2 m^3/s (see Table 3.1, Section 3.1.1).

The Waingawa River is a steep gravel-carrying river. Immediately downstream of the Atiwhakatu Stream confluence the river has a single channel form but with distance downstream the river channel widens into a highly mobile semi-braided form.

Waingawa River in November 2006

A number of faults cut across the river on the plains, and recent fault movements have displaced the river channel engendering a progressive migration of the channel towards one side. Complete changes in river course have also taken place where the faults cross (Williams 1988). It is evident from the LIDAR image in Figure 3.3 (see also Figure 3.5) that the Waingawa River once followed a different path through the Masterton area and probably merged with the Waipoua River.

(b) Waiohine River

The Waiohine River has a catchment area of 378 km^2 and originates at the drainage divide of the Tararua Range south of Mt Arete. The upper 24 km or so of the river traverse a mountainous catchment after which the river emerges onto the Wairarapa plains at the Waiohine Gorge. From here, it flows a further 20 km in an easterly direction to the Ruamahanga River confluence about 5 km east of Greytown. Approximately 6 km upstream of the confluence, the Mangatarere stream joins the Waiohine River.

On leaving the Tararua Range at the gorge, the Waiohine River has a single thread channel form with alternating gravel beaches exposed during low flows, confined by high river terraces. The river gradually widens to a semi-braided form. Downstream of the rail bridge, the river terraces are lower or absent allowing the river to widen considerably during high flows. However, downstream of State Highway 2, the river returns to a narrow single thread form with pronounced gravel beaches. The unusual and sudden change in the channel form, from semi-braided to a narrow single-thread, is probably due to a combination of:

- Reduced gravel supply and gravel extraction in the vicinity of the SH 2 bridge;
- A significant reduction in channel gradient; and
- Inflow from the Mangatarere Stream which has a low gravel load (Heslop 1996).

The Waiohine River tends toward a single channel form more than the Waingawa River. The difference between the rivers is due to a relatively smaller sized bed material in the Waiohine River as a result of an overall lesser grade.

The Waiohine River's main tributary, Mangatarere Stream, is a small single-channel, gravel-bed river (see photo, next page). It drains a catchment of 90 km^2, of which 56 km^2 lies in the foothills of the Tararua Range.

Mangatarere Stream at Belvedere Road during summer low flow. This is the gaining section of stream below Anderson Line. When this photo was taken in 2008 the stream was dry upstream at Andersons Line. Note the wide active stream bed indicating high flows at certain times of the year

(c) Ruamahanga River

The Ruamahanga River is the principal drainage system of the Wairarapa Valley. The river originates in the north eastern Tararua Range near Mt Dundas (1,500 metres above mean sea level) and flows south through the Wairarapa Valley to Lake Onoke (which discharges directly into the sea). The river is about 162 km long with a catchment area of approximately 3,430 km^2. It has three major tributaries rising in the Tararua Range: the Waipoua, Waingawa and Waiohine rivers.

The Ruamahanga River emerges onto the Wairarapa plains at Mt Bruce, about 21 km north of Masterton. Between the Waingawa River and the Waiohine River confluence, a length of approximately 25 km, the river alternates between semi-braided and single thread form. At the top of this reach there is a large input of coarse sediment from the Waingawa River.

Ruamahanga River near Carters Bush during winter 2008

3.1.2 Hydrology

Rainfall within the Waingawa and Waiohine catchments is strongly influenced by the Tararua Range. Annual rainfall varies from 800 mm on the Wairarapa plains, to about 2,000 mm in the Tararua foothills and up to 8,000 mm in the tops of the Tararua Range. Major floods in the Waingawa and Waiohine rivers tend to be caused by north-westerly rainfall events.

Flow in the Waingawa and Waiohine rivers and the Mangatarere Stream is measured in the foothills, a short distance before each waterway emerges onto the plains (see Figure 3.1 for gauge locations). Flow statistics for the sites are shown in Table 3.1 (including the estimated statistics for the Waingawa River downstream of the confluence with Atiwhakatu Stream). Flow in the Ruamahanga River is measured a short distance upstream of the Waingawa River confluence at the Wardells Bridge gauge.

Table 3.1: Flow statistics for principal rivers in the Middle valley catchment

	Catchment area above flow site (km^2)	Mean flow (m^3/s)	Median flow (m^3/s)	Mean annual low flow (m^3/s)	Maximum recorded flood (m^3/s)
Ruamahanga River at Wardells (upstream of Waingawa River	637	23.8*	12.5*	2.7*	844
Waingawa River at Kaituna	79	10.2	5.1	1.2	426
Waingawa River downstream of Atiwhakatu Stream	129	13.8#	7.0#	1.6#	255#
Waiohine River at Gorge	180	24.5	13.0	3.0	1558
Mangatarere Stream at Gorge	33	1.9	0.84	0.13	122

*Flow statistic likely to be affected by upstream abstraction of water.
#Estimate based on Waingawa River plus historic Atiwhakatu Stream flow data.

There are complex patterns of flow gains and losses along the Waingawa, Waiohine and Ruamahanga rivers and the Mangatarere Stream. These are discussed in Section 7.4.

3.2 Springs and wetlands

Groundwater discharges in the Middle Valley catchment as springs and wetland and as base flow to many small streams and larger rivers. This section describes the location and character of the main springs and wetlands (Figure 3.3). While base flow-dominated streams[3] are not technically springs, they are also described here.

[3] Groundwater discharge as base flow maintains flows in a number of streams in the Middle Valley catchment, particularly in summer low flow conditions.

It has not been possible to map every spring and wetland system across the Middle Valley catchment. Instead, documented studies in combination with field reconnaissance studies were relied upon to define and characterise principal groundwater discharge areas. Characterisation of the flows in each spring system has relied upon qualitative visual estimates in combination with historical spot gaugings.

There is considerable interaction between "natural" spring-fed streams and the artificial water race systems. This interaction often makes it difficult to accurately quantify natural flows from groundwater discharge.

3.2.1 Greytown springs (Papawai, Tilsons, Muhunoa)

Substantial quantities of groundwater discharge into the roughly parallel Papawai, Tilsons and Muhunoa streams from the shallow alluvial aquifers on the Greytown-Waiohine plain (Figure 3.3). The combined mean outflow from this spring system is estimated to be in the order of 1.5 m^3/s (1,500 L/s). The springs flow to the southeast and discharge either into the Waiohine River (Muhunoa Stream) or Ruamahanga River (Papawai Stream and Tilsons Creek). The flow characteristics of the Papawai Stream and Tilsons Creek are provided by a recent instream flow assessment for the Papawai Stream (Keenan 2009).

The southern-most Papawai Stream rises from springs immediately southeast of Greytown. Two main spring channels converge near Fabians Road to form the main channel of the Papawai Stream which flows for about another 5 km to the Ruamahanga River at an estimated mean annual flow of 230 L/s (Table 3.2). Tilsons Creek joins Papawai Stream at the Greytown oxidation ponds a short distance upstream of its confluence with the Ruamahanga River. Most of the spring discharge occurs from the first 1 km or so of the channel (Butcher 2007a). Summer flow rates are strongly affected by a direct surface water take for border dyke irrigation and by adjacent, shallow, irrigation bores. The stream is also fed by minor inputs from the Moroa Water Race but it appears that this inflow is negligible during summer periods.

Flow has been continuously monitored in the Papawai Stream upstream of the Tilsons Creek confluence since 2005 (Figure 3.4).

Table 3.2: Estimated spring flows – Middle Valley catchment (from Butcher 2007a and Keenan 2009)

	Mean annual flow (L/s)	Mean annual low flow (L/s)
Papawai Stream	380	200**
Tilsons Creek	235	140
Muhunoa Stream	800	550
Masterton Fault*	120	30
Carterton Fault*	110	230
Parkvale Springs*	70	150
Beef Creek	1,900	60

* Approximations based upon very limited data

** From Keenan (2009)

Tilsons Creek originates in the vicinity of Jellicoe Street in Greytown (see photo) and gains flow over the first 1.5 km of its course before joining the Papawai Stream near the oxidation ponds. Flow in the stream is affected by siltation. Dredging/weed clearance can increase flow by up to 50% (Butcher 2007a). A major off-take for stock watering of about 40 L/s occurs via the Kaikokirikiri Drain. Flow has been monitored in the creek at Scotts Culvert since 2005 (Figure 3.4). Historic monitoring data indicate that the mean annual flow is approximately 300 L/s (Table 3.2).

Tilsons Creek spring emerging at Jelicoe Street on the eastern side of Greytown

The largest spring-fed stream on the Waiohine plain is the Muhunoa Stream which originates near the end of Ahikouka Road in Greytown and flows into the Waiohine River. It gains flow over its upper 2.5 km section and has two major tributary channels (probably groundwater-fed) joining it about 700 m upstream of the Waiohine confluence. Historically, the Muhunoa Stream has not been used for irrigation and there is little information regarding its hydrology besides sporadic flow gaugings. Butcher (2007a) has estimated a mean annual flow in the order of 800 L/s.

3.2.2 Masterton and Carterton fault springs

Figure 3.3 shows the locations of the principal spring discharges associated with the Masterton and Carterton faults. The fault structures create topographic breaks[4] and appear to impede the flow of groundwater in some areas resulting in the emergence of springs along the fault traces. There is very limited information regarding the flow rates from these springs but estimates have been made by Butcher (2007b) using historic spot gauging data and visual flow estimates.

[4] Generally the land is several meters lower on the southern side of both faults causing topographic lows.

Three main springs occur along the Masterton Fault line – the Waingawa Spring and wetland, Parkers Stream and Wiltons Drain (Figure 3.3). Diffuse spring discharges also appear to occur along the length of the fault trace. The Waingawa Wetland (swamp) receives flow from both the Waingawa Spring and from Taratahi Water Race. The estimated mean spring discharge along the Masterton Fault is 120 L/s which reduces significantly during dry summer periods to about 30 L/s. However, the flows may be higher due to the diffuse nature of the discharge and losses to evapotranspiration.

Considerably more groundwater discharges along the Carterton Fault from a number of major springs are shown in Figure 3.3. The springs are interlinked with the Taratahi Water Race system making it difficult to quantify the groundwater discharge component. Butcher (2007b) has provided an initial assessment of mean spring flow from the Carterton Fault of about 230 L/s.

3.2.3 Parkvale springs

Groundwater discharge in the Parkvale area occurs along drainage systems rather than as discrete springs. These spring-fed streams, shown on Figure 3.3, merge with the Taratahi Water Race system making it difficult to quantify spring flow. A limited number of flow gaugings on various drainage systems have been used to estimate spring flows in Parkvale (Butcher 2007b). The mean flow for the entire Parkvale spring system has been estimated to be about 150 L/s. Flow has been continuously monitored at the outflow of the Parkvale Stream system since January 2002 but represents a combination of spring discharge and flow in the Taratahi Water Race.

Tributary of Parkvale springs emerging from Lowes/Allens Bush on the Carterton Fault

Outflow from Parkvale Stream at Greater Wellington's stream gauge

3.2.4 Beef Creek, Enaki and Kaipaitangata diffuse springs

Widespread, diffuse spring discharges occur towards the base of Waiohine-Mangatarere fan system west of Carterton (Figure 3.3). The principal base flow-dominated streams here are the lower reaches of Beef Creek and the Enaki and Kaipaitangata streams. The lower reaches of these streams, prior to discharging into the Mangatarere Stream, appear to be the main discharge zones.

Flow in Beef Creek at SH 2 was measured at 60 L/s and 1,880 L/s for March and August 2008 respectively. Another spot gauging on Beef Creek at SH 2 in Feburary 2005 provided a flow of 97 L/s. During winter, the creek gains by over 1,000 L/s between Jervois Road and Watersons Line.

3.2.5 Wetlands

Two types of wetland occur within the Middle Valley catchment – those associated with spring discharge zones along faults and riparian wetlands which are associated with the main river channel systems.

Figure 3.3 shows the locations of the principal wetland systems. Riparian wetlands include Carters Bush and Taumata Lagoon near the confluence of the Waiohine and Ruamahanga rivers. Spring-fed wetlands include the Waingawa Swamp (see photo on next page) on the Masterton Fault, and Lowes/Allens Bush (see photo on previous page) on the Carterton Fault. Linear wetland systems occur along the lengths of both faults.

The Masterton fault visible as a break of slope in the foreground with Waingawa Swamp (wetland) and spring forming on the downgradient (south) side of the fault

3.3 Water races

The Wairarapa Valley has an extensive network of gravity-fed water races that divert water from the main rivers into a system of unlined channels. The water is used principally for stock water supply and limited irrigation[5]. Water races were constructed in the first half of the 20th century by the local authority (now the Masterton and Carterton district councils) and are still administered by them under consent from Greater Wellington. The races distribute water across catchment boundaries and probably contribute to some groundwater recharge in more permeable fan areas. The races also receive spring discharges in low-lying areas.

Figure 3.5 shows the water race network for the Middle Valley catchment. The complex network of race channels often link in with existing natural waterways, agricultural drainage systems, springs and wetlands.

Water race systems and major residential water supply represent some of the largest diversions from river systems within the Middle Valley catchment. The amount of water diverted to water races is discussed further in this report as they significantly influence the flow in rivers during times of low flow. This is important to the accurate simulation of flows in rivers and their interaction with groundwater systems.

The three water race systems in the Middle Valley catchment are described in turn below.

[5] Some areas in the Wairarapa Valley use weirs to increase water race water levels during summer to passively irrigate adjoining land. Weirs are often removed during winter to reduce water levels and help drain land. Some pumping from water races for irrigation may also occur.

3.3.1 Taratahi Water Race

The Taratahi Water Race diverts water from the Waingawa River downstream from the confluence of the Atiwhakatu River[6] at a consented rate of up to 482 L/s. The race system extends southwards through the Taratahi area combining with spring flows from the Masterton and Carterton faults. The race then flows southward as a network of channels through the Parkvale area and merging with the Parkvale spring system before eventually discharging to the Ruamahanga River. Greater Wellington Environmental Regulation staff conducted a survey of the Taratahi Water Race system in 2008 to quantify the amount of water race versus natural water course in the network (Ewington and Thawley 2009). The study classified the water races and natural water courses on the Taratahi plains into four categories (Figure 3.5):

- Category 1: water race sourced soley from the Waingawa River with no interaction with natural water courses.
- Category 2: water races with minor input from natural water courses (either surface run-off or spring discharge).
- Category 3: natural water courses with minor input from water races – natural water courses containing a reasonble quantity of water from the water race system.
- Category 4: natural water courses but may receive oveflow water from the end-points of the water race network.

3.3.2 Carrington Water Race

The Carrington Water Race is fed from the Mangatarere Stream outside the Middle Valley study area boundary and is consented to take up to 113 L/s. It comprises a channel network extending southwards through the alluvial fan area west of the Mangatarere Stream (see Figure 3.5). The race system discharges water back to the Mangatarere Stream between Andersons Line and Brooklyn Road, particularly during wetter periods (the channels will also receive surface water runoff). The volumes of this discharge have not been quantified.

3.3.3 Moroa Water Race

Water is diverted into the Moroa water race from the Waiohine River upstream of the Railway Bridge at a consented rate of up to 450 L/s. The majority of the water in the Moroa Water Race flows into the Tauherenikau catchment in the adjacent Lower Valley catchment. Part of this water race also flows into the Greytown springs (Figure 3.5).

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6 Upstream of the Middle Valley catchment study area.

4. Previous work

4.1 Wairarapa Catchment Board 1980s study

Following a review and documentation of available scientific information (Scientific Advisory Group 1980) the Wairarapa Catchment Board in 1980 resolved that comprehensive investigations were required to determine the extent and availability of the Wairarapa groundwater resource.

An eight-year investigation programme ensued which included exploratory drilling, geophysical surveying, chemical and isotopic analysis of groundwater, water level monitoring and aquifer testing. Only a summary of the investigations was ever published (Wairarapa Catchment Board 1989).

The summary report confirmed that there was a considerable groundwater resource in the Wairarapa of comparable magnitude to the annual discharge of the Ruamahanga River at Wardells Bridge. Average annual recharge was estimated to be 5.4 x 10^8 m^3/year. The report concluded that the ability of the aquifers to hold and yield water varies from area to area and with depth, as does water quality.

4.2 Groundwater management zones

The Wairarapa Catchment Board (1989) identified a number of spatial zones to facilitate the management of groundwater resources in the Wairarapa Valley. These have formed the basis of management policy in the Wairarapa and were adopted in Greater Wellington's current Regional Freshwater Plan (WRC 1999). Figure 4.1 shows the groundwater zones within the Middle Valley catchment – these are listed in Table 4.1 along with their individual previously defined safe yield estimates and current status of water allocation.

The groundwater zones are convenient management subdivisions based upon local geological and hydrogeological criteria but they often do not have physically definable (i.e. hard) boundaries. The zones have been defined and characterised over a number of years in the absence of a coherent conceptualisation of the wider groundwater environment. As a result, there has been a lack of consistency in the definition of aquifer zones and insufficient consideration has been given to the hydraulic connection both between zones and with the surface water environment. Since the wider groundwater environment is recognised to be a hydraulic continuum which is closely connected to surface water, the zones should not be managed as separate resource entities as they currently are.

The calculated 'safe yields' for the zones are based upon rainfall recharge and aquifer throughflow estimates but do not take into account (or do so only in a rudimentary way) the interaction between the groundwater environment and surface waters, including groundwater dependent ecosystems.

Table 4.1: Existing groundwater management zones within the Middle Valley catchment, as defined in Greater Wellington's Regional Freshwater Plan (RFP) and associated safe yield planning documents

Groundwater zone	Area (km^2)	Groundwater zone in Middle Valley catchment (%)	RFP safe yield (m^3/year)	Safe yield allocated* (%)	Resource potential
Greytown	18	96	20,000,000	24	High
Ahikouka	12	100	3,300,000	88	High
Parkvale (unconfined)	50	100	3,500,000	24	Low
Parkvale (confined)	50	100	3,300,000	82	Moderate
Hodders	10	100	4,000,000	33	Low–moderate
Carterton	15	100	3,900,000	73	Moderate
Mangatarere	9	87	7,600,000	16	Moderate
Matarawa	39	90	10,000,000	4	Low
East Taratahi	21	100	6,800,000	3	Low
West Taratahi	21	87	5,300,000	12	Low
Fernhill	31	100	4,700,000	16	Poor
Middle Ruamahanga (shallow)	40	95	7,300,000	100	High
Middle Ruamahanga (deep)	40	95	2,200,000	71	High
(Upper Plain)**	35	15	17,000,000	20	Poor
(Riverside)**	19	16	3,900,000	100	High

* Zones listed in brackets only partially lie within the Middle Valley groundwater catchment.
** Percentage safe yield allocated as at 16 February 2009.

The most heavily used zones are Parkvale, Greytown, Carterton and Middle Ruamahanga. General descriptions of the zones are contained in Butcher (1995 and 1996) as part of an assessment to determine the 'safe yields' for each of the zones based upon calculated recharge and through-flow. These reports form the basis for the allocation limits specified in the current Regional Freshwater Plan.

Butcher (2004) also undertook a more detailed hydrogeological study and yield assessment of the Parkvale groundwater zone. This zone is not yet fully allocated yet has declining water levels and as a consequence, Greater Wellington has placed it under an allocation moratorium.

4.3 Conceptual and steady state numerical groundwater model study

Regional conceptual and numerical modelling of the Wairarapa groundwater basin was undertaken in 2005–2006 (Jones and Gyopari 2006) as Phase 1 of Greater Wellington's Wairarapa Valley groundwater resource investigation. This study included a review of the geology of the Wairarapa led by Geological and Nuclear Sciences Limited (GNS) to assist the development of a conceptual hydrogeological model for the Wairarapa Valley (outcomes reported in Begg et al. 2006). The worked focussed on the hydrostratigraphy of the valley and geological structure (such as active faults and folding) which control aquifer depositional processes and groundwater movement. The study demonstrated 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 change.

The study defined the three sub-areas on the basis of groundwater flow patterns – the Upper, Middle and Lower sub-regional catchments (refer Figure 1.2) – for which preliminary sub-regional water balance estimates were presented. This was achieved using a regional, valley-wide steady state numerical model (using MODFLOW).

For the Phase 2 investigation documented in this report, each of the sub-regions was re-evaluated in terms of their geological characteristics and hydrogeological functioning. Therefore, some of the quantitative outputs from the 2006 study (e.g., the sub-regional water balances) were revised in this Phase 2 investigation following more comprehensive analysis and numerical modelling.

5. Field studies

Field investigations were carried out in the Middle Valley catchment to support and fill critical gaps in existing data-sets. The work programme comprised the following activities:

- Stratigraphic drilling and monitoring bore construction
- Water meter surveys of selected groundwater takes
- Groundwater sampling and analysis
- Low flow river concurrent gauging
- Springs surveys
- Piezometric surveys
- Low flow stream gauge establishment
- Wetland level monitoring
- Differential GPS surveying
- Seismic reflection surveying.

5.1 Stratigraphic drilling and monitoring bore construction

A total of eight monitoring bores were constructed at five locations[7] in the Middle Valley catchment (Figure 5.1) between April and July 2008 in key areas where significant information gaps were identified. Six bores were constructed using a rotary percussion drill rig and two deeper double-cased holes were drilled using a cable tool rig. Double casing was used in potentially artesian aquifers[8].

Construction of monitoring bores on the Parkvale plain in mid 2008

Table 5.1 summarises the drilling operation and detailed descriptions of drilling targets and stratigraphic drill logs are presented in Appendix 1. All drilling targets were completed as groundwater level monitoring bores.

[7] At some sites nested or multi bores were constructed – Parkvale, Carterton and Taumata Lagoon.

[8] Parkvale at Renall and Carterton Hilton Road drill holes were outlined as potentially artesian. Shallow drill holes and monitoring bores were initially constructed to outline depths for outer casing to be set.

Table 5.1: Summary of drilling locations and monitoring bores constructed in the Middle Valley catchment over April to July 2008. See Figure 5.1 for a map of drilling locations.

Description	Bore No.	Easting	Northing	Depth Drilled (m)	Screen interval (m)	Casing material
Middle Ruamahanga – Taumata Lagoon 1	S27/0878	2721488	6009637	24.8	22 – 24.8	50 mm ID PVC, 3m pre-slotted screen
Middle Ruamahanga - Taumata Lagoon 2	S27/0881	2721678	6009673	9.3	5.7 – 8.7	50 mm ID PVC, 3m pre-slotted screen
Parkvale at Renall 'Shallow'	S26/1033	2723355	6011589	14.7	6 – 9	50 mm ID PVC, 3m pre-slotted screen
Parkvale at Renall 'Deep'	S26/1032	2723355	6011589	19.0	14.9 – 17.9	200 mm outer steel casing, 150mm inner steel casing, 0.5mm SS screen
Greytown (Papawai) at Bicknell	S27/0883	2720203	6008909	19	11 – 14	50 mm ID PVC, 3m pre-slotted screen
Carterton Hilton Road 'Shallow'	S26/1035	2721205	6015348	12	3.4 – 6.4	50 mm ID PVC, 3m pre-slotted screen
Carterton Hilton Road 'Deep'	S26/1034	2721205	6015348	25	19.3 – 21	200 mm outer steel casing, 150mm inner steel casing, 0.5mm SS screen
Parkvale at McNamara 'Shallow'	S26/1053	2724068	6014202	12	6.5 – 9.5	50 mm ID PVC, 3m pre-slotted screen

5.2 Water meter study

Historical groundwater abstraction data are inadequate for the Middle Valley catchment because the records are restricted to annual quantities abstracted by larger users. To provide information on intra-seasonal abstraction patterns, a weekly meter reading programme involving 21 high-volume bores was implemented during 2006/07. Data loggers were also installed in nine of the 21 bores in the programme (Figure 5.2). A further nine abstraction bores were added to the weekly meter reading programme late in the 2006/07 irrigation season.

During the subsequent 2007/08 irrigation season an expanded meter reading programme was implemented when all consented groundwater abstractions of greater than 10 L/s across the Wairarapa Valley were metered on a fortnightly basis. The meter study incorporated 122 bores, 43 of which were located in the Middle Valley catchment (as shown in Figure 5.2). The 2007/08 meter reading programme provided the first comprehensive data-set of temporal groundwater usage across the entire Wairarapa Valley.

The same 122 water meters were read on a monthly basis during the 2008/09 irrigation season.

5.3 Supplementary hydrochemical sampling

Hydrochemical data support and contribute to the formulation of a regional conceptual model. Although a significant amount of historical hydrochemistry data were available (Figure 5.3), several supplementary sampling programmes were carried out. Historical data-sets include the following:

- Groundwater State of the Environment (GWSoE) quarterly water quality sampling results;
- One-off historical groundwater samples (usually of private bores);
- Limited historical river sampling data for major ions and isotopes;
- Stable isotope data from selected groundwater bores; and
- Tritium, SF6 and CFC data from selected groundwater bores for age determination.

Supplementary hydrochemistry sampling included:

- Stable isotope (oxygen and deuterium) and water age determination (tritium, SF6, CFC & radiocarbon) using selected bores (Table 5.2);
- Major ion analysis at River State of the Environment (RSoE) sites; and
- Stable and major ion testing at selected spring locations (Table 5.2).

Table 5.2: Summary of isotope sampling programme carried out during June 2008

Bore No.	Owner/name	Tritium	Radio carbon	Stable isotopes	CFC/SF6
S26/0568	Denbee, J.M		x	x	
S26/0675	McNamara, J	x	x	x	x
S26/0705	Carterton District Council	x		x	
S26/0824	Carterton District Council	x		x	
	Papawai Spring	x	x	x	

All historical isotope results are reported in Appendix 2.

5.4 River gauging

Concurrent river flow gaugings during low flows were used to characterise the gaining and losing patterns in major river systems in the Middle Valley catchment. Several concurrent gauging surveys were carried out on the Ruamahanga, Waiohine and Waingawa rivers, and on the Mangatarere Stream. Table 5.3 lists the gauging surveys carried out for each of the rivers.

Table 5.3: Concurrent gauging runs carried out in the Middle Valley catchment during 2006–2008

River	Dates for concurrent gauging
Middle Ruamahanga	22/02/2006*, 16/03/2006, 21/02/2007
Waiohine	22/02/2006*, 27/02/2006, 21/02/2007, 22/05/2007*, 23/05/2007*, 30/05/2007
Waingawa	21/02/2006, 22/02/2007, 20/02/2008
Mangatarere	21/02/2007

* Data were not used due to issues on the day of gauging (e.g, fresh midway through run).

5.5 Springs survey

Numerous springs occur in the Middle Valley catchment but limited data existed on their locations and flow characteristics. Subsequently, additional work was conducted to map and gauge the flow characteristics of the following springs:

- Greytown springs – Papawai Stream, Tilsons Creek and Muhunoa Stream (Butcher 2007a)
- Springs associated with the Carterton and Masterton faults (Butcher 2007b)
- Parkvale springs – areas where the Parkvale Stream gains from groundwater discharge in the central Parkvale plain
- Beef Creek – gaining sections of the lower reaches of Beef Creek west of Carterton.

5.6 Piezometric survey

Piezometric surveys (the collection of concurrent water level data from a large number of bores spread across the catchment) provide a time-instant 'snap shot' of regional groundwater head conditions. The surveys contribute to conceptual model development and numerical model calibration.

A whole-valley summer piezometric survey was carried out between 21 March 2007 and 2 April 2007, and a winter survey was carried out between 17 and 26 September 2008 (Figure 5.4). A localised detailed piezometric survey was also carried out for the Greytown area on 23 May 2007 (see inset in Figure 5.4).

5.7 Low flow stream gauge installation

The importance of installing temporary low flow river gauges at critical points on the main rivers and streams was a key recommendation of the Phase 1 investigation. The existing river gauge network was designed for flood management purposes and most gauges are accordingly situated high in the catchment above the plains (often at gorge locations). There is a distinct lack of monitoring sites in the lower reaches of the river systems with which to characterise low-flow conditions.

Ideally, a number of low flow gauging sites should be established but resource constraints allowed only one temporary gauge to be installed in the Waiohine River at SH 2 Road Bridge. This gauge has been operating since mid summer 2007/08 and a rating curve has been developed for it.

5.8 Wetland level monitoring

Wetland monitoring has not historically been undertaken in the Middle Valley catchment. Limited data relating to specific resource consent applications are available but are generally not readily accessible.

The establishment of the following monitoring sites at selected groundwater-fed wetland sites was planned, although only one site at Taumata Lagoon has eventuated to date[9]:

- Allen/Lowes Bush
- Carters Bush / Pikes Lagoon
- Waingawa Swamp
- Taumata Lagoon

The monitoring system at the Taumata Oxbow Lagoon at the confluence of Waoihine and Ruamahanga rivers involves continuous measurement of both shallow groundwater level and lagoon water level (see photo). Shallow groundwater is measured in two bores (Table 5.1; Taumata Lagoons 1 and 2) and a surface water level pressure transducer was also installed there in June 2008.

Taumata Oxbow Lagoon groundwater and surface water level monitoring site installation in autumn 2008

[9] Installation of some wetland level monitoring is covered partially in the hydrological network review (Watts 2006)

5.9 Elevation surveying

Analysis of surface water – groundwater interaction requires accurate stream and river bed elevation data, stream/river stage and groundwater elevation. Although detailed river cross-section data were available for major rivers within the Middle Valley catchment, insufficient data existed for the bed levels of minor streams, springs and wetlands. In addition, data on river stage away from stream gauge locations were lacking.

A survey company (Recon Geo Tech) was commissioned to carry out a differential GPS survey to collect key level information for the Middle Valley Catchment groundwater model. The work involved a spring bed level survey and river water level (summer low flow and winter stable flow) survey (Figure 5.5). Differential GPS surveying was also undertaken to provide accurate elevation data for the new groundwater level monitoring bores.

5.10 Geophysical surveying

A seismic reflection survey was conducted across the Parkvale basin between June and August 2008 to assist in the refinement of the conceptual groundwater model for this structurally complex area. The results of the survey are discussed in Section 6.3.1 and the report is provided in full in Appendix 3.

Geophysics seismic reflection survey on the Parkvale plain in July 2008. A heavy sledge hammer source with digital trigger link was selected as the seismic source. Due to the very favourable near-surface conditions and saturated ground, the hammer source provided excellent energy to over 300 ms two-way travel time.

6. Geology

6.1 Regional geological setting

The Wairarapa Valley groundwater basin occupies a northeast-southwest orientated structural depression 110 km long and up to 15 km wide (Figure 6.1). The basin is bounded by basement greywacke which outcrops on the fringing Tararua Range to the north and west and is also exposed as isolated uplifted blocks, such as Tiffen Hill. The Aorangi Range and hills to the east are formed by Early Pleistocene/late Tertiary marine strata (mudstones) which lie above the greywacke basement.

The north-western edge of the Wairarapa Valley is controlled by the Wairarapa Fault. Numerous other major faults and folds cross-cut the basin and deform younger (Quaternary age) infill fluvial sediments. This deformation – both the broad regional strain and more local deformation associated with faults and folds – strongly influences the hydrogeological environment.

A review of the geology of the Middle Valley catchment was undertaken with assistance from GNS Science. This work built on the previous Phase 1 study geological review work (reported in Begg et al. 2006).

The Wairarapa Valley basin contains an unconsolidated sequence of Quaternary age fluvial sediments. The younger late Quaternary deposits (oxygen isotope stages Q1 to Q8) consist of greywacke-sourced gravels and sands derived from erosion of the Tararua Range and deposited by southeast flowing rivers and alluvial fan systems. These host a relatively shallow 'dynamic' groundwater system which is the focus of the present study. Older sediments (mQa and eQa) also contain limited quantities of groundwater and are exploited by some bores. However, these aquifers tend to be low-yielding and are regarded as a minor resource containing extensive very low permeability aquitard sequences.

Table 6.1 lists the younger stratigraphic succession which is regarded to be of hydrogeological significance above the mQa (middle Quaternary, Q8) surface. The late Quaternary and Holocene sediments are of variable thickness due to tectonic influences and are up to about 100 m thick beneath the Te Ore Ore plain, but generally less than 50 m thick on the higher Waingawa, Waipoua and Ruamahanga fans.

The late Quaternary deposits are dominated by aggradational alluvial and glacial outwash gravels laid down by the major rivers draining the Tararua Range (Ruamahanga, Waingawa and Waipoua rivers). The gravels represent high energy, poorly sorted alluvial fan depositional environments. These are interdigitated with fine-grained overbank, swamp, lacustrine or estuarine deposits.

Table 6.1: Wairarapa Valley – basin fill sequence. The grey shading indicates older sequences with poor groundwater potential.

Relative age	Material	Name	Depositional environment	Map symbol[1]	Absolute age (ka)
Holocene	Mud & silt		Estuarine, lacustrine	Q1m Q1s	0-7
Holocene	Gravel & sand		Alluvial	Q1a	0-10
late Quaternary Late Otiran	Gravel & sand	Waiohine *[Equivalent to Waiwhetu Gravel in L. Hutt Basin]*	Alluvial	Q2a	10-25
late Quaternary middle Otiran	Gravel & sand	Ramsley	Alluvial	Q3a	50-25
late Quaternary Early Otiran	Gravel & sand	Waipoua	Alluvial	Q4a	70-50
late Quaternary Kaihinu Interglacial	Mud, silt, sand & minor gravel	Francis Line	Swamp, lacustrine	Q5m	125-70
late Quaternary Kaihinu Interglacial	Sand, some gravel	Eparaima	Marginal marine	Q5b	125-70
middle Quaternary Waimea Glacial	Gravel & sand	*[Equivalent to Moera Gravel in L. Hutt Basin]*	Alluvial	Q6a – Q8	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.

Alluvial gravels are commonly clast-supported and rich in sand and silt, with frequent sandier or siltier horizons. As such, they generally represent poor aquifers except where they have been reworked. Broad areas of reworked, high-yielding gravels are recognisable in the vicinity of former and modern drainage courses (mostly mapped as Q1 age), and in the distal areas of fans at variable depths.

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 (i.e. delivered by the Whangaehu River) and break down rapidly upon weathering.

The units shown in Table 6.1 were mapped out on the valley floor (Figure 6.1), relying upon stratigraphic principles to help constrain their three-dimensional distributions. The ages of terrace surfaces were 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 a level higher, 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 yet higher elevation which are overlain by a red loess (Rata loess) as well as the Ohakea loess are Porewan in age (Q4a). Weathered gravels at even higher elevations again have a cover of three loesses. 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.

6.2 Middle Valley geology

The sub-regional characterisation of the complex geology of the Middle Valley catchment was undertaken as a basis for understanding and interpreting the hydrogeological functioning of the area.

The depositional environments during the late Quaternary have been strongly influenced by subsidence, uplift and sea level change. The sequence has also been tectonically deformed by uplifting blocks of greywacke basement and older Quaternary and Tertiary sediments as a result of deep-seated faulting and folding.

Faulting and structural deformation are associated with plate margin processes. The area is intensely tectonically active and experiences exceptionally high rates of structural movement including major earthquake events. This has exerted a significant control on surface water drainage patterns and erosional and depositional processes, which in turn has influenced the groundwater environment.

Although it is clearly not feasible to fully characterise the structural and sedimentological complexity of the area, any regional groundwater resource analysis requires geological characterisation to a sufficient level of complexity to be able to adequately describe the principal features controlling groundwater occurrence and flow. This study has aimed to strike a difficult balance between avoiding over-simplification and avoiding unnecessary complexity or local-scale analysis.

6.2.1 Principal faults

The Wairarapa Fault is one of a series of long sub-parallel active faults in the southern North Island. These carry most of the shear associated with plate boundary displacement. The western side of the Wairarapa Valley is controlled by the Wairarapa Fault.

In the Middle Valley, two major cross-valley active faults branch eastwards from the Wairarapa Fault. These are the Masterton and Carterton faults (Figure 6.2). Each fault cuts across the Mangatarere Stream, the Waingawa River and their associated fan systems. The faults are regarded as forming local partial barriers to groundwater flow as a result of tilting and deformation (as shown by the emergence of springs along the fault traces).

The Masterton Fault splays from the Wairarapa Fault near Hoeke Road in the Enaki Stream catchment and can be traced across the Waingawa River and through Masterton. It raises and back-tilts to the northwest Miocene-Pliocene mudstone.

The more southerly Carterton Fault splays from the Wairarapa Fault near Beef Creek and cuts across Waiohine fan gravels behind Carterton. Gravel units to the northeast of this fault are not as clearly back-tilted as those along the Masterton Fault. Nevertheless, the fault trace is associated with a number of springs indicating that movement of the fault has created an impedence to groundwater flow.

6.2.2 Folding, uplift and sub-basin development

The presence of greywacke, last interglacial sediments (Q5, Francis Line Formation), and middle to early last glacial gravel (Q4, Waipoua Gravel and Q3, Ramsley gravel) near Tiffen Hill suggest the presence of anticline structures and/or a fault in this area. Tiffen Hill is an up-faulted block of greywacke bedrock (exposed on the summit) 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 uplifted block.

To the northwest of Tiffen Hill a groundwater sub-basin occupies a synclinal structure, the Taratahi Syncline – or Parkvale sub-basin (Figure 2.2). This syncline contains a sequence of confined aquifers (thin reworked gravels) and is an important local groundwater resource.

The Parkvale sub-basin 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 + Q4a) are exposed on the anticline, which partially separates the groundwater resources of the Parkvale sub-basin from the adjacent Carterton sub-basin (Figure 2.2). Geophysical surveying was carried out across the Parkvale sub-basin to help discern its morphology and the geometry of individual aquifers (Appendix 3). The survey revealed the highly complex structural geology of the sub-basin which is discussed in more detail below.

The Carterton sub-basin represents another down-warped area parallel to the Parkvale sub-basin and separated from it by the Brickworks anticline. To the west of the anticline, the sedimentary sequence and ground surface dips westwards towards Carterton and the Mangatarere Stream. The western side of the Carterton sub-basin is not well-defined and merges with the easterly-prograding alluvial fan deposits.

6.3 Three-dimensional geological model

The development of a three-dimensional conceptual hydrogeological model for the Middle Valley catchment is a crucial component in the analysis of the regional groundwater flow system.

Data from bore logs were used to construct geological cross sections to help develop the three-dimensional model and understand the groundwater environment. Figure 6.2 shows the locations of five cross sections (four orientated northwest to southeast across valley, and one aligned northeast to southwest along the valley) and the locations of bore for which reliable geological bore log data are available.

The cross sections show the interpreted aquifer sequences and the way that they have been affected by the different structures (Figures 6.3-6.7). They also depict the conceptual geology as transferred to the numerical groundwater flow model – a process which has necessarily required a degree of simplification. Some sections also portray higher degrees of interpreted deformation (particularly across faults) than can be practically modelled. Simplifications were made on the basis that available evidence suggests that, despite deformation, the fluvial sequence tends to behave as a hydraulic continuum (i.e. a single leaky aquifer system).

The salient features of the sections are as follows:

6.3.1 'Tiffen' and 'Parkvale' sections

Two of the cross sections – 'Tiffen' (Figure 6.3) and 'Parkvale' (Figure 6.4) – traverse the Carterton and Parkvale sub-basins and were constructed using a large number of bore logs. New seismic data collected during the project were used to assist in the construction of the cross sections (Section 5.10 and Appendix 3).

The dominating feature of both cross sections is the northwards-plunging up-faulted mass of greywacke bedrock which forms Tiffen Hill. This structure constitutes a barrier within the groundwater flow system. To the east of Tiffen Hill the Ruamahanga River has eroded a shallow channel into older Tertiary and early Quaternary sediments. The aquifer depth is probably less than 15 m (Q1 and Q2) on the Tiffen cross section (Figure 6.3), but deepens to 20-30 m on the upgradient Parkvale cross section (Figure 6.4) as a result of the northwards-plunging Tiffen structure.

The Parkvale cross section (Figure 6.4) shows the raised Fernhill terraces on either side of Tiffen Hill which are generally older than Q4 age and contain inliers of Q5 age interglacial silts and clays. Several loess cover layers blanket the older terraces, restricting recharge to underlying formations. It is also apparent that the Fernhill mass has poorer groundwater potential than the Parkvale area due to the absence of clearly defined horizons of reworked gravel.

West of Tiffen Hill, the Parkvale sub-basin occupies a synclinal structure to a depth of about 45 m. Although it is shown on the sections as a simple basin structure, in reality it is expected to have a complex internal structure. The syncline is delimited on its western side by a steep, possibly fault-bounded, anticlinal structure known as the 'Brickworks Anticline'. Last interglacial (Q5m, Francis Line Formation swamp deposits) and last glacial gravels (Q3a + Q4a), are exposed at the surface on the crest of the anticline. Compared with the Tiffen cross section the more northerly Parkvale cross section depicts the Parkvale sub-basin broadening and shallowing, but still mildly deformed over the Brickworks anticlinal structure.

It became apparent during the numerical model calibration process that the eastern side of Parkvale sub-basin is far more complex structurally than is shown in the cross sections. This prompted a seismic reflection survey to be undertaken along the approximate line of the Parkvale section across the sub-basin edge (see photo on page 26). This survey was carried out in July/August 2008 and the results are provided in Appendix 3 together with the survey methodology. Figure 6.8 summarises the interpretaton of Line 1 which was conducted in six parts (segments) across the Parkvale plain (see Figure 6.2 for profile location map). It is apparent that the survey penetrated far deeper than the base of the groundwater system and the arrows on Figure 6.8 indicate the interpreted base of the late Quaternary sequence in relation to the Tiffen cross section (Figure 6.3). The seismic profile indicates a complexly folded and faulted 'basement' at depth – probably within the Tertiary mudstone sequence and greywacke. Particularly apparent is the complex structure on the western edge of Tiffen Hill (Part 6) and also the intensely faulted basement in the central part of the Parkvale sub-basin (Part 3). Overall, the survey confirmed the conceptual interpretation of the younger sequences presented in Figure 6.3 but provides very little useful detail on the morphology of individiual aquifers within the top 50 m or so of the seismic profile.

Layers of reworked gravels occupy the Parkvale sub-basin below a persistent Q5 clay/silt aquitard. Two layers of reworked gravels with sands are identifiable beneath the aquitard. The uppermost one is likely to be of Q6 age (20-30 m deep), and the lower one of Q8 age (35-45 m deep). These aquiferous horizons are separated by an aquitard of probable Q7 age[10]. Both aquifers are heavily utilised for irrigation supply and exhibit a large abstraction-related drawdown of about 5-6 m across the sub-basin.

The distinct aquitard–aquifer layered sequence, characteristic of the Tiffen cross section, dissipates as the sediment sequence merges with the (Waingawa) fan system to the north. The fan is regarded to be an important recharge area to the confined Parkvale and Carterton aquifers downgradient.

West of the Brickworks Anticline, another sub-basin is evident in the Carterton area where the strata and the land surface (the 'Carterton Surface') dips westwards towards the Mangatarere Stream on the Tiffen cross section. A relatively deep productive aquifer horizon at a depth of about 20-30 m occurs

[10] The Q6 aquifer equates to 'Parkvale Aquifer 2', and the Q8 Aquifer is 'Parkvale Aquifer 3' under the current RFP groundwater allocation framework.

around Carterton that is speculated to be equivalent to the Q6 reworked gravels identified in the Parkvale sub-basin. The Carterton sub-basin merges to the west with the poorly-sorted Waiohine fan gravels.

The Carterton Fault is shown near to the northwestern end of the section lines but the off-set across the fault does not appear to be as extreme as the Masterton Fault. Therefore its influence on groundwater movement is expected to less significant. This area comprises relatively homogeneous clay-bound gravels with thin discontinuous silt horizons and has poor groundwater resource potential.

6.3.2 Waingawa section

The dominant feature on the Waingawa section line (Figure 6.5) is the Masterton Fault which raises Miocene-Pliocene mudstone and early to middle Quaternary impermeable sediments close to the surface. Older terrace gravels on the northwestern side of the fault are back-tilted resulting in a considerable thinning of the aquifer thereby restricting groundwater movement across the fault and forcing groundwater to the surface. Spring discharges occur along the fault line (e.g. Waingawa Swamp).

The area to the northwest of the Masterton Fault is therefore considered to be a largely isolated aquifer compartment filled with rapidly deposited, poorly sorted, clay-bound alluvial fan material of lower permeability. Groundwater from the compartment discharges as springs and river base flow along, or immediately upstream of, the fault line.

Between the Masterton Fault and the Carterton Fault there is a sequence dominated by dense poorly sorted silty-sandy Waingawa fan gravels which yield only small volumes of groundwater. Deformation (upward flexure) over a structure called the 'Peter Cooper Anticline' is depicted based upon the structural interpretation of the area and seismic profiling data (Cape et al. 1990). This structure appears to be a continuation of the Tiffen Hill complex to the south.

The Carterton Fault is downthrown to the west, although the displacement of younger sediments is not expected to be large. There is no evidence from bore logs of a large dislocation of the sequence. Along the eastern end of the cross section the lower, younger, modern-day terraces and floodplains of the Ruamahanga River are incised within the older Q2-4 terrace sequence.

6.3.3 Greytown-Waiohine section

The Greytown Waiohine cross section (Figure 6.6) depicts a relatively simple conceptual geology based on the Quaternary depositional and structural understanding of the area (there are no deep bores in this area). The section shows a wedge of late Quaternary alluvium thinning towards the Ruamahanga River over an area of postulated uplift associated with the Tiffen-Te Marie structure occupying this side of the valley. Most bores intersect only the upper, highly permeable 10-15 m thick Q1 sequence. Groundwater discharge from the Papawai – Tilsons spring system occurs where the aquifer succession thins.

6.3.4 Long valley section

The Long valley cross section (Figure 6.7) extends from the Waingawa River in the north, across the Waingawa fan and through the Parkvale sub-basin to the Ruamahanga River (see Figure 6.2 for location). It depicts a relatively simple alluvial fan sequence descending into the Parkvale basin where the segregation of distinct gravel and silt-rich horizons occurs (as discussed above). The Carterton and Masterton faults are also shown which are regarded as variably impeding the flow of groundwater. The probable displacement of strata across the faults is indicated.

7. Hydrogeology

7.1 Hydrostratigraphic units of the Middle Valley catchment

The geology of the Middle Valley catchment was described in detail in Section 6 with the assistance of a series of cross section interpretations. This analysis explained the nature of the heterogeneous unconsolidated sedimentary sequence within the catchment. By implication, the sequence has a large spectrum of aquifer potential due to widely varying grain size distributions, gravel matrix compositions, degrees of sediment sorting/reworking, and degrees of compaction. Although all units are saturated below the water table, enhanced transmissivities in the coarser-grained sand and gravel units will locally develop as a result of better sediment sorting and reworking by drainage systems.

Five broad hydrostratigraphic units are recognised within the Middle Valley catchment on the basis of formation lithology, well yield and aquifer properties. Table 7.1 lists the units, their spatial distribution and the general nature of their hydraulic properties. Figure 7.1 shows the spatial distribution of the different units.

Table 7.1: Principal hydrostratigraphic units of the Middle Valley catchment

Name	General hydraulic nature	Distribution
Alluvial fan gravels (Q2 – Q8)	Poor aquifers: low K, poor yields.	Major fan systems on western valley side of Waiohine, Waingawa and Mangatarere rivers.
Q1 Unconfined aquifer	Aquifer: high K, reworked, strong connection with rivers.	Main river channels, Waiohine floodplain, Ruamahanga floodplain.
Q2-4, Q6, Q8 aquifers	Aquifers: medium-low K, layered gravel/sand/silts.	All distal fan areas either at surface or below Q1 deposits.
Q5 + Q7 silts/clay aquitards	Aquitards: very low K silty/clay swamp deposits.	Parkvale, Carterton, Ruamahanga, Fernhill.
Uplifted blocks	Aquitards: very low or low K. Form flow barriers.	Tiffen Hill/Fernhill.

K – hydraulic conductivity

7.1.1 Alluvial fans gravels (Q2 – Q8)

The fan complexes occupying the northwestern side of the valley are the product of rapid deposition of coarse, matrix-rich sediment during glacial periods by major rivers draining the Tararua Range. The fans prograde towards the eastern hills and are responsible for forcing the Ruamahanga River over to the eastern side of the valley.

The alluvial fans are mapped at the surface as last glacial (Q2) deposits becoming progressively older with depth. The main fan complexes in the Middle Valley are associated with the Waiohine River and the Waingawa River in the north. The Mangatarere Stream does not appear to be associated with any significant fan deposition, possibly due to its considerably smaller catchment area and the low gradient of its upper catchment.

The Carterton and Masterton faults have deformed the fan sequences and have been responsible for altering the drainage pattern on the plains. The Carterton/Parkvale area seems to lie in a structurally-controlled depression between the major fans.

Where they have not been reworked, the fan sequences are commonly poorly sorted and matrix supported, becoming very compact and matrix-bound with depth. They exhibit a low hydraulic conductivity and therefore do not form good aquifers. Locally enhanced hydraulic conductivity as a result of sediment reworking sometimes enables wells to yield larger quantities of water.

7.1.2 Q1 unconfined aquifer

Holocene age (Q1) gravels represent a shallow (<15 m deep) highly dynamic unconfined aquifer which exhibits a strong interaction with the surface water environment. These gravels are associated with present-day river channels and the postglacial floodplains of the Waiohine, Ruamahanga and Waingawa rivers (Figure 7.1). They also occur as a very extensive cover in the Greytown area on the Waiohine River plains. The unit is shallower and less well sorted along the Mangatarere Stream.

The Q1 gravels are derived from the degradation and high-energy transport of the extensive poorly sorted glacial fan gravels eroded from the Tararua Range. As a consequence, they exhibit medium to high hydraulic conductivities. Most large groundwater abstractions in the Middle Valley catchment taken from this unit which is generally less than 15 m deep.

7.1.3 Q6 and Q8 aquifers

The geological logs for many bores at the edge of the main alluvial fan systems, and also those within the Carterton and Parkvale sub-basins, show evidence of thin (<10 m) highly permeable gravel aquifers. These gravels can sustain higher bore yields and are a product of post-deposition sorting that has removed the fine silt and sand matrix. Sediment reworking and sorting are likely to have occurred during interglacial periods. The warmer climate of interglacials meant rain fell throughout the year with smaller, more frequent floods. The climate also encouraged vegetation cover which reduced sediment supply to the plains. As a result the rivers began down-cutting and reworking fan and floodplain deposits.

A result of this sediment reworking by sorting and lateral spreading is that aquifers can be more easily identified and correlated between bores, particularly within subsiding areas away from the massive glacial outwash fan deposits – such as in the Parkvale sub-basin. Thin, 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 changes between alternating glacial and interglacial periods, has been repeated many times throughout the Quaternary creating a series of thin gravel aquifers in downstream depositional environments.

7.1.4 Q5 + Q7 aquitards

The central part of the Middle Valley catchment contains extensive swamp and lacustrine deposits. The most prominent and extensive of these is the Q5 interglacial 'Francis Line Formation' which outcrops around Tiffen Hill, Fernhill and on the 'Carterton Surface' (crest of the Brickworks Anticline) between Parkvale and Carterton. This unit is 3-5 m thick and forms an important aquitard confining deeper reworked gravel aquifers. A deeper interglacial Q7 silt/clay unit is less well defined.

7.2 Temporal and spatial groundwater levels

7.2.1 Middle Valley groundwater level monitoring network

At the time of commencing groundwater model development in 2007 Greater Wellington operated a network of 18 automatic and manual groundwater level monitoring sites in the Middle Valley catchment. Historical monitoring data for an additional eight observation bores no longer in operation were also available. Most of the current monitoring sites were installed in 1983. Another eight monitoring bores were drilled in the Middle Valley under the field programme component of the Phase 2 groundwater investigation (refer Section 5.1). The locations of the bores are shown in Figure 7.2 and Table 7.2 summarises the key details for each currently active monitoring bore as well as eight discontinued bores.

7.2.2 Regional groundwater flow pattern

Regional groundwater flow patterns in the Middle Valley catchment were characterised using groundwater level measurements taken over the past two decades in a number of surveyed monitoring bores. Figure 7.3 shows the piezometric surface based upon level measurements made in March 2007 for bores shallower than 20 m depth.

The general regional flow pattern reflects the regional topography and groundwater flows in a southerly to south-westerly direction off the outwash fan areas towards the Parkvale and Carterton areas. Flows converge on the Ruamahanga River south of Tiffen Hill near the Waiohine River confluence.

In the Greytown area on the Waiohine plain the regional flow direction is to the southeast towards the Ruamahanga River. The contours for this area are relatively widely spaced reflecting the high transmissivity of the Q1 gravel aquifer.

The flow pattern shows that the Ruamahanga River controls regional groundwater discharge and it is probable that the river receives more base flow from groundwater downstream of Tiffen Hill where the Parkvale, Carterton and Greytown flow systems converge.

Table 7.2: Middle Valley catchment groundwater level monitoring sites and details

Bore ID	Owner/name	Automatic/Manual	Monitoring started	Monitoring stopped	Depth (m)	Top screen/ Bottom screen (m depth)	Screen type	Use	RFP zone (WRC 1999)
Greytown – Waiohine plains									
S26/0352	WCB	Manual	03/08/1980	21/12/1988	92	86 – 92	slotted	Not used	Woodside
S26/0490	Perry	Automatic	13/08/1990	current	5	–	–	Not Used	Greytown
S26/0500	Rogan	Manual	03/08/1983	1/7/1997	3.4	Dug	No screen	Not used	Greytown
S26/0537	Harding	Automatic	12/08/1983	12/5/1992	6	–	–	Domestic	Greytown
S26/0545	Craig	Manual	03/08/1983	current	18	–	No screen	?	Ahikouka
S26/0547	Craig	Manual	03/08/1983	current	4.3	–	No screen	Stock	Ahikouka
S27/0225	Hammond	Automatic	06/09/1994	current	4.6		Open hole	Monitoring	Greytown
S27/0883*	GW (Papawhai)	Automatic	17/08/2008	current	14	11–14	Slotted PVC	Monitoring	Riverside
Parkvale-Carterton sub-basin									
S26/0568	Denbee	Manual	17/08/1983	current	45	41 – 44	SS continuous	Irrigation	Parkvale
S26/0675	McNamara	Manual	30/10/1996	current	31.5	27.5 – 31.5	SS continuous	Monitoring	Parkvale
S26/0738	Towgood	Automatic	03/08/1983	current	5.4	–	Concrete liner	Domestic	Parkvale
S26/0743	Baring	Automatic	06/11/1986	current	33	31 – 33	SS continuous	Stock	Parkvale
S26/0400	Fitzgerald	Manual	03/03/1986	11/12/1989	16	13 – 16	SS continuous	Irrigation	Hodders
S26/0658	Craig	Manual	03/08/1983	current	8	–	No screen	Stock	Mangatarere
S26/0155	Tulloch (Shallow)	Manual	03/08/1983	current	13.4	10.3 – 13.4	SS continuous	Irrigation	Parkvale
S26/0656	Tulloch (Deep)	Manual	12/05/1982	current	78	?	No screen/open	Monitoring	Parkvale
S26/1032*	GW (Renall Deep)	Automatic	29/09/2008	current	17.9	14.9 – 17.9	SS continuous	Monitoring	Parkvale
S26/1033*	GW (Renall Shallow)	Automatic	29/09/2008	current	9	6 – 9	Slotted PVC	Monitoring	Parkvale
S26/1034*	GW (Hilton Rd Deep)	Automatic	29/09/2008	current	21	19.3 – 21	SS continuous	Monitoring	Carterton
S26/1035*	GW (Hilton Rd Shallow)	Automatic	29/09/2008	current	6.4	3.4 – 6.4	Slotted PVC	Monitoring	Carterton
S26/1053*	GW (McNamara	Automatic	21/08/2008	current	9.5	6.5 – 9.5	Slotted PVC	Monitoring	Parkvale

* New monitoring bore drilled for Phase 2 investigation (2008)

Table 7.2 *cont*.: Middle Valley catchment groundwater level monitoring sites and details

Bore ID	Owner/name	Automatic/Manual	Monitoring started	Monitoring stopped	Depth (m)	Top screen/ Bottom screen (m depth)	Screen type	Use	RFP zone (WRC 1999)
Upper Waingawa fan									
S26/0223	Nicholson	Manual	18/03/1998	22/01/2009	9.9	-	No screen	Stock	East Taratahi
S26/0229	E. Coast Fertiliser	Manual	14/05/1984	current	23.8	?	?	Not used	East Taratahi
S26/0236	WCB/Oldfields	Manual	03/08/1983	current	41.4	38.4 – 41.4	Galv slotted	Not used	East Taratahi
S26/0242	E. Coast Fertiliser	Manual	03/08/1983	current	7.5	-	?	?	East Taratahi
Waingawa floodplain									
S26/0298	Oldfields	Automatic	27/1/1992	11/9/2000	7.0	1.7 – 7.0	Multiple screen	Industrial	Upper Plain
S26/0308	Oldfields	Automatic	16/9/1993	6/10/1995	5.5	-	None	Industrial	Upper Plain
Fernhill									
T26/0326	McKay	Manual	02/08/1991	current	10.0	?	?	Domestic	Fernhill
Middle Ruamahanga valley									
S26/0749	Blundell	Automatic	17/12/1997	current	10.0	8 – 10	?	Not Used	Mid Ruam
S26/0756	Stevenson	Manual	29/05/1998	current	19.0	17 – 19	SS continuous	Irrigation	Mid Ruam
S27/0248	Morrison	Manual	03/08/1983	current	7.9	?	Open hole	Domestic	Mid Ruam
T26/0602	Gladstone Supply	Automatic	04/08/1999	30/01/2002	11.4	?	SS continuous	Public supply	Mid Ruam
S27/0878*	GW (Taumata Lagoon 1)	Automatic	04/08/2008	current	24.8	22 – 24.8	Slotted PVC	Monitoring	Mid Ruam
S27/0881*	GW (Taumata Lagoon 2)	Automatic	29/08/2008	current	8.7	5.7 – 8.7	Slotted PVC	Monitoring	Mid Ruam

* New monitoring bore drilled for Phase 2 investigation (2008).

7.2.3 Temporal groundwater level characteristics

(a) Greytown-Waiohine plain (Q1 aquifer)

There are eight monitoring bores in this area (Figure 7.2). Figure 7.4 shows the hydrographs from 1990 to the present time for three representative sites, including the two continuously monitored bores (S26/0490, Perry and S27/0225, Hammond). Waiohine River stage (measured at the gorge site; Figure 3.1) is also shown for the same period to illustrate the inter-relationship between the river and the aquifer.

The river stage record shows a gradual recession between about 1990 and 2004 after which the trend levels off. The recession is attributed to a lowering of the bed level in the vicinity of the Waiohine Gorge gauge, and possibly also downstream (there is no downstream bed elevation data to confirm this). The Waiohine River, like other rivers in the valley, has a very mobile gravel bed and is subject to cycles of degradation and aggradation. Gravel abstraction from the river in the vicinity of the SH 2 bridge may also significantly influence bed level.

Groundwater levels in shallow monitoring bores near the Waiohine River should reflect changes in bed level since the river and aquifer are in hydraulic continuity. The Perry monitoring site (S26/0490, 5 m deep) is located close to the river and does not show the same trend as the Waiohine Gorge stage monitoring site but instead has a stable long-term level. The Craig monitoring bore (S26/0545) is close to the SH 2 bridge where gravel extraction is occurring and shows a slight long-term recession from about 2004 which could be related to gravel extraction in this area.

Located about 4 km from the river the shallow Hammond monitoring bore (S27/0225, 4.6m deep) also shows a slight long-term recession in groundwater level in the order of 0.3 m over about 14 years. The trend could reflect changing bed levels in the Waiohine River in the reaches upstream of the Perry site where significant flow losses to the aquifer occur.

Figure 7.5 shows detailed groundwater level and river monitoring data for the period 1 September 2007 to 1 January 2008 to demonstrate the interdependence of surface water and shallow groundwater in the Greytown area. The plot for the Perry observation bore (S26/0490) shows that groundwater levels respond quickly, within about a day, to rises in the river level. Groundwater levels start rising about one day after a rise in the flow, and peak after about three days. Periods of high river flow can cause groundwater levels to rise by about 1m as shown by the wet period during the first three weeks of October 2007 when multiple floods in the river occurred. Groundwater levels also appear to recede over about a month during prolonged low flow conditions in the river.

Figure 7.5 also shows groundwater levels for the Hammond observation bore (S27/0225) which is close to the Papawai Stream. The groundwater level at this site is strongly influenced by local irrigation abstraction and the flow in the Papawai Stream is also affected by direct irrigation abstraction as indicated on the plot. The flow records for the Waiohine River and the spring-fed Papawai

Stream show how spring flow and groundwater level closely mirror conditions in the Waiohine River.

From a distance of more than 4 km, the Waiohine River clearly has a strong influence on the shallow Q1 Greytown aquifer which represents a series of gravel-filled channels deposited by the migrating river since the last glaciation.

(b) Parkvale sub-basin and Carterton

Figure 7.6 presents monitoring hydrographs of four bores in the Parkvale sub-basin, one shallow (Towgood S26/0738; 5.4 m), and three in the underlying confined artesian aquifers (Baring S26/0743, Denbee S26/0568 and McNamara S26/0675). Also shown on this figure is the cusum plot for long-term monthly rainfall measured at the Bagshot rainfall station (see Section 2.3.2 for an explanation of this plot).

The Towgood site, located about 3 km up-valley (NE) from the other three sites (Figure 7.2), measures groundwater level in a shallow unconfined aquifer. The monitoring data show a strong seasonal fluctuation of about 2 m. When this hydrograph is compared against the other three plots in Figure 7.6 (bearing in mind that the Towgood site is located 3 km up-valley which equates to about a 10 m change in water table height), the head in the shallow aquifer is clearly about 4-5 m lower than the underlying confined and flowing artesian aquifers during winter. This demonstrates an upward vertical flow gradient in the Parkvale sub-basin.

The three other hydrographs in Figure 7.6 relate to monitoring bores located in the deeper confined Q6 and Q8 aquifers in the Parkvale sub-basin. All of these show winter heads above ground level – the confined Parkvale aquifers are artesian. Both the McNamara and Denbee bores are at about the same ground elevation and have similar head characteristics. The Baring site has about a 10 m higher elevation and therefore the aquifer that it intersects has a significantly lower head than the other two. Structural complexity on the edge of Tiffen Hill probably accounts for the difference in head.

The main feature of these three hydrographs is the dramatic increase in summer drawdown from about 1997, accompanied by a progressive reduction in winter levels from 1997 onwards (in the order of about 2 m). Development of irrigation activities from this time appears to be responsible for the increased seasonal drawdowns. The long-term trend in winter levels can be explained partly by rainfall patterns as shown by the cumulative devation from the long-term monthly mean (cusum) plot. However, even though the cusum rainfall trend ‘recovers’ in 2003, groundwater levels continue to decline in the deeper monitoring bores (shown by the arrows on Figure 7.6). This observation suggests that abstraction stresses must also contribute to the declining trends in the Parkvale sub-basin.

Figure 7.7 displays three hydrographs for the Carterton area (Tulloch ‘Deep’ S26/0656; Tulloch ‘Shallow’ S26/0155; Craig S26/0658) and the cusum plot for monthly rainfall at Bagshot. The side-by-side Tulloch sites measure groundwater levels at 13 m and 78 m – the deeper bore (S26/0656) shows a groundwater head 12-15 m below the shallow bore (S26/0155). The 78-m deep well is influenced by irrigation pumping, the effects of which have become more pronounced over the past decade. This bore now experiences a 4 to 5 m level drop in summer. Winter levels in this bore also receded by about 2 m between 1998 and 2003. This could reflect the long-term rainfall trend as shown by the cusum plot. However, the recession is not reflected in the record of the shallow monitoring bore (S26/0155) and may therefore relate to abstraction stresses from the deeper aquifer.

The Craig bore (Figure 7.7, S26/0658) is close to the Mangatarere Stream and is 8 m deep. The hydrograph is probably influenced by stream flow but because this bore is not continuously monitored (it is manually dipped monthly) it is not possible to make a detailed comparison between river flow and groundwater level.

(c) Upper Waingawa fan

Figure 7.8 presents hydrographs for three monitoring bores in the broad fan area above the Parkvale sub-basin. The two ECF bores provide groundwater level information at 7.5 m and 24 m depth (ECF 'Shallow' – S26/0242 and ECF 'Deep' – S26/0229). Both of these bores exhibit large seasonal fluctuations (3-5 m) reflective of rainfall recharge within an aquifer of generally low hydraulic conductivity. The deeper of these bores has a winter groundwater head about 2-3 m lower than the shallower bore showing there to be a downward head gradient in this area during winter. During summer, the heads of both bores are about the same, possibly as a result of abstraction (particularly from the shallow aquifer). The downward gradient of the head in this area during winter implies a potential recharge zone (this area is perceived to be the recharge zone for the Parkvale sub-basin).

Figure 7.8 also shows a hydrograph for a deeper bore, S26/0236 (WCB Oldfield, 41 m deep). The higher head at this site is because this bore is upgradient of the two ECF bores (topographically about 7 m upgradient). Similar to the deeper aquifer levels in the Parkvale-Carterton area, groundwater levels here receded between about 1998 and 2003 which is possibly attributable to long-term rainfall recharge trends (as shown by the cusum plot). The trend is not evident in either of the shallower ECF bores.

(d) Fernhill

There is only one groundwater level monitoring bore in the Fernhill area (T26/0326 McKay, 10 m deep). The groundwater level characteristics of this site are quite different from other parts of the Middle Valley catchment (Figure 7.9). This shallow groundwater system displays long sinusoidal water level fluctuations over several years of about 1 m – typical of an aquifer which receives rainfall recharge pulses transmitted very slowly through a thick and low permeability unsaturated zone. A series of at least three clay-rich loess deposits have been mapped on Fernhill (Section 6.1). This type of system exhibits a groundwater level trend which closely reflects the long-term rainfall recharge pattern for the area as demonstrated by the cusum rainfall plot shown in Figure 7.9.

(e) Middle Ruamahanga

Figures 7.10 and 7.11 show weekly and monthly groundwater level hydrographs for the middle Ruamahanga valley for bores situated in close proximity to the river. Groundwater levels respond very quickly to changes in river stage as demonstrated by Figure 7.11 which shows continuously monitored water levels for bore S26/0749 (Blundell, 10 m deep and 500 m from the river) and bore T26/0602 (Gladstone Water Supply, 11 m deep, 200 m from the river) for the period 1 September 1999 to 1 March 2000. Both bores show a similar magnitude in level response to the river despite their differences in distance to the river. This is suggestive of a highly transmissive aquifer in close hydraulic connection to the Ruamahanga River.

7.3 Rainfall recharge

7.3.1 Occurrence and spatial variability

One of the principal groundwater recharge processes in the Middle Valley catchment is rainfall infiltration (or 'land surface recharge') – the portion of rainfall which is not diverted to runoff or lost to evapotranspiration, but which soaks directly into the ground.

The steep rainfall gradient across the valley from the Tararua Range to the eastern hills results in a considerable spatial variability in recharge. The highest annual rainfall of 1,800-1,900 mm occurs against the range, reducing to 800-900 mm on the eastern side of the valley (Section 2.3; Figure 2.5). Soil type, underlying shallow geology and the thickness of the unsaturated zone also exert a significant influence on rainfall recharge processes.

7.3.2 Distributed soil moisture balance modelling

To estimate rainfall recharge, a methodology that incorporates the large spatial variability in climatic and soil conditions was devised. The methodology is based on a soil moisture balance technique developed by Rushton et al. (2006) which calculates recharge on a 500 m^2 grid system. Appendix 4 provides details of the recharge model and input parameters for the Middle Valley catchment.

Key input parameters for the recharge model were provided by climate modelling and soil specialists as follows:

- Climate data processing and spatial modelling – spatial interpolation of daily rainfall and potential evapo-transpiration using a spline model (Tait and Woods 2007) into the recharge grid was undertaken by NIWA using all available climate monitoring data (from NIWA and Greater Wellington databases).
- Soil property mapping – spatial mapping data and soil hydraulic parameters were provided by Landcare Research (T. Webb).

7.3.3 Spatial recharge pattern

Outputs from the recharge model are shown in Figures 7.12 to 7.18.

The mean annual average rainfall distribution derived from the NIWA climate model (Appendix 4) for the Middle Valley catchment is shown in Figure 7.12. The data are distributed on a 500 m^2 grid. Also shown on this plot presented 5 are the mean rainfall isohyets based upon an indepently modelled dataset for the period 1920 to 1970 (the same model used for Figure 2.5) for comparision. The two data-sets are somewhat different but the NIWA climate model is regarded to be more accurate due to the more robust nature of the climate modelling algorithyms which take into account additional factors such as topography.

Figure 7.13 displays the soil moisture balance outputs in the form of annual average recharge on a 500 m^2 grid. The recharge pattern is strongly influenced by the annual rainfall distribution (Figure 7.12) and ranges from 600-700 mm along the northern edge over the upper fan areas, to less than 100 mm on the southern side of the catchment over Fernhill and the Ruamahanga valley. The influence of soil type on recharge is also evident over the central part of the catchment.

Figure 7.14 is derived from Figures 7.12 and 7.13 and shows recharge as a percentage of rainfall on an average annual basis. Over the upper fan areas (north of Carterton and Greytown) up to about 40% of rainfall becomes groundwater recharge. On the drier southern side of the valley less than 10% of rainfall becomes recharge due to higher proportional losses to evapotranspiration. Areas of poorly drained soil are also evident in the Parkvale and Fernhill areas. The thick loess sequences over the Fernhill terraces prevent rainfall infiltration where it is estimated that less than 5% of rainfall becomes recharge.

Figures 7.15 and 7.16 contain representative recharge maps derived from the distributed recharge model for the wet winter of 2004 (24 August 2004) and for the very dry winter of 2005 (5 July 2005). The output for August 2008 shows the pronounced rainfall-recharge gradient across the catchment particularly well – recharge ranges from in excess of 5 mm/day against the Tararua Range to less than 1 mm over the Fernhill-Ruamahanga valley. The example output for July 2005 shows a much weaker gradient from about 1 mm in the west to zero recharge in the east and southern part of the cathcment.

7.3.4 Simulated recharge trends 1992–2007

Recharge trends for the modelled period (1992–2007) can be characterised using the recharge model outputs. Figures 7.17A and 7.17B show the calculated daily recharge (as a weekly mean) and total annual recharge respectively for the entire Middle Valley catchment for the period 1992 to 2007. The average annual recharge for the 15 year period is 68.2 x 10^6 m^3 and the average daily recharge is 190,000 m^3.

The large inter-seasonal recharge variability reflects temporal rainfall patterns as shown by the cusum monthly rainfall trend superimposed on the annual recharge plot (Figure 7.17B). Low recharge years occurred in 1993 and 2001 but the cusum plot shows that only 2003 was particuarly dry – this may be due to the location of the Bagshot long-term rainfall site which is outside the catchment (see Figure 2.6). Years when the total catchment recharge exceeded the annual average of 68 x 10^6 m^3/year occurred in 1992, 1995, 1996, 2004 and 2006.

To provide an appreciation of the spatial variability of recharge across the catchment, Figure 7.18 shows the annual recharge depth modelled over 1992-2006 in four 500 m^2 recharge cells. The locations and soil properties relating to the cells are listed in Table 7.3.

Table 7.3: Soil properties for representative cells used in the distributed recharge model

Cell ID	Location	FC (mm)	Wilt (mm)	SCS	Fract
43345	Featherston	120	40	89	0.7
47239	Parkvale (alluvium)	120	40	89	0.7
46463	Parkvale (peat)	400	200	91	0.7
51387	Ruamahanga valley/Gladstone	330	120	86	0.7

FC – field capacity; Wilt – wilting point; SCS – runoff curve number; Fract – fracstor term in Ruston model.

The cells mirror each other with respect to temporal trends in annual recharge depths. However, the magnitude of recharge varies significantly due principally to rainfall variation across the valley, but also due to the variation in soil properties.

Cell 43345 on the Featherston fan against the foothills is in a higher rainfall zone and has a relatively free-draining soil with low field capacity. These conditions are conducive to rainfall infiltration as shown by the significantly higher annual recharge compared to the other cells (Figure 7.18). By contrast, cell 51387 in the Ruamahanga valley lies in an area with significantly lower rainfall (Figure 7.12) which, coupled with the effects of the more retentive soil, results in significantly reduced rainfall recharge. Some years experience only minor levels of recharge with nil recharge occurring in extreme drought years such as 2000/01.

Between Featherston and the Ruamahanga valley the two Parkvale cells (47239 and 46463) show recharge characteristics for the centre of the catchment in two different soil types. This area also has markedly reduced rainfall recharge compared to the wetter Featherstone fan.

7.3.5 Recharge model verification

The soil moisture balance recharge model was verified using two separate methodologies:

- Comparison with lysimeter data (direct recharge measurement); and
- Comparison with basic saturated aquifer volume fluctuation calculations.

The accuracy of the Rushton et al. (2006) soil moisture balance model was verified by comparing calculated recharge with lysimeter data from the

Canterbury plains (data provided by Environment Canterbury). The SOILMOD and the Soil Water Balance Model outlined in White et al. (2003) were also tested for comparison. Details of the verification exercise are provided in Appendix 4. This exercise showed that the Rushton model provides the most accurate estimation of weekly rainfall recharge of all the three soil moisture balance models (Rushton, SOILMOD and White) when compared to the lysimeter data. The verification simulation also showed that the Rushton model is more sensitive during periods of low rainfall, and accurately simulates rainfall recharge during these periods.

A second basic check for the soil moisture balance model involved employing a simplified saturated volume fluctuation method (SVF-Hill method; Domenico 1972) which uses the following linear relationship:

$$RE + (I - O) - Q = \Delta V$$
$$= S.A.dh$$

where
- RE = recharge
- I = mean lateral inflow
- O = mean lateral outflow
- Q = abstraction from the aquifer
- ΔV = saturated volume change effected over time Δt
- S = specific yield
- A = area of the aquifer receiving recharge
- dh = average water level fluctuation

Performing this calculation over an average year for a selected recharge area should provide a comparable recharge volume to the soil moisture balance model. Under average conditions the natural inflows and outflows (I and O) can be regarded as constant and the groundwater abstraction neglected since it represents a small relative quantity compared to recharge. Therefore, the rate of change in the saturated aquifer thickness represents the aquifer storativity, and:

$$-S. \Delta V = RE$$

The Tauherenikau fan was selected as a reference site for which basic recharge could be estimated using the above calculation in order to verify the soil moisture balance model. This fan lies in the lower Wairarapa Valley but is adjacent to the Waiohine plain and is considered to be a recharge area for deeep aquifers and the confined aquifers in the lake basin. Aquifer specific yield together with the annual average change in aquifer storage volume were estimated using available data as follows:

Specific yield: In the absence of reliable and consistent groundwater pump test data within the unconfined aquifers, a specific yield of 0.1 was taken as representative.

Seasonal water level change: shallow monitoring bore hydrographs outside the influence of major rivers show an average seasonal level rise in the unconfined aquifer of about 3 m.

The basic recharge calculation for the Tauherenikau fan is as follows:

Aquifer recharge area	125,521,400 m^2
Average annual level rise	3 m
Change in volume (ΔV)	376,564,200 m^3
Specific yield (S)	0.1
Average annual recharge (RE)	37,656,420 m^3

Average daily recharge comparison

SVF calculation	103,200 m^3
Soil moisture balance model	99,500 m^3

Overall, the soil moisture balance model provides a comparable recharge estimate to the basic SVF calculation. Although by no means an unequivocal verification of the soil moisture balance model, the comparison proves an order of magnitude consistency between the recharge model and a basic water balance calculation.

7.4 Groundwater–surface water interaction

7.4.1 Background

Large components of the groundwater balance for the Middle Valley catchment are associated with fluxes between shallow groundwater and surface water. Hydrographs for shallow bores in the vicinity of rivers exemplify the connection between these environments (see Section 7.2.3). Natural groundwater discharges occur as river base flow, spring flow and diffuse seepage into wetlands and lakes. The major fault systems also appear to impede the flow of groundwater forcing discharge to springs and into rivers near their surface expressions.

In addition to groundwater discharge, some reaches of the major river channels recharge groundwater by losing part, or sometimes all, of their flow into adjacent aquifers. In the Middle Valley catchment, river recharge appears to be of equal importance in terms of regional flux magnitudes to rainfall recharge. For this reason, developing new policy to sustainably manage the surface water and groundwater resources in the Middle Valley catchment is reliant on understanding the nature and degree of groundwater–surface water interaction. The flux dynamics between these environments can also be influenced considerably by large groundwater abstractions near rivers.

The degree of the interaction between groundwater and surface water is dependent upon the head gradient between the aquifer and the river, and upon the degree of connectivity between both water bodies. The connectivity is a function of the permeability of the stream/river bed and aquifer, as well as the size and geometry of the contact area. Geological structure and the impedance of groundwater flow (either through deformation of the aquifer sequence or the creation of flow barriers) also exerts a strong control on vertical flow gradients in an aquifer.

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Exploitation of groundwater therefore has the potential to impact the surface water environment and vice versa. Depletion effects can be significant and immediate, particularly during low flow periods and where the abstraction occurs from highly permeable aquifers in contact with surface water systems. The longer-term cumulative effects of groundwater abstraction on a catchment scale can also ultimately impact on the water balance of the system and impact on the surface water environment over a long period of time.

7.4.2 Connected surface water environments

The principal surface water environments which exhibit complex interactions with groundwater are:

- Ruamahanga River
- Waiohine River
- Mangatarere Stream
- Waingawa River
- Springs (Parkvale, Beef Creek/Enaki system, Papawai-Tilsons system, faultline springs)
- Water races (may recharge groundwater and receive groundwater discharge).

To help understand and quantify the patterns of gain and loss, and thereby characterise groundwater–surface water interaction in the catchment, concurrent gauging surveys were carried out between 2006 and 2008. By measuring flow at various points along a river on the same day during stable base flow (summer conditions) the gaining and losing patterns which characterise each of the river systems were able to be observed.

Figure 7.19(A-D) provides an analysis of the concurrent gauging surveys as a series of longitudinal profile plots for each of the rivers in the Middle Valley catchment. Each plot shows the observed losing (loss of flow to the aquifer below) and gaining (the river gains water from the aquifer below) reaches of each river after inputs and outputs from tributaries or diversions have been taken into account.

The same data are represented in Figure 7.20 as a map identifying losing, gaining or neutral (neither gaining nor losing) reaches. A river can therefore have simultaneous gaining, losing and neutral reaches in a seasonally varying pattern.

It is important to recognise that these plots represent the groundwater–surface water interaction during base flow and low groundwater level conditions. It is probable that the pattern may be somewhat different under different flow regimes (i.e. high flows) for which concurrent flow data are not available (it is often not feasible to gauge these rivers accurately under higher, turbulent flows).

The following observations can be made from Figures 7.19 and 7.20 in relation to each river:

7.4.3 Waiohine River

Numerous concurrent gauging runs on the Waiohine River in 1981, 2006 and 2007 (Figure 7.19A) show a losing stretch of river between the Railway bridge and the SH 2 bridge (upstream from the confluence with the Mangatarere Stream). The loss is in the order of 0.5 to 1.5 m^3/s during summer low flow conditions. This losing stretch of river coincides with the river passing over highly permeable Q1 gravels and aquifers associated with the Waiohine plain (Figure 7.20).

A temporary flow site was installed at the SH 2 bridge between January and December 2008 so that the temporal pattern of loss and gain could be studied between the permanent gauging site at the Waoihine Gorge and the temporary SH 2 site. Figure 7.21A shows the results of the gaugings in terms of losses and gains, and the correlation between flow at the gorge and flow at SH 2 is shown in Figure 7.21B. Data relating to flows in excess of 10 m^3/s have been ommitted from the plots since the SH 2 gauge was only rated to low flow conditions and there is a proportionately larger gauging error at higher flows (so that the difference between the gauged flows at the two sites becomes meaningless).

Figure 7.21A shows flow losses during the first half of 2008 to lie between 0.5 and 1.5 m^3/s, apparently becoming smaller towards winter. Gain/loss data is lacking after July due to the prevalence of high flow conditions (greater than 10 m^3/s). The data show occasional large gains which could be gauging errors. River stage at SH 2 and groundwater level at the automatic monitoring bore S26/0490 (see Figure 7.2 for location near the Waoihine River west of Greytown) are also superimposed on Figure 7.21A. It appears that there is a negative correlation between river flow loss and groundwater level (and river stage) – i.e. as groundwater level and river level decline, the leakage rate through the bed of the river appears to increase.

An explanation is that during a recession phase, the groundwater mound beneath the river is dissipating following a high flow event thereby allowing a greater volume of leakage through the river bed. For example Figure 7.21A (inset) shows that at the end of March 2008 the flow loss from the river increased from about 700 L/s to about 1,000 L/s over a recession phase lasting about 2 weeks. This pattern is repeated is repeated during the other recession phases shown in Figure 7.21A.

Figure 7.21B presents the correlation between flow at the Waiohine Gorge and flow at the SH 2 bridge. The strong correlation up to about 6-7 m^3/s becomes more scattered as gauging errors increase. The gross trend however shows that the Waiohine River loses flow to groundwater up until the flow (measured at the Gorge and SH 2) reaches about 8 m^3/s. Above this, it appears that the river begins to gain flow from groundwater (during winter conditions when groundwater levels are higher).

The river is fairly neutral between SH 2 bridge and the confluence of the Muhunoa Stream. No significant groundwater discharges from either the Carterton or Parkvale aquifers are evident from gauging data along this stretch of the Waiohine River.

Most of the water lost from the upper stretches of the Waiohine River migrates through the highly permeable aquifers in the Greytown area and emerges as discharge at the Greytown area springs. This is substantiated by hydrochemistry data presented in Section 8 of this report.

7.4.4 Mangatarere Stream

Like many Tararua-sourced easterly flowing rivers and streams in the Wairarapa, the Mangatarere Stream loses water in its upper reaches as it travels across the upper parts of the Waingawa alluvial fan. The gauged loss is up to about 0.15 m^3/s between the Valley Road bridge and Andersons Line (Figure 7.19B). In some dry summers the stream is known to dry up completely in the area of Andersons Line.

The streambed was inspected during the dry summer of 2007/08. A large water pool was evident where the Carterton Fault crosses the stream and the stream was dry downstream of this point. Groundwater is postulated to flow in the near surface gravel bed of the stream over this dry section. Approximately 0.5–1.0 km downstream a series of pools were observed, eventually becoming a flowing stream again over a few hundred metres. Flow is usually permanent below the Belvedere Road bridge.

The Mangatarere Stream and its major tributaries (Beef Creek, Enaki Stream and Kaipaitangata Stream) gain from groundwater in the lower half of the catchment between Andersons Line and Belvedere Road bridge. The Mangatarere gains up to 0.25 m^3/s over this lower stretch of stream to the confluence with the Waiohine River.

7.4.5 Waingawa River

The Waingawa River tends to lose water for most of its length at about 0.5 m^3/s during low flow conditions. Small gains are probable where the river crosses the Mokonui Fault at Totara Farm and the Masterton Fault around the SH 2 bridge. Gains and losses are hard to distinguish in the river at low flows as gauging errors are expected to be quite high due the braided-channel form of the river at some locations.

It is not known if the Waingawa River gains or loses under low flow conditions in its lower reaches. Gauging results between the SH 2 gauging site to the confluence with the Ruamahanga River show conflicting results (Figure 7.19C). This is probably because there is a complex changing pattern of gains and loses due to changing bed elevations and groundwater level conditions.

Groundwater level and hydrochemistry data suggest that the Waingawa River loses water to both the aquifers to the south (Taratahi plains and upper Parkvale) and southeast to aquifers in the Masterton area.

7.4.6 Ruamahanga River

The relatively large rates of flow in this river (mean annual low flow = 2.7 m^3/s) means that it only possible to detect general losing and gaining patterns given the standard gauging error of +/- 10%. Figure 7.19D shows that between the Waingawa confluence and Gladstone bridge the river neither significantly gains nor loses flow (it is ‘neutral’). Between Gladstone bridge and Kokotau bridge the river gains approximately 1 m^3/s of flow (during summer) from groundwater seepage. Downstream to the Waiohine River confluence there is conflicting data from gauging indicating this stretch of river is either neutral or gains over 1 m^3/s during summer.

7.5 Aquifer hydraulic properties

The hydraulic properties of the hydrostratigraphic units within the Middle Valley catchment were assessed using pumping test analyses contained in Greater Wellington’s Wells database. Tests were either classified as *Type 1* reliable (pumping tests analysed using appropriate methods), or tagged as *Type 2* basic yield tests (transmissivity has been derived using a simple yield-drawdown calculation). The more reliable Type 1 tests were preferentially relied upon to characterise the hydraulic properties of the various hydrostratigraphic units in the project area.

Figure 7.22 shows the spatial distribution of transmissivity data derived from pumping tests. The map shows a pattern that reflects the distribution of the principal hydrostratigraphic units. Particularly apparent is the low hydraulic conductivity of the major fan deposits and the contrasting elevated hydraulic conductivity of shallow Q1 gravels located along the major drainage courses.

Table 7.4 contains a summary of the data – segregated into the following hydrostratigraphic units:

- Greytown area Q1 unconfined gravel aquifers (<15 m deep)

- Ruamahanga Q1 unconfined gravel aquifers (<15 m deep)
- Deep Parkvale/Carterton confined gravel aquifers (Q6-Q8) deeper than 15 m
- Alluvial fan gravels (<15 m deep).

Table 7.4: Summary of hydraulic conductivity (K)* and transmissivity (T) values derived from pumping tests for the Middle Valley catchment

	Greytown Q1 aquifer		Ruamahanga Q1 aquifer		Parkvale/ Carterton Q4/Q6 aquifer		Alluvial fan system	
	T (m^2/day)	K (m/day)	T (m^2/day)	K (m/day)	T (m^2/day)	K (m/day)	T (m^2/day)	K (m/day)
No. of observations	19	19	15	15	20	20	10	10
Mean	6,800	680	3,900	390	700	70	1,700	170
Geomean	4,000	400	3,000	300	500	50	1,400	140
Min	275	30	500	50	60	6	234	23
Max	17,300	1,700	6,500	650	1,930	190	3,300	330
Standard deviation	5,500		2,065		547		853	

*Hydraulic conductivity is calculated by assuming an aquifer thickness of 10 m.

The geometric mean, unlike the arithmetic mean, tends to dampen the effects of very high or very low values which would tend to skew the arithmetic mean. It is particularly useful for data-sets such as this, which display a high standard deviation. Although the geometric mean values in Table 7.4 are regarded to be representative of the test data, they are not necessarily representative of the 'bulk' material properties for the hydrostratigraphic units. This is because most of the tests are performed on successful, higher-yielding bores for resource consenting purposes and therefore the data-set is inherently biased towards areas and horizons more favourable for groundwater development.

High transmissivities are characteristic of the Q1 aquifer in the Greytown/Waiohine plains area and along the Ruamahanga River. The Waiohine gravels appear to be more permeable with a geometric mean transmissivity of 4,000 m^2/day compared to 3,000 m^2/day for the Ruamahanga alluvium. The high standard deviation associated with the data exemplifies the heterogeneity of the deposits.

Deeper semi-confined and confined aquifers (Q4 and Q6) in the Parkvale sub-basin are less permeable and have an apparent transmissivity from the pumping test data-set in the order of 500 m^2/day.

Data relating to the alluvial fan systems indicates a high apparent transmissivity (1,400 m^2/day). However, due to the small sample size (10) and the very large range in transmissivity values, the calculated mean is not regarded to be representative of the bulk unit value and is biased towards high-yielding bores.

Table 7.5 provides estimated representative bulk hydraulic properties of the hydrostratigraphic units based upon a synthesis of groundwater pump test data and reasonable ranges of parameters consistent with the physical nature of the units and their known groundwater potential. Consideration is also made regarding the bias inherent in the pump test data which relate almost exclusively to higher yielding bores.

Table 7.5: Representative transmissivity, hydraulic conductivity and storage properties for Middle Valley catchment hydrostratigraphic units

Hydrostratigraphic unit	Representative (bulk) transmissivity (m^2/day)	Representative hydraulic conductivity (m/d)	Storage (S or St)
Alluvial fan gravels – Tararua-sourced (Q2 +)	Waingawa and Mangatarere fans: 100-500	10-50	St: 5-1\50% S: 1-5 E-4
Q1 Holocene alluvium (Tararua-sourced) Unconfined aquifers	Waiohine: 4,000-6,000 Ruamahanga: 3,000 – 4,000 Mangatarere: 1,500 – 2,000 Waingawa: 2,000-3,000	300-600 300 - 400 200-300 200-300	St: 5-15%
Q6 + Q8 Aquifers Parkvale/Carterton basin fill alluvium	Parkvale sub-basin: 500 – 1,000	50-150	S: 1-5 E-4

7.6 Groundwater abstraction

7.6.1 Abstraction trends and allocation status in 2008

Groundwater abstractions in the Middle Valley catchment have increased significantly over the past 20 years, and more than doubled over the past 10 years. The growth in water demand has been driven primarily by the dairy industry for seasonal pasture irrigation (generally from November to April).

Consented abstraction trends for the Middle Valley catchment are shown in Figures 7.23 (A and B – annual and daily consented rates respectively). The locations of consented groundwater abstractions are shown in Figure 7.24.

At the start of groundwater model development in 2007 the total consented abstraction from 126 bores in the Middle Valley catchment was 155,000 m^3/day (155 ML/D), and 28 x 10^6 m^3/year. However, the actual quantity of groundwater abstracted is estimated to be significantly less than the consented volumes.

The majority of shallow, high yielding bores are located in the Q1 unconfined aquifer. A high number of bores occur in the Greytown-Waiohine plains area and along the Ruamahanga River in this aquifer. The Q1 unconfined aquifer is hydraulically connected to the Waiohine and Ruamahanga rivers and therefore abstraction has the potential to result in significant effects on the flows in these rivers.

7.6.2 Actual versus consented abstraction

The actual quantity of groundwater used is somewhat less than the consented volumes. Annual meter readings are available for most large groundwater takes, but only from 2002 onwards. Figure 7.25 provides a broad evaluation for the Wairarapa Valley regarding the proportion of the maximum consented annual abstraction volume which was used over the period 2002/03 to 2008. Reliable annual meter readings were compared against the consented take and the resulting plot illustrates that very few takes exceed 50% of their annual maximum allocation and that most water users abstract 10-30% of their allocation on an annual basis.

Figure 7.26 shows a cumulative frequency plot for the same data from which it can be seen that 75% of meter readings show that the annual use was 35% (or less) of the consented annual volume. It also shows that only 10% of readings have an actual annual use greater than 50% of the allocated volume.

Manual weekly meter readings were taken during the 2006/07 irrigation season from 21 larger takes in the Tawaha and Riverside groundwater zones in the Lower Valley catchment. These readings showed that annual use during the irrigation season was on average 27% of the annual allocated volume (the range 11-40%). It is expected that irrigation behaviour is similar in the Middle Valley catchment.

The metering exercise demonstrated that resource consent holders tend to abstract on a daily basis, at a rate of up to about 60-70% of the consented daily rate when required. However, on an annual basis, the usage is considerably less than allocated volumes. It is therefore clear that the methodology used to calculate annual allocations requires review.

7.6.3 Abstraction modelling

Analysis of the Middle Valley catchment requires a reasonably good knowledge of groundwater use, particularly the timing of irrigation abstraction, short-term (weekly) abstraction rates, and the total amount of water abstracted during each irrigation season. Depending upon climatic conditions and changes in irrigated area, there is often a considerable inter-seasonal variability in both abstraction scheduling and in the total amount of water abstracted over any particular season.

Continuous weekly or fortnightly groundwater abstraction (metering) data are required in order to adequately characterise and quantify both current and historical water usage. However, there are limited absraction records available amd therefore modelling was required to produce a synthetic abstraction record for this study.

A methodology based upon the utilisation of soil moisture balance modelling and annual metering data (where available) was developed to model historic groundwater abstractions on a weekly basis for the period 1992 to 2007 (the numerical model calibration period). A variable soil moisture deficit linked ‘adjustment factor’ was also applied to consented daily maximum volumes to account for the observed disparity between maximum consented and actual abstraction quantities.

Estimation of historic irrigation season timing was made using a ‘soil moisture deficit trigger’ as an indicator of when pumping was likely to have started and stopped for a particular season. The pilot meter reading project carried out during 2006/07 (28 water takes) and the more extensive water meter survey in 2007/08 were used to help identify the trigger level.

Appendix 5 contains the detailed methodology developed for this study of abstraction simulation. Figure 7.23B shows the results of the abstraction modelling for the Middle Valley catchment for the period 1992 to 2007. Also shown in the diagram is the consented abstraction for this period to illustrate the disparity between actual (modelled) and consented abstraction.

7.6.4 Non-consented (‘permitted’) takes

Groundwater takes of less than 20 m^3/day do not require resource consent under the current Regional Freshwater Plan (Wellington Regional Council 1999) and are termed ‘permitted’. The volume of groundwater taken as a permitted activity within the Middle Valley catchment was estimated from the location of known bores, associated land use (using the ‘Agribase’ database) and the assumed abstraction rates in Table 7.6.

Table 7.6: Assumed daily water demand in relation to land use applied in the estimation of groundwater taken in the Middle Valley catchment as a permitted activity

Use	Quantity (L/day)
Arable	20
Dairy	1–40
Domestic / lifestyle	0.5
Forestry	20
Industrial	20
Irrigation	20
Pig	1
Poultry	10
Public supply	20
Stock	0.5–20
Swimming pool	20
Unknown	0.5

The distribution of permitted takes is shown in Figure 7.27. There are a total of 750 bores in the catchment cumulatively abstracting an estimated volume of 4,000 m^3/day, or approximately 2.5% of consented groundwater abstraction volume. Cumulatively, the volume of permitted groundwater takes is therefore not significant in relation to consented takes, although there may be localised effects from dense clusters of permitted takes within lower permeability sediments – such as around the Carterton area.

8. Hydrochemistry

8.1 Introduction

Water chemistry data for the Middle Valley catchment supported the development and refinement of the conceptual hydrogeological model. In particular, water chemistry data assisted in stratigraphic correlation work where evidence from other sources was weak or lacking. This section presents the main findings of multivariate statistical analyses carried by GNS Science (Daughney 2007) on the groundwater and surface water chemistry of the Middle Valley catchment. It also summarises the results of groundwater age dating and isotope testing. The analysis builds on previous work presented by Morgenstern (2005) as part of Phase 1 of the Wairarapa Valley groundwater resource investigation (documented by Jones and Gyopari (2006)).

8.2 Multivariate statistical analysis

8.2.1 Background

Multivariate statistical analysis of hydrochemistry data can provide valuable insights into chemical patterns within the groundwater systems of the Middle Valley catchment. Two kinds of multivariate statistical analysis incorporating both groundwater and surface water chemistry data were undertaken by GNS Science (Daughney 2007). A full account of the work is contained in Appendix 6. The methods employed were:

a. **Hierarchical cluster analysis (HCA)**: used to define hydrochemical categories and assign monitoring sites to specific groups. This approach was recently employed to categorise monitoring sites in the New Zealand National Groundwater Monitoring Programme (Daughney and Reeves 2005). HCA is performed purely on the basis of groundwater chemistry, and does not explicitly account for any factors such as bore location, bore depth or aquifer lithology. Thus HCA can provide a simple summary of the variation in groundwater chemistry across the Middle Valley catchment without any prior assumptions regarding the conceptualised hydrogeology.

b. **Discriminant analysis (DA)**: used to categorise sample sites into two or more pre-defined groups (Riley et al. 1990; Lambrakis et al. 2004). DA can be used to predict the likelihood of whether a particular bore belongs to a hydrostratigraphic unit on the basis of its water chemistry. DA is similar to HCA, but whereas HCA completely ignores the location and depth of a bore, DA considers the bore's assumed hydrostratigraphic unit explicitly.

The investigation utilised analytical results (44 analytes) for 554 water samples collected from 137 monitoring sites. Not all samples were analysed for every analyte and 78 monitoring sites were sampled on only one occasion. To facilitate application of the multivariate statistical methods, the median value for each analyte was calculated at each monitoring site (see Daughney 2005, Appendix 6).

8.2.2 Hydrostratigraphic unit classification for chemistry study

Seven hydrostratigraphic units were identified as a basis for DA analysis. These are consistent with general hydrostratigraphic divisions identified in Table 7.1, although further subdivision of some units was made to identify individual gravel aquifers. Table 8.1 lists the units adopted for the hydrochemistry study and the corresponding hydrostratigraphic units. Each hydrochemical monitoring site was assigned to a particular unit based on the conceptual hydrogeological model but without any specific reference to hydrochemistry (see Appendix 6, Figure 1 for spatial distribution and further discussion).

Table 8.1: Hydrochemical units and corresponding hydrostratigraphic units for the Middle Valley catchment

Hydrostratigraphic unit	Hydrochemistry study unit
Alluvial fans gravels (Q2 – Q8)	Unit 6 (Q2 – Q8 fan gravels)
Q1 Unconfined aquifer	Unit 1 (Q1 Alluvium)
Q2-4, Q6, Q8 Aquifers	Unit 2 (Q2-4 – Parkvale sub-basin) Unit 3 (Q204 – Ruamahanga valley) Unit 4 (Q6 Parkvale sub-basin) Unit 5 (Q8 Parkvale sub-basin)
Q5 + Q7 Silts/clay aquitards	
	Unit 7 (older than Q8)

8.2.3 Hierarchical cluster analysis

HCA was conducted using log-transformed median values of conductivity and the concentrations of the seven major ions (Ca, Mg, Na, K, HCO_3, Cl and SO_4)[11]. These analytes were selected for HCA as the most likely to reflect differences in aquifer lithology. Analytes such as Mn, NO_3 and NH_4 were excluded from HCA because their concentrations are probably controlled more by redox potential rather than by aquifer lithology. Variations in pH across the study area were quite small and thus pH was also excluded from HCA.

HCA analysis (detailed in Appendix 6) resulted in the identification of two major hydrochemical categories:

- **Category A**: groundwater is relatively dilute with Ca and HCO_3 as the dominant cation and anion, respectively. This type of chemistry might be expected for young groundwaters recently recharged from rivers.
- **Category B**: groundwater is more concentrated with Na and HCO_3 as the dominant cation and anion, respectively. This type of chemistry might indicate that the groundwaters are slightly older and/or a greater proportion of recharge is from rainfall infiltration (salts are accumulated during passage through the soil zone).

[11] Ca – Calcium, Mg – Magnesium, Na – Sodium, K – Potassium, HCO_3 – Bicarbonate, Cl – Chloride, SO_4 – Sulphate, Mn – Manganese, NO_3 – Nitrate as NO_3-N, and NH_4 – Ammonia as NH_4-N.

Category A groundwater can be divided into two subcategories (A1 and A2), and Category B can be divided into seven subcategories (B1, B2 and B3 are hydrochemically similar to each other, B4, B5 and B6 are hydrochemically similar to each other, and B7 is more distinct). Figure 8.1 shows the distribution of these units.

The results of HCA appear to be broadly consistent with the conceptual hydrogeological model (compare Appendix 6, Figures 1 and 3). Most of the hydrochemical categories defined by HCA appear to correspond to one of the hydrostratigraphic units. For example, subcategories A1, A2, B1, B2, B3, B5 and B7 are generally consistent with the hydrochemical expectation for units 1, 6, 4, 3, 5, 2 and 7, respectively. Subcategories B4 and B6 are distinguished by high concentrations of K and SO_4 (as well as high NO_3, although this analyte was not considered in the HCA) which might indicate that the hydrochemistry is controlled more by the impacts of local land use than by hydrostratigraphy. Specific details of their relationships between subcategories defined by HCA and the hydrostratigraphic units are discussed in Appendix 6.

HCA classification has therefore proved useful in both testing and refining the hydrogeological conceptual model for the Middle Valley catchment. HCA groups A1 and A2 show probable young water recharge from river leakage and rainfall respectively (Figure 8.1). Deeper semi-confined aquifers and confined aquifers in the Parkvale and Carterton sub-basins show more evolved water types (B1-B3 & B4-B6). The definition of the B7 group has highlighted a more complex groundwater system in the area on the eastern margin of the Parkvale sub-basin.

8.2.4 Discriminant analysis

Results from discriminant analysis (DA) are broadly consistent with the defined hydrostratigraphic units (compare Appendix 6, Figures 1 and 6). For the 99 monitoring sites that could be classified by DA, 75 were correctly assigned to the assumed hydrostratigraphic unit.

8.3 Groundwater residence time

Groundwater residence times and flow pathways in the Middle Valley catchment were examined using tritium, CFC, SF6 and C14 data. A detailed description of this work is discussed in Morgenstern (2005). Since this study, supplementary historical data and new data collected during this project (Section 5.3) contributed to a revised compilation of mean residence times as shown in Figure 8.2 (see also Appendix 6).

8.3.1 Greytown area (Waiohine plain)

Three sites were sampled for age-determination in the Greytown area which indicated a groundwater age of about one year[12] (Figure 8.2). The downgradient Tilsons Creek spring mean residence time was measured at about two years on three separate occasions.

[12] One year at bore S26/0487 and S26/0911 and two years at the Tilsons Creek Spring head on Jericoe Street, Greytown.

8.3.2 Alluvial fans

One spring[13] was sampled on the Waingawa alluvial fan on two separate occasions providing a consistent residence time of one year.

8.3.3 Carterton and Parkvale sub-basins

Several bores in close proximity were sampled in the Carterton area[14], all providing mean residence times of 40-54 years in semi-confined aquifers.

Two previous age-dates for the deeper confined aquifers in the Parkvale sub-basin (Jones and Gyopari 2006) provided residence times of greater than 110 and 150 years. Radio-carbon analysis determined a mean residence time of 100 years for the confined Q6 aquifer at bore S26/0576, and 6,000 years for the deeper bore S26/0568 (possibly Q8 aquifer).

8.4 Stable isotopes

The stable isotopes of water (^{18}O and ^{2}H) can indicate the source of recharge (river or rain) because they are able to distinguish between high altitude rainfall which characterises rivers sourced in the Tararua Range, and low-altitude rainfall on the valley floor. Additional stable isotope data from historical sources and new samples were used to supplement the historic isotope database from which a revised analysis of groundwater residence time for the Middle Valley was made.

Gunn et al. (1987) concluded that predominantly river-recharged groundwater will be less negative than -6.3 ‰ in ^{18}O. Butcher (1996) postulated that predominantly rainfall-recharged groundwater has a more negative ‰ D (deuterium) than -41. The stable isotope data are contained in Appendix 6 and Figure 8.3 shows ^{18}O plotted against D for groundwater samples collected in the catchment to help discern predominant recharge signatures.

8.5 Discussion

The multivariate statistical analysis, mean residence time data and stable isotope data were used to support the conceptual hydrogeological model. The main conclusions are outlined below.

8.5.1 Greytown-Waiohine plains

HCA classification of shallow bores within the Q1 gravel-dominated aquifers of the Waiohine plains show a water type consistent with young river recharge (HCA class A1-Figure 8.1). The one outlier in the data-set (S26/0395) is a Greytown bore at greater depth than the rest in the data-set.

Groundwater residence time data concur with HCA analysis, with young groundwater (one year) sampled from two bores (S26/0487 and S26/0911) downgradient of the Waiohine River. Three results (between 1983 and 2008) at one of the major spring out-flows in the area at Tilsons Creek show a mean residence time of two years (Figure 8.2).

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13 S26/0244.

14 Two of these wells are used by Carterton District Council for public water supply.

Stable isotope data from bore S26/0487 and Tilsons Creek spring also concur with a western river recharge signature (Figure 8.3).

The major recharge source as defined by hydrochemical data for this area is presumed to be river.

8.5.2 Upper fan systems

A number of sites on the fan systems north of the Carterton Fault and west of the Mangatarere Stream have a HCA classification of young, possibly rainfall-recharged water (HCA class A2 – Figure 8.1). Available age-dating results for the Waingawa spring are consistent with these data, having a mean residence time of one year (Figure 8.2). Stable isotope data support the rainfall-recharge hypothesis suggested by the HCA data (Figure 8.3).

8.5.3 Carterton and Parkvale sub-basins

HCA analysis shows a number of groupings in the Carterton and Parkvale sub-basins with more evolved and reduced water types occurring in semi-confined and confined aquifers (Figure 8.1). Mean residence time data are consistent with the HCA data suggesting more evolved groundwaters in the sub-basins. Residence times of approximately 50 years occur in the semi-confined Carterton aquifer; 100 years in the upper confined Parkvale aquifer (bore S26/0576 – 32 m depth) and 6,000 years in the lower confined Parkvale aquifer (bore S26/0568 – 45 m depth). Although there appears to be a connection between the different confined Parkvale aquifers, the age-dating results suggest a substantial separation of the deeper aquifer due to its considerable age.

Stable isotope sample results for the confined Parkvale aquifer imply a rainfall-recharge signature supporting the concept of a recharge source in the upper fan areas for the basin aquifers. Isotope results from the Carterton sub-basin aquifers suggest a river or mixed river / rainfall source of recharge (Figure 8.3).

Samples from several sites (HCA group B7) located on the eastern side of the Parkvale sub-basin associated with uplifted older sediments of Fernhill-Tiffen Hill do show slightly different water types. This outlines the probably complex compartmentalisation in the structurally deformed area as shown by geophysics (Section 6.2.2).

8.5.4 Middle Ruamahanga valley

Due to limited HCA results no mean residence time or stable isotope results are available for the middle Ruamahanga valley. There is one grouping of slightly reduced groundwater clustered south of Tiffen Hill but the limited data means that it is difficult to determine if these waters are influenced by outflow from older groundwaters of the Parkvale sub-basin, or shallow aquifers associated with the Ruamahanga River.

9. Conceptual hydrogeological model

9.1 Purpose

The numerical groundwater modelling process draws together large quantities of data from which a conceptual interpretation for a groundwater system is developed. The conceptual framework is subsequently translated into a quantitative numerical model relying upon hydrogeological analysis to build and calibrate the model under a range of stress conditions. Emphasis was therefore placed on producing a sound conceptualisation of the groundwater system as a fundamental basis for numerical modelling.

The Murray Darling Basin Commission (MDBC) modelling guidelines (Middlemis 2001) describe the purpose, form and significance of a conceptual model as follows:

- *Development of a valid conceptual model is the most important step in a computer modelling study.*
- *The conceptual model is a simplified representation of the essential features of the physical hydrogeological system and its hydro-geological behaviour, to an adequate degree of detail.*
- *Conceptual models are subject to simplifying assumptions which are required because a complete reconstruction of the field system is not feasible, and because there is rarely sufficient data to completely describe the system in comprehensive detail.*
- *The conceptualisation is developed using the principle of parsimony such that the model is as simple as possible while retaining sufficient complexity to adequately represent the physical elements of the system and to reproduce system behaviour.*

Figures 6.3 to 6.7 are a series of cross sections which describe the conceptual model developed for the Middle Valley catchment. The various boundaries, physical geological framework, hydrological features, and water balance components are discussed separately below.

9.2 Groundwater environment characteristics

The Middle Valley catchment covers an area of approximately 300 km^2 and incorporates the Waiohine, Mangatarere, middle Ruamahanga, and part of the Waingawa fluvial systems. The groundwater basin contains a heterogeneous sequence of basin-fill late Quaternary fluvio-glacial sediments.

The basin is structurally complex as a result of extensive (active) faulting and folding, which have influenced drainage patterns and the depositional environments of the ‘ate Quaternary aquifers. Fold and fault structures have additionally caused blocks of older less permeable sediments and basement greywacke rock to be uplifted and displaced against younger water-bearing strata around Tiffen Hill and Fernhill. The structural deformation is responsible for the creation of localised sub-basins beneath the Parkvale and

Carterton areas where sequences of thin reworked confined gravel aquifers have developed.

On a broad scale, the Middle Valley catchment groundwater environment consists of a shallow unconfined, highly dynamic flow system connected to rivers. Large areas of relatively low permeability, poorly-sorted fan gravels occur on the western side of the valley against the Tararua Range. The fan sequence, as it becomes more distal, grades and segregates into a sequence of discrete reworked permeable aquifers in the sub-basin areas. Intervening poorly sorted gravels and fine grained interglacial aquitards confine and separate reworked gravel intervals.

9.3 Groundwater system boundaries

The boundaries of the Middle Valley groundwater catchment are shown in Figure 9.1 and are as follows:

Western boundary: this boundary coincides with the Wellington Fault and represents the emplacement of the younger Quaternary sequence against very low permeability greywacke bedrock along a sub-vertical plane.

Northern boundary: this boundary separates the Middle Valley from the Upper Valley catchment. It is placed along a groundwater divide coincident with the Waingawa River.

Eastern boundary: the eastern hill country consists of a sequence of low permeability greywacke basement, or mudstones, shales, limestones and clay-bound gravels of Tertiary and early Quaternary age. This no-flow boundary dips westwards into the groundwater basin.

Southern boundary: this boundary separates the Middle Valley from the Lower Valley catchment and represents a groundwater divide. It is also a geological boundary at the contact between Q1 Waiohine gravels and the older Tauherenikau fan gravel sequence to the south.

Internal physical boundaries: Tiffen Hill and Fernhill represent low permeability older sediments and basement greywacke rock. These structures represent internal physical boundaries within the flow system.

Groundwater system depth and base: The Middle Valley groundwater system has a variable depth ranging from about 10 m in the east to about 50 m beneath the Parkvale sub-basin. The top of the middle Quaternary deposits (mQa) is assumed to be the base of the groundwater flow system (Table 6.1). Formations beneath the top of mQa are regarded to be largely isolated from the shallower actively recharged system since they are more compact and, because of their general lithological nature, are likely to be of significantly lower permeability. However, groundwater also occurs where conditions are favourable within mQa and older formations and reasonable yields may be encountered locally.

9.4 Geological framework

The catchment can be viewed as six general areas which exhibit distinctive hydrogeological characteristics. They are delinated on Figure 9.1 and their distinguishing characteristics are listed in Table 9.1 which also identifies the hydrostratigraphic units (described in Section 7.1) within each area.

Table 9.1: Hydrogeological sub-areas of the Middle Valley catchment

Area	Principal hydrostratigraphic units / main features
Area 1: Greytown-Waiohine plains	Q1 Unconfined aquifer – shallow (<15 m) reworked highly permeable gravels deposited by the Waiohine River. The river is a groundwater recharge source. The unconfined aquifer discharges into Papawai/ Tilsons/ Muhunoa spring-fed streams.
Area 2a: Carterton sub-basin	Q2-4, Q6 and Q8 aquifers; Q5 and Q7 aquitards– discrete gravel zones within overall relatively low permeability poorly sorted gravels and silts. Merges with upper fan deposits to the west and Parkvale to the east across the Brickworks flexure.
Area 2b: Parkvale sub-basin	Q2-4, Q6 and Q8 aquifers; Q5 and Q7 aquitards – thin (<5 m) reworked gravel Q6 and Q8 aquifers, confined, artesian in lower Parkvale to at least 50m depth. Basin is disrupted by geological structure. Spring discharges from Q2-4 gravels. Large seasonal ranges in groundwater level exaggerated by abstraction (4-5 m).
Area 3: Main fan systems (Waiohine, Mangatarere, Waingawa)	Alluvial fan gravels (Q2-Q8) – wedge of fan poorly sorted gravels, low yielding aquifers. Spring discharges along faults.
Area 4: Waingawa floodplain	Q1 Unconfined aquifer – permeable gravels 10-20 m thick; significant river/aquifer connection.
Area 5: Fernhill-Tiffen block	Uplifted blocks – uplifted terraces of low permeability Q5 and older. Greywacke exposed on Tiffen and Fernhill. Anticlinal structures.
Area 6: Middle Ruamahanga valley	Q1 Unconfined aquifer – permeable gravels 10-20 m thick; significant river/aquifer connection.

9.5 Hydrological framework and water balance estimation

The conceptual model for the Middle Valley catchment incorporates the hydrological framework – the system stresses in terms of inputs, outputs, regional flows and flows between the various hydrostratigraphic units.

The conceptual components of the water balance as follows.

Inputs:

- Rainfall recharge
- Runoff recharge – surface water inflow from rivers, stream and water races
- Irrigation returns*
- Throughflow from the Upper Valley catchment*

Outputs: Discharge to rivers and streams
Diffuse seepage to wetlands and ET loss
Spring flow
Abstraction from bores (or, more strictly, supply to bores)
Throughflow to the Lower Valley catchment*

* Water balance components shown are regarded to be relatively minor in the context of the regional scale flow budget.

Section 7 provided a comprehensive discussion of the various water balance components, spatial and temporal flow patterns and aquifer hydraulic properties.

It was possible to calculate an independent 'steady state' water balance to provide a basic 'order of magnitude' assessment of the various system inflows and outflows. This provides a a valuable check on the numerical model flow balance predictions. Table 9.2 summaries the estimated water balance for the Middle Valley groundwater catchment.

Table 9.2: Estimated steady-state water balance for the Middle Valley catchment

	In (m^3/day)	**Out (m^3/day)**
Rainfall recharge	190,000	
River flow loss/groundwater recharge	143,000	
River flow gain/ groundwater discharge		170,000
Springs and diffuse evapo-transpiration		140,000
Abstraction		20,000
Total	*333,000*	*331,000*

Bearing in mind the limitations of the estimated equilibrium water balance, it is interesting to note that rainfall recharge and river recharge contribute approximately the same proportions into the balance. Discharge from the groundwater system is dominated by flows back to the surface water environment (rivers, streams and springs). Abstraction appears as a relatively minor component of the balance only because the balance calculation represents average conditions. The peak summer daily consented abstraction rate is 155,000 m^3 (Section 7.6.1), a volume which would clearly equal the natural discharges to rivers, streams and springs.

The sources of the various balance quantities presented in Table 9.2 are as follows:

- *Rainfall recharge*: soil moisture balance model (annual average rate)
- *River inflow and outflow*: values based on concurrent gaugings (average fluxes) (Section 7.4)

- *Springs/evapo-transpiration (ET):* combination of gauging data estimate and balance error
- *Abstraction*: 20% of current daily estimated abstraction (60% of consented rate).

10. Numerical model construction

10.1 Groundwater modelling purpose and objectives

The purpose of the numerical model is to create a reliable tool to assist with the development of new groundwater allocation policy for the Middle Valley catchment of the Wairarapa plains.

Specific objectives of the modelling study are to be achieved in two stages:

Stage 1 objectives:

- Develop a conceptual hydrogeological model for the Middle Valley groundwater system based upon a synthesis of available geological and hydrogeological information.

- Build a numerical groundwater flow model for the Middle Valley groundwater system using an appropriate model code to a level of complexity consistent with the model's purpose and available information.

- Calibrate the model to long-term transient climatic and abstraction stresses using appropriately weighted observed groundwater level and water balance targets. The model should accurately simulate the connection between surface water and groundwater.

- Provide a parameter sensitivity and optimisation analysis and quantify the uncertainties inherent in the calibrated model.

- Quantify regional water balances and their long-term seasonal variability in response to changes in climate and abstraction stresses.

- Identify the limitations of the model.

Stage 2 objectives:

In order to fulfil the purpose of the model a further objective of the study is to simulate a range of detailed abstraction scenarios. These will quantify the sustainable allocation of the Middle Valley groundwater resource and explore effective management options.

Stage 1 objectives are reported in this document; the Stage 2 objectives form Phase 3 of the Wairarapa Valley groundwater investigation and will be documented in a supplementary report later in 2010.

10.2 Model code selection

A number of numerical computer codes can simulate groundwater flow; each has inherent strengths and weaknesses. To meet the objectives of this investigation, important considerations when selecting a suitable model code were:

- Requirement to represent both regional and local-scale features in one integrated model and incorporate important features at both scales.

- Ability to represent complex and irregular geology and complex aquifer conditions.

- Capability to coarsely discretise the mesh/grid in areas where there is little data and low groundwater use (i.e. alluvial fans), but refine the numerical mesh around important features such as rivers.

- Ability to accurately simulate the interaction between groundwater and surface water and facilitate the coupling of a surface water model (MIKE 11) with the groundwater model.

The finite element model FEFLOW (Diersch 2002) was selected because it meets the above criteria, particularly its capability to simulate groundwater flow in complex geological environments in three dimensions. FEFLOW (Finite Element subsurface FLOW system) is an interactive groundwater modelling system for three-dimensional flow and transport in subsurface water resources developed by DHI-WASY GmbH. Finite element methods use sophisticated and powerful algorithms resulting in stable solutions which are suited to modelling in complex geologic areas (Wang and Anderson 1995).

The specific advantages of the FEFLOW application include:

- Flexibility of the mesh design enabling a refinement in areas of interest and therefore a more precise simulation of physical features (pumping bores, rivers, etc.).

- Ability to shape the triangular mesh to complex boundary conditions and along specific features.

- Ability of the elements to conform to the pronounced vertical variation of aquifer / aquitard layers.

- Stable water table simulation that facilitates more accurate simulation of the shallow subsurface (FEFLOW avoids the wetting-drying cycling typical of finite difference models such as MODFLOW that can cause solution convergence and stability problems).

- The possibility to couple FEFLOW with MIKE 11 to simulate the dynamic flow exchange between surface water and groundwater, as a result of the recent development of the IFM Tool (FEFLOW Open Inter-Face Module)

10.3 Model complexity

The MDBC (Middlemis 2001) and Ministry for the Environment (2002) modelling guidelines define model complexity as the degree to which a model application resembles the physical hydrogeological system. A complex model ("Aquifer Simulator") is capable of being used to assist policy decisions regarding sustainable resource management and must be substantiated by the availability of adequate data and a sufficiently detailed conceptual understanding of the groundwater system. Such models require a considerable investment of time, skills and data to develop. It is generally sound practice in the development of such models to stage the process of introducing complexity.

Phase 1 of the Wairarapa groundwater investigation (Jones and Gyopari 2006) resulted in the development of a simple, lumped model which was calibrated to steady-state conditions. This model showed that the essentially single aquifer approach was too simplistic for areas in which multiple confined aquifers exist. Specifically, the steady state 'lumped' model was unable to simulate the multiple deep confined aquifers in the Parkvale sub-basin.

The Phase 2 model for the Middle Valley catchment therefore represents a progression to a complex multi-layer simulation consistent with the purpose and objectives of the Wairarapa groundwater resource investigation. A sufficiently detailed conceptual understanding of the Middle Valley catchment has been developed Section 9) and a large volume of data exists to support model development and calibration.

10.4 Groundwater model development

10.4.1 Domain definition

The model domain was defined using the geological and hydrogeological analyses presented in Sections 6 and 9, in particular the cross sections in Figures 6.3 to 6.7. The groundwater system is defined by the presence of late Quaternary and Holocene alluvial sediments.

The active model domain (Figure 9.1) for the Middle Valley catchment contains the lowland catchments of the Waiohine, Mangatarere and middle Ruamahanga rivers on the main valley floor. Tiffen Hill consists of an uplifted greywacke basement block and is represented as an impermeable area (or hole in the model domain).

The model domain is approximately 13 km wide between the Tararua foothills and the Ruamahanga River (NW-SE), and approximately 19.5 km in length between the Waingawa River and the edge of the Greytown/Waiohine plains (NE-SW).

10.4.2 Finite element mesh

Design and generation of the finite element mesh is the single-most important stage of model construction. A well-formulated mesh is essential for the creation of a stable and accurate numerical simulation.

FEFLOW also requires the creation of a 'super-element mesh' as a basis for controlling the spatial generation and refinement of the finite element mesh. The super-element mesh consists of sub-domains representing hydrogeologically distinct areas defined by physical aquifer boundaries (such as geological boundaries, faults and rivers). Figure 10.1 shows the super-element mesh created for the model domain which contains 25 elements. The Carterton and Masterton faults are represented as individual narrow super-elements of 100 m width.

The super-element mesh also contains line and point 'add-ins' corresponding to rivers, streams and bores; the add-ins are used to ensure that finite element nodes are generated on these features. There are also buffer zones along the edges of some of the super-elements to facilitate a gradation in mesh size between areas where a fine mesh is required (i.e. over the Q1 aquifers) and areas where a coarse mesh is sufficient (i.e. over the low permeability fan areas).

The finite element mesh was generated using the Triangle algorithm (Shewchuk 2002) and is shown in Figure 10.2. Triangle generates high-quality triangular meshes with no numerically unstable small or large angles, and is thus suitable for finite element analysis. Triangle is also an extremely fast meshing tool for complex super-element meshes and incorporates line and point add-ins. The number of elements for each super-element was adapted to give the required mesh density over different areas of the model – the highest density being generated around rivers and over productive aquifer areas. The mesh was also refined along the rivers to enable more accurate simulations of flows between groundwater and surface water.

The resulting finite element model consists of 189,666 elements, 109,200 nodes and nine layers. The distance between the nodes varies from about 500 m on the alluvial fan areas and Fernhill down to about 100 m in the vicinity of rivers and areas underlain by Q1 gravels.

10.4.3 Model configuration

Table 10.1 summarises the model configuration settings.

Table 10.1: Middle Valley catchment model configuration

Type of model	3-D saturated flow
Type of aquifer	Unconfined top layer with phreatic surface
Model layers	Nine layers (10 slices)
Type of simulation	Steady state and transient flow
Type of elements	6-node, triangular prisms
Number of elements	189,666
Number of nodes	109,200
Equation solver	Iterative
Time stepping	AB/TR predictor-corrector

10.4.4 Model layers

The model has nine layers (= 10 slices) to represent the stratified nature of the aquifer system and to adequately simulate vertical head gradients, particularly across aquitard layers. Table 10.2 lists the layer sequence and the corresponding hydrostratigraphic units.

Table 10.2: Middle Valley catchment model layer configuration and corresponding hydrostratigraphic units

Slice and layer sequence	Principal unit	Elsewhere	Slice definition
Slice 1 ----- Ground surface ---	--------------------	-------------------	Phreatic (unconstrained)
LAYER 1	Q1 Gravels (aq)	Dry/inactive	
Slice 2 -----------------------------	--------------------	-------------------	Unspecified
LAYER 2	Q1 Gravels (aq)	Dry/inactive	
Slice 3 -----------------------------	--------------------	-------------------	Unspecified
LAYER 3	Q2-4 Alluvial (aq/at)	Fan gravels	
Slice 4 -----------------------------	--------------------	------------------	Unspecified
LAYER 4	Q2-4 Alluvial (aq/at)	Fan gravels	
Slice 5 -----------------------------	--------------------	------------------	Unspecified
LAYER 5	Q5 Aquitard	Fan gravels	
Slice 6 -----------------------------	--------------------	-------------------	Unspecified
LAYER 6	Q5 Aquitard	Fan gravels/Q6	
Slice 7 -----------------------------	--------------------	-------------------	Unspecified
LAYER 7	Q6 Gravels (aq)	Fan gravels	
Slice 8 -----------------------------	--------------------	-------------------	Unspecified
LAYER 8	Q6 Gravels (aq)	Fan gravels	
Slice 9 -----------------------------	--------------------	-------------------	Unspecified
LAYER 9	Q7-8 Alluvial (aq/at)	Fan gravels	
Slice 10 ---------------------------	-------------------	------------------	Fixed

The layer surfaces were modelled using bore log data and were based upon the geological cross sections shown in Figures 6.3–6.7. Where there were no bore log data layer surfaces were extrapolated to maintain consistency with the conceptual hydrogeological model. Each layer surface (slice) was modelled externally using ArcMap and then imported into FEFLOW as a grid file. The process of developing the slice surfaces was essentially an iterative one of using the cross sections as a control and tailoring the surfaces to maintain consistency with the conceptual model and the geological interpretation of the catchment.

Appendix 7 (Figures 1–5) contains the structure contours for each of the model slices.

Slice 1 represents the ground surface and was modelled using the 20 m contour topographic map. The error in ground surface definition is estimated to be up to +/-5 m.

Layers 1 and 2 are only active where Q1 (postglacial) gravels occur (Figure 10.3). Because FEFLOW requires model layers to extend continuously across the model domain, where the Q1 unit is absent, layers 1 and 2 were fixed at

0.1 m thickness below Slice 1 (land surface) and will become dry during the simulation. Because the free surface (water table) was set as 'unconstrained', the residual water depth does not affect the mass balance for the model or control heads in the unconfined aquifer.

The base of the model coincides with the interpreted lower boundary of the Q8 alluvial sediments which is assumed to represent the base of the groundwater flow system. Figure 10.4 shows structure contours of the model base which has the form of a basin structure deepening in the Greytown, Carterton and Parkvale areas. The influence of structural uplift over Fernhill and between the Parkvale and Carterton sub-basins is clearly visible. The base of the groundwater system rises in the fan areas towards the Tararua foothills. Figure 10.5 shows the total thickness of the groundwater system by subtracting the groundwater surface from the model base elevation. Appendix 6 contains structure contours for the main model layers.

Figure 10.6B-F shows a series of cross sections through the model to illustrate the layer geometry. Specific areas of interest included the Parkvale sub-basin and adjacent Carterton sub-basin separated by an anticline structure ('Brickworks Anticline'). The locations of the section lines are shown on Figure 10.6A.

10.4.5 Initial head conditions

Preliminary initial head conditions for the transient flow model were derived from the heads generated by an initial steady-state model. However, the steady state generated head distribution was not considered to be consistent with the commencing boundary conditions of the transient model and therefore an initial head condition was subsequently generated using the head output from the end of a semi-calibrated transient run. The head output at the end of the 15-year simulations closely matched the starting heads at the beginning of the simulation (both winter conditions).

10.5 Boundary conditions

10.5.1 External model boundaries

The external model boundary (Figure 9.1) coincides with the catchment boundaries as defined during the conceptual model development (Section 9.2). All external model boundaries are of 'no-flow' type.

10.5.2 Rivers and spring-fed streams

Transfer (Cauchy/3rd kind) boundary conditions were assigned along the full lengths of the Waiohine, Mangatarere, Waingawa and Ruamahanga rivers to simulate the interaction between the rivers and the aquifer system. This kind of boundary condition was also used to simulate spring-fed streams such as the Papawai Stream, Tilsons Creek and Muhunoa Stream in the Greytown area.

Diffuse groundwater discharges associated with the Parkvale, Beef Creek and faultline spring systems were simulated using transfer boundary condition as well, but in a slightly different manner to main channel systems.

The locations of transfer boundary nodes for main river and stream channels are shown in Figure 10.7. The northern model boundary is represented by the Waingawa River boundary (a groundwater divide), whilst the other rivers occur as internal boundary arrays.

The transfer type of boundary condition describes a time-varying reference hydraulic head (river stage) which has an imperfect hydraulic contact with the groundwater system. The boundary type allows inflow and outflow of water at a rate proportional to the hydraulic head difference between groundwater and surface water. River stage and a proportionality constant – the 'transfer rate' - need to be assigned to each boundary node.

Transfer boundary conditions require the definition of an area across which flux is calculated. In a regional 3-D model this is achieved by assigning the lines of boundary nodes to two neighbouring slices (slice 1 and slice 2) to create a vertical exchange area. The exchange area in an unconfined aquifer will naturally vary depending upon the saturated thickness of the layer.

10.5.3 Transient river stage modelling using MIKE11

The transfer boundary nodes require the assignment of a time-varying stage height. This was achieved using a surface water model – MIKE11 (DHI 2009). Originally it was intended that the MIKE11 model would be coupled to FEFLOW using the IFMMIKE11 interface module developed by WASY. However, it proved problematic to fully couple the surface water and groundwater models due to numerical instability problems with MIKE11 and exceedingly large model run times. Consequently, MIKE11 transient stage data modelled for each H node were transferred manually to the FEFLOW model river boundary nodes.

The MIKE11 surface water model incorporates the Waingawa and Waiohine rivers, the Mangatarere Stream and the Ruamahanga River between its confluences with the Waingawa and Waiohine rivers. Appendix 8 contains a full description of the MIKE11 model.

The surface water model requires information on channel geometry (in the form of river cross section survey data) and flow monitoring data in order to predict the channel stage heights at specific points (Hnodes) down the river profile over a specified time interval and at specific time steps. The stage data are required by the transfer boundary nodes in FEFLOW.

Regular river cross section surveying is carried out by Greater Wellington as part of its flood protection role. A total of 171 river cross sections with corresponding level data and location co-ordinates were incorporated into the MIKE11 model. Channel cross section surveys are available at approximately 100 m intervals down each of the rivers. Figure 3.2 contains the bed profiles for each of the rivers as modelled by MIKE11.

Measured river flow data for each of the rivers were derived from a number of continuous recorder sites within the model area as listed in Table 10.3 (Figure 3.1 shows the locations of the gauging sites).

Table 10.3: Flow gauging sites used in the MIKE11 surface water model for the Middle Valley catchment

Site	Site No.	Map reference
Ruamahanga River at Wardells	29201	T26:347192
Waingawa River at Upper Kaituna	29246	S26:227324
Mangatarere Stream at Gorge	292243	S26:721485
Waiohine River at Gorge*	292224	S26:117183

* The Mangatarere Stream at Gorge site only started in 1999 but synthetic flow data from 1992 have been correlated from a nearby site thereby extending the flow record.

10.5.4 Transfer of MIKE11 modelled stage data to FEFLOW

Transient river stage heights required by the FEFLOW transfer boundary nodes have been supplied from the MIKE 11 model. The MIKE11 H node stage data, referenced to specified geographic locations, were imported as power function files into FEFLOW. These data were extrapolated to any intermediate transfer boundary nodes between H node sites. This procedure has enabled the accurate representation of the river stage conditions in the groundwater model as it takes into account channel geometry, major surface water abstractions, and time lags between the up-valley gauging sites and points further down the catchment.

10.5.5 Transfer rates

Transfer boundaries require the assignment of a transfer rate to control the leakage rate (or transfer rate) between the river and aquifer. Large values of transfer rate allow free movement of water across the boundary depending upon the head gradient. The transfer rate is calculated by dividing the hydraulic conductivity of the river bed by the thickness of the bed (colmation layer) to provide a value in d^{-1}. Table 10.4 lists the values used in the model which were derived through model calibration.

Table 10.4: Calibrated transfer rates for 3rd kind (Cauchy) boundary conditions in the Middle Valley catchment model

River/stream	Transfer rate (1/d)
Waiohine	
– upper	5
– lower	8
Waingawa, Mangaterere	3
Ruamahanga	2
Papawai, Tilsons	5
Muhunoa	8
Parkvale	8
Beef Creek	8
Fault line springs	8

10.5.6 Diffuse spring discharge boundaries

For the diffuse spring discharge areas of Parkvale, Beef Creek and the fault line springs, the transfer boundary nodes were assigned as an areal network on a single slice (slice 3) to create a horizontal exchange area. Figure 10.7 shows the transfer boundary conditions for the diffuse spring discharge areas. The stage heights for these boundary networks were derived using regionalised bed and water level survey data.

10.5.7 Recharge grid

Recharge was externally modelled on a 500 m^2 grid using the methodology described in Appendix 4 (Section 7.3 provides summary information on the recharge model outputs). Recharge was calculated on a daily time step for the 15-year calibration period, and then 7-day averages were calculated for input to the FEFLOW model. The one-day time step was used because significant errors can occur when running soil moisture balance models at larger time steps.

The gridded recharge data were imported into FEFLOW by overlaying the 500 m^2 square grid as an ArcGIS polygon shape file and then tying each of the grid polygons/cells (1160 in total) via a unique cell ID to a corresponding FEFLOW power function file. The power function file contains multiple time-varying recharge data-sets relating to each rectangular polygon of the grid. The resulting input therefore consists of 1,160 polygons, each having a unique 7-day average recharge record for the 15-year run period.

10.5.8 Groundwater abstractions

Appendix 5 describes the methodology used to create synthetic abstraction data for the calibration period. Each abstraction bore is linked to a FEFLOW power function file which contains the unique time-varying pumping schedules and commencement dates for each consented groundwater take.

10.6 Hydraulic property zonation framework

Development of the hydraulic property zonation framework for the Middle Valley groundwater system has maintained consistency with the conceptual hydrogeological model presented in Chapter 9. The adopted framework was used by the parameter estimation model (PEST).

Figures 10.8 to 10.11 show the hydraulic conductivity and storage zones assigned to each of the model layers. Model layers 1 and 2 represent distinct hydrostratigraphical units, or distinct changes within units. Each of these layers consequently has unique sets of parameter zones. By contrast, layers 3 and 4 provide a broad representation of the deeper heterogeneous fluviatile sequence – the boundary between the layers enables the general stratification of the system to be simulated facilitating the control of vertical flow in the aquifer sequence. These two layers therefore share parameter zones and a more complex parameter zonation framework has been used in the upper two layers due to better characterisation from available data in comparison to the deeper system. Further detail on the model layer design was provided in Section 10.4.4.

10.6.1 Horizontal hydraulic conductivity (Kx,y) zones

(a) Layers 1 and 2

Figure 10.8 shows the horizontal hydraulic conductivity (Kx) parameter zonation for all model layers. The top two layers are active only where the Q1 gravel aquifers associated with the modern drainage pattern occur. Each river system has one or several property zones in recognition that the gravel characteristics can vary between the rivers. The Waiohine River has three Kx zones in layers 1 and 2 (Kx1, Kx23, Kx24). The eastern-most zone (Kx23) is regarded to possess an elevated hydraulic conductivity and represents the most recent alluvium on the Waiohine plains. The remaining rivers (the Waingawa, Ruamahanga and Mangatarere) are represented by a single zone each - Kx20, Kx22 and Kx21 respectively. The Ruamahanga zone (Kx21) extends through all model layers because the late Quaternary alluvium is fairly thin along the eastern edge of the model and below layer 2, the layer thickness is very small.

(b) Layers 3 and 4

Layer 3 represents the first partially saturated layer over much of the model domain, other than where the Q1 alluvium occurs (in which gravels the water table sits in Layer 1). These layers generally represent Q2-4 age last-glaciation alluvium. The dominant zone is Kx22 which represents the poorly sorted alluvial fans found on the western side of the catchment and at depth beneath the Waiohine plains. This zone extends through all model layers. A central zone (Kx3) represents more distal, better sorted alluvium of potentially high hydraulic conductivity. A separate zone (Kx58) is used for the Fernhill area where older, less permeable sediments occur near the surface.

(c) Layers 5 and 6

These layers correspond to Q5 age interglacial deposits and the presence of a widespread aquitard layer across much of the middle part of the model domain (centred on the Parkvale sub-basin). Zones Kx5 and Kx6 represent the aquitard whilst other areas share the same zones as overlying layers.

(d) Layers 7 and 8

The central part of the catchment contains reworked alluvium of Q6 age – the most productive horizon in the Parkvale and Carterton areas. Three zones are used to represent the Q6 aquifer in a concentric fashion to facilitate a gradual increase in hydraulic conductivity from the outer fan areas (Kx2) through zones Kx7 and Kx8 to the innermost zone centred on the Parkvale sub-basin (Kx9). A separate zone on the western edge of Tiffen Hill is also introduced in recognition of higher yielding bores in this elevated area, distinct from the low-permeability Fernhill mass to the north.

(e) Layer 9

Layer 9 is the lowermost layer in the model and represents Q7-8 age alluvium. The catchment is dominated by zone Kx11 corresponding to the mass of older, low permeability fan gravels. A central zone around Parkvale is recognised as being more permeable and capable of yielding reasonable quantities of groundwater and is represented by zone Kx32.

10.6.2 Vertical hydraulic conductivity (Kz) zones

Figure 10.9 shows the vertical hydraulic conductivity parameter zones for each of the model layers. The zones are identical to the horizontal hydraulic conductivity zone framework.

10.6.3 Specific yield (St) zones

Specific yield (unconfined storage) parameter zones are assigned to layers 1 and 2 for the Holocene Q1 gravels, and to layers 3 and 4 to represent other units within which the water table is situated. Figure 10.10 shows that only one zone is used to represent the Q1 aquifer – Kx35 – in layers 1 and 2. For layers 3 and 4, two zones are used – Kx36 (central area) and Kx37 (upper fans and Fernhill).

10.6.4 Specific storage (Ss) zones

One specific storage (confined storage) zone is used for layers 1 to 6 (Ss38) in recognition of a relatively high and uniform value for this parameter to the base of the Q5 aquitard layer. In deeper layers (7-9) a more complex zonation has been adopted consistent with the observation of increasing confined conditions developing into the centre of the Parkvale sub-basin and the lower storage properties of the deeper fan areas. Four confined storage zones are used for these layers as shown in Figure 10.11 (from the outer fan to Parkvale: Kx39, Kx42, Kx41, Kx40).

10.6.5 Major fault lines

The Masterton and Carterton faults are known to influence the regional flow of groundwater as discussed in earlier sections. To enable the model to simulate the effects of the faults, they are represented as a 100 m wide band extending through all model layers and have been assigned separate hydraulic conductivity zones: Masterton Fault – Kx25 and Kz14; Carterton Fault – Kx10 and Kz13.

11. Model calibration

11.1 Calibration process

The model calibration process entails the adjustment of independent variables (parameters and fluxes) within realistic limits to produce the best match between simulated and measured data (groundwater levels and water balance components such as spring flows and measured river flow losses/gains). The calibration process is therefore an inverse approach conducted by adjusting parameters such as hydraulic conductivity, storage coefficient and recharge, until the solution matches observed data.

Calibration is a necessary, but not sufficient, condition that must be obtained to attain a degree of confidence in a model's prediction. It shows that a model can reproduce system behaviours under a certain set of conditions (Middlemis 2001). However, a sensitivity analysis should also be undertaken to assess the uncertainties inherent in the calibration.

The calibration process traditionally involves a manual trial-and-error phase of systematic parameter adjustment until a relatively good fit between simulated and observed data is achieved. The process is time-consuming and subjective, but nevertheless regarded to be a valuable first step in the model calibration process through which the conceptual model can be tested and the sensitivity of input parameters adjusted if necessary. Automated calibration using inverse estimation algorithms (such as PEST) removes the subjectivity of manual calibration and is able to provide a useful insight to the non-uniqueness of a model.

Manual calibration under steady-state conditions was initially undertaken as a first step for the Middle Valley catchment model as part of the process to evaluate and adjust the conceptual model. This was followed by a manual transient flow calibration phase to obtain a sense of model sensitivity and further test the appropriateness of the conceptual model, boundary conditions and hydraulic conductivity zonation framework.

Following completion of a manual pre-calibration phase, the automated parameter estimation code PEST was used to optimise the calibration, perform a sensitivity analysis and provide information on the uniqueness, or robustness, of the calibration. The PEST calibration was performed over a four-year period during which a wide range of system stresses occurred. Lastly, a verification run was performed over a 15-year period (1992–2007).

11.2 Addressing non-uniqueness

Non-uniqueness is inherent in most complex groundwater flow models and arises because a number of different parameter sets can produce the same model outputs – i.e. multiple calibrations are possible using different combinations of model inputs because certain parameters (such as recharge and transmissivity) are highly correlated. The matching of measured heads alone by a calibrated model does not mean that the hydraulic properties used in the model are correct. This has important implications when it comes to using the model to predict the response of the system to a set of hypothetical stresses (such as future increases in abstraction).

The MDBC modelling guidelines (Middlemis 2001) suggest that the following methods should be employed together to reduce the non-uniqueness of a model:

a) Calibrate the model using hydraulic conductivity (and other) parameters that are consistent with measured values. The range for various parameters is justifiably restricted.

b) Calibrate the model to a range of hydrogeological conditions (a variety of climate conditions plus induced stresses such as abstraction).

c) Where possible calibrate the model using measured water balance fluxes (such as spring flows, river losses/gains) as calibration targets.

The three recommendations were implemented in the Middle Valley catchment model as far as the available data would allow.

With reference to requirement a) hydraulic conductivity ranges have been evaluated using pumping test data (Table 7.5) for the main aquifer units, where available. However, the biased nature of these data towards more productive aquifer zones (rather than regionally representative bulk material values) is recognised.

To address requirement b) the transient model calibration and verification period covered a 15-year period over which both climate stresses and abstraction stresses experienced large variation. This is discussed further in Section 11.5. Figure 7.17 illustrates the calculated range in annual recharge quantities during the transient model calibration period.

In terms of requirement c) Section 7.4 provided a description of the surface water–groundwater connection dynamics and also provided quantification of some of the exchange fluxes between the two systems (such as spring discharge, spatial patterns and amounts of river flow losses and gains). This information was assigned a relatively high weighting during the calibration process to ensure that the simulated water balance was comparable to observed data.

11.3 Calibration evaluation

Model calibration was evaluated in both quantitative and qualitative terms.

Quantitative measures included:

- Mathematical and graphical comparison between measured and simulated heads. Two types of groundwater level measurements were used for calibration – the data collected from monitoring sites (Table 7.2) and data collected during one-off (concurrent) groundwater level surveys.

- Comparison between simulated and measured water balance components. Measured flow losses and gains in rivers (Section 7.4) and spring flows were used to constrain the calibration.

The qualitative assessment of the calibration entailed comparing simulated and observed groundwater flow patterns, comparison of model outputs with the conceptualisation of the groundwater system and evaluation of the patterns of groundwater-surface water interaction with reference to observed patterns.

The MDBC modelling guidelines (Middlemis 2001) provide a list of calibration acceptance measures which were adopted here. The measures are summarised in Table 11.1.

Table 11.1: Calibration acceptance measures employed for the Middle Valley catchment model (after Middlemis 2001)

	Performance Measure	Criteria	Comments
1	**Water balance:** The water balance error term at the end of each model time step is the difference between total modelled inflow and total modelled outflow, including changes in storage, expressed as a percentage of total flux.	A value of less than 1% is a normal guideline for each stress period or for the entire simulation (steady state).	FEFLOW does not calculate the balance error for transient simulations ('imbalance' term includes the error and change in storage).
2	**Iteration residual error:** The error term is the maximum change in head between successive iterations.	Iteration convergence criterion should be set one or two orders of magnitude smaller than the level of accuracy desired in the model head results.	
3	**Qualitative measures:** Patterns of observed groundwater flow. Patterns of groundwater-surface water interaction. Patterns of aquifer response to stresses. Distributions of aquifer properties adopted to achieve calibration.	Subjective assessment of the accuracy of fit between modelled and measured groundwater levels, flow patterns, bore hydrographs, and surface water flows. Justification for adopted model aquifer property zonation and ranges of values.	Should take into consideration the adopted conceptual model, particularly relating to surface water interaction, model descretisation effects and interpolation effects.
4	**Quantitative measures:** Statistical measures of the differences between modelled and measured head data. Mathematical and graphical comparisons between measured and simulated aquifer heads, and flow system components.	Use residual head statistics. Consistency between modelled head values and observed values. Comparison of simulated and measured components of the water budget, including surface water flows, groundwater abstraction and evapotranspiration rates.	A range of quantitative measures should be carefully selected for use in the calibration procedure. It is expected that any model calibration is unlikely to be good in all areas, but it should be good in critical areas.

11.4 Climatic bias check for the transient calibration interval

To ensure that the transient model is not biased towards a particular climatic period (such as an unusually wet or dry period) an analysis of long-term rainfall patterns was undertaken for the Wairarapa Valley.

As discussed in Section 2.3.2, the El Nino Southern Oscillation (ENSO) is the primary mode of natural climate variability that affects New Zealand's precipitation over the two to seven year timescale and the frequency and intensity of ENSO events may be affected by the Interdecadal Pacific Oscillation (IPO). During the 1992-2008 model calibration period a shift in the IPO occurred, with the first six years being during a positive phase and the latter ten years in a neutral phase (although tending negative). The calibration period therefore contains both La Nina and El Nino episodes. La Nina occurred during 1998 to 2000, 2000/01, and notably resulted in the drought of 2007/08. El Nino events occurred in 1993, 1994, 1997/98, 2002/03, 2004/05, and 2006/07. The 'worst' droughts of the calibration period on the Wairarapa plains occurred during the El Nino events of 1997/98 and 2002/03 (Figure 11.1). Overall, when categorising the 16 growing seasons (November to April) of the model calibration period, six were during El Nino, five during La Nina, and five during neutral conditions. This indicates that the calibration is not biased toward any particular phase.

To determine how rainfall within the model calibration period compares to average rainfall conditions, long-term daily rainfall records were obtained from NIWA's National Climate Database. A range of sites that represent different parts of the Wairarapa Valley were selected. Unfortunately, there are no long-term daily rainfall records for the Tararua Range or the foothills along the western side of the Wairarapa Valley. The longest rainfall record for the range is from Greater Wellington's Angle Knob site (starting in 1974), although the initial eight years of data are storage gauge readings (approximately six weekly totals). The site Waiorongomai site in the Rimutaka Range gives an indication of long-term trends on the western side of the valley, although data are only available until the end of 2007.

For the sites with at least 50 years of rainfall data (Bagshot, Bannockburn, Mahaki and Waiorongomai), the mean annual rainfall during the model calibration period was equal to or less than 4.1% different to the mean annual rainfall of the entire data record (Table 11.2). In general, there was a slightly higher standard deviation of annual rainfall totals during the model period indicating, perhaps, that the model period displayed slightly more variability than during the longer-term. However, the range of observed annual rainfalls during the model period fits within the historical range, with the exception of the low annual total for 1997/98 recorded at Mahaki. The annual rainfall graphs in Figure 11.2 show that there was a roughly equal number of 'high', 'low' and 'about average' rainfall years within the calibration period.

Table 11.2: Mean annual rainfall statistics for long-term monitoring sites in or near the Wairarapa. Note annual rainfalls were computed for a July to June year.

Site	Records begin	Mean annual rainfall (entire record) (mm)	Mean annual rainfall,1992-2008 (mm)	Difference
Putara	1974	3,357	3,392	1.1%
Angle Knob	1975	6,934	7,358	6.1%
Bagshot	1924	1,076	1,037	-3.6%
Bannockburn	1937	923	920	-0.3%
Mahaki	1958	764	766	0.3%
Waiorongomai	1929	1,575	1,640*	4.1%

*Does not include data for 2008.

Comparison of seasonal rainfall totals shows that average spring rainfall totals in the model period were higher than average spring rainfall in the long-term records. At all sites except Bagshot, the difference was 10% or more. This could be a reflection of the occurrence of strong El Nino conditions during the model calibration period, enhancing the usual westerly fronts of spring. In contrast, autumn rainfall totals appear to have been lower during the model calibration period than in the long-term records, particularly at the eastern Wairarapa Valley sites (e.g., on average at Bannockburn autumn rainfall was 11% lower in 1993-2008 compared to the records since 1937). The reason for this is unclear, although particularly low autumn rainfalls occurred during El Nino events in 1998, 2003 and 2007 and during the autumn La Nina of 2001.

Overall, data for the 15-year model calibration period (1992-2007) shows that this period had a high variability in climate and is not biased towards any particular climatic phase.

11.5 Preliminary manual steady state calibration

It is customary practice to use a steady state simulation to test the conceptual model, ensure that the parameter zonation framework is appropriate, and check that the model predicts a realistic water balance which is consistent with the estimated fluxes (discussed in Section 7). The steady state process additionally serves to check on model set-up and identify any technical problems prior to proceeding with the transient model calibration.

When an aquifer is in ‘steady state’, inputs and outputs (and therefore groundwater heads) are assumed to remain constant. In other words, the groundwater system is in equilibrium. True equilibrium conditions rarely occur in any groundwater system especially those (such as the Wairarapa Valley systems) which are dominated by volatile river-aquifer fluxes and highly variable rainfall recharge processes. Periods when heads and fluxes remain stable over a relatively long period of time, such as late summer or late winter, are the closest that an equilibrium condition is approached.

Choice of a steady state calibration instant is controlled by the availability of detailed concurrent groundwater head survey data which coincides with relatively stable aquifer conditions. A regional groundwater level survey was undertaken in March 2007 and a second localised survey in the Greytown area in May 2007. Figure 7.3 shows the measurement sites and contoured groundwater levels associated with these surveys.

The steady state model was set up using climate and river stage conditions corresponding to late March 2007 during which there was no rainfall recharge. Since groundwater levels stabilise towards the end of the summer, the system is assumed to approach a pseudo steady state condition. Initial hydraulic conductivity values used were derived from the ranges presented in Table 7.5 but these values were later refined during the steady state and subsequent transient calibration.

Steady state calibration was achieved by manually calibrating the model to head targets measured in 36 bores of various depths. The results of the steady state run are shown in Figure 11.3 and the calibration statistics are summarised in Table 11.3. The overall residual mean of the calibration is encouragingly low at -1.9 m. The highest residual of -8.1 m (bore S26/0779) relates to a very shallow dug well which possibly intersects a perched water table.

Table 11.3: Steady-state calibration statistics for the Middle Valley groundwater model

Statistical performance measure	Calibration statistic	Unit
Absolute residual mean	-1.93	m
Min. residual	-8.12	m
Max. residual	1.46	m
Sum of residuals	76.6	m
Residual standard deviation	2.1	m
Observed range in head	90.31	m
Mean sum of residuals	2.19	m
Scaled mean sum of residuals	0.07	%
Sum of residual squares	319.9	m^2
Root mean square (RMS) error	3.01	m
Scaled RMS	3.34	%

The root mean square (RMS) statistic is an absolute measure of the calibration and is problem-specific (its value is affected by the measured values). It is a good indicator of error, along with the scaled RMS. A scaled RMS of 3.3% shows that the ratio of error to the total head differential is small and is indicative of a good match between measured and observed groundwater levels, flow gradients and spatial flow patterns.

Figure 11.4 shows both the simulated steady state head distribution and the observed head distribution derived from the March 2007 piezometric survey. Both data-sets have been contoured using the same data points and contouring algorithms. Comparison of the two contour sets shows a good agreement with the simulated regional flow pattern.

At a regional scale within such a heterogeneous aquifer system, the preliminary steady state calibration provides confidence in the conceptualisation of the flow system and the assumptions that have been adopted.

11.5.1 Steady state mass balance

The steady state mass balance (inflow and outflow rates) is outlined in Table 11.4. Because the Middle Valley groundwater catchment is effectively a closed system, the inputs via rainfall recharge and river leakage must balance the outflows to the surface water environment (and abstraction).

Total inflow is about 230 million litres per day (ML/d) – solely from river recharge. Outflow from the groundwater system is dominated by discharge back into the rivers (172 ML/d).

Table 11.4: Modelled steady-state mass balance for the Middle Valley groundwater model (March 2007 conditions)

Flow component	Inflows (m^3/day)	Outflows (m^3/day)
Rivers	230,500	172,000
Abstraction		59,000
Rainfall recharge	0	
Total	*230,500*	*231,000*

Comparison of the steady state model output and the estimated water balance for the catchment presented in Table 9.2 shows that the simulated and estimated flows are of a consistent order of magnitude. Table 9.2 presents an estimated average annual balance which incorporates recharge and therefore the total fluxes in this balance would be expected to be higher than the steady state balance for late summer. The lower groundwater levels at this time of year induce more flow out of the rivers compensating for the neglibible rainfall recharge. This result is encouraging as it provides confidence in the conceptualisation of the groundwater system, including boundary condition assignment and aquifer stress conditions.

11.6 Transient model calibration

11.6.1 Transient calibration set-up

The transient calibration model was set up using just over four years of data for the period 1 August 2000 to 14 December 2004. The relatively short time period was selected to ensure workable model run times for the PEST-automated calibration process. The calibration period incorporates a wide range of climatic conditions (from very dry to wet years) and covers a period during which groundwater abstraction significantly increased. It therefore represents a timeframe over which there were a large range of system stresses to facilitate a more robust calibration.

A calibration verification run was subsequently performed using monitoring data both prior to and after the calibration data-set for the period 1 July 1992 to 1 May 2007.

The transient groundwater model was run at a weekly time step. Choice of a seven-day stress period is consistent with the temporal responses of the groundwater system to stresses and monitoring data availability.

11.6.2 Automated calibration (PEST)

Calibration of the transient model was undertaken using the PEST inverse model (Version 11, Doherty 2008) in parameter estimation mode. The calibration process relied principally on groundwater level observation targets and also on water balance data relating to fluxes between the aquifer and surface water systems.

Because FEFLOW (version 5.4) does not support the most recent version of PEST, scripts to facilitate the exchange of data between the FEFLOW input and output files (*.fem and *.dar) and PEST were written. Appendix 9 contains a description of the PEST interface developed for FEFLOW.

PEST utilises the parameter zonation framework described in Section 10.6 (see Figures 10.8 to 10.11). The PEST inverse model was initially run for a single iteration to identify highly correlated parameters and insensitive parameters resulting in the fixing of some parameters prior to proceeding to the automated calibration process.

A total of 29 unknown hydraulic conductivity (horizontal and vertical) and unconfined and confined storage parameters were initially presented for estimation by PEST. The unknown parameters were allowed to vary between prescribed upper and lower bounds whilst the objective function was minimised. The bounds were prescribed on the basis of groundwater pump test data and plausible ranges for the type of material contained within each zone. As parameters reached their bounds or became insensitive during the PEST inversion process, additional zones were fixed by manual intervention of the PEST run. Eventually, a total of 42 zones were fixed, including river boundary transfer rate zones. Table 11.5 lists the initial unknown and fixed parameter zones.

Recharge was not estimated using PEST due to the complexity of the distributed model which incorporates 1,160 recharge zones. Confidence in the recharge inputs was gained through the independent verification process as documented in Appendix 4. Therefore recharge was not treated as a variable parameter in the calibration process.

Table 11.5: Middle Valley model transient PEST calibration parameter zone designation (Kx – horizontal hydraulic conductivity, Kz – vertical hydraulic conductivity, St – specific yield, Ss – specific storage, it – transfer rate in, ot – transfer rate out). Kx and Kz values are in m/day. All PEST estimated parameters are log-transformed.

Unknown parameter	Initial value	Lower bound	Upper bound	Fixed parameter	Value
Kx01	323	100	400	it43	5.0
Kx02	10	10	60	it44	8.0
Kx03	56	20	90	it45	3.0
Kx07	40	10	40	it46	2.0
Kx08	45	10	150	it47	3.0
Kx09	90	50	200	it48	8.0
Kx21	350	150	350	Kx04	34.6
Kx22	300	100	300	Kx05	0.003
Kx23	450	100	450	Kx06	1.0
Kx25	0.25	1.00E-02	2	Kx10	0.7
Kx26	54	10	70	Kx11	10.0
Kx32	20	20	50	Kx20	270.0
Kz12	0.2	5.00E-02	0.5	Kx24	46.0
Kz15	3	1	10	Kx58	20.0
Kz17	0.0003	5.00E-06	5.00E-03	Kz13	0.1
Kz18	0.0017	1.00E-05	5.00E-03	Kz14	0.5
Kz28	0.8	0.1	1.5	Kz16	0.8
Kz29	0.4	0.1	1.5	Kz19	0.001
Kz30	0.9	0.5	2	Kz27	0.010
Kz31	0.5	0.1	0.8	Kz33	0.04
Kz57	0.00011	5.00E-06	5.00E-03	Kz34	0.04
Ss38	0.00015	5.00E-06	5.00E-04	Kz55	0.5
Ss39	0.00003	5.00E-06	5.00E-04	Kz56	0.1
Ss40	0.00001	1.00E-06	5.00E-04	Kz59	0.1
Ss41	0.00005	5.00E-05	5.00E-04	ot49	5.0
Ss42	0.00021	5.00E-06	5.00E-04	ot50	8.0
St35	0.10	8.00E-02	0.15	ot51	3.0
St36	0.06	2.00E-02	0.15	ot52	2.0
St37	0.02	1.00E-02	0.15	ot53	3.0
				ot54	8.0

11.6.3 Calibration targets, observation data processing and weighting

Figure 11.5 shows the locations of 21 long-term monitoring bores used in model calibration. The bore details are listed in Table 11.6. The sites are distributed across the Middle Valley catchment and measure groundwater levels at various depths ranging from less than 0 m to greater than 50 m.

Table 11.6: Middle Valley catchment transient model groundwater level calibration targets (refer to Figure 11.5 for locations)

Monitoring bore	Depth (m)	Continuous or Manual / Dedicated or Pumping	Geological unit	Calibration weighting*
Area 1: Greytown-Waiohine plains				
S26/0490 (Perry)	5	M / D	Q1	1
S26/0500 (Rogan)	3.4	M / D	Q1	1
S27/0225 (Hammond)	4.6	C / D	Q1	1
S26/0547 (Craig)	4.3	M / P	Q1	0.75
S26/0545 (Craig)	18	M / D	Q2-4	0.75
Area 2: Parkvale-Carterton sub-basins				
S26/0675 (McNamara)	31.5	M /D	Q8	1
S26/0568 (Denbee)	45	M / P	Q6	0.5
S26/0743 (Baring)	33	C / P	Q6	1
S26/0738 (Towgood)	5.4	C / P[15]	Q2-4	1
S26/0155 (Tulloch)	13.4	M / P	Q2-4	0.75
S26/0656 (WCB Tulloch)	78.05	M / D[16]	Q8[#]	0.5
S26/0658 (Craig)	8	M / P	Q2-4	0.5
Area 3: Upper Waiohine fan				
S26/0223 (Nicolson)	9.9	M / P	Q2-4	0.5
S26/0242 (E Coast Fert)	7.5	M / D	Q2-4	1
S26/0229 (E Coast Fert)	23.8	M / D	Q2-4	1
S26/0236 (WCB Oldfield)	41.4	M / D	Q6	1
Area 4: Waingawa floodplain				
S26/0308 (Oldfield)	5.5	C / D	Q1	1
S26/0298 (Oldfield)	7	C / P	Q1	0.5
Area 5: Fernhill				
T26/0326 (McKay)	10	M / P	Q2-4	0.75
Area 6: Middle Ruamahanga valley				
S26/0749 (Blundell)	10	C / D	Q2-4	1
S27/0248 (Morrison)	7.9	M / P	Q2-4	0.75

* Calibration weighting: 1 = reliable, 0.75 = reasonable, 0.5 = poor.

The data were processed to provide a representative value every seven days resulting in 10,205 head observations at the 21 monitoring sites. The monitoring data for bores with automatic recorders were averaged over seven days, whilst manually collected groundwater level monitoring data were used in their raw form in the calibration and the data points extrapolated to the model output times at the end of each stress period. Monitoring nodes were set up on specific slices dependent upon the bore depth.

[15] Manual up to December 2001 and continuous monitoring after this date.

[16] Continuous for the first two years.

A calibration weighting was assigned to the monitoring bores according to an assessed reliability of the data; those bores which are dedicated monitoring bores and are either continuously or manually operated were given a weighting of 1 (reliable). Sites which are pumping bores or that have unreliable bore construction information were assigned a weighting of 0.75 (reasonable) or 0.5 (poor).

Concurrent river flow gaugings (see Section 7.4) also provided important information on the quantities of water moving between surface water and groundwater for specific reaches of river. Spring flow gaugings additionally provided data on the magnitude of groundwater discharge to the various spring systems in the Middle Valley catchment.

Concurrent river flow data and the spring gauging data were used as calibration targets for the transient model. The targets were not used by PEST due to the restrictions inherent in the FEFLOW model output file format. However, parameters which are sensitive to surface water interactions (hydraulic conductivity in the vicinity of rivers and springs and transfer rates) were manually constrained during the PEST calibration to ensure the final calibration was consistent with the water balance targets.

11.6.4 Objective function formulation

The objective function is used to describe the match between the simulated groundwater heads and the observation data. Its formulation is therefore critical for automated model calibration and for this model the objective function was formulated as the sum of squares of residual between target groundwater levels (historic monitoring data) and model simulated groundwater levels.

11.6.5 PEST optimisation results

Table 11.7 presents the PEST optimisation results. The overall objective function (phi) reduced from 14,150 m^2 to 4,640 m^2 (i.e. 67% reduction); the contribution from each of the monitoring bores is also listed. Table 11.7 provides a summary of quantitative measures for the calibration quality following the automated PEST calibration procedure.

The model calibration has a high correlation coefficient (R) which is a measure of the overall unweighted goodness-of-fit between modelled outputs and observations. Ideally, R should be above 0.9.

Table 11.7 shows that Area 2 – the Parkvale and Carterton sub-basin – dominates the objective function (phi = 2,697 m^2). This is partly because the area has more observation bores (and residuals) in comparison to other areas, but it is mainly due to the larger residuals associated with the deeper aquifers in the Parkvale sub-basin (this is discussed further below). The highest phi of 819 m^2 relates to bore S26/0743 (Baring) which is located on the edge of Tiffen Hill in an area of high geological complexity.

The errors and scaled errors presented in Table 11.8 provide further detail on the calibration performance for individual monitoring bores.

Table 11.7: Summary of PEST optimisation for the Middle Valley transient groundwater flow model

Objective function ----->	
Sum of squared weighted residuals (i.e. phi)	4,640
AREA 1 (Greytown–Waiohine plains)	
Contribution to phi from observation group "S26/0490"	15
Contribution to phi from observation group "S26/0500"	0.0
Contribution to phi from observation group " S27/0225 "	14
Contribution to phi from observation group " S26/0547 "	147
Contribution to phi from observation group " S26/0545 "	25
Total contribution Area 1 (916 residuals)	*(201)*
AREA 2 (Parkvale–Carterton sub-basin)	
Contribution to phi from observation group " S26/0675 "	713
Contribution to phi from observation group " S26/0568"	279
Contribution to phi from observation group " S26/0743"	819
Contribution to phi from observation group " S26/0738"	155
Contribution to phi from observation group " S26/0155 "	671
Contribution to phi from observation group " S26/0656"	0.0
Contribution to phi from observation group " S26/0658"	60
Total contribution Area 2 (1,374 residuals)	(2,697)
AREA 3 (upper Waingawa fan)	
Contribution to phi from observation group " S26/0223"	238
Contribution to phi from observation group " S26/0242"	264
Contribution to phi from observation group " S26/0229"	145
Contribution to phi from observation group " S26/0236"	356
Total contribution Area 3 (893 residuals)	(1,003)
AREA 4 (Waingawa floodplain)	
Contribution to phi from observation group " S26/0308"	0.0
Contribution to phi from observation group " S26/0298"	15
Total contribution Area 4 (458 residuals)	(15)
AREA 5 (Fernhill)	
Contribution to phi from observation group " T26/0326"	264
Total contribution Area 5 (229 residuals)	(264)
AREA 6 (middle Ruamahanga valley)	
Contribution to phi from observation group " S26/0749"	114
Contribution to phi from observation group " S27/0248"	346
Total contribution Area 6 (458 residuals)	(460)
Correlation Coefficient ----->	
Correlation coefficient (R)	0.998
Analysis of residuals ----->	
All residuals:-	
Number of residuals with non-zero weight	4,099
Mean value of non-zero weighted residuals	-0.0054
Maximum weighted residual [observation "o1082" t26_0243]	2.85
Minimum weighted residual [observation "o2991" t26_0494]	-5.07
Standard variance of weighted residuals	1.14
Standard error of weighted residuals	1.07

Table 11.8: Measures of calibration performance for the Middle Valley transient groundwater flow model

Monitoring bore	Error (m)					Scaled error (%)	
	No. of residuals	Minimum	Maximum	Absolute mean	Root mean square (RMS)	Scaled mean sum of residuals (SMSR)	Scaled RMS (SRMS)
AREA 1 (Greytown–Waiohine plains)							
S26/0490	229	-0.66	0.84	-0.95	0.26	10.26	13.68
S27/0225	229	-0.64	0.5	-0.17	0.24	27.63	31.58
S26/0547	229	0.43	0.98	0.8	0.8	130.32	131.15
S26/0545	229	-0.17	0.56	0.3	0.32	30.39	32.00
AREA 2 (Parkvale–Carterton sub-basin)							
S26/0675	229	-4.35	0.94	-1.48	1.76	25.34	28.57
S26/0568	229	-0.84	2.81	0.84	1.1	16.87	20.52
S26/0743	229	-5.07	2.24	-1.39	1.89	26.52	31.82
S26/0738	229	-1.67	1.5	-0.52	0.82	26.96	32.28
S26/0155	229	-0.13	2.57	1.57	1.7	70.50	76.23
S26/0658	229	-0.88	0.12	-0.47	0.51	30.33	32.48
AREA 3 (upper Waingawa fan)							
S26/0223	206	-2.4	2.19	-0.4	1	15.65	17.24
S26/0242	229	-2.37	2.85	0.13	1.07	15.17	18.77
S26/0229	229	-1.63	1.33	-0.23	0.8	17.37	21.39
S26/0236	229	-0.33	2.08	1.08	1.25	27.29	31.25
AREA 4 (Waingawa floodplain)							
S26/0298	229	-0.71	0.5	-0.015	0.26	32.24	40.63
AREA 5 (Fernhill)							
T26/0326	229	-3.13	1.38	0.46	1.07	165.79	184.48
AREA 6 (middle Ruamahanga valley)							
S26/0749	229	-0.21	1.82	0.62	0.7	25.84	29.05
S27/0248	229	-2.4	-0.27	-1.15	1.23	38.97	41.55

Table 11.8 provides weighted error measurements from which the calibration can be appraised. The scaled errors are particularly relevant since they take into account the range in measured values. Both SMSR and SRMS are expressed as a percentage and should be relatively low if the error to total head differential is small and hence errors will be a small part of the overall model response.

For a regional-scale groundwater model which has a high degree of geological complexity and in which aquifers are recognised to be heterogeneous scaled errors of up to about 30% are considered satisfactory. This magnitude of error generally equates to a calibration fit of less than a metre or so. The majority of monitoring bores have errors within this range except for the following exceptions:

- Area 1 – S26/0547 (‘Craig’, 4.3 m deep). This is both a manually measured and pumped observation bore and may therefore be of questionable reliability. The model predicts a water level consistently about 1 m lower than the observed levels. The bore is also very shallow and may record the water level in a perched aquifer.

- Area 2 – S26/0155 ('Tulloch', 13.4 m deep). This is also both a manually measured and pumped observation bore with a lower weighting. Modelled waters level are consistently 2-3m lower than measured levels during the summer. The reason for the poor calibration may be over-exaggerated pumping drawdown effects from this bore.

- Area 5 – S26/0326 ('McKay', 10 m deep). A manually measured and pumped observation bore with a lower weighting. This bore is in an area with an attenuated rainfall recharge dynamic due to a thick low permeability unsaturated zone. The soil moisture balance recharge model does not take this into account resulting in a seasonally more variable water level than observed. However, average water levels and long-term trends are reasonable.

- Area 6 – S27/0248 ('Morrison', 8 m deep). A manually measured and pumped observation bore with a lower weighting. The model consistently over-predicts water level by 2-3 m at this site. The reason for this is unknown.

Figures 11.6 to 11.9 graphically show the match between modelled and observed groundwater levels for the calibration period August 2000 to December 2004 (within the longer validation run). The model-to-measurement fit for bores within each of the areas is discussed in Section 11.6.7.

11.6.6 Calibration validation

Validation (or verification) is performed to test whether or not the model can be used as a predictive tool by demonstrating that the calibrated model is an adequate representation of the physical system (Middlemis 2001). The validation process entails running the calibrated model to check that its predictions reasonably match the observations of a reserved data-set excluded from the calibration. Validation addresses some of the non-uniqueness issues discussed in Section 11.2, particularly if the verification data-set was from a distinct hydrological period.

A calibration validation run of 15 years duration was performed for the period 1 July 1992 to 1 May 2007. The PEST calibration data-set for 1 August 2000 to 14 December 2004 was incorporated into the run and therefore the validation data-set used additional monitoring data both prior to and after the PEST calibration data-set. The transient model validation run had 771 seven-day stress periods, and a run duration of 5,400 days.

11.6.7 Model-to-measurement fit

Figures 11.6 to 11.9 show the simulated and observed groundwater levels for the 15-year calibration period for the head calibration target sites, grouped into the six areas: Greytown–Waiohine plains, Parkvale–Carterton sub-basin, upper Waingawa fan, Waingawa floodplain, Fernhill and Ruamahanga valley (see

Table 9.1). The model-to-measurement calibration is discussed for each area below.

(a) Area 1: Greytown–Waiohine plains

Figure 11.6 presents the calibration hydrographs for five shallow monitoring bores in this area. The additional monitoring bore S26/0500 ('Rogan') was not included in the calibration data-set because it has not been operational since 1997.

Four of the monitoring sites show a very good match between the observed and modelled heads. The larger error associated with bore S26/0547 (Craig) was discussed above (Table 11.8). The larger seasonal fluctuation in bore S26/0490 (Perry) reflects the control the river exerts on adjacent groundwater levels. The area around bore S27/0225 (Hammond) is dominated by rainfall recharge resulting in a much smaller seasonal fluctuation due to the high transmissivity of the aquifer in this area.

(b) Area 2: Parkvale–Carterton sub-basin

Figure 11.7 shows the simulated and observed hydrographs for the shallow Q2-4 aquifers [S26/0738 (Towgood) and S26/0155 (Tulloch)], and the deep leaky-confined 'Q6' aquifer [S26/0675 (McNamara), S26/0743 (Baring), and S26/0568 (Denbee)] beneath the Parkvale plain. A close calibration to observed heads both in magnitude and long-term trend is evident for both the shallow and deep aquifers in this area.

Of particular importance is the simulation of the observed declining trends in the deep Parkvale aquifer in the three deep monitoring bores. Summer drawdowns of up to 5 m observed in these bores are attributable largely to abstraction from the confined aquifers. However, the simulated drawdowns do not always match the observed summer drawdown data which is probably related to inaccuracies in the abstraction model. Although the Baring and McNamara bores show a good head calibration, the modelled heads at the Denbee bore (being about 10 m deeper) tend to be underestimated by about 2m. This is thought to reflect an oversimplification of the Parkvale sub-basin geology in an area of known structural complexity. A further contributing factor to the high objective function for observation bores in the confined aquifers relates to the limitations of accurately modelling pumping drawdowns in thin highly permeable gravel bodies embedded in the heterogeneous sediment sequence. The model necessarily uses bulk aquifer parameters representative of each layer.

(c) Area 3: upper Waingawa fan

Groundwater levels in the upper Waingawa fan above the Parkvale and Carterton sub-basins exert control on downstream heads within the deeper aquifer systems. Figure 11.8 shows calibration hydrographs for the four monitoring sites in this area. The two deepest bores are S26/0236 (Oldfield, 41 m) and S26/0229 (EC Fertiliser, 23.8 m), the latter showing a very close match to the observed data. A higher error is associated with bore S26/0236

(WCB Oldfield) prior to 2000/01, with later data showing a good model-to-measurement fit (Table 11.8).

The two shallow monitoring sites in this area show a particularly good model-to-measurement fit. Simulation of deeper levels in the fan system therefore appears less robust than simulation at shallow depth.

(d) Area 4: Waingawa floodplain

Figure 11.9 shows the simulated hydrographs for the two bores located close to the Waingawa River (S26/0308 and S26/0298). Both bores are very shallow (<8 m) and although the simulated and observed data are of closely comparable magnitude, the modelled levels have a much higher seasonal fluctuation of 1 to 2 m – significantly more than the observed hydrographs. It appears that the aquifer in this area has a very close association with the river stage and therefore levels are highly buffered. The model does not replicate the connection as well.

(e) Area 5: Fernhill

There is only one monitoring bore on the elevated Fernhill terraces, T26/0326 (Figure 11.9). The observed hydrograph for this bore shows a very subdued response to recharge and is characterised by long-term sinusoidal trends. This behaviour reflects the slow recharge dynamics through very low permeability loess-covered terraces (as discussed in Section 7.3). The simulated hydrograph for this site shows a more ‘peaky’ character due to the way in which the recharge model calculates drainage through the soil zone as discreet pulses rather than as slow leakage through the unsaturated zone. Calibration of the model in this area required that the recharge be reduced to only about 5% of annual average rainfall. The high scaled error for this site (Table 11.8) was discussed in Section 11.6.5.

(f) Area 6: middle Ruamahanga valley

Figure 11.9 shows the hydrographs for four monitoring bores located in the middle Ruamahanga valley. Good model-to-measurement matches are evident for bores S26/0749, S26/0756[17] and T26/0602[17] – located close to the Ruamahanga River at depths of 10 m to 19 m. The higher error associated with S27/0248, which is located further from the river, was discussed in Section 11.6.5.

In summary, validation simulation predicts groundwater levels in all six areas in the Middle Valley catchment accurately. The few bores having model-to-measurement matches with higher errors can be reasonably expected in such a heterogeneous and structually complex groundwater system.

[17] These bores were not used in model calibration but were used for model calibration verification.

11.6.8 Water balance calibration

(a) Global water balance

Figure 11.10 illustrates the simulated water balance dynamics on a bulk catchment-wide scale. The first two plots (A and B) depict modelled recharge on a daily and annual basis. Rainfall recharge is highly seasonal, averaging 190,000 m^3/day over the 15-year calibration period – which is equivalent to the average net discharge to surface water (Figure 11.10A). The annual average recharge for this period is 68 x 10^6 m^3. Figure 11.10B shows the contribution to recharge for the six sub-areas. Area 3 (the Waingawa and Mangatarere fans) and Area 6 (Ruamahanga valley) contribute the largest amounts of recharge on an annual basis due to their high rainfall and high soil permeability characteristics respectively.

Figure 11.10C shows modelled total groundwater abstraction for the Middle Valley catchment and also the modelled total abstractions for the six sub-areas. The peak abstraction rate during the 2006/07 irrigation season was about 60,000 m^3/day (60 ML/d). Area 2 (the Parkvale-Carterton sub-basin) has the highest abstraction rate of the six sub-areas, followed closely by Areas 1 and 6.

The simulated interaction between groundwater and the surface water environment is shown in Figure 11.10D. This plot depicts the total catchment fluxes, but it should be remembered that the temporal interactions between rivers and groundwater at a local scale differ considerably – as will be described later in this section.

The solid black line in Figure 11.10D shows the total net flux between rivers (and springs) and groundwater for the whole Middle Valley catchment. A negative flux means a gain in river flow due to groundwater discharge (i.e. the groundwater-supported base flow to the river). A positive flux means a loss of water through the river bed to groundwater. The net flux is calculated as the difference between the Rivers IN flux (flux from rivers to groundwater), and Rivers OUT flux (flow from groundwater to rivers) which are also shown in Figure 11.10D.

Figure 11.10D shows that, when totalled on a catchment-wide scale, groundwater provides a net base flow to the rivers for most of the year. This flow is significantly higher in mid to late winter (400,000 to 800,000 m^3/day), reducing to less than 100,000 m^3/day (1.15 m^3/s) in summer. Occasionally, during May-June, the net catchment-wide flow reverses and the rivers recharge groundwater. This trend is driven by the hydraulic gradient between the rivers (and springs) and the water table. During mid-late winter groundwater levels are at their highest and therefore discharge of groundwater to surface water peaks. In late summer to early winter when groundwater levels are lowest the average gradient between the aquifer and surface water flattens and even reverses. This results in a smaller base flow contribution from groundwater and occasionally causes a net flow of river water into the aquifers.

Modelled spring discharges (Figure 11.10E) in the Middle Valley catchment are shown as both as the total catchment discharge and the contributions from each of the spring zones (Greytown, Parkvale, Featherston/Beef Creek, and springs associated with the Masterton and Carterton faults). The largest spring discharge occurs on the Greytown-Waiohine plains which has a summer base flow of about 50,000 to 70,000 m^3/day (this is the combined flow from the Papawai, Tilsons and Muhunoa springs). The spring discharge from this area appears to have declined since about 2004, possibly as a result of increased groundwater abstraction.

At any particular time the global water balance for the Middle Valley catchment is highly variable. This is shown in Table 11.9 which displays the modelled global water balances for two stress periods, one in summer 2005 and one in winter 2005. This was a particularly dry year (see Figure 11.10B).

Table 11.9: Global transient water balances for summer and winter 2005 from the Middle Valley catchment transient groundwater model

	Flux in (m^3/day)	Flux out (m^3/day)
25 January 2005 – summer		
Rainfall recharge	0	
River recharge	114,000	
Abstraction		49,000
River base flow		225,000
Spring discharge		108,000
Change in storage	268,000	
Total	*382,000*	*382,000*
19 July 2005 – winter		
Rainfall recharge	388,000	
River recharge	137,000	
Abstraction		4,000
River base flow		159,000
Spring discharge		201,000
Change in storage		161,000
Total	*525,000*	*525,000*

Table 11.9 shows that groundwater discharge to rivers and springs dominates the balance during mid-late summer, providing an important base flow component to surface water ecosystems. There is also a large loss from storage (recorded as a flux in as water is released from storage) which results in dropping groundwater levels. During summer, groundwater abstraction represents about 13% of the total water balance for the catchment.

The winter 2005 balance shows that rainfall recharge was the dominant input to the groundwater system, about three times greater than river recharge. There is a large increase in spring discharge compared to the summer balance and a slight reduction in river base flow (probably due to higher river levels during this stress period). Comparison of the two balances shows the significant storage replenishment occurring during winter when groundwater levels recover from summer lows (note storage increase is shown as an ‘out’ component in the mass balance denoting water passing into storage). About 30% of the recharge (from rainfall and rivers) contributes to the storage replenishment.

(b) Simulated river and spring boundary fluxes

The patterns of river flow losses and gains discussed in Section 7.4 as well as quantitative observations of river/spring losses and gains (Figure 7.22), were used as calibration targets. The automated PEST calibration process was periodically interrupted and manually checked against water balance observations. Parameters such as transfer rate and hydraulic conductivity parameters adjacent to transfer boundaries were adjusted or constrained where necessary so that the calibration maintained consistency with water balance observations. Note that the output file format of FEFLOW version 5.4 does not allow PEST to directly access water balance information and thereby introduce water balance targets in the automated calibration process.

Figure 11.11 shows the simulated pattern of flow gains and losses at the model transfer boundary nodes on the main river and spring systems during the summer of 2005 (25 January 2005; model day 4,585). Comparison with Figure 7.20 in Section 7.4 shows that the simulated pattern of gains and losses along the main river courses and main fault structures is consistent with observed patterns and the conceptual model.

From a quantitative perspective the calibration has relied on measured flow losses and gains for specific river reaches (or transfer node groups) and spring discharge zones as delineated in Figure 11.12. The observed fluxes represent intermittent measurements and by no means provide a complete characterisation of the interaction between groundwater and surface water. However, they do provide a general guide for the magnitude and nature of the fluxes.

Spring flows

The simulated flows in the Greytown springs (Papawai, Tilsons and Muhunoa streams) are shown in Figure 11.13. Flow monitoring data for the Papawai Stream and Tilsons Creek are also plotted in order to compare the simulated flows with observed data. The monitoring record is subject to surface runoff (including stormwater from Greytown) and therefore shows a more ‘peaky’ record when compared to the simulated flows (representing only groundwater base flow).

Modelled flows in the Papawai Stream and Tilsons Creek are closely comparable to the monitoring data (excluding runoff peaks). Papawai Stream has a simulated mean annual flow of 250 L/s and a mean summer low of about 200 L/s. Tilsons Creek has a modelled mean flow of about 100 L/s and a summer base flow of about 700 L/s. These flows compare favourably to the flows estimated by Butcher (2007a) as well as actual monitoring data.

The model slightly under-predicts the flow to the Muhunoa Stream, simulating an average flow of 450 L/s and summer low flow of 400 L/s in comparison to an observed flow of 500-600 L/s. The discrepancy may be related to a high permeability gravel channel linking the Muhunoa Stream to the Waiohine River above SH 2. It is also probably related to the simulation of low groundwater levels in this area.

Butcher (2007b) estimated a mean annual flow for the Parkvale spring system of 150 L/s and a mean annual low flow of 70 L/s on the basis of sparse gauging data. The model simulates a mean flow of 150 L/s and summer low flow of around 50-70 L/s (Figure 11.14). The Parkvale springs comprise a network of numerous spring-fed channels which are interlinked with the Taratahi Water Race system.

Spring systems on the Masterton and Carterton faults were described in Section 3.2.2. The simulated base flows for these spring systems (Figure 11.14) are in the order of 100 L/s and 50 L/s for the Carterton and Masterton fault spring systems respectively – in close agreement with estimated and measured spring flows reported by Butcher (2007a). The model indicates that flow drops to about 50% of the mean flow during summer, consistent with available observation data.

Waiohine River

Figure 11.15 shows the modelled fluxes between the Waiohine River and groundwater for the two reaches. A positive flux shows a loss of river flow to groundwater, and a negative flux shows a gain in river flow due to groundwater discharge (i.e. a base flow input). The Waiohine River was divided into two reaches on the basis of the observed interaction between the river and groundwater (see Figure 11.12).

Gaugings during low-flow conditions consistently show that the river reach above the Mangatarere Stream confluence (near the SH 2 bridge) loses flow to groundwater. The summer gauged loss on this reach is 0.5-1.0 m^3/s (see Section 7.4.3 and Figure 7.19). Much of this loss reappears as spring flow into the downgradient Papawai, Tilsons and Muhunoa streams. Between the SH 2 bridge and the confluence with the Ruamahanga River, gaugings indicate that there is a small flow gain in the order of 100-300 L/s.

Above the Mangatarere Stream confluence the model predicts an average flow loss from the Waiohine River to groundwater of about 550 to 600 L/s. The simulated loss increases during the summer to about 1-1.2 m^3/s as the hydraulic gradient between the aquifer and the river steepens. During the winter when groundwater levels are higher the losses to groundwater reduce significantly, with small gains occurring occassionally.

Below the Mangatarere confluence the simulated fluxes show that the river predominantly gains a small flow of between 0 and 500 L/s. It is also occasionally simulated to gain up to 500 L/s.

Compared to the gauged losses and gains for this river (see Figure 7.19) the model accurately simulates the patterns and magnitudes of fluxes between the Waiohine River and the groundwater environment.

Mangatarere Stream

The simulated fluxes associated with the Mangatarere Stream are presented for two reaches – between the Wairarapa Fault and Carterton Fault, and from the Carterton Fault to the Waiohine River confluence (Figure 11.15).

Gaugings indicate that above the Carterton Fault, the Mangatarere Stream loses flow to groundwater at a rate of up to 200 L/s during summer. The stream also frequently runs dry above the fault. The simulated fluxes (Figure 11.15) show that during summer the flow losses above the fault are about 100-150 L/s (positive flux), falling to zero flux or gaining up to about 100 L/s during winter.

Between the Carterton Fault and the Waiohine River the stream is observed to gain flow from groundwater (Figure 7.20). Along this reach the model simulates the Mangatarere Stream gaining flow from the groundwater year-round, ranging from about 200-300 L/s in summer, and increasing to about 500-600 L/s in winter. These fluxes are consistent with gauging data as shown in Figure 7.19B.

Waingawa River

The Waingawa River represents the north-eastern boundary of the model and interacts with groundwater on both sides of its channel. Only the south-westerly portion of the flux is represented in the Middle Valley model, although most of the movement out of the river to groundwater probably occurs to the east through the Masterton area via a network of permeable gravel-filled channels.

The Waingawa River generally loses flow at an estimated rate of about 0.5 m^3/s during low flow conditions along its entire length from the Wairarapa Fault to the Ruamahanga River confluence during the summer (Figure 7.19C). Figure 11.16 displays the simulated aquifer-surface water fluxes for two reaches – upstream and downstream of the Masterton Fault (see Figure 11.12). However, gains and losses are hard to quantify accurately for this river as gauging errors are expected to be quite high due the braided nature of the river at some locations.

The upper river reach has a simulated summer loss to groundwater of between 300 and 500 L/s. The gauged summer loss (Figure 7.19C) is also within this range. The next downstream reach (Group 13) has a measured neutral gain/loss pattern and simulated neutral flux in the summer.

The simulated fluxes are shown in Figure 11.16. Modelled flow losses from the upper reach range from less than 100 L/s in late winter to 300-400 L/s in summer.

Ruamahanga River

The model outputs for the Ruamahanga River (Figure 11.16) are divided into two reaches, above and below the Waiohine River confluence. Above the confluence there is a simulated river gain at an annual average rate of between about 500-1,000 L/s, rising to about 1,000-1,500 L/s during winter. This is consistent with gauging data (Figure 7.19D). During the summer there are intermittent losses to the aquifer relating to sporadic river stage rises.

Downstream of the Waiohine River confluence the model predicts that the Ruamahanga River does not interact significantly with groundwater (gaining less than 100 L/s). This is also consistent with gauging infromation which indicates that the river is relatively neutral in terms of its interaction with groundwater.

11.6.9 Calibrated parameter values

Table 11.10 shows the calibrated values for the final PEST optimisation run for unknown and fixed model parameters. Additional parameters were fixed as the PEST optimisation progressed when values either reached acceptable bounds or became highly correlated and insensitive. The process of progressively fixing parameters is recommended practice in obtaining effective PEST outcomes (John Dougherty, pers. comm. 2009).

Table 11.10 also shows the 95% confidence intervals for the unknown/estimated parameters. Although the confidence limits are highly dependent upon the assumptions underpinning the model, they provide a useful means of comparing the certainty with which the parameters were estimated by PEST.

Figure 11.17 compares the measured ranges of horizontal hydraulic conductivity for various areas and hydrostratigraphic units (refer to Table 7.5) with the calibrated values. It is clear that the calibrated model retains values for hydraulic conductivity which are consistent with the observed ranges in value for this parameter. Such consistency tends to reduce the level of uncertainty and non-uniqueness associated with the model (Section 11.2).

Table 11.10: Calibrated parameters for the Middle Valley transient groundwater flow model (Kx – horizontal hydraulic conductivity, Kz – vertical hydraulic conductivity, St – specific yield, Ss – specific storage, it – transfer rate in, ot – transfer rate out). Kx and Kz values are in m/day.

Parameter	Calibrated value	95% confidence limits		Hydrostratigraphic unit and model layers
		Lower	Upper	
Final PEST optimisation run – unknown parameters				
Kx01	320.9	282.3	364.7	Q1 Unconfined aquifer Greytown-Waiohine plains (w) L1-2
Kx02	10.0	8.5	11.8	Q2+ Upper alluvial fan gravels L1-8
Kx03	60.0	56.4	63.9	Q2-4 Aquifer Parkvale L2-3
Kx07	35.7	32.6	39.1	Q6 Aquifer outer Parkvale sub-basin L7-8
Kx08	40.0	35.7	44.8	Q6 Aquifer intermediate band Parkvale sub-basin L7-8
Kx09	104.6	101.7	107.5	Q6 Aquifer inner Parkvale sub-basin L7-8
Kx10	1.8	1.5	2.0	Carterton F L1-9
Kx21	328.5	286.8	376.2	Q1 Unconfined aquifer Ruamahanga valley L1-9
Kx22	291.9	142.5	598.0	Q1 Unconfined aquifer Mangatarere valley L1-2
Kx23	408.0	344.3	485.70	Q1 Unconfined aquifer Waiohine plains (E) L1-2
Kx25	0.30	0.3	0.4	Masterton F L1-9
Kx26	42.8	21.6	84.6	Q6 Aquifer west Tiffen Hill L7-8
Kx32	20.00	17.8	22.0	Q8 Aquifer Parkvale sub-basin L9
Kz12	0.2	0.2	0.3	Q2+ Alluvial fans L2-3
Kz15	2.3	2.0	2.7	Q1 Unconfined aquifer Waiohine plains L1-2
Kz17	0.00086	0.0008	0.0009	Q5 Aquitard, Parkvale L5-6
Kz18	0.005	0.004	0.006	Q5 Aquitard outer Parkvale L5-6
Final PEST optimisation run – fixed parameters				
Kx04	34.6			L1-2 Inactive layers
Kx05	0.003			Q5 Aquitard Parkvale L5-6
Kx06	1.0			Q5 Aquitard Parkvale L5-6
Kx11	10.0			Q8+ Alluvial fan gravels L9
Kx20	270.0			Q1 Aquifer Waingawa Valley L1-4
Kx24	46.0			Q2 Fan terrace W Greytown L1-2
Kx58	20.0			Q4+ Uplifted block/alluvium, Fernhill L1-9
Kz13	0.1			Carterton F L1-9
Kz14	0.5			Masterton F L1-9
Kz16	0.8			Q1 Unconfined aquifer L1-2
Kz19	0.0011			Q5 Aquitard (outer) L5-6
Kz27	0.01			Q6+ Alluvial fan gravels – upper fans L7-8

Table 11.10 *cont.*: Calibrated parameters for the Middle Valley transient groundwater flow model (Kx – horizontal hydraulic conductivity, Kz – vertical hydraulic conductivity, St – specific yield, Ss – specific storage, it – transfer rate in, ot – transfer rate out). Kx and Kz values are in m/day.

Parameter	Calibrated value	95% confidence limits		Hydrostratigraphic unit and model layers
		Lower	Upper	
Final PEST optimisation run – fixed parameters				
Kz28	0.9			Q6 Aquifer outer Parkvale L7-8
Kz29	0.4			Q6 Aquifer middle Parkvale L7-8
Kz30	0.8			Q6 Aquifer inner Parkvale L7-8
Kz31	0.4			Q6 Aquifer West Tiffen Hill L7-8
Kz33	0.04			Q8 Aquifer Parkvale sub-basin L9
Kz34	0.04			Q8+ Alluvial fan gravels L9
Kz55	0.5			Q2-4 Alluvial fan gravels L1-2
Kz56	0.1			Q1 Unconfined aquifer L5-9
Kz57	0.0001			Q6 Aquifer Parkvale/Tiffen L5-6
Kz59	0.08			Q4+ Uplifted block Fernhill L3-9
Ss38	0.00013			Whole model L1-6
Ss39	0.00002			Alluvial fan gravels and Fernhill L7-9
Ss40	0.000007			Parkvale sub-basin aquifers L7-9
Ss41	0.00005			Parkvale sub-basin aquifers (outer band) L7-9
Ss42	0.000035			Parkvale sub-basin aquifers transition band L7-9
St35	0.1			Q1 Unconfined aquifers L1-2
St36	0.05			Parkvale-Carterton central area L1-4
St37	0.022			Alluvial fan gravels (upper fans) L1-4
it43	5.0			Waiohine River (upper) + Papawai springs
it44	8.0			All other springs
it45	3.0			Waingawa River
it46	2.0			Ruamahanga River
it47	3.0			Mangatarere Stream
it48	8.0			Waiohine River (lower) + Muhunoa springs
ot49	5.0			Waiohine River (upper) + Papawai springs
ot50	8.0			All other springs
ot51	3.0			Waingawa River
ot52	2.0			Ruamahanga River
ot53	3.0			Mangatarere Stream
ot54	8.0			Waiohine River (lower) + Muhunoa springs

11.6.10 Parameter sensitivity

Parameter sensitivities are listed in Table 11.11 for those parameters which remained adjustable at the end of the PEST optimisation process. PEST calculates the composite sensitivities following the calculation of the Jacobian matrix for each iteration. The relative sensitivity (obtained by multiplying the composite value by the magnitude of the log of the value of the parameter) assists in comparing the effects of different parameters of different magnitude on the calibration process.

Table 11.11: Parameter composite and relative sensitivity for the Middle Valley transient groundwater flow model (final optimisation adjustable parameters). Kx – horizontal hydraulic conductivity, Kz – vertical hydraulic conductivity.

Parameter	Hydrostratigraphic unit(s), area and age	Composite sensitivity	Relative sensitivity
Kx01	Q1 Unconfined aquifer Greytown-Waiohine plains (w) L1-2	0.04	0.09
Kx02	Q2+ Upper alluvial fan gravels L1-8	0.02	0.02
Kx03	Q2-4 Aquifer Parkvale L2-3	0.06	0.10
Kx07	Q6 Aquifer outer Parkvale sub-basin L7-8	0.04	0.06
Kx08	Q6 Aquifer intermediate band Parkvale sub-basin L7-8	0.02	0.03
Kx09	Q6 Aquifer inner Parkvale sub-basin L7-8	0.06	0.12
Kx10	Carterton F L1-9	0.04	0.01
Kx21	Q1 Unconfined aquifer Ruamahanga valley L1-9	0.03	0.09
Kx22	Q1 Unconfined aquifer Mangatarere valley L1-2	0.04	0.09
Kx23	Q1 Unconfined aquifer Waiohine plains (E) L1-2	0.02	0.05
Kx25	Masterton F L1-9	0.03	0.02
Kx26	Q6 Aquifer West Tiffen Hill L7-8	0.04	0.06
Kx32	Q8 Aquifer Parkvale sub-basin L9	0.02	0.03
Kz12	Q2+ Alluvial fans L2-3	0.04	0.02
Kz15	Q1 Unconfined aquifer Waiohine plains L1-2	0.04	0.01
Kz17	Q5 Aquitard Parkvale L5-6	0.04	0.11
Kz18	Q5 Aquitard outer Parkvale L5-6	0.03	0.07

The relative sensitivities are graphically displayed in Figure 11.18 to help identify those parameters which most affect the calibration, and to identify any parameters which may degrade the performance of the parameter estimation process (i.e. very insensitive parameters due to high degrees of correlation and/or an absence of observation data within some parameter zones). Parameter sensitivity is also partly a function of the availability of a good spread of observation data; areas or aquifer depths with little or no prior information will tend to produce apparently insensitive parameters.

Figure 11.18 shows that horizontal hydraulic conductivity parameters Kx2, Kx10 and Kx25 are relatively insensitive. These relate to upper fan gravels in the west, and the Carterton and Masterton faults respectively. Thus the faults may not play a significant role in influencing the flow dynamics of the Middle Valley groundwater system.

Vertical hydraulic conductivity parameters Kz12 (alluvial fan gravels and shallow aquifers in Parkvale/Carterton) and Kz15 (Q1 unconfined aquifers) are also relatively insensitive. This is probably because there are insufficient observation sites located in different model layers from which this parameter can be accurately estimated. The assignment of relatively narrow bounds to insensitive parameters during the estimation process helped to reduce their effect on the calibration process.

Parameters which are highly sensitive and which were therefore estimated with a higher degree of certainty are listed in Table 11.12.

Table 11.12: Summary of sensitive parameters for the Middle Valley transient groundwater flow model estimated with a high degree of confidence (Kx – horizontal hydraulic conductivity, Kz – vertical hydraulic conductivity)

Parameter	Relative sensitivity	Area
Kx01	0.09	Q1 Unconfined aquifer Greytown-Waiohine plain (w) L1-2
Kx03	0.1	Q2-4 Aquifer Parkvale sub-basin L2-3
Kx09	0.12	Q6 Aquifer inner Parkvale sub-basin L7-8
Kx21	0.09	Q1 Unconfined aquifer Ruamahanga valley L1-9
Kx22	0.09	Q1 Unconfined aquifer Mangatarere valley L1-2
Kz17	0.11	Q5 Aquitard Parkvale L5-6

The most sensitive parameter is horizontal hydraulic conductivity for the principal aquifer in the catchment – the Q1 unconfined aquifer of the Greytown-Waiohine plains (Kx01), Mangatarere Stream (Kx22) and Ruamahanga valley (Kx21). Parameters representing the heavily utilised Q6 aquifer in the Parkvale sub-basin (Kx03, Kx09 and Kz17) are also highly sensitive and therefore were estimated with greater accuracy.

11.7 Summary

The Middle Valley catchment transient-flow groundwater model was calibrated for the period 1992–2007 to groundwater level and mass balance observations. The calibration was evaluated in both qualitative and quantitative terms by comparing the simulation results with field measurements. Simulated mass balances and groundwater heads exhibit a good overall visual and statistical fit to observed data.

The calibration was qualitatively assessed by comparing simulated and observed groundwater flow patterns to ensure that the model outputs were consistent with the conceptualisation of the groundwater system. The observed pattern of groundwater-surface water interaction was also replicated by the model.

The appropriateness of the conceptual hydrogeological model at a regional scale was validated through the calibration. This is particularly relevant given the geological complexity of the aquifer system and the broad interpretations of the structure and deformation of the aquifer sequences. From this outcome it is clear that the regional groundwater system behaves as a hydraulic continuum.

The importance of accurately incorporating surface water–aquifer fluxes in the calibration process is stressed. Because the Middle Valley groundwater system is essentially ‘closed’, the modelled fluxes out of the system (principally via discharges to springs and rivers) are highly correlated with the inputs (rainfall recharge and river bed losses). Calibration of the model to observed surface water fluxes therefore provides a validation of the simulated spatial and temporal recharge dynamics.

Model non-uniqueness was minimised by following the MDBC modelling guidelines (Middlemis 2001). In particular this entailed calibration using ranges for hydraulic conductivity (and other) parameters consistent with measured data, calibrating the model to a wide range of climatic and abstraction stresses, and calibrating to measured water balance fluxes (such as spring flows, river losses/gains).

Automated calibration using the inverse estimation algorithm PEST removed some of the subjectivity of manual calibration and provided an insight into the non-uniqueness of the model. The relative sensitivities of parameters helped identify parameters which were accurately estimated plus those which are insensitive and therefore were not estimated accurately. The sensitivities are partly related to the uneven spread of observation sites both across the model domain and vertically through the aquifer sequences and are also partly a result of parameter correlation.

Overall, confidence can be placed in the calibration robustness for the principal aquifers in the catchment – the Q1 unconfined aquifer (Waiohine, Ruamahanga and Mangatarere) and the confined Q6 Parkvale aquifer. Reduced confidence in the calibration in the upper fan areas largely reflects a paucity of observation data. The calibration process suggests that the major Carterton and Masterton faults may not exert significant controls on the groundwater flow dynamics of the catchment.

11.8 Model limitations

There are a number of limitations and assumptions associated with the Middle Valley groundwater model. These are outlined below.

- *Homogeneous domains*: the aquifer system is highly heterogeneous, on both microscopic and macroscopic scales. The fluvial depositional environment and active tectonism have resulted in a highly heterogeneous groundwater flow system comprising a mixture of coarse permeable gravels and less permeable sands and silts. The model generally assumes discrete areas of homogeneous material using a mesh size of 300–500 m and does not consider local-scale heterogeneity. The model can therefore only reliably provide useful information at a regional or sub-regional scale and will be unable to accurately simulate small areas in detail.

- *Surface water flow gaugings*: the concurrent flow gauging database is limited in both the number of gaugings and the number of gauging locations. It therefore provides a relatively broad characterisation and flux quantification of groundwater–surface water connections. The gaugings are also restricted to low flow conditions and therefore the modelled losses and gains to rivers are calibrated to seasonal low flows and not to higher flows. However, it is under low flow summer conditions when surface waters are most vulnerable to the effects of abstraction.

- *River stage simulation*: the river stages were externally simulated using a surface water model (MIKE11), then transferred to FEFLOW. The MIKE11 model allows for time lags through the system, and also surface water abstractions. The stage modelling in MIKE11 does not take into account flows to and from groundwater which may influence river stage conditions, particularly in rivers which have a relatively small flow in summer (e.g. the Mangatarere Stream). However, the way in which the rivers were simulated is significantly more accurate than the more rudimentary standard groundwater modelling approach of basing river stage on an upstream gauge and assuming instantaneous changes in stage at all downstream locations.

- *Spring characterisation*: there is a lack of flow monitoring data for the spring systems. This is mainly due to the fact that springs have a number of channels distributed over a wide area. Also, many groundwater discharges probably lose a significant amount of water to evapotranspiration around wetland areas. Accurate quantification of the discharges for model calibration purposes therefore proved difficult.

- *Historic groundwater abstraction records*: historical groundwater abstractions used for the model calibration were synthesised using a theoretical pumping regime based upon climatic and soil conditions. It assumes every irrigator behaves in a similar way and optimises their use of water to suit soil moisture conditions. In reality, this will not be the case. It is recommended that policies for requiring monitoring of both surface water and groundwater abstractions be developed.

- *Permitted abstractions*: there are a large number of permitted takes (generally less than 20 m^3/day) in the Middle Valley catchment for domestic and stock supply. These were not incorporated into the model and are assumed to be relatively minor in magnitude when compared to the large consented groundwater abstractions.

- *Recharge model*: assumptions and estimates were made when assigning hydraulic parameters to soil properties for recharge modelling. Recharge calculation is sensitive to some parameters, such as rooting depth and SCS runoff curve number. Particularly with higher rainfall areas near the

Tararua Range, the infiltration-runoff partition will be dependent upon soil moisture conditions and runoff will be higher when the soil is fully saturated (i.e. recharge may be over-estimated during wet periods). A soil moisture-dependent runoff coefficient should ideally be used, but is reliant upon adequate catchment runoff characterisation – at present lacking. However, verification of the model through comparison with lysimeter data (Appendix 4) and the water balance calibration of the model serve to verify the accuracy of the recharge calculations.

Despite the above limitations and assumptions, the calibration outputs provide confidence that the transient numerical FEFLOW model provides a good representation of the Middle Valley groundwater system. It can be appropriately used to investigate resource sustainability through the simulation of various theoretical abstraction scenarios.

12. Summary and conclusions

Phase 2 of the Wairarapa Valley groundwater resource investigation provides a technical basis for Greater Wellington to develop new policy for sustainable groundwater allocation. This technical basis was achieved through the development of a conceptual hydrogeological model and an associated calibrated transient numerical groundwater flow model.

The Phase 2 investigation has characterised a geologically complex groundwater basin termed the 'Middle Valley catchment' of the Wairarapa Valley. Filled with late Quaternary alluvium and glacial outwash deposits to depths of up to 50 m, the basin hosts a highly heterogeneous groundwater system containing multiple discontinuous water-bearing strata. Major faulting and folding, both historical and contemporary, add considerable complexity to the hydrogeological functioning of the basin. Despite these complexities, the groundwater system appears to behave as a hydraulic continuum on a regional scale.

The most important hydrogeological characteristic of the Middle Valley catchment is the strong interdependence between surface water and groundwater. A shallow unconfined dynamic aquifer is of particular significance since it is freely connected to the surface water environment (rivers, springs and wetlands). It is therefore vital that groundwater allocation policy take this interdependence into consideration.

The Middle Valley basin is effectively a 'closed' groundwater system in which the dominant water balance components are rainfall recharge and fluxes between surface water and groundwater (in both directions). Recharge from rainfall infiltration and river bed leakage are of equal magnitude on an annual average basis. Groundwater abstractions constitute more than 10% of the catchment water balance during the summer months and may significantly impact aquifer discharge processes.

Climate and recharge modelling suggest that around 40% of rainfall becomes groundwater recharge over the western and northern areas of the catchment, whilst less than 10% of rainfall reaches the water table over the drier eastern part. Large inter-seasonal variability in recharge reflects temporal rainfall patterns driven by the El Nino Southern Oscillation. These patterns are reflected in groundwater levels and groundwater discharge rates.

Groundwater abstraction has increased rapidly over the past 20 years and has more than doubled over the past 10 years. Estimates and direct measurement of groundwater abstraction from the catchment provide evidence that most resource consent holders on average use only 10–30% of their annual allocation and 60–70% of their daily allocation. The peak total estimated abstraction at the start of groundwater model development in 2007/08 was in the order of 60,000 m^3/day, whilst the total maximum allocation was about 155,000 m^3/day.

Temporal changes in the dynamics of the groundwater system are attributable to a combination of natural climatic variability and rapidly developing abstraction stresses. Areas such as the Parkvale sub-basin show clear evidence of abstraction-related seasonal and long-term declines in groundwater level. It is also highly probable that in some areas abstractions impact on the base flow to surface water systems, or directly deplete flows in rivers such as the Ruamahanga.

The conceptual hydrogeological model was verified and transformed into a numerical transient flow model. The model was qualitatively and quantitatively calibrated to field measurements of groundwater level and fluxes to and from surface water environments. The calibration process followed procedures that minimise non-uniqueness and predictive uncertainty.

Calibration robustness was achieved for the principal aquifers – the Q1 shallow unconfined aquifer of the Waiohine, Ruamahanga and Mangatarere river floodplains and the confined Q4 and Q6 aquifers in the Parkvale sub-basin.

Simulated water balances show that groundwater provides a base flow to rivers and springs in the catchment year-round and is critically important during summer when the base flow to rivers and springs dominates the catchment water balance. Simulated spring discharges on the Greytown-Waiohine plains show a long-term decline from about 2004, possibly as a result of increased groundwater abstraction.

Model limitations include the bulking (or averaging) assumption used to represent a very heterogeneous environment, limited surface water gauging data and assumptions made in the recharge model. Despite these limitations, the model has been assessed as being a reliable ‘aquifer simulator’. It is suited for use by Greater Wellington as a dependable predictive tool at a sub-regional scale in the development of policy for sustainable groundwater allocation in the middle Wairarapa Valley catchment.

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- Thom Krom (data processing and programming for distributed recharge model);
- Scott Wilson (recharge model algorithm development and testing);
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Figures

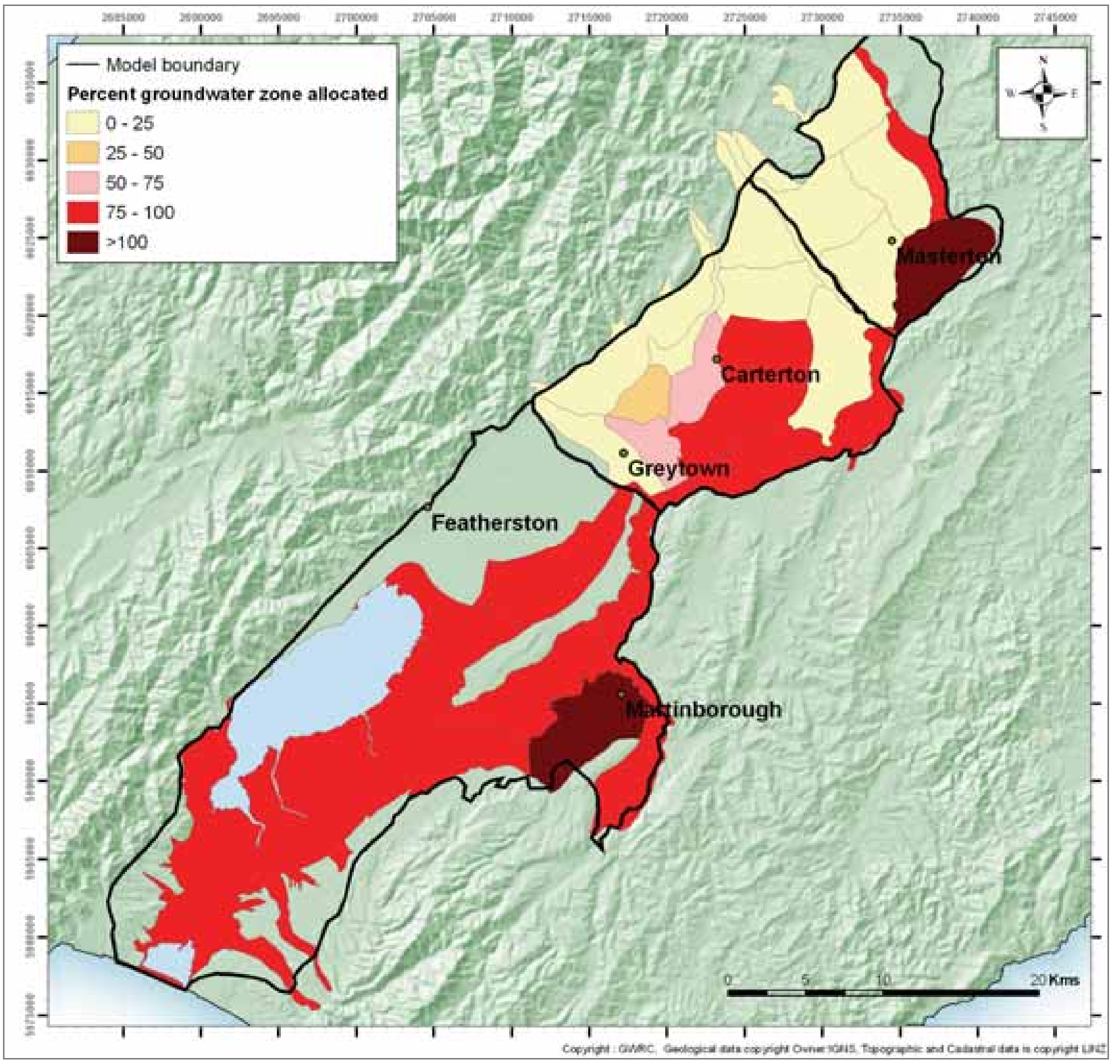
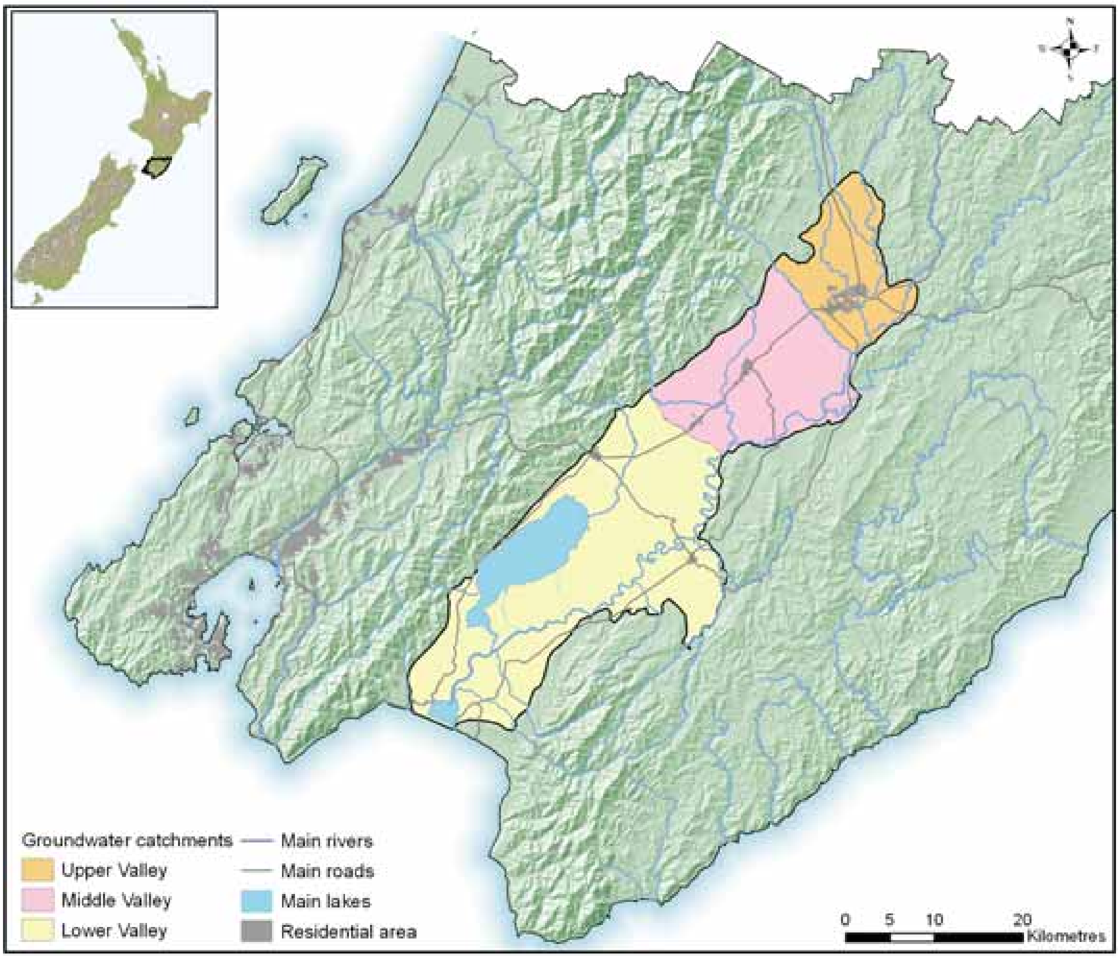


Figure 1.1: Allocation (%) of Wairarapa Valley groundwater zones as at June 2008



(Source: Jones and Gyopari 2006)

Figure 1.2: The Wairarapa Valley groundwater investigation study area showing the three main groundwater sub-catchments defined during Phase 1 of the investigation

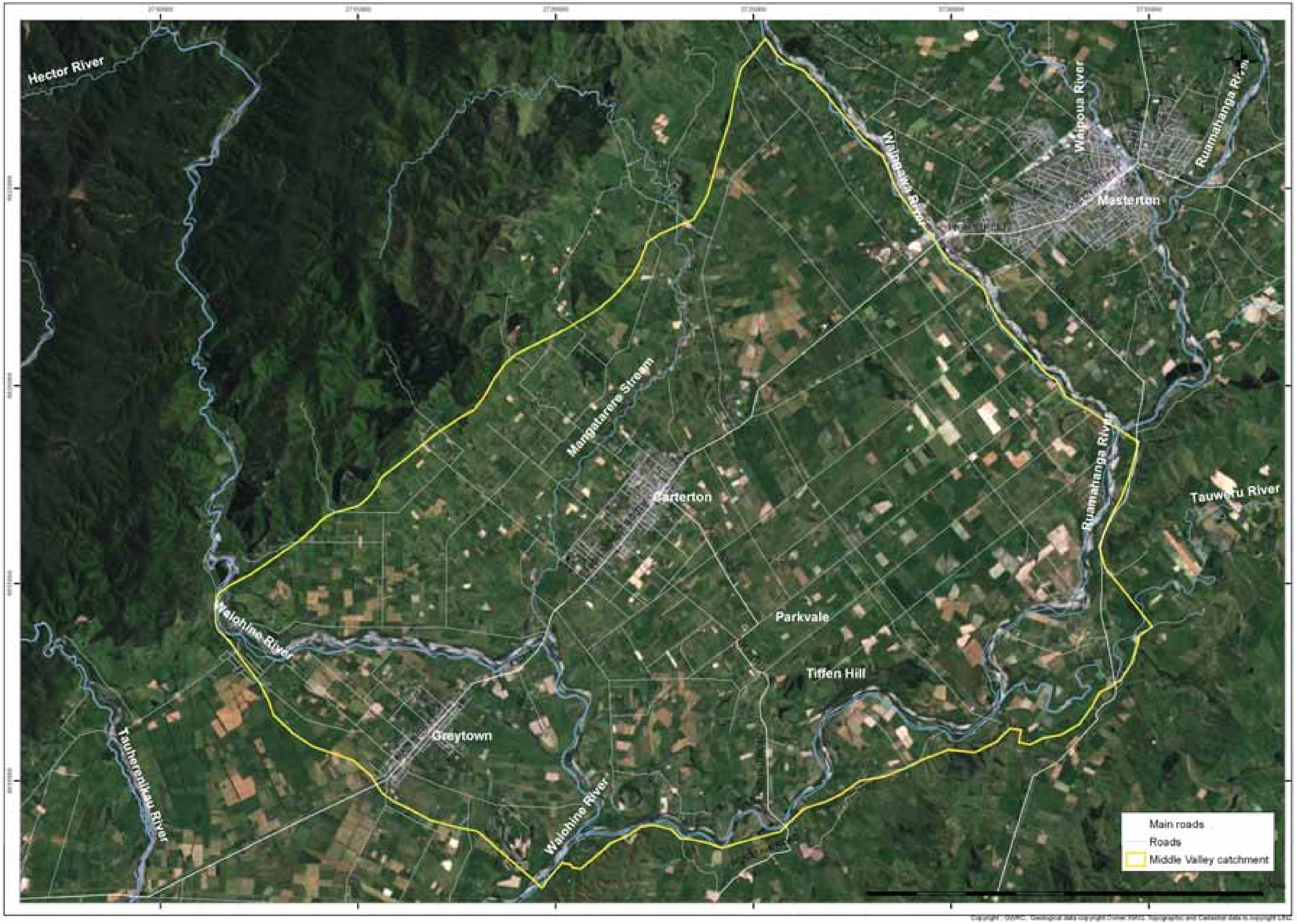


Figure 2.1: Middle Valley catchment study area. Background image is Landsat 7 EMT 2003.

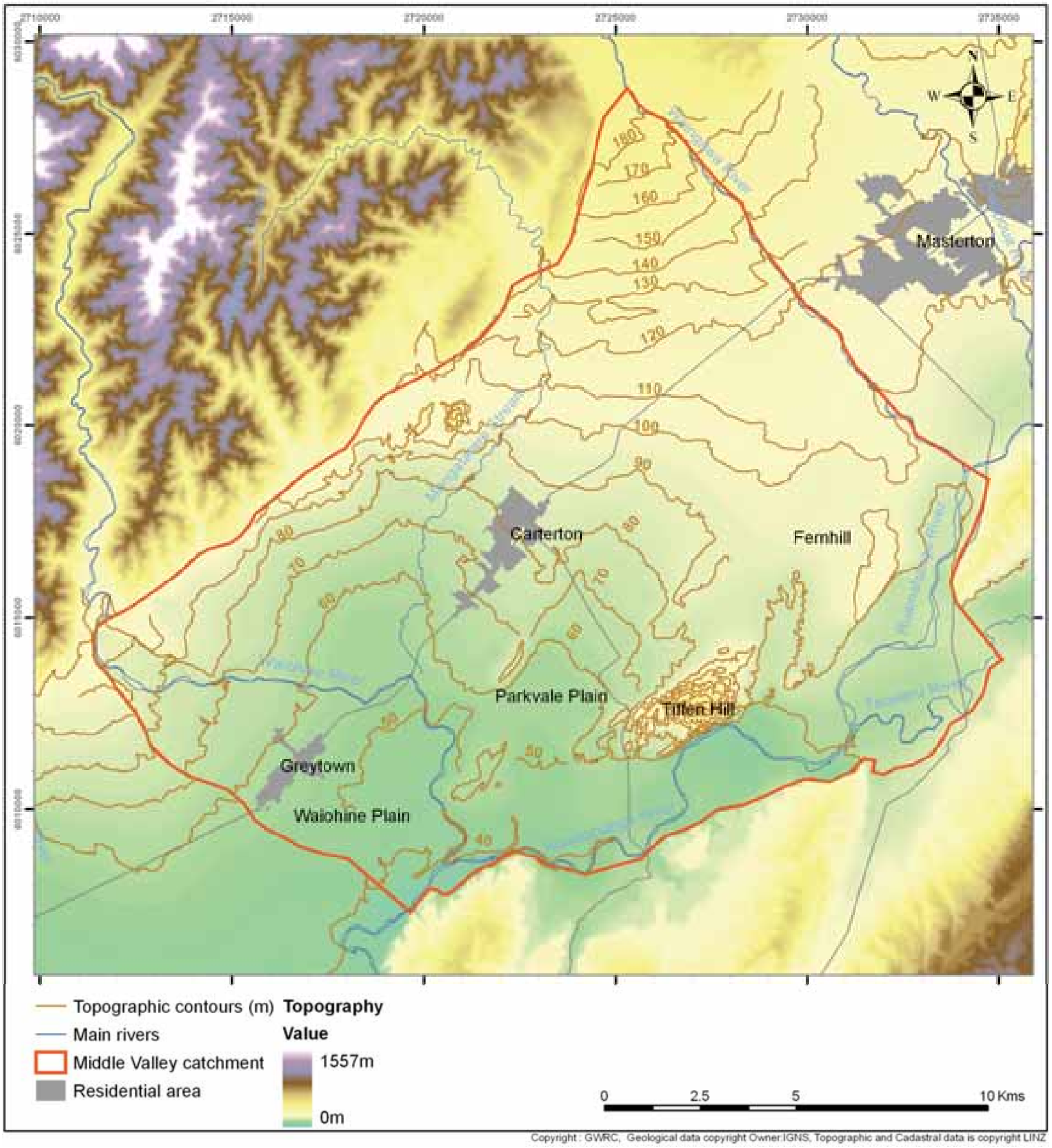


Figure 2.2: Middle Valley catchment – topographic contours

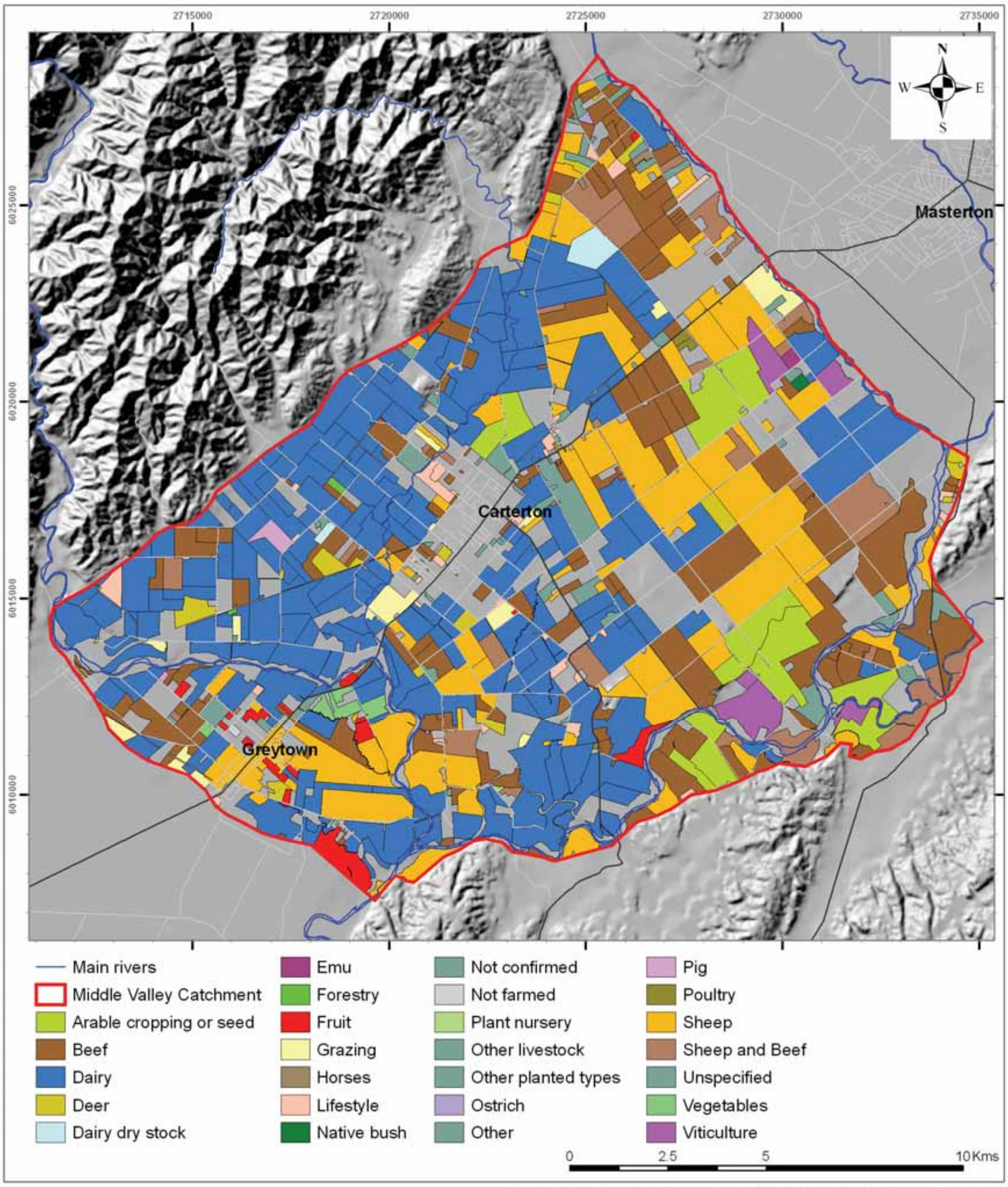


Figure 2.3: Landuse map for the Middle Valley catchment, derived from Agribase (2001 version). Note the dominant dairy, beef and sheep landuses.

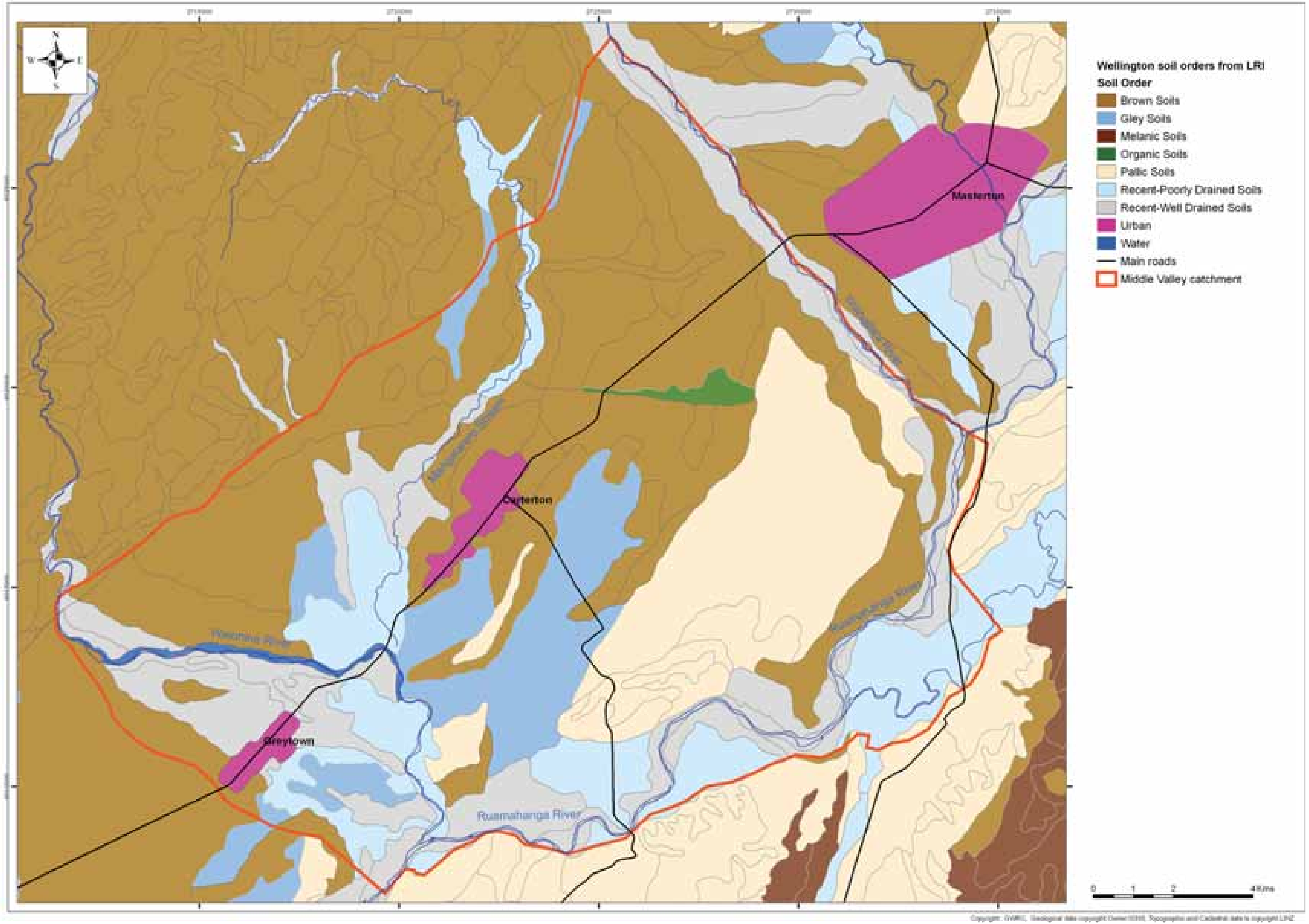


Figure 2.4: Soils of the Middle Valley catchment. Digital soil data were sourced from the NZLRI (Noble 1985) and further summarised to produce this map. Original soil mapping and soil descriptions (e.g. 013d) were sourced from Heine (1975).

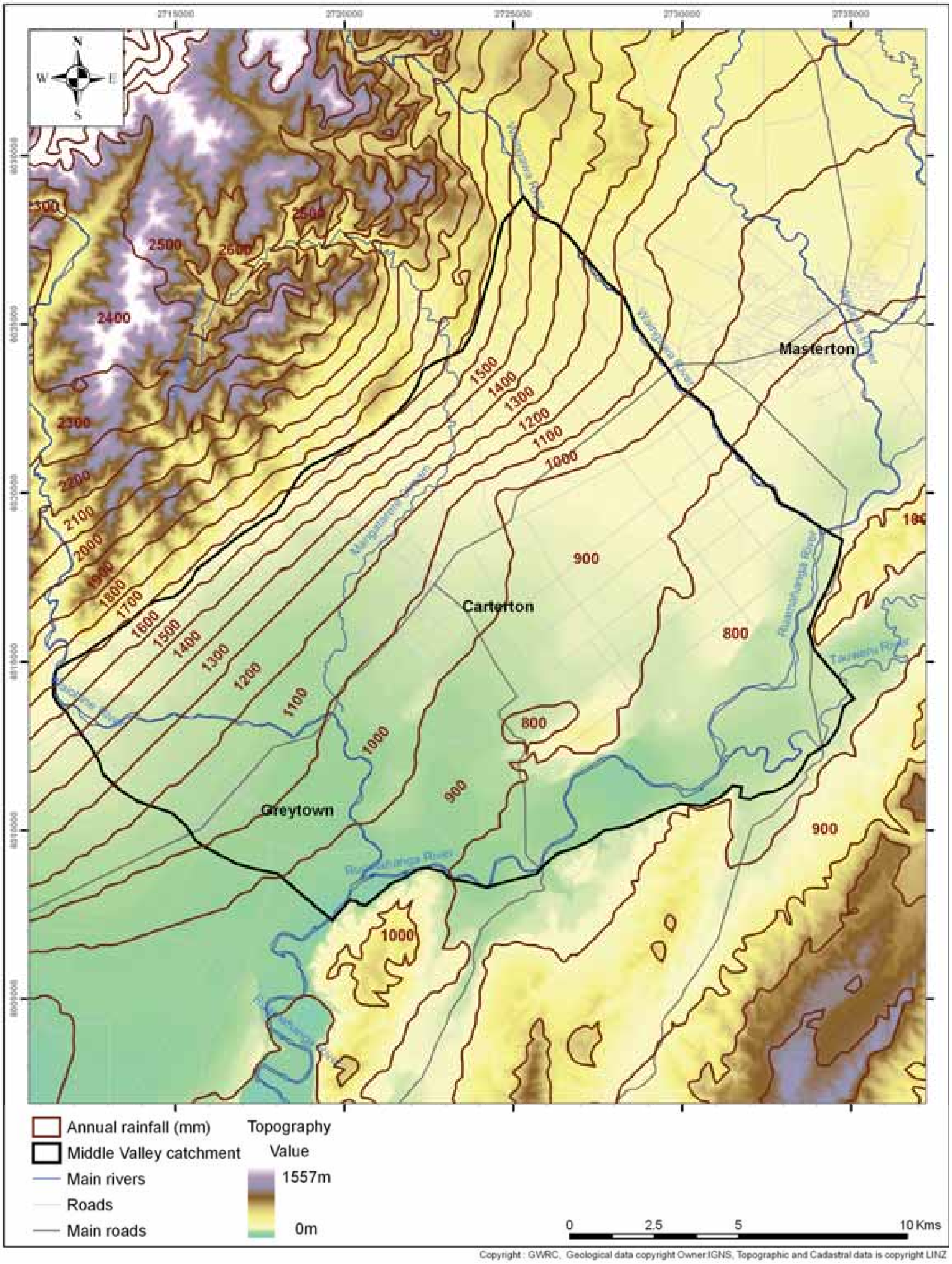


Figure 2.5: Annual average rainfall for the Middle Valley catchment (source LENZ)

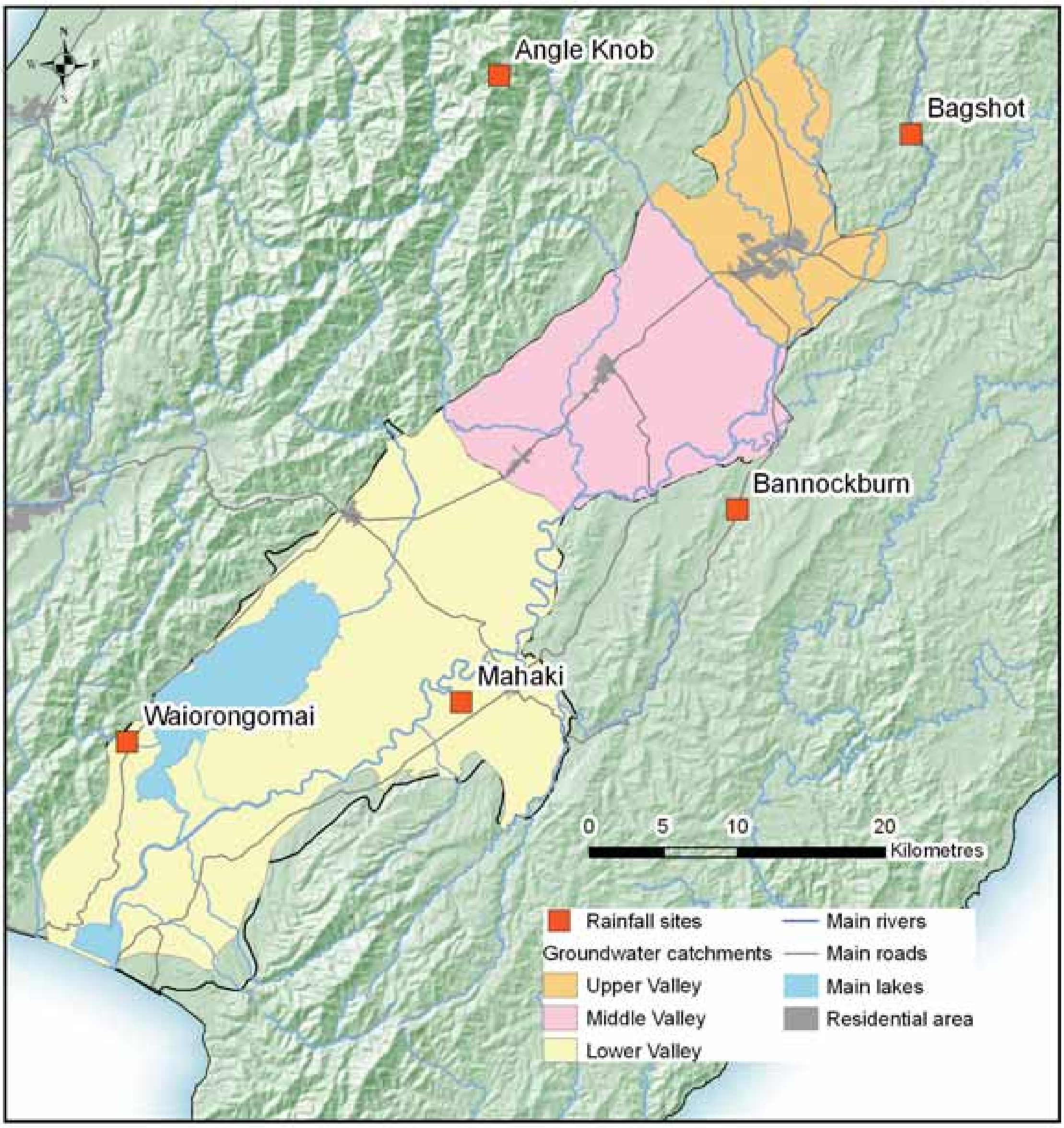


Figure 2.6: Long-term rainfall monitoring sites in the Wairarapa Valley and surrounding area (note the Putara rainfall site is not pictured but is located north of the region)

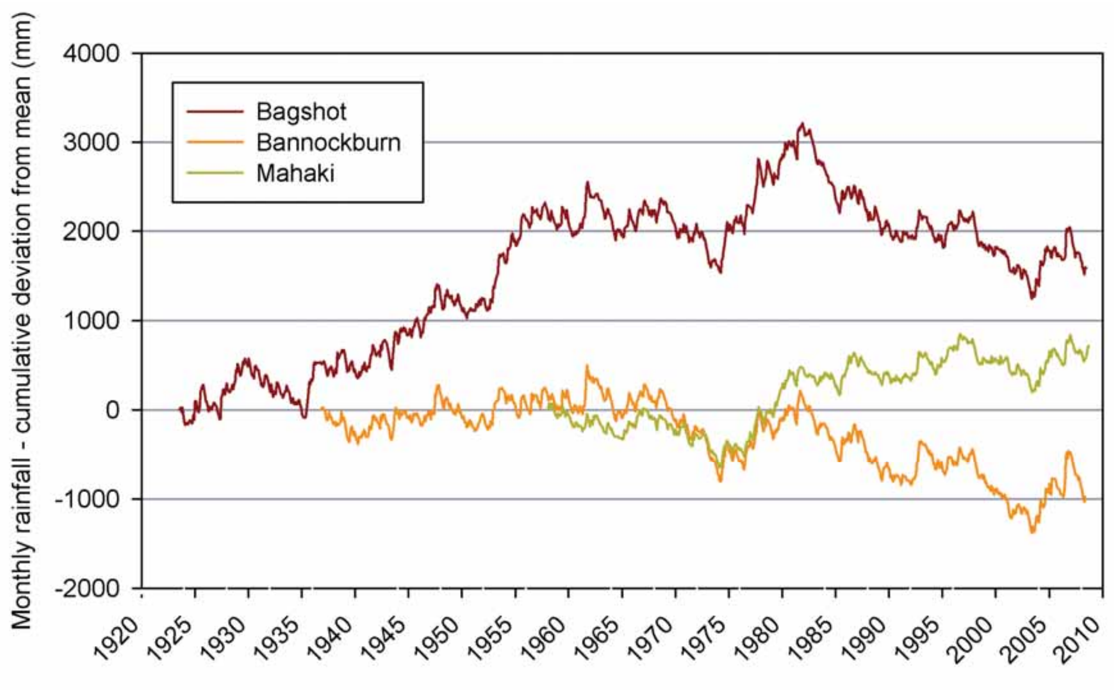


Figure 2.7: Cumulative deviation from the monthly mean rainfall ('cusum') trends at long-term gauging sites around the Wairarapa Valley

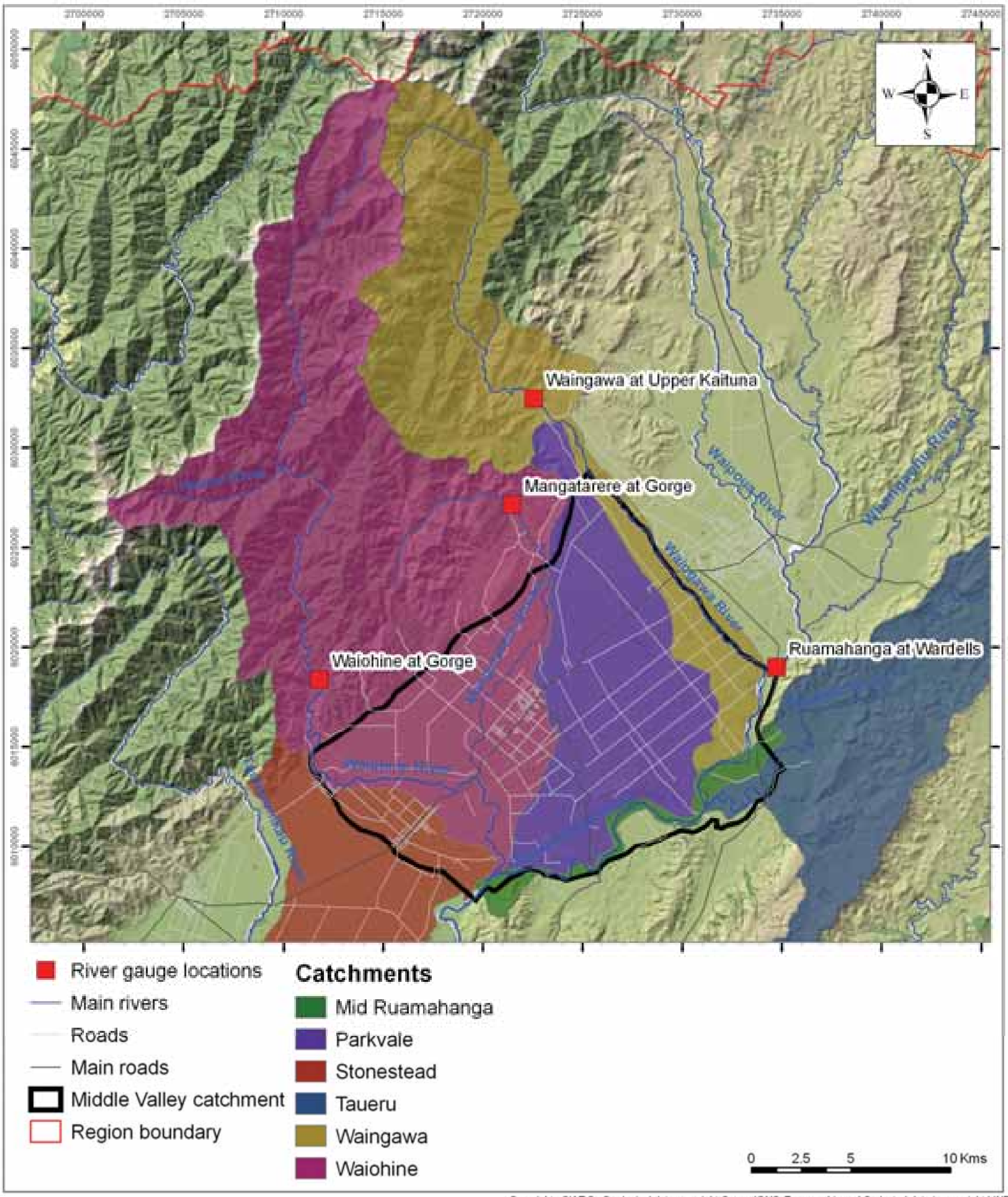
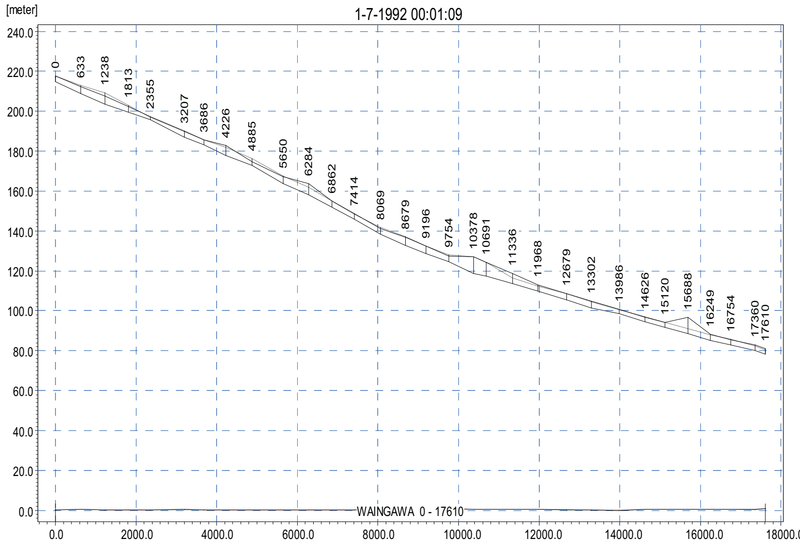
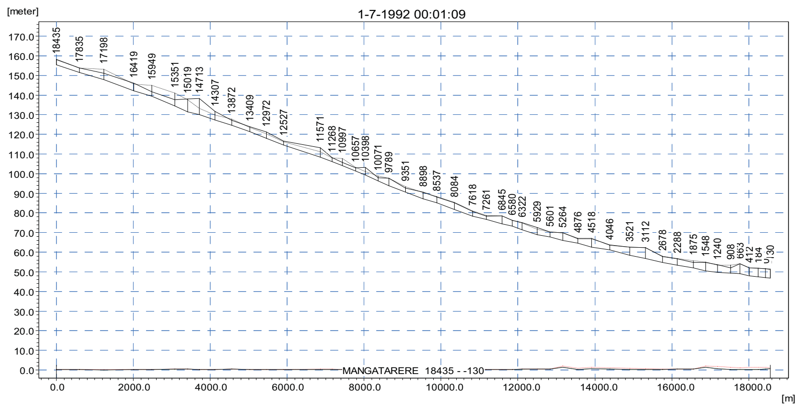


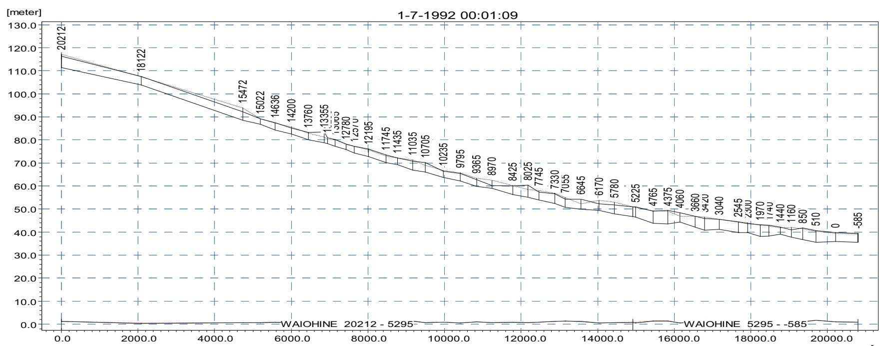
Figure 3.1: Surface water flow monitoring sites in the Middle Valley catchment



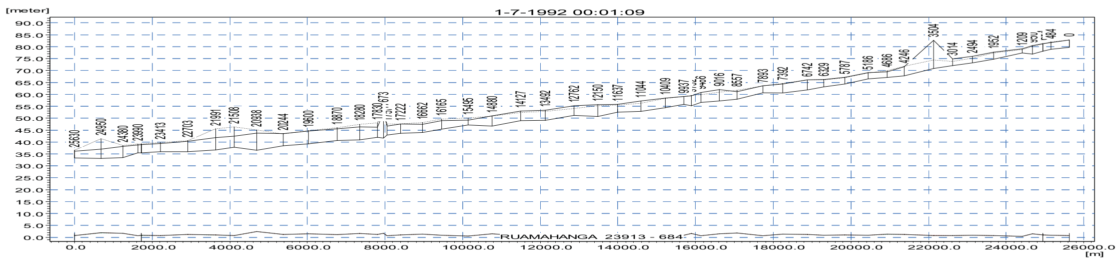
Waingawa River



Mangatarere Stream



Waiohine River



Ruamahanga River

Figure 3.2: Sections along main rivers within the Middle Valley catchment, all shown at approximately the same scale

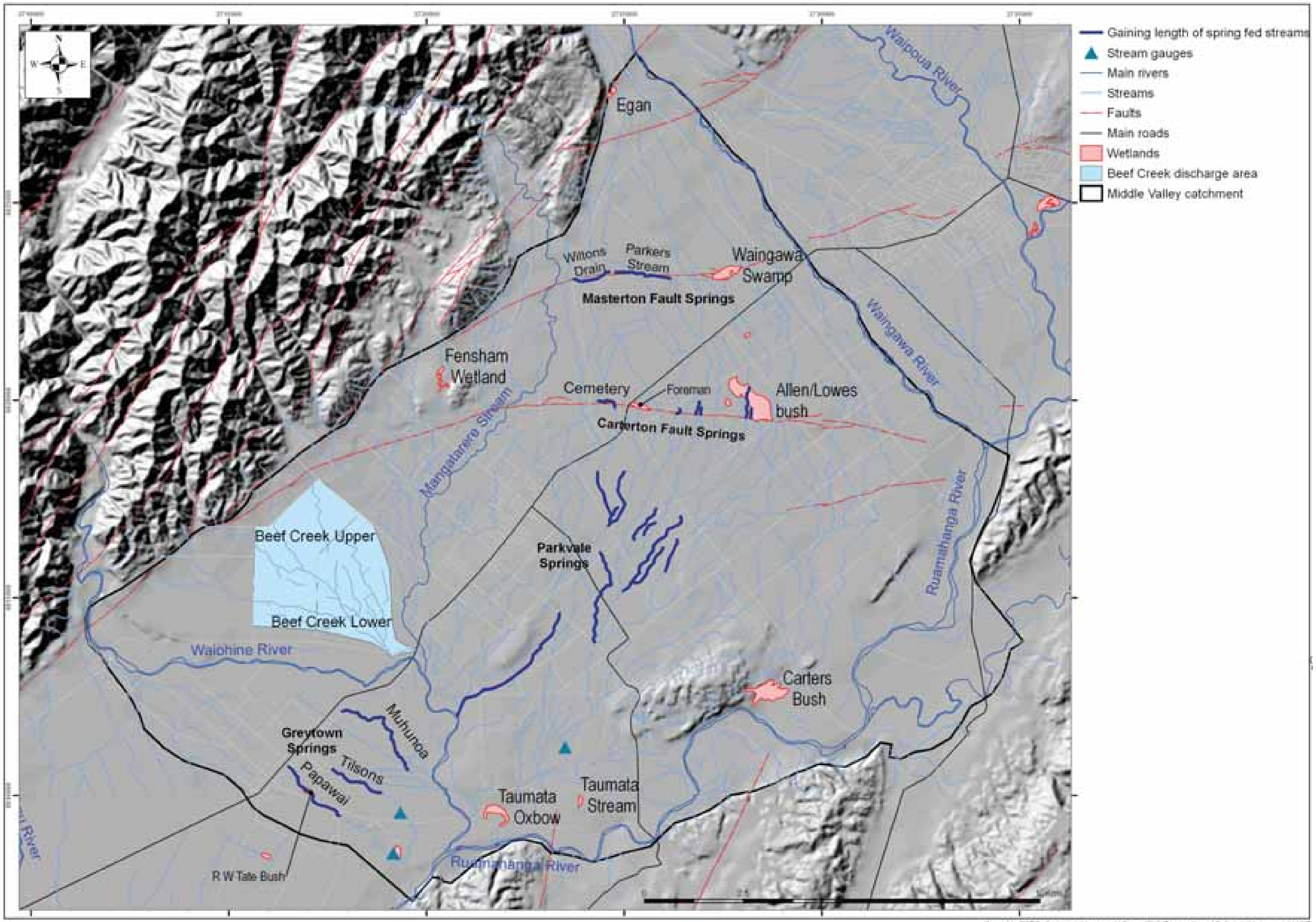


Figure 3.3: Main spring systems and water races within the Middle Valley catchment

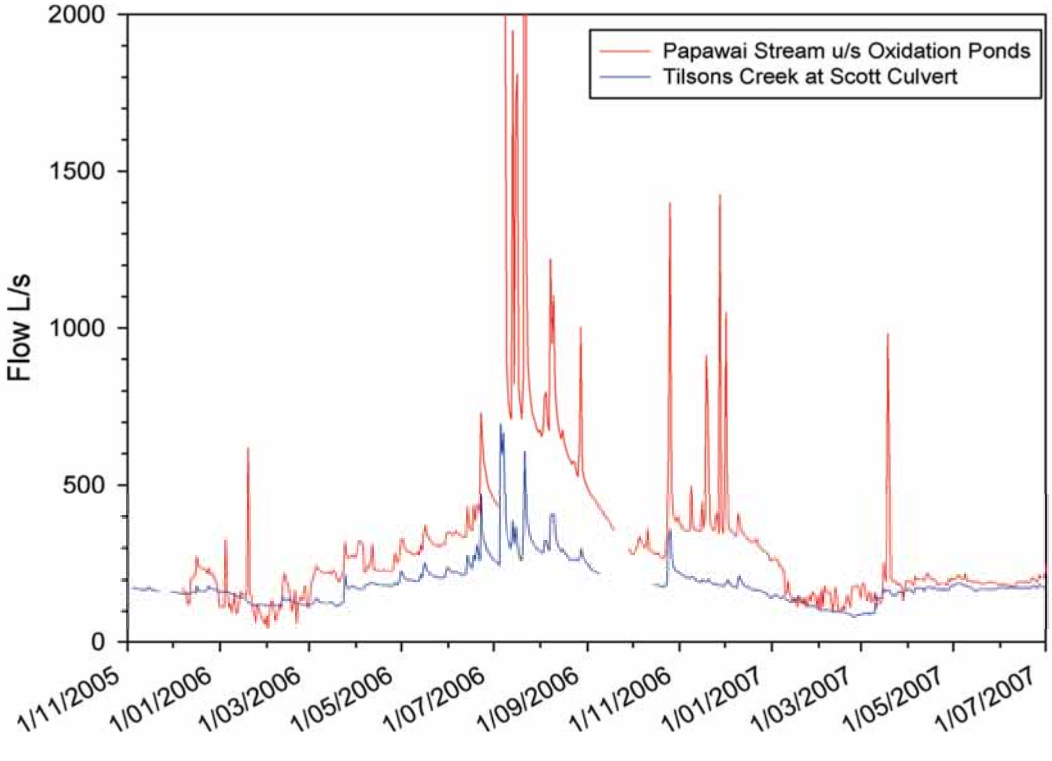


Figure 3.4: Papawai Stream and Tilson Creek mean daily flow derived from automatic recorder sites, November 2005 to July 2007

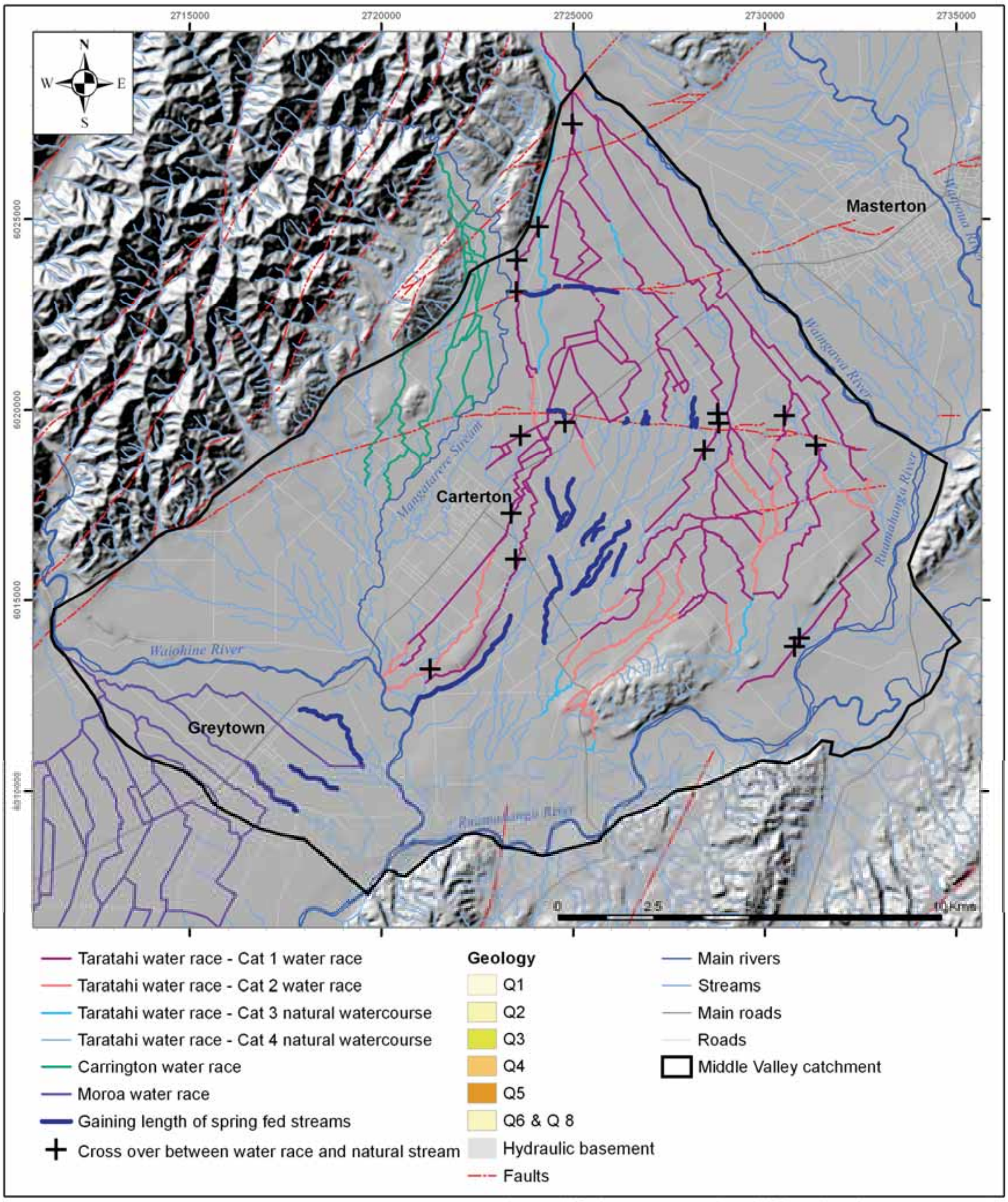


Figure 3.5: Water races in the Middle Valley catchment. The Taratahi Water Race is divided into four categories from predominantly water race to predominantly natural water course (Sourced from Ewington and Thawley 2009).

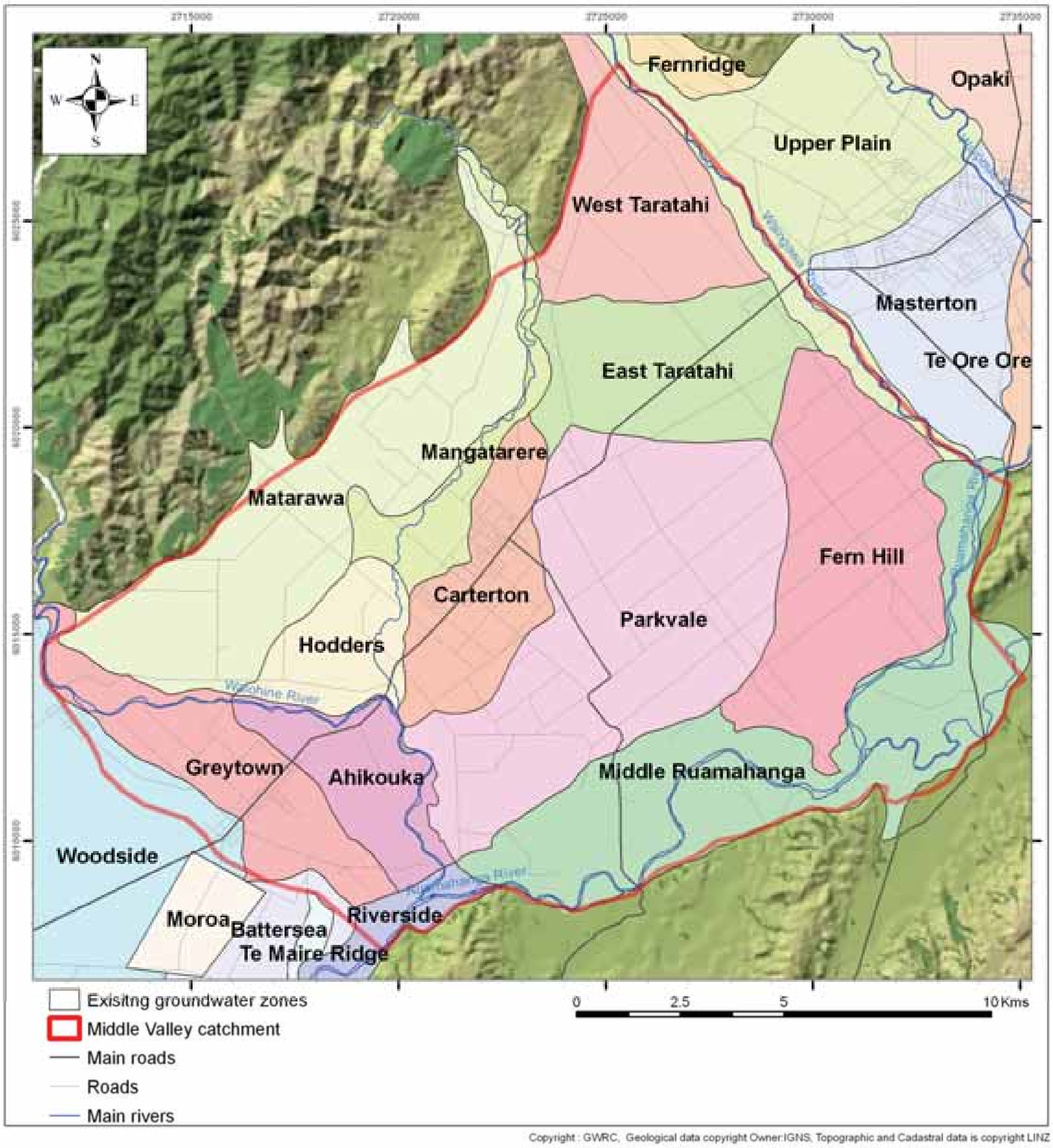


Figure 4.1: Existing groundwater zones identified in Greater Wellington's Regional Freshwater Plan (WRC 1999). Note that some groundwater zones are partially within the Upper and Lower Valley catchments.

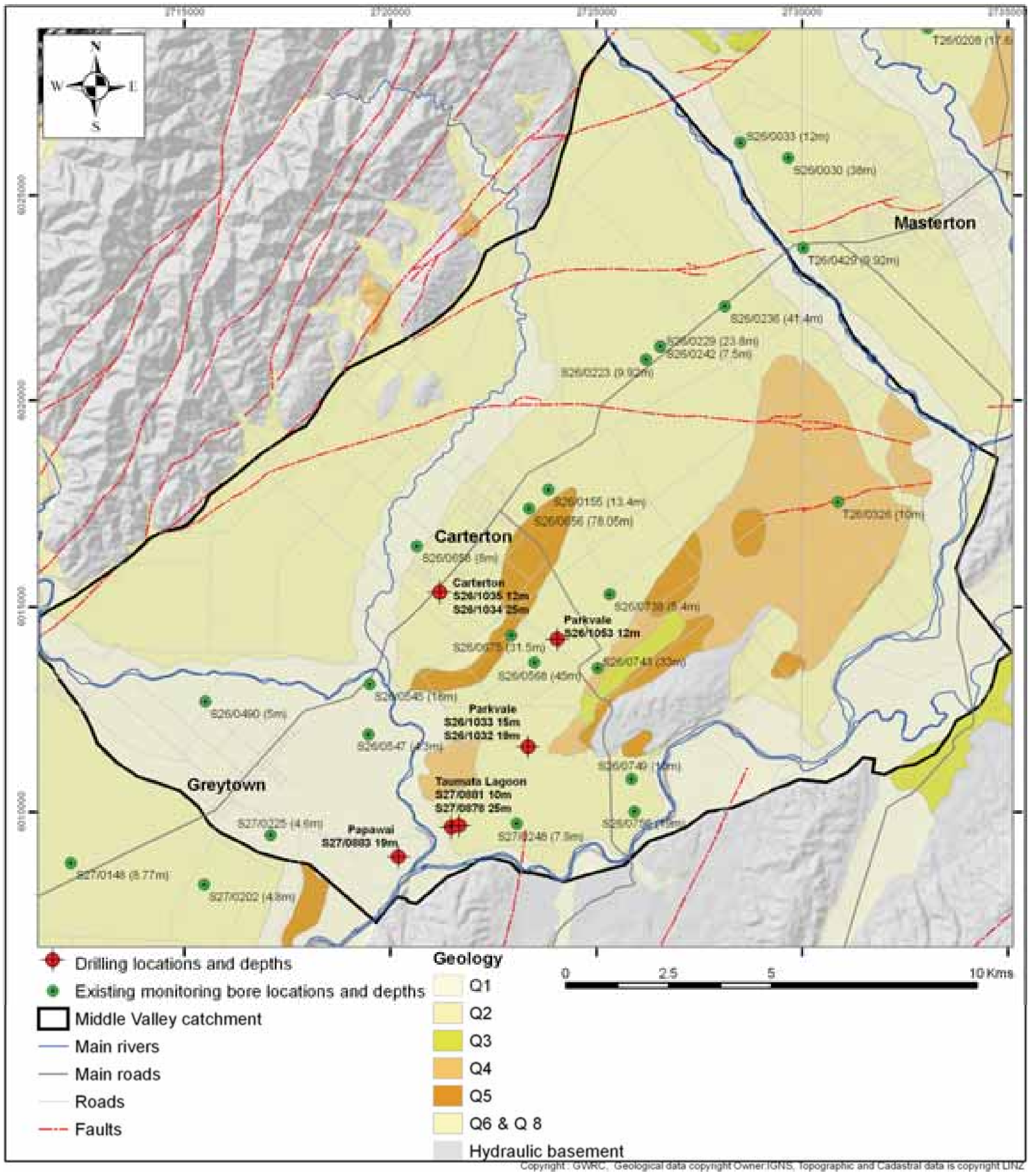


Figure 5.1: Location of stratigraphic drilling sites and constructed monitoring bores in the Middle Valley catchment. Existing groundwater level monitoring bores are also shown.

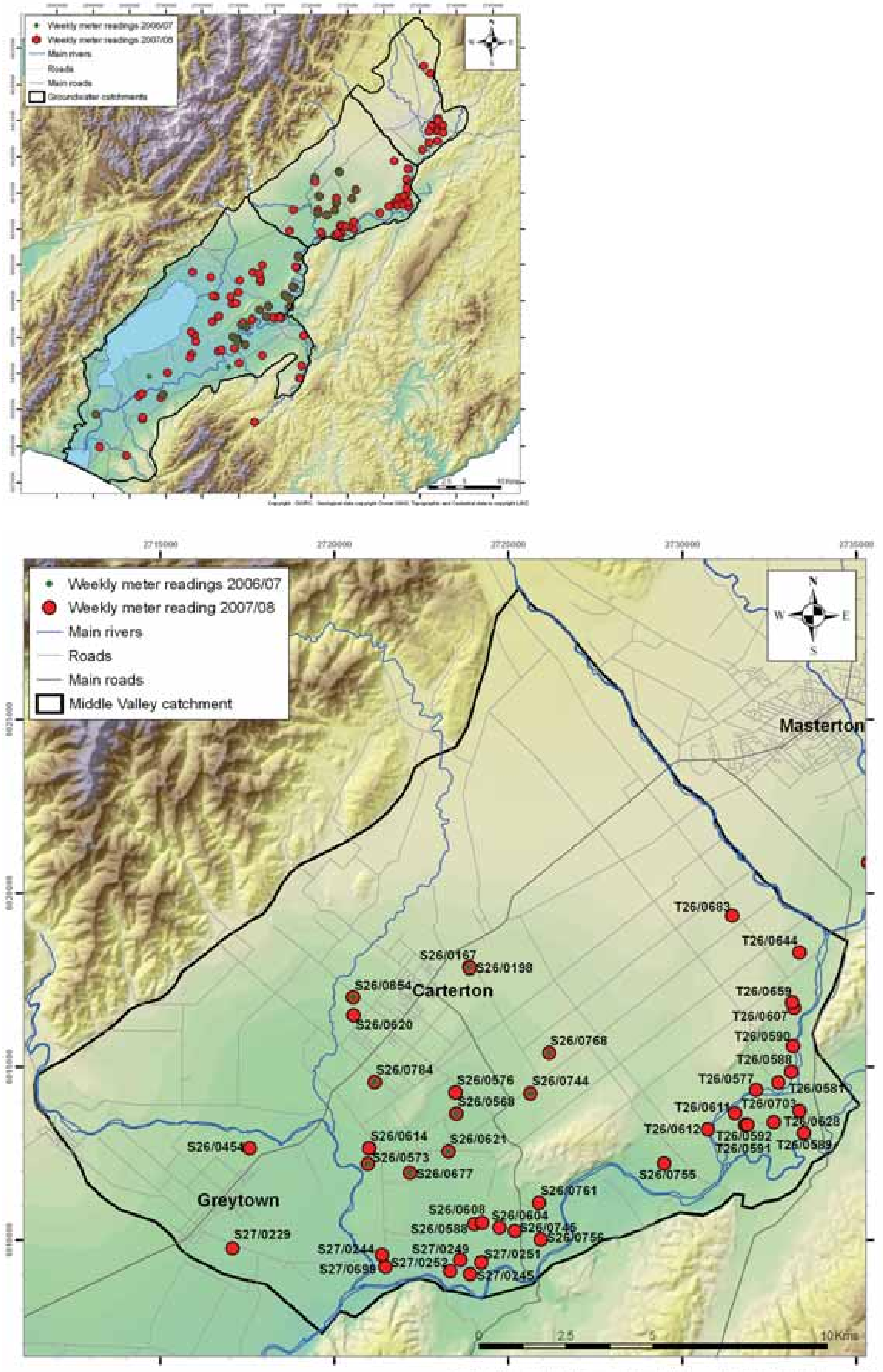


Figure 5.2: Water meter survey locations (2006/07 and 2007/08) in the Wairarapa Valley (top) and Middle Valley catchment

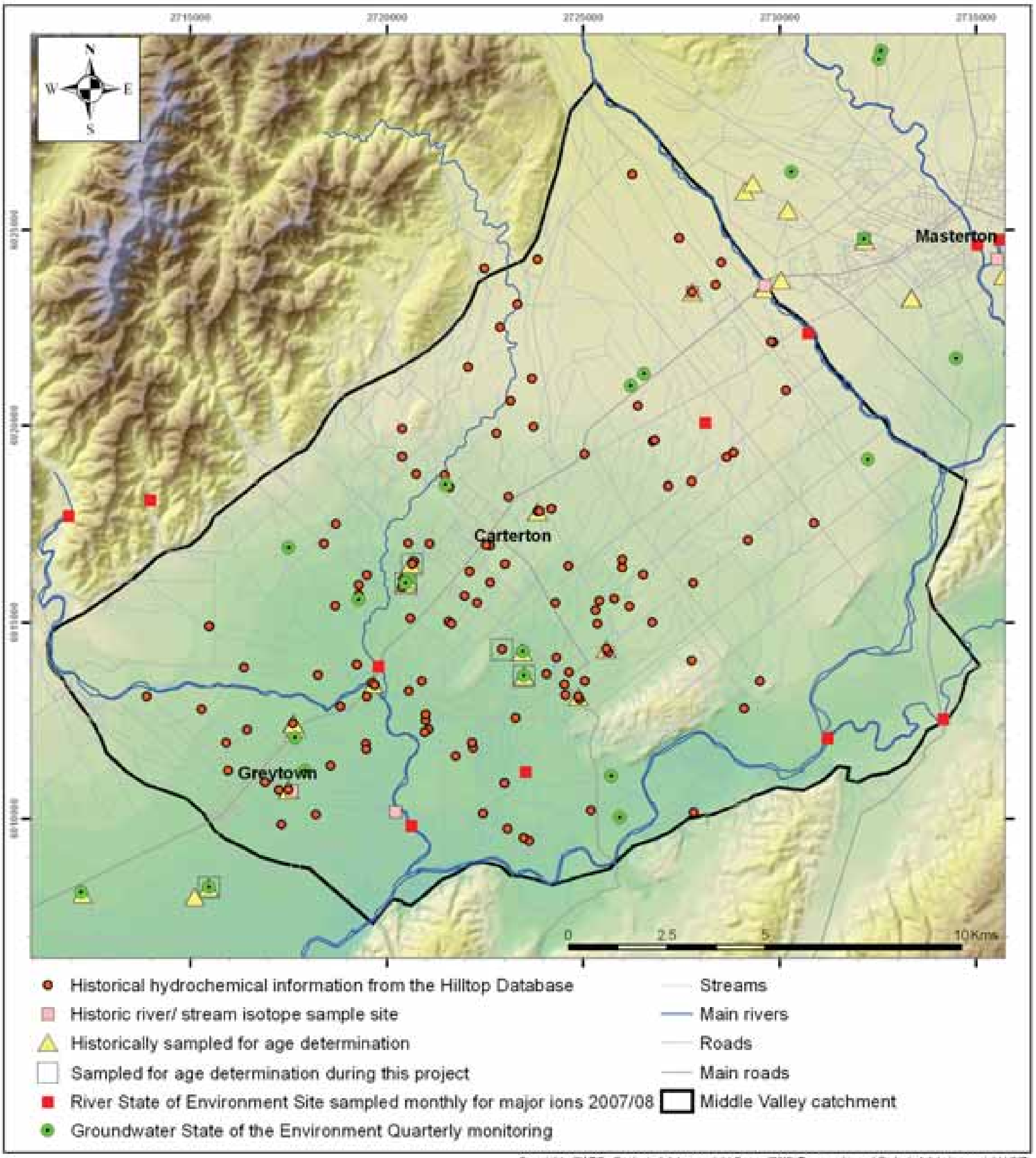


Figure 5.3: Middle Valley catchment bores with hydrochemistry data

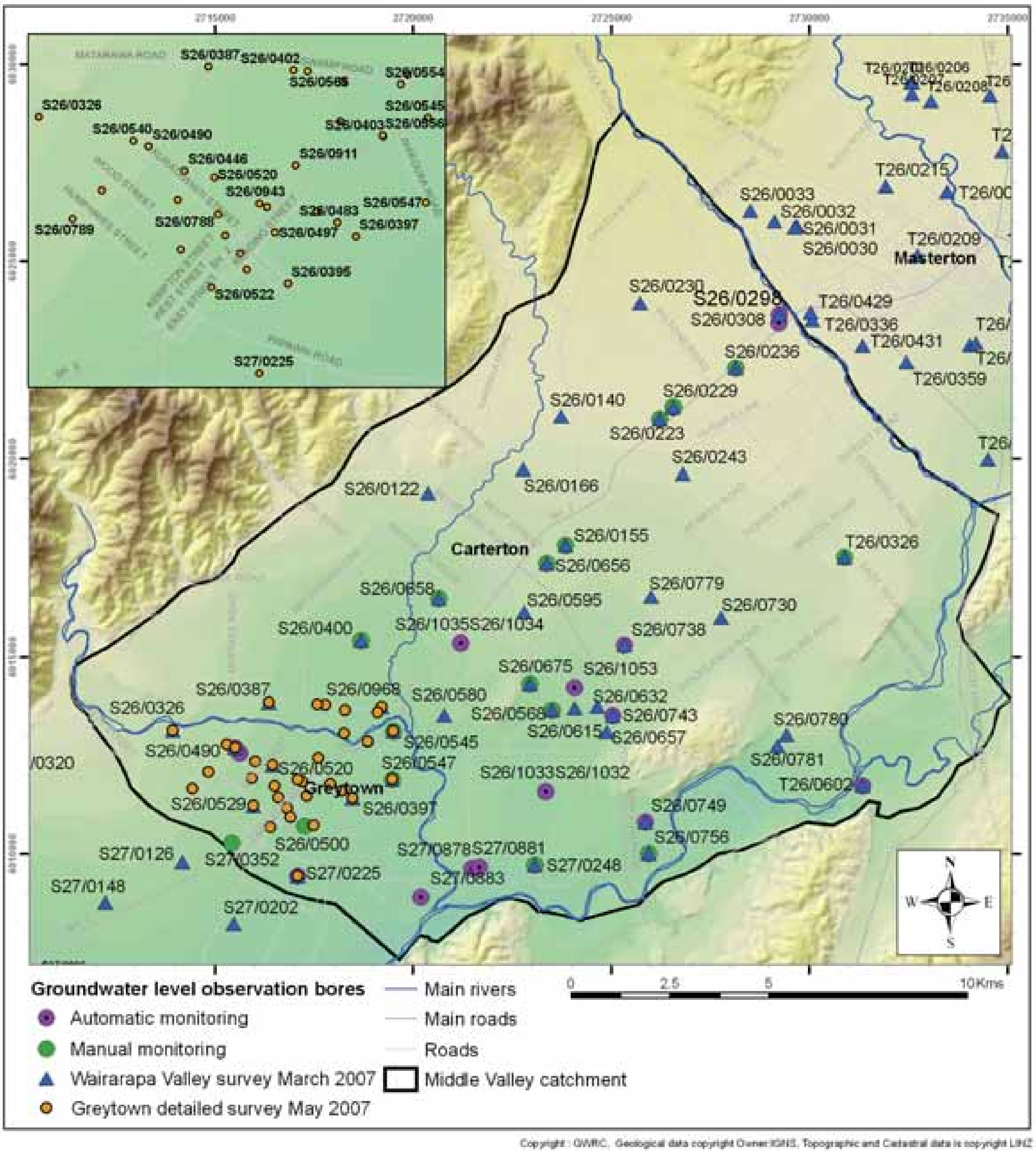


Figure 5.4: Location of bores used in the Middle Valley catchment piezometric survey, 2007 and 2008

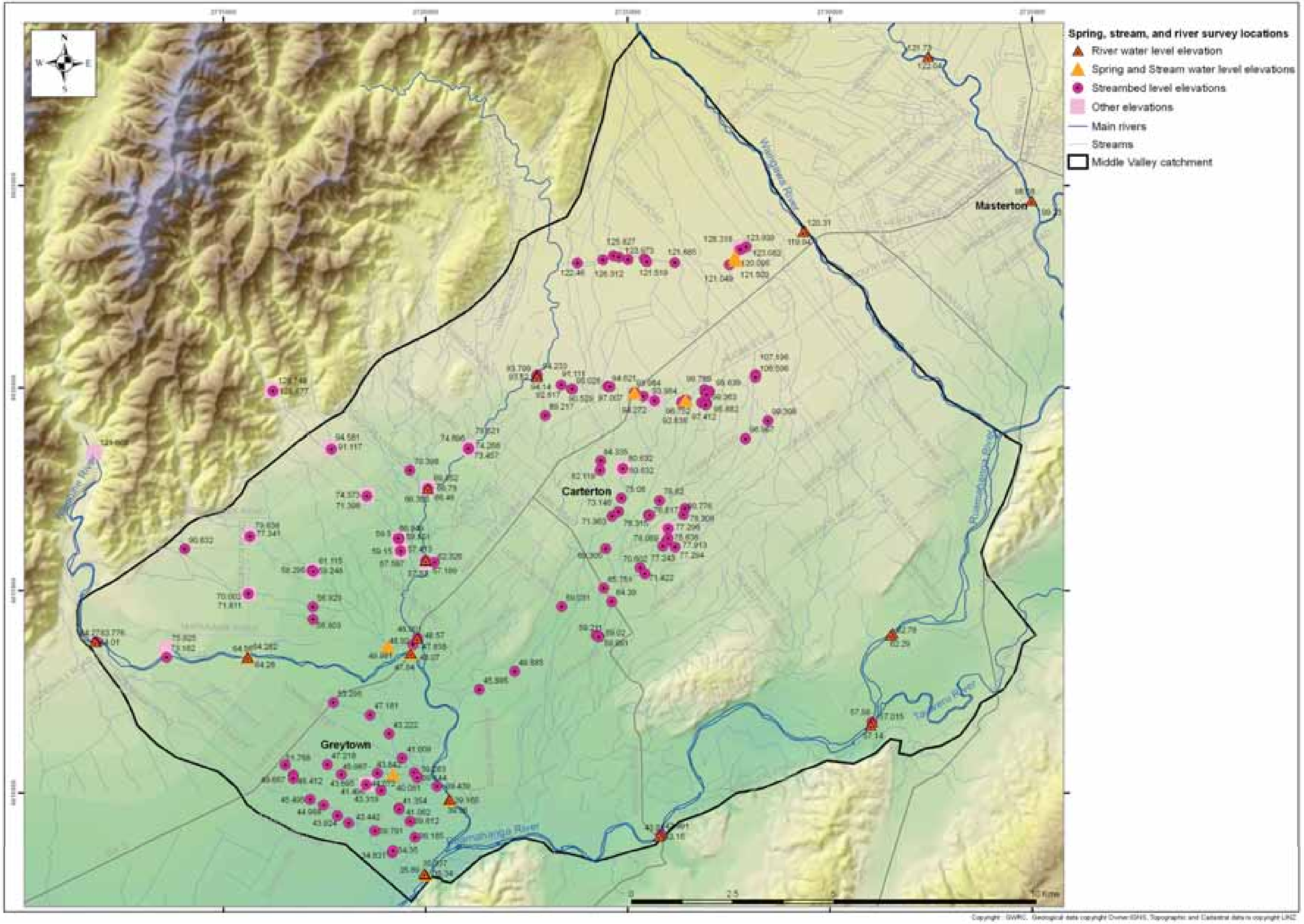
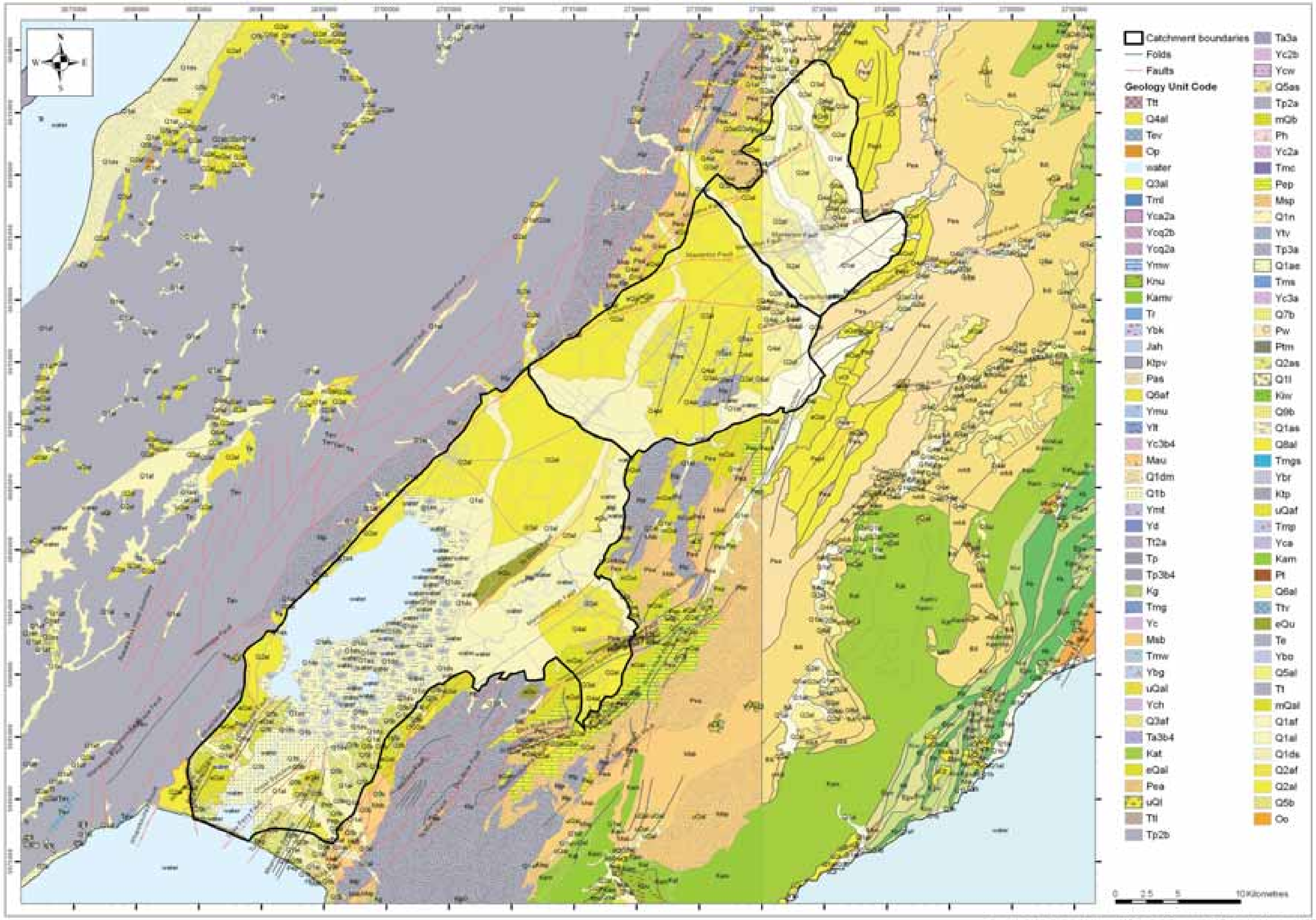


Figure 5.5: Spring, stream and river stage survey locations in the Middle Valley catchment



Copyright : GWRC. Geological data copyright Crown (GNS). Topographic and Cadastral data is copyright LINZ

(Source: GNS 1:25,000 geological maps for the Wellington and Wairarapa areas, 2002)

Figure 6.1: Geological map for the Wairarapa Valley showing major folds and faults

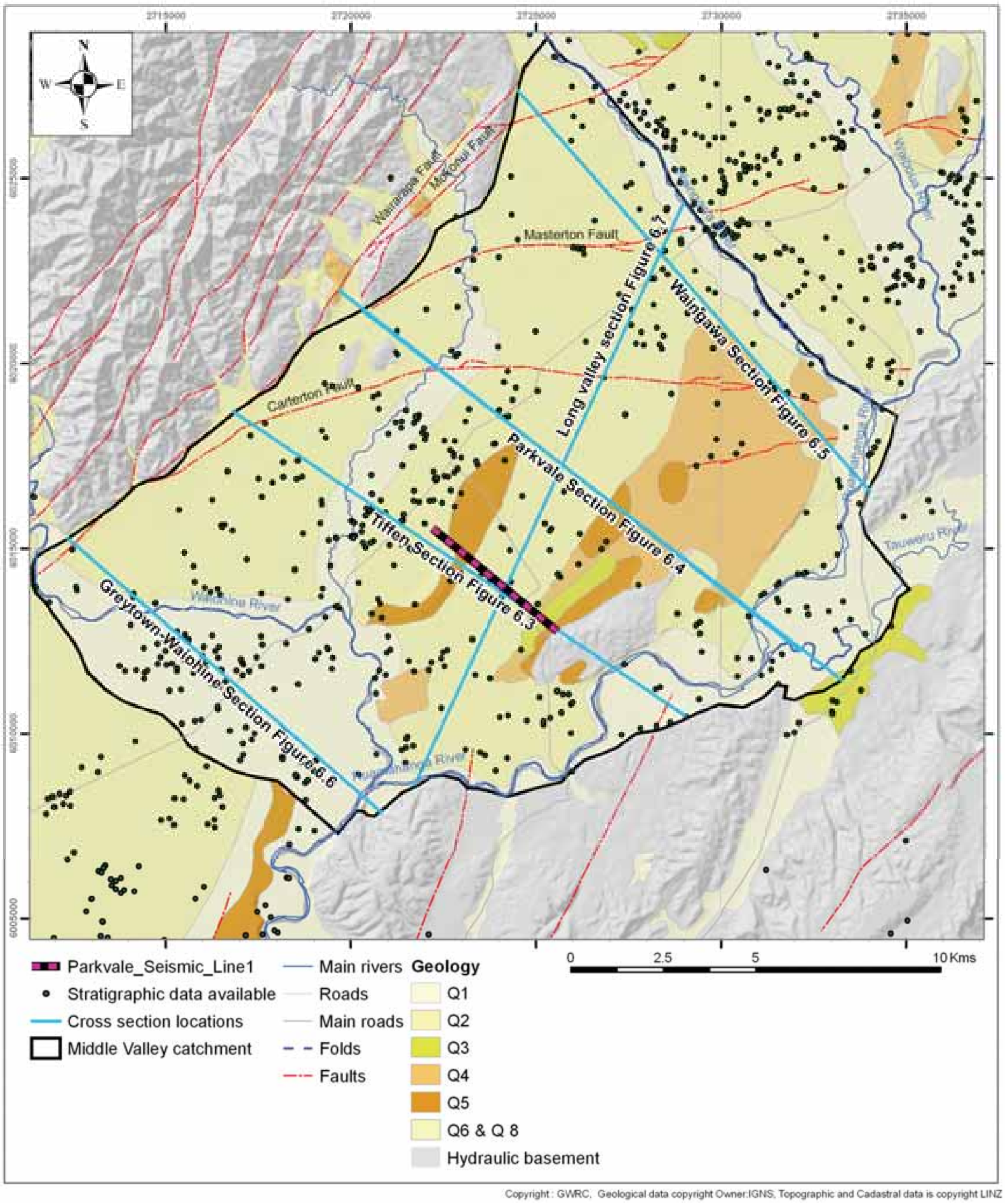


Figure 6.2: Geology of the Middle Valley catchment. Grey areas show hydraulic basement to the west and east and the uplifted basement block of Tiffen Hill. The location of bores with drill logs from Greater Wellington's Wells database are shown along with cross section line locations. Also shown is the location of seismic section line 1 across the Parkvale sub-basin.

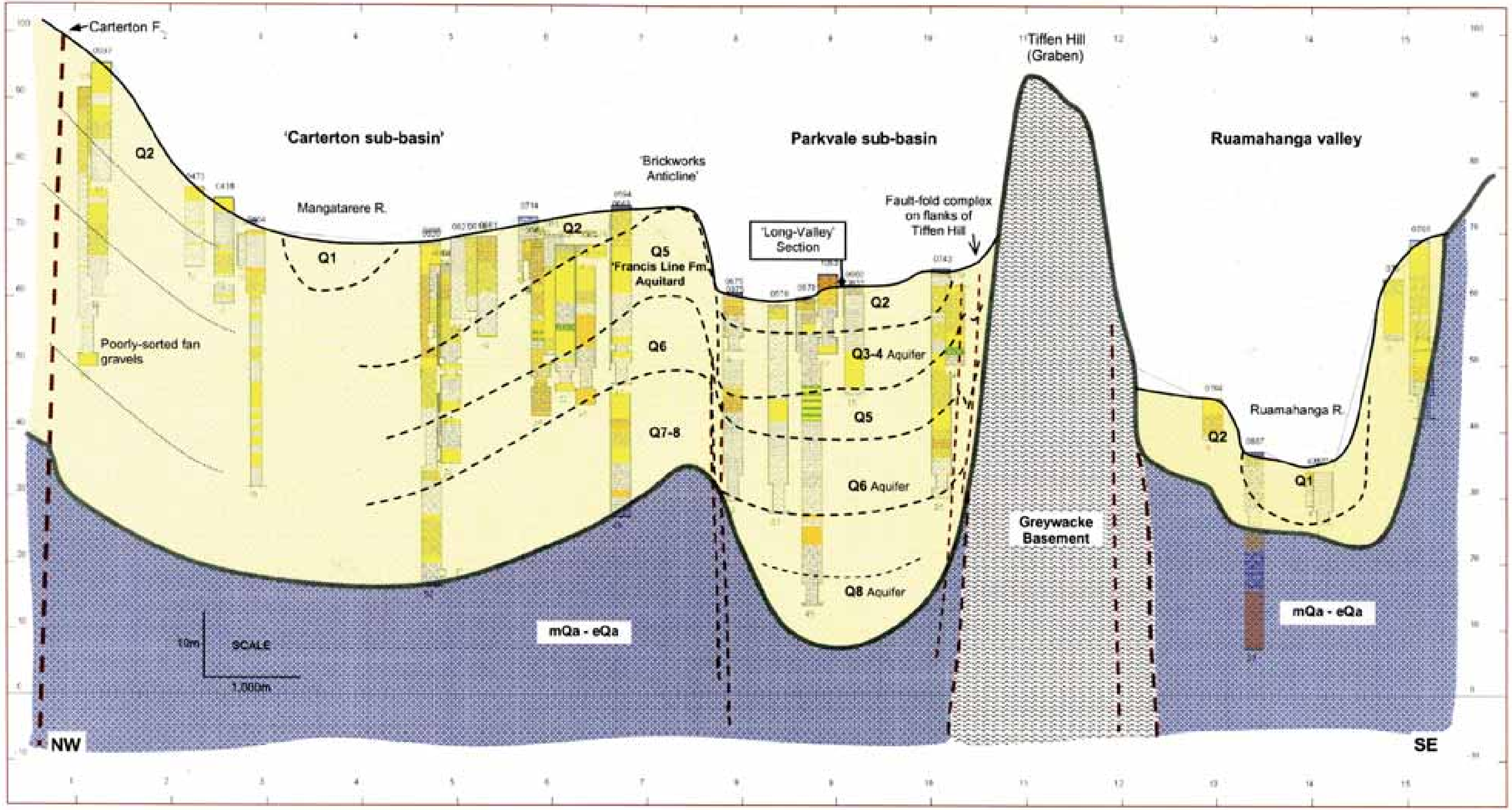


Figure 6.3: Middle Valley catchment: ''Tiffen' geological cross section

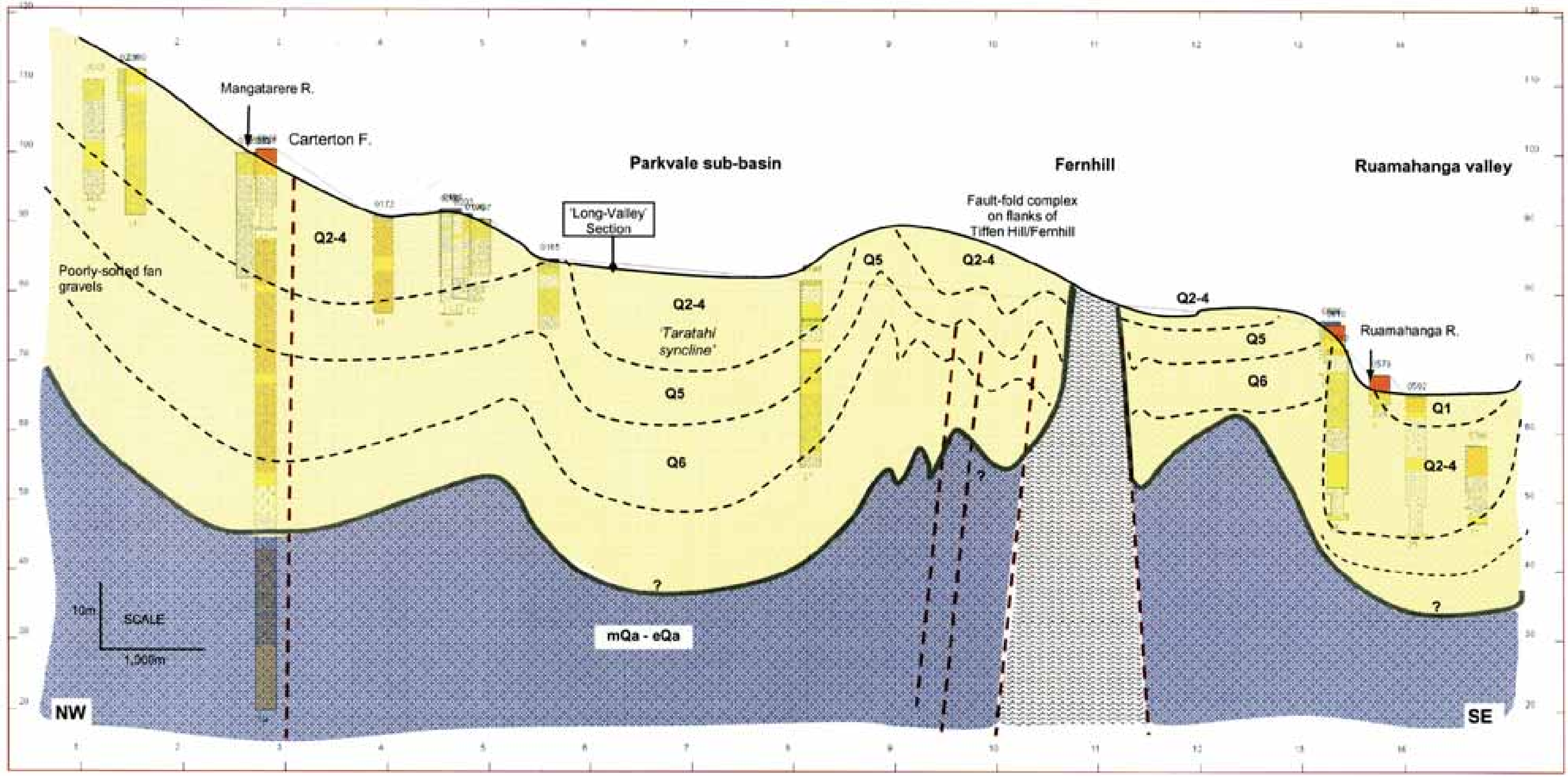


Figure 6.4: Middle Valley catchment: 'Parkvale' geological cross section

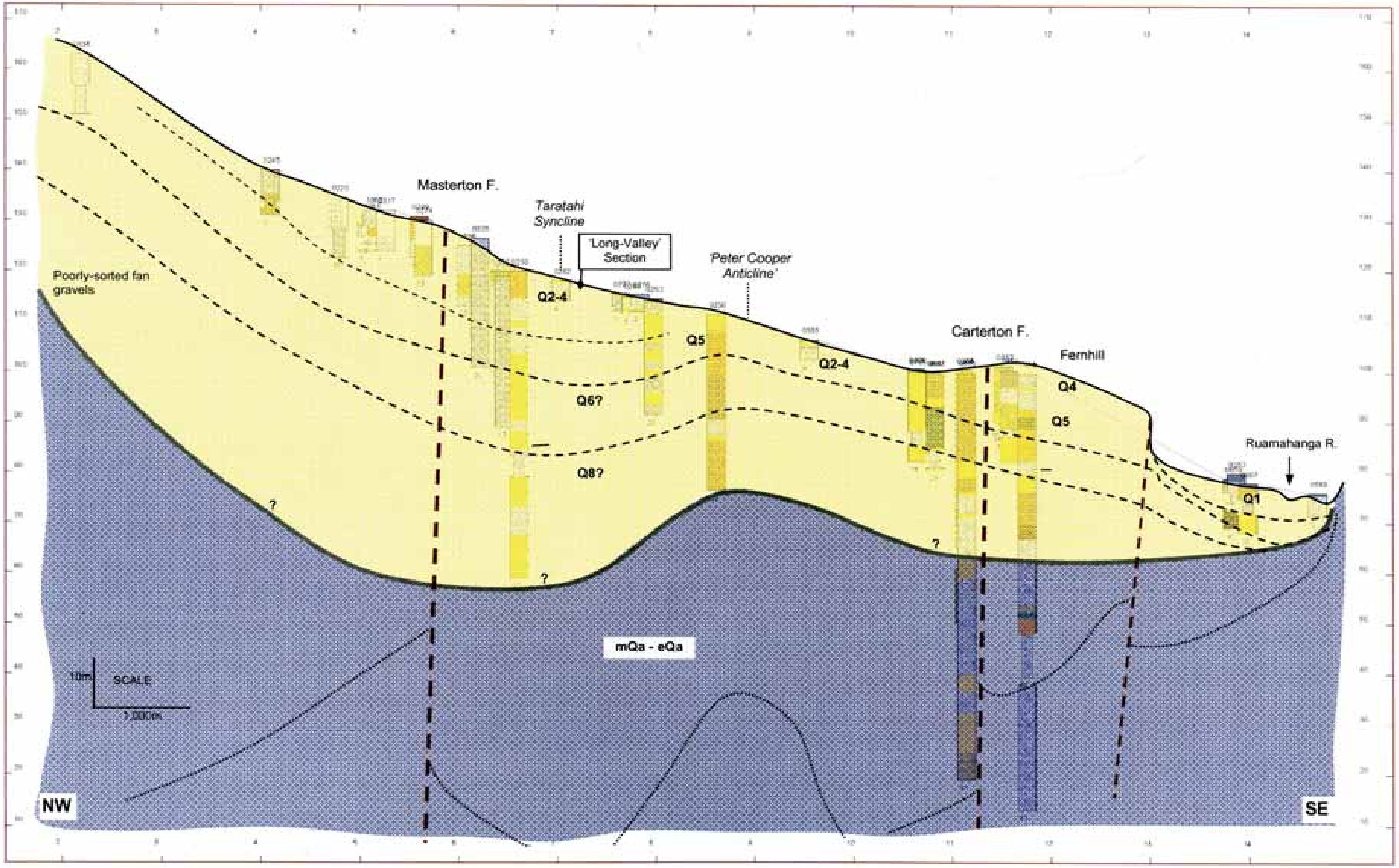


Figure 6.5: Middle Valley catchment: 'Waingawa' geological cross section

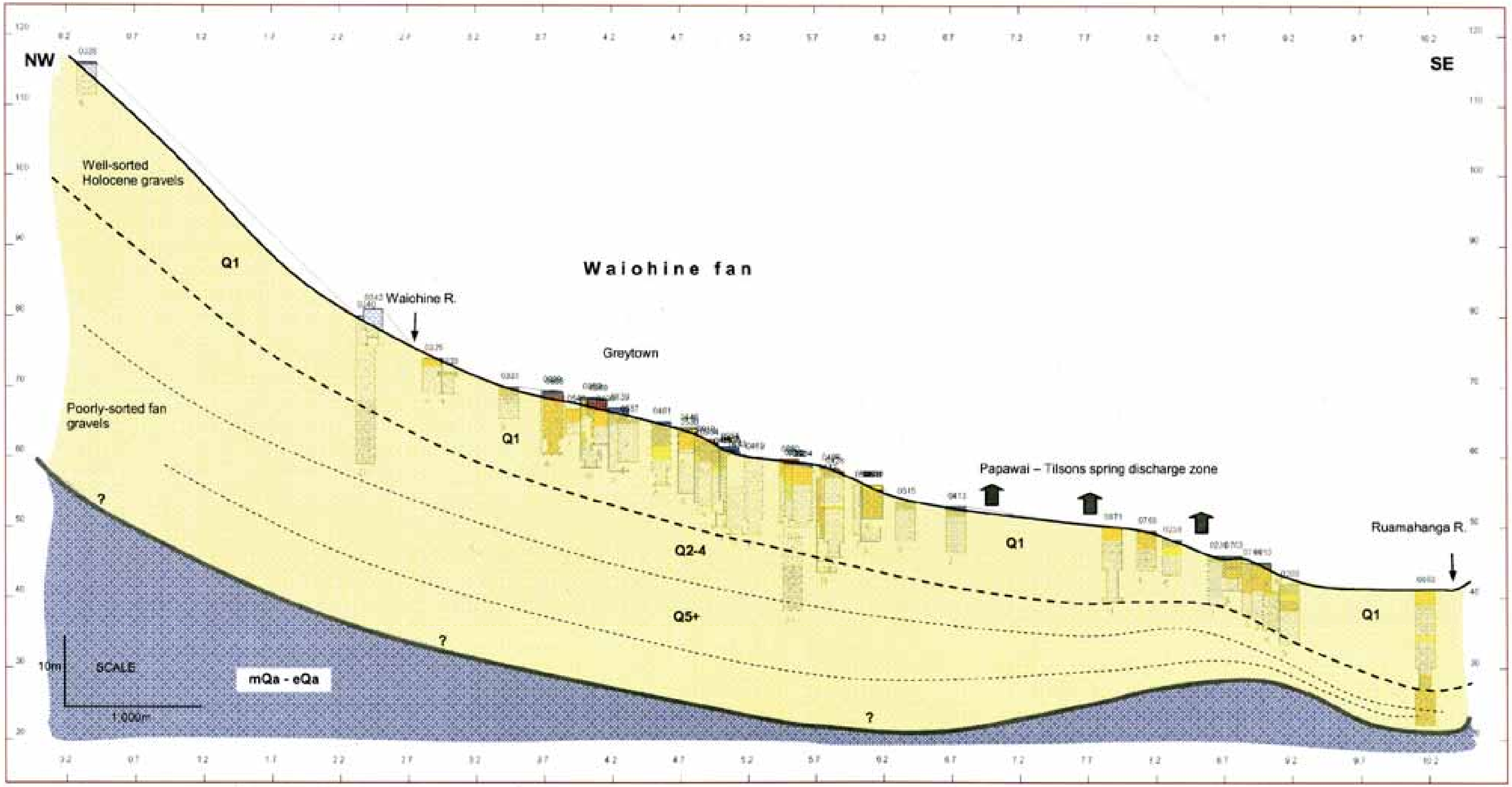


Figure 6.6: Middle Valley catchment: 'Greytown–Waiohine' geological cross section

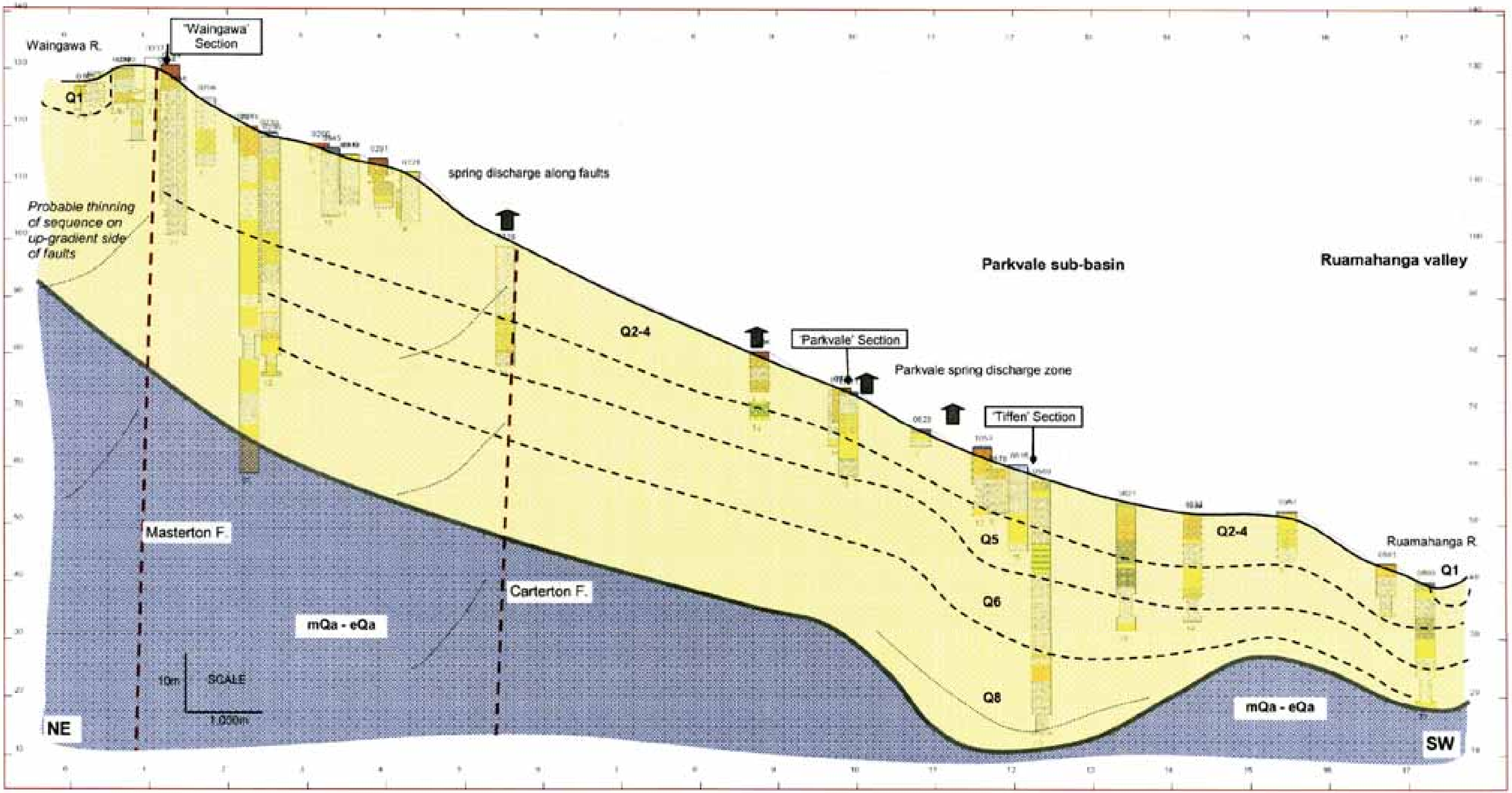


Figure 6.7: Middle valley catchment: 'Long valley' geological cross section

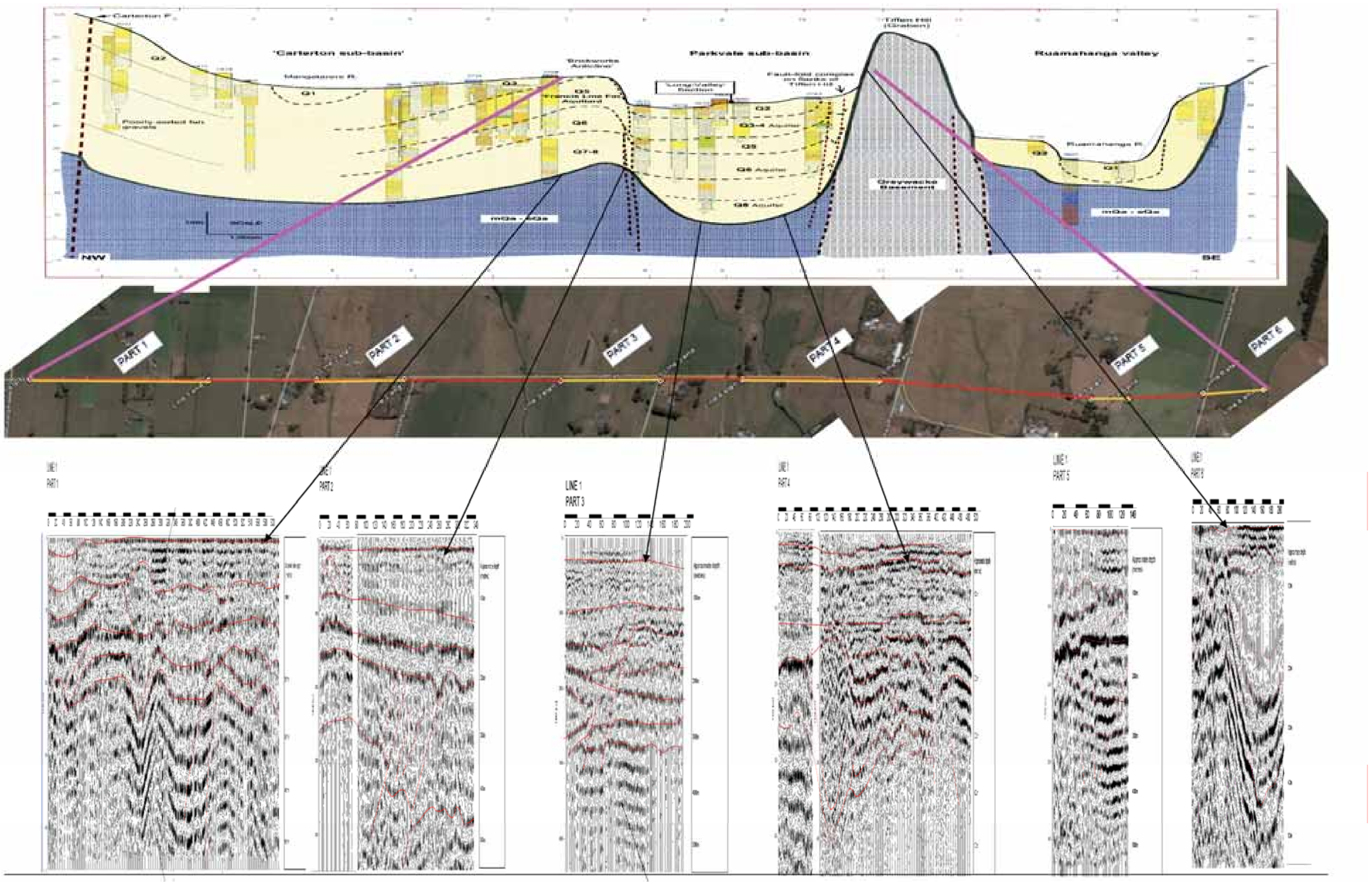


Figure 6.8: Seismic survey line 1 (in 6 parts) across the Parkvale plain showing interpretation (see Figure 6.2 for location). Note the survey 'looks' considerably deeper than the base of the groundwater system.

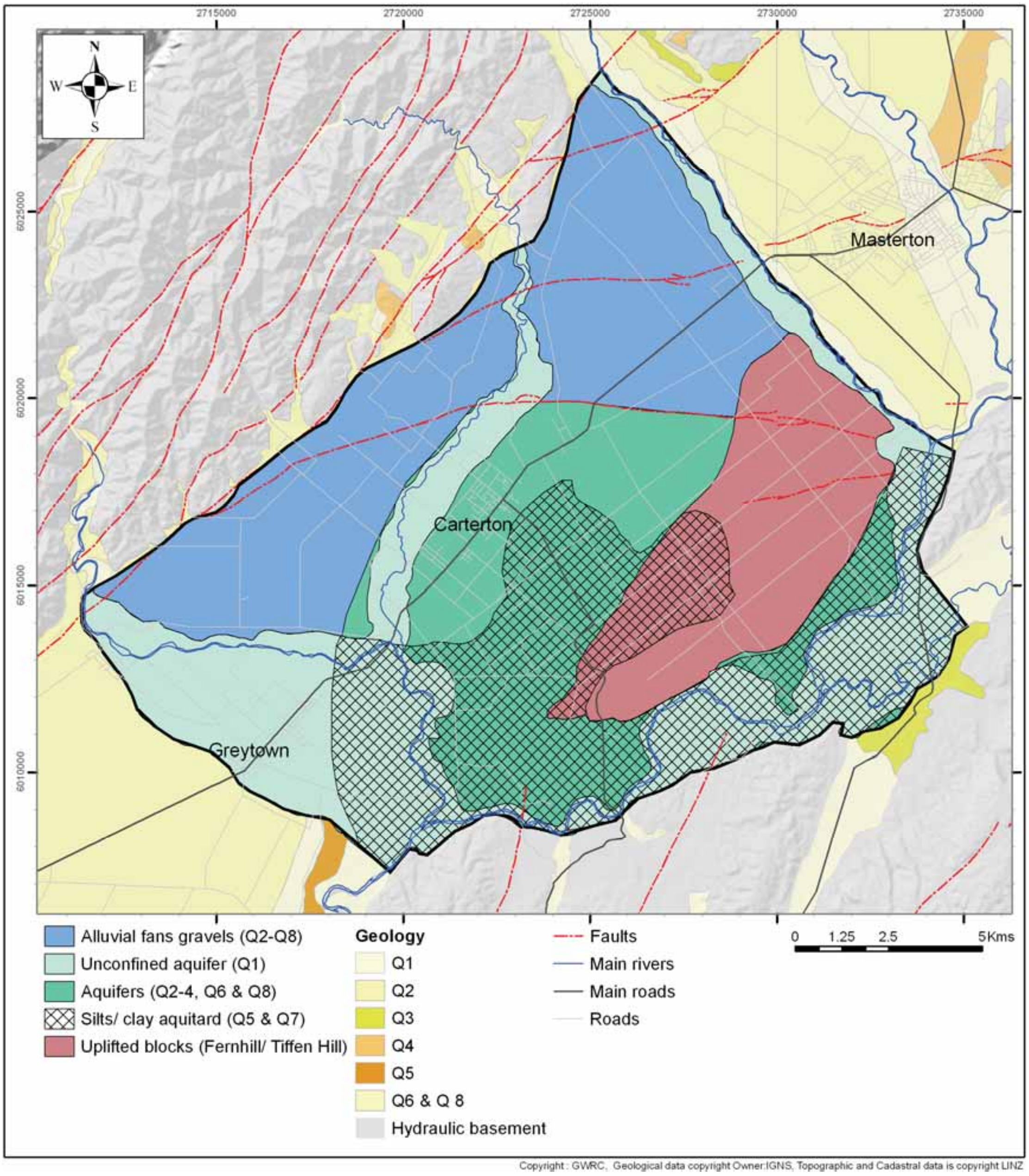


Figure 7.1: Principal hydrostratigraphic units of the Middle Valley catchment

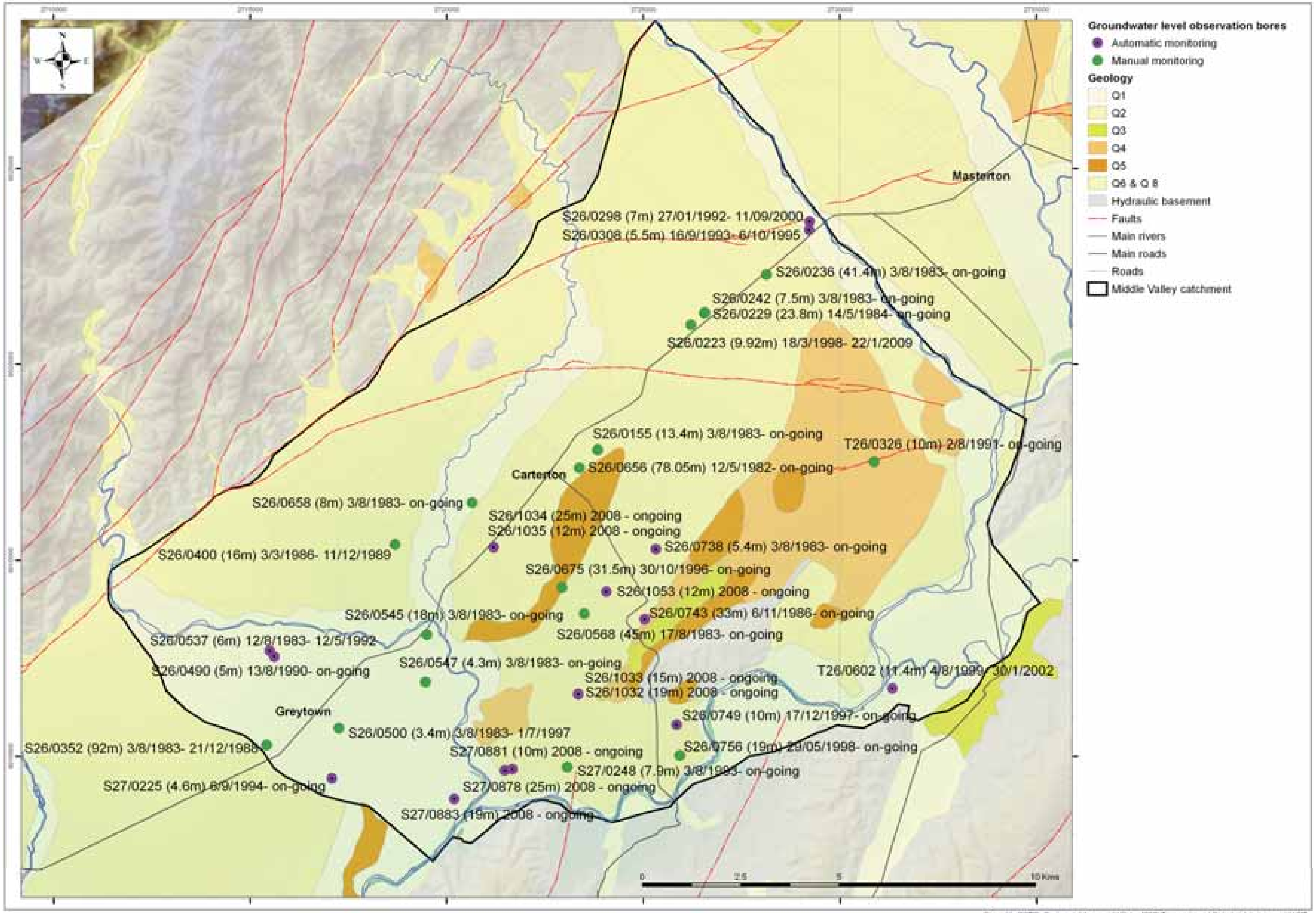


Figure 7.2: Groundwater level monitoring bores used during the Middle Valley catchment investigation. The bore number, length of data record available for each bore, and bore depth are labelled.

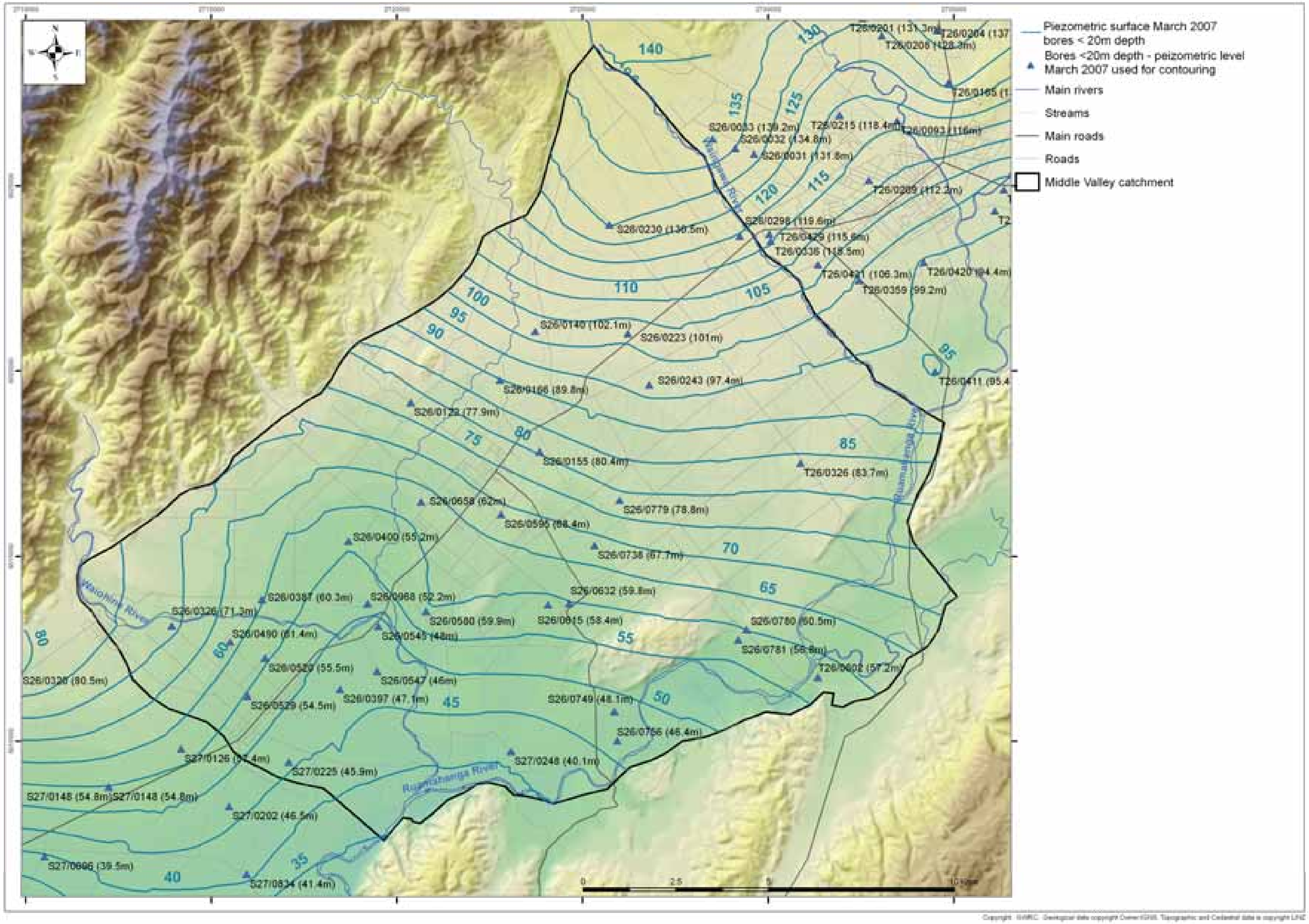


Figure 7.3: Piezometric contours for March 2007, based on piezometric data from groundwater bores <20 m in depth. Point data used to develop the surface are shown.

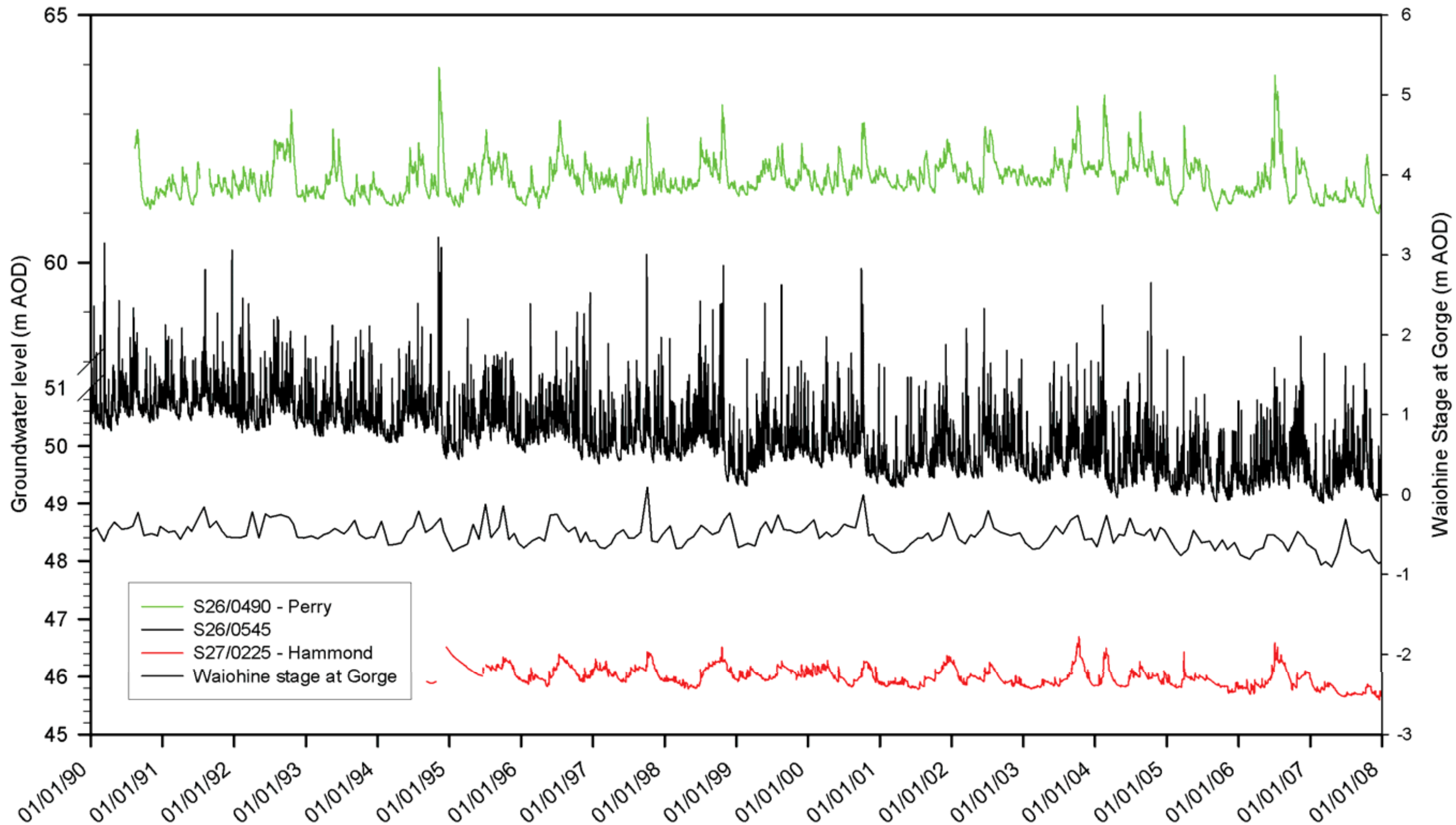


Figure 7.4: Groundwater level hydrographs (1 day average) from the Greytown/Waiohine plains and stage in the Waiohine River (at Gorge)

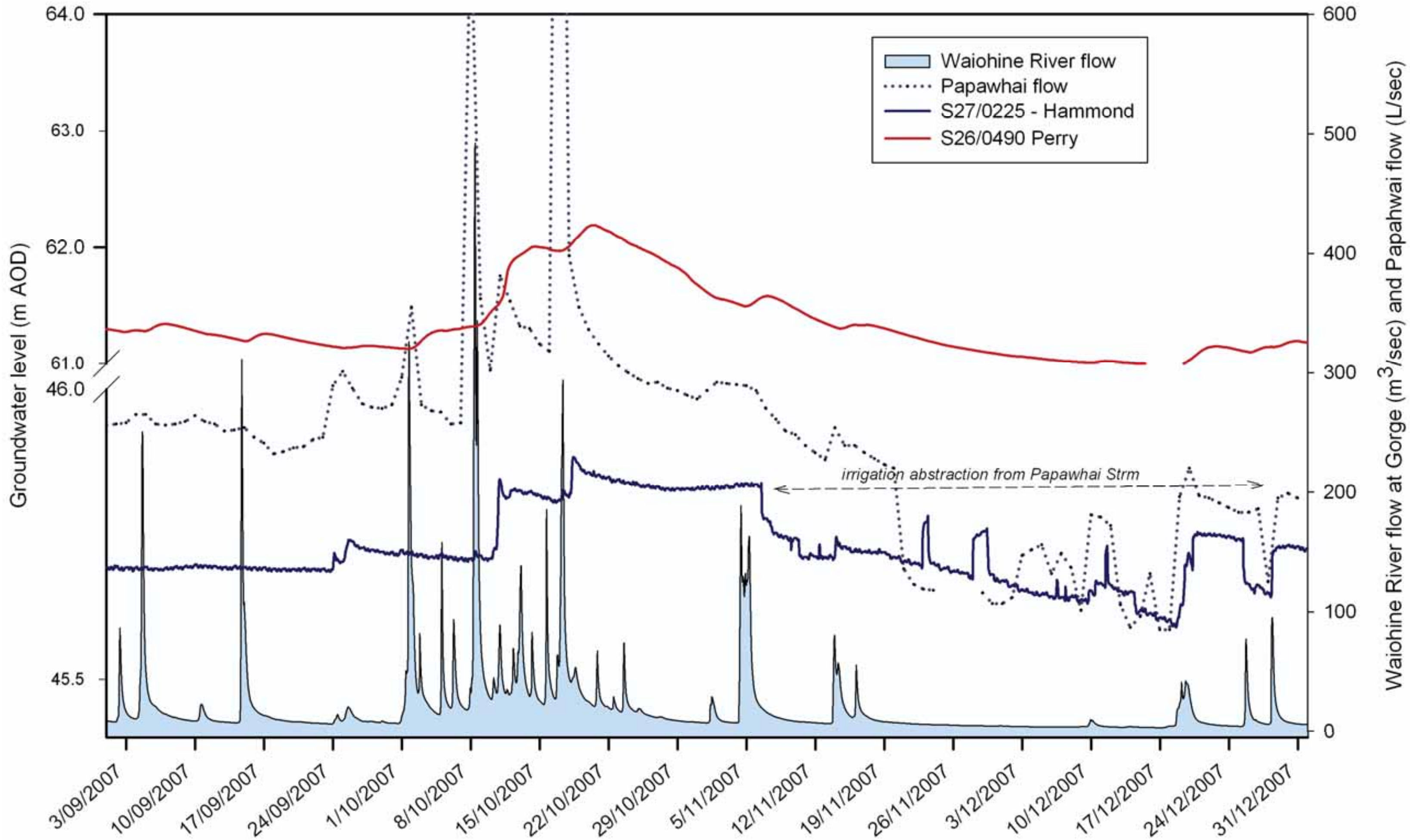


Figure 7.5: Groundwater level at the Perry and Hammond groundwater level monitoring sites, flow in the Waiohine River (measured and the Gorge recorder site) and flow in the Papawai Stream

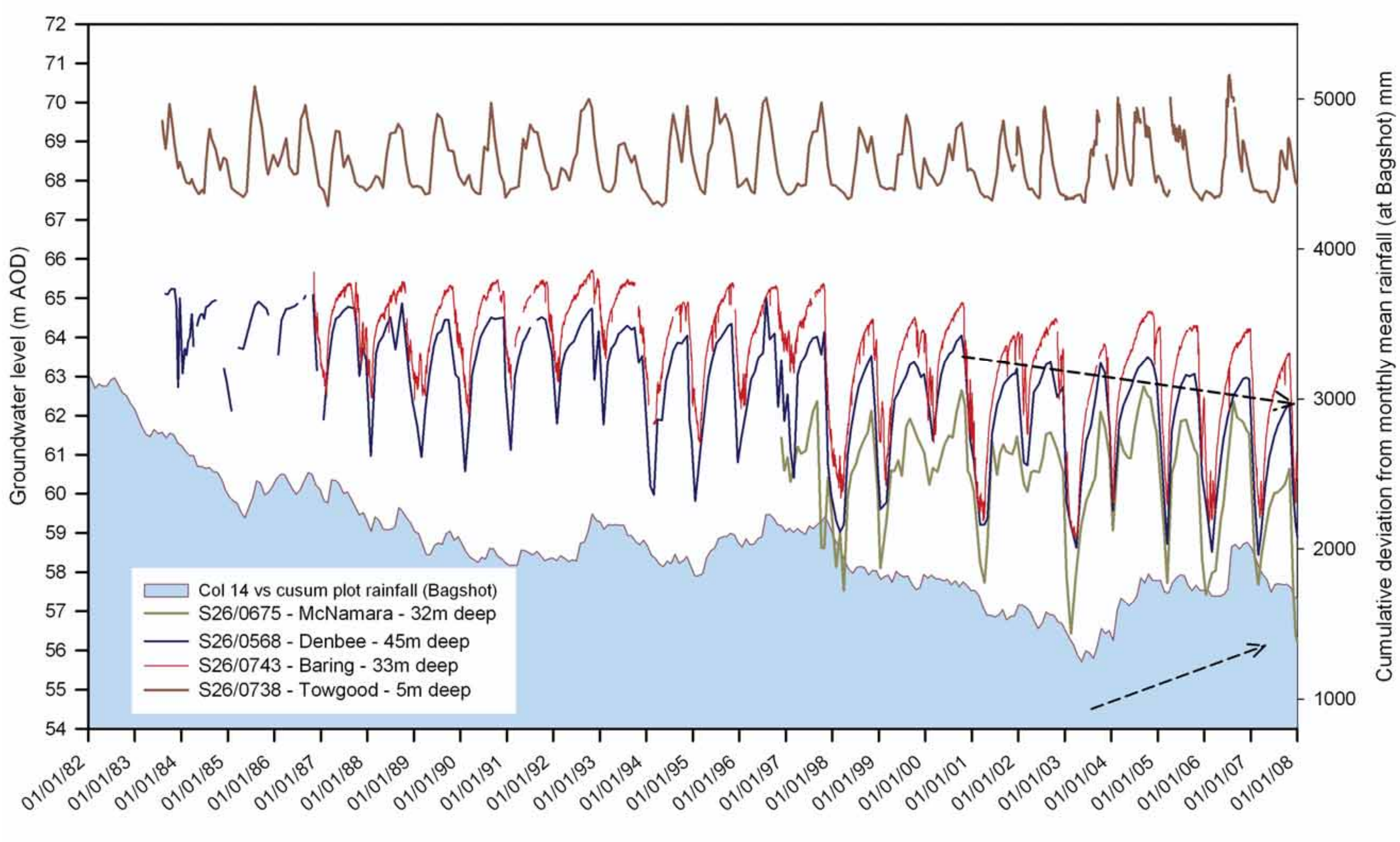


Figure 7.6: Groundwater level hydrographs for the Parkvale area and cusum monthly rainfall plot for the Bagshot rainfall station

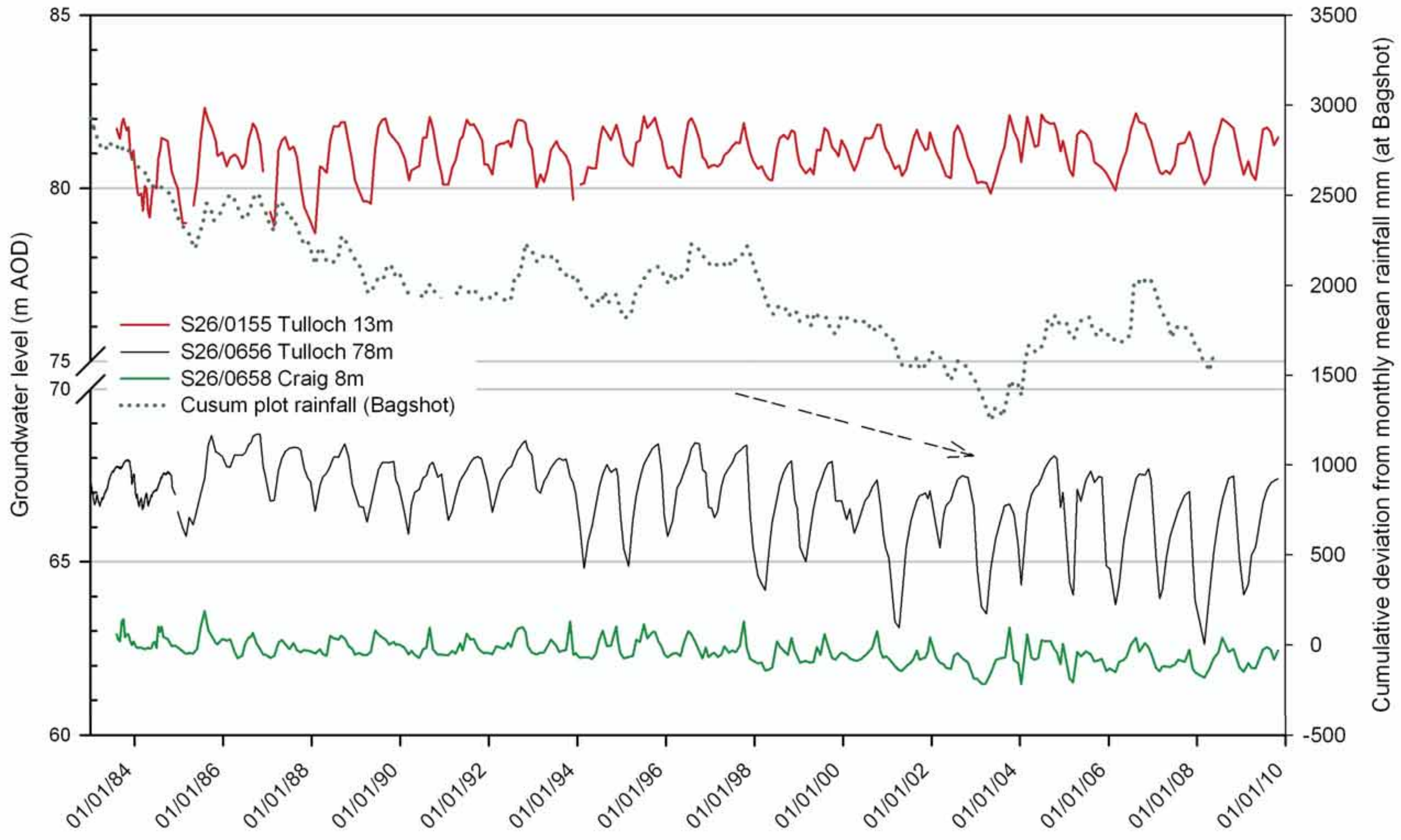


Figure 7.7: Groundwater level hydrographs for the Carterton area and cusum rainfall plot for the Bagshot rainfall station

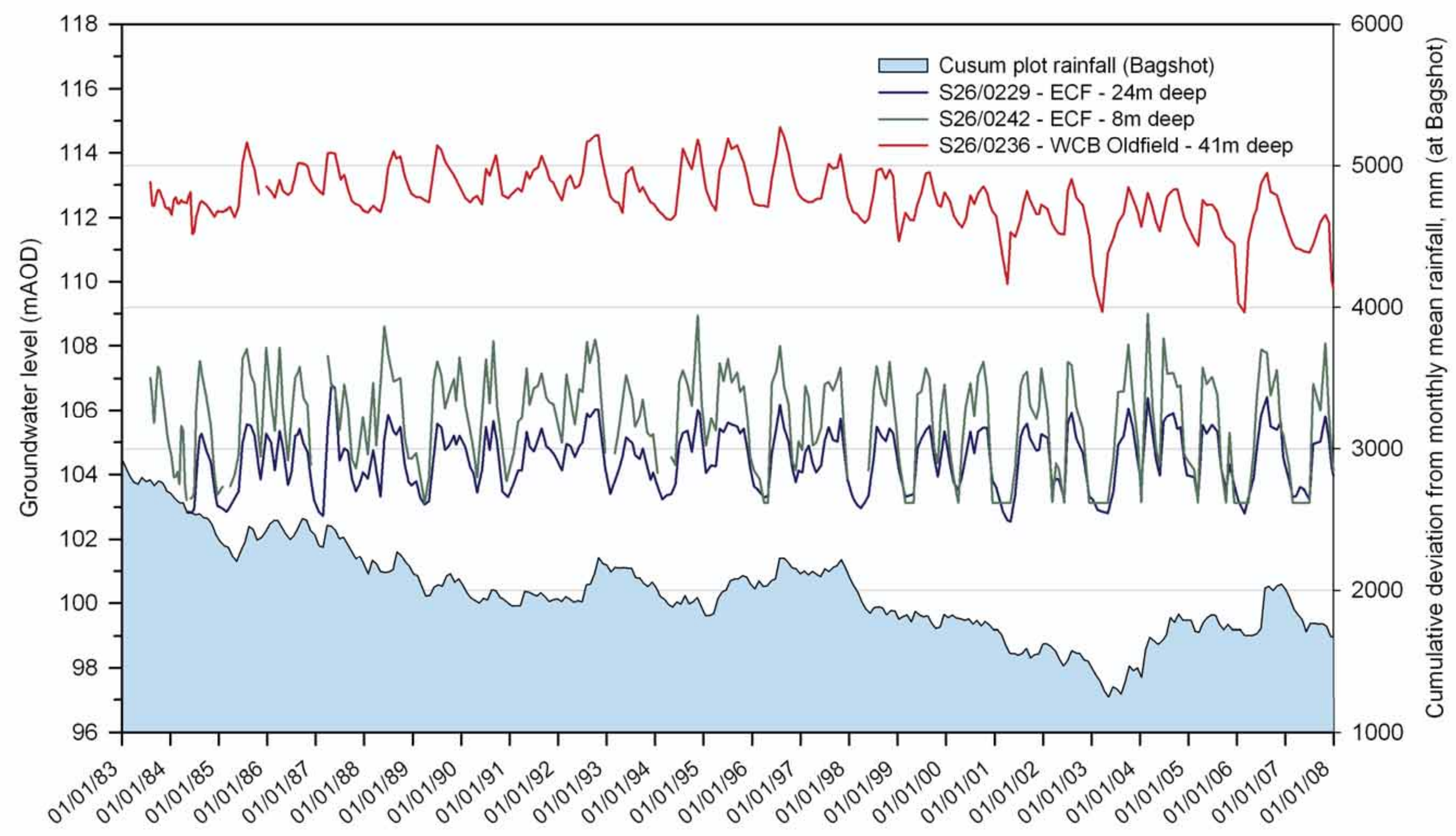


Figure 7.8: Groundwater level hydrographs for the Upper Waingawa alluvial fan and cusum rainfall plot for the Bagshot rainfall station

Figure 7.9: Groundwater level hydrograph for Fernhill and cusum monthly rainfall plot for the Bagshot rainfall station

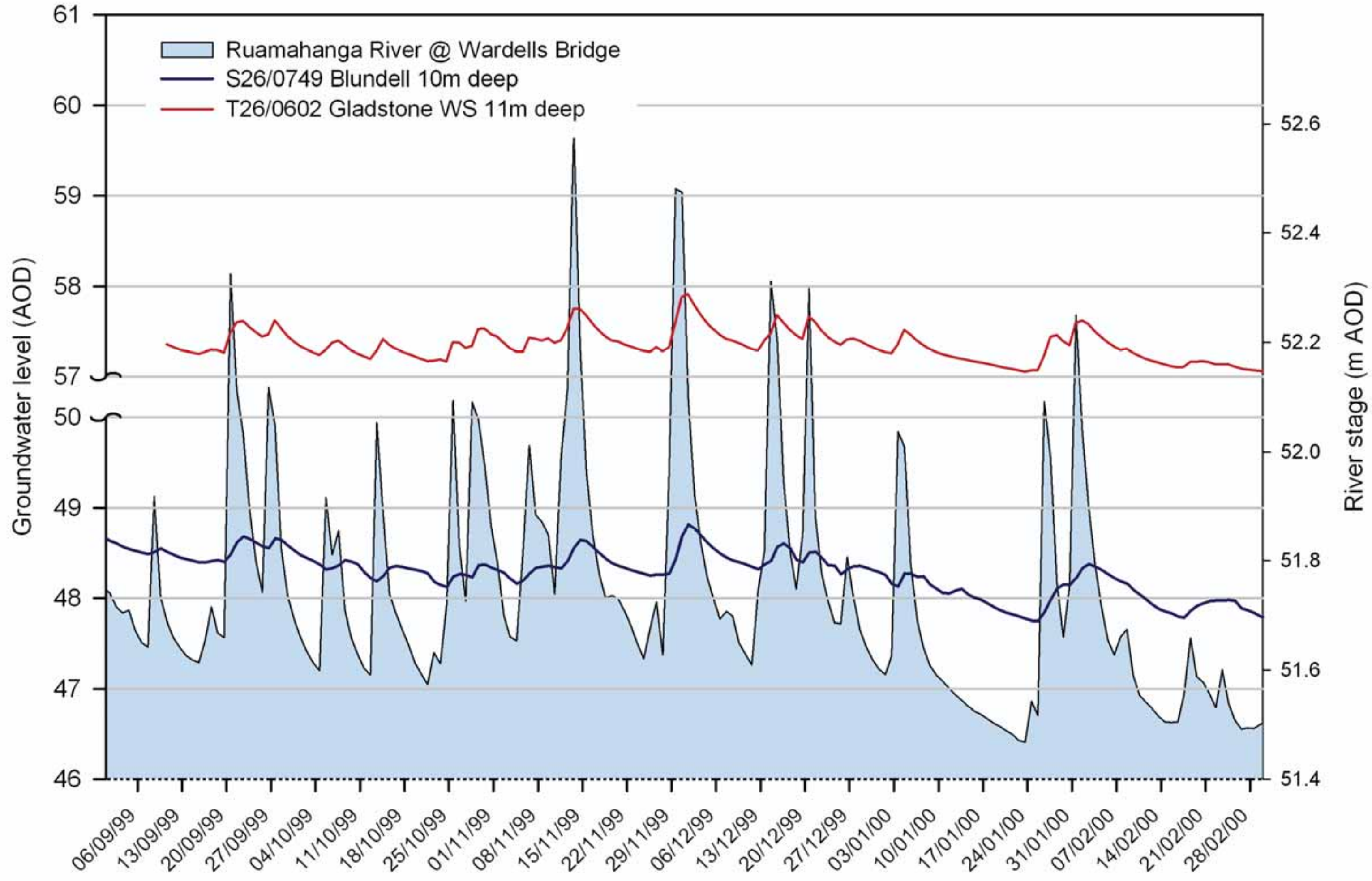


Figure 7.10: Groundwater level at shallow groundwater monitoring sites on the Ruamahanga River floodplain and stage in the Ruamahanga River (measured and the Wardell's Bridge recorder site)

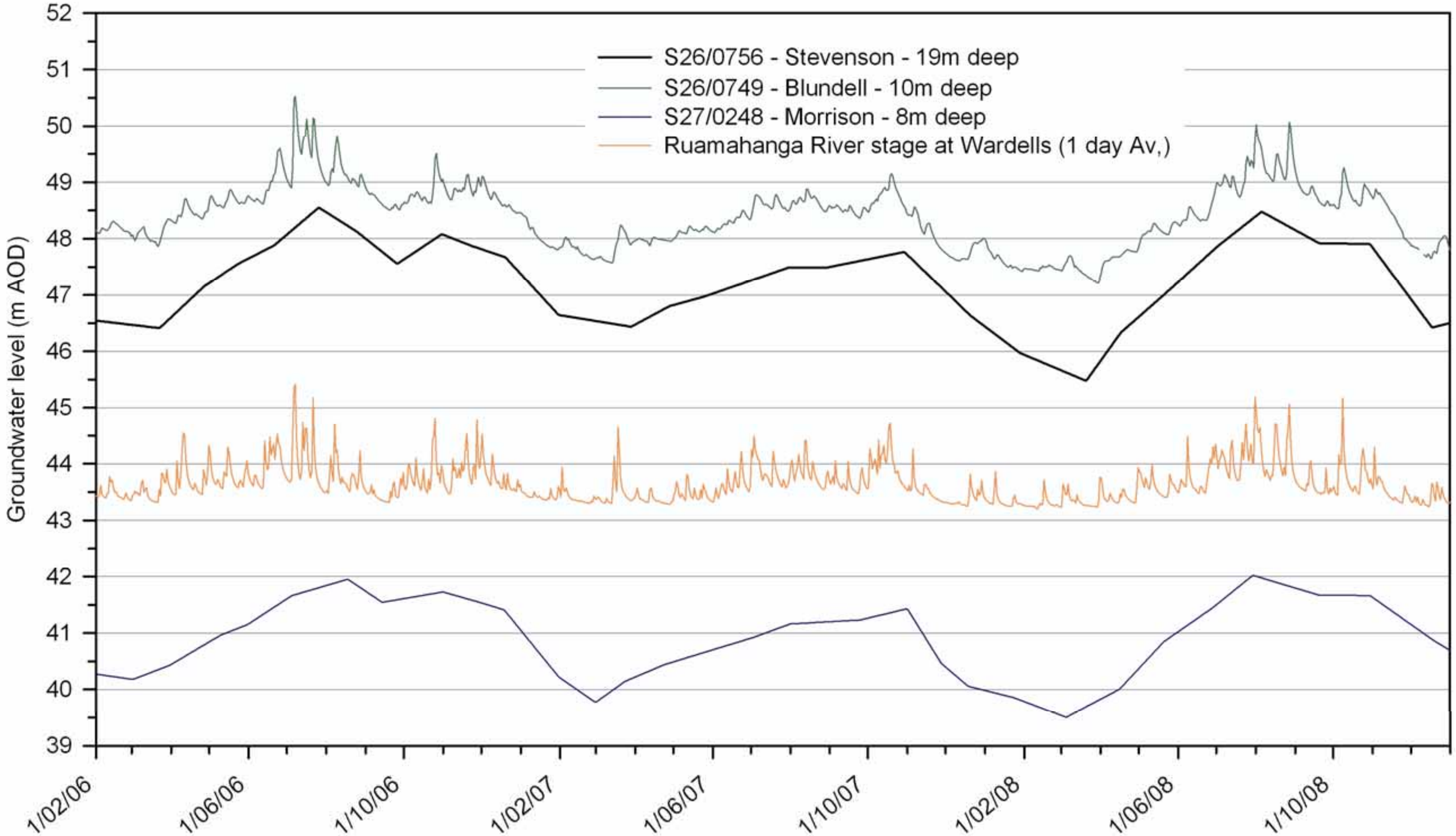


Figure 7.11: Groundwater level at groundwater monitoring sites on the Ruamahanga River floodplain for the period 1 February 2006 to 1 September 2008. Also shown is flow in the Ruamahanga River measured at the Wardell's Bridge recorder site.

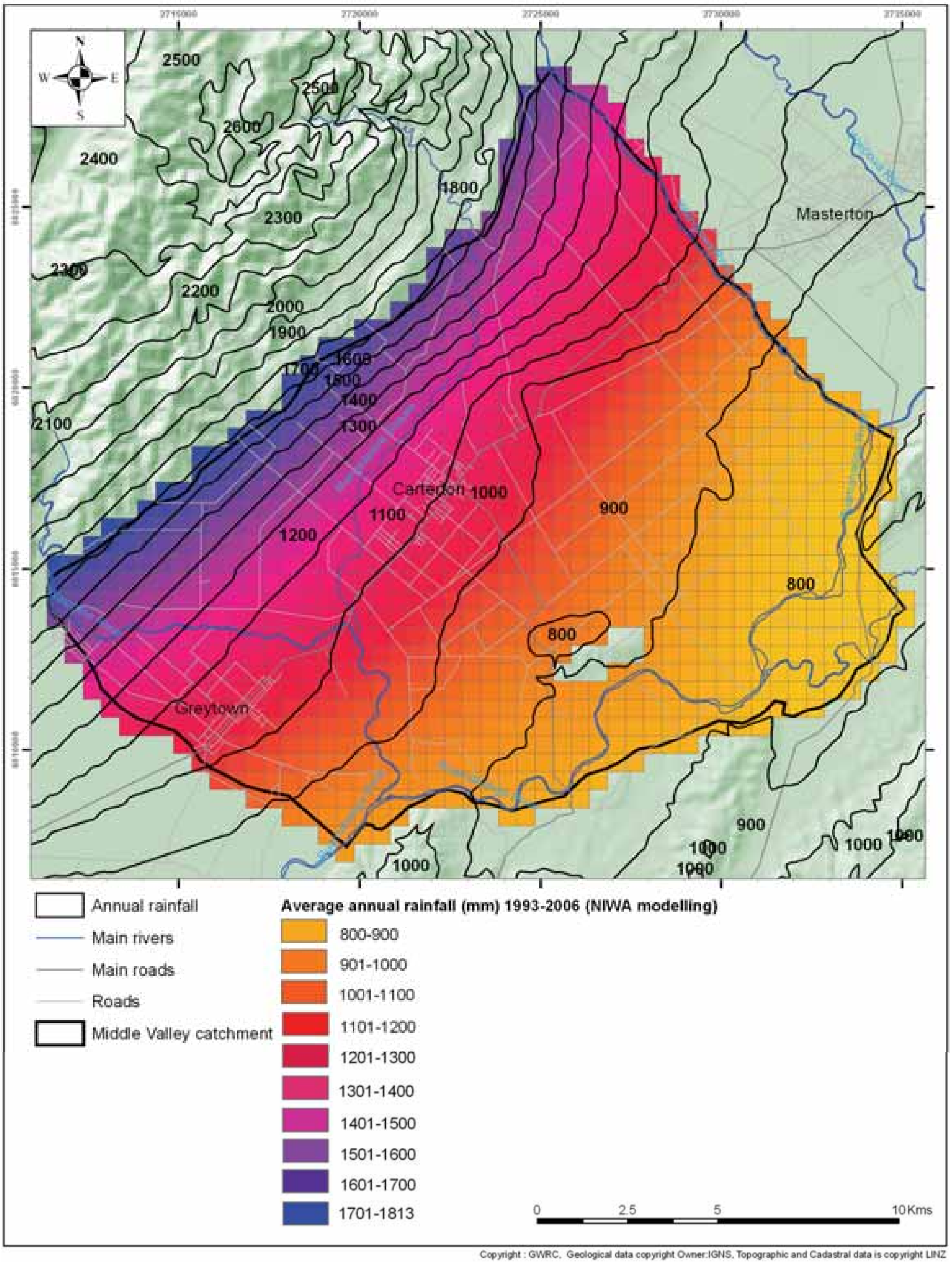


Figure 7.12: Average annual rainfall data for the Middle Valley catchment sourced from NIWA modelling for a 500 m^2 grid cell centre. Mean (1920-1970) rainfall isohyets are overlaid in the figure for comparison.

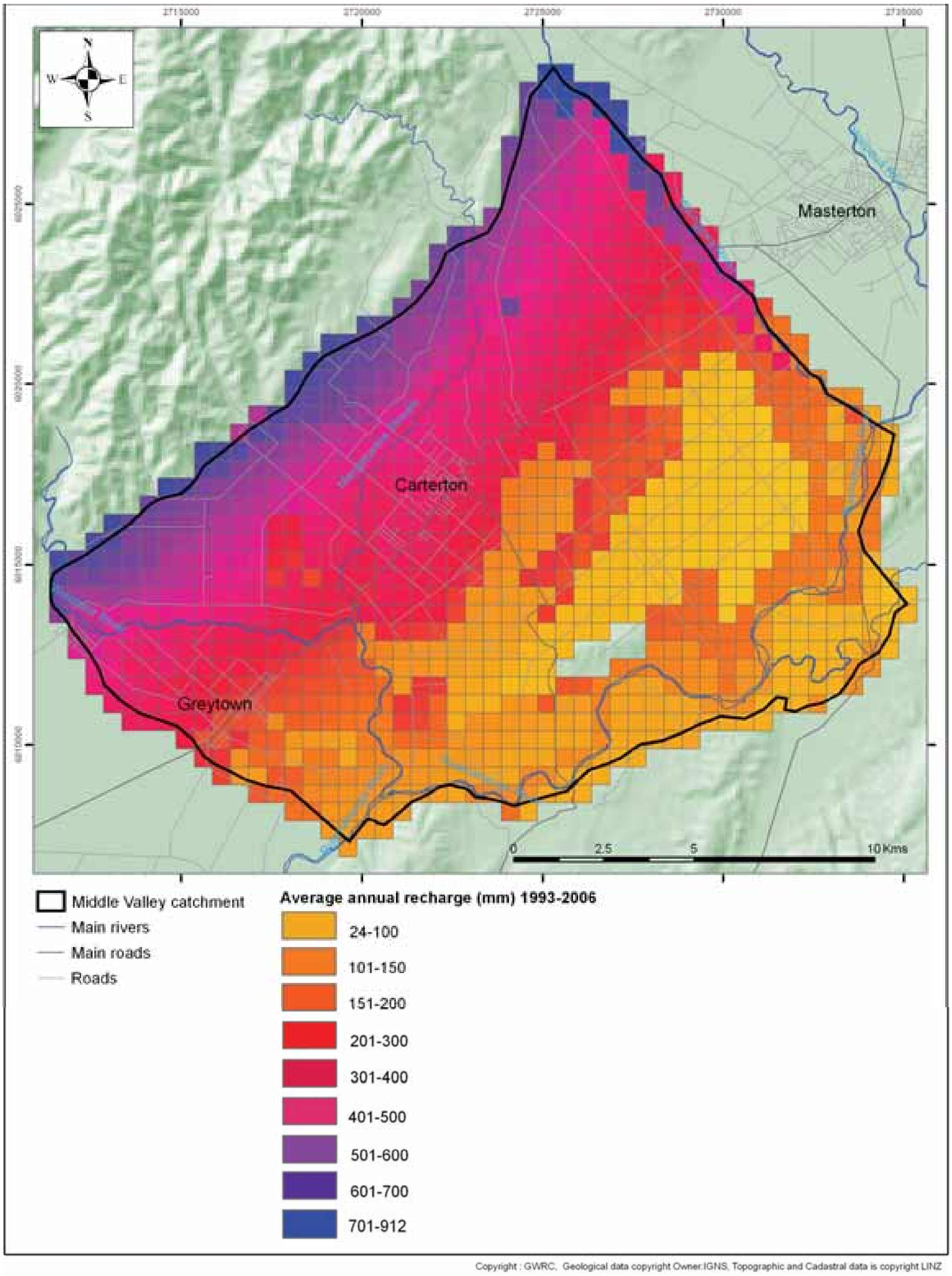


Figure 7.13: Average annual recharge for the Middle Valley catchment over the model period 1992-2007. Displayed data were used to develop the FEFLOW model.

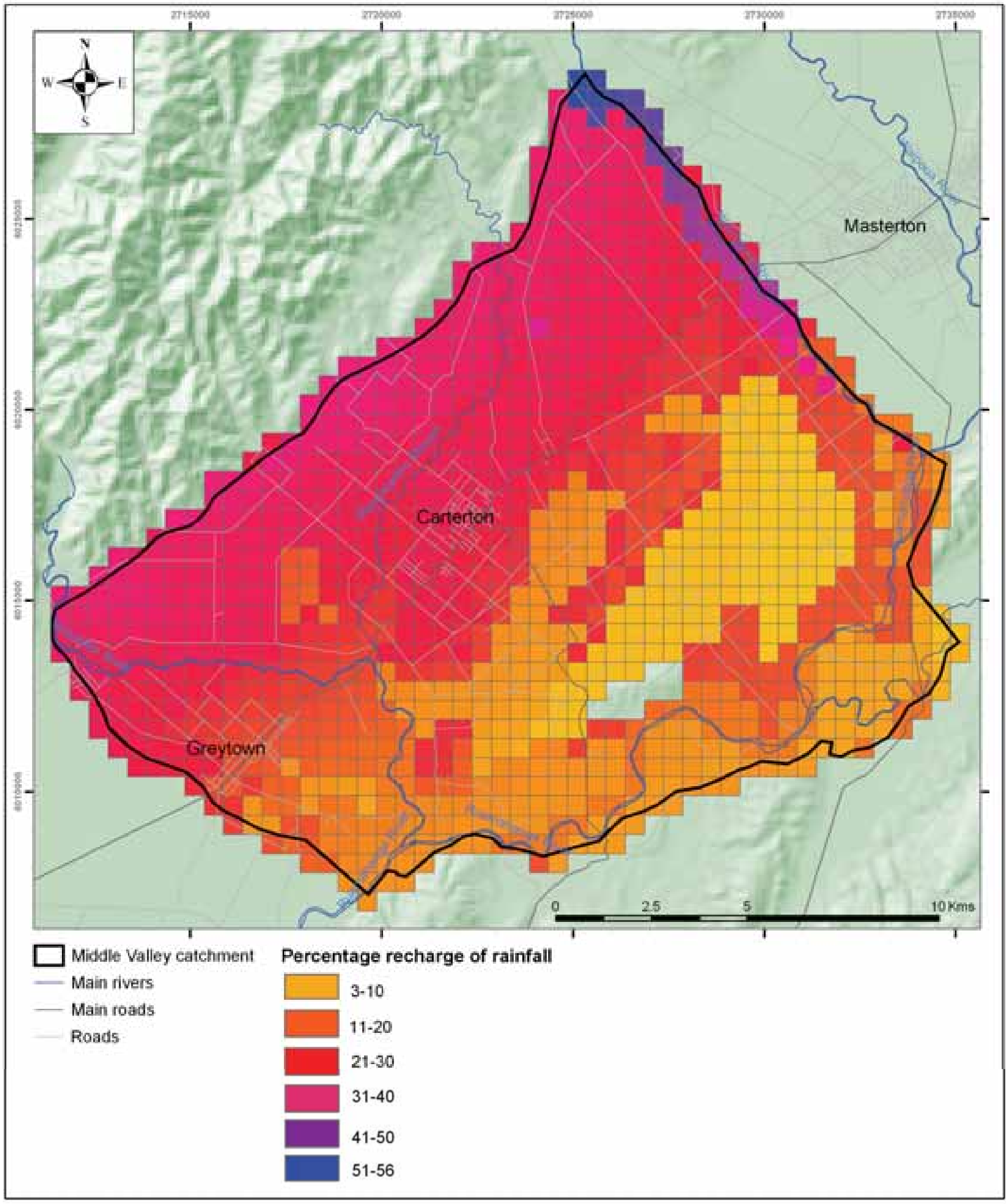


Figure 7.14: Percentage of rainfall that recharges the Middle Valley catchment

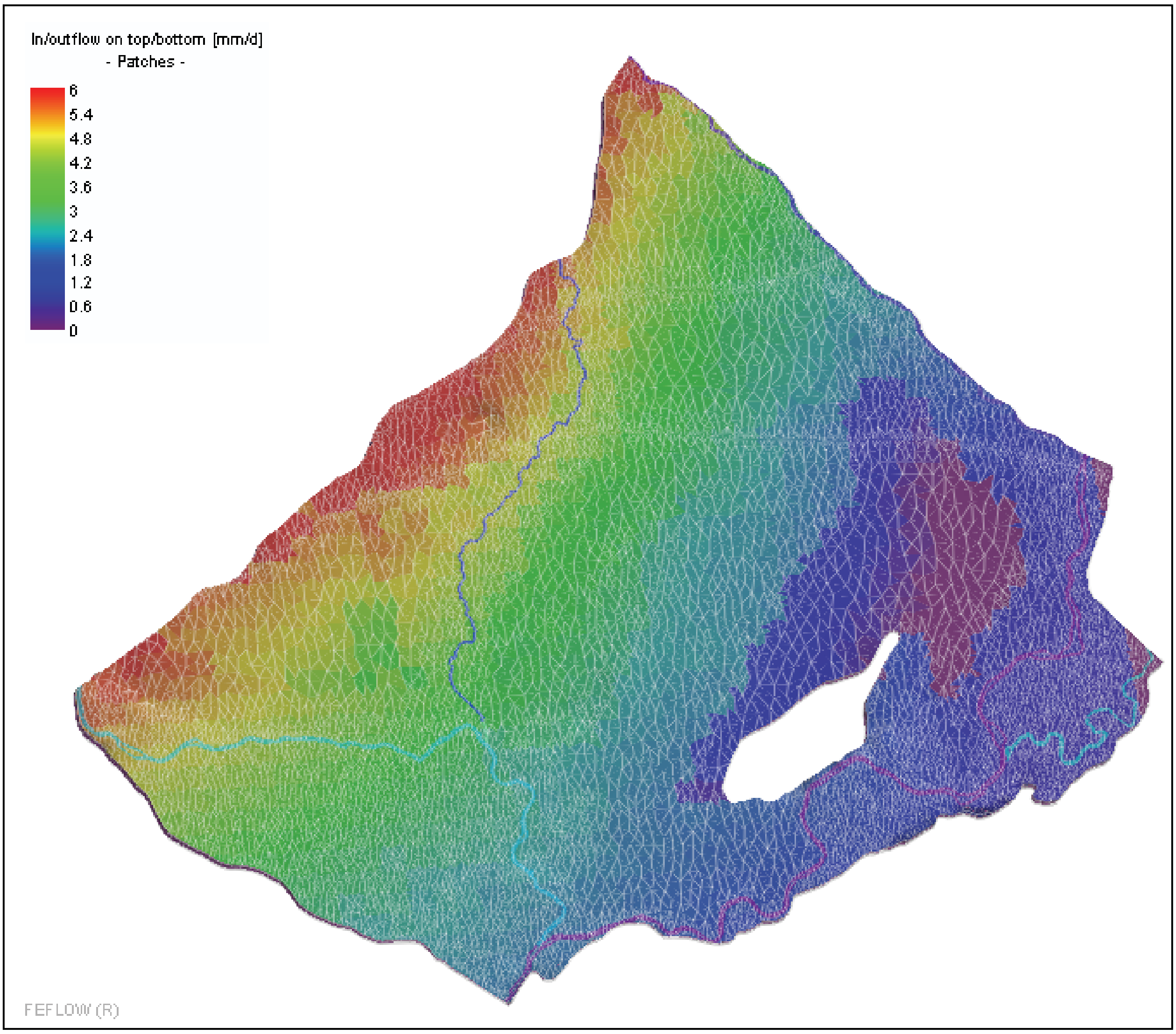


Figure 7.15: Middle Valley catchment simulated recharge for model day 4,438 (24 August 2004) in mm/day

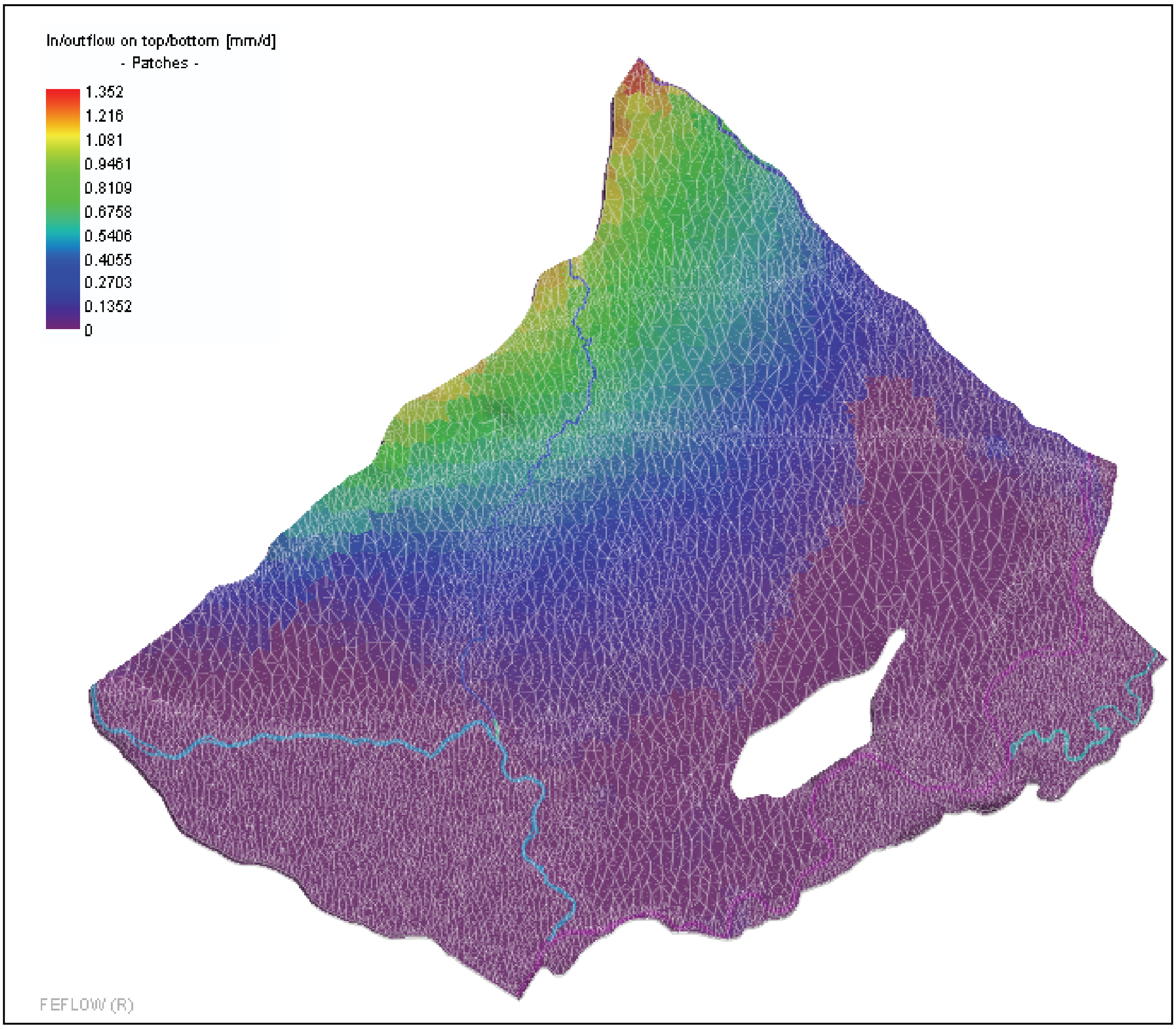


Figure 7.16: Middle Valley catchment simulated recharge for model day 4,753 (5 July 2005) in mm/day

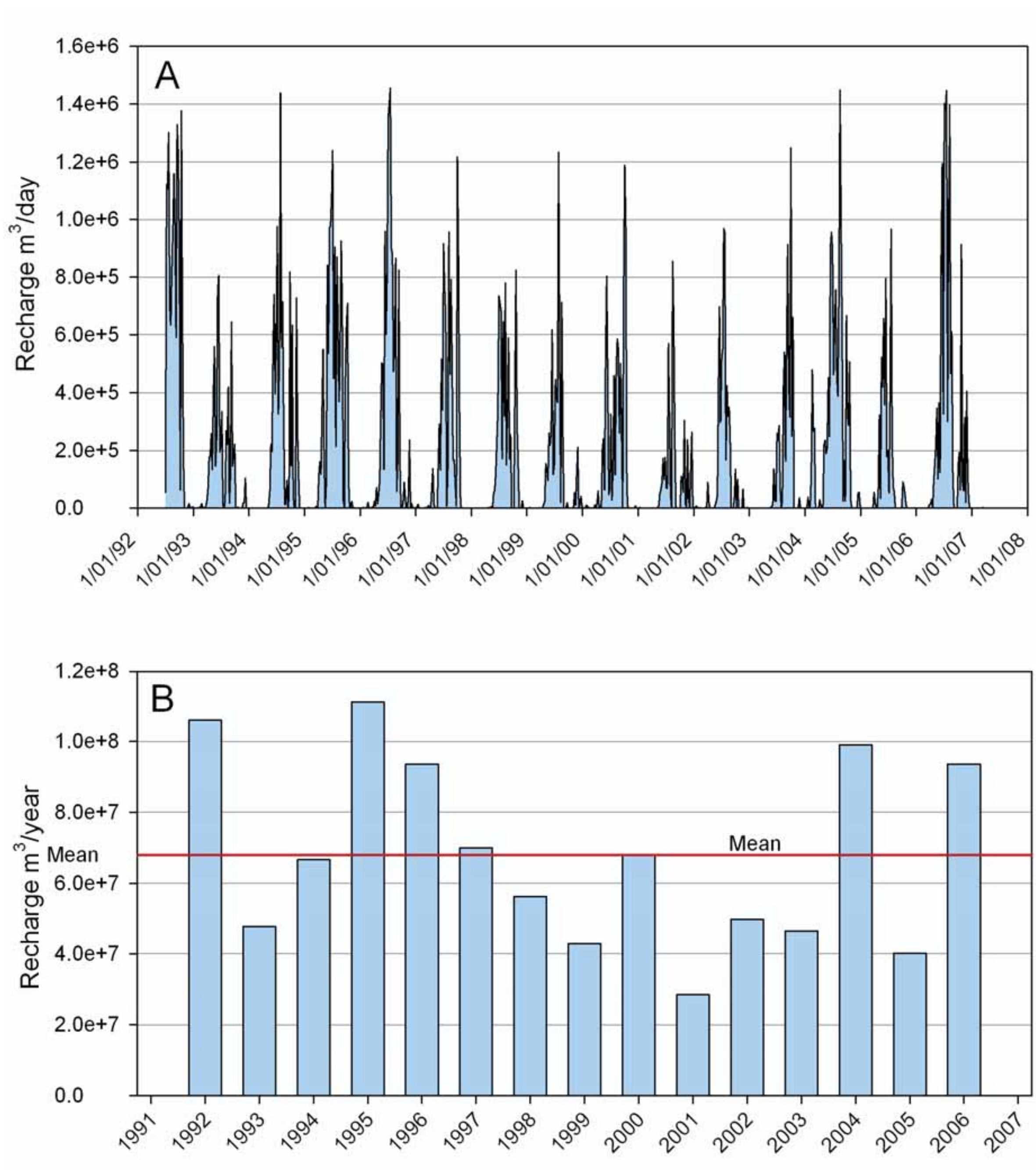


Figure 7.17: Calculated rainfall recharge for the Middle Valley catchment A – daily recharge, B – annual recharge

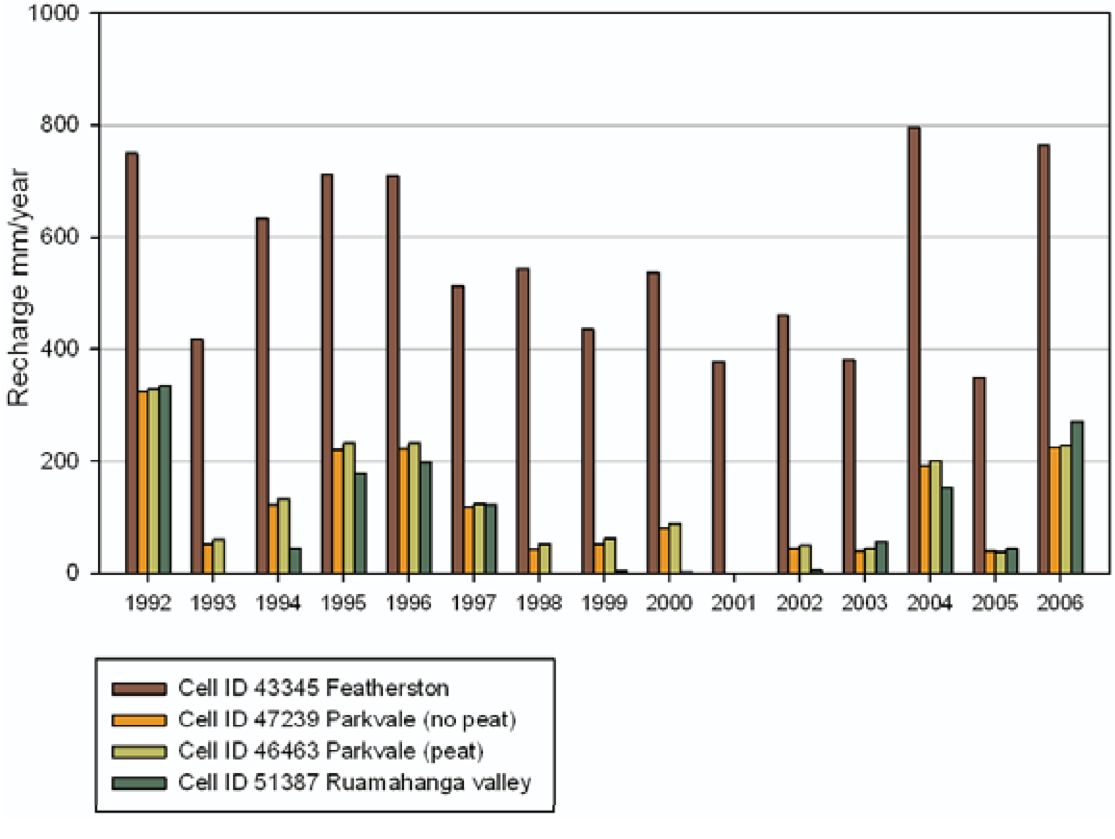


Figure 7.18: Graph of recharge from three cells across the Wairarapa Valley

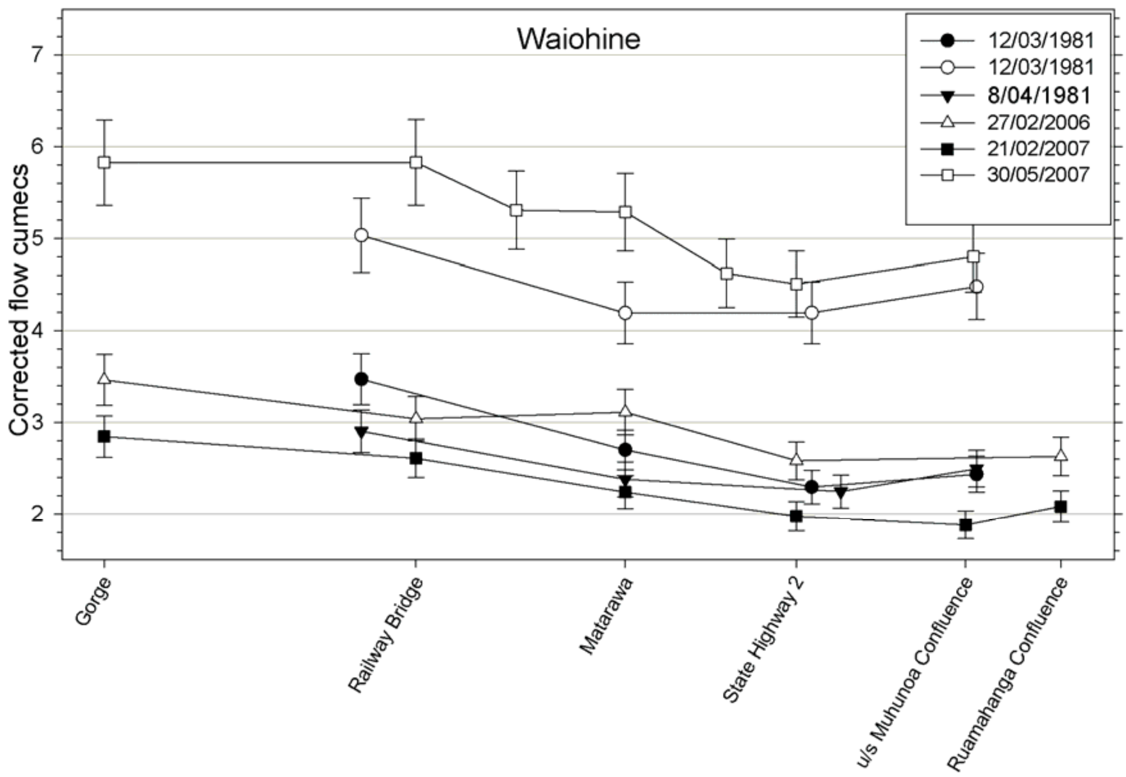


Figure 7.19A: Corrected concurrent gauging plots for the Waiohine River. Where possible, estimated major surface inputs and outputs have been excluded to gain and loss from adjacent groundwater systems.

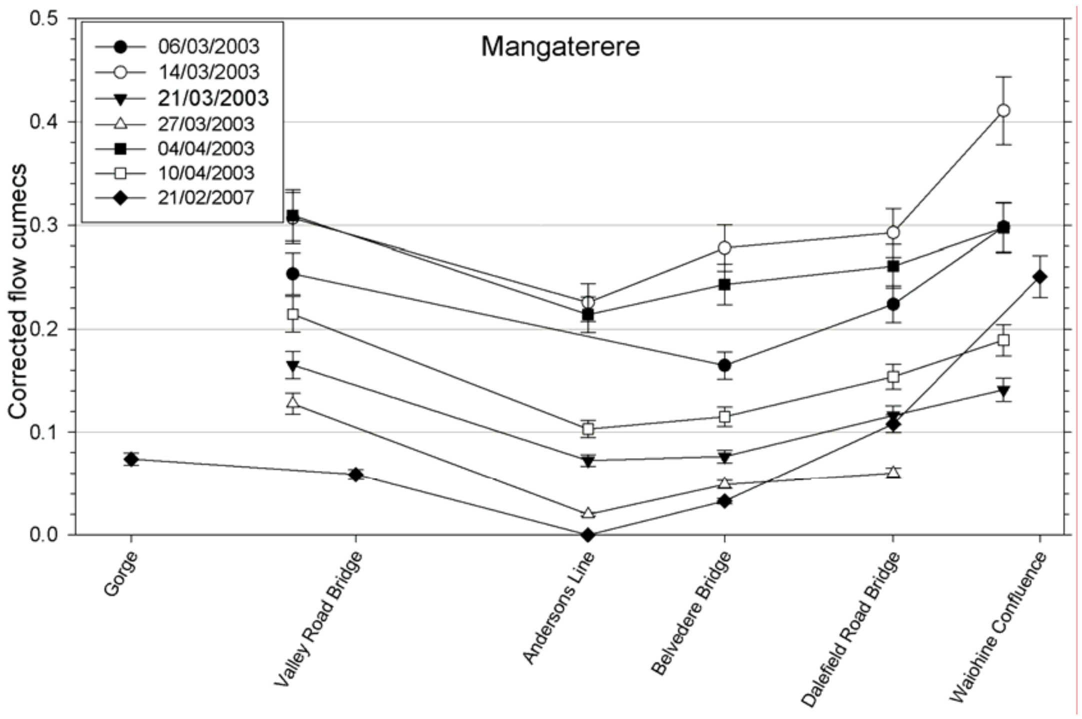


Figure 7.19B: Corrected concurrent gauging plots for the Mangatarere Stream. Where possible, estimated major surface inputs and outputs have been excluded to gain and loss from adjacent groundwater systems.

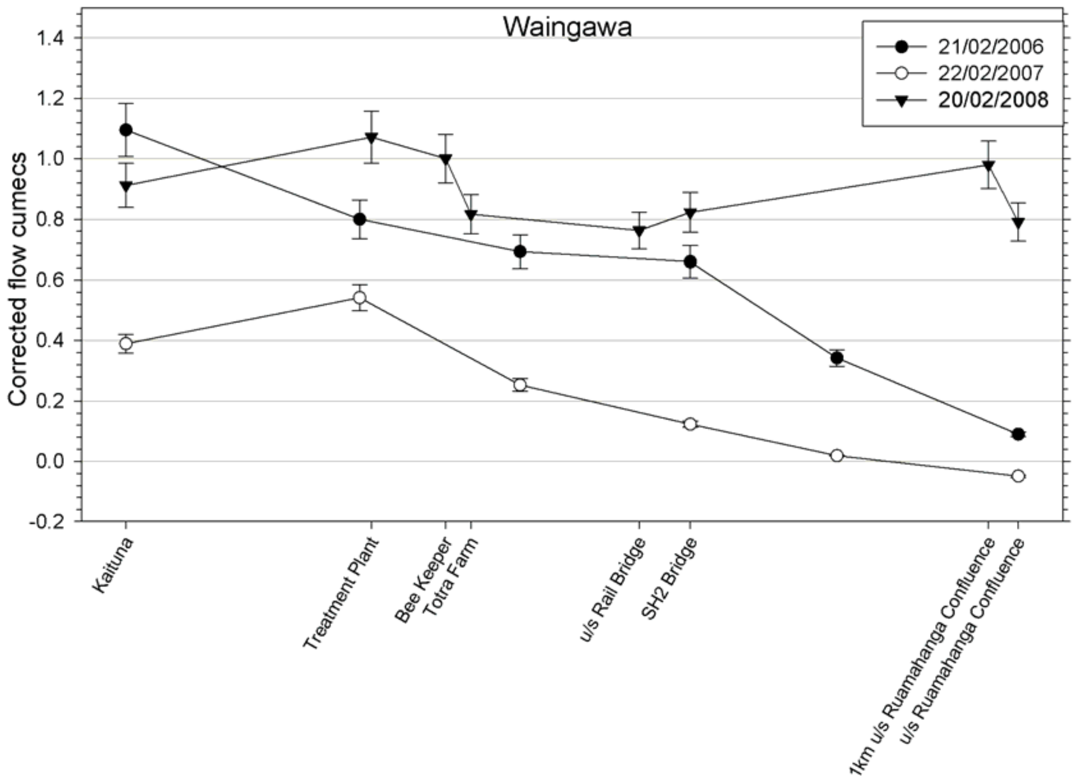


Figure 7.19C: Corrected concurrent gauging plots for the Waingawa River. Where possible, estimated major surface inputs and outputs have been excluded to gain and loss from adjacent groundwater systems.

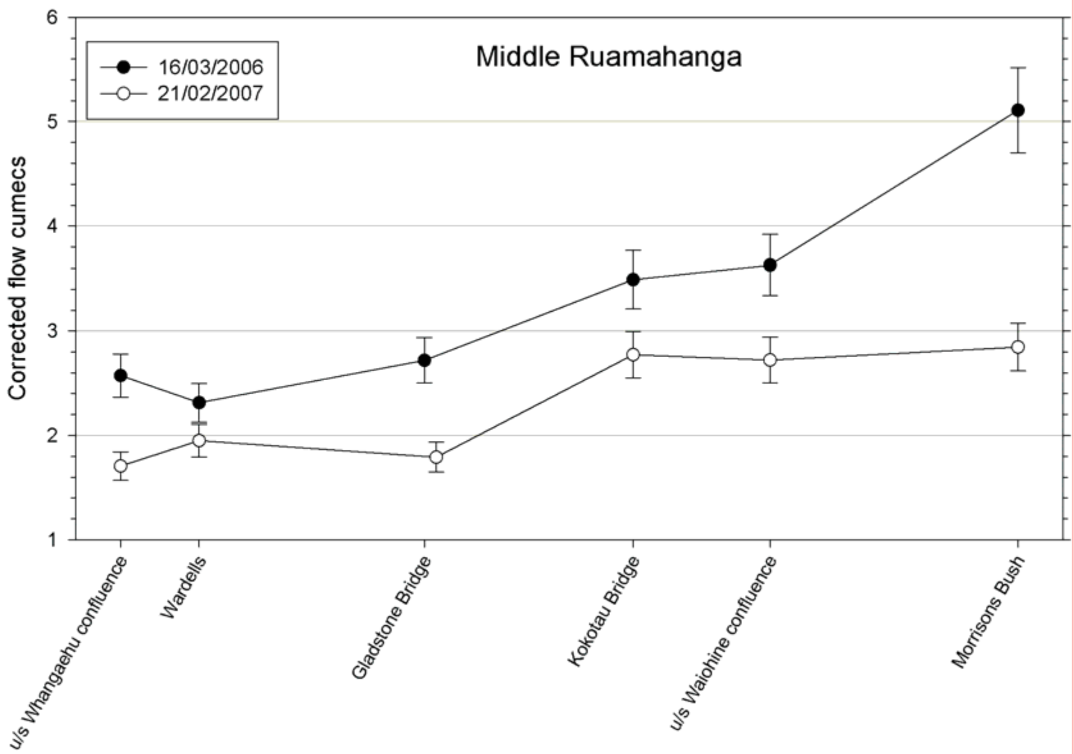


Figure 7.19D: Corrected concurrent gauging plots for the Ruamahanga River. Where possible, estimated major surface inputs and outputs have been excluded to gain and loss from adjacent groundwater systems.

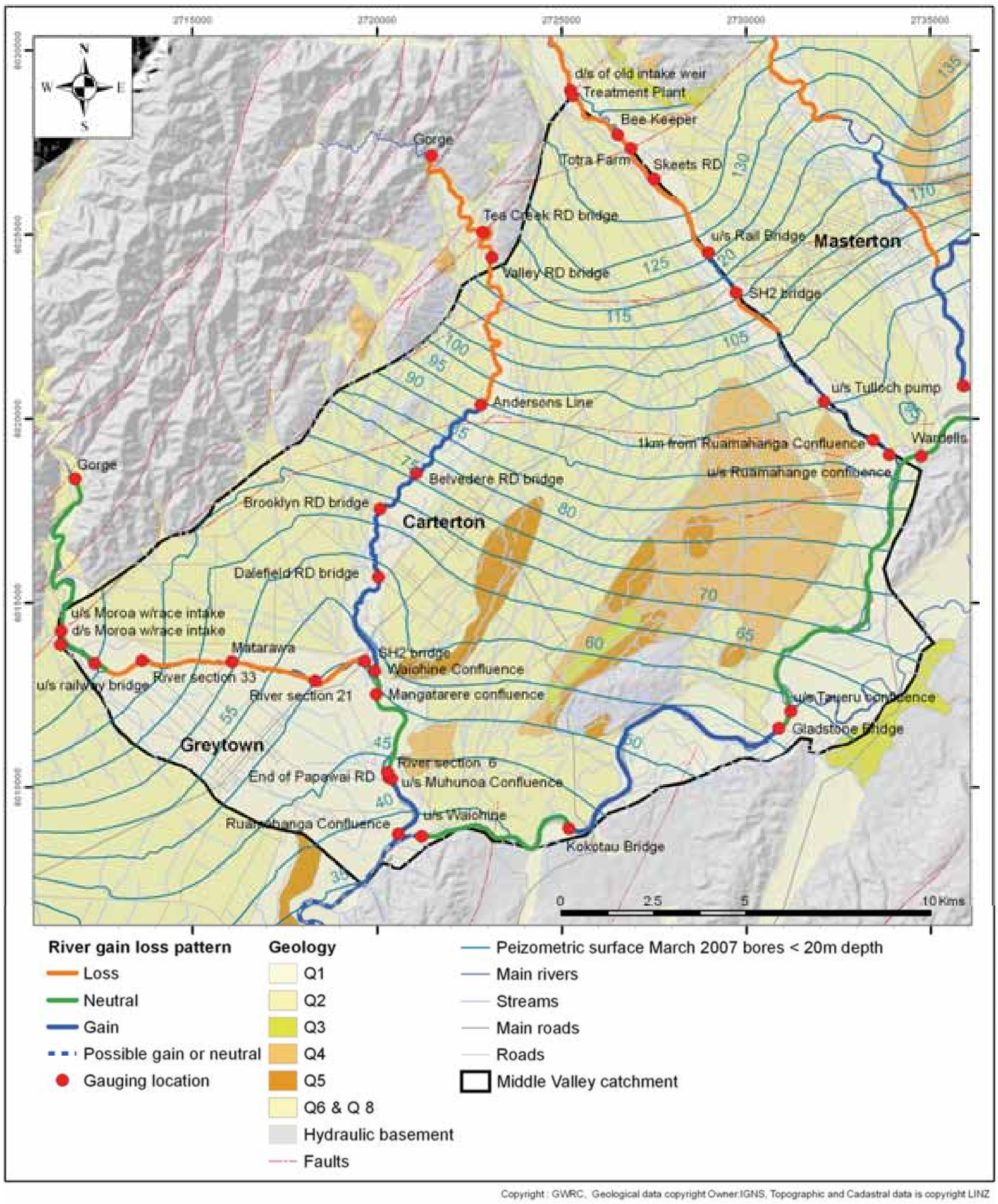
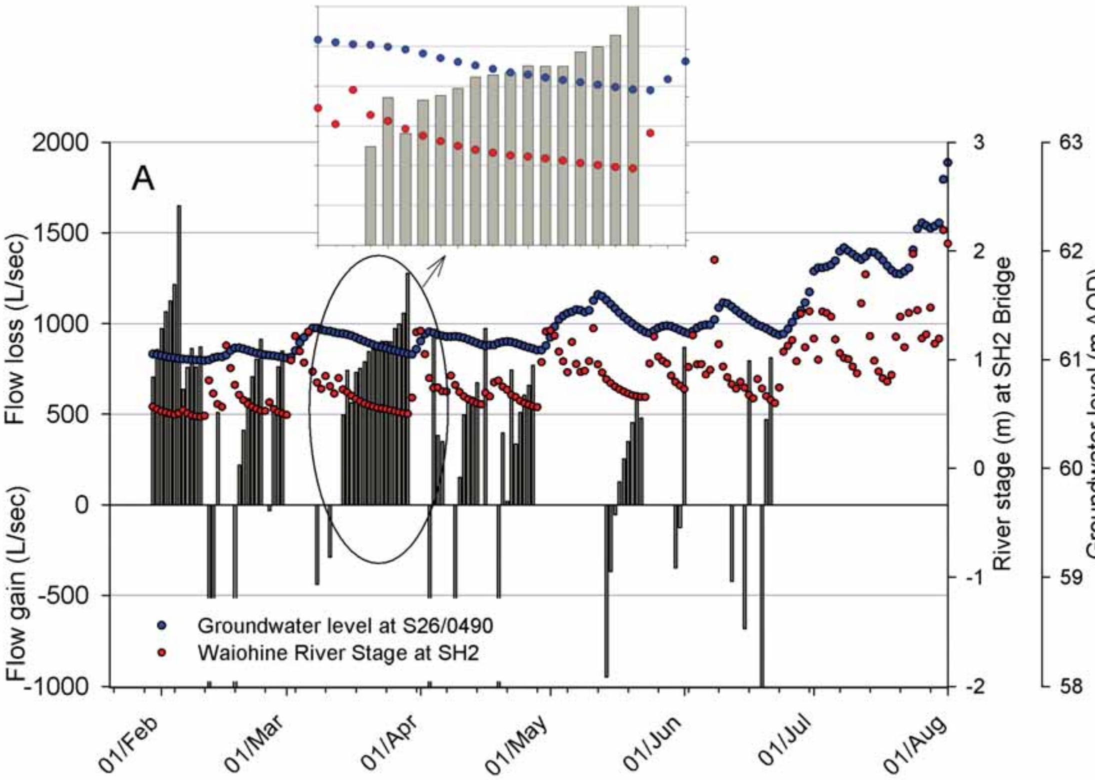


Figure 7.20: Concurrent gauging data summarised into river stretches that, on average, gain, lose or remain neutral during summer low flow



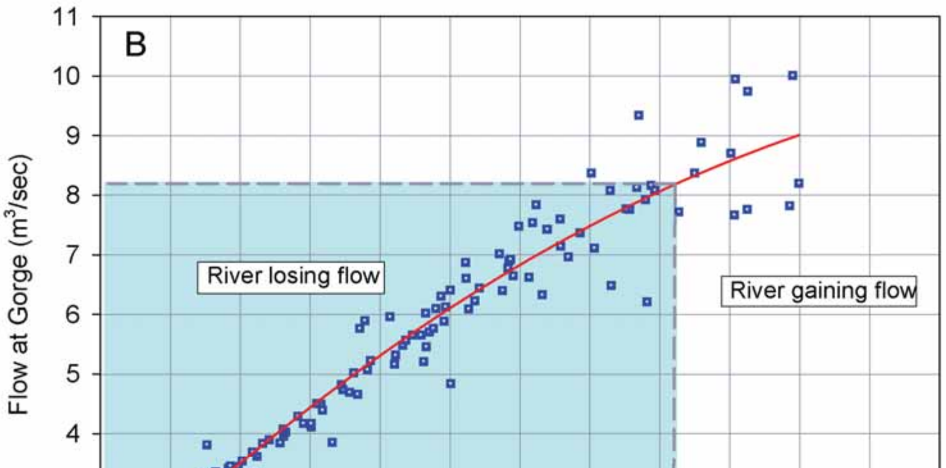


Figure 7.21: Flow data from a temporary gauge on the SH2 bridge, Waiohine River

A – Groundwater level at bore S26/0490, river stage at SH2 and calculated river flow loss between the Gorge gauge and the SH2 gauge

B – Correlation between Waiohine River flow at SH2 and flow at the Gorge gauge

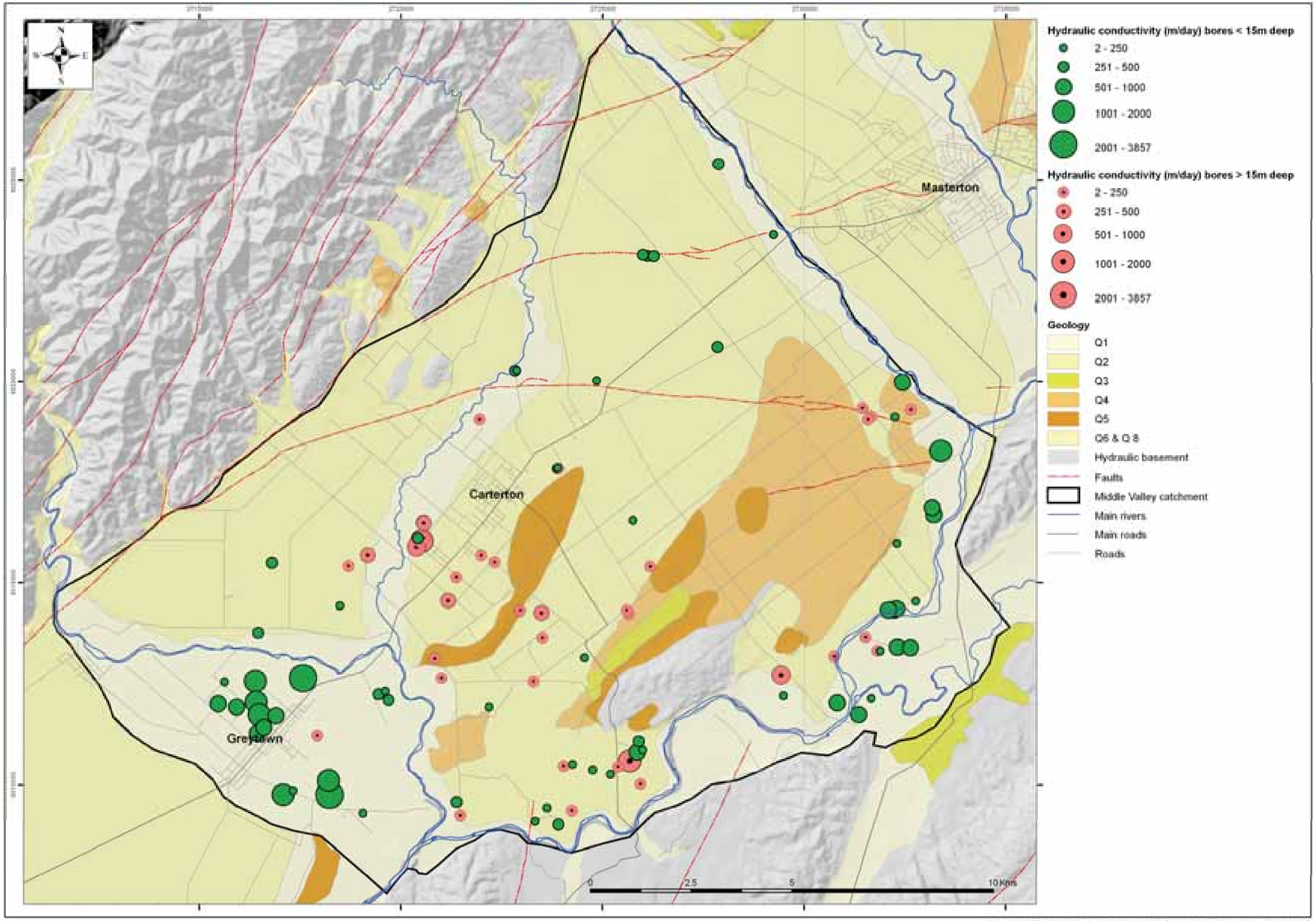


Figure 7.22: Spatial distribution of calculated hydraulic conductivity (k) data from pumping tests in the Middle Valley catchment. Higher k values are generally located in Q1 sediments associated with the Ruamahanga River and Waiohine flood plains.

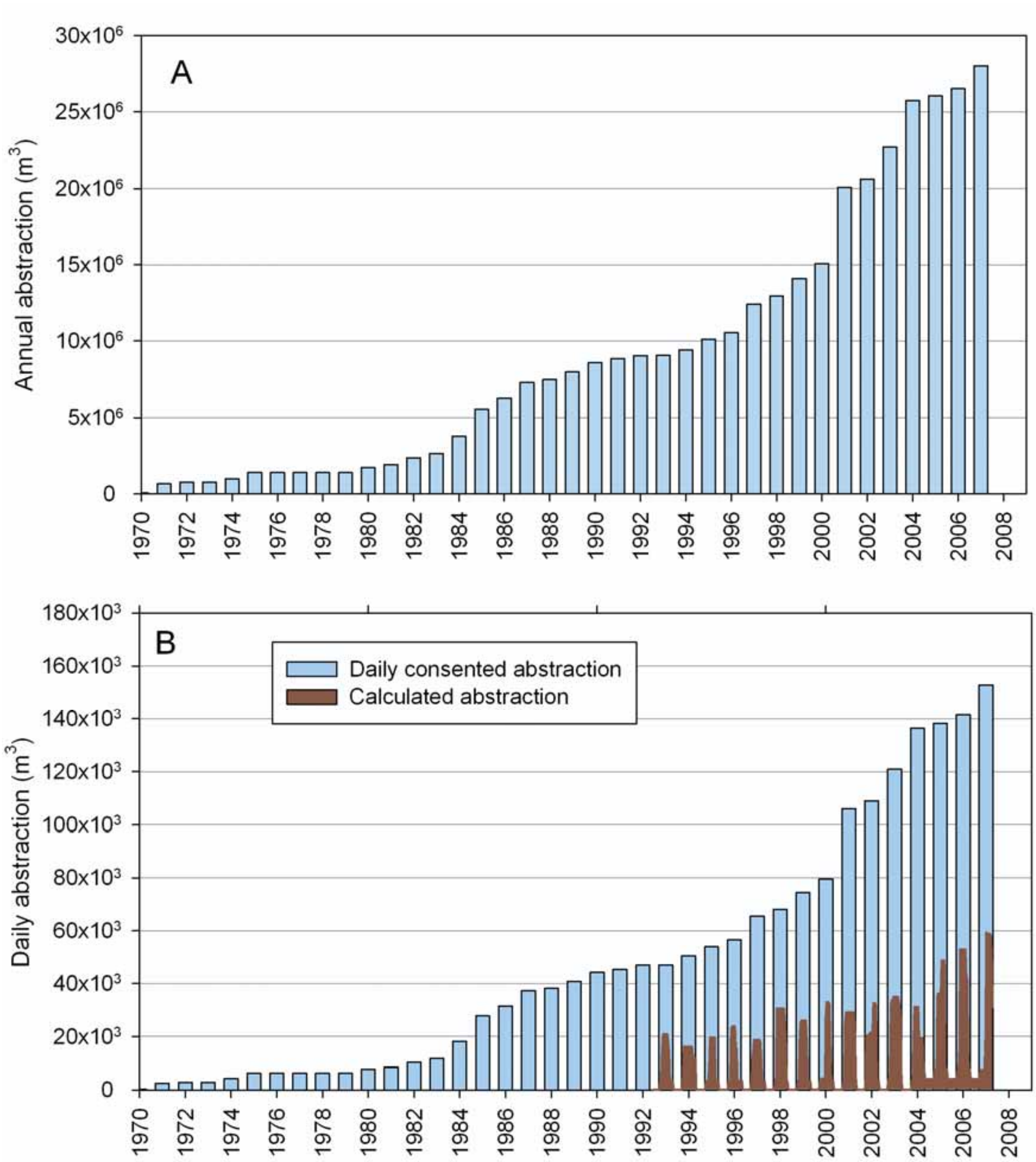


Figure 7.23: Consented and estimated actual groundwater abstraction in the Middle Valley catchment

A – Annual consented abstraction

B – Daily consented abstraction and calculated abstraction

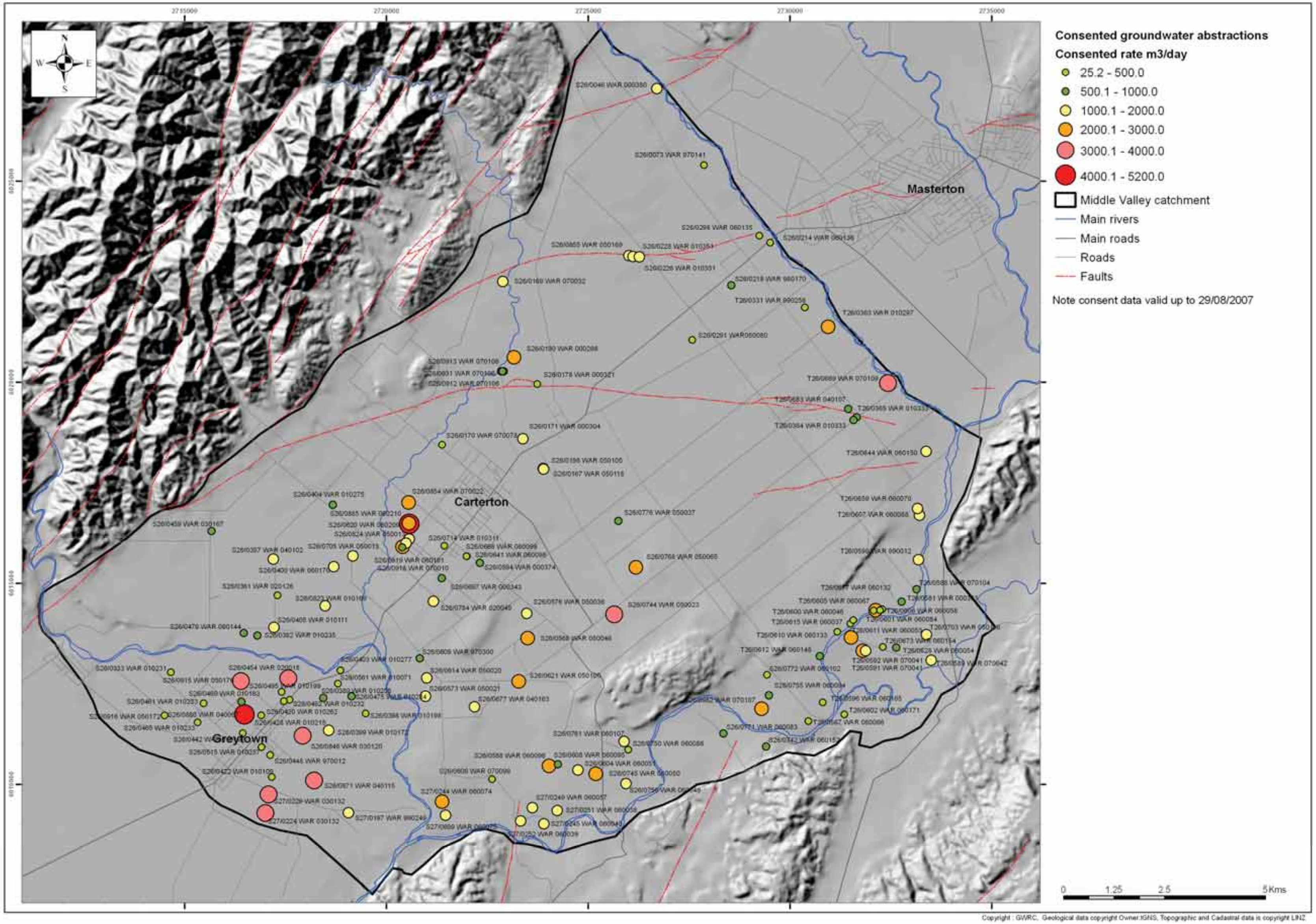


Figure 7.24: Consented groundwater abstractions within the Middle Valley catchment in m³/day as at 29 August 2007. The bore number and consent number are also shown. A total of 128 consented takes are shown on this figure. Permitted groundwater takes or consented surface water takes are not shown.

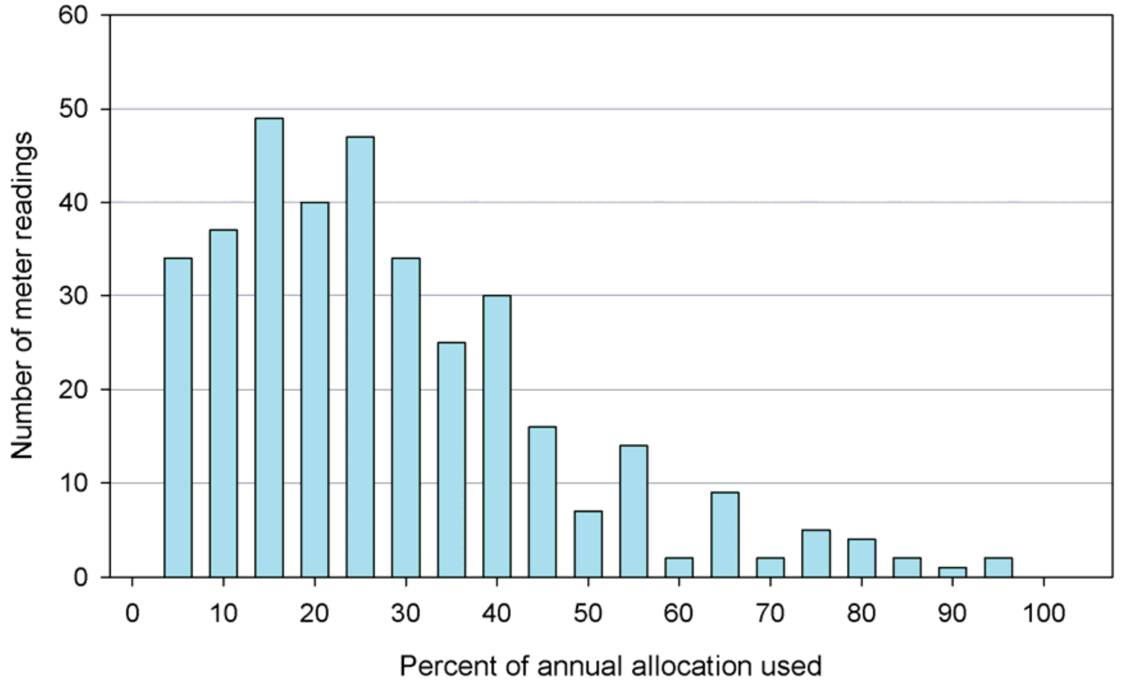


Figure 7.25: Frequency distribution of metered annual water use (as a percentage of annual allocation) in the Wairarapa Valley over the period 2002 to 2008

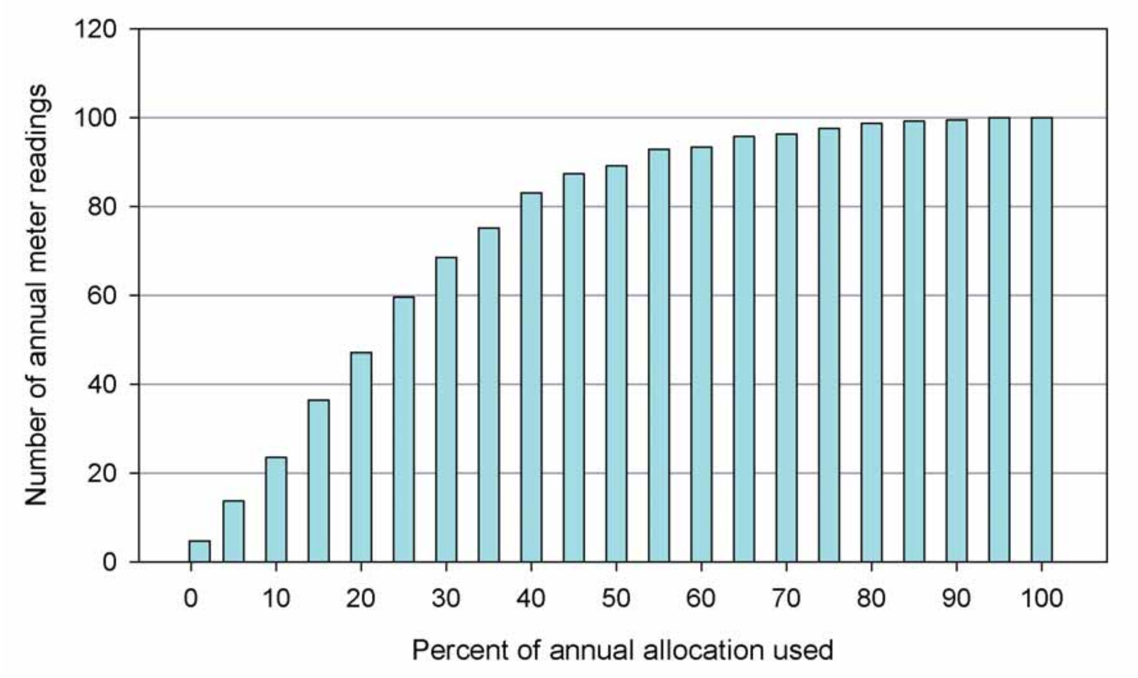


Figure 7.26: Cumulative frequency plot for percentage allocation used (based on all annual meter readings for the Wairarapa Valley over 2002-2008)

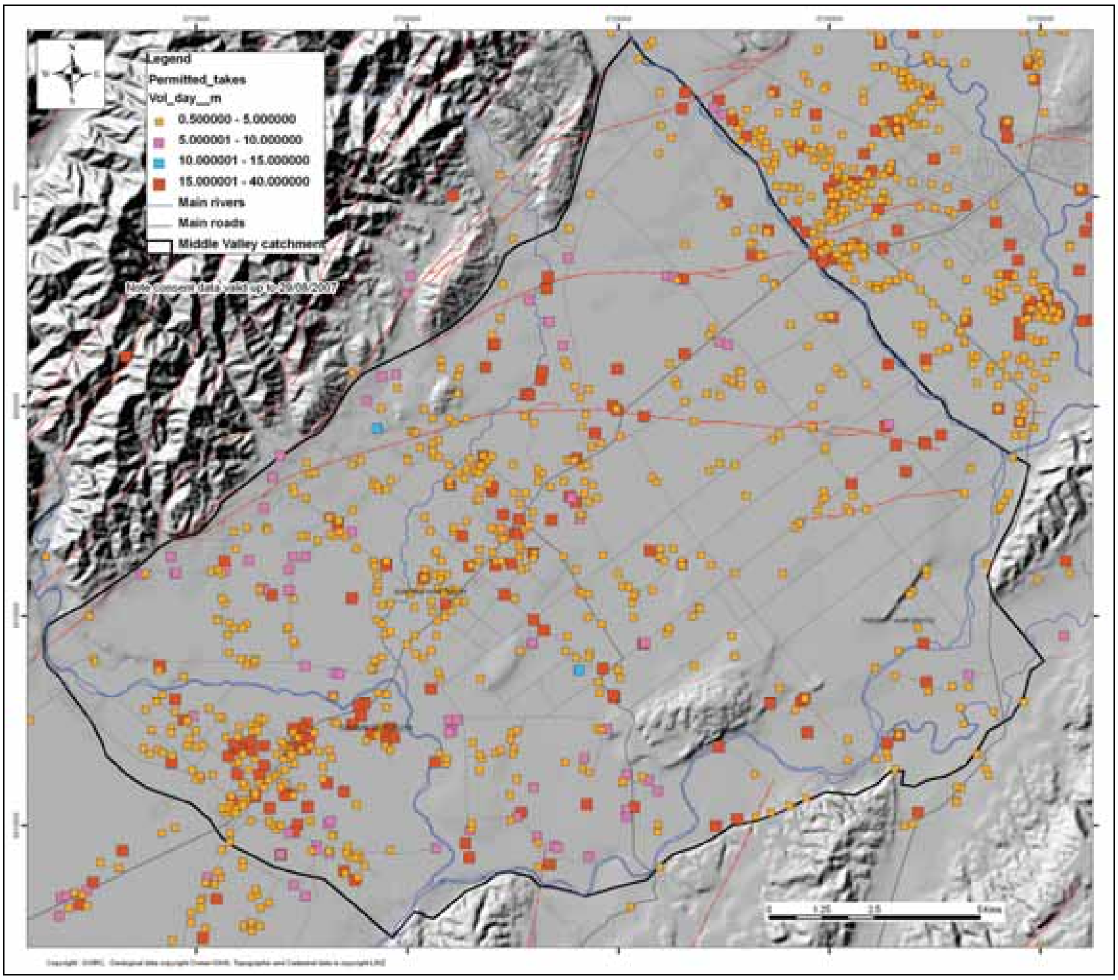


Figure 7.27: Estimated distribution of permitted (or un-consented) groundwater abstractions in the Middle Valley catchment (in m^3/day as at 29 August 2007). There are a total of 750 bores located in the catchment abstracting an estimated 4,000m^3/day (46 L/s).

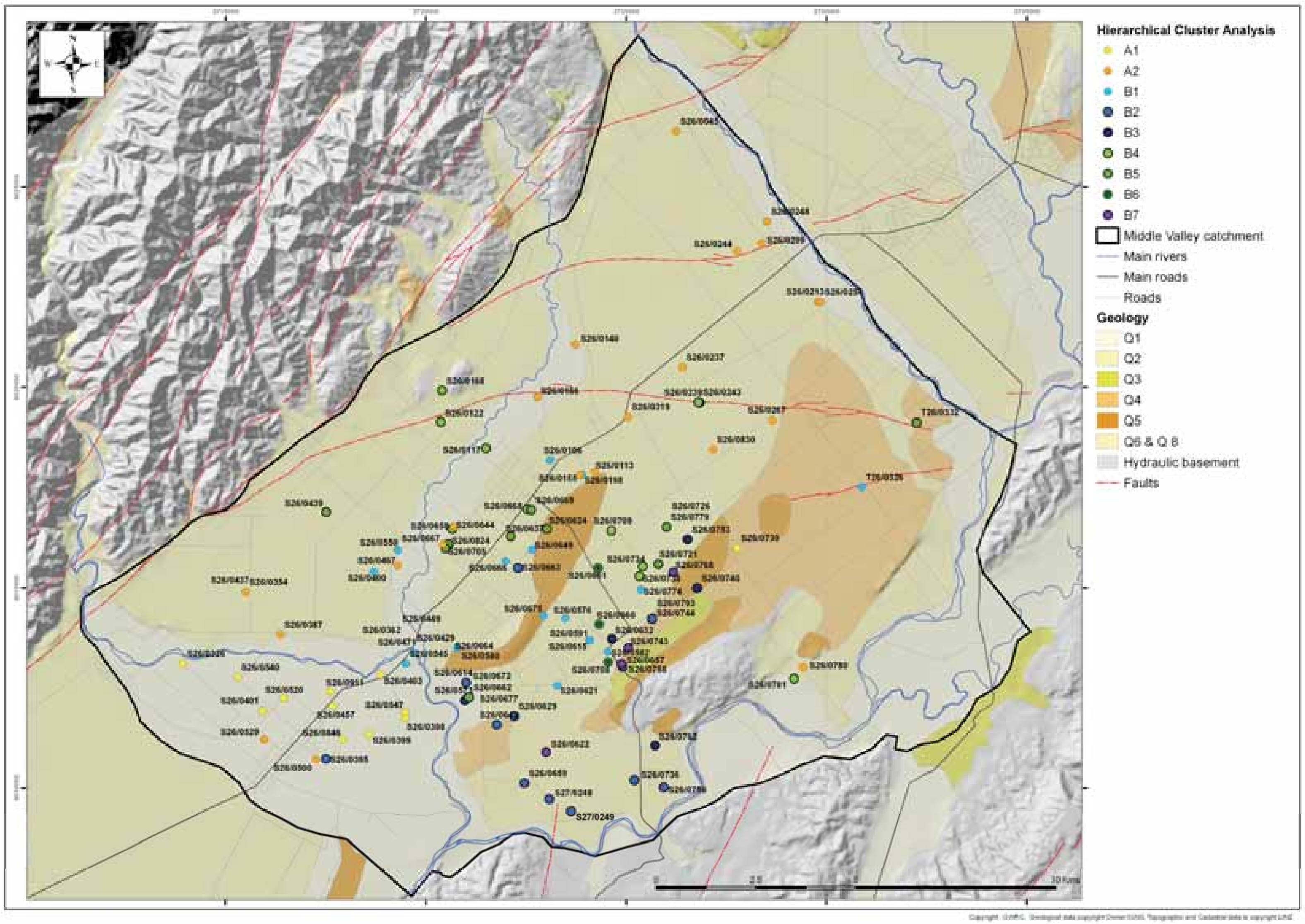


Figure: 8.1: Results from hierarchial cluster analysis (HCA) presented in Figure 3 of Appendix 6. HCA outlines two major recharge areas with A1 'river like" water quality located downgradient of the Waiohine River and A2 rainfall-recharged groundwater associated with alluvial fans. More evolved groundwater (B1-B6) is associated with deeper confined and semi-confined aquifers in the Carterton and Parkvale sub-basins. Note B7 groundwater is possibly associated with groundwater within deeper older sediments found in line along the edge of the Fernhill system. B1-B6 groundwater is associated with the mid-depth Q6 aquifers of the Parkvale and Carterton sub-basins.

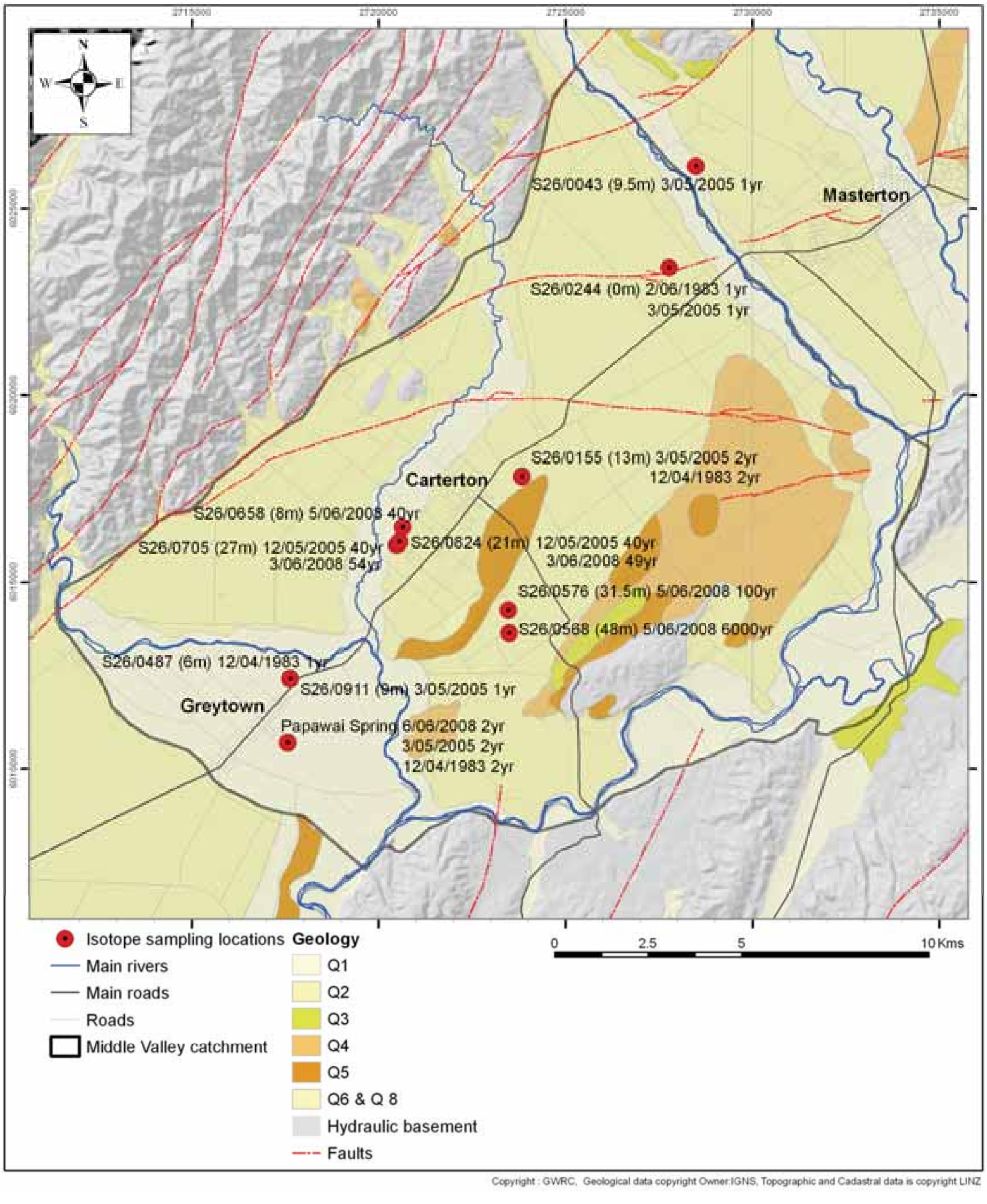
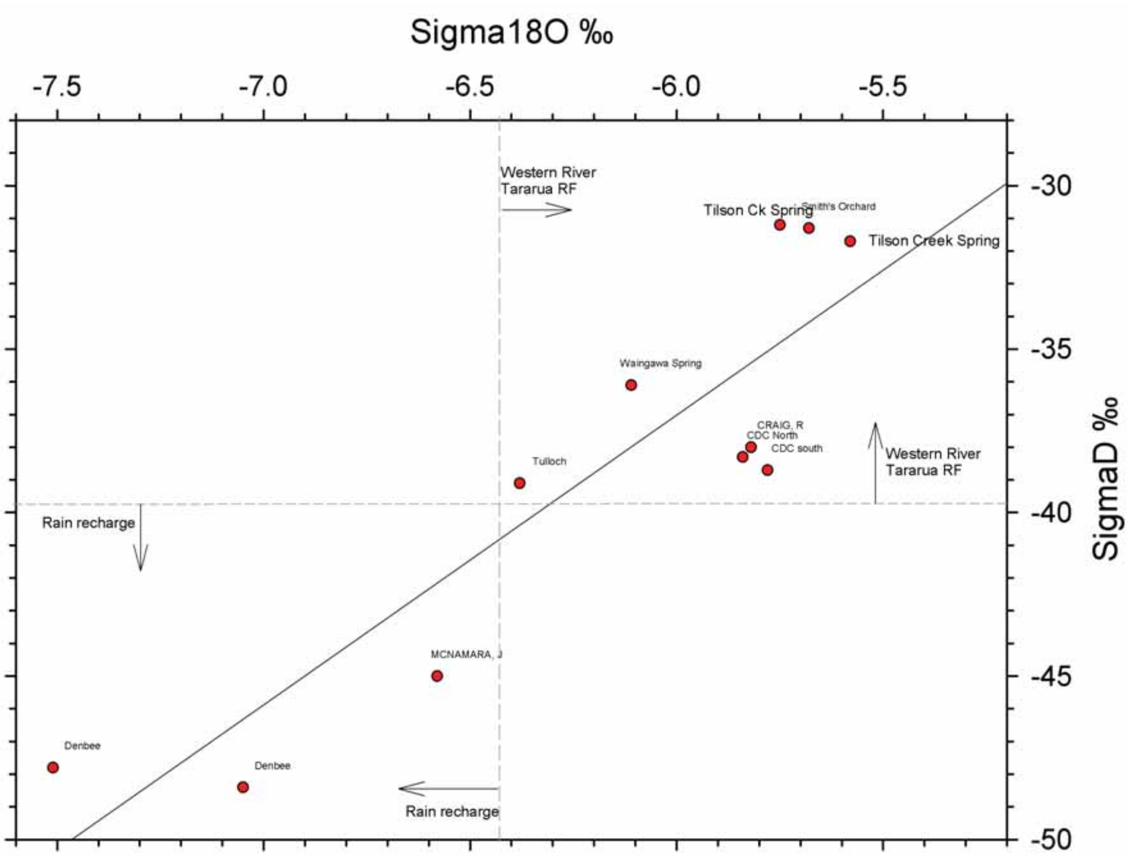


Figure 8.2: Mean residence time data for the Middle Valley catchment



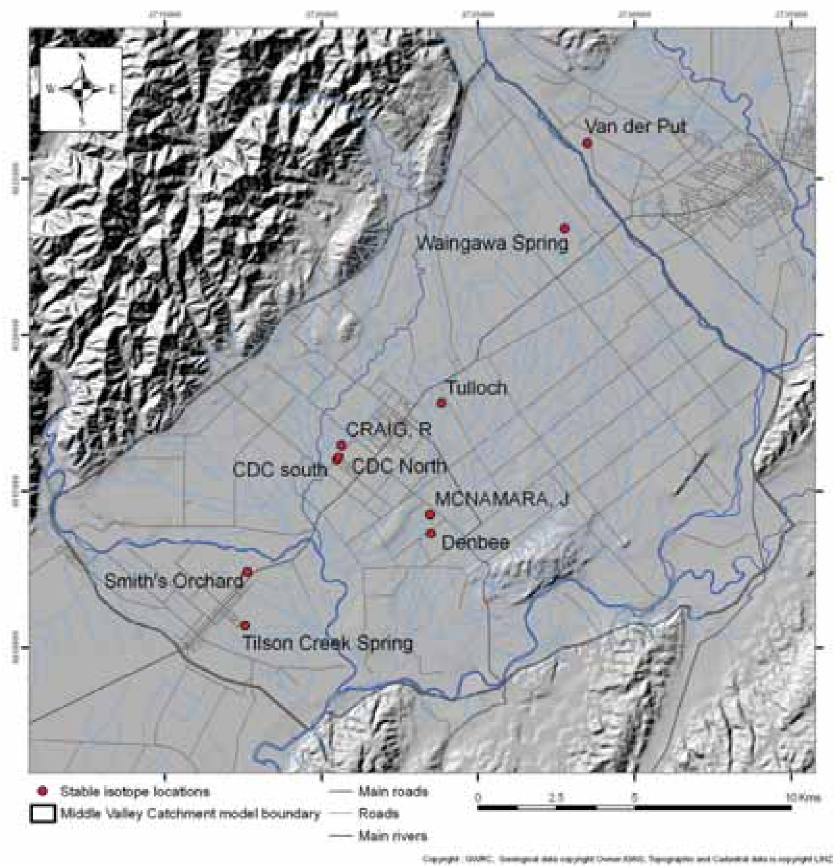


Figure 8.3: Stable isotope data for the Middle Valley catchment

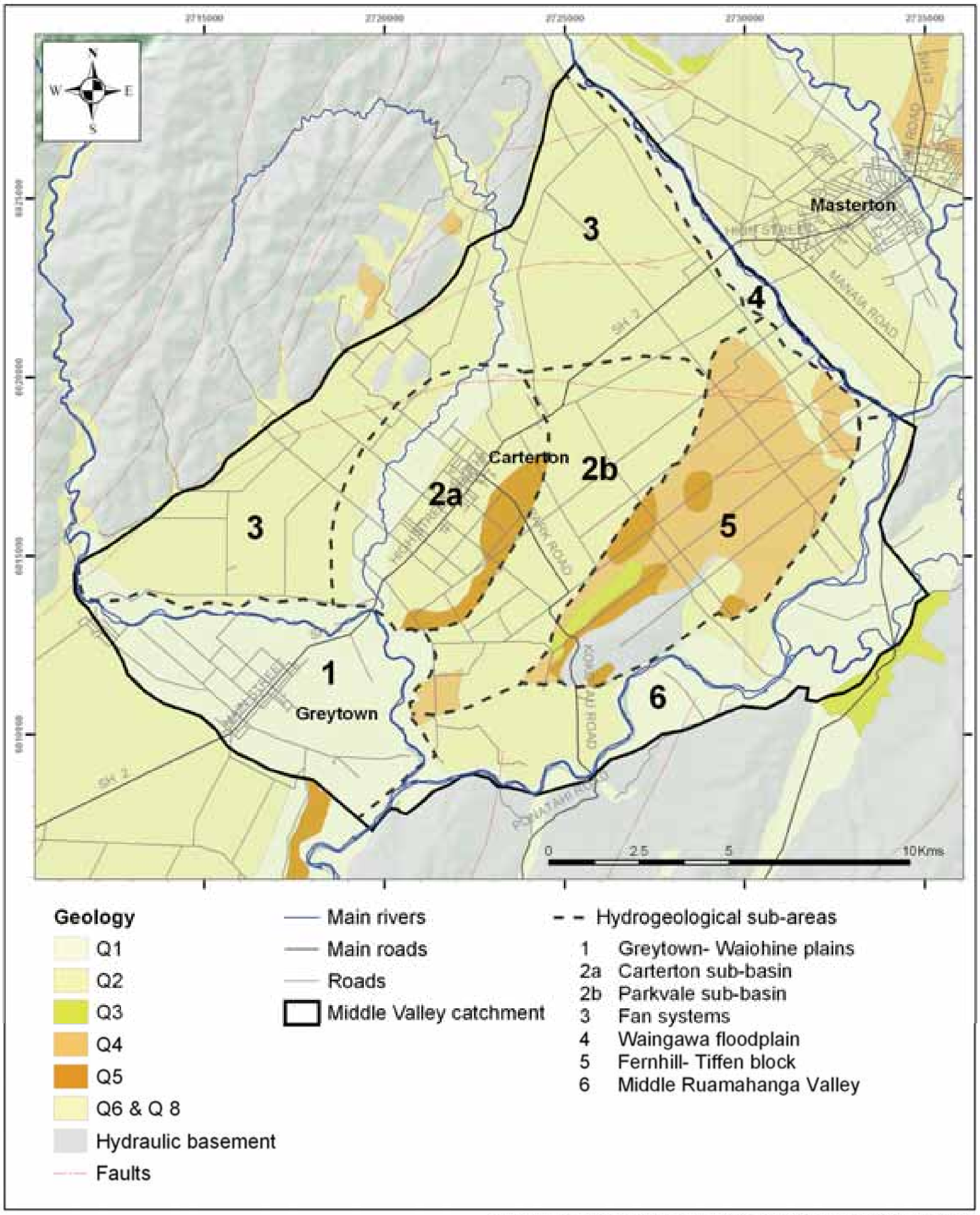


Figure 9.1: The Middle Valley catchment showing model domain boundary and hydrogeological sub-areas

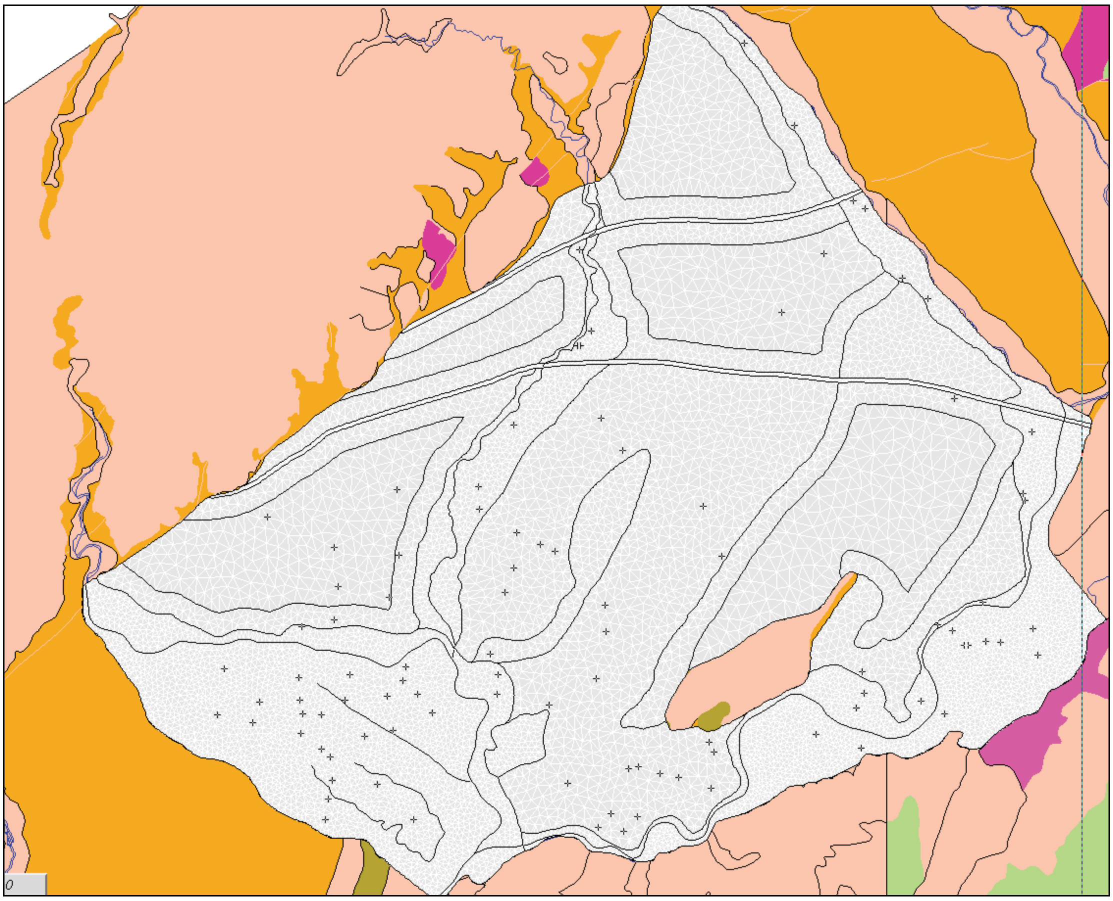


Figure 10.1: Super-element mesh (SEM) for the Middle Valley catchment. The Carterton and Masterton faults have been represented as individual narrow SEMs of 100 m width. The SEM also contains line and point 'add-ins' corresponding to rivers, streams and wells (the add-ins are used to ensure that finite element nodes are generated along and on these features). There are also 'buffer zones' along the edges of some of the super-elements to facilitate a gradation in mesh size between areas where a fine mesh is required (i.e. over the Q1 aquifers), and areas where a coarse mesh is sufficient (i.e. over the low permeability fan areas). The bedrock of Tiffen Hill is simulated as a hole in the SEM.

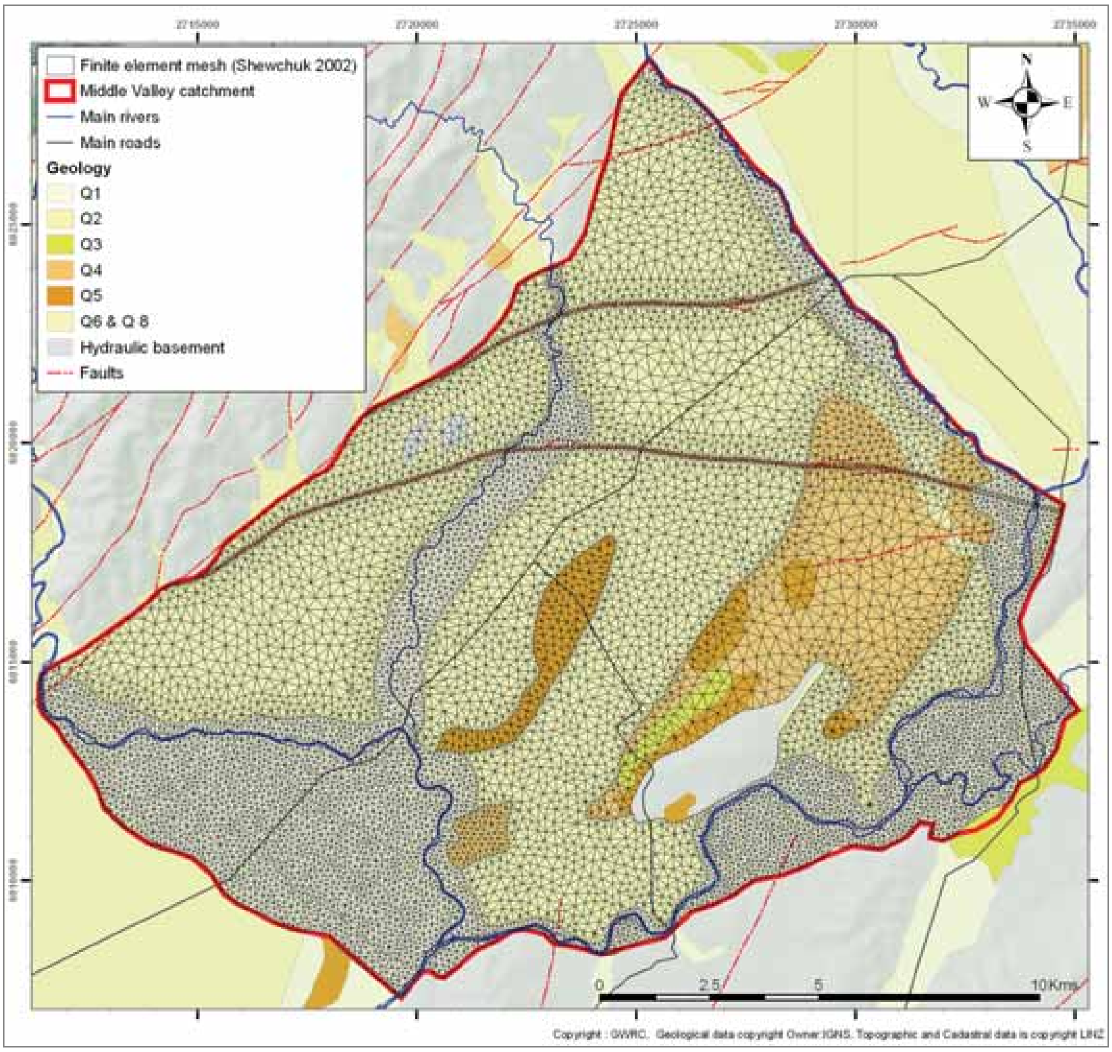


Figure 10.2: Finite element mesh for the Middle Valley catchment generated using "Triangle" (Shewchuk 2002)

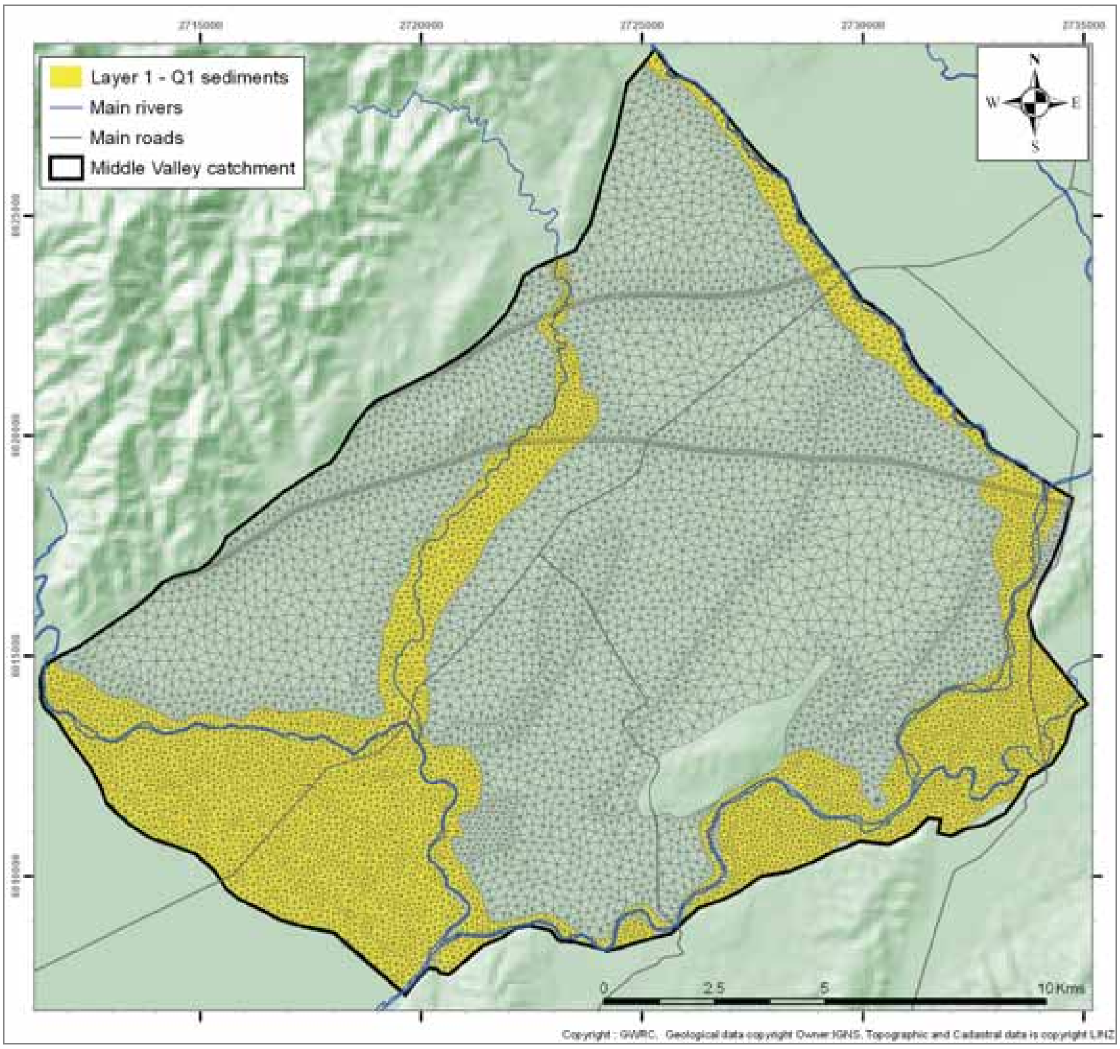


Figure 10.3: Finite element mesh for the Middle Valley catchment with Q1 age sediments highlighted

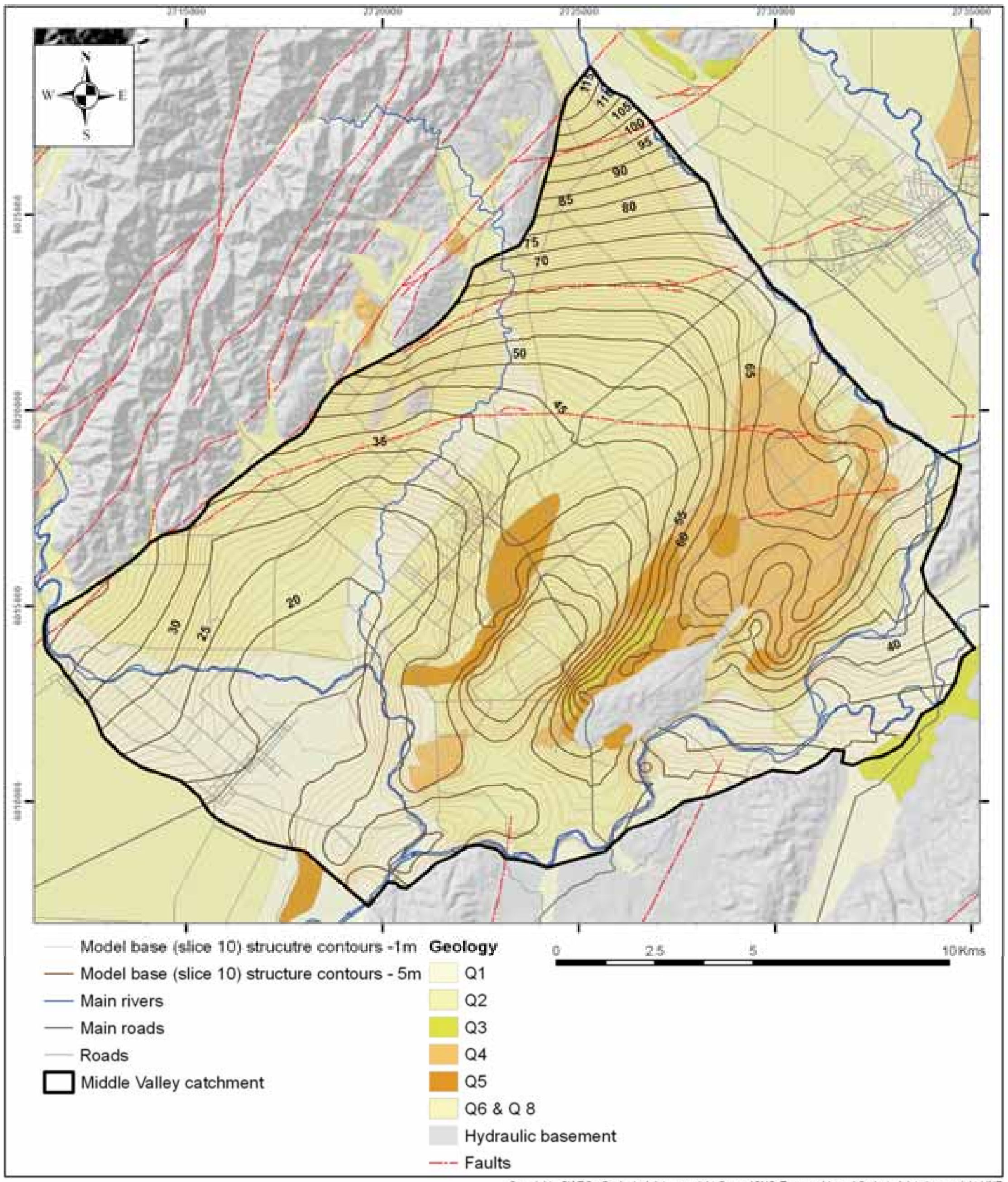


Figure 10.4: Model base (slice 10) structure contours, Middle Valley catchment model

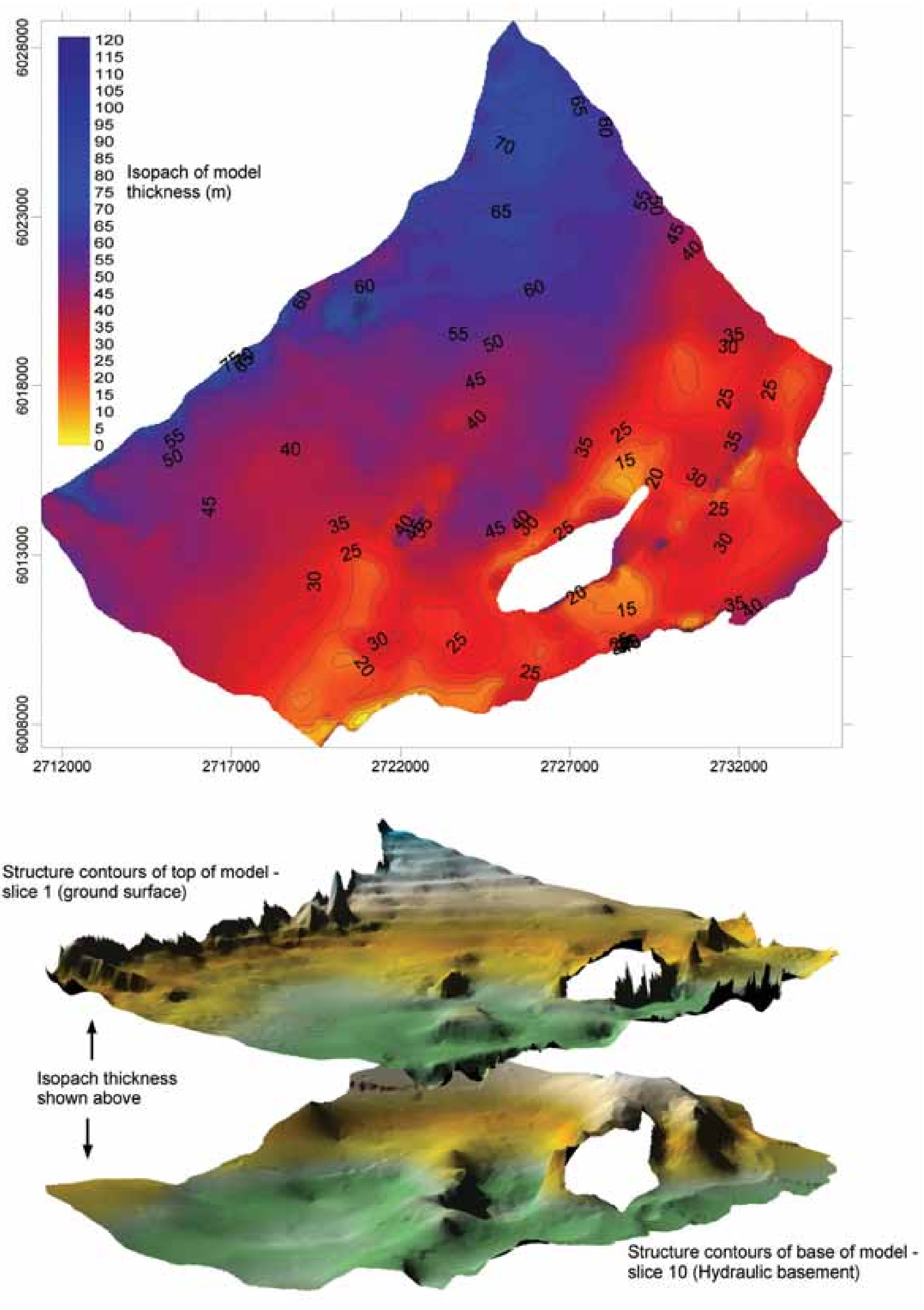


Figure 10.5: Total aquifer thickness (isopach map), Middle Valley catchment model

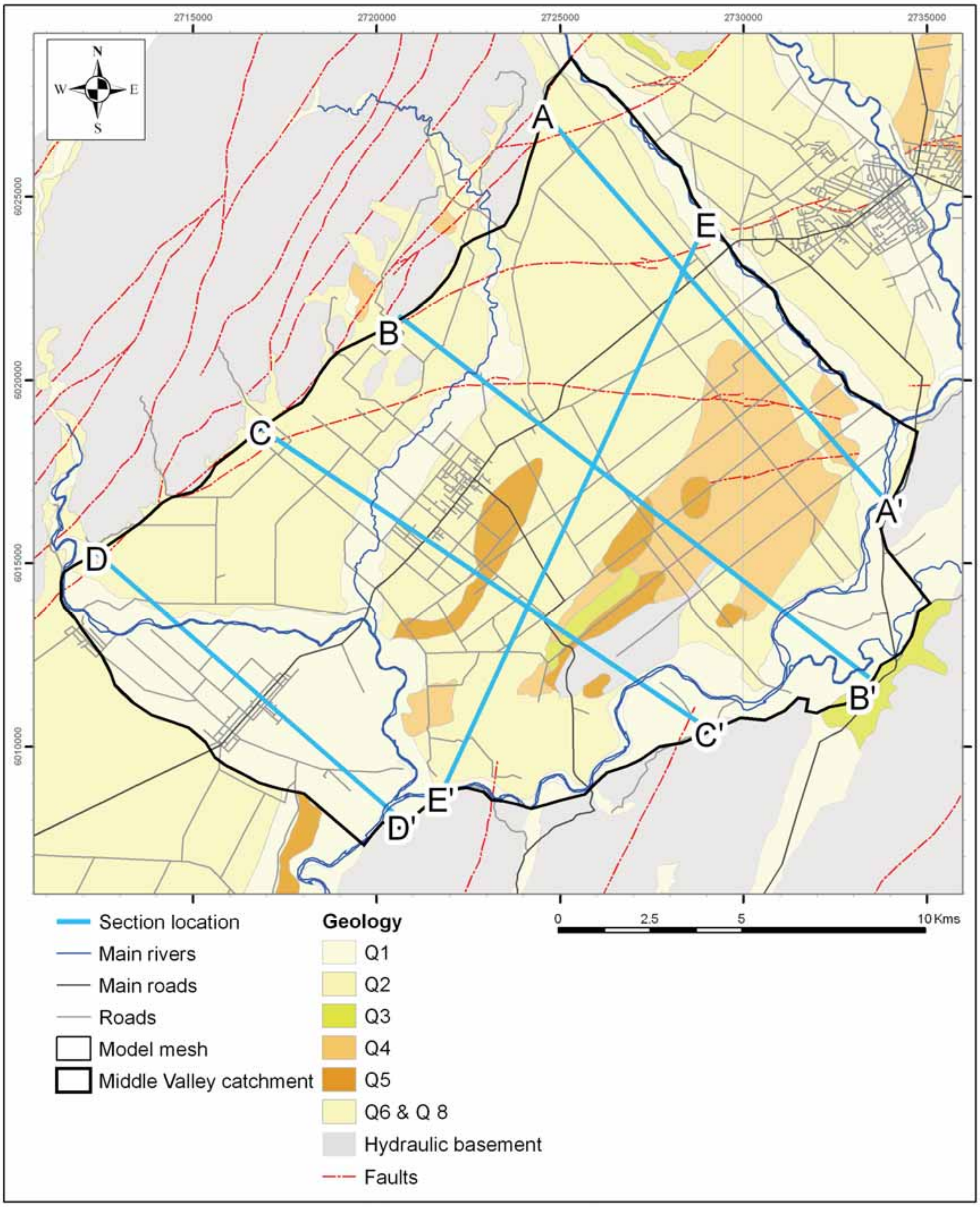


Figure 10.6A: Middle Valley catchment model cross section locations

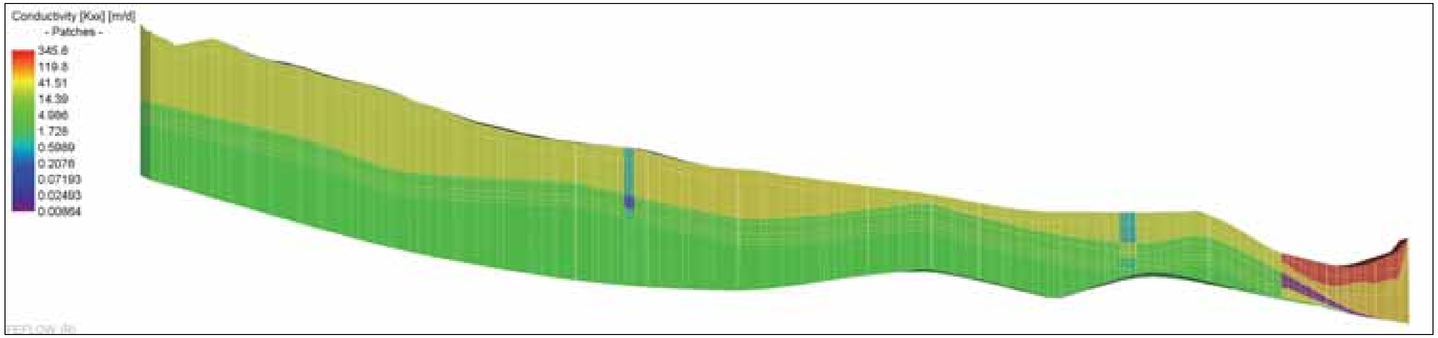


Figure 10.6B: Waingawa Section A-A' showing hydraulic conductivity (K) distribution in model layers. Note the gradient and uniform K distribution representing upper fan sediments, low K vertical units simulating the Masterton and Carterton faults, and the high K zone representing the Q1 sediments associated with the Ruamahanga River.

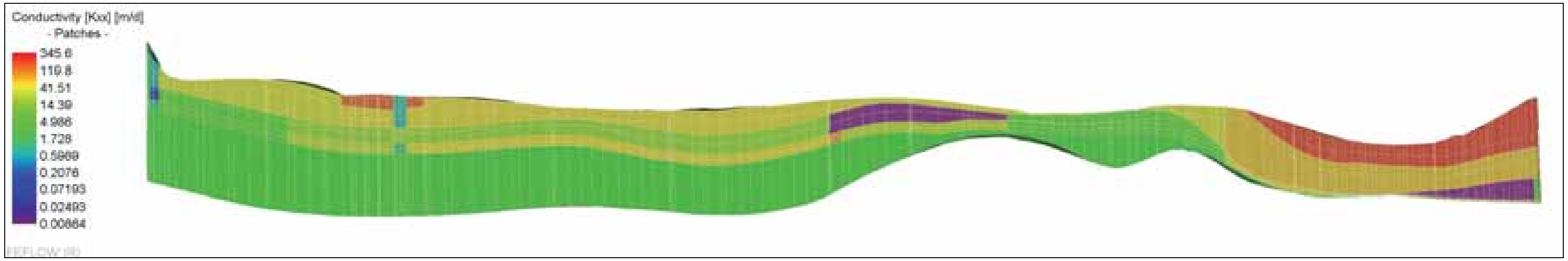


Figure 10.6C: Upper Parkvale Section B-B' showing hydraulic conductivity (K) distribution in model layers. The Masterton and Carterton faults are simulated as low K vertical units to the left (west) of the section, the Mangatarere Stream is represented as a thin high K slice, and the dynamic aquifers associated with the Ruamahanga River are shown on the right (east) side of the section.

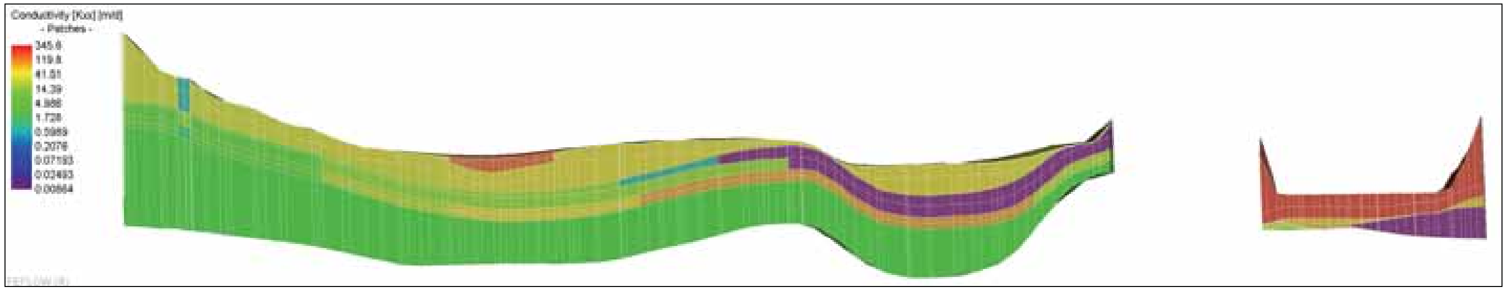


Figure 10.6D: Parkvale Section C-C' showing hydraulic conductivity (K) distribution in model layers. Note the low K Q5 sediments aquitard separating aquifers in the Parkvale sub-basin, Tiffen Hill (gap or hole) and the high K zone associated with the Ruamahanga River.

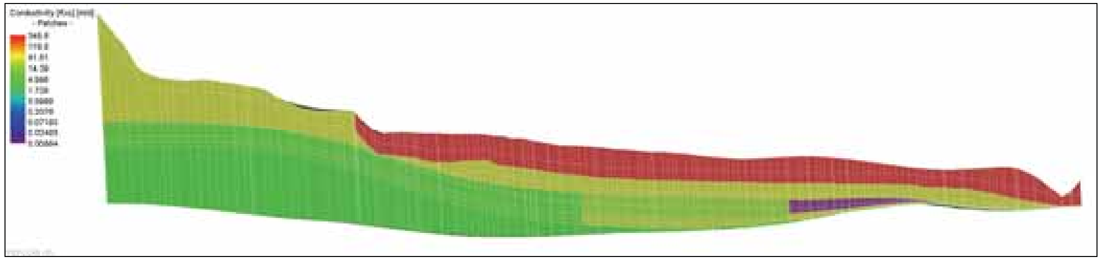


Figure 10.6E: Greytown Section D-D' showing hydraulic conductivity (K) distribution in model layers. Note the high K Q1 sediments of the Waiohine Plain shown in orange.

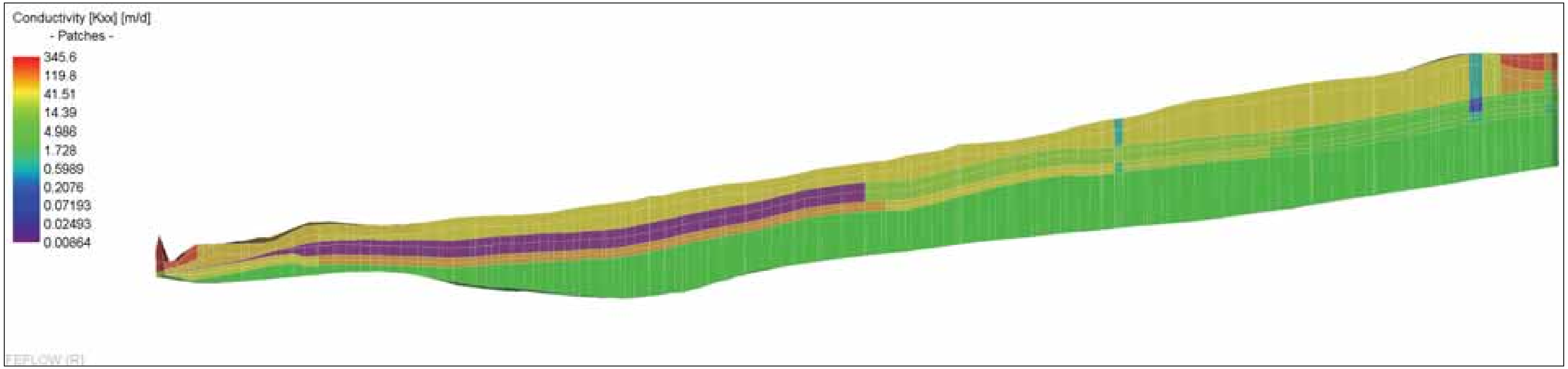


Figure 10.6F: Parkvale Long Section E-E' showing hydraulic conductivity (K) distribution in model layers. This section shows relatively uniform K distribution to the right (north) simulating poorly sorted upper fan material. The Masterton and Carterton faults are shown as low K vertical slices.

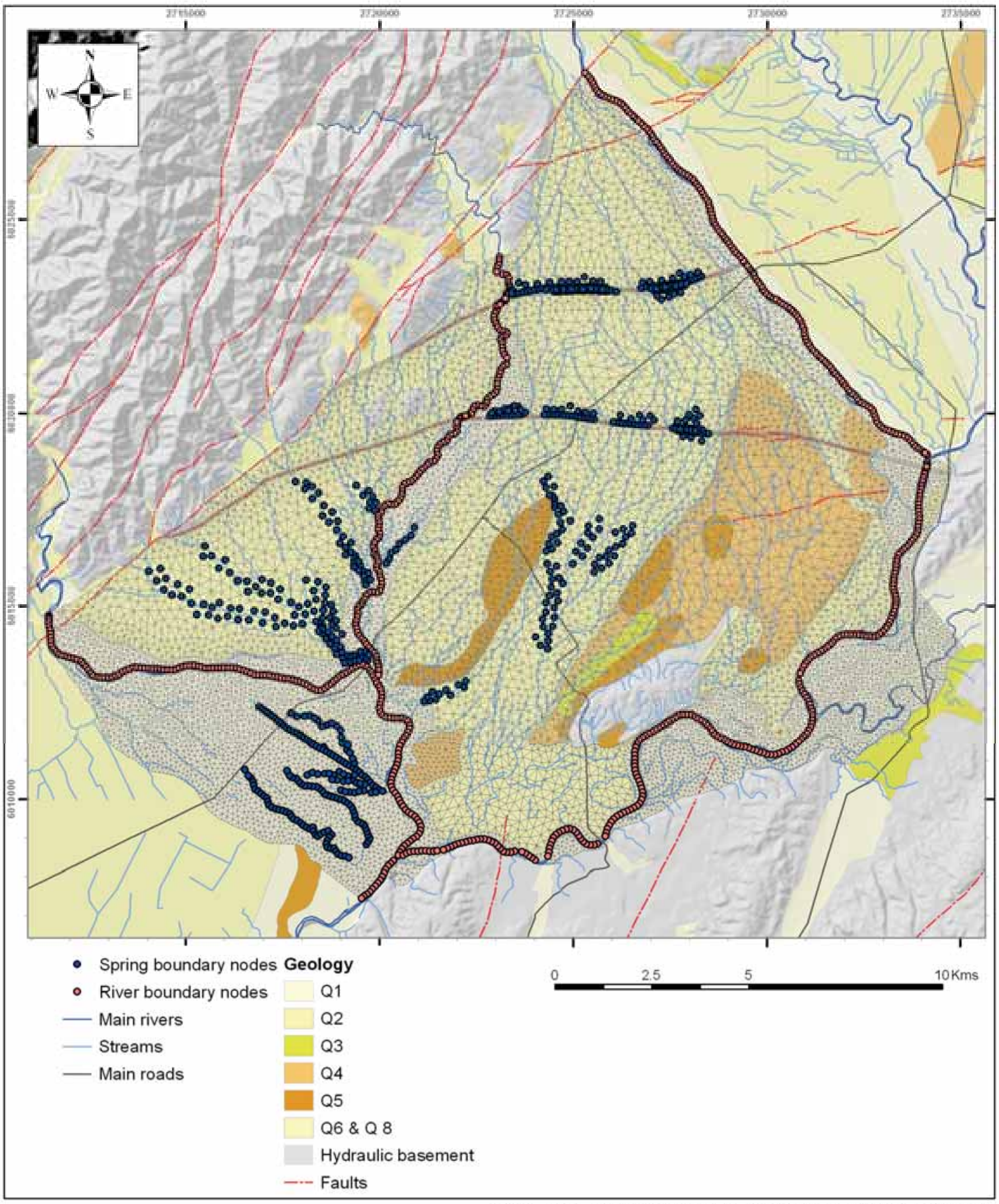


Figure 10.7: River and spring transfer boundary nodes in the Middle Valley catchment model

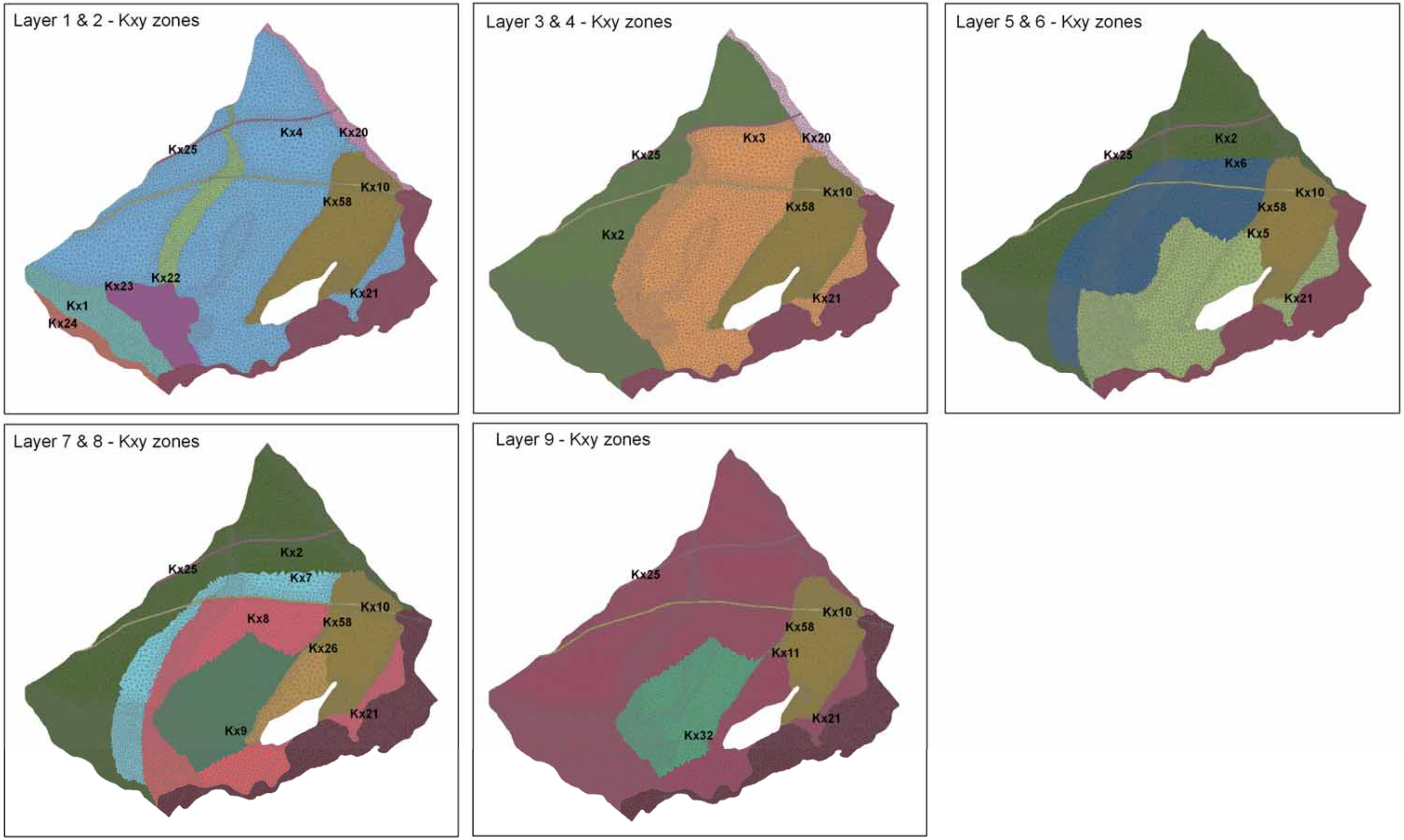


Figure 10.8: Horizontal hydraulic conductivity (Kx) zonation framework for the Middle Valley catchment groundwater model

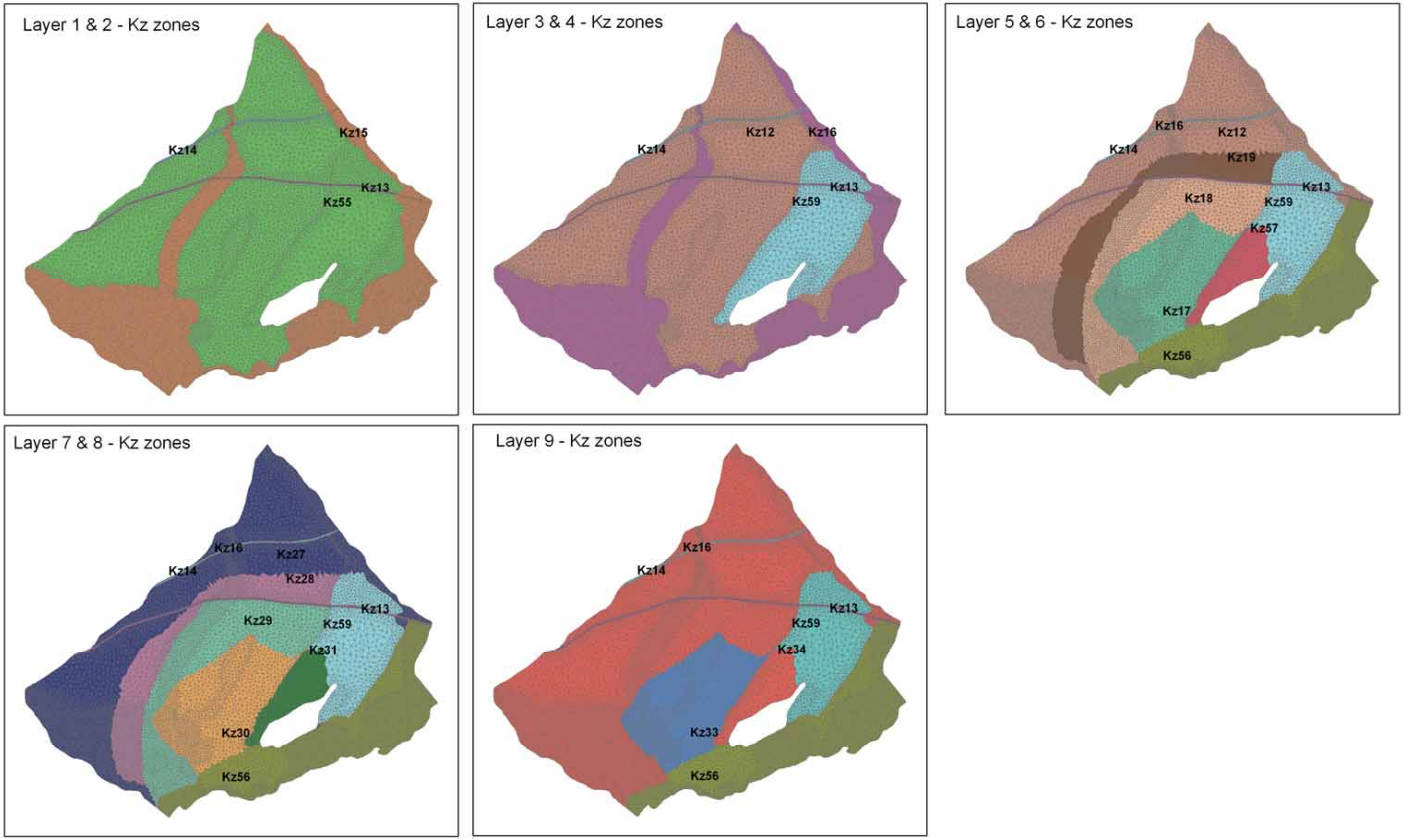
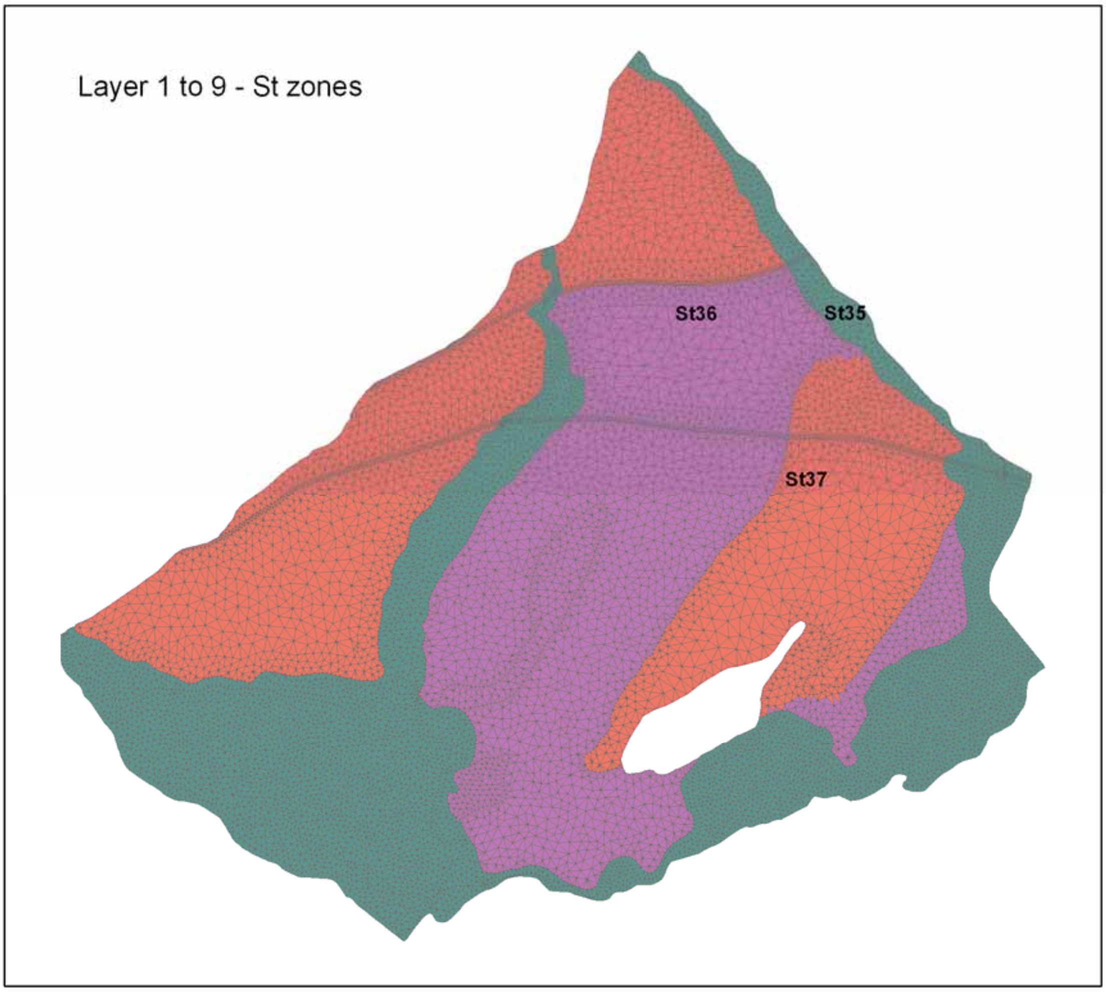


Figure 10.9: Vertical hydraulic conductivity (Kz) zonation framework for the Middle Valley catchment groundwater model



Figures 10.10: Unconfined storage (St) zonation framework for the Middle Valley catchment groundwater model

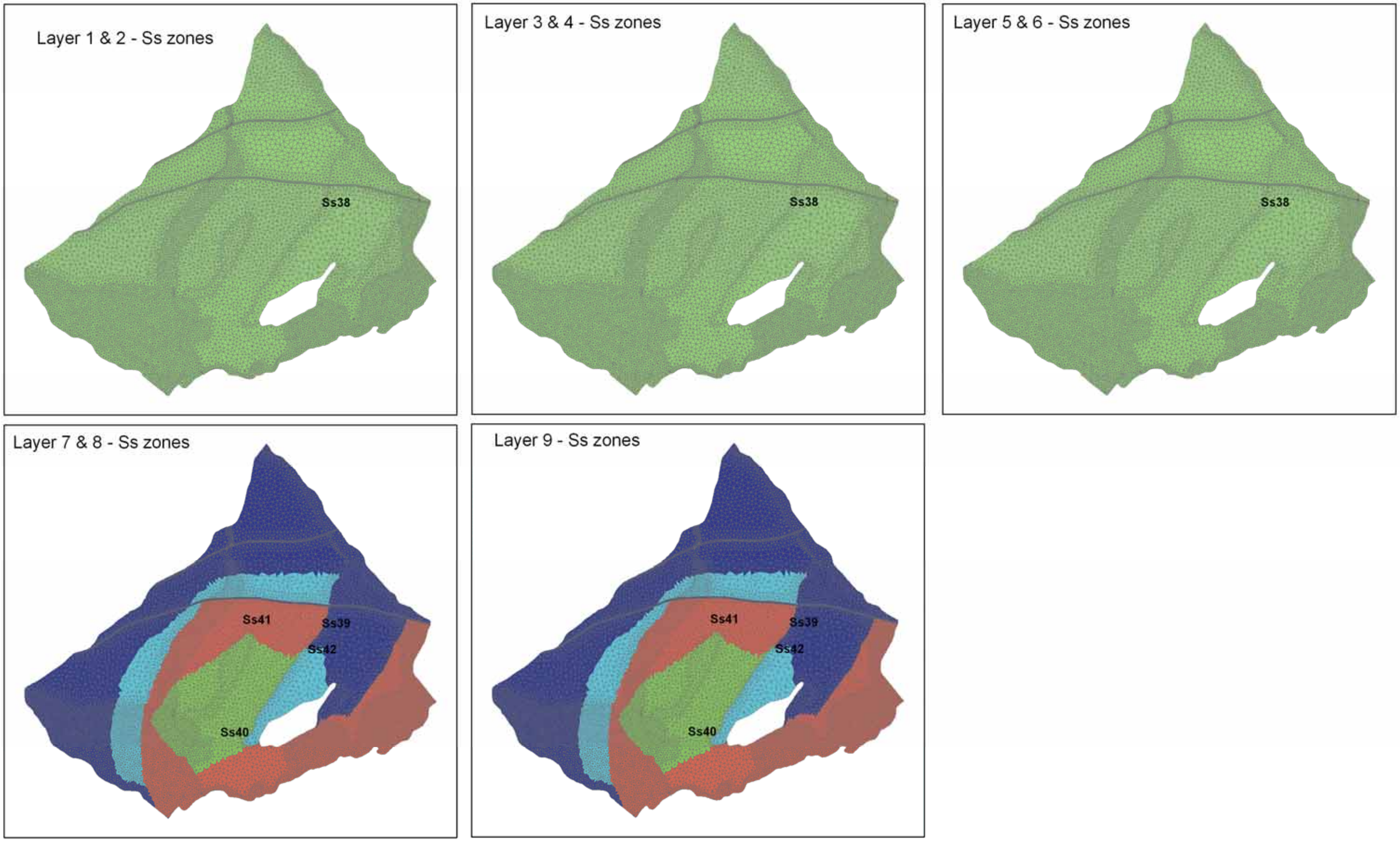


Figure 10.11: Confined storage (Ss) zonation framework for the Middle Valley catchment groundwater model

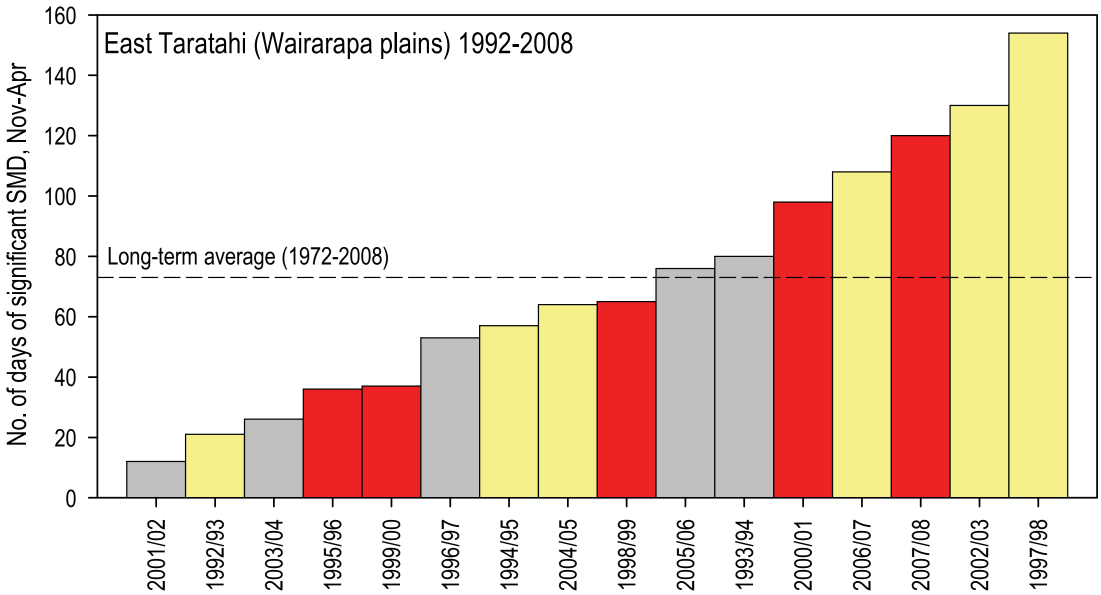


Figure 11.1: Number of days per growing season (November to April) with significant soil moisture deficit (greater than 110 mm) at East Taratahi near Masterton during the model calibration period 1992-2008. Yellow bars indicate El Nino, red indicate La Nina, and grey indicate neutral years. Soil moisture deficit data were provided by NIWA.

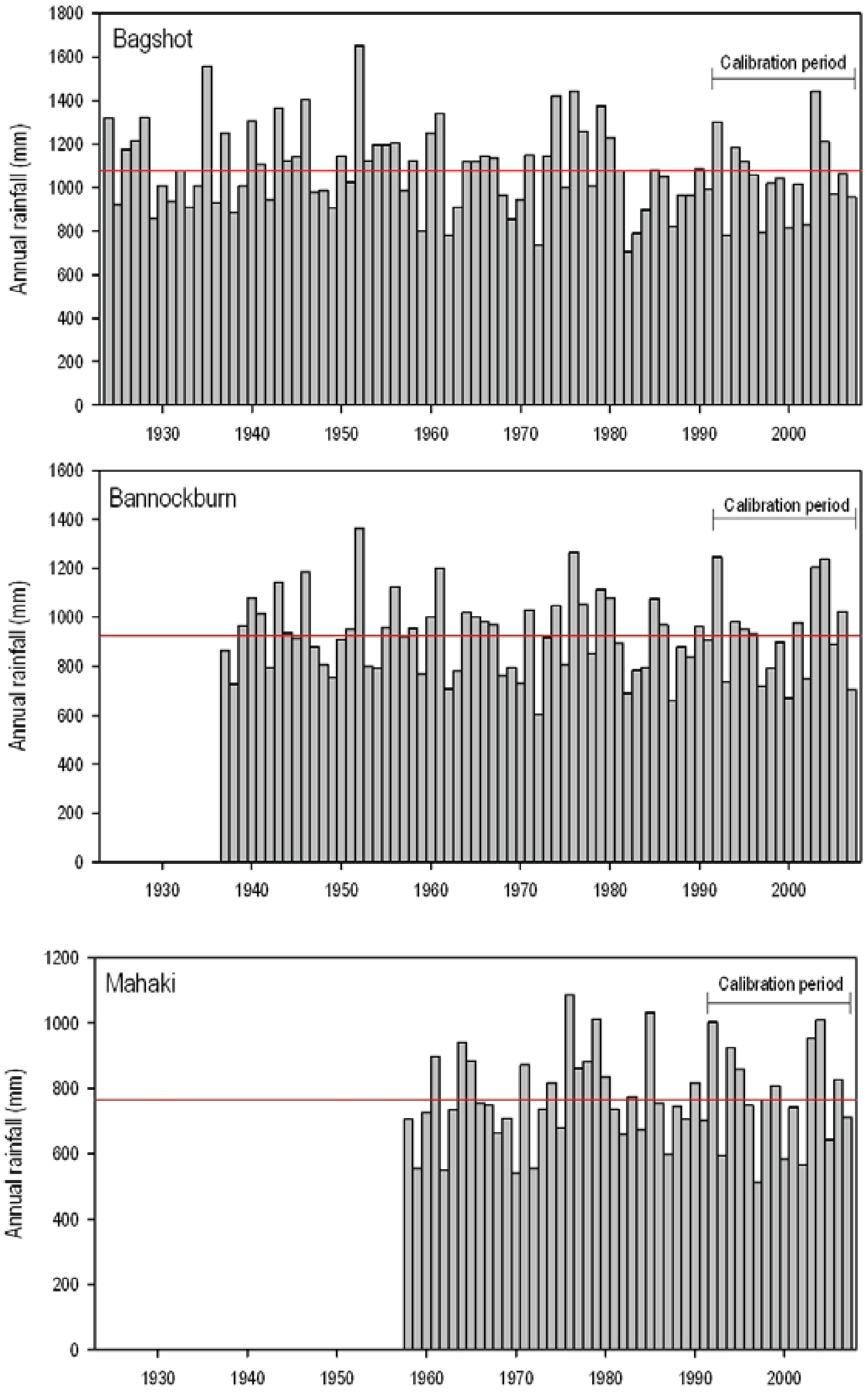
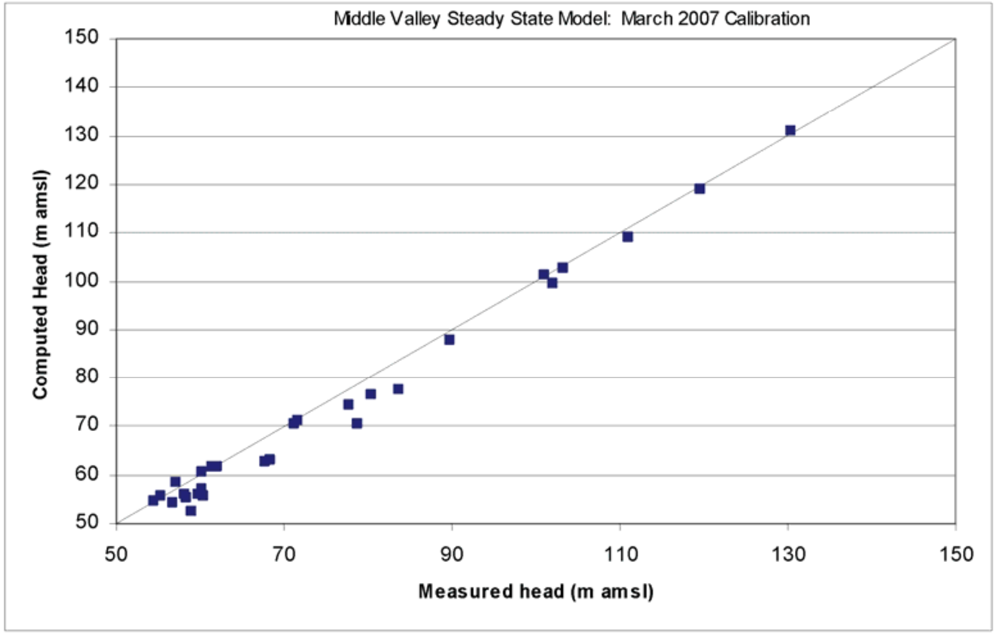


Figure 11.2: Annual rainfall at three long-term monitoring sites in the Wairarapa. The red line indicates the long-term mean at each site. Note the annual rainfalls shown are for a July to June year (data provided by NIWA).

Well No	Slice	Measured Head m	Computed Head m	Residual m	Abs residual m	Squared residual m2
S26/0122	17	77.85	74.53	-3.32	3.32	11.00
S26/0155	13	80.44	76.44	-4.00	4.00	16.01
S26/0166	13	89.81	87.76	-2.05	2.05	4.22
S26/0140	12	102.08	99.61	-2.47	2.47	6.11
S26/0229	39	103.34	102.68	-0.66	0.66	0.43
S26/0230	21	130.45	131.04	0.59	0.59	0.35
S26/0326	3	71.32	70.37	-0.95	0.95	0.90
S26/0490	5	61.41	61.78	0.37	0.37	0.14
S26/0529	7	54.53	54.74	0.21	0.21	0.04
S26/0545	18	47.99	48.29	0.30	0.30	0.09
S26/0547	4	46.04	45.17	-0.87	0.87	0.77
S26/0387	6	60.28	60.77	0.49	0.49	0.24
S26/0397	4	47.07	46.40	-0.67	0.67	0.44
S26/0568	45	58.89	52.48	-6.41	6.41	41.11
S26/0632	11	59.81	56.15	-3.66	3.66	13.36
S26/0658	8	61.98	61.69	-0.29	0.29	0.08
S26/0779	3	78.77	70.65	-8.12	8.12	65.86
S26/0780	10	60.45	55.67	-4.78	4.78	22.84
S26/0781	8	56.79	54.20	-2.59	2.59	6.73
S26/0730	33	71.67	71.37	-0.30	0.30	0.09
S26/0738	5	67.72	62.76	-4.96	4.96	24.59
S26/0743	33	60.24	56.91	-3.33	3.33	11.09
T26/0326	10	83.69	77.64	-6.05	6.05	36.61
S27/0225	5	45.88	45.42	-0.46	0.46	0.21
S27/0248	8	40.14	40.55	0.41	0.41	0.17
S26/0675	32	58.24	55.96	-2.28	2.28	5.20
S26/0756	22	46.44	44.56	-1.88	1.88	3.54
S26/0749	10	48.13	47.21	-0.92	0.92	0.84
S26/0236	41	111.05	108.91	-2.14	2.14	4.60
S26/0615	15	58.41	55.27	-3.14	3.14	9.83
S26/0400	16	55.24	55.74	0.50	0.50	0.25
S26/0595	12	68.40	63.14	-5.26	5.26	27.68
S26/0223	10	101.02	101.20	0.18	0.18	0.03
T26/0602	12	57.18	58.64	1.46	1.46	2.13
S26/0298	7	119.57	119.02	-0.55	0.55	0.30



Calibration Statistics

Absolute residual mean	-1.93	m
Min residual	-8.12	m
Max residual	1.46	m
Sum of residuals	76.60	m
Residual Standard deviation	2.10	m
Observed range in head	90.31	m
Mean sum of residuals	2.19	m
Scaled mean sum of residuals	0.07	%
Sum of residual squares	317.88	m2
Root mean square (RMS error)	3.01	m
Scaled RMS	3.34	%

Figure 11.3: Steady-state model groundwater head calibration statistics and model-to-measurement fit scatter plot

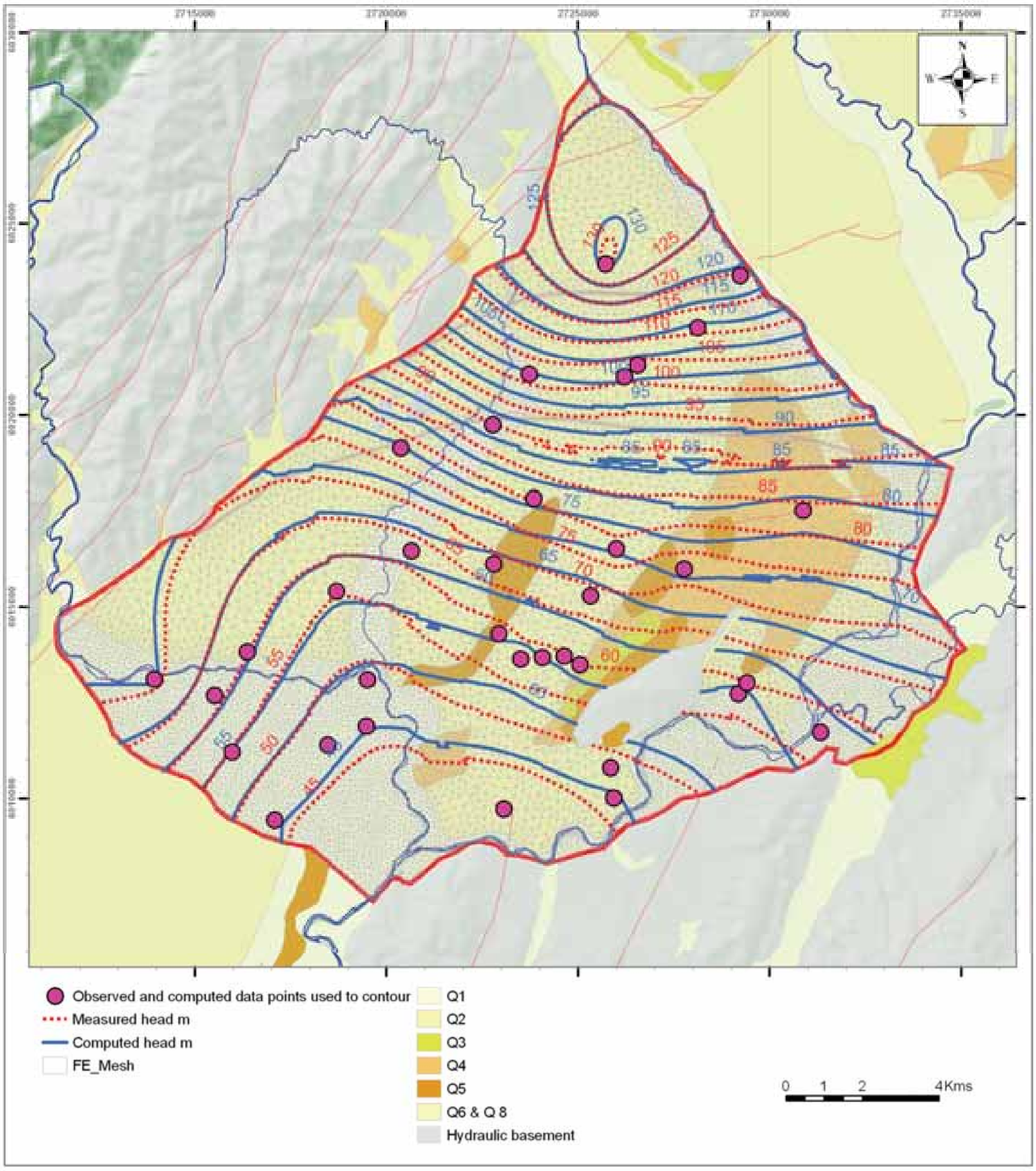


Figure 11.4: Steady-state modelled heads compared to observed head pattern. Both data sets were contoured using the same technique and data points to visually demonstrate model fit.

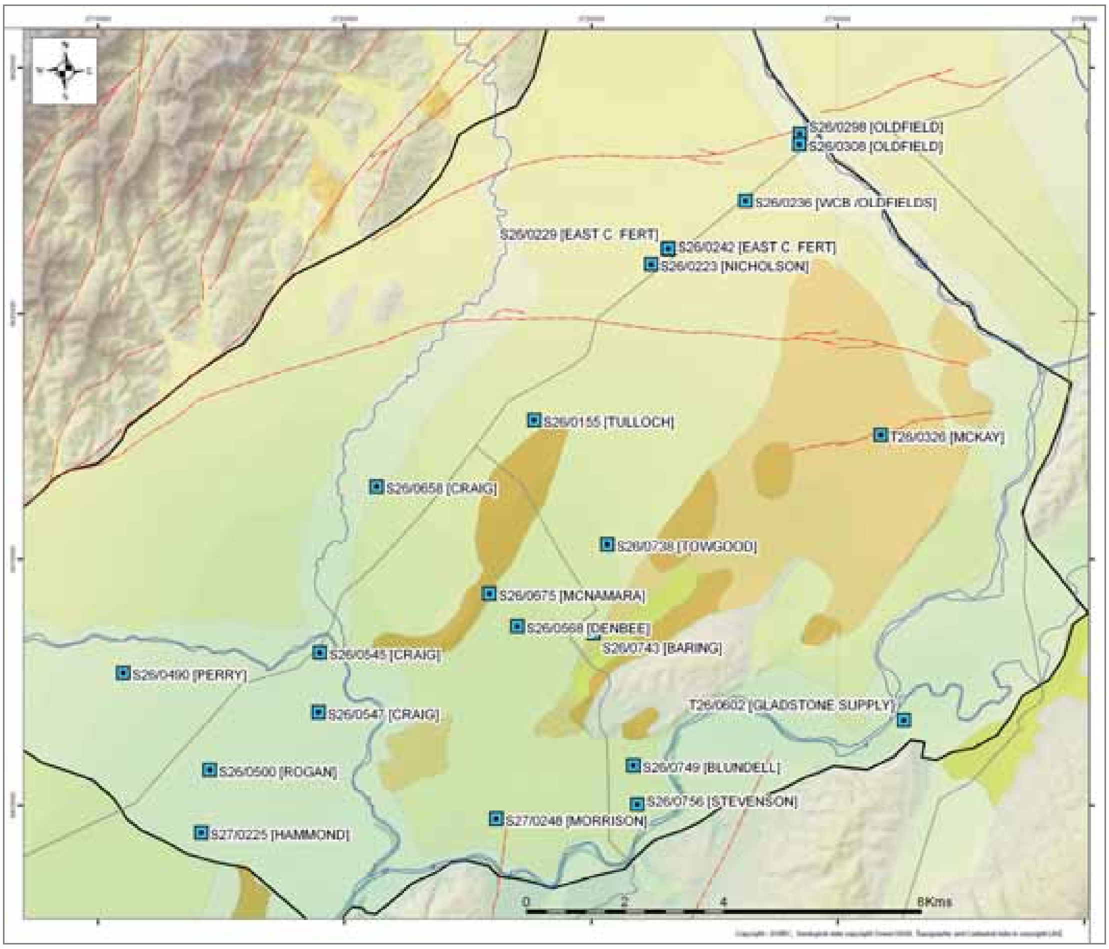


Figure 11.5: Head calibration targets used in the Middle Valley catchment transient groundwater flow model

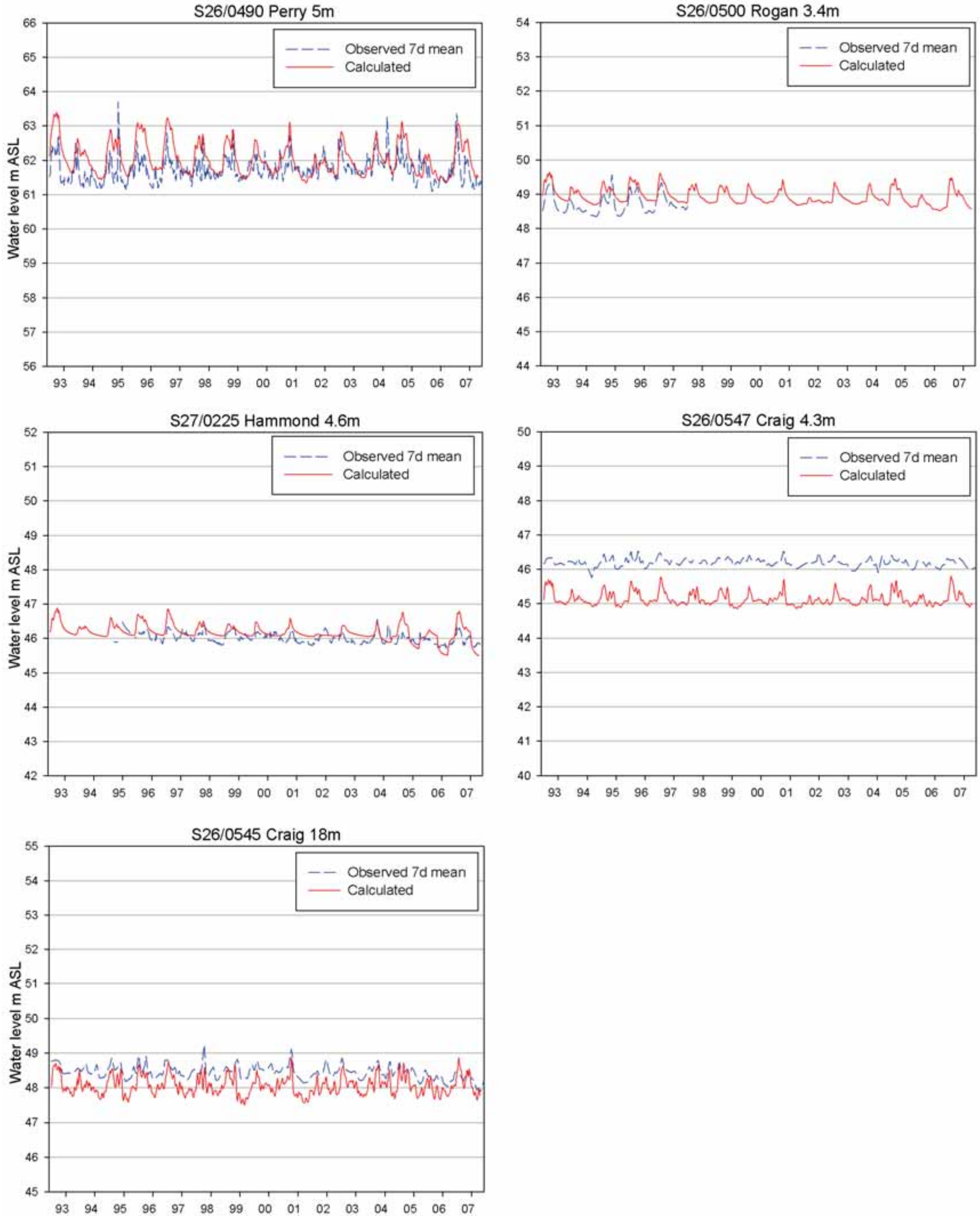


Figure 11.6: Simulated and observed groundwater levels for Area 1 – Greytown/Waiohine plains

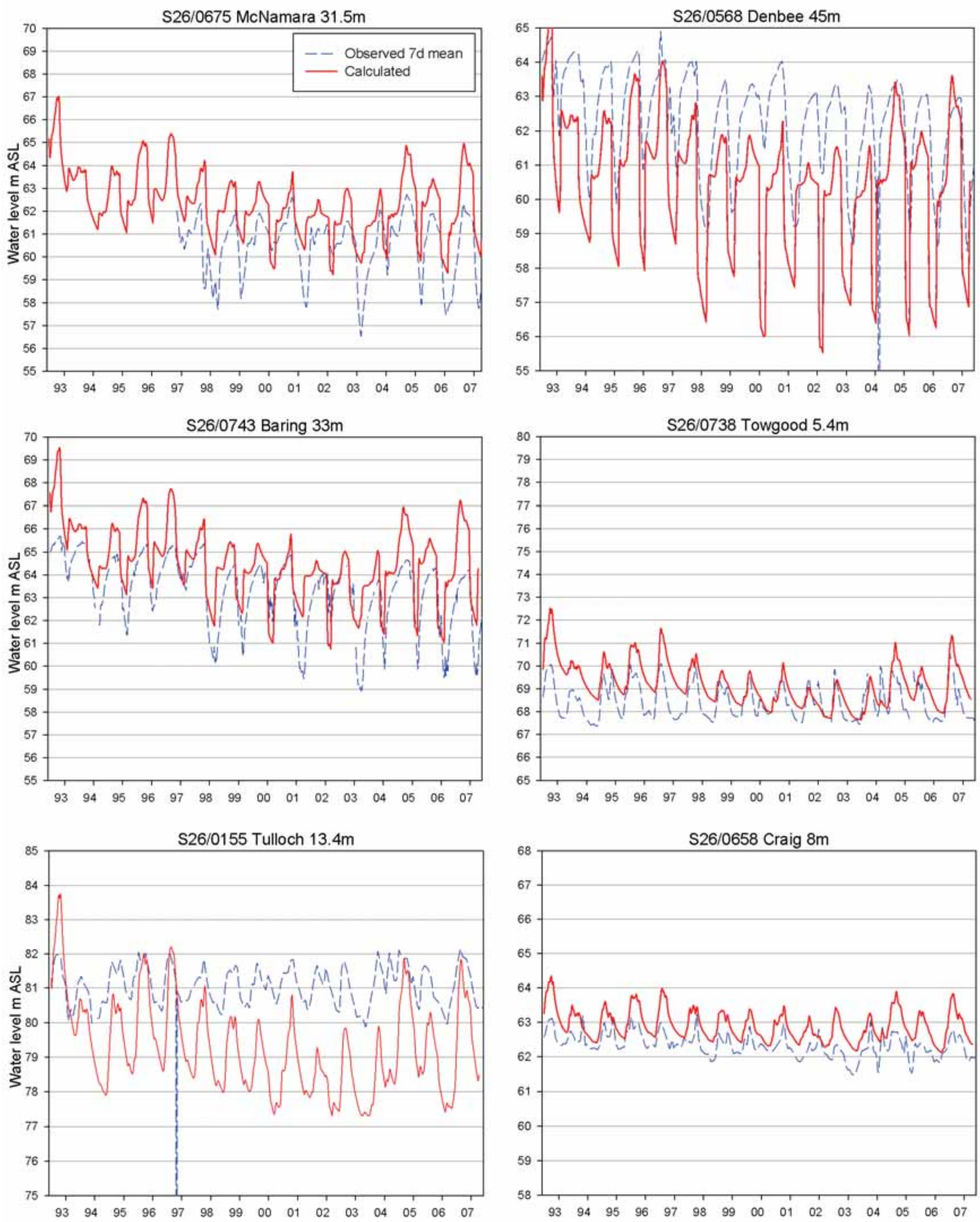


Figure 11.7: Simulated and observed groundwater levels for Area 2 – Parkvale/Carterton sub-basins

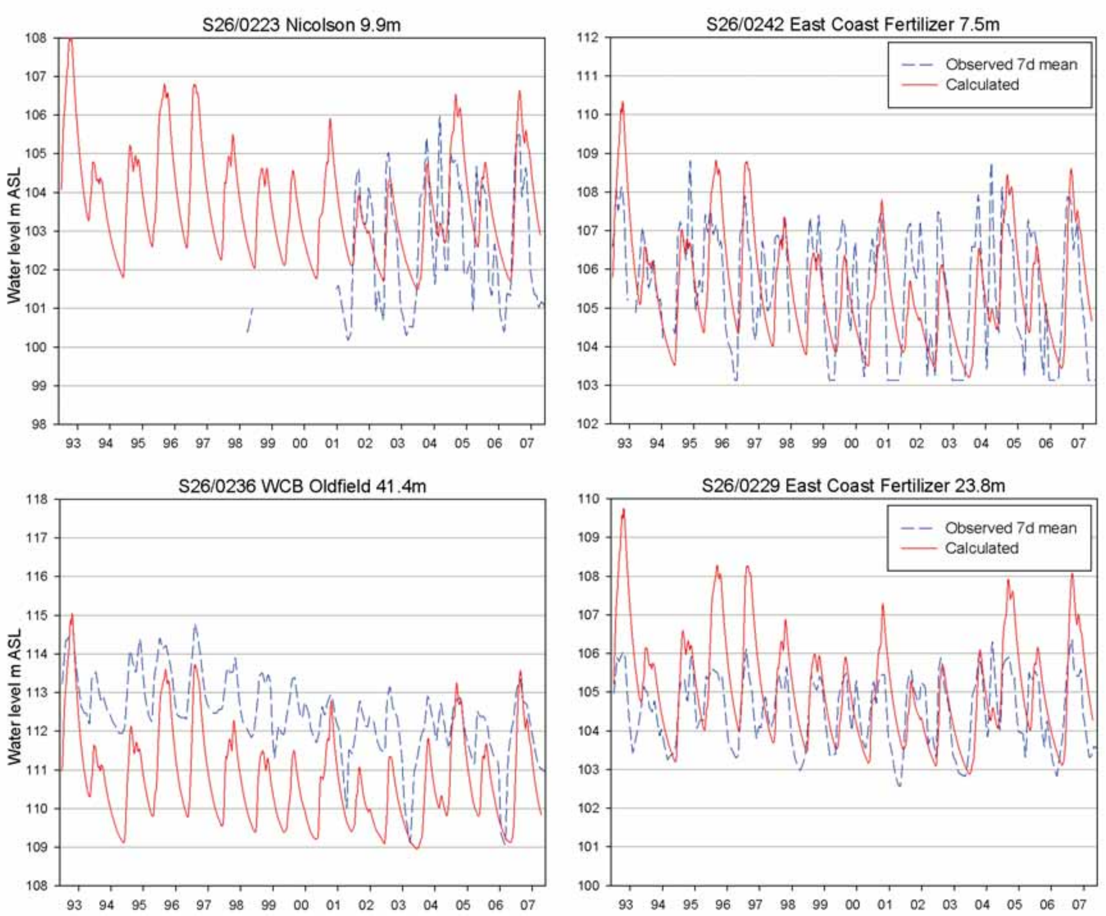


Figure 11.8: Simulated and observed groundwater levels for Area 3 – Upper Waingawa fan

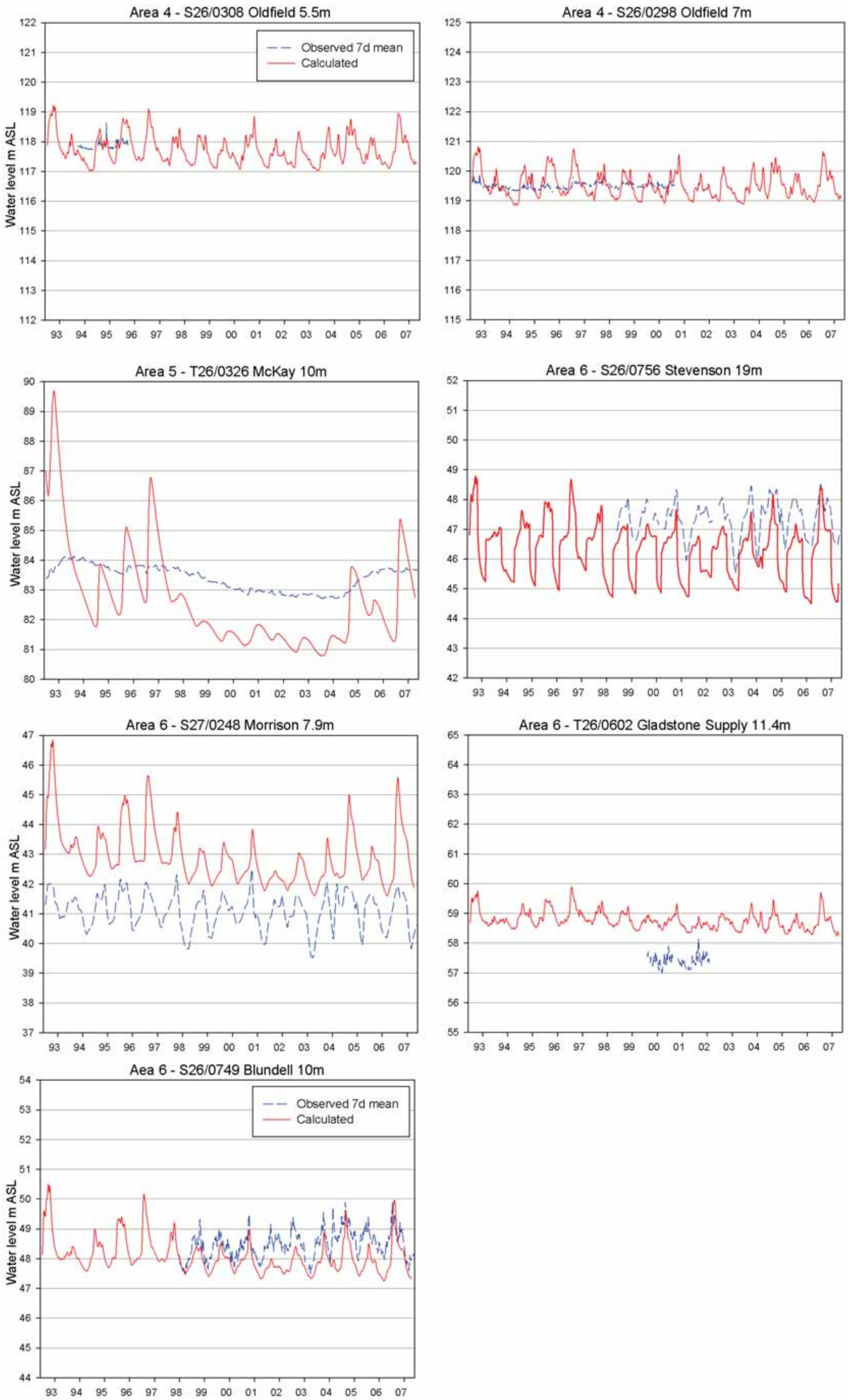


Figure 11.9: Simulated and observed groundwater levels for Area 4 (Waingawa floodplain), Area 5 (Fernhill) and Area 6 (middle Ruamahanga valley)

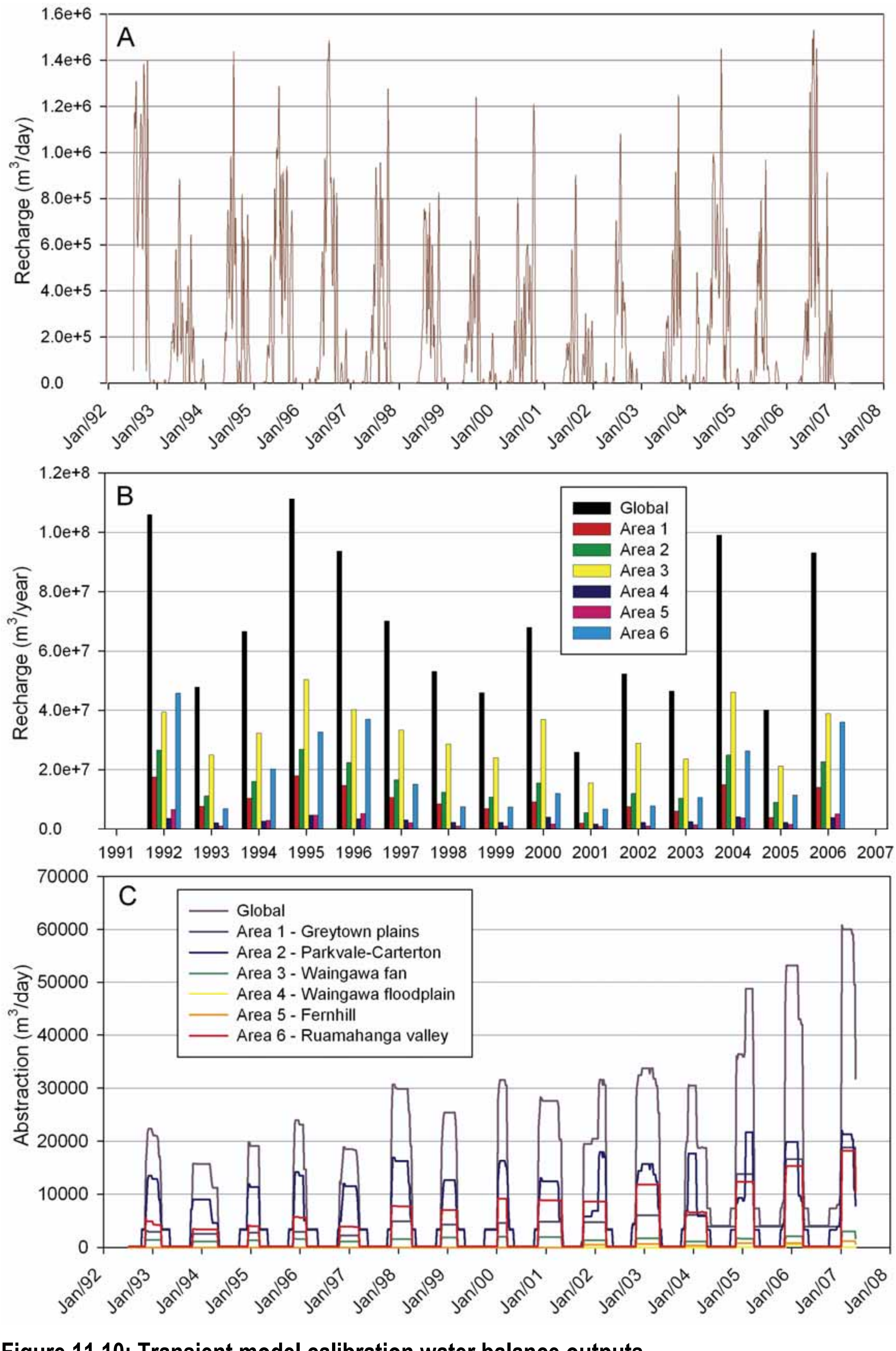


Figure 11.10: Transient model calibration water balance outputs
A – Daily recharge, B – Annual recharge, C – Abstraction rate

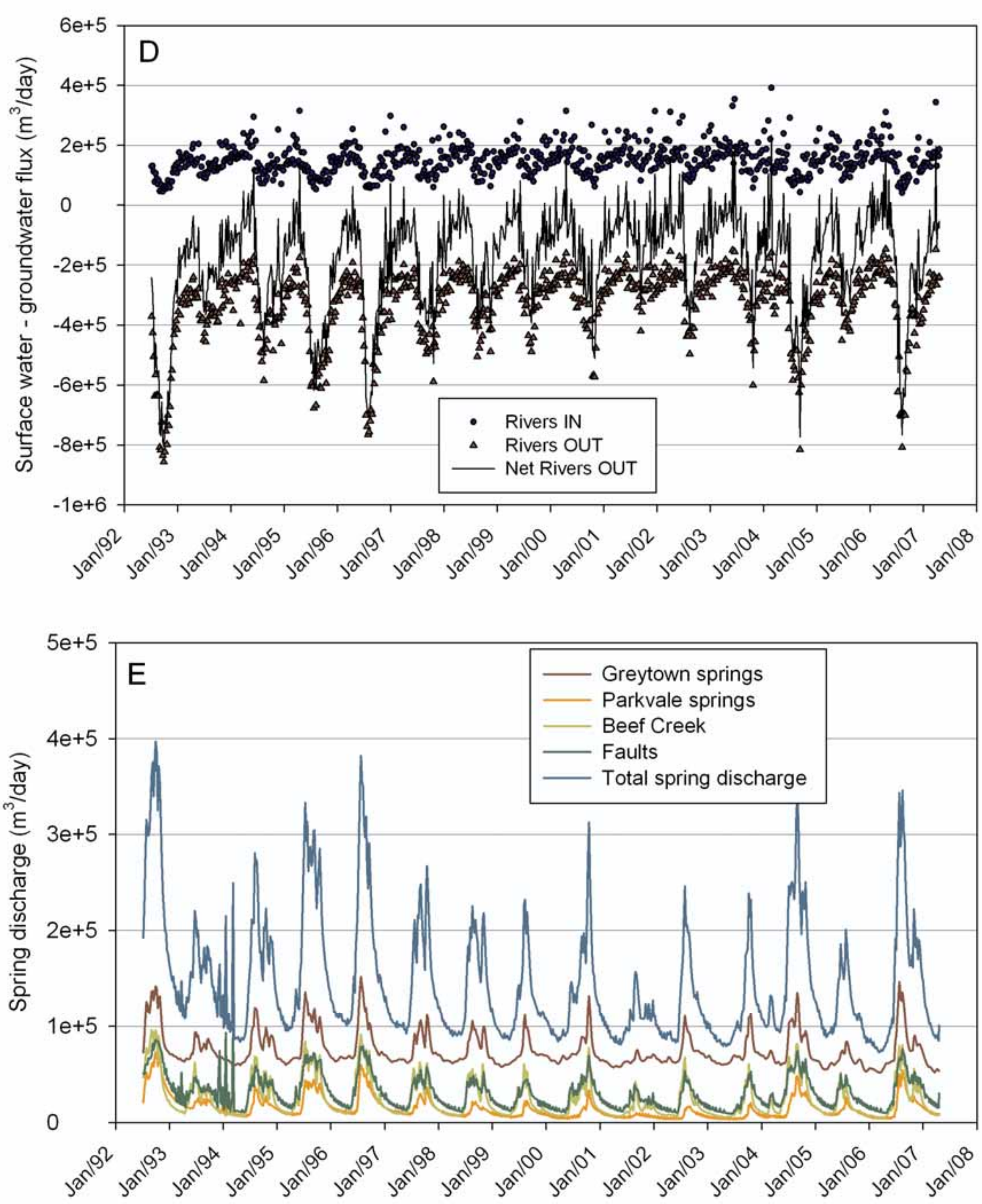


Figure 11.10: Transient model calibration water balance outputs:
D – Surface water groundwater fluxes, E – Spring discharges

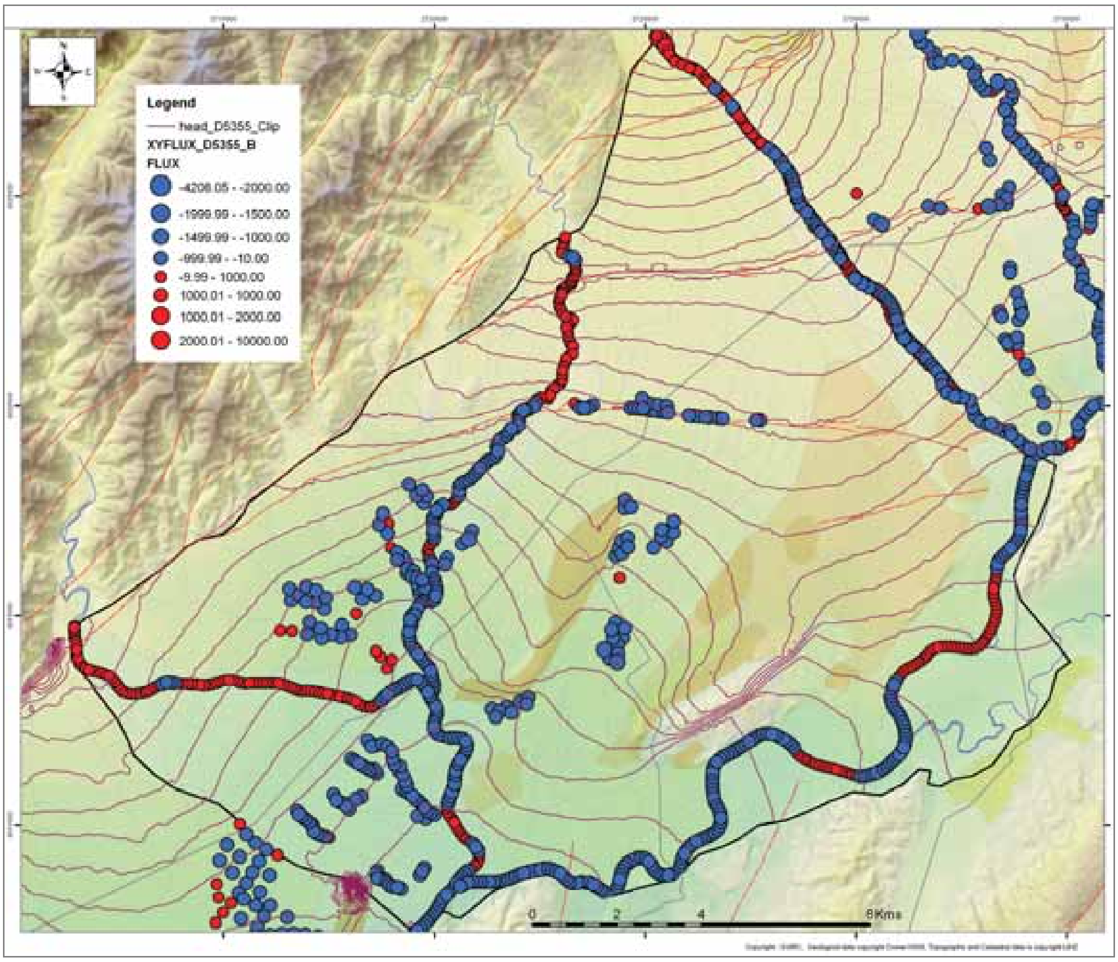


Figure 11.11: Transfer node fluxes on model day 5355 (27 February 2007) illustrating gaining river reaches and springs (coloured blue) and losing river reaches (coloured red). The simulated pattern corresponds closely to observed gain/loss characteristics.

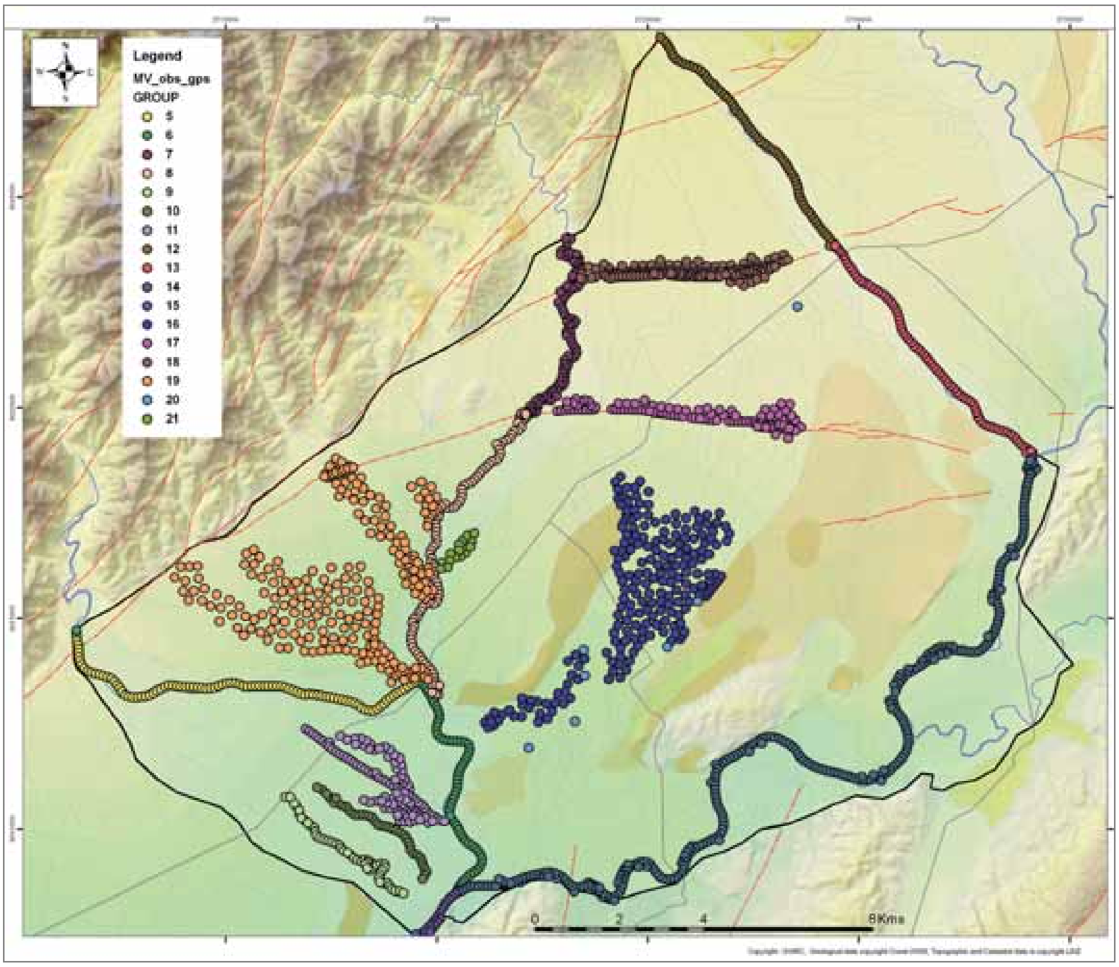


Figure 11.12: Fluid flux observation point groups used in FEFLOW for the Middle Valley catchment groundwater model

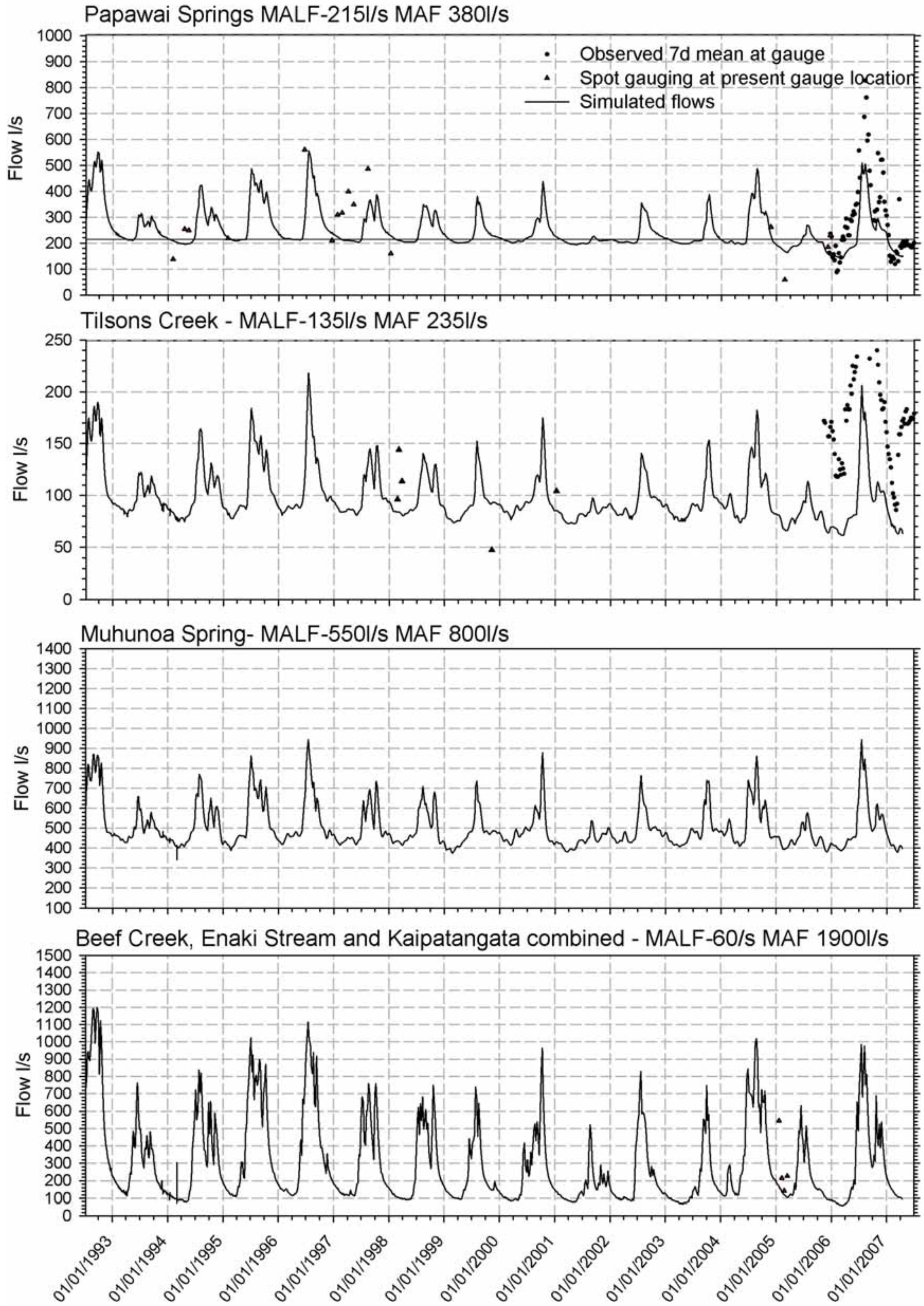


Figure 11.13: Simulated groundwater discharge to the Greytown springs and Mangatarere Stream tributaries (Beef Creek, Enaki Stream and Kaipaitangata Stream). Gauging data are shown where available.

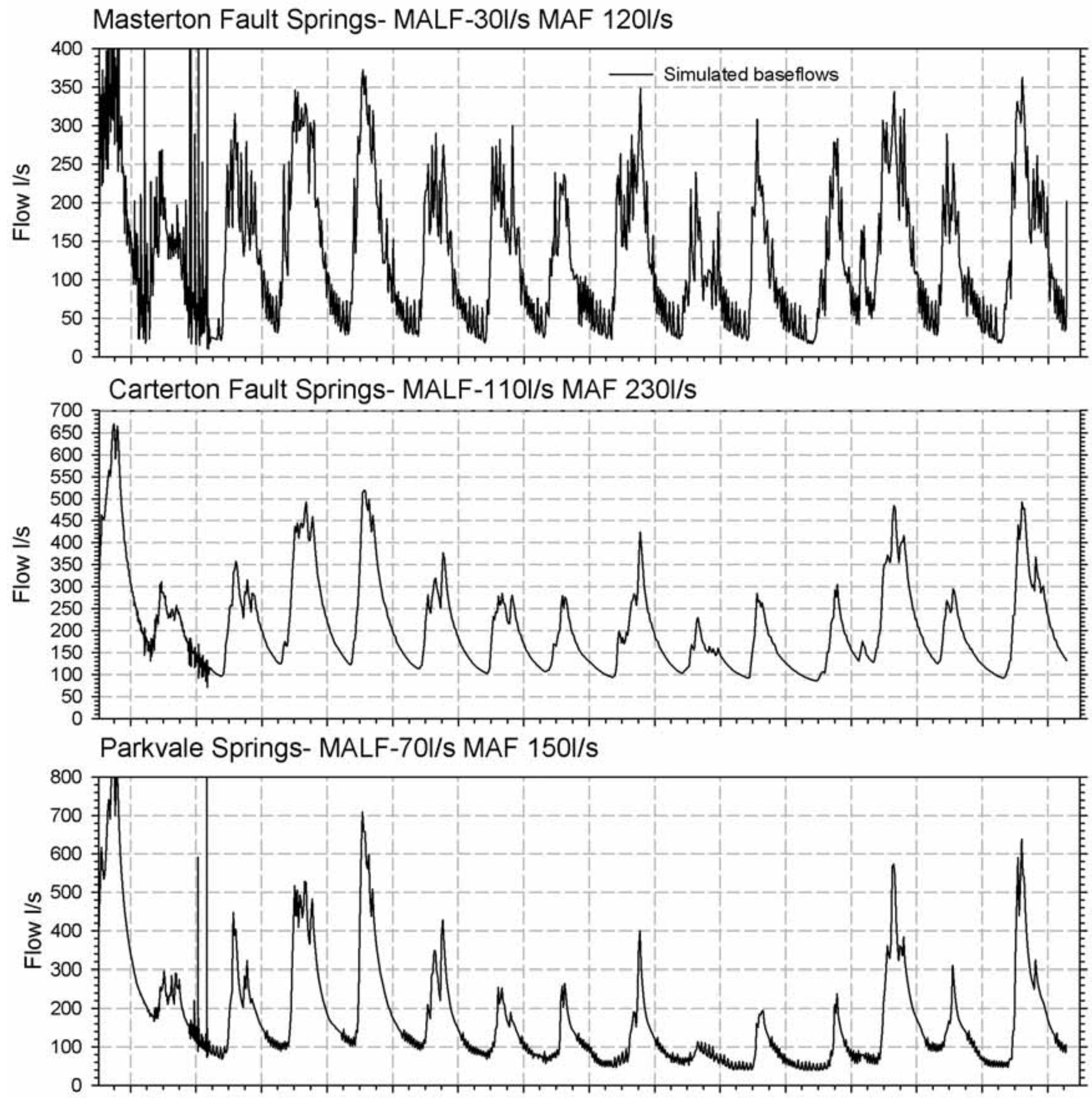


Figure 11.14: Simulated groundwater discharge to the Masterton Springs

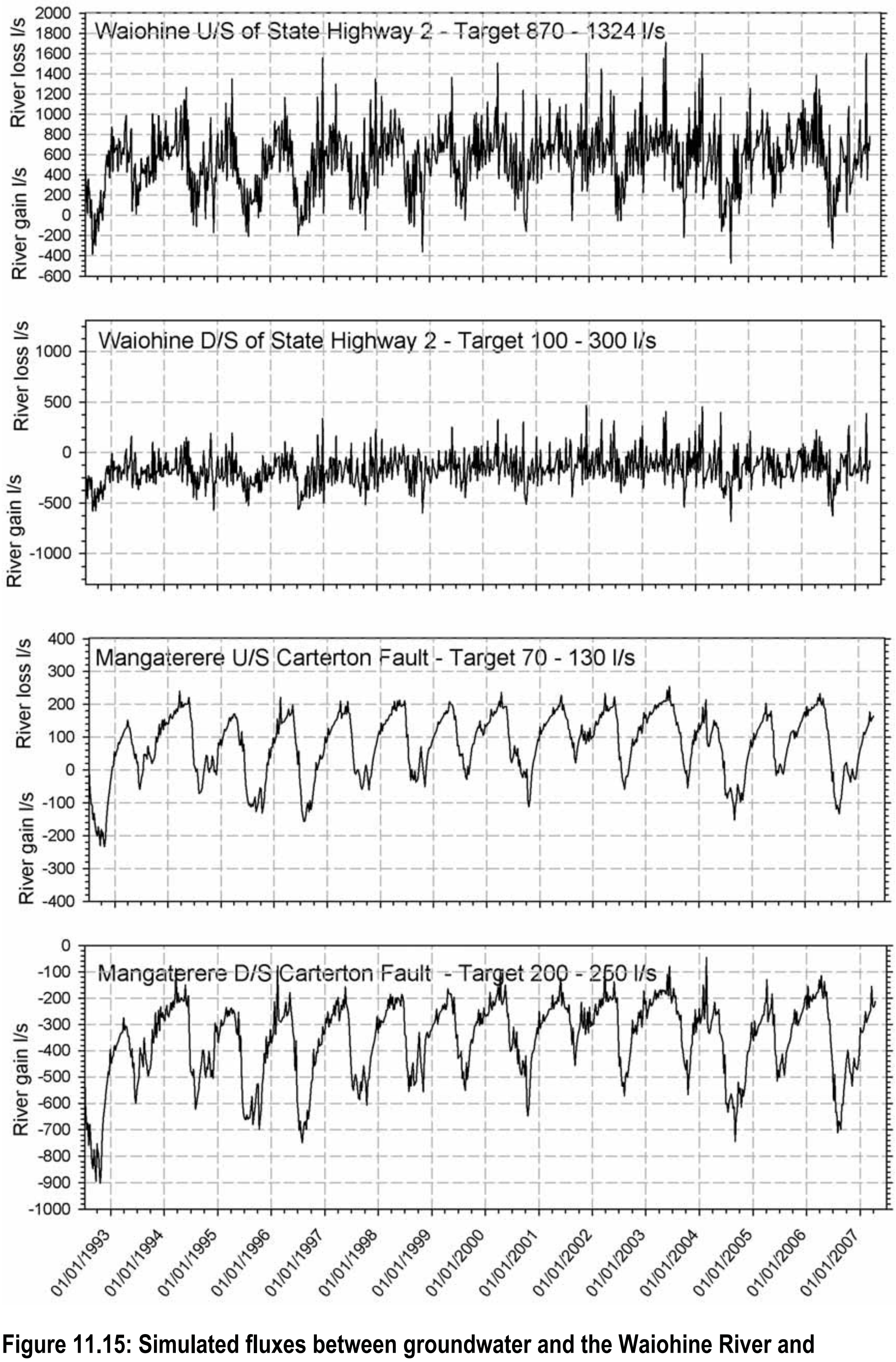


Figure 11.15: Simulated fluxes between groundwater and the Waiohine River and Mangatarere Stream. Negative fluxes show flow out of the aquifer to the river/stream, and vice versa.

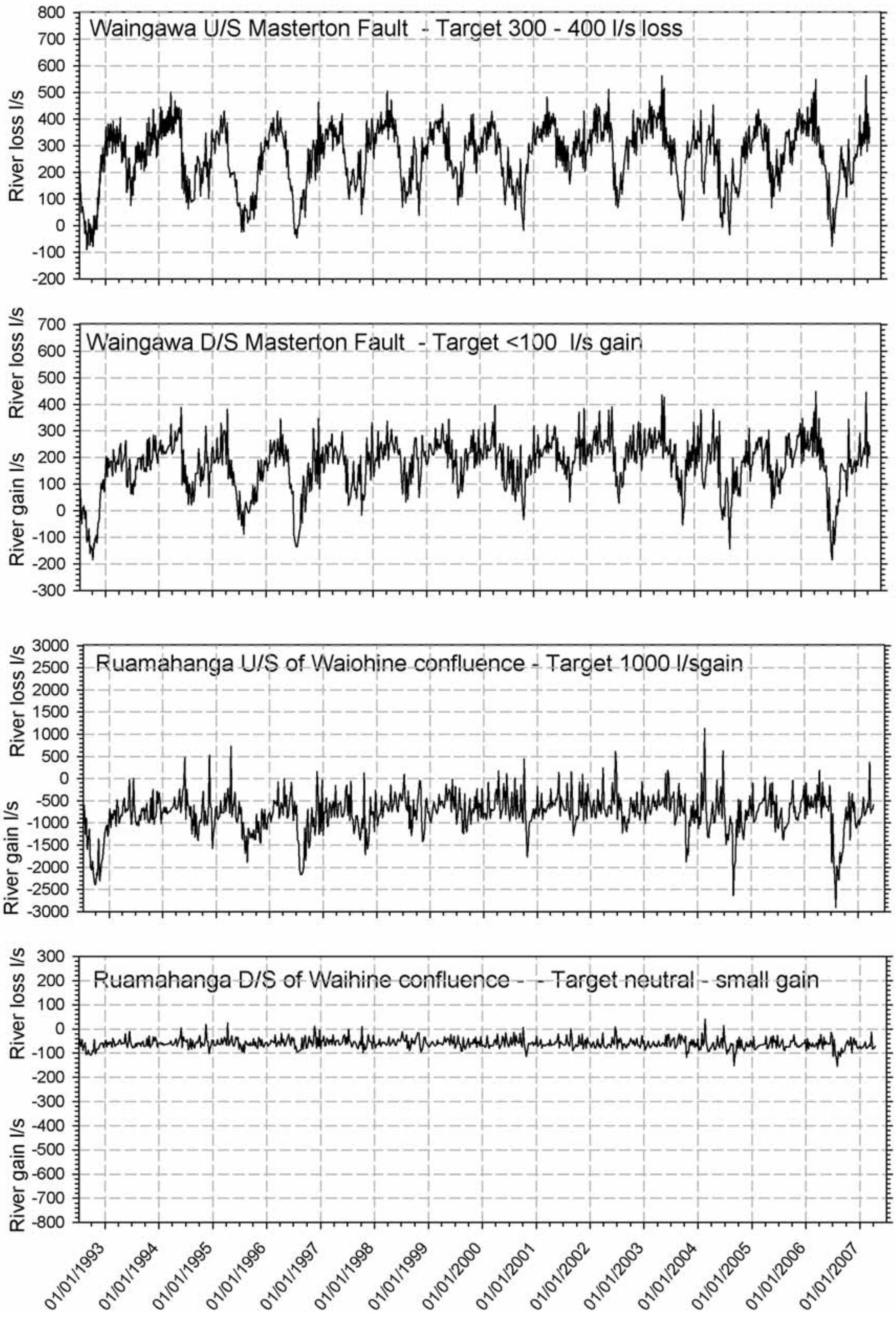


Figure 11.16: Simulated fluxes between groundwater and the Waingawa and Ruamahanga rivers. Negative fluxes show flow out of the aquifer to the river/stream, and vice versa.

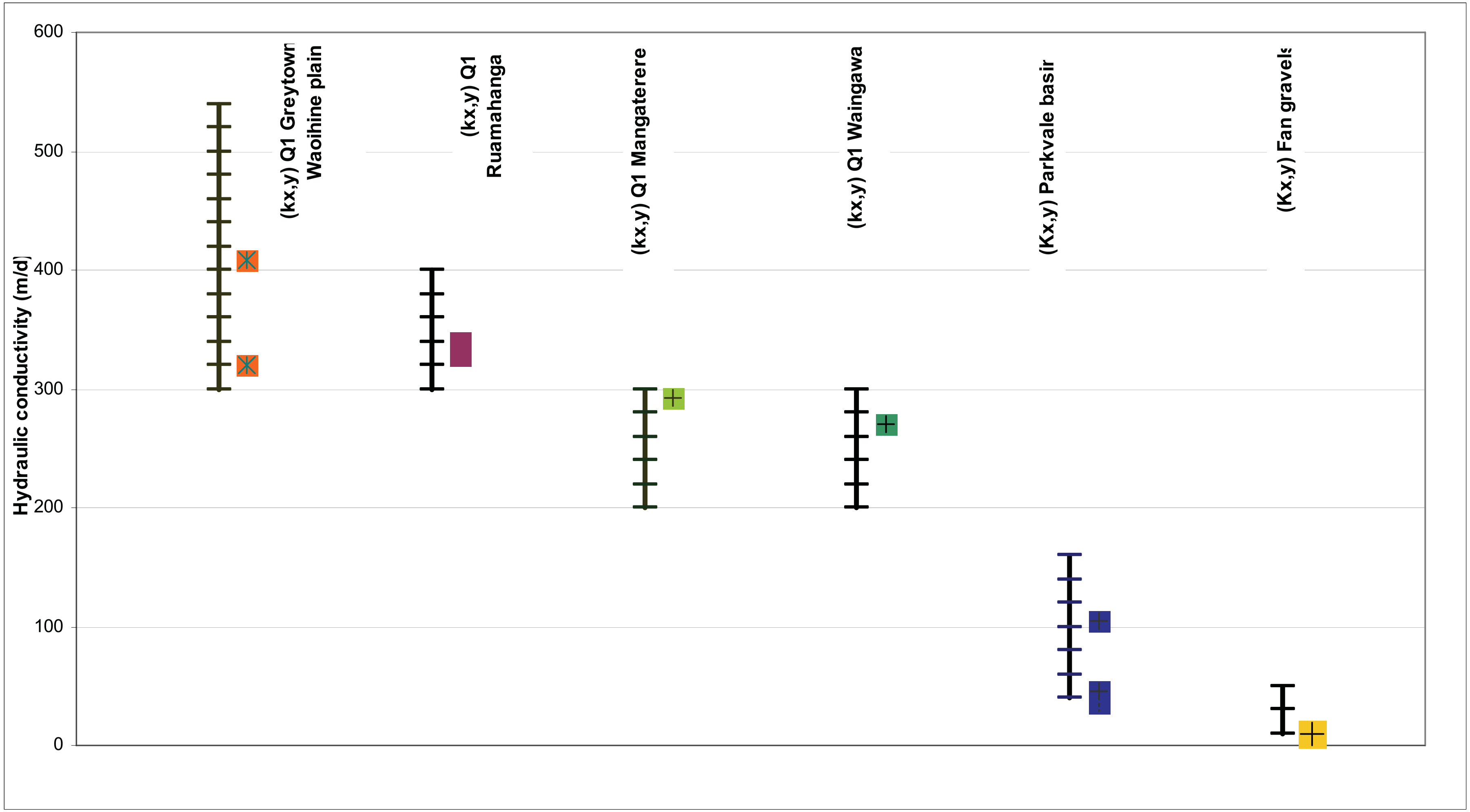


Figure 11.17: Comparison of calibrated hydraulic conductivity parameter values with measured values for the Middle Valley catchment calibrated transient flow groundwater model

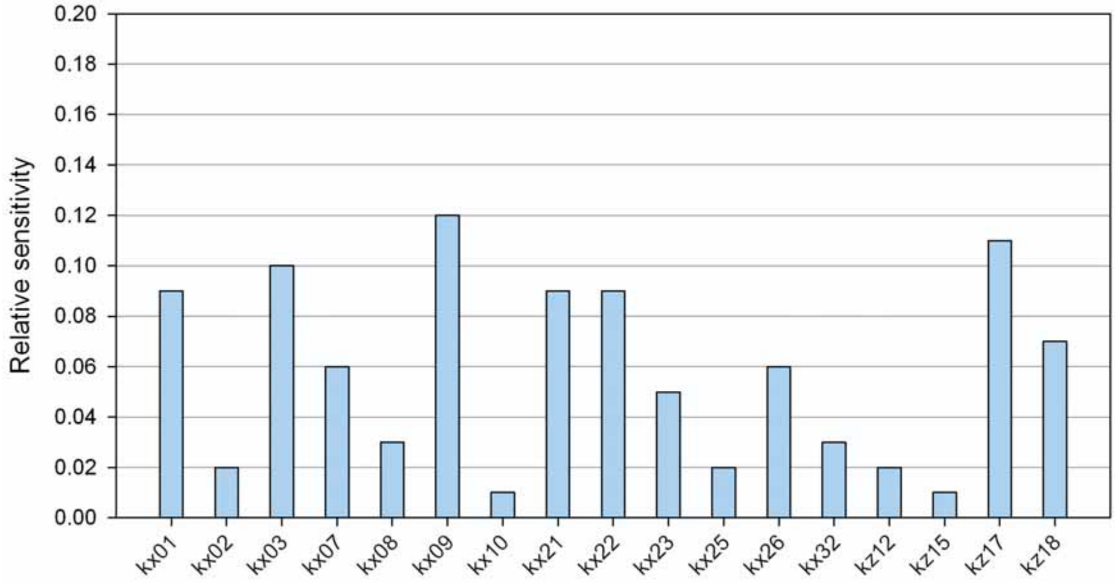


Figure 11.18: Relative sensitivity for final calibration optimisation adjustable parameters used in the Middle Valley transient groundwater flow model

Appendix 1:

Description of field drilling targets and results

A total of eight monitoring bores were constructed at five locations in the Middle Valley catchment in key areas where significant information gaps were identified (Figure A1.1). These were drilled between April and June 2008.

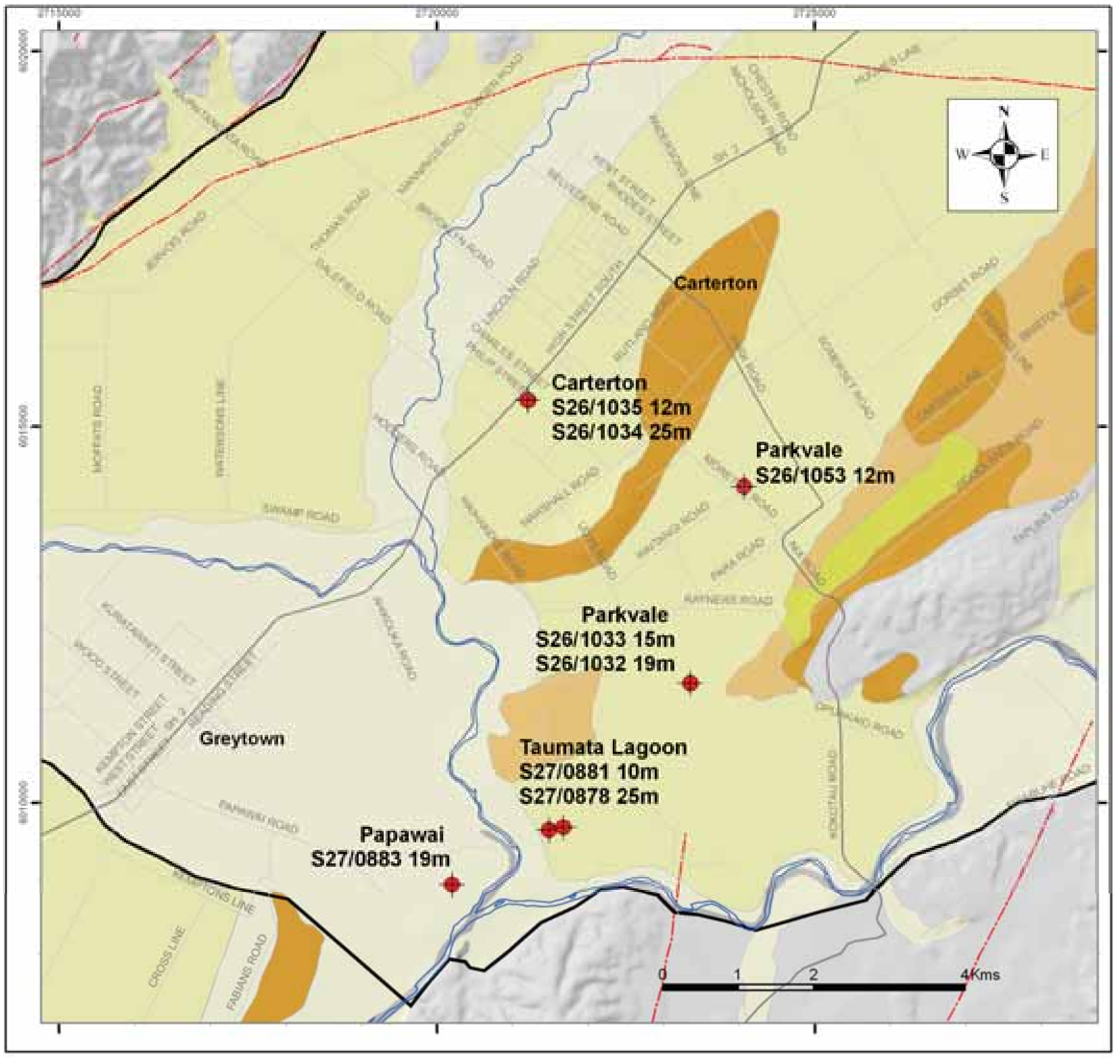


Figure A1.1: Drilling and monitoring bore installation sites in the Middle Valley catchment

Carterton sub-basin at Hilton Road – S26/1034 and S26/1035

The target aquifers at this site were the poorly sorted layered aquifer system underlying Carterton which is relatively poorly understood. A multi-level monitoring installation was established at this site using two adjacent bores. During drilling, poorly sorted sediments were intercepted and a cohesive clay layer was logged between 10–12 metres below ground level (m bgl).

The first monitoring bore was installed above this clay layer (screened 3.4–6.4 m bgl and completed with a 50 mm ID pvc casing and slotted screen) to monitor the shallow unconfined aquifer. Due to the possibility of artesian conditions in the area, a second deeper monitoring bore was double cased. This bore was drilled to 25 m bgl and intercepted several low-yielding poorly sorted gravel layers. The screen was installed in the best producing of these layers at 19.4–21 m bgl.

During drilling it was discovered that lower layers were not confined and no artesian conditions were observed. The hydraulic gradient at this location is downwards with the static water level at the time of drilling measured at 3.2m bgl in the shallow bore (S26/1035) and 4.6 m bgl in the deeper bore (S26/1034).

Parkvale sub-basin at McNamara S26/1053

Several pumped privately owned bores are currently monitored for groundwater level in the Parkvale groundwater basin (Towgood – S26/0738, Baring – S26/0743, Denbee S26/0568 and McNamara – S26/0675). Since these sites are strongly affected by pumping and there are no multi-level sites it was considered necessary to construct dedicated monitoring bores to improve the understanding of the Parkvale sub-basin aquifers.

A drilling site was selected on Moreton Road to avoid being affected by drawdown effects associated with large irrigation abstractions. However, plans to construct a multi-level monitoring site were abandoned due to budget restrictions. A single shallow monitoring bore (S26/1053) was drilled to 12 m depth and screened (6.5–9.5 m bgl) in the unconfined shallow aquifer.

Parkvale sub-basin at Renall S26/1032 and S26/1033

To investigate whether the confined aquifers of the Parvale sub-basin continue to the south towards the Ruamahanga River and thereby allow throughflow to exit the sub-basin, a drill site was located on the southern edge of the sub-basin near the edge of Tiffen Hill.

Two bores were drilled side-by-side to create a multi-level monitoring site at this location. The first bore (S26/1033) was screened in a shallow unconfined aquifer between 4.6 and 7.6 m bgl. A second bore (S26/1032l) was screend in an artesian aquifer between 14 and 17 m depth. At the time of drilling the water level in the shallow bore was -0.9 m bgl and the water level in the deeper aquifer was +2.7 m above ground level.

Taumata Lagoon at Waihakeke Road

Taumata Lagoon was selected as an important site to help understand the connectivity between wetlands and the shallow groundwater environment. Two groundwater monitoring sites were established next to the lagoon; one on the outside of the oxbow lake (north side) drilled to 25 m bgl (S27/0878, screened 21.7–24.7 m bgl), and a shallower bore on the inside (south side) of the lake to drilled 10 m bgl (S27/0881, screened 5.7 m–8.7 m bgl) in a gravel aquifer.

A surface water level gauge was also installed in the open water of the lagoon.

Papawai at Bicknell

Part of the scope of the drilling operation was to install dedicated monitoring bores at locations where there is significant interaction between groundwater and surface water. Model calibration at these sites will increase accuracy in coupled surface water/groundwater models at these important locations. A site was selected (S27/0883) in the Papawai area north of the confluence of the Waiohine and Ruamahanga rivers. Stratigraphic drilling showed that the unconfined Greytown aquifer in this area extended to at least 19 m in depth. Mudstone basement was not encountered at this site. A monitoring bore was screened between 11 and 14 m bgl

Appendix 2:

Isotope data for the Middle Valley catchment

Name	Bore ID	Easting (NZMG)	Northing (NZMG)	Date sampled	δ18O ‰	δD ‰	Tritium 2005 scale	sigTR	SF6 (pptv)	CFC11 (pptv)	CFC12 (pptv)	DIC mmol/kg	δ13C ‰	pmC norm	±pmC	E% PM %	MRT[y] more likely	MRT[y] less likely	Source
CDC North	S26/0824	2720564	6016101	12/05/2005	-6.07		1.74	0.04	3.86	1050	6200					35	40		Greater Wgtn– GW Dating 2005
CDC North	S26/0824	2720564	6016101	03/06/2008	-5.84	-38.3	1.51	0.04								32	49		Greater Wgtn – GW Dating 2008
CDC South	S26/0705	2720489	6015999	12/05/2005	-6.08		1.41	0.06	2.71	112	20000					50	40		Greater Wgtn – GW Dating 2005
CDC South	S26/0705	2720489	6015999	03/06/2008	-5.78	-38.7	1.28	0.04								38	54		Greater Wgtn – GW Dating 2008
CRAIG, R	S26/0658	2720650	6016480	05/06/2008	-5.82	-38	1.47	0.05	4.81	504	483	1.85	-23.2	103.3	0.33	0-100/30	40.00	4	Greater Wgtn – GW Dating 2009
Denbee	S26/0568	2723504	6013642	12/04/1983	-7.51	-47.80	0.05	0.1								70	>110		WCB - GW Recharge & Dating 1983
Denbee	S26/0568	2723504	6013642	01/09/1990	-7.42		0.09	0.07								70	>110		Greater Wgtn – Recharge & Dating 1990
Denbee	S26/0568	2723504	6013642	05/06/2008	-7.05	-48.4						2.9	-23.1	34.89	0.18	0	6000		Greater Wgtn – GW Dating 2008
GP Orchard	S26/0911	2717612	6012423	03/05/2005	-5.55		1.85	0.05	5.93	259	716					70	1		Greater Wgtn – GW Dating 2005
McNamara, J	S26/0576	2723479	6014255	05/06/2008	-6.58	-45	0.482	0.026	0.26	0.6	7	2	-22.6	68.97	0.24	80	100		Greater Wgtn – GW Dating 2008
Smith's Orchard	S26/0487	2717636	6012424	12/04/1983	-5.68	-31.30	5.09	0.24								70	1		WCB – GW Recharge & Dating 1983
Smith's Orchard	S26/0487	2717636	6012424	11/04/1983		-31.30													WCB – GW Recharge & Dating 1983
Smith's Orchard	S26/0487	2717636	6012424	26/09/1983		-38.00													WCB – GW Recharge & Dating 1983
Smith's Orchard	S26/0487	2717636	6012424	23/12/1983		-38.10													WCB – GW Recharge & Dating 1983
Smith's Orchard	S26/0487	2717636	6012424	29/03/1984		-34.10													WCB – GW Recharge & Dating 1983
Smith's Orchard	S26/0487	2717636	6012424	29/06/1984		-34.80													WCB – GW Recharge & Dating 1983
Tilson Creek Spring	S26/0395	2717581	6010704	12/04/1983	-5.75	-31.20	3.92	0.22								84	2		WCB – GW Recharge & Dating 1983
Tilson Creek Spring	S26/0395	2717581	6010704	03/05/2005			1.81	0.05	6.37	1431	917					84	2		Greater Wgtn – GW Dating 2005
Tilson Creek Spring	S26/0395	2717581	6010704	06/06/2008	-5.58	-31.70	1.88	0.05				0.54	-13	101.8	0.31	29/78	1.5	1	Greater Wgtn – GW Dating 2008
Tulloch	S26/0155	2723845	6017830	12/04/1983	-6.38	-39.10	4.65	0.22								90	1.5		WCB – GW Recharge & Dating 1983
Tulloch	S26/0155	2723845	6017830	03/05/2005			1.74	0.06	5.24	442	2263					90	1.5		Greater Wgtn – GW Dating 2005
Van der Put	S26/0043	2728492	6026138	03/05/2005	-5.49		1.92	0.04	5.94	272	595					70	1		Greater Wgtn – GW Dating 2005
Tilsons Spring		2717581	6010704	11/04/1983		31.20													WCB – GW Recharge & Dating 1983
Tilsons Spring		2717581	6010704	26/09/1983		-36.10													WCB – GW Recharge & Dating 1983
Tilsons Spring		2717581	6010704	23/12/1983		-38.40													WCB – GW Recharge & Dating 1983
Tilsons Spring		2717581	6010704	29/03/1984		-34.90													WCB – GW Recharge & Dating 1983
Tilsons Spring		2717581	6010704	29/06/1984		-34.10													WCB – GW Recharge & Dating 1983
Waingawa River @ SH2 - DS		2729616	6023571	11/04/1983		n/a													WCB – GW Recharge & Dating 1983
Waingawa River @ SH2 - DS		2729616	6023571	30/05/1983		-40.60													WCB – GW Recharge & Dating 1983

Name	Bore ID	Easting (NZMG)	Northing (NZMG)	Date sampled	δ18O ‰	δD ‰	Tritium 2005 scale	sigTR	SF6 (pptv)	CFC11 (pptv)	CFC12 (pptv)	DIC mmol/kg	δ13C ‰	pmC norm	±pmC	E% PM %	MRT[y] more likely	MRT[y] less likely	Source
Waingawa River @ SH2 - DS		2729616	6023571	30/05/1983		-40.60													WCB – GW Recharge & Dating 1983
Waingawa River @ SH2 - DS		2729616	6023571	29/06/1983		-40.00													WCB – GW Recharge & Dating 1983
Waingawa River @ SH2 - DS		2729616	6023571	29/07/1983		-40.00													WCB – GW Recharge & Dating 1983
Waingawa River @ SH2 - DS		2729616	6023571	25/08/1983		-41.50													WCB – GW Recharge & Dating 1983
Waingawa River @ SH2 - DS		2729616	6023571	26/09/1983		-39.20													WCB – GW Recharge & Dating 1983
Waingawa River @ SH2 - DS		2729616	6023571	27/10/1983		-38.60													WCB – GW Recharge & Dating 1983
Waingawa River @ SH2 - DS		2729616	6023571	24/11/1983		-38.80													WCB – GW Recharge & Dating 1983
Waingawa River @ SH2 - DS		2729616	6023571	23/12/1983		-38.30													WCB – GW Recharge & Dating 1983
Waingawa River @ SH2 - DS		2729616	6023571	26/01/1984		-34.50													WCB – GW Recharge & Dating 1983
Waingawa River @ SH2 - DS		2729616	6023571	28/02/1984		-36.80													WCB – GW Recharge & Dating 1983
Waingawa River @ SH2 - DS		2729616	6023571	29/03/1984		-36.90													WCB – GW Recharge & Dating 1983
Waingawa River @ SH2 - DS		2729616	6023571	30/04/1984		-39.00													WCB – GW Recharge & Dating 1983
Waingawa River @ SH2 - DS		2729616	6023571	01/06/1984		-40.50													WCB – GW Recharge & Dating 1983
Waingawa River @ SH2 - DS		2729616	6023571	29/06/1984		-33.70													WCB – GW Recharge & Dating 1983
Waingawa Spring	S26/0244	2727780	6023410	02/06/1983	-6.11	-36.10	4.21	0.2								70	1		WCB – GW Recharge & Dating 1983
Waingawa Spring	S26/0244	2727780	6023410	03/05/2005			1.91	0.05	6.18	3121	772					70	1		Greater Wgtn – GW Dating 2005
Waiohine River @ SH2 - DS		2719663	6013425	26/09/1983		-36.40													WCB – GW Recharge & Dating 1983
Waiohine River @ SH2 - DS		2719663	6013425	23/12/1983		-37.40													WCB – GW Recharge & Dating 1983
Waiohine River @ SH2 - DS		2719663	6013425	29/03/1984		-34.80													WCB – GW Recharge & Dating 1983
Waiohine River @ SH2 - DS		2719663	6013425	29/06/1984		-31.30													WCB – GW Recharge & Dating 1983
Masterton rainfall - Wilmshurst		2733290	6023165	27/10/1983		-36.60													WCB – GW Recharge & Dating 1983
Masterton rainfall - Wilmshurst		2733290	6023165	24/11/1983		-41.90													Cumulative between dates
Masterton rainfall - Wilmshurst		2733290	6023165	23/12/1983		-44.90													Cumulative between dates
Masterton rainfall - Wilmshurst		2733290	6023165	26/01/1984		-50.00													Cumulative between dates
Masterton rainfall - Wilmshurst		2733290	6023165	28/02/1984		-49.80													Cumulative between dates
Masterton rainfall - Wilmshurst		2733290	6023165	29/03/1984		-41.10													Cumulative between dates
Masterton rainfall - Wilmshurst		2733290	6023165	30/04/1984		-51.40													Cumulative between dates
Masterton rainfall - Wilmshurst		2733290	6023165	01/06/1984		-66.90													Cumulative between dates
Masterton rainfall - Wilmshurst		2733290	6023165	29/06/1984		-57.70													Cumulative between dates

Appendix 3:

Geophysics report (ScanTec)

<u>*Geophysical Survey Report*</u>

Seismic Reflection Survey
Line 1
Wairarapa 2008

Project:	**WR311- Part A**
Client:	**Greater Wellington Regional Council**
Location:	**Wairarapa Valley – Line 1**
Date:	**February 20th 2009**
Author:	**Matt Watson**

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CONTENTS

1.0 Scope of geophysical survey

A high resolution seismic reflection survey was carried out in the Wairarapa Valley for Greater Wellington Regional Council by ScanTec Ltd, between June-July and August 2008. The objective was to investigate near surface geological structure to assist with the geological and hydrogeological modeling of the region.

This report covers seismic reflection work on Line 1, which runs across the middle of the Parkvale Basin, to the South-East of Carterton.

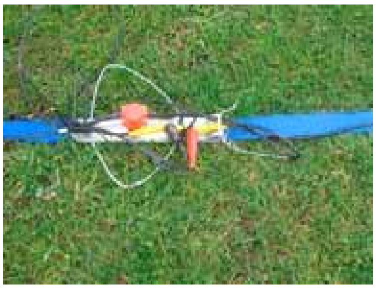
2.0 Geophysical Survey methodology

2.1 Seismic reflection data acquisition

Seismic measurements were recorded using a combination of Geometrics Geode 24-channel seismograph, and SR Research 24-bit 16-channel seismograph, connected to a field laptop. Geophone frequencies used were 14Hz on stage 1 of the survey and dual frequency (14Hz and 100Hz) on stage 2 of the survey.

It was initially intended that the geophones would be deployed as a landstreamer, which uses 24 geophones mounted on a heavy steel coupling blocks and towed between readings (Figure 1). The use of the landstreamer signficantly increases productivity compared with conventional geophone deployment. However, the wind strengths during the survey were typically too high (greater than 20kmph), with only about 10% of the survey days being suitable for land streamer deployment. Therefore, geophones had to be manually deployed using standard ground spike which is much slower. Coverage rates were therefore lower than originally anticipated. Along some of the road sections where loose gravel was placed beside the road, geophone coupling was often poor due to the presence of loose fill and roading aggregate. Certain sections could not be covered in June/July due to standing surface water or very wet paddocks.

After initial seismic energy tests, a heavy sledge hammer source with digital trigger link was selected as the seismic source. Due to the very favourable near-surface conditions and saturated ground, the hammer source provided excellent energy to over 300ms two-way travel time.



Geophone on land streamer

Geometrics GEODE seismograph and computer control equipment in back of vehicle

Seismic Line 1, SE end.

Seismic shot (sledge hammer) in action. Typically 3 shots (stacked) at each location.

Geophone cable in road verge

Weather conditions for this survey were generally poor in all of three trips to record measurements. The average wind strength was very high which resulted in an increase of high frequency noise on the data. Other sources of noise included traffic (truck and tractor units working in nearby fields) and livestock in paddocks beside the road. It was possible to reduce some of the effect of wind noise using high cut frequency filtering.

Measurements were recorded using a standard seismic reflection common offset technique. Shots were deployed at 2m intervals, with typically 3 shots (stacked) recorded per station. Geophone spacing was 2m throughout the survey. Shot to 1st geophone offset was between 20 and 40metres. Geophones were either Geospace 14Hz or 100Hz standard p-wave geophones.

2.2 Data processing

Data were processed using REFLEX software and processing involved the following steps;

- **Static correction:** corrections for elevation and weathering between adjacent traces.
- **Stacking:** combining several records for which shot and geophone locations are the same, which cancels out random noise and reinforces the reflected signals (improves signal to noise ratio).
- **Muting** and trace editing, to eliminate unwanted measurements generally due to noise.
- **Amplitude adjustments** (scaling) were applied to correct for any amplitude decay. AGC (automatic gain control) was used, at about 15 times the dominant period of reflection events.
- **Predictive deconvolution:** reduce the effect of multiple reflections.
- **Bandpass frequency filtering** (butterworth). The frequency characteristics of the traces were assessed (using fourier transform) and appropriate high and low cut filters were designed for each line (or line segment) to eliminate unwanted signal (eg due to wind noise or ground roll).

Seismic Velocities

A basic layered seismic velocity model was assumed to provide an indication of depth for the seismic sections. This consisted of velocities of 1500m/s to approximately 150ms, then increasing to 2000m/s at TWTT greater than 150ms, and up to 3000m/s at the end of the time window. Revision of the velocity model is recommended if deeper geological information (eg drillholes) become available near the seismic lines.

2.0 Geophysical survey results and interpretation

A map (Figure 1) shows the location of the individual sections along seismic Line 1.

The seismic sections are presented as figures 2 to 5 in both wiggle trace and variable area display (colour intensity scale).

Figures 6 to 9 are annotated to provide some geological interpretation interpretation such as stratigraphy and faults, and processing or acquisition artefacts.

Start and end GPS coordinates for each part of the seismic line are provided in the Appendix.

4.0 Summary

A high resolution seismic reflection line has been recorded in the Wairapapa Valley, to the SE of Carterton. The line of approximately 4.5km total length, was acquired in 6 individual sections.

Reflections were obtained from alluvial layers and greywacke basement to depth of up to approximately 400m. Some annotation of the geological structure is included with the seismic sections in this report. Further interpretation is recommended in combination with existing geological information.

If you have any questions relating to this report please do not hesitate to contact Matt Watson on 021-376-644 or matt@scantec.co.nz.

Matt Watson *M.Sc.(hons)*
Geophysicist / Director
ScanTec Ltd
July 2008

APPENDIX

GPS latitude/longitude coordinates, seismic Line 1 (WGS-84)

	WGS Lat	WGS Long
Line 1 start	-41.039114	175.5247897
Line 1 end	-41.042953	175.5310547
Line 2 start	-41.045	175.5345493
Line 2 end	-41.046713	175.5374194
Line 3 start	-41.049769	175.542432
Line 3 end	-41.051667	175.5456666
Line 4 start	-41.053193	175.5482241
Line 4 end	-41.056284	175.553392
Line 5 start	-41.060186	175.558843
Line 5 end	-41.061144	175.560526
Line 6 start	-41.062435	175.563097
Line 6 end	-41.063469	175.565098

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GEOPHYSICAL SURVEY DATA

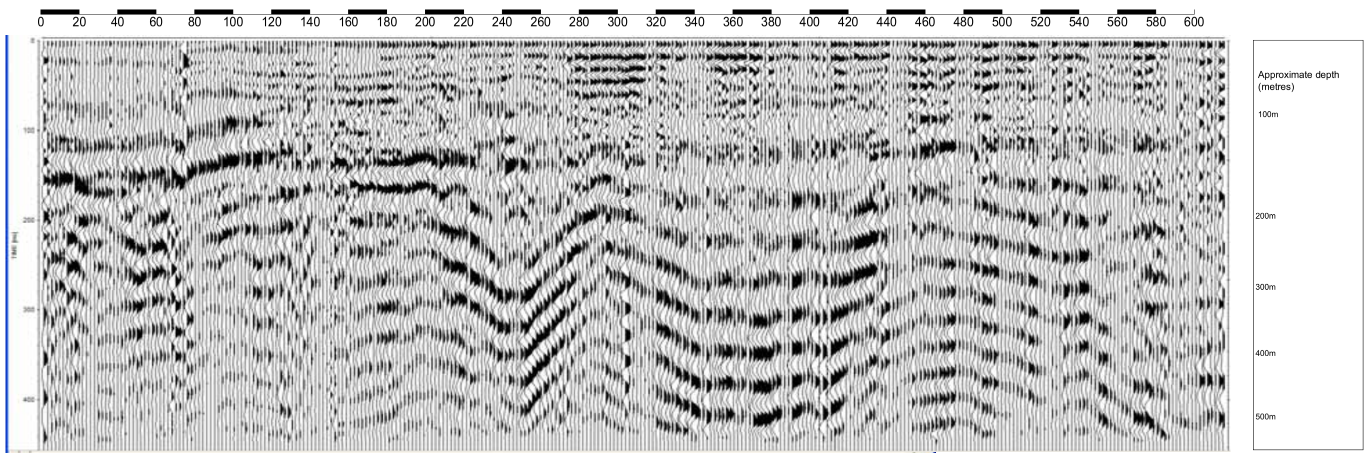
CLIENT: Wellington Regional Council
PROJECT: WR340 Seismic Reflection
DATE: Feb 2009
DATA ACQUISITION / PROCESSING: Matt Watson
EQUIPMENT USED: 14Hz / 100Hz geophones, 24-bit SR seismic system, sledge hammer source

CONTACT: matt@scantec.co.nz Ph021-376644

Figure 1

Seismic Reflection Survey
Line 1 - map

LINE 1
PART 1



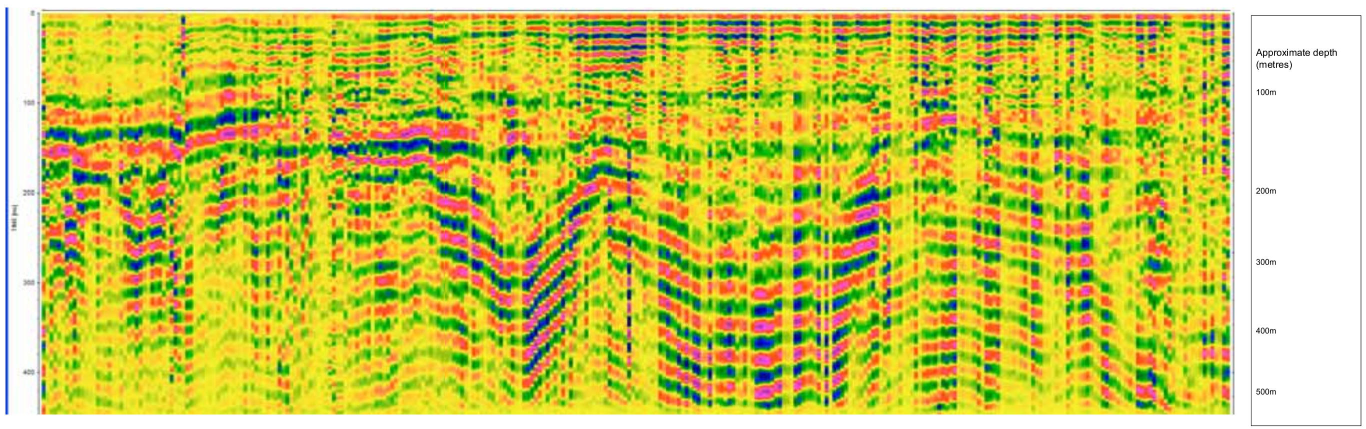


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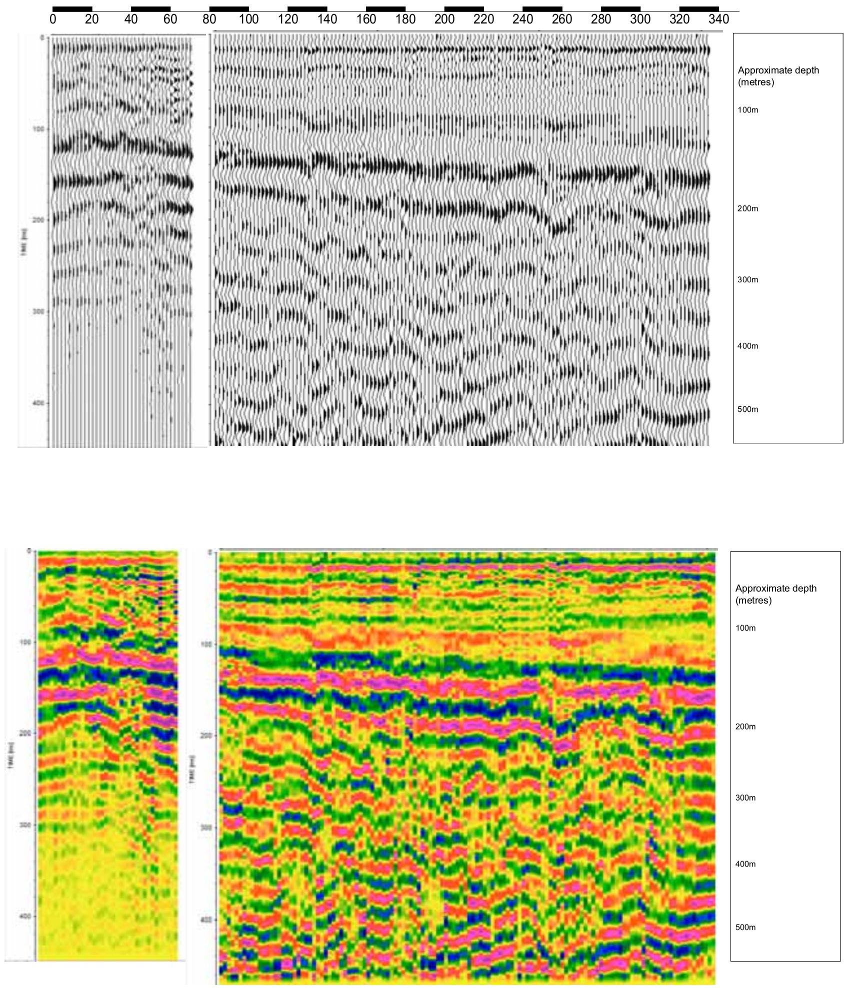
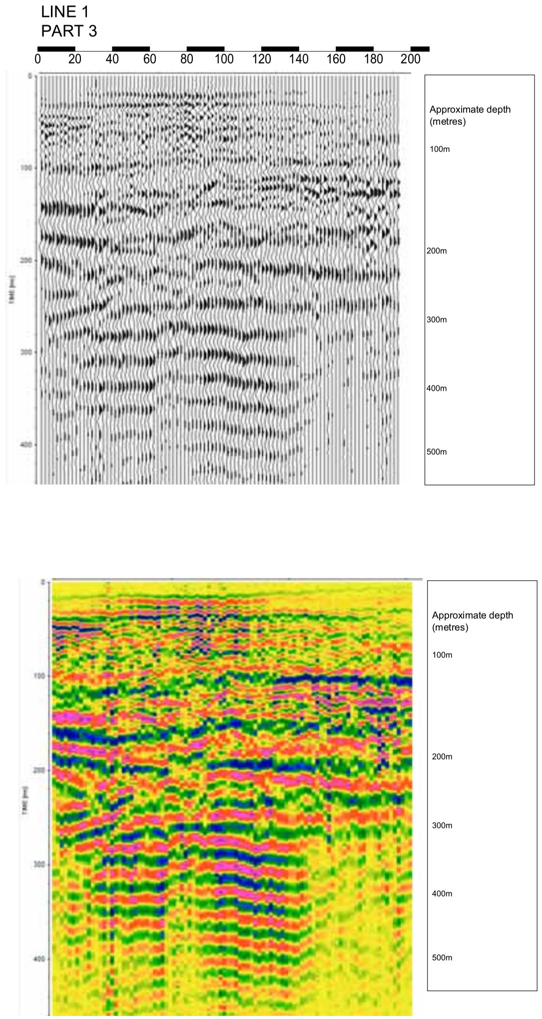
Figure 2

Seismic Reflection Survey
Line 1 - part 1
14Hz geophones





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GEOPHYSICAL SURVEY DATA

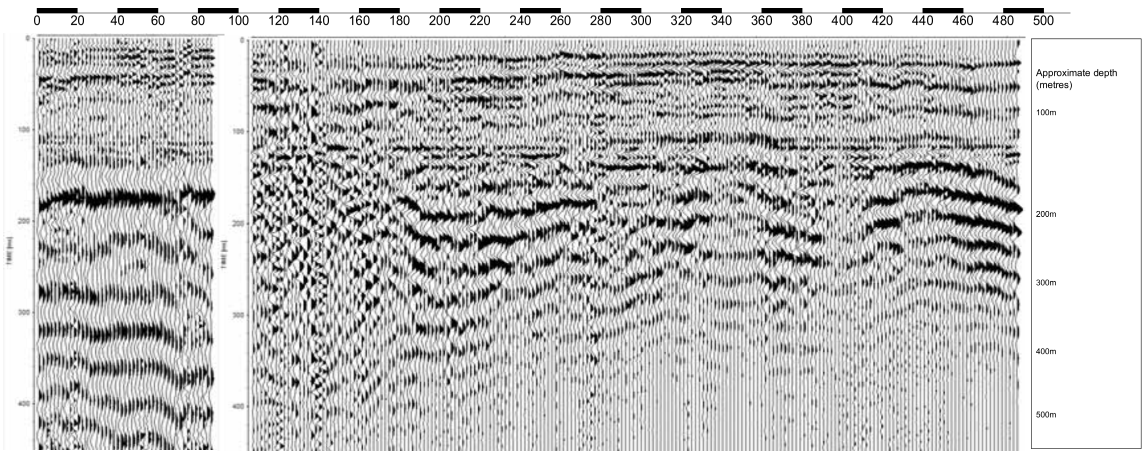
CLIENT: Wellington Regional Council
PROJECT: WR340 Seismic Reflection
DATE: Feb 2009
DATA ACQUISITION / PROCESSING: Matt Watson
EQUIPMENT USED: 14Hz / 100Hz geophones, 24-bit SR seismic system, sledge hammer source

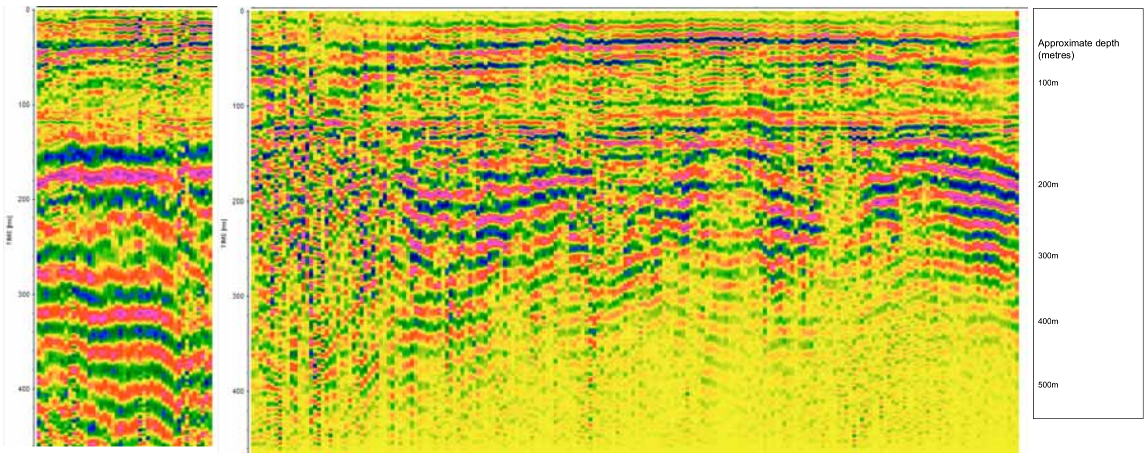
CONTACT: matt@scantec.co.nz Ph021-376644

Figure 3

Seismic Reflection Survey
Line 1 - part 2,3
14Hz geophones

LINE 1
PART 4





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GEOPHYSICAL SURVEY DATA

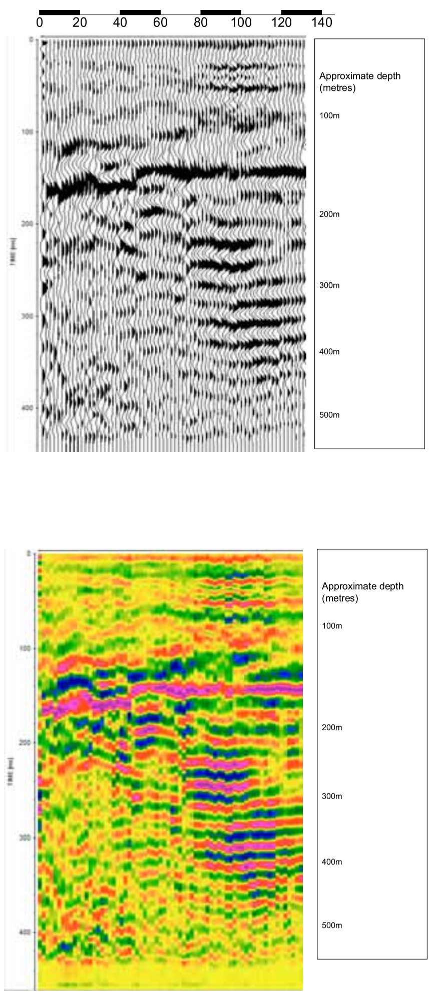
CLIENT: Wellington Regional Council
PROJECT: WR340 Seismic Reflection
DATE: Feb 2009
DATA ACQUISITION / PROCESSING: Matt Watson
EQUIPMENT USED: 14Hz / 100Hz geophones, 24-bit SR seismic system, sledge hammer source

CONTACT: matt@scantec.co.nz Ph021-376644

Figure 4

Seismic Reflection Survey
Line 1 - part 4
14Hz geophones

LINE 1
PART 5



LINE 1
PART 6

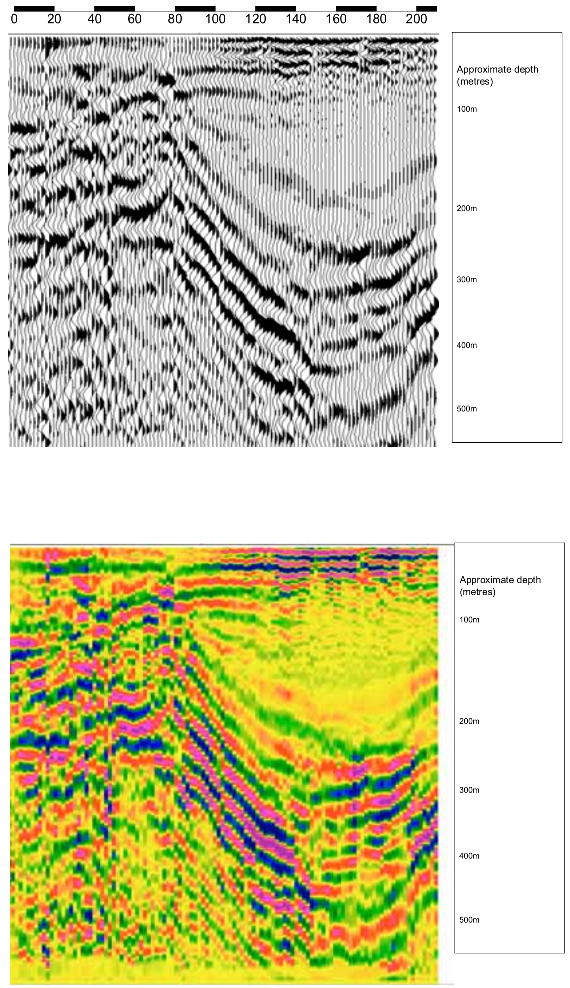


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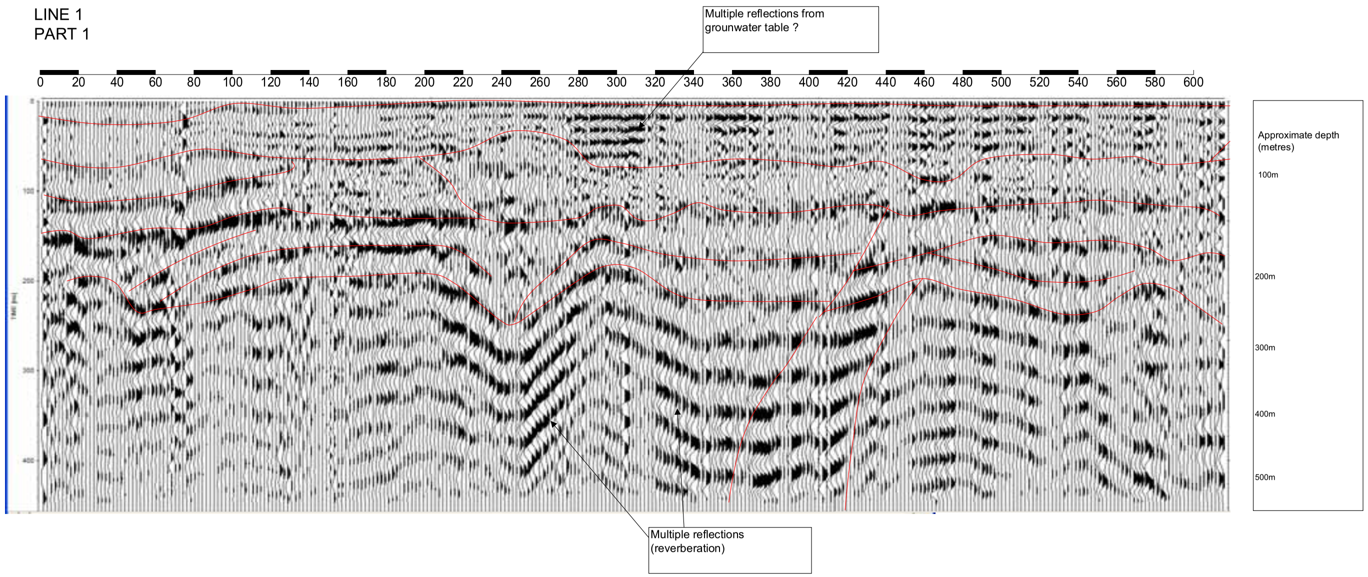
Figure 5

Seismic Reflection Survey
Line 1 - part 5,6
14Hz geophones



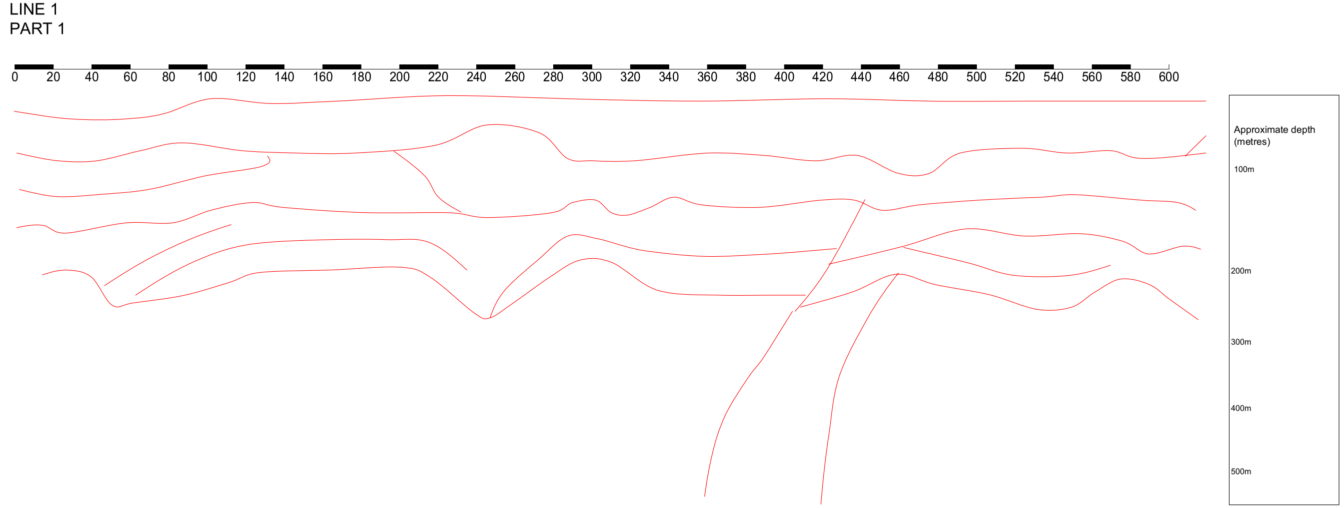


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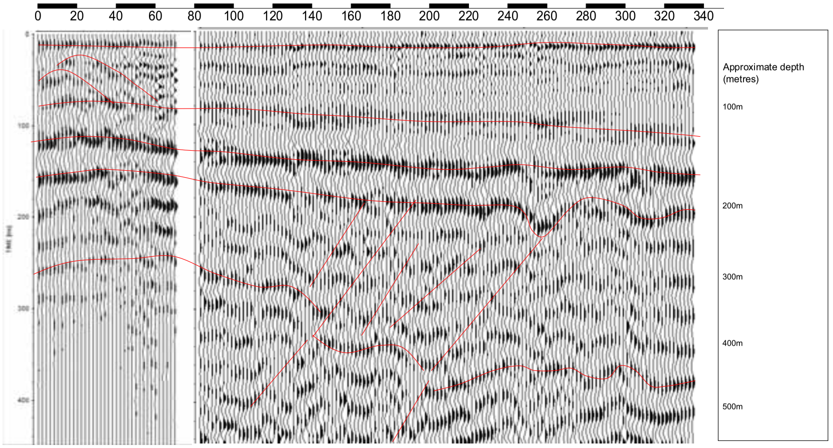
Figure 6

Seismic Reflection Survey
Line 1 - part 1
14Hz geophones

LINE 1
PART 2



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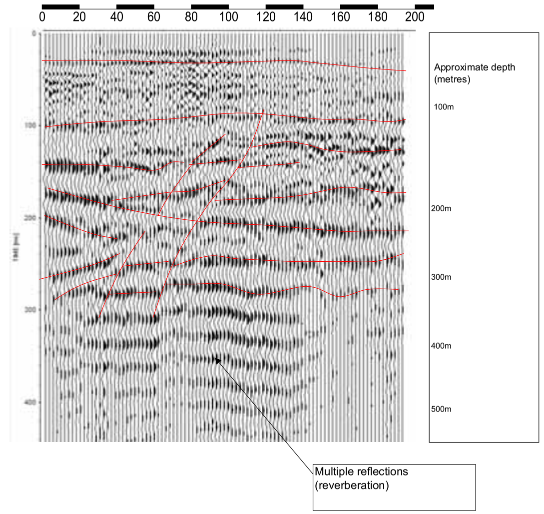

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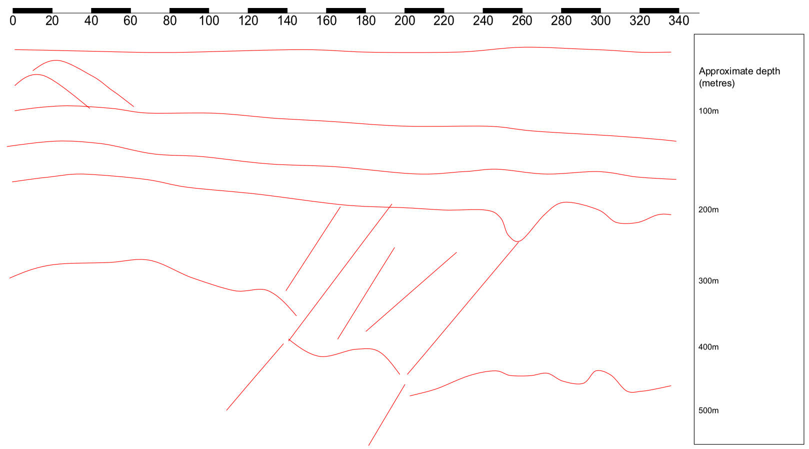

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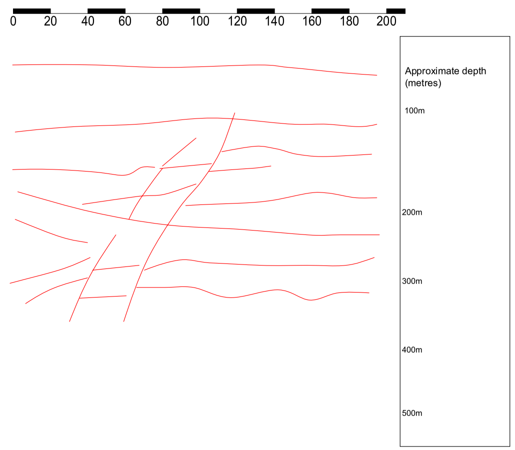

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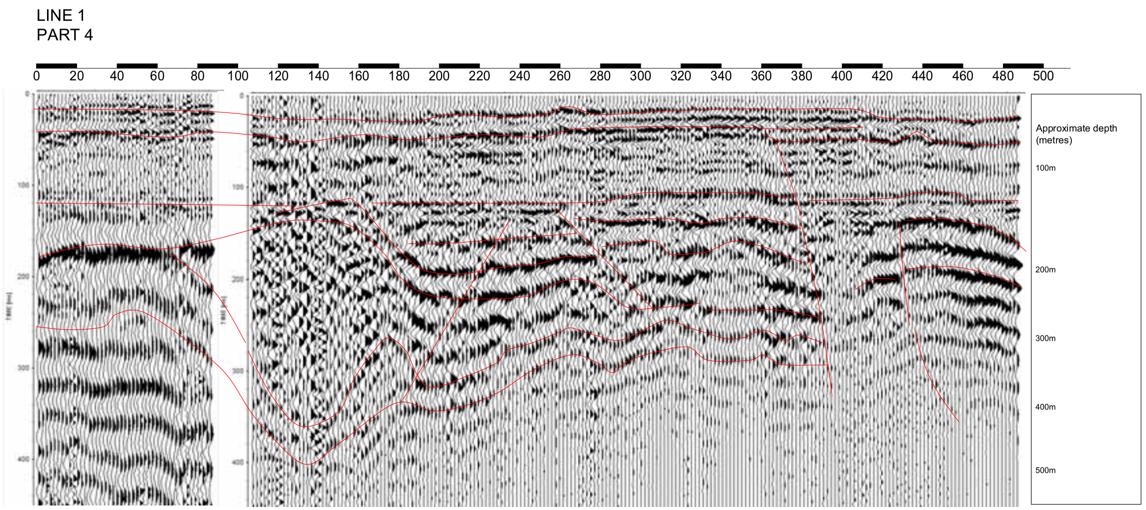
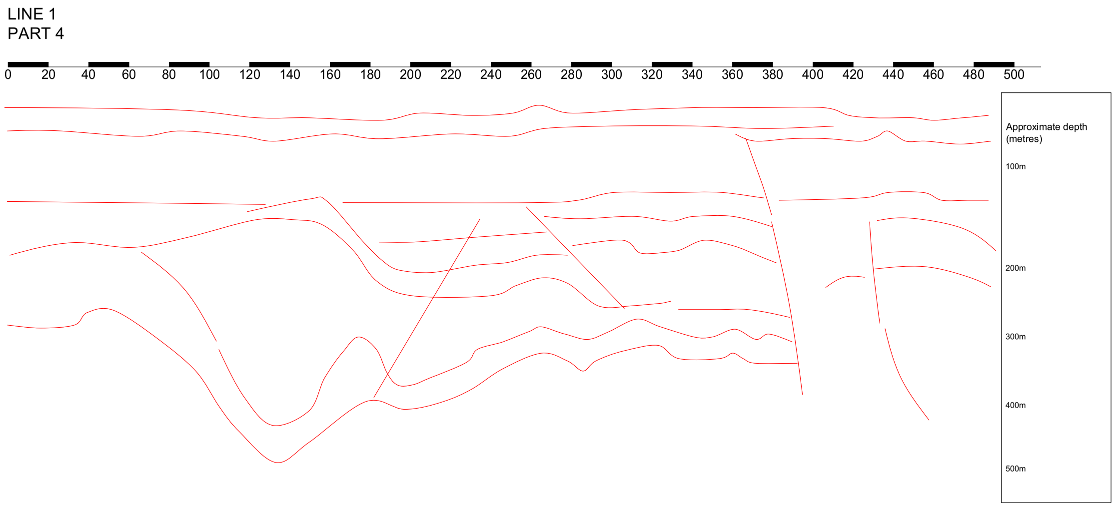
Figure 7

Seismic Reflection Survey
Line 1 - part 2,3
14Hz geophones





GEOPHYSICAL SURVEY DATA

CLIENT: Wellington Regional Council
PROJECT: WR340 Seismic Reflection
DATE: Feb 2009
DATA ACQUISITION / PROCESSING: Matt Watson
EQUIPMENT USED: 14Hz / 100Hz geophones, 24-bit SR seismic system, sledge hammer source

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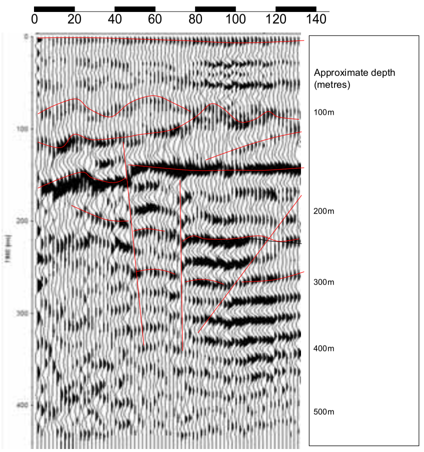
Figure 8

Seismic Reflection Survey
Line 1 - part 4
14Hz geophones

LINE 1
PART 5



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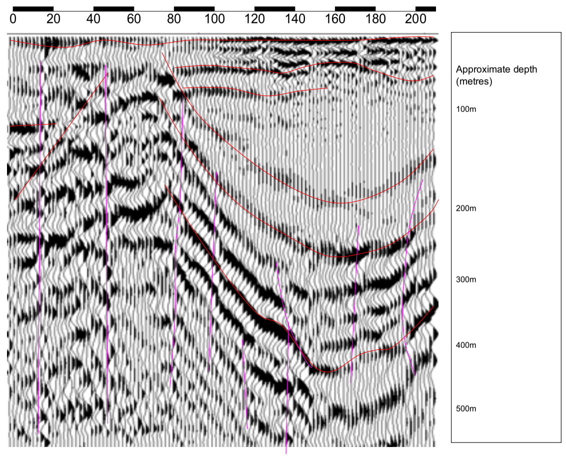

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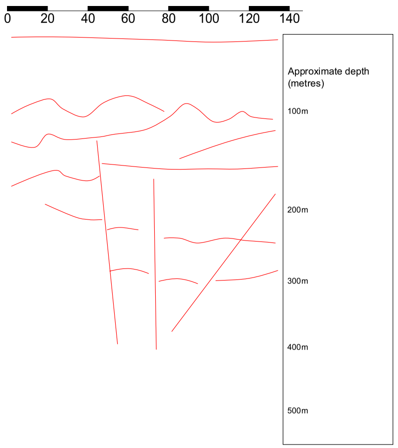

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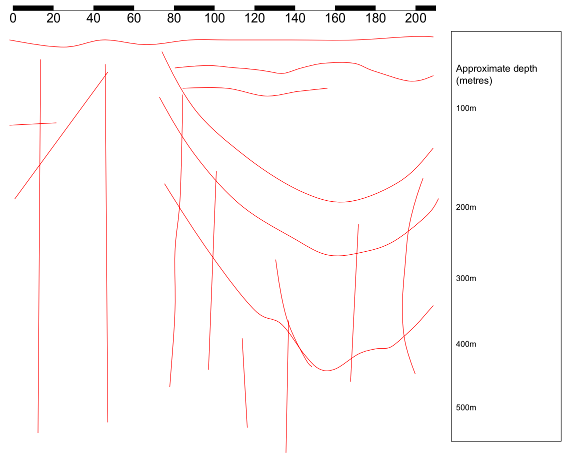

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Figure 9

Seismic Reflection Survey
Line 1 - part 5,6
14Hz geophones

Appendix 4:

Rainfall recharge modelling

Distributed recharge modelling on a 500 m^2 grid

A methodology was devised to model rainfall recharge so that the large spatial variability in climate and soil types across the Middle Valley catchment were adequately represented. The methodology is based on a soil moisture balance technique developed by Rushton et al. (2006) distributed across the catchment using a 500 m^2 grid.

A unique recharge record was therefore calculated for each grid cell based upon climate and soil data specific to each 500 m^2 cell. The large number of grid cells in the model domain required an enormous amount of data processing in the form of climate modelling, soil parameter assignment and soil moisture balance calculations. The process was automated with the use of computer scripts developed to provide the recharge data in the necessary import format for the FEFLOW groundwater flow model.

Soil moisture balance method of Rushton et al. (2006)

The Rushton model estimates recharge using a daily soil moisture balance based on a single soil store. Actual evapotranspiration is calculated in terms of the readily and total available water ('RAW' and 'TAW') – parameters which depend on soil properties and the effective depth of the roots. The model introduces a new concept – near surface soil storage – which allows some infiltration to be held near to the soil surface to enable continuing potential evapotranspiration on days following heavy rainfall even though the soil is dry at depth.

Base data required for soil moisture balance models are daily climatic data (rainfall and potential evapotranspiration), spatial distribution of soil type and related soil properties (field capacity and wilting point), and vegetation cover (crop rooting depth). The base data are unique to each 500 m^2 grid cell.

The soil moisture balance algorithm consists of a two-stage process: calculation of near surface storage, followed by calculation of the moisture balance in the subsurface soil profile. The near surface soil storage reservoir provides moisture to the soil profile after all near surface outputs have been accounted for. If there is no moisture deficit in the soil profile, recharge to groundwater occurs.

The Rushton model was adapted for this study to take into account runoff using a USDA Soil Conservation Service (SCS) runoff curve number model. The SCS runoff model is described by Rawls et al. (1992).

Soil moisture balance calculation procedure

The soil moisture balance calculation, following the method of Rushton et al. (2006), involved four steps:

1. Calculation of runoff using the USDA SCS runoff method.
2. Calculation of infiltration to the soil zone (In) and near surface soil storage for the end of the current day (SOILSTOR). Infiltration (In), as specified by the Rushton algorithms, is infiltration (rainfall-runoff) plus SOILSTOR from the previous day.
3. Estimation of actual evapotranspiration (AET) using potential evapotranspiration (PET) as derived by the Priestly-Taylor (1972) equation. A crop coefficient is not

applied since the crop is assumed to be pasture. Most pastures in New Zealand are regarded to behave like the reference crop for most of the year (Scotter and Heng 2003).

4. Calculation of soil moisture deficit and groundwater recharge. Recharge occurs only when the soil moisture deficit is negative (i.e. there is surplus water in the soil moisture reservoir). The soil moisture deficit for the first day of the model is assumed to be zero.

The steps outlined above partition soil moisture between near surface soil storage for the following day, AET, and the soil moisture deficit/reservoir respectively. In addition to rainfall and PET, the soil moisture balance model requires four different input parameters to calculate the daily soil moisture deficit. These parameters are described below.

- **SCS Curve Number:** A curve number estimated for each soil type is used to calculate maximum soil retention of runoff (this is the same method used for the HortResearch SPASMO model). Lower curve numbers result in higher soil retention thresholds, which induce less runoff. Pasture in good condition on free draining soil has a low curve number (40). Pasture in poor condition on a poorly drained soil has a high curve number (90). Additional values are given in Table 5.5.1 of Rawls et al. (1992). The SCS runoff calculation also has the capacity to incorporate slope and soil moisture (Williams 1991).

- **Total Available Water (TAW):** TAW is calculated from field capacity, wilting point and rooting depth data.

- **Readily Available Water (RAW):** RAW is related to TAW by a depletion factor, p. The depletion factor is the average fraction of TAW that can be depleted from the root zone before moisture stress (reduction in evapotranspiration). For New Zealand conditions p should be around 0.4 to 0.6, typically 0.5 for grass.

- **Fracstor:** This is the near-surface soil retention, and values are estimated. Typical values are 0 for a coarse sandy soil, 0.4 for a sandy loam, 0.75 for a clay loam (Rushton et al. 2006).

Climate modelling

Spatial interpolation of daily rainfall and potential evapotranspiration using a spline model (Tait and Woods 2007) into the distributed recharge grid was undertaken by NIWA using all available climate monitoring data from both NIWA and Greater Wellington rain gauge and climate sites.

Verification of the climate model

The NIWA climate model was verified using additional 2007/08 rainfall data collected from six relatively new Greater Wellington stations across the region. These data were not used in the NIWA model and therefore provide a check on the accuracy of the model.

The supplementary rainfall data were supplied from the six rainfall stations shown on Figure A4.1. Only one of these stations actually lies in the Wairarapa Valley (Parkvale), but the Westons and Mauriceville sites are located just a short distance north of the valley. Overall, the data from all six stations contribute to an assessment of the NIWA interpolation model.

Figure A4.2 provides a comparision in the form of a cumulative rainfall plot of measured daily rainfall and modelled rainfall at the three rainfall sites within or close to the Wairarapa Valley. A quantitative comparison of modelled and measured rainfall on a weekly basis is also presented in Figure A4.3. The plots show very low errors in the modelled data, particularly in respect to the Parkvale rainfall site and verify the accuracy of the NIWA interpolation methodology.

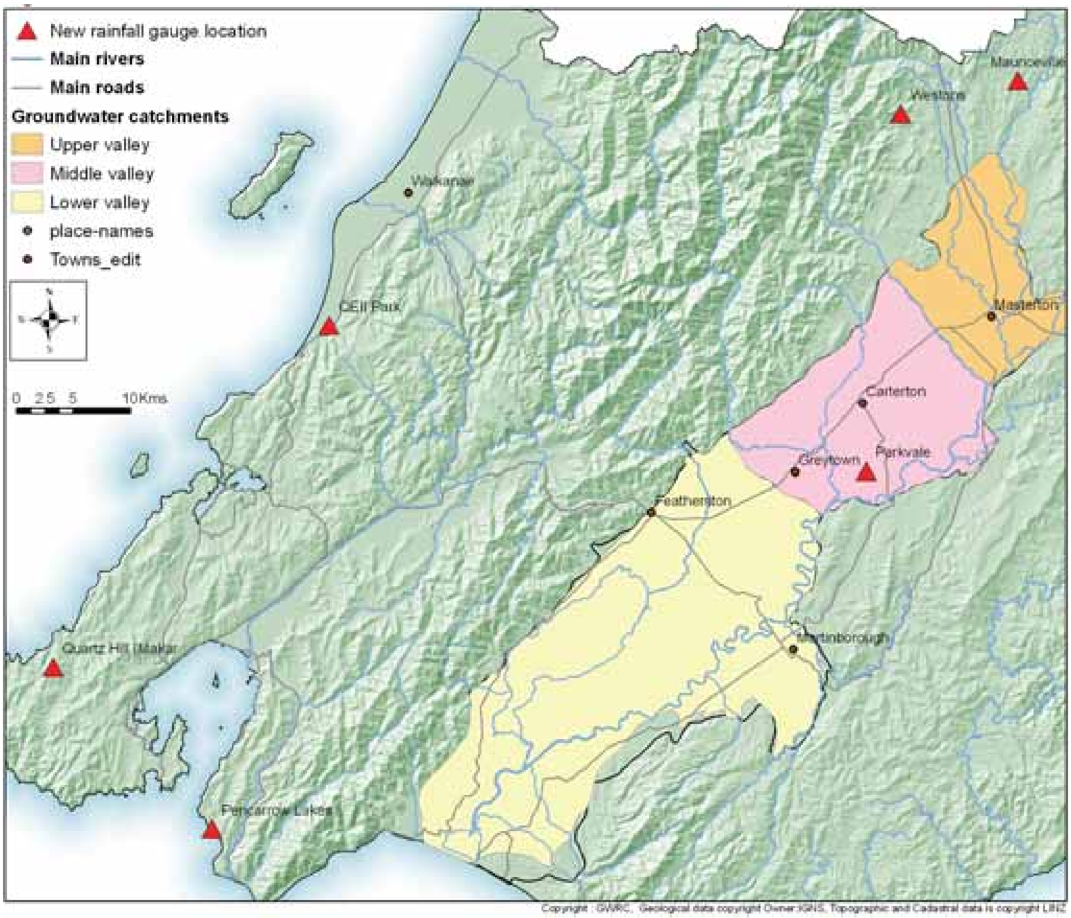


Figure A4.1: Location of “new” rainfall stations used to verify the NIWA model

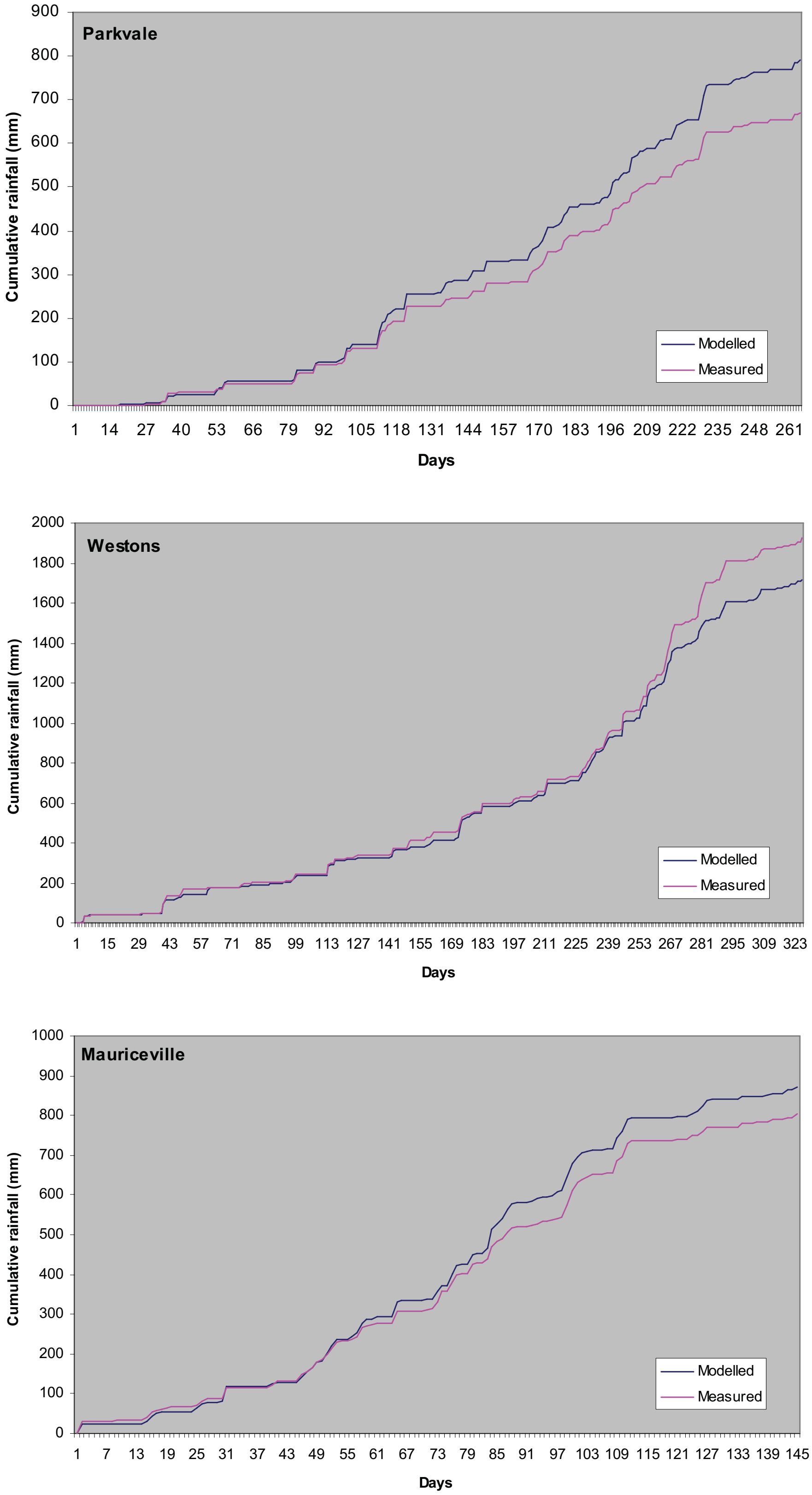


Figure A4.2: Cumulative measured and modelled daily rainfall graphs for three rainfall stations within or close to the Wairarapa Valley using available data (2007/08)

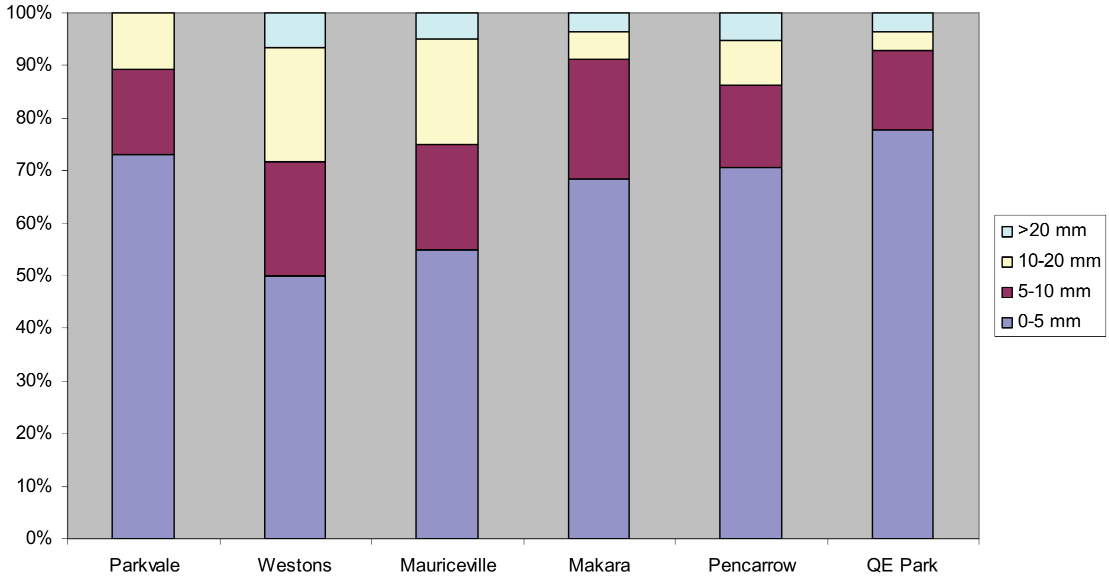


Figure A4.3: Weekly prediction errors for the NIWA 500 m² grid rainfall interpolation model for the Wellington region using supplementary data from six independent rainfall stations (excluded from the groundwater model)

Soil mapping and assignment of parameters

Soil moisture balance modelling requires knowledge of the spatial distribution of principal soil types and a knowledge of their physical properties in terms of water storage capacities. For this study, Landcare Research (T. Webb) was commissioned to evaluate the spatial distribution of soils within the project area based upon the New Zealand Soils Database. This work entailed the following process in order to quantify field capacity (FC), wilting point (WP), profile available water ('PAW', or 'TAW') and profile readily available water ('PRAW', or 'RAW'):

- Matching mapped soil series with the same or similar soil series within the national soils database.
- Determining the average FC and WP as percentages for these soil classes to 1 m depth.
- Multiplying the percentage FC and WP values by the estimated rooting depth of the soils, for soils with rooting depth less than 1 m (moderately deep soils were estimated to have an average rooting depth of 0.7 m, shallow soils 0.45 m, stony soils 0.35 m and very stony soils 0.2 m). This provided an estimate of FC and WP (in mm) for the profile.
- Subtracting WP from FC to obtain PAW.
- Determining PRAW by multiplying PAW by a ratio of PRAW/PAW found from the database for similar soils. In the case of shallow and stony soils, the ratio was modified according to expert opinion. As soils become shallower, the percentage of PRAW/PAW becomes larger.

The SCS number proved a more difficult parameter to estimate. The intent of the classification is to help partition rainfall or irrigation into through-flow or runoff. The SCS number may be considered to be derived from a combination of soil permeability and soil water storage in the moist condition (air capacity). The SCS number is not static but varies with antecedent moisture condition and with land use. Soils were rated according to tables in SCS (1967) for land under pasture in a moist antecedent state. The SCS number was increased or decreased according to relative permeability and air capacity.

During the groundwater model calibration process it became evident that initial SCS measurements were set too low by Landcare Research; this meant that too much water was being directed to soil moisture balance modelling. During the calibration process SCS numbers were increased while maintaining their ratios to each other.

Table A4.1 provides a summary of properties assigned to the dominant soil classes in the model area.

Table A4.1: Soil properties used in the Rushton soil moisture balance model for the Middle Valley catchment groundwater model

	Soil (symbol)	Soil Name	Soil Class	FC	WP	TAW	RAW	Drainage	SCS[1]	SCS[2]	Fracstor
1	o1c	Ruamahanga stony sand	Recent soils	65	25	40	30	Well	40	60	0.7
2	o75b/u1c/ o78a	Tauherenikau stony silt loam/ Ruamahanga stony sand/Kohinui stony loam	Yellow-brown shallow soils/ Recent soils	80	26	54	32	Well	60	80	0.7
3	o75b	Tauherenikau stony silt loam	Yellow-brown shallow soils	110	40	70	42	Well	65	85	0.7
4	o1b/o75/o76b/ o75b	Ruamahanga sand/Tauherenikau silt loam/Opaki brown stony loam/ Tauherenikau stony silt loam	Recent soils/Yellow-brown shallow soils	120	40	80	48	Imperfect-Well	65-68	88-89	0.7
5	o29/o13b/o13c	Pirinoa silt loam/ Wharekaka fine sandy loam/ Tawaha silt loam	Intergrades between yellow-grey earths and yellow-brown earths/yellow-grey earths	220	120	100	45	Imperfect	70-74	91	0.7
6	o1b/o78/o76c	Ruamahanga sand/ Kohinui loam/ Carterton shallow silt loam	Recent soils/Yellow-brown shallow soils	280	110	170	70	Well	65	85	0.7
7	o2/o1/o106	Ahikouka silt loam/ Greytown silt loam and sandy loam/ Otukura silt loam	Recent soils/Gley soils	330	120-140	190-210	80-90	Well-Poor	65-74	86	0.7
8	o13d	Kokotau silt loam	Yellow-grey earths	340	230	110	55	Poor	74	86-96	0.7-0.95
9	o35b/o41a/	Kaikouta silt loam/ Tuhitarata silt loam	Yellow-brown earths	400	240	160	72	Imperfect	70	91	0.7
10	o99/o107c	Moroa loam and stony loam/ Taratahi peat, loamy peat and peaty loam	Gley soils/Organic soils	450	250-260	190-200	50-100	Poor	74	91	0.7

1: Original SCS curve number developed by Webb (2008)

2: Changed SCS curve number as used in the final model

The soil properties data were matched to mapped NZLRI soil polygons and then overlain on the 500 m^2 grid. Properties were assigned to each grid cell for the dominant soil type occurring within it.

Distributed recharge modelling

A computer script was developed to write the large FEFLOW transient recharge power function files for each 500 m^2 recharge cell. The application uses the time series NIWA climate data (Rainfall and PET) residing in an external database, and the soil data in the form of a shapefile containing the recharge model input parameters (TAW, RAW, WP, FC, Fracstor, and SCS number) for each cell.

Run-off calculation methods

Rushton et al. (2006) proposed a method of calculating run-off coefficients based on soil moisture deficit (SMD) and rainfall intensity. This is an ideal way of simulating run-off but is heavily dependent upon the availability of good field data from gauged catchments exhibiting a wide spectrum of different soil types, land use and slope conditions. This data allows the development of rainfall-runoff coefficients for different soil types, slope categories and land uses.

In the case of the Wairarapa Valley, very few catchments have downstream gauges with which to measure rainfall run-off relationships. This means that run-off coefficients could not be defined. The SCS method (USDA Soil Conservation Service runoff curve number model described in Rawls et al. (1992) was, therefore, used as an alternative.

Limitations to estimated recharge reaching the groundwater environment

Soil moisture balance modelling assumes all soil drainage below the soil root zone reaches the water table instantaneously. For a well-drained soil overlying a permeable aquifer with a water table relatively close to the surface, this assumption is realistic. However, in some situations, a thick and low permeability unsaturated zone (i.e. in which a number of clay loess deposits occur on older terrace sequences), the migration of percolating water below the root zone may be severely attenuated and recharge reaches the water table as a slowly moving wetting front over considerable time. The vertical hydraulic conductivity of the unsaturated zone therefore limits the maximum rate at which recharge can reach the water table. In such areas, groundwater level hydrographs do not show the usual short-duration, or even annual recharge peaks, but rather tend to exhibit smoothed trends which are more reflective of long-term rainfall patterns (e.g. the stratigraphic profile for Fernhill in the Middle Valley catchment contains several loess layers). Standard soil moisture balance modelling cannot account for such a situation and tends to apply recharge instantaneously. It can be taken into account by increasing run-off over certain units, and by applying a daily cap of maximum recharge in certain hydrogeological domains. Fortunately, the areas which display such characteristics are small and the bulk of the modelled catchments are underlain by a relatively permeable, thin unsaturated zone.

Recharge model verification

The accuracy of the Rushton soil moisture balance model was verified by comparing calculated recharge with lysimeter data from Canterbury, New Zealand. Lysimeter data for three sites were provided courtesy of Environment Canterbury. Other soil moisture balance models – SOILMOD and the Soil Water Balance Model (described by White et al. 2003) were also tested for comparison. Soil properties were kept consistent for the three models (Table A4.2) and are the same values as those used by White et al. (2003). No surface runoff was incorporated in these simulations.

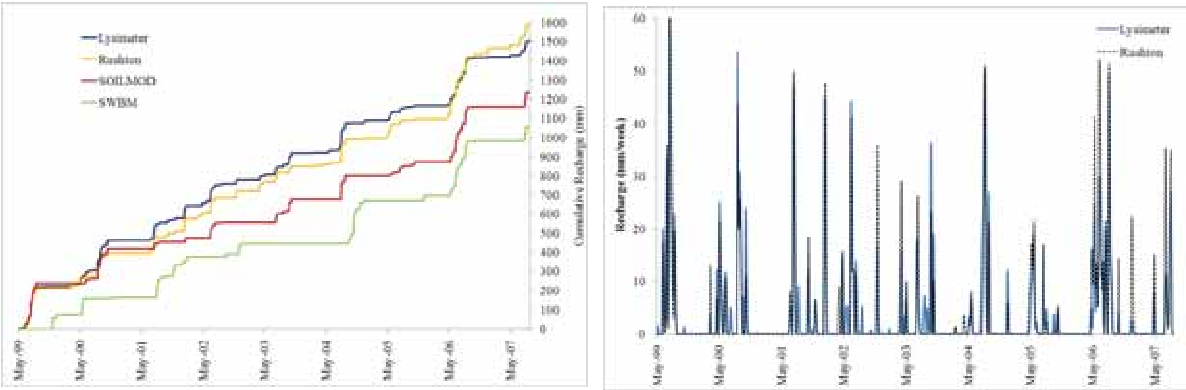
Table A4.2: Soil properties used for Canterbury recharge simulations

	Christchurch Airport	Lincoln University	Hororata
Soil Series	Waimakariri	Templeton	Hororata
Soil Type	V stony sandy loam	Silt loam on sand	Stony silt loam
Drainage	Excessively drained	Well drained	Well drained
Profile Depth (mm)	300	650	300-400
PAW (mm)	45	170	75
FC (mm)	115	253	189
Rooting Depth (mm)	650	650	400
FRACSTOR	0.4	0.45	0.6

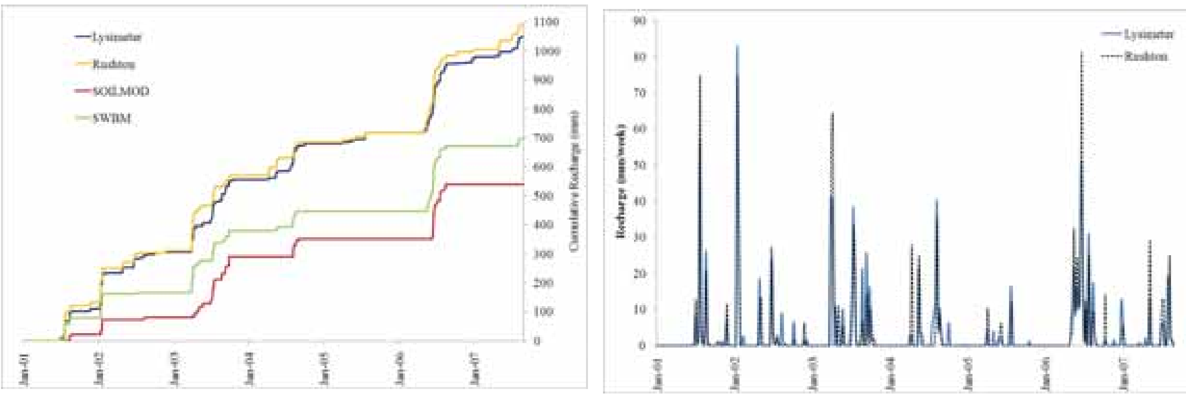
Results for the three soil moisture balance models are compared graphically with lysimeter data in Figure A4.4. Statistics to compare the three models are provided in Table A4.3. The Rushton model gives the most accurate estimation of weekly rainfall recharge of all the three models. Recharge at the Airport site was simulated most accurately, with an RMS error of 3.6 mm/wk. The estimate of recharge at the Hororata site was poorest, with an RMS error for the Rushton model of 4.2 mm/wk.

The period of record for this simulation is longer than reported in White et al. (2003), which only simulated from May 1999 to March 2001. Conditions were drier than normal from 2003 to 2005 and this led to an overall reduction in the percentage of rainfall recharge recorded at the three sites. SOILMOD and the Soil Water Balance Model did not respond well to drier conditions, and have greatly underestimated recharge. The simulation shows that the Rushton model is more sensitive to periods of low rainfall, and accurately simulates rainfall recharge during these periods.

Airport



Hororata



Lincoln

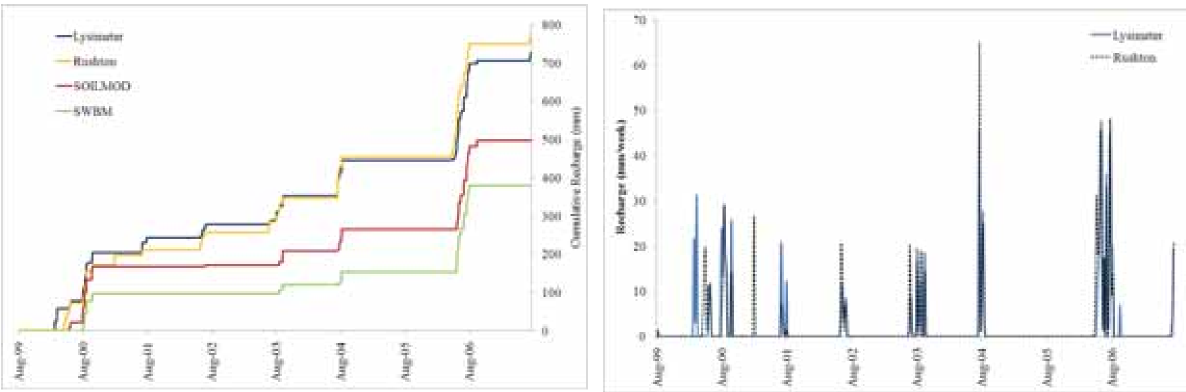


Figure A4.4: Hydrographs of cumulative recharge calculated by three soil moisture balance models (Rushton, SOILMOD and SWBN) compared to lysimeter data (left). Weekly recharge for the Rushton model compared with lysimeter recharge (right)

Table A4.3: Observed and modelled recharge statistics for the three Canterbury lysimeter sites. Lys - lysimeter, R - Rushton model, SM - SSOILMOD, WB - Soil Water Balance Model

	Airport				Hororata				Lincoln			
	Lys	R	SM	WB	Lys	R	SM	WB	Lys	R	SM	WB
Total recharge (mm)	1,502	1,591	1,234	1,057	1,047	1,089	540	697	726	779	498	379
Mean weekly recharge (mm)	3.5	3.7	2.8	2.4	3.0	3.1	1.6	2.0	1.7	1.9	1.2	0.9
% of total rainfall	29	30	24	20	22	23	12	15	14	15	9	7
Max recharge (mm/wk)	65	67	69	85	82	81	87	85	47	65	49	46
RMS error (mm/wk)		3.6	4.7	11.3		4.2	7.0	4.4		4.0	4.1	4.1
Max weekly diff (mm/wk)		22	25	85		30	36	34		31	16	12
Min weekly diff (mm/wk)		-13	-42	-65		-16	-68	-38		-31	-41	-46
Period of record	07-May-99 to 24-Aug-07				23-Aug-99 to 28-Aug-07				02-Jan-01 to 06-Aug-07			
Total rain (mm)	5,240				4,682				5,262			

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Appendix 5:

Groundwater abstraction modelling

Weekly groundwater abstraction data are required in order to both calibrate the groundwater model and to assess the current and future impacts of groundwater pumping on the environment. These data are not routinely collected and at best annual usage records since about 2002 are available for some bores.

In order to estimate seasonal groundwater abstraction for the entire transient model calibration period (1992–2008), a soil moisture deficit-based methodology was developed. The methodology involves the use of soil moisture balance modelling and water use records in the form of annual metering data and detailed weekly meter readings when available.

The methodology is described by the following steps:

Step 1: Estimation of historic annual irrigation scheduling

Estimation of historic irrigation season timing and duration was made using a 'soil moisture deficit trigger' (SMD) as an indicator of when pumping should start and stop each season. A pilot metering project carried during 2006/07 involving 28 water takes in the Wairarapa Valley, and a subsequent more widespread metering survey conducted during the 2007/08 irrigation season, were used to help identify a SMD trigger level.

Daily soil moisture conditions were firstly modelled using the soil moisture balance methodology used for recharge estimation (Appendix 4). Representative rainfall and PET data were obtained for a location in the central part of the model area near the confluence of the Waiohine River and Mangatarere Stream. The soil moisture balance model was then run using this climate data at daily time-steps from which the weekly average SMD was plotted for the 1992–2007 period. The plot (Figure A5.1) shows weekly SMD with a range of 0–25 mm/day.

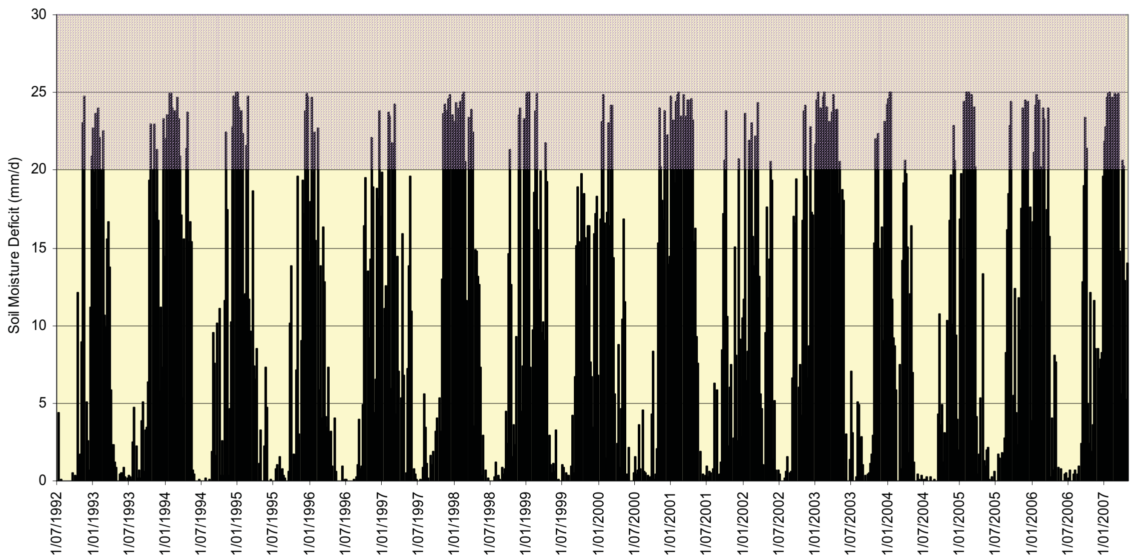

Figure A5.1: Calculated soil moisture deficit – central Waiohine Plains (1997-2007)

Metering data for the 2006/07 summer (for the Tawaha groundwater zone) show that irrigation started in early January 2007. At this time the SMD was about 20 mm/day and exceeded this value for about 13 weeks. The metered length of irrigation season was about 12 weeks.

The subsequent 2007/08 irrigation season meter readings within the Carterton-Greytown area showed that irrigation commenced in early November 2007 and continued through to early April 2008. The soil moisture model predicts that the SMD reached 20 mm/day during the week of 9 November 2007 and dropped below 20 mm by 4 April 2008.

The information presented in Figure A5.1 indicates that it is reasonable to assume that irrigation commenced when the SMD reaches about 20 mm. During the 2006/07 irrigation season metering data (in the Tawaha Groundwater Zone) show that irrigation started in early January 2007. The date when the SMD exceeded 20 mm was 28 November 2006 (over the previous 7 days). The calculated SMD was above 20 mm for 13 weeks; the metered length of irrigation season was 9–14 weeks (average = 12 weeks). The 2007/08 irrigation season irrigation also commenced when SMD reached about 20 mm during the week of 28 October 2007.

Further verification of the SMD trigger is provided by examining some of the monitoring bore hydrographs for deeper aquifers in the Parkvale sub-basin. These records are sensitive to regional pumping and provide a good indication of when irrigation commenced and ended.

These findings can be compared to another area of New Zealand – the Motueka River catchment in Tasman District – where Landcare Research has studied how farmers irrigate in relation to soil moisture conditions (Tim Davie, pers. comm.). This study found that irrigation generally commences when soil moisture is about 0.5 RAW (Readily Available Water). RAW is 75 mm for soil conditions at the Alloa reference site, so irrigation should start when SMD is less than 30 mm. Landcare Research has also looked at SMD 'triggers' for when irrigation generally occurs. 'Aggressive irrigators' usually start at about 15 mm SMD and use their full weekly allocation. Other irrigators generally start at about 25–30 mm. The RAW for their soils is about 70 mm.

Commencement of irrigation at about 20 mm SMD therefore appears to be consistent with experience in the Tasman District of New Zealand.

The Wairarapa Valley 2007/08 abstraction and calculated SMD data show that irrigation stopped in early April 2008 when SMD was about 80 mm, well before SMD levels recovered to 20 mm. This may have been in anticipation of winter rainfall, to avoid creating water-logged soils.

Step 2: Calculation of weekly pumping rates

Since it is not realistic to assume that irrigators use their full consented allocation, it is necessary to estimate the proportion of the annual consented take that is actually used. This amount is then spread over the calculated irrigation season length using the methodology discussed above.

To assess the relationship between the percentage of the annual take volume and the length of irrigation season, the following analysis was carried out:

- Calculate the percentage of a nominal irrigation season of 30 weeks for which SMD >20 mm/day (=30-70% for the period 2002–present)
- Plot this percentage against the metered annual abstraction (as a percent of consented annual take).

Figure A5.2 shows the relationship between the duration for which SMD exceeds 20 mm and annual usage (as a percentage of the consented annual take). By evaluating the number of weeks over which irrigation occurs for any particular season (i.e. the number of weeks SMD >20 mm), the relationship in Figure A5.2 can be used to estimate the fraction of the annual allocation used. This lies between 15 and 35%.

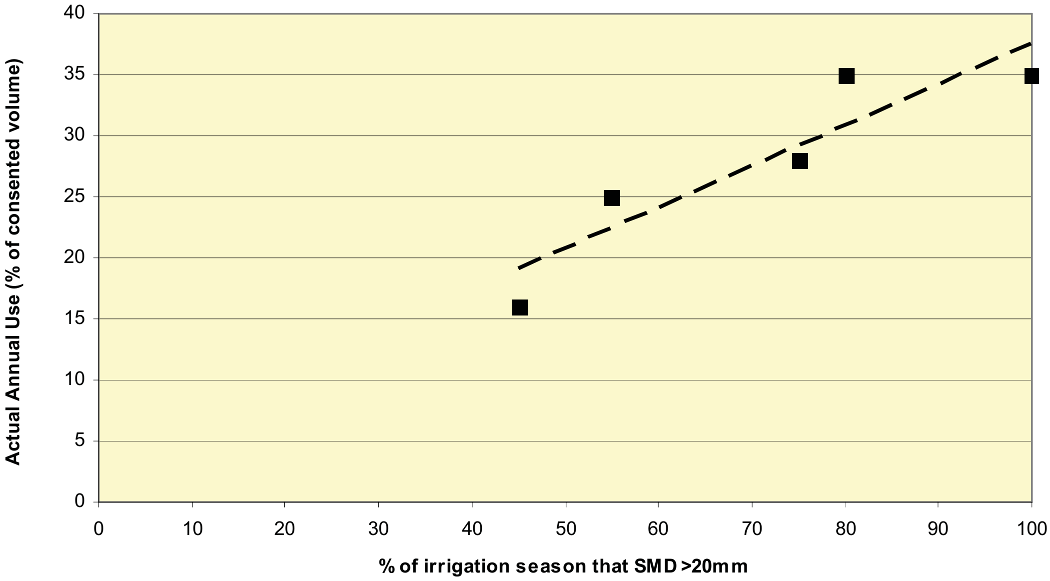

Figure A5.2: Percentage of time during an irrigation season that SMD exceeds 20 mm vs annual quantity of water used (as percentage of annual consented volume)

Procedure for creating a synthetic groundwater abstraction record

The transient numerical groundwater model requires the temporal simulation of groundwater abstractions over the period 1992–2007. Using the methodologies described above, the following procedure was used to create a synthetic abstraction record:

i) List all consented bores within the Middle Valley catchment (locations, screen depths, consent conditions) and identify when each take commenced by examining the consent files.

ii) Use the calculated SMD at the reference site (Figure A5.1) to identify the start and end dates for each irrigation season using a SMD trigger of 20 mm/day. (note: SMD may drop below 20 mm between start/end – this step only defines the irrigation window).

iii) Count how many weeks SMD is over 20 mm/day within the irrigation window.

iv) For each irrigation season, use Figure A5.2 to calculate the 'annual use fraction' from the number of weeks SMD >20 mm (step iii), then calculate the predicted annual abstraction volume for each bore.

v) Divide the predicted annual volume by the length of the irrigation window. This assumes that pumping is spread evenly over the irrigation season, rather than only during the weeks SMD >20 mm because it would prove too complex and time-consuming to split each season into numerous pumping periods.

Table A5.1 summarises the calculated irrigation season durations and average annual allocation fraction (percentage of consented abstraction used). The resulting modelled abstraction rates for all consented bores in the Middle Valley catchment are shown in Figure A5.3 for the period 1992 to 2007.

Table A5.1: Summary of irrigation abstraction modelling for the Middle Valley catchment

Irrigation season	No weeks irrigation SMD >20 mm	Season length (weeks)	Season length (Days)	Start date	Stop date	Annual allocation fraction used (%)
1992/93	10	15	105	03/11/1992	23/02/1993	25
1993/94	22	27	189	12/10/1993	19/04/1994	35
1994/95	13	16	112	29/11/1994	21/02/1995	25
1995/96	10	14	98	01/11/1995	07/02/1996	25
1996/97	10	21	147	09/10/1996	05/03/1997	25
1997/98	22	22	154	29/10/1997	01/04/1998	40
1998/99	10	16	112	11/11/1998	11/03/1999	25
1999/00	6	9	63	06/01/2000	09/03/2000	15
2000/01	22	25	175	26/10/2000	19/04/2001	40
2001/02	10	24	168	27/09/2001	15/03/2002	25
2002/03	20	25	175	25/10/2002	18/04/2003	35
2003/04	10	23	161	24/10/2003	02/04/2004	20
2004/05	13	18	126	12/11/2004	18/03/2005	25
2005/06	16	20	140	05/11/2005	18/03/2006	35
2006/07	15	15	105	26/12/2006	10/04/2007	30

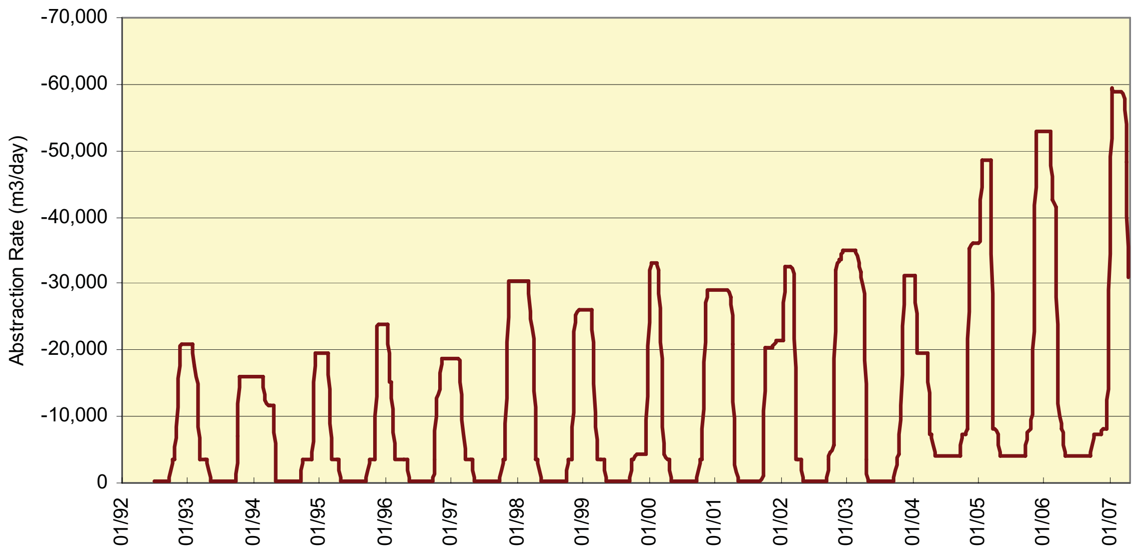

Figure A5.3: Calculated groundwater abstraction for the period 1992 to 2007 in the Middle Valley catchment

Appendix 6:

Assessment of groundwater chemistry between the Waingawa and Waiohine rivers, Wairarapa Valley

Multivariate statistical methods for assessment of groundwater chemistry between the Waingawa and Waiohine Rivers, Wairarapa Valley

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ABSTRACT

This investigation explored the use of multivariate statistical methods to provide insight into the groundwater chemistry in the Wairarapa Valley, covering the area between and near the Waingawa and Waiohine Rivers. Prior to this investigation, Greater Wellington Regional Council (GWRC) had defined seven preliminary hydrostratigraphic units within this study area. An independent comparison to the GWRC conceptual hydrostratigraphy was provided by hierarchical cluster analysis (HCA), which was used to re-categorise the monitoring wells based on major ion concentrations without any consideration of well location, depth, or assumed hydrostratigraphic unit. Two major hydrochemical categories and nine subcategories were defined by HCA, and these were generally consistent with the GWRC conceptual hydrostratigraphy. However, HCA revealed some cases where a well's hydrochemistry was inconsistent with the expectation for its assumed hydrostratigraphic unit. Thus discriminant analysis (DA) was used to predict the likelihood that each well taps into each GWRC hydrostratigraphic unit, on the basis of major ion chemistry and well depth. The results of DA were also generally consistent with the GWRC conceptual hydrostratigraphy, with the DA prediction matching the assumed hydrostratigraphic unit for 75% of the monitoring wells (n = 99). Most of the wells for which the DA prediction did not agree with the GWRC unit assignment were clustered in three parts of the study area: 1) near the confluence of Managatere and Waiohine Rivers, where DA suggested that older sediments are closer to the surface than the GWRC conceptualisation implies; 2) along a line roughly parallel to the axis of the Tararua Ranges, where DA suggested that fan gravels are thinner than the GWRC conceptualisation implies, or absent altogether; and 3) for shallow sites in the Parkvale sub-basin, where DA performed poorly where hydrochemistry is controlled more by local land use than by regional hydrostragraphy. Overall, this investigation has shown that multivariate statistical methods can be valuable for the development and validation of a conceptual hydrogeological model.

KEYWORDS

Groundwater chemistry, groundwater quality, hierarchical cluster analysis, discriminant analysis, multivariate statistics, Wairarapa, Wellington

1. INTRODUCTION

Greater Wellington Regional Council (GWRC) is developing a transient groundwater flow model for the section of the Wairarapa Valley south of the Waingawa River and extending to just south of the Waiohine River (this area is referred to below as the Case Study area). The transient groundwater flow model for the Case Study area is an extension of the steady-state groundwater model that GWRC has recently developed for the entire Wairarapa Valley (Begg et al., 2005; Morgenstern, 2005; Jones and Gyopari, 2006). At the time of writing of this report, the development of the transient model for the Case Study area was at an early stage, and the model layers defined were preliminary. To assist with the refinement of the model layers and the overall conceptual understanding of the local and regional hydrogeology, an evaluation and characterisation of groundwater chemistry is required.

The aim of this investigation is to explore the use of multivariate statistical methods that may provide insight into the groundwater chemistry within the Case Study area and assist with development and substantiation of the GWRC transient groundwater flow model. Multivariate statistical methods have been widely employed in hydrochemical investigations (Riley et al., 1990; Suk and Lee, 1999; Güler et al., 2002; Reghunath et al., 2002; Güler and Thyne, 2004; Lambrakis et al., 2004; Daughney and Reeves, 2005). Two multivariate methods are of particular interest in this investigation:

1. Hierarchical cluster analysis (HCA) can be used to define categories on the basis of hydrochemistry, and assign monitoring sites to these groups on the basis of groundwater quality. This approach was recently employed to categorise monitoring sites in the New Zealand National Groundwater Monitoring Programme (Daughney and Reeves, 2005). HCA is performed purely on the basis of groundwater chemistry, and does not explicitly account for any factors such as well location, well depth or aquifer lithology. Thus HCA can provide a simple summary of the variation in groundwater chemistry across the Case Study area, without any *a priori* assumptions about relationships to the model layers defined by GWRC.

2. Discriminant analysis (DA) can be used to predict into which of two or more pre-defined groups an observation is most likely to fall, based on its characteristics (Riley et al. 1990; Lambrakis et al. 2004). Thus DA can potentially be used to predict the likelihood that a particular well is within a particular GWRC model layer, purely on the basis of its groundwater chemistry. DA is similar to HCA, but whereas HCA completely ignores the location and depth of the well, DA considers the well's assumed model layer explicitly.

This investigation makes use of groundwater quality data supplied by GWRC. The data array provided by GWRC consists of analytical results for a total of 44 analytes in 554 water samples collected from 137 monitoring sites. Not all samples were analysed for every analyte, and 78 monitoring sites were sampled on only one occasion. To facilitate application of the multivariate statistical methods, the median value for each analyte was calculated at each monitoring site (see Daughney, 2005, 2007). These median values are compiled in Appendix 1, along with a description of the methods used for calculation and data screening. Because of the number of 'one-off' samples, this investigation does not consider temporal variation in groundwater chemistry.

2. CONCEPTUAL GROUNDWATER MODEL

This section provides a brief overview of the conceptual model that, at the time of writing, GWRC was developing for groundwater flow within the Case Study area. The conceptual groundwater flow model for the Case Study area is based on the steady-state model recently developed by GWRC (see Begg et al., 2005; Morgenstern, 2005; Jones and Gyopari, 2006).

2.1 HYDROSTRATIGRAPHIC UNITS

The preliminary GWRC conceptual groundwater model of the Case Study area includes seven hydrostratigraphic units, which for the remainder of this report are termed Units 1 to 7. All units are of Quaternary age, covering oxygen isotope stages Q1 to Q8 or older (see Begg et al., 2005). As part of the development of the conceptual model, GWRC has assigned each monitoring site within the Case Study area to a particular unit (Figure 1; Table 1). General descriptions for the various units and inferences from the preliminary GWRC conceptual groundwater model are as follows (D. McAlister, pers. comm. June 2007):

- **Unit 1** (Q1 Alluvium): Oxygen isotope stage Q1 alluvium associated with present day rivers. These are highly transmissive gravel aquifers which are inferred to have a strong interaction with surface water, for example via river recharge.

- **Unit 2** (Q2 Parkvale): Oxygen isotope stage Q2, Q3 and Q4 sediments within the Parkvale and Carterton sub-basins. These are medium- to low-yield unconfined or semi confined gravel aquifers that are presumed to be recharged primarily from rainfall.

- **Unit 3** (Q2, Q3, Q4 Ruamahanga): Oxygen isotope stage Q2, Q3, and Q4 sediments associated with the Ruamahanga River. These aquifers are assumed to be recharged primarily from rivers with possible minor recharge from rainfall.

- **Unit 4** (Q6 Parkvale): Oxygen isotope stage Q6 sediments within the Parkvale and Carterton sun-basins. These are medium-yield aquifers that are confined by overlying low permeability sediments. Recharge is inferred to be from downward percolation from overlying Unit 2 sediments.

- **Unit 5** (Q8 Parkvale): Oxygen isotope stage Q8 sediments within the Parkvale and Carterton sun-basins. These are medium-yield aquifers confined by overlying low permeability sediments, with recharge inferred to be from downward percolation from overlying Unit 4 sediments.

- **Unit 6** (Q2, Q3, Q4 Fan): Oxygen isotope stage Q2, Q3, and Q4 poorly sorted alluvial fan sediments associated with the western edge of the study area against the Tararua Ranges. These are low-yield aquifers that are inferred to be recharged principally from rainfall with possible lesser recharge from minor streams and/or the Managatere River.

- **Unit 7** (Older than Q8): Boreholes inferred to tap into sediments older than oxygen isotope stage Q8, assumed to be recharged from overlying aquifers.

2.2 HYDROCHEMICAL VARIATIONS BETWEEN HYDROSTRATIGRAPHIC UNITS

The hydrostratigraphic units listed above have been defined by GWRC on the basis of bore log geology and groundwater levels and contours, without any specific reference to hydrochemistry. This section examines the range of groundwater chemistry encountered in each unit, and applies statistical methods to identify the hydrochemical factors that differentiate the various units from one another. Thus, this assessment defines the “typical” groundwater chemistry for each hydrostratigraphic unit as a whole, based on data for all wells within each unit. An obvious caveat of this analysis is the assumption that all monitoring sites have been correctly assigned to the proper unit.

Box-whisker plots can be used to graphically display hydrochemical variations between the hydrostratigraphic units (Figure 2). On these plots, each rectangular “box” covers the variable’s interquartile range (i.e. from the 25th percentile to the 75th percentile) for all monitoring wells that are assumed to be screened within (or open to) each particular hydrostratigraphic unit. The centre horizontal lines within each box represent the medians (50th percentile) for each hydrostratigraphic unit. The “whiskers” extend from the box to the 5th and 95th percentiles in each unit, i.e. excluding any “outside points”, which are plotted separately. Outside points lie more than 1.5 times the interquartile range above or below the box, and may indicate analytical error or cases where a well has been assigned to the wrong hydrostratigraphic unit. Table 2 provides essentially the same information as the box-whisker plots, namely the values of the 5th, 25th, 50th, 75th and 95th percentiles for selected analytes for the various hydrostratigraphic units. From the box-whisker plots and tabulated percentiles, the following general hydrochemical characteristics can be inferred:

- **Unit 1** (Q1 Alluvium): Wells in Unit 1 are shallow compared to wells in most other units, and hydrochemistry is characterised by low conductivity and low concentrations of most major ions, which is consistent with the assumption that this unit is recharged primarily from recent river seepage.

- **Unit 2** (Q2 Parkvale): Wells in Unit 2 are also relatively shallow. In terms of hydrochemistry, wells in Unit 2 are similar to wells in Units 3, 4 and 5. Compared to Unit 1, the higher concentration of Na and Cl relative to Ca and HCO_3 is consistent with the assumption that wells in Unit 2 receive a greater proportion of recharge from rainfall instead of from river seepage.

- **Unit 3** (Q2, Q3, Q4 Ruamahanga): Wells in Unit 3 are also relatively shallow. Wells in Unit 3 have similar hydrochemistry to wells in Units 2, 4 and 5, although Unit 3 wells tend to have higher concentrations of Ca and HCO_3.

- **Unit 4** (Q6 Parkvale): Wells in Unit 4 are of intermediate depth compared to wells in other units in the Case Study area. Wells in Unit 4 have similar hydrochemistry to wells in Units 2, 3 and 5. This is consistent with the assumption that Unit 4 is recharged via seepage from Unit 2, and in turn recharges Unit 5 by the same process.

- **Unit 5** (Q8 Parkvale): Wells in Unit 5 are quite deep compared to wells in other units in the Case Study area. In terms of hydrochemistry, this unit is similar to Units 2, 3 and 4 for most major ions, but Unit 5 tends to have lower SO_4 and NO_3 and higher NH_4 and Mn, which indicates that its groundwater is more reduced (i.e. oxygen-poor). It is quite common for groundwater to become increasingly reduced with time and distance along a flow path, which is consistent with the inference that Unit 5 is recharged from Unit 4.

- **Unit 6** (Q2, Q3, Q4 Fan): Wells in Unit 6 are shallow compared to wells in most other units. Wells in Unit 6 tend to have Na-to-Ca and Cl-to-HCO_3 ratios that suggest rainfall recharge (salts are accumulated by infiltrating rainwater as it passes through the soil zone). Wells in Unit 6 also tend to have relatively high concentrations of SO_4 and/or NO_3, which is also consistent with recharge primarily from rainfall and might also reflect the effects of local land use.

- **Unit 7** (Older than Q8): Wells in Unit 7 are among the deepest in the Case Study area. In terms of hydrochemistry, wells in Unit 7 tend to have relatively high conductivity and high concentrations of most major ions, which is consistent with the assumption that these groundwaters are recharged from overlying aquifers and are hence older and more chemically evolved. Most wells in Unit 7 have low SO_4 and NO_3 and elevated NH_4 and Mn, indicating reducing conditions.

The box-whisker plots and tabulated percentiles show that the variations in hydrochemistry between some units are quite subtle. Thus more rigorous statistical approaches are required to identify those hydrochemical differences that are significant at a particular confidence level. StatGraphics 5 software (Manguistics Inc., Maryland USA) was used to identify significant differences in groundwater chemistry between the hydrostratigraphic units on the basis of 1) the non-parametric Kruskal-Wallis test and 2) Multiple Range Tests based on Fisher's least significant difference (LSD) procedure (see also Daughney and Reeves, 2005). As summarised in Table 3, these tests reveal that many of the subtle variations in hydrochemistry between certain units are in fact statistically significant at the 95% confidence level. The information presented in Table 2 is also encapsulated in Figure 2: the box-whisker plots include “notches” that cover a distance above and below each median; if the two notches for any pair of medians *do not overlap*, then there is a statistically significant difference between the medians at the 95% confidence level. The statistical tests do not reveal any significant differences in Fe, PO_4, As, B, Br, F, SiO_2, Zn or Pb between any of the hydrostratigraphic units within the Case Study area (possibly because few samples have been analysed for these parameters and so the statistical tests have lower power), and so these analytes are not discussed further.

In summary, the GWRC conceptual model is generally consistent with the observed hydrochemistry within and between the various hydrostratigraphic units. Unit 1 hydrochemistry is generally consistent with river recharge, whereas the hydrochemistry for Units 2 and 6 is more consistent with a greater proportion of recharge from rainfall. Units 2, 4 and 5 have similar hydrochemistry, which is consistent with the hypothesis that Unit 2 recharges Unit 4 which in turn recharges Unit 5. The hydrochemical progression from Unit 4 to 5 is indicative of increasingly reducing (oxygen-poor) conditions, which would be expected along a groundwater flow path. Unit 7 contains the most reduced and chemically evolved groundwater in the Case Study area, which matches the assumption that it is recharged primarily from seepage from overlying units. Overall though, it is important to bear in mind that many of the hydrochemical variations between units are quite subtle, such that hydrochemistry might be rather weak as a tool for critiquing the GWRC conceptual groundwater model.

3. HIERARCHICAL CLUSTER ANALYSIS

HCA was conducted as described by Daughney and Reeves (2005), using log-transformed median values of conductivity and the concentrations of the seven major ions (Ca, Mn, Na, K, HCO_3, Cl and SO_4). These parameters were selected for HCA as the most likely to reflect differences in aquifer lithology. Parameters such as Mn, NO_3 and NH_4 were excluded from HCA because their concentrations are probably controlled more by redox potential than by aquifer lithology (this assumption will need to be tested later). Variations in pH across the study area are quite small, and thus pH was also excluded from HCA.

Results from HCA are presented in four ways. First, a "membership list" is used, in which each site is unequivocally assigned to one of several clusters (Table 1). Second, the cluster assignments can be displayed in map form (Figure 3). Third, results of HCA are presented in terms of cluster centroids, where a centroid for a particular cluster gives the average value of each variable considered in the HCA algorithm (Table 4). Third, HCA results are displayed graphically in the form of dendrograms (Figures 4 and 5). On a dendrogram, the terminus of each vertical line represents a single monitoring site. Sites or groups of sites are joined together by horizontal lines. The position of any horizontal line, relative to the Y axis, indicates how similar or dissimilar the sites or groups it joins actually are. Two sites that are joined together by a horizontal line that is low on the Y axis are very similar to each other (in terms of the variables considered in the HCA algorithm), whereas two sites or groups of sites that are joined by a horizontal line that is higher on the Y axis are less similar to one another.

3.1 NEAREST NEIGHBOUR LINKAGE RULE

First, HCA was conducted using the Nearest Neighbour linkage rule. This approach identifies sites that have unusual chemistry (these sites are termed "residuals") based on the analytes used in the clustering algorithm (Daughney and Reeves, 2005). Three sites with unusual hydrochemistry were identified (the three rightmost sites on the dendrogram, Figure 4):

- **S26/0793**: Na-Cl type water with conductivity ca. 5100 μS/cm
- **S26/0568**: Unusually low Cl relative to HCO_3
- **S26/0739**: Na-Cl type water with conductivity ca. 2250 μS/cm

3.2 WARD'S LINKAGE RULE

Second, HCA was conducted with Ward's linkage rule. Ward's method is typically the most appropriate for hydrochemical assessments (Güler et al., 2002), but it can be biased if sites with unusual chemistry are included. Thus the three sites with unusual hydrochemistry listed above were excluded. The remaining sites can be divided into two major hydrochemical categories at a separation distance of ca. 600 (Figure 5).

- **Category A** groundwaters (sites on the left side of the dendrogram) are relatively dilute with Ca and HCO_3 as the dominant cation and anion, respectively. This type of chemistry might be expected for young groundwaters recently recharged from rivers.
- **Category B** groundwaters (sites on the right side of the dendrogram) are more concentrated with Na and HCO_3 as the dominant cation and anion, respectively. This type of chemistry might indicate that the groundwaters are slightly older and/or that they receive a greater proportion of recharge from rain (salts are accumulated during passage through the soil zone).

At a lower separation threshold of ca. 200, Category A can be divided into two subcategories (A1 and A2), and Category B can be divided into seven subcategories (B1, B2 and B3 are hydrochemically similar to each other, B4, B5 and B6 are hydrochemically similar to each other, and B7 is more distinct). The centroids, i.e. the chemical composition of the "average" member of each category and sub-category, are displayed in Table 4.

3.3 RELATIONSHIPS TO HYDROSTRATIGRAPHY

The results of HCA appear to be broadly consistent with the GWRC conceptual model (compare Figures 1 and 3). Most of the hydrochemical categories defined by HCA seem to correspond to one of the GWRC hydrostratigraphic units. For example, subcategories A1, A2, B1, B2, B3, B5 and B7 are generally consistent with the hydrochemical expectation for Units 1, 6, 4, 3, 5, 2 and 7, respectively (Table 1). Subcategories B4 and B6 are distinguished by high concentrations of K and SO_4 (as well as high NO_3, although this analyte was not considered in the HCA), which might indicate that the hydrochemistry is controlled more by the impacts of local land use than by hydrostratigraphy. Specific details of the relationships between subcategories defined by HCA and the GWRC hydrostratigraphic units are as follows:

- **Subcategory A1:** Young (?) "river-like" groundwater found almost exclusively on the down-gradient side of the Waiohine River near and to the north of Greytown. Morgenstern (2005) determined Mean Residence Time (MRT) to be 1 or 2 years in this area with recharge predominantly from rivers. The chemistry also suggests that these sites are in a unit that is hydraulically connected to a river: the undersaturation with respect to calcite might also indicate that the groundwater at these sites is young (or that this mineral has been leached from the aquifer by recharging river water over a long period of time). This subcategory appears to correspond to the hydrochemical expectation for Unit 1.

- **Subcategory A2:** Most sites are shallow and found near the Tararua Ranges, on both sides of the Managatere River and on both sides of the Carterton Fault. Hydrochemistry is differentiated from subcategory A1 by a higher proportion of Na relative to Ca, which probably indicates recharge from rainfall as well as rivers (a conclusion also reached by Morgenstern, 2005). In agreement with this assessment, the few A2 sites south of the Waiohine River are farther from the river than any A1 sites in the vicinity. As another indicator of the importance of rainfall recharge, the A2 sites tend to have higher NO_3 than A1 sites, but redox is overall no different (i.e. A1 and A2 both have similarly low concentrations of Mn and NH_4). This HCA subcategory appears to correspond to the hydrochemical expectation for Unit 6.

- **Subcategory B1:** The hydrochemistry at sites in this subcategory is generally similar to subcategories B2 and B3 and in terms of proportions of major ions, but the B1 sites typically have slightly lower concentrations. Compared to B2 and B3 sites, the B1 sites also have relatively high Na-to-Ca concentration ratios. The B1 sites are found in both the Carterton and Parkvale sub-basins, and hence appear to correspond to the location, depth and hydrochemical expectation for Unit 4.

- **Subcategory B2:** The hydrochemistry at sites in this subcategory is generally similar to B1 in terms of proportions of major ions, but the B2 sites typically have slightly higher concentrations (similar to B3 sites). Several of the B2 sites are located near the Ruamahanga River, so this subcategory corresponds to the expectation for Unit 3.

- **Subcategory B3:** The hydrochemistry at sites in this subcategory is generally similar to sites in B1 and B2, but B3 sites tend to have higher concentrations of most major ions compared to B1 sites, and although B2 and B3 sites are hydrochemically similar, B3 sites have much lower concentrations of SO_4. This suggests that B3 groundwaters are slightly older, more chemically evolved equivalents of B1 or B2 groundwaters. Subcategory B3 seems to correspond to the expectation for Unit 5.

- **Subcategory B4:** The hydrochemistry at sites in this subcategory is generally similar to subcategories B5 and B6 and in terms of concentrations of major ions (which are in most cases lower than for subcategories B1, B2 and B3, except for SO_4, which is higher for subcategories B4, B5 and B6). B4 sites are distinguished by high K relative to Na, perhaps as a result of fertiliser leaching or ion exchange, but they are otherwise hydrochemically similar to B5 sites. The B4 sites are all shallow and found along a line that strikes northwest-southeast near the northeast limit of the Parkdale and Carterton sub-basins; the significance of this spatial distribution is unclear.

- **Subcategory B5**: The hydrochemistry at sites in this subcategory is generally similar to subcategories B4 and B6. Compared to B4 sites, the B5 sites have lower K and higher Na, and compared to B6 sites, the B5 sites have lower concentrations of most major ions. This subcategory includes the Carterton District Council well, for which Morgenstern (2005) determined MRT of 40 years and recharge from a mixture of river water and rain. The B5 sites are found relatively near the Tararua Ranges (but not as close as the A2 sites), and thus seem to correspond to the location and hydrochemical expectation of Unit 2.

- **Subcategory B6**: The hydrochemistry at these sites is similar to subcategories B4 and B5, but the B6 sites have the highest proportion of K relative to other cations, and the highest proportion of SO_4 relative to other anions. As for the B4 sites, the high K and SO_4 and the fact that all of the B6 wells are shallow could simply indicate a dominance of rainfall recharge in an area of relatively intense land use; it would not be unusual for the recharge water to accumulate these ions during passage through the soil zone.

- **Subcategory B7:** Moderate to deep wells almost exclusively found in the Parkvale sub-basin (i.e. just west of Tiffen Hill). These groundwaters are differentiated from others in this classification scheme by the highest conductivity and low SO_4, indicating that the groundwater is strongly anoxic and possibly old and/or stagnant. This subcategory seems to correspond with the hydrochemical expectation for Unit 7.

4. DISCRIMINANT ANALYSIS

DA was conducted using well depth, log-transformed conductivity, and log-transformed median values of the seven major ions (Ca, Mn, Na, K, HCO_3, Cl and SO_4). These parameters were selected for DA as the most likely to reflect differences in aquifer lithology, based on results obtained for HCA described above (Section 3). Parameters such as Mn, NO_3 and NH_4 were excluded from DA because their concentrations are expected to be controlled more by redox potential than by aquifer lithology.

Results from DA are presented in two ways. First, a "prediction list" is generated, for which the DA algorithm determines the hydrostratigraphic unit in which each site is most likely to be located (Table 1). In addition to the highest probability prediction, the DA algorithm also returns the second-highest probability hydrostratigraphic unit for each well. Second, hydrostratigraphic unit assignments predicted by DA can be displayed in map form (Figure 6). On such a map, it is instructive to highlight the sites for which the GWRC hydrostratigraphic unit assignment is not matched by the DA prediction. In this study, a distinction is made between Type 1 errors, where the highest probability DA prediction does not match the GWRC unit assignment but the second-highest probability DA prediction does, versus Type 2 errors, where neither the highest nor second-highest probability DA prediction matches the GWRC unit assignment.

The results of DA appear to be broadly consistent with the GWRC conceptual model (compare Figures 1 and 6). For the 99 monitoring sites that could be classified by DA (i.e. for which all of the required variables had been measured), 75 were assigned to the same hydrostratigraphic unit selected by GWRC. This represents an algorithm accuracy of ca. 75% For the wells for which the DA prediction and the GWRC unit assignment are *not* in agreement, either the DA prediction might be wrong, the GWRC unit assignment might be wrong, or both might be wrong. There are three parts of the Case Study area where a relatively high proportion of DA misclassifications occur:

- **Confluence of Managatere and Waiohine Rivers:** There are some sites in this vicinity that are assigned to Unit 1 by GWRC, but are predicted to be in older sediments by the DA algorithm. In other words, DA suggests that the older sediments are closer to the surface than the GWRC conceptual model implies.
- **Zone of transition between Units 6 and 2:** There is a line of sites roughly parallel to the valley axis that are assigned to Unit 6 by GWRC but to Unit 2 or 4 by DA. These sites are found close to the proposed margin of Unit 6 in the GWRC conceptual model. The GWRC conceptual model has Unit 6 overlying Unit 2, and thus the DA misclassifications in this area may simply indicate that Unit 6 is absent or thin, in other words that the edge of Unit 6 occurs closer to the Tararua Ranges than assumed in the conceptual model.
- **S26/0661, S26/0734 and S26/0709:** These three shallow sites are found close together in the Parkvale sub-basin. These sites are assigned to Unit 2 by GWRC but to Unit 6 by DA. These sites have elevated K, SO_4 and/or NO_3, and thus their hydrochemistry seems to be controlled more by land use than by hydrostratigraphy, which would probably cause the DA algorithm to perform poorly.

It is instructive to consider the site-specific DA misclassifications on a unit-by-unit basis. For these assessments, the hydrochemistry for each well that is misclassified by DA is compared to the expectation for the unit to which it is assigned by GWRC (Table 5).

UNIT 1

The DA algorithm correctly assigned 12 out of 14 sites to Unit 1 (86% accuracy). The following sites were assigned to Unit 1 by GWRC on the basis of hydrostratigraphy, but were misclassified by the DA algorithm:

- **S26/0395**: DA indicated the highest probability to be Unit 3 and the second highest probability to be Unit 1 (Error Type 1). The conductivity, alkalinity and Ca concentration exceed the 95th percentile expected for Unit 1. The nitrate concentration, although not considered by the DA algorithm, is also quite high (3.2 mg/L), which likely indicates a high degree of human impact relative to other Unit 1 sites. This site is a spring located amongst several other Unit 1 sites south of the Waiohine River, but it is further from the river than most other sites.
    - S26/0395 is probably in Unit 1. Its unusual hydrochemistry probably results from

human and/or agricultural impact, which is likely facilitated by the fact that this site is a spring and thus quite vulnerable to contamination.

- **S26/0662**: DA indicated the highest probability to be Unit 2 and the second highest probability to be Unit 6 (Error Type 2). This site has Na concentration above the 95th percentile and alkalinity, conductivity and concentrations of Ca and Cl above the 75th percentile expected for Unit 1. Ammonia concentration exceeds nitrate concentration and manganese concentration is elevated, which indicate that the groundwater is oxygen-poor at this site. Phosphate concentration is high. This site is located west of the Waiohine River, not far from several other sites classified into Unit 2.

  - Based on hydrochemistry S26/0662 is more likely to be in Unit 2 than in Unit 1. The fact that the water is oxygen-poor with high conductivity suggests that this site may tap the discharge area of a deeper aquifer, perhaps Unit 4.

UNIT 2
The DA algorithm correctly assigned 18 out of 28 sites to Unit 2 (64% accuracy, the lowest for any unit). The following sites were assigned to Unit 2 by GWRC on the basis of hydrostratigraphy, but were misclassified by the DA algorithm:

- **S26/0237**, **S26/0637**, **S26/0667**, **S26/0709** and **S26/0734**: For these five sites, DA indicated the highest probability to be Unit 6 and the second highest probability to be Unit 2 (Error Type 1). The hydrochemistry at these sites differs from the expectation in a variety of ways, but in general the conductivity, alkalinity and concentrations of Na, K, Mg and/or Cl are lower than expected for Unit 2, whereas the concentration of SO_4 is commonly higher than expected. Although nitrate is not considered by the DA algorithm, the nitrate concentration at these sites is quite high (2-7 mg/L) compared to other sites assigned to Unit 2. In terms of location, all five of these sites seem to be situated close to the boundary or transition between Units 2 and 6.

  - S26/0237, S26/0637, S26/0667, S26/0709 and S26/0734 could all be in Unit 6 instead of Unit 2. If these sites are in fact in Unit 2, then their hydrochemistry, particularly with respect to elevated concentrations of SO_4 and/or NO_3, seems to indicate land use impact and probably a predominance of rainfall recharge.

- **T26/0332**: DA indicated the highest probability to be Unit 6 and the second highest probability to be Unit 2 (Error Type 1). This well is marginally deeper than expected for Unit 2, although it is located quite far away from all other sites. The hydrochemistry at this site is not dramatically unusual compared to the expectation for Unit 2, but the concentration of Cl is slightly high.

  - T26/0332 is probably in Unit 2, but based on hydrochemistry, it is possible that it is in Unit 6 instead.

- **S26/0545** and **S26/0580**: For these two sites, DA indicated the highest probability to be Unit 4 and the second highest probability to be Unit 2 (Error Type 1). Both of these wells are quite deep, with S26/0545 and S26/0508 exceeding the 95th and 75th percentiles expected for Unit 2, respectively. Both sites also have relatively low SO_4 concentrations compared to other sites assigned to Unit 2. S26/0545 also has a relatively low Cl concentration, and S26/0580 has a relatively high alkalinity. These two sites are only about 1.5 km apart, nearby but on opposite sides of the confluence of the Waiohine and Managatere Rivers, where a few other Unit 4 and Unit 5 sites are found.

- Based on hydrochemistry, depth and location, S26/0545 and S26/0580 are probably in Unit 4 instead of Unit 2.

- **S26/0708**: DA indicated the highest probability to be Unit 3 and the second highest probability to be Unit 2 (Error Type 1). This well is shallow (3.4 m) and is located near several other sites of similar depth that are assigned to Unit 2. Compared to other sites in Unit 2, this well has relatively high alkalinity, conductivity and concentrations of K and Ca. These hydrochemical characteristics may indicate land use impact, or perhaps a very localised variation in aquifer properties.

  - S26/0708 is probably in Unit 2. Slight differences in hydrochemistry compared to other Unit 2 sites might indicate a land use effect or might suggest a localised variation in aquifer mineralogy.

- **S26/0661**: DA indicated the highest probability to be Unit 6 and the second highest probability to be Unit 3 (Error Type 2). Compared to other sites assigned to Unit 2, this site has a very high concentration of K, and relatively high concentrations of Ca and SO_4. Although nitrate is not considered by the DA algorithm, it is telling that this site has a very high nitrate concentration (29 mg/L). This site is located nearby other sites that are assigned to Units 2 and 6.

  - S26/0661 probably receives a very large proportion of its recharge from rainfall, as indicated by the high concentrations of K, SO_4 and nitrate, all of which could be accumulated by recharge water that passes through the soil zone. There is a roughly equal probability that this site is in Unit 2 or in Unit 6.

UNIT 3

The DA algorithm correctly assigned 6 out of 7 sites to Unit 3 (86% accuracy). The only site assigned to Unit 3 by GWRC on the basis of hydrostratigraphy that was not correctly classified by DA was:

- **S26/0781**: DA indicated the highest probability to be Unit 6 and the second highest probability to be Unit 2 (Error Type 2). This site has conductivity, alkalinity and concentrations of Na, Ca, Mg and Cl less than the 5^{th} percentile expected for Unit 3. Although not considered in the DA algorithm, nitrate concentration at this site is quite high (6.6 mg/L). This site is located east of Tiffen Hill, far from all other sites in Unit 6.

  - If S26/0781 is in fact in Unit 3, it is very likely to be in the recharge zone. Alternatively, the hydrochemistry would be consistent with assignment to Unit 2.

UNIT 4

The DA algorithm correctly assigned 16 out of 20 sites to Unit 4 (80% accuracy). The following sites were assigned to Unit 4 by GWRC on the basis of hydrostratigraphy, but were misclassified by the DA algorithm:

- **S26/0753**: DA indicated the highest probability to be Unit 5 and the second highest probability to be Unit 4 (Error Type 1). This site is deeper and has lower concentrations of K and SO_4 than anticipated for Unit 4.

- S26/0753 is probably in Unit 4, with anoxic hydrochemistry that suggests that it is within a deeper, more confined, more stagnant and/or older part of the unit.

- **S26/0155**: DA indicated the highest probability to be Unit 6 and the second highest probability to be Unit 2 (Error Type 2). This site has Na concentration and alkalinity less than the 5th percentile expected for Unit 4 and depth, conductivity and calcium and magnesium concentrations less than the 25th percentile expected for Unit 4. The nitrate concentration, though not used for the DA classification, is relatively high (6.5 mg/L).

    - S26/0155 is likely to be in Unit 6 instead of Unit 4.

- **S26/0624**: DA indicated the highest probability to be Unit 2 and the second highest probability to be Unit 6 (Error Type 2). Note that in the conceptual model, Unit 2 is thought to provide recharge to Unit 4 via downward percolation of groundwater. This site has depth less than the 5th percentile expected for Unit 4, and a lower Ca concentration and a higher SO_4 concentration than anticipated for Unit 4. The higher SO_4 concentration in particular indicates that the groundwater at this site is less reduced than expected for Unit 4. Although nitrate (0.8 mg/L) and iron (0.4 mg/L) are not considered in the DA classification, their concentrations are consistent with a moderate degree of oxygen depletion.

    - S26/0624 is probably near the boundary of Units 2 and 4, and might in fact be located within the former.

- **S26/0780**: Similarly to S26/0624, DA indicated the highest probability to be Unit 2 and the second highest probability to be Unit 6. This site has conductivity and concentrations of Ca and Mg less than the 5th percentile expected for Unit 4; depth, alkalinity and Na concentration are all less than the 25th percentile expected for Unit 4. As for S26/0624, the nitrate (0.4 mg/L) and iron (0.7 mg/L) concentrations at S26/0780 are consistent with a moderate degree of oxygen depletion.

    - S26/0780 is probably near the boundary of Units 2 and 4, and might in fact be located within the former.

UNIT 5

The DA algorithm correctly assigned 4 out of 5 sites to Unit 5 (80% accuracy). The only site assigned to Unit 5 by GWRC on the basis of hydrostratigraphy that was not correctly classified by DA was:

- **S26/0743**: DA indicated the highest probability to be Unit 7 and the second highest probability to be Unit 5 (Error Type 1). This site has conductivity, alkalinity and concentrations of Na, Ca, Mg and Cl that exceed the 95th percentiles expected for Unit 5. Several analytes, although not considered by the DA algorithm, clearly indicate that this groundwater is oxygen poor: ammonia exceeds nitrate, and Mn concentration is atypically high (2.29 mg/L).

    - S26/0743 is probably in Unit 7 instead of Unit 5.

UNIT 6

The DA algorithm correctly assigned 13 out of 18 sites to Unit 6 (72% accuracy). The following sites were assigned to Unit 6 by GWRC on the basis of hydrostratigraphy, but were misclassified by the DA algorithm:

- **S26/0467** and **S26/0550**: For these two sites, DA indicated the highest probability to be Unit 2 and the second highest probability to be Unit 6 (Error Type 1). At S26/0550, conductivity, alkalinity and concentrations of Na and Cl exceed the 95th percentiles expected for Unit 6, and concentrations of Ca and Mg exceed the 75th percentiles expected for Unit 6. In contrast, the hydrochemistry at S26/0467 is not dramatically different from the expectation for Unit 6, although the Na concentration is slightly elevated and the Mg concentration is slightly low. These two sites are only about 400 m apart and they are both shallow (ca. 5 m deep).

    - S26/0467 and S26/0550 might both be in Unit 6, although if this is true they likely have a higher proportion of rainfall recharge than other sites in Unit 6. Alternatively, these two sites may be in Unit 2, which would be consistent with the conclusion reached for S26/0400 (see below).

- **S26/0644**: DA indicated the highest probability to be Unit 2 and the second highest probability to be Unit 6 (Error Type 1). S26/0644 is unusual compared to other sites in Unit 6 because of low concentrations of Ca and Cl and a slightly elevated concentration of SO_4.

    - S26/0644 is probably in Unit 6, but could alternatively be within a near-surface recharge area for Unit 4.

- **S26/0045**: DA indicated the highest probability to be Unit 4 and the second highest probability to be Unit 6 (Error Type 1). This site is deep (25 m) compared to the expectation for Unit 6, but it is hydrochemically relatively dilute: concentrations of K and Ca are below the 5th percentile expected for Unit 6, and conductivity and concentrations of Cl and SO_4 are below the 25th percentiles for Unit 6.

    - S26/0045 is probably in Unit 6. The hydrochemistry and location of this site suggest that it receives a significant proportion of its recharge from the Waingawa River.

- **S26/0400**: DA indicated the highest probability to be Unit 4 and the second highest probability to be Unit 2 (Error Type 2). This well is deep (16 m) relative to others in Unit 6, and the alkalinity and Ca concentration exceed the 95th percentile expected for Unit 6. Conductivity and concentrations of Na and Mg exceed the 75th percentiles expected for Unit 6. This well is located close to S26/0467 and S26/0550 (see above).
    - S26/0400 is probably in Unit 4 or possibly Unit 2 rather than Unit 6. Note that this conclusion would be consistent with sites S26/0467 and S26/0500 being in Unit 2 instead of Unit 6.

UNIT 7

The DA algorithm correctly assigned 5 out of 7 sites to Unit 6 (71% accuracy). The following sites were assigned to Unit 7 by GWRC on the basis of hydrostratigraphy, but were misclassified by the DA algorithm:

- **S26/0614**: DA indicated the highest probability to be Unit 4 and the second highest probability to be Unit 7 (Error Type 1). The hydrochemistry at this site is not dramatically different from the expectation, but the concentrations of Ca and Mg are below the 25th percentile for Unit 7. This well is also quite shallow (35 m) compared to other wells in Unit 7.
    - Based on hydrochemistry and depth, there is a roughly equal likelihood that S26/0614 is in Unit 7 or in Unit 4.
- **S26/0730**: DA indicated the highest probability to be Unit 5 and the second highest probability to be Unit 1 (Error Type 2). This well is shallow (33 m), with depth below the 5th percentile expected for Unit 7. The hydrochemistry at this site is also dramatically different from the expectation, with conductivity, alkalinity and concentrations of Na, Ca, Mg and Cl all below the 5th percentile for Unit 7. This site is located about 1.3 km from its closest neighbour, S26/0753, which is assigned to Unit 5.
    - S26/0730 is probably in Unit 5 instead of Unit 7.

5. SUMMARY AND CONCLUSIONS

This investigation explored the use of multivariate statistical methods to provide insight into the groundwater chemistry in the Wairarapa Valley, covering the area between and near the Waingawa and Waiohine Rivers. The aim was to provide insight into the groundwater chemistry within the area and assist with development and substantiation of the transient groundwater flow model being developed by GWRC. The preliminary GWRC conceptualisation of the area includes seven hydrostratigraphic units (Units 1 to 7), defined on the basis of bore log geology and groundwater levels and contours, without any specific reference to hydrochemistry.

The first part of this investigation evaluated the “typical” groundwater chemistry for each hydrostratigraphic unit as a whole, based on data for all wells that are assumed to tap into each unit. This assessment revealed significant differences in hydrochemistry between the various units, although in many cases these differences were subtle. Unit 1 hydrochemistry is generally consistent with river recharge, whereas the hydrochemistry for Units 2 and 6 is more consistent with a greater proportion of recharge from rainfall. Units 2, 4 and 5 have similar hydrochemistry, which is consistent with the hypothesis that Unit 2 recharges Unit 4 which in turn recharges Unit 5. The hydrochemical progression from Unit 4 to 5 is indicative of increasingly reducing (oxygen-poor) conditions, which would be expected along a groundwater flow path. Unit 7 contains the most reduced and chemically evolved groundwater in the Case Study area, which matches the assumption that it is recharged primarily from seepage from overlying units. Overall, the GWRC conceptual model is generally consistent with the observed hydrochemistry within and between the various hydrostratigraphic units.

The second part of this investigation involved the use of HCA to provide an independent comparison to the GWRC conceptual hydrostratigraphy. HCA was used to re-categorise the monitoring wells based on major ion concentrations without any consideration of well location, depth, or assumed hydrostratigraphic unit. The two major hydrochemical categories (A and B) and nine subcategories (A1, A2 and B1 to B7) defined by HCA are generally consistent with the GWRC conceptual hydrostratigraphy. Subcategories A1, A2, B1, B2, B3, B5 and B7 appear to correspond to the hydrochemical expectation for Units 1, 6, 4, 3, 5, 2 and 7, respectively. Subcategories B4 and B6 have hydrochemistry that appears to be related more to local land use than to hydrostratigraphy (e.g. elevated concentrations of K, SO_4 and/or NO_3).

In the third part of this investigation, discriminant analysis (DA) was used to predict the likelihood that each well taps into each GWRC hydrostratigraphic unit, on the basis of major ion chemistry and well depth. The results of DA were also generally consistent with the GWRC conceptual hydrostratigraphy, with the DA prediction matching the assumed hydrostratigraphic unit for 75% of the monitoring wells (n = 99). There were three parts of the study area where a relatively high proportion of sites were misclassified by DA: 1) near the confluence of Managatere and Waiohine Rivers, DA suggested that older sediments are closer to the surface than the GWRC conceptualisation implies; 2) along a line roughly parallel to the axis of the Tararua Ranges, DA suggested that the edge of the Q2 to Q4 fan gravels is closer to the Tararua Ranges than assumed in the GWRC conceptual model; and 3) for a few shallow sites in the Parkvale sub-basin, DA performed poorly presumably because hydrochemistry is controlled more by local land use than by regional hydrostragraphy.

This investigation has shown that multivariate statistical methods can be valuable for the development and validation of a conceptual hydrogeological model. HCA can provide a simple summary of hydrochemical variations without any *a priori* assumptions about relationships to the conceptualised hydrostratigraphy. DA is similar to HCA, but whereas HCA completely ignores the location and depth of the well, DA yields an explicit prediction of which hydrostratigraphic unit (or model layer) each well is most likely to tap. DA is complementary to HCA, and their combined use has particular merit for development and validation of conceptual hydrogeological models. One further advantage of this approach is that mismatches between the HCA/DA predictions and the conceptual model can help identify wells that are adversely impacted by land use.

6. RECOMMENDATIONS

This investigation has demonstrated the merit of hydrochemical assessment using multivariate methods for the purpose of validating a conceptual groundwater model. It is therefore recommended that this combined HCA/DA approach should be employed in other Case Study areas, first ideally in the Wairarapa Valley adjacent to the area considered in this investigation, and ultimately across New Zealand. Alternative methods for HCA and DA should be tested and compared to the methods used in this investigation. For example, different substitution methods for censored results should be compared in terms of the effects on HCA and DA output (e.g. Farnham et al., 2002). The effects of including different or additional analytes such as PO_4 and SiO_2 should be tested (see below). The use of the F-test (Helsel and Hirsch, 1992) for selection of analytes to include in DA on the basis of their contribution to algorithm accuracy should also be explored.

In order to employ the multivariate methods, there is a need to compile a hydrochemical data set that is meaningful and complete. First, it is essential that groundwater samples are collected using an appropriate protocol, to ensure that the analytical results will be representative of the groundwater within the aquifer. For this purpose consistent use of the recently developed National Protocol for State of the Environment Groundwater Sampling (Daughney et al., 2007) is recommended. Second, the samples must be analysed for a sufficient number of parameters so that the multivariate methods can be employed. Routinely analysed parameters should at minimum include the major ions (Na, K, Ca, Mg, HCO_3, Cl, SO_4), nutrients (NO_3, NH_4, PO_4), field parameters (pH, conductivity, temperature) and the minor elements Fe, Mn and SiO_2. In this investigation for example, 38 out of the total 137 monitoring sites had not been analysed for two or more of the major ions, and as a result these sites could not be included in the HCA/DA analysis. Very few sites considered in this investigation had been analysed for PO_4 or SiO_2, and so the value of including these parameters in the HCA/DA analysis is questionable; however, hydrochemical assessments in other parts of New Zealand have shown that PO_4 or SiO_2 often have strong correlations to aquifer lithology and groundwater age (Jones et al., 2003; Morgenstern et al., 2004; Daughney and Reeves, 2005).

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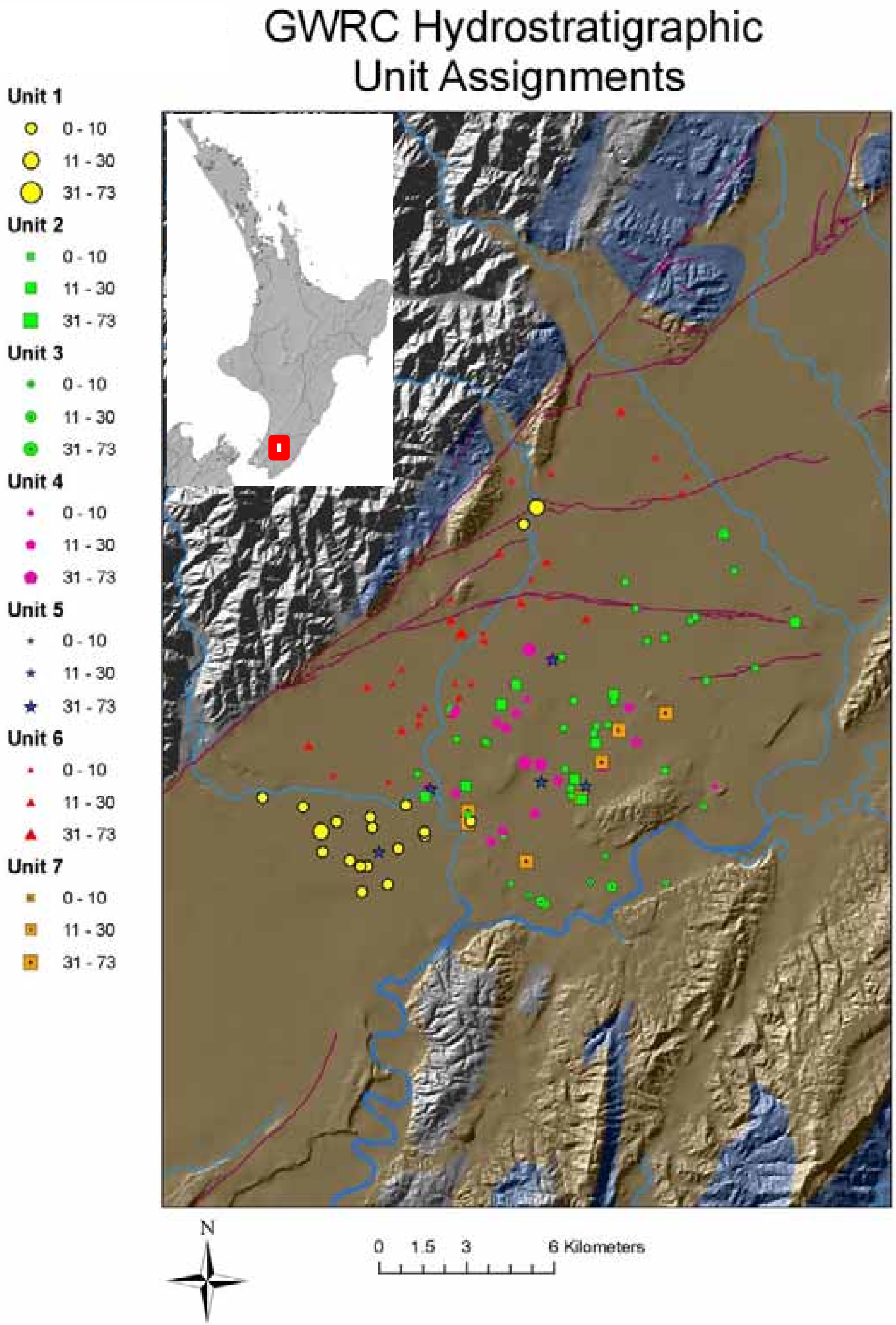

Figure 1. GWRC hydrostratigraphic unit assignments. Symbol size indicates well depth (m). Map inset shows location of Case Study area (red box).

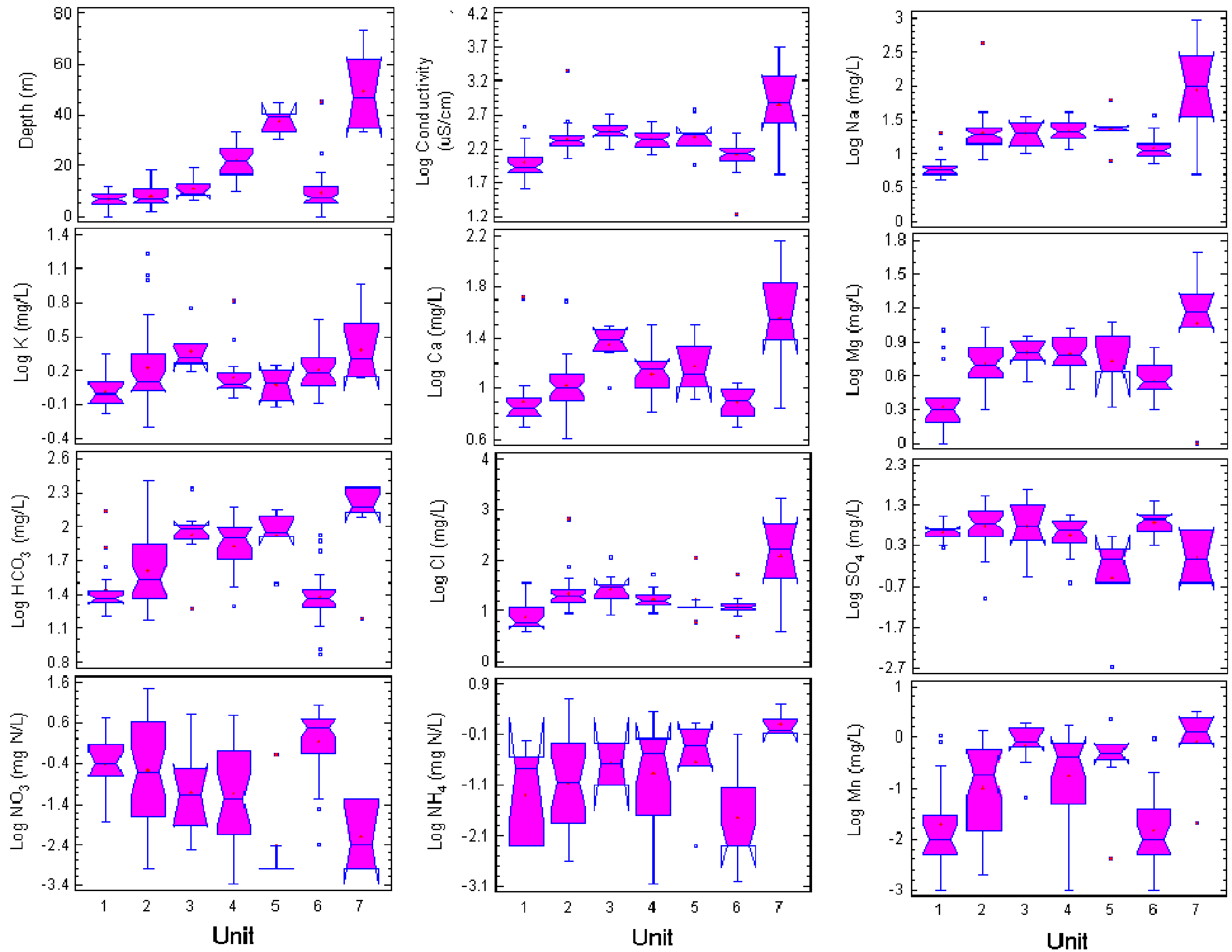

Figure 2. Box-whisker plots showing variation of selected analytes between GWRC hydrostratigraphic units.

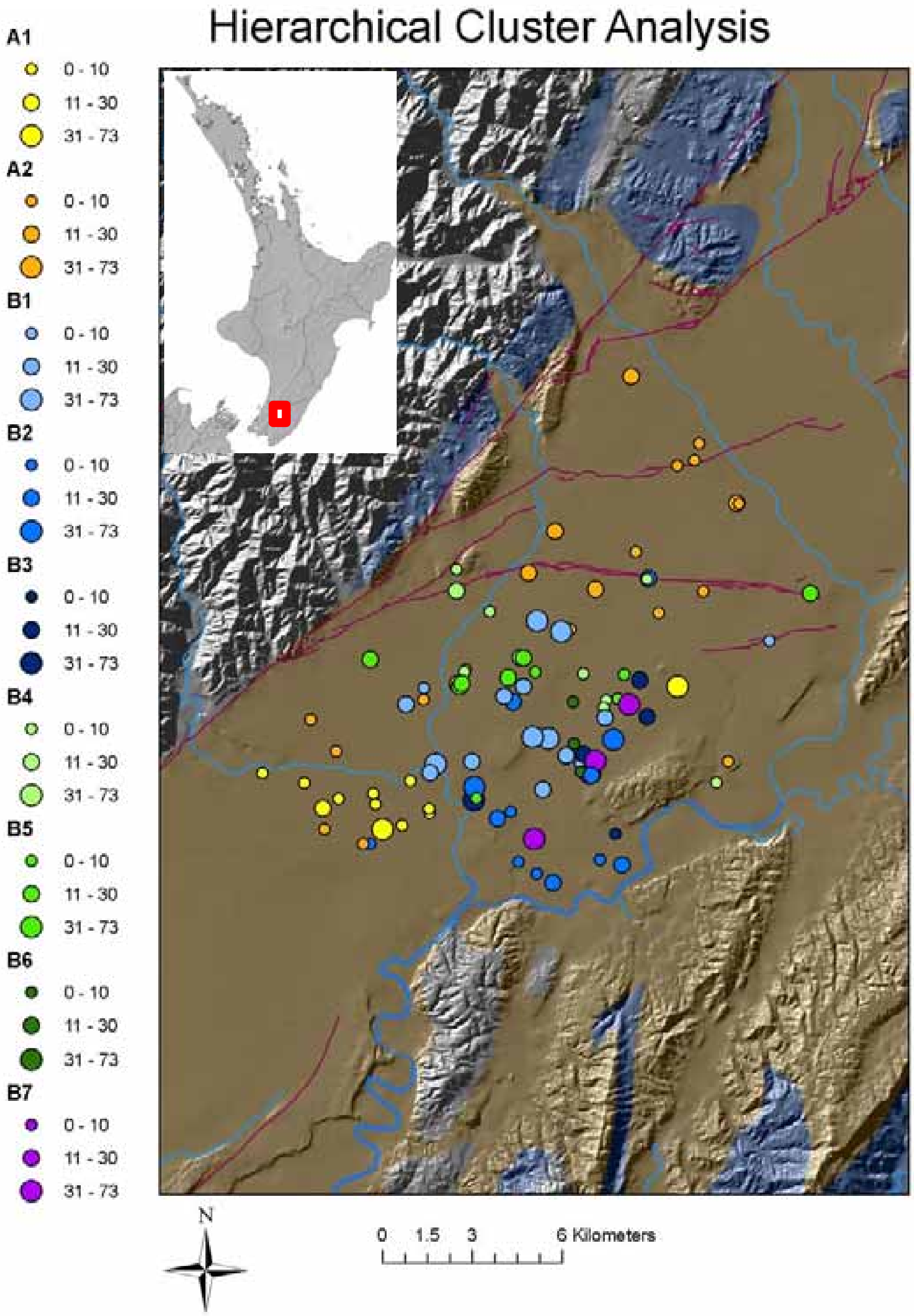

Figure 3. Classification of wells based on Hierarchical Cluster Analysis. Symbol size indicates well depth (m). Map inset shows location of Case Study area (red box).

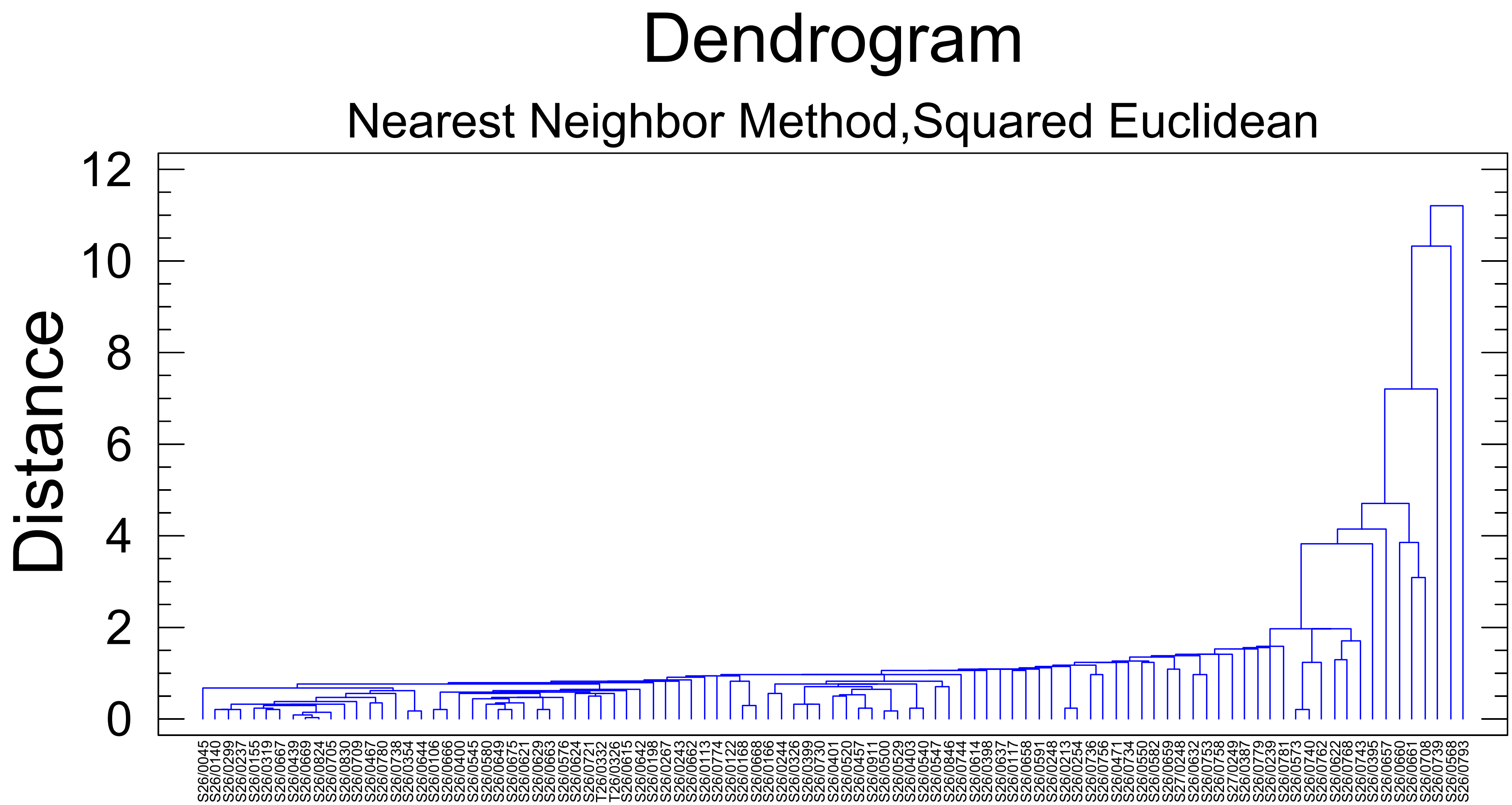

Figure 4. Hierarchical cluster analysis dendrogram, Nearest Neighbour linkage rule. Distance axis is dimensionless.

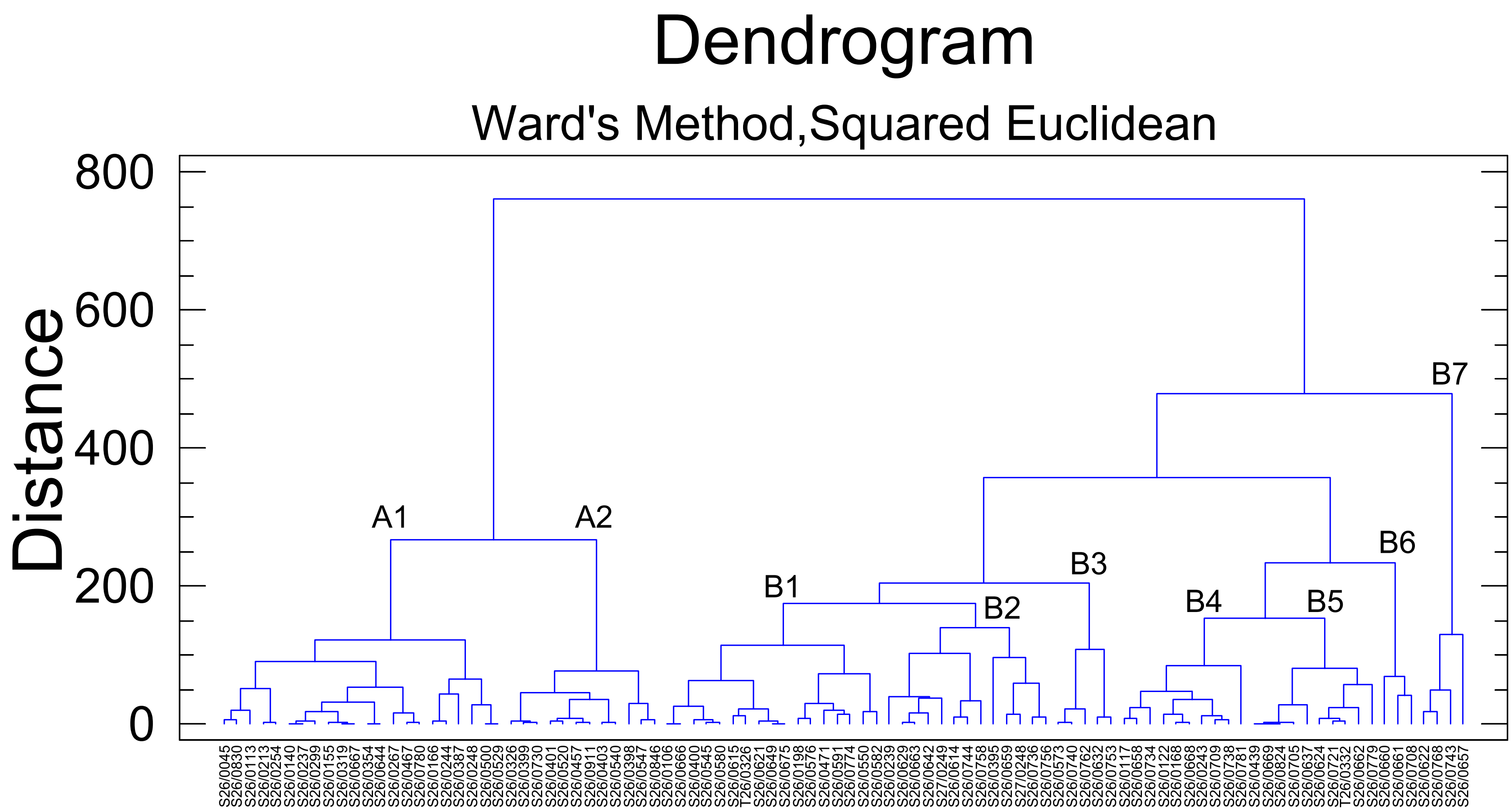

Figure 5. Hierarchical cluster analysis dendrogram, Ward's linkage rule. Distance axis is dimensionless.

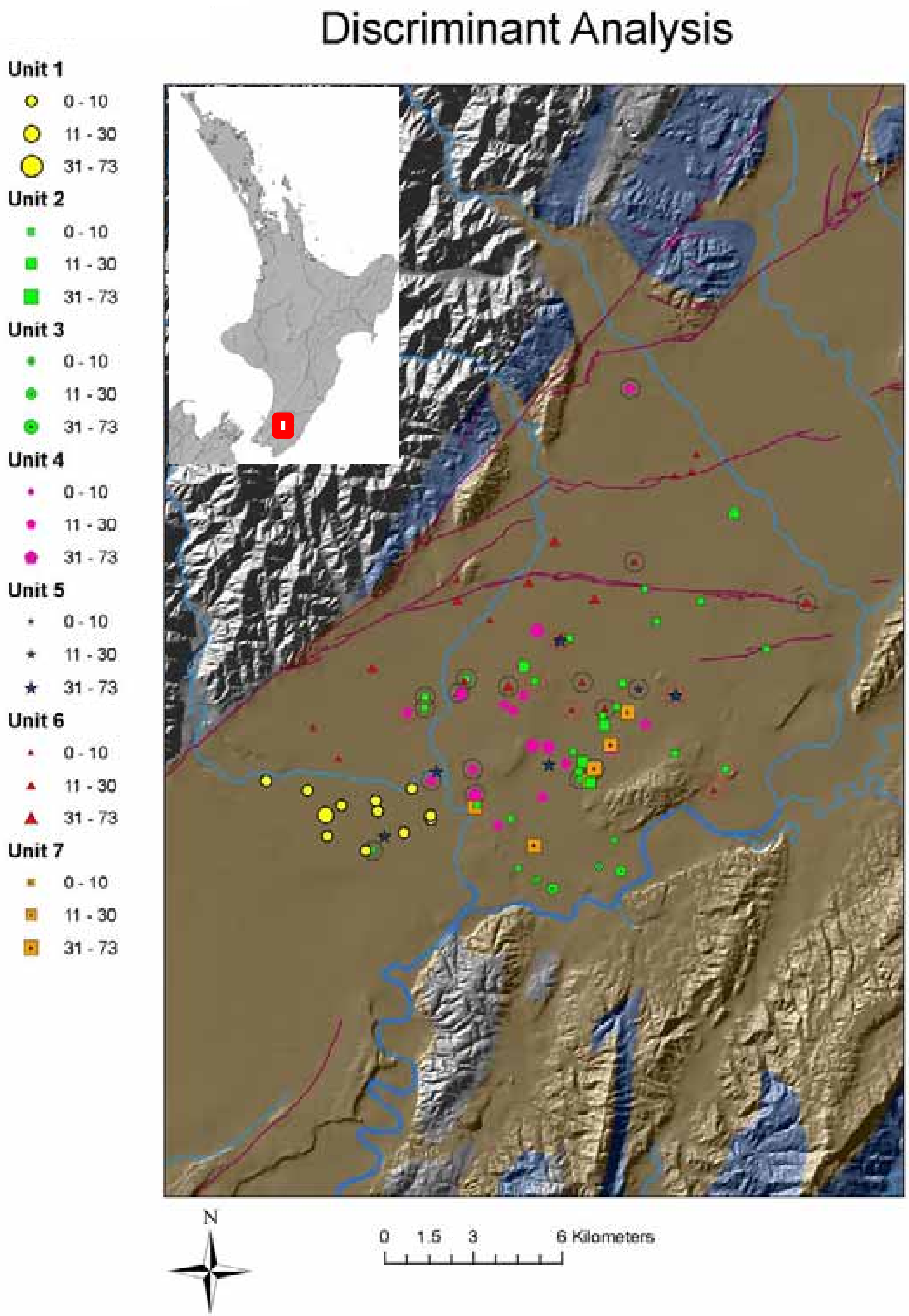

Figure 6. Classification of wells based on Discriminant Analysis. Symbol size indicates well depth (m). Circles around sites indicate cases where the DA prediction does not agree with the GWRC unit assignment (compare to Figure 1): Black circles represent Type 1 errors where the highest probability prediction from DA does not match GWRC unit assignment, but the second-highest probability DA prediction does; Red circles represent Type 2 errors where neither the highest nor second-highest DA prediction matches the GWRC unit assignment. Map inset shows location of Case Study area (red box).

Table 1. GWRC unit assignments for sites in the Case Study area and their assignments to categories defined by Hierarchical Cluster Analysis and Discriminant Analysis.

Site[1]	GWRC Unit	Cluster Analysis	Discriminant Analysis[2]			Site[1]	GWRC Unit	Cluster Analysis	Discriminant Analysis[2]			Site[1]	GWRC Unit	Cluster Analysis	Discriminant Analysis[2]		
			High	2nd	Error				High	2nd	Error				High	2nd	Error
S26/0045	6	A2	4	6	Type 1	S26/0248	6	A2	6	1	Correct	S26/0471	5	B1	5	4	Correct
S26/0106	4	B1	4	5	Correct	S26/0254	2	A2	2	6	Correct	S26/0480	1				
S26/0113	2	A2	2	6	Correct	S26/0267	2	A2	2	1	Correct	S26/0481	6				
S26/0117	6	B4	6	3	Correct	S26/0268	2					S26/0500	1	A2	1	6	Correct
S26/0122	6	B4	6	4	Correct	S26/0277	2					S26/0515	1				
S26/0140	6	A2	6	2	Correct	S26/0299	6	A2	6	2	Correct	S26/0520	1	A1	1	6	Correct
S26/0155	4	A2	6	2	Type 2	S26/0319	6	A2	6	2	Correct	S26/0529	1	A2	1	6	Correct
S26/0164	6					S26/0326	1	A1	1	3	Correct	S26/0540	1	A1	1	6	Correct
S26/0166	6	A2	6	1	Correct	S26/0354	6	A2	6	2	Correct	S26/0545	2	B1	4	2	Type 1
S26/0168	6	B4	6	2	Correct	S26/0362	6					S26/0547	1	A1	1	6	Correct
S26/0169	1					S26/0378	6					S26/0550	6	B1	2	6	Type 1
S26/0178	6					S26/0387	6	A2	6	2	Correct	S26/0552	6				
S26/0179	6					S26/0395	1	B2	3	1	Type 1	S26/0563	6				
S26/0185	1					S26/0398	1	A1	1	3	Correct	S26/0568	5		5	4	Correct
S26/0188	6					S26/0399	1	A1	1	6	Correct	S26/0573	7	B3	7	5	Correct
S26/0190	6					S26/0400	6	B1	4	2	Type 2	S26/0574	2				
S26/0193	6					S26/0401	1	A1	1	6	Correct	S26/0575	2				
S26/0198	5	B1	5	4	Correct	S26/0403	1	A1	1	6	Correct	S26/0576	4	B1	4	5	Correct
S26/0213	2	A2	2	6	Correct	S26/0429	4					S26/0580	2	B1	4	2	Type 1
S26/0237	2	A2	6	2	Type 1	S26/0437	6					S26/0582	2	B1	2	6	Correct
S26/0239	4	B2	4	5	Correct	S26/0439	6	B5	6	2	Correct	S26/0591	4	B1	4	2	Correct
S26/0243	2	B4	2	6	Correct	S26/0449	2					S26/0614	7	B2	4	7	Type 1
S26/0244	6	A2	6	2	Correct	S26/0457	1	A1	1	3	Correct	S26/0615	4	B1	4	2	Correct
S26/0245	6					S26/0467	6	A2	2	6	Type 1	S26/0621	4	B1	4	2	Correct

Notes:
1. Site locations, depths and median values of selected hydrochemical parameters are compiled in Appendix 1
2. Discriminant analysis results: High = highest probability unit assignment; 2nd = second highest probability unit assignment; Error = Type 1 or Type 2 error (see Section 4).
* Blank cells indicate that HCA and DA could not be performed because some of the required input data were not available.

Table 1. Continued.

Site[1]	GWRC Unit	Cluster Analysis	Discriminant Analysis[2]			Site[1]	GWRC Unit	Cluster Analysis	Discriminant Analysis[2]			Site[1]	GWRC Unit	Cluster Analysis	Discriminant Analysis[2]		
			High	2nd	Error				High	2nd	Error				High	2nd	Error
S26/0622	7	B7	7	5	Correct	S26/0675	4	B1	4	5	Correct	S26/0779	2	B5	2	6	Correct
S26/0624	4	B5	2	6	Type 2	S26/0677	4					S26/0780	4	A2	2	6	Type 2
S26/0629	2	B2	2	3	Correct	S26/0693	6					S26/0781	3	B4	6	2	Type 2
S26/0632	2	B3	2	1	Correct	S26/0705	4	B5	4	5	Correct	S26/0793	7		7	5	Correct
S26/0637	2	B5	6	2	Type 1	S26/0708	2	B6	3	2	Type 1	S26/0824	4	B5	4	6	Correct
S26/0642	4	B2	4	3	Correct	S26/0709	2	B4	6	2	Type 1	S26/0830	2	A2	2	6	Correct
S26/0643	6					S26/0721	2	B5	2	6	Correct	S26/0846	5	A1	5	7	Correct
S26/0644	6	A2	2	6	Type 1	S26/0726	2					S26/0877	6				
S26/0646	6					S26/0730	7	A1	5	1	Type 2	S26/0879	6				
S26/0649	4	B1	4	2	Correct	S26/0732	2					S26/0911	1	A1	1	3	Correct
S26/0651	2					S26/0734	2	B4	6	2	Type 1	S27/0185	1				
S26/0657	7	B7	7	5	Correct	S26/0736	3	B2	3	1	Correct	S27/0248	3	B2	3	2	Correct
S26/0658	6	B4	6	2	Correct	S26/0738	2	B4	2	6	Correct	S27/0249	3	B2	3	1	Correct
S26/0659	3	B2	3	6	Correct	S26/0739	2		2	6	Correct	S27/0250	3				
S26/0660	2	B6	2	6	Correct	S26/0740	4	B3	4	5	Correct	T26/0302	2				
S26/0661	2	B6	6	3	Type 2	S26/0743	5	B7	7	5	Type 1	T26/0326	2	B1	2	6	Correct
S26/0662	1	B5	2	6	Type 2	S26/0744	4	B2	4	7	Correct	T26/0332	2	B5	6	2	Type 1
S26/0663	4	B2	4	5	Correct	S26/0752	3										
S26/0664	4					S26/0753	4	B3	5	4	Type 1						
S26/0666	4	B1	4	2	Correct	S26/0756	3	B2	3	4	Correct						
S26/0667	2	A2	6	2	Type 1	S26/0758	2	B2	2	6	Correct						
S26/0668	4	B4	4	6	Correct	S26/0762	3	B3	3	2	Correct						
S26/0669	2	B5	2	6	Correct	S26/0768	7	B7	7	5	Correct						
S26/0672	2					S26/0774	2	B1	2	4	Correct						

Notes:
1. Site locations, depths and median values of selected hydrochemical parameters are compiled in Appendix 1
2. Discriminant analysis results: High = highest probability unit assignment; 2nd = second highest probability unit assignment; Error = Type 1 or Type 2 error (see Section 4).
* Blank cells indicate that HCA and DA could not be performed because some of the required input data were not available.

Table 2. Percentiles in hydrochemistry for selected analytes for each GWRC hydrostratigraphic unit.

Unit	Percentile	Depth m	Na mg/L	K mg/L	Ca mg/L	Mg mg/L	HCO_3 mg/L	Cl mg/L	SO_4 mg/L	NO_3 mg N/L	NH_4 mg N/L	Cond. uS/cm	pH pH units
1	5	2.7	4.7	0.7	5.8	1.0	17.8	4.0	1.9	0.0	0.0	60.8	6.1
	25	4.8	5.0	0.8	6.0	1.5	21.0	5.3	3.8	0.2	0.0	70.6	6.3
	50	6.8	5.5	1.0	7.0	2.0	22.8	6.0	5.0	0.4	0.2	82.0	6.4
	75	8.2	6.4	1.2	8.5	2.5	26.9	10.7	5.4	1.1	0.2	114.8	6.6
	95	11.1	14.8	1.7	18.7	7.6	74.6	23.6	7.7	3.6	0.5	239.4	6.9
2	5	2.0	11.5	0.6	6.0	2.9	16.7	10.3	0.9	0.0	0.0	125.5	5.8
	25	5.0	14.0	1.0	8.0	3.8	23.0	14.6	3.9	0.0	0.0	177.5	6.2
	50	6.4	19.0	1.3	10.0	5.0	34.0	19.3	7.2	0.3	0.1	202.0	6.6
	75	11.0	23.5	2.1	12.5	6.9	69.0	26.8	13.9	4.4	0.5	242.0	6.7
	95	15.0	35.3	10.7	18.2	9.3	105.7	55.0	26.9	9.3	1.7	384.0	7.3
3	5	6.8	10.9	1.6	13.2	4.0	39.0	10.7	1.1	0.0	0.1	176.0	5.8
	25	8.0	15.5	1.9	19.8	5.6	78.0	18.2	2.9	0.0	0.2	246.0	6.3
	50	9.0	20.0	2.0	24.6	6.4	96.0	30.0	6.3	0.1	0.3	275.5	6.5
	75	13.0	24.8	2.4	27.8	8.0	104.2	35.0	19.5	0.3	0.4	341.0	6.5
	95	17.8	33.9	4.8	30.7	8.7	174.2	88.4	42.0	4.5	0.5	455.6	6.9
4	5	10.3	12.5	0.9	7.0	3.7	29.5	10.1	0.3	0.0	0.0	151.5	6.1
	25	17.3	16.5	1.1	10.0	5.0	52.0	13.0	2.8	0.0	0.0	170.0	6.3
	50	21.7	22.3	1.2	14.4	6.0	79.2	15.7	5.0	0.1	0.3	212.5	6.8
	75	26.8	28.0	1.5	16.2	8.8	99.0	20.6	8.1	0.7	0.6	265.0	6.9
	95	31.5	32.0	3.2	23.0	9.0	141.8	29.1	11.0	6.0	1.7	370.0	7.3
5	5	30.6	10.7	0.8	8.7	2.5	41.0	7.2	0.1	0.0	0.0	108.6	6.6
	25	33.0	21.9	0.9	10.2	4.3	81.0	11.8	0.3	0.0	0.2	179.0	6.8
	50	39.3	23.6	1.2	13.1	4.4	89.1	11.8	1.0	0.0	0.5	254.5	7.0
	75	40.7	25.0	1.6	21.3	9.0	122.1	11.9	1.6	0.0	1.0	269.0	7.1
	95	44.1	53.6	1.8	29.6	11.2	136.4	90.4	3.0	0.5	1.3	524.2	7.2
6	5	3.9	8.0	1.1	5.2	2.0	10.2	8.6	3.1	0.0	0.0	84.3	5.5
	25	5.0	9.0	1.2	6.5	3.0	19.0	9.9	4.9	0.7	0.0	104.0	6.0
	50	7.0	11.0	1.5	8.0	3.5	23.2	11.5	8.8	2.9	0.0	134.5	6.3
	75	11.6	14.0	1.9	9.7	4.5	28.0	13.2	10.7	4.9	0.1	165.8	6.9
	95	19.0	24.0	3.2	10.9	6.0	68.4	16.6	15.6	6.1	0.3	223.2	58.8
7	5	33.5	14.1	1.4	12.1	3.9	50.5	16.0	0.3	0.0	0.8	158.7	6.8
	25	40.4	44.0	1.4	24.5	10.7	139.0	55.0	0.4	0.0	0.8	391.5	6.9
	50	47.0	97.5	2.0	34.5	14.5	147.0	161.5	1.0	0.0	0.9	749.0	7.0
	75	55.3	209.5	3.1	58.4	18.0	191.7	394.0	3.0	0.0	1.6	1415.5	7.1
	95	69.8	744.8	7.7	122.6	40.3	216.7	1346.5	5.0	0.1	2.8	4119.0	7.2

Notes:

1. Percentiles for cations pertain to “combined” fields based on reported values for both dissolved and total concentrations; percentiles for conductivity and pH pertain to “combined” fields based on reported values for both laboratory and field measurements (see Appendix 1).

Table 3. Summary of significant hydrochemical variations between hydrostratigraphic units. Based on Kruskal-Wallis tests and Multiple Range tests conducted at the 95% confidence level. Highlights indicate hydrostratigraphic units that are differentiated by only a small number of parameters.

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6
Unit 2	Compared to Unit 1, Unit 2 has higher Na, K, Ca, Mg, HCO3, Cl, Mn and conductivity. There is no difference in depth, SO4, NO3, NH4 or pH.					
Unit 3	Compared to Unit 1, Unit 3 has higher Na, K, Ca, Mg, HCO3, Cl, NH4, Mn and conductivity. There is no difference in SO4, NO3, NH4 or pH.	Compared to Unit 2, Unit 3 has higher Ca, HCO3 and Mn. There is no difference in depth, Na, K, Mg, Cl, SO4, NO3, NH4, conductivity or pH.				
Unit 4	Compared to Unit 1, Unit 4 is deeper and has higher Na, Ca, Mg, HCO3, Cl, NH4, Mn, conductivity and lower NO3. There is no difference in K, SO4 or pH.	Compared to Unit 2, Unit 4 is deeper and has higher Ca, HCO3, Cl and pH. There is no difference in Na, K, Mg, SO4, NO3, NH4 or conductivity.	Compared to Unit 3, Unit 4 is deeper and has lower K and Ca. There is no difference in Na, Mg, HCO3, Cl, SO4, NO3, NH4, Mn, conductivity or pH.			
Unit 5	Compared to Unit 1, Unit 5 is deeper and has higher Na, Ca, Mg, HCO3, Mn, conductivity and pH, and lower NO3 and SO4. There is no difference in K, Cl or NH4.	Compared to Unit 2, Unit 5 is deeper and has higher pH and lower Cl, SO4 and NO3. There is no difference in Na, K, Ca, Mg, HCO3, NH4, Mn or conductivity.	Compared to Unit 3, Unit 5 is deeper and has lower K, Ca, Mg, Cl, SO4, NO3, Mn and conductivity. There is no difference in Na, HCO3, NH4 or pH.	Compared to Unit 4, Unit 5 is deeper and has lower Mg and SO4. There is no difference in Na, K, Ca, HCO3, Cl, NO3, NH4, Mn, conductivity or pH.		
Unit 6	Compared to Unit 1, Unit 6 has higher Na, K, Ca, Mg, Cl, SO4, NO3 and conductivity, and lower pH. There is no difference in depth, HCO3, NH4 or Mn.	Compared to Unit 2, Unit 6 has higher SO4 and NO3, and lower Na, Mg, HCO3, Cl, NH4, Mn, conductivity and pH. There is no difference in depth, K or Ca.	Compared to Unit 3, Unit 6 has higher SO4 and NO3, and lower Na, Ca, Mg, HCO3, Cl, NH4, Mn, conductivity and pH. There is no difference in depth or K.	Compared to Unit 4, Unit 6 is shallower has higher SO4 and NO3, and lower Na, Ca, Mg, HCO3, NH4, Mn, conductivity and pH. There is no difference in K or Cl.	Compared to Unit 5, Unit 6 is shallower has higher SO4 and NO3, and lower HCO3, NH4, Mn and pH. There is no difference in Na, K, Ca, Mg, Cl or conductivity.	
Unit 7	Compared to Unit 1, Unit 7 is deeper and has higher Na, K, Ca, Mg, HCO3, Cl, NH4, Mn, conductivity and pH, and lower SO4 and NO3.	Compared to Unit 2, Unit 7 is deeper and has higher Na, K, Ca, Mg, HCO3, Cl, NH4, Mn, conductivity and pH, and lower SO4 and NO3.	Compared to Unit 3, Unit 7 is deeper and has higher Na, Ca, Mg, HCO3, Cl, NH4, conductivity and pH, and lower SO4 and NO3. There is no difference in K or Mn.	Compared to Unit 4, Unit 7 is deeper and has higher Na, K, Ca, Mg, HCO3, Cl, NH4, Mn and conductivity, and lower SO4 and NO3. There is no difference in pH.	Compared to Unit 5, Unit 7 is deeper and has higher Na, K, Ca, Mg, HCO3, Cl, NH4, Mn and conductivity. There is no difference in SO4, NO3 or pH.	Compared to Unit 6, Unit 7 is deeper and has higher Na, Ca, Mg, HCO3, Cl, NH4, Mn, conductivity and pH, and lower SO4 and NO3. There is no difference in K.

Table 4. Hydrochemistry at centroids defined by hierarchical cluster analysis (Ward's method, three residual sites excluded).

Category[1]	Number[2]	Ca	Mg	Na	K	HCO_3	Cl	SO_4	Cond.
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	uS/cm
A	34	6.9	2.4	8.3	1.1	20.7	8.1	5.5	100.8
B	62	14.4	6.1	23.0	1.8	61.5	23.1	3.9	246.9
A1	12	6.7	1.4	5.5	0.9	21.4	5.2	3.9	70.6
A2	22	7.0	3.1	10.4	1.1	20.3	10.3	6.5	122.5
B1	17	11.6	5.7	21.4	1.2	73.9	17.8	2.8	206.0
B2	13	23.0	7.2	25.7	1.6	102.2	25.0	4.8	305.6
B3	5	19.0	7.5	27.3	1.3	108.5	29.1	0.2	291.5
B4	10	9.5	4.3	14.5	2.9	23.8	14.4	11.2	175.2
B5	10	10.0	5.3	18.6	1.3	36.1	19.5	9.4	191.9
B6	3	12.1	5.4	16.2	12.3	36.6	21.3	27.0	251.0
B7	4	43.6	15.2	123.2	2.3	160.8	220.2	0.6	947.7

Notes:
1. Categories A and B represent the two main clusters defined by HCA; Category A can be subdivided into subcategories A1 and A2, and Category B can be subdivided into subcategories B1 to B7 (see Section 3).
2. Number of sites in each category and subcategory.

Table 5. Comparison of site hydrochemistry, GWRC hydrostratigraphic unit and highest and second-highest probability assignments for all sites that are misclassified according to discriminant analysis.

Site	GWRC Unit	Discriminant Analysis			Depth	Na	K	Ca	Mg	HCO_3	Cl	SO_4	Cond.
		High	2nd	Error	m	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	uS/cm
S26/0395	1	3	1	Type 1	0.0	12.1	1.1	51.7	2.4	135.0	17.5	6.5	332.5
S26/0662	1	2	6	Type 2	5.2	19.9	2.2	10.4	5.5	64.0	22.1	10.5	203.0
S26/0237	2	6	2	Type 1	9.0	12.0	1.2	7.0	3.0	16.0	9.0	8.0	111.0
S26/0637	2	6	2	Type 1	12.0	19.0	1.0	11.0	6.0	17.0	17.0	5.0	184.0
S26/0667	2	6	2	Type 1	10.8	13.0	1.1	9.0	4.0	23.0	12.0	8.0	156.0
S26/0709	2	6	2	Type 1	6.0	13.0	1.8	9.2	4.4	22.0	14.9	15.0	165.0
S26/0734	2	6	2	Type 1	6.3	19.0	3.2	11.6	2.9	19.0	18.5	18.9	193.0
T26/0332	2	6	2	Type 1	13.4	20.0	1.1	11.5	4.8	38.0	29.1	12.4	202.0
S26/0545	2	4	2	Type 1	18.0	18.5	1.3	10.0	4.5	62.6	14.5	3.5	179.0
S26/0580	2	4	2	Type 1	15.0	20.0	1.2	11.5	6.5	69.6	16.0	3.5	191.0
S26/0708	2	3	2	Type 1	3.4	21.9	10.0	16.9	6.5	75.0	23.6	34.4	287.0
S26/0661	2	6	3	Type 2	9.0	14.0	11.0	16.0	6.5	20.5	19.5	20.0	288.5
S26/0781	3	6	2	Type 2	9.0	10.0	5.7	10.0	3.5	18.4	8.5	2.5	157.0
S26/0753	4	5	4	Type 1	27.0	21.0	1.1	15.1	6.2	94.0	20.8	0.3	235.0
S26/0155	4	6	2	Type 2	13.4	11.4	1.4	8.4	3.7	19.5	14.5	11.0	151.5
S26/0624	4	2	6	Type 2	9.5	22.0	1.2	7.0	6.0	52.0	20.0	11.0	185.0
S26/0780	4	2	6	Type 2	10.0	12.5	1.5	6.5	3.0	29.5	14.5	5.0	129.0
S26/0743	5	7	5	Type 1	33.0	60.7	1.8	31.7	11.7	140.0	110.0	0.3	588.0
S26/0045	6	4	6	Type 1	25.0	9.0	0.8	5.0	3.0	25.0	9.0	4.7	100.0
S26/0467	6	2	6	Type 1	6.2	15.0	1.7	7.1	2.7	27.0	12.2	9.0	135.0
S26/0550	6	2	6	Type 1	5.0	37.5	1.6	10.5	6.0	83.0	53.5	3.2	236.5
S26/0644	6	2	6	Type 1	4.0	11.0	1.4	6.0	4.0	28.0	9.0	11.0	123.0
S26/0400	6	4	2	Type 2	16.0	17.8	1.8	11.0	6.0	74.0	13.9	4.2	180.0
S26/0614	7	4	7	Type 1	34.7	52.5	1.4	24.0	10.6	147.0	65.9	5.0	408.0
S26/0730	7	5	1	Type 2	33.0	5.0	1.4	7.0	1.0	15.6	4.0	5.0	66.0

Notes:

1. Colour coding is used to compare the observation to the expectation for a given hydrostratigraphic unit (cf. Table 2): Red – observation is below the 5th percentile expected for the unit; pink – below 25th percentile; light green – above 75th percentile; dark green – above 95th percentile.
2. Discriminant analysis results: High = highest probability unit assignment; 2nd = second highest probability unit assignment; Error = Type 1 or Type 2 error (see Section 4).

APPENDIX 1: PREPARATION OF DATA FOR APPLICATION OF MULTIVARIATE METHODS

The data array provided by GWRC consisted of analytical results for a total of 44 analytes in 554 water samples collected from 137 monitoring sites. Not all samples were analysed for every analyte, and 78 monitoring sites were sampled on only one occasion. The GWRC data were prepared for application of multivariate statistical methods in three stages as described below.

A1.1 CALCULATION OF MEDIANS ON A PER-SITE BASIS

The log-probability method of Helsel and Cohn (1988) was used to calculate the median value for each of the 44 analytes at all 59 monitoring sites that had been sampled more than once. This method is appropriate for water quality datasets, which typically include censored values reported as being less than some detection limit. The method of Helsel and Cohn (1988) provides a reasonable estimate of the median even when up to 70% of the available results are reported as being below some detection limit, and multiple detection limits are accounted for. All calculations were performed using software for automatic processing of groundwater quality data (Daughney, 2005, 2007). The calculated medians were then listed together with the results from sites that had been sampled on only one occasion, resulting in a 44 analyte $\times$ 137 site array. Note that no distinction is made in this report between the results for the 78 sites that had been sampled only once (which might have high uncertainty) compared to the median values calculated at the 59 sites that had been sampled more than once.

A1.2 COMBINATION OF RESULTS FIELDS

Linear regression was used to compare the values of potentially analogous analytes on a per-site basis. For example, the dataset provided by GWRC included separate result fields pertaining to “dissolved” versus “total” concentrations of Na, K, Ca, Mg, B, Fe, Mn, Pb and SiO_2 corresponding to analyses conducted on unfiltered and field-filtered samples, respectively (e.g. analytes called “Iron (Total)” and “Iron (Dissolved)”). For each of these elements, the slope and intercept of the regression line (dissolved versus total concentration at each site) were tested for departures from their ideal values of one and zero, respectively. Note that these regressions were based on data from only 10 to 15 sites, i.e. the only sites for which results were available for both dissolved and total concentrations. A similar approach was used to compare separate result fields for “field” and “lab” measurements of pH and conductivity on a per-site basis. These regressions were based on data from 15 and 18 sites for pH and conductivity, respectively.

The linear regressions revealed that dissolved and total concentrations are statistically indistinguishable (95% confidence level) for all of the above-mentioned analytes except Mn. Similarly, field and lab measurements of pH and conductivity are statistically indistinguishable. Thus it is legitimate to create a single “combined” data field, where the median dissolved concentration is used if available, and the median total concentration is used otherwise. For the “combined” pH and conductivity fields, the median field measurement is used if available, and the lab measurement is used otherwise. The resulting 35 analyte $\times$ 137 site array, including the combined fields instead of the separate dissolved versus total or lab versus field results, is used for all subsequent data analysis. However, care must be taken though to ensure that the statistical tests are not biased by combined results for Mn, or by data from the few sites such as S26/0395 and S26/0400 at which total concentrations are significantly higher than dissolved concentrations for several elements.

A1.3 CHARGE BALANCE ERROR

All waters are electrically neutral, meaning that the sum of concentrations (equivalents per litre) of all positive ions (cations) must be equal to the sum of concentrations of all negative ions (anions). Thus computation of the charge balance error (CBE) can be used as a measure of the analytical accuracy of water quality data (Freeze and Cherry, 1979):

$$CBE = \frac{\sum zm_c - \sum zm_a}{\sum zm_c + \sum zm_a} \times 100\%$$

Where z is the absolute value of the ionic valance, m_c is the molality of the cationic species, m_a is the molality of the anionic species, and CBE is expressed as a percentage. A threshold of 5% or 10% is often used as a cut-off for acceptable CBE (Freeze and Cherry, 1979; Güler et al., 2002).

In this study, the following ions were considered in the calculation of CBE: Na, K, Ca, Mg, HCO_3, Cl and SO_4. Other ions such as Br, F, Fe, Mn, NO_3, NH_4 and PO_4 were excluded from the CBE calculations because they are present at most sites at relatively small concentrations. Missing analyses and results below the analytical detection limit are assigned values of zero and ½ the detection limit, respectively, to permit calculation of CBE.

CBE could be calculated for 99 sites; for the remaining 38 sites, CBE could not be calculated because two or more major ions had not been analysed. The median and average CBE were -4.6% and -2.3%, respectively. Of all sites for which CBE could be calculated, 26 had CBE below -10% and 13 had CBE above +10%. The proportion of sites with CBE above ±10% is quite high, probably because for several sites total concentrations had to be used because dissolved concentrations were not available (strictly speaking CBE calculations should only be performed with the latter). Sites with large CBE were not excluded from subsequent statistical analysis, but their possible biasing influence must be kept in mind.

A1.4 ESTIMATION OF MISSING RESULTS

The dataset included seven sites that were missing results for just one of the major ions. In order to provide the maximum amount of data for subsequent statistical analysis, missing values were replaced with ion concentrations that would yield CBE = 0%, as follows:

- S26/0122: SO_4 is estimated to be 25.5 mg/L
- S26/0168: HCO_3 is estimated to be 35.5 mg/L
- S26/0213: K is estimated to be 0.5 mg/L
- S26/0254: K is estimated to be 0.5 mg/L
- S26/0354: SO_4 is estimated to be 14.5 mg/L
- S26/0644: SO_4 is estimated to be 11.0 mg/L
- S26/0663: K is estimated to be 1.5 mg/L

The dataset also included one site for which a conductivity result was missing. For this site, S26/0471, the missing value was estimated to be 254.5 uS/cm, based on a regression of measured conductivity versus calculated total dissolved solids concentration.

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Table A1. Site locations, bore depths, GWRC hydrostratigraphic unit assignments, and calculated medians for selected water quality parameters (page 1 of 5).

Site	Easting	Northing	Depth (m)[1]			GWRC Unit	Na*	K*	Ca*	Mg*	HCO3	Cl	SO4	NO3	NH4	Cond*	pH*
			Total	Scrn Top	Scrn Bot		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg N/L	mg N/L	uS/cm	pH
S26/0045	2726250	6026400	25	23	25	6	9	0.8	5	3	25	9	4.7	2.2	0.13	100	6.3
S26/0106	2723100	6018200	30	?	?	4	15	0.9	9	6	53	13	5	0.32	0.1	159	7.1
S26/0113	2724200	6017900	5	?	?	2	8	0.8	4	5	23	9	6	4.5	0.02	131	6.7
S26/0117	2721500	6018500	5	?	?	6	10.3	2.73	9.69	3.2	24	12.5	8.4	3.28	<0.01	135	5.72
S26/0122	2720400	6019200	17	?	?	6	15	3.1	8	5	27	15	25.5	5.4		180	5.97
S26/0140	2723700	6021200	12	?	?	6	11	1.2	8	3.5	14.377	9	9	4.945		133	5.95
S26/0155	2723845	6017830	13.4	10.31	13.41	4	11.4	1.365	8.375	3.66	19.5	14.5	11	6.49	0.02	151.5	6.285
S26/0164	2720760	6018760	45	37.1	44.8	6	24	1.3						0.05	0.03		
S26/0166	2722800	6019800	12.4	?	?	6	8	1.1	6	2	13.115	9	4.5	0.88		92	
S26/0168	2720400	6019920	7	?	?	6	13	2.7	10	7	35.5	16	13	2.9		196	
S26/0169	2722884	6022504	7.65	3.75	6.75	1			9	7	27	12.5		5.375	<0.01	170	
S26/0178	2723740	6019960	3.6	?	?	6			8	5	23	13		4.7		17	6.5
S26/0179	2721610	6018440	6.1	?	?	6	9		8	3	28	8		2.5	<0.005	110	5.96
S26/0185	2723332	6023091	11	7.25	4.2	1						11.3		0.25	0.62	118	
S26/0188	2722500	6024000	4.7	?	?	6						15.45		5.4	<0.01	166	59
S26/0190	2723160	6020620	4.3	?	?	6	10				19	12		0.65	0.03	96.5	6.65
S26/0193	2721481	6018738	8.8	?	?	6											
S26/0198	2723897	6017834	40.7	36.7	40.7	5	23.6	0.87	10.2	4.35	81	11.8	1.6	0.001	0.19	179	7.26
S26/0213	2729780	6022140	14.6	?	?	2	14	0.5	8	3	29	11	5	4.2		141	6.6
S26/0237	2726400	6020500	9	?	?	2	12	1.2	7	3	16	9	8	5.1	0.02	111	6.6
S26/0239	2726829	6019622	21.3	?	?	4	32	1.5	31.5	9	141.8	9	3	0.055		400	7.105
S26/0243	2726780	6019600	2	?	?	2	23.5	2.25	10	5	21.148	18.5	10	3.65		217	
S26/0244	2727780	6023410	0	?	?	6	8.53	1.235	5.77	2.17	8.1885	9.35	7.7	4.385	0.005	101.5	5.72
S26/0245	2727445	6024780	7.8	6.3	7.8	6					15	13		6.9	0.29	130	5.2
S26/0248	2728520	6024150	4.32	?	?	6	7	1.5	10	3	18	10	2	5.52	0.04	131	6.7
S26/0254	2729855	6022130	6	?	?	2	14	0.5	6	3	28	12	5	6	0.11	128	6.5
S26/0267	2728655	6019186	6.64	?	?	2	16.7	0.98	7.58	2.77	41	19	6.1	0.057	0.1	136	6.23
S26/0268	2727770	6018580	4.2	?	?	2			18	7	63		18	2.7	0.08	405	6.4
S26/0277	2728830	6019300	6.4	?	?	2			6	10	44	37		0.36		223	6.6
S26/0299	2728370	6023590	8.1	?	?	6	8.955	1.14	9.65	3.25	13.1	9.75	9.8	5.31	0.001	126	5.765
S26/0319	2725038	6019262	13.6	12.6	13.6	6	12.5	1.11	7.45	3.51	20	12.6	8.8	5.45	<0.01	135	5.91

Notes:

1. Depth listings correspond to total bore depth and the top and bottom of the screened or open interval. “?” indicates data not available

* Tabulated results are for “combined” fields based on reported values for both dissolved and total concentrations, or “combined” fields based on reported values for both laboratory and field measurements of conductivity and pH.

Table A1. Continued (page 2 of 5).

Site	Easting	Northing	Depth (m)			GWRC Unit	Na*	K*	Ca*	Mg*	HCO3	Cl	SO4	NO3	NH4	Cond*	pH*
			Total	Scrn Top	Scrn Bot		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg N/L	mg N/L	uS/cm	pH
S26/0326	2713900	6013100	3	?	?	1	5	1.4	8.5	1	21.107	5.5	4.5	0.79		79.5	6.475
S26/0354	2715500	6014900	7	?	?	6	11	1.6	6	4	23.205	10.5	14.5	4.85	0.16	130	6.1
S26/0362	2718250	6013650	10	?	?	6								0.004		70	2.4
S26/0378	2719500	6016200	7	?	?	6			8	4	28	14	5	0.56	0.05	150	6.4
S26/0387	2716367	6013839	6	?	?	6	9	2	8	4	7.377	10	7	2.4		135	
S26/0395	2717500	6010730	0	?	?	1	12.09	1.09	51.69	2.375	135	17.5	6.45	3.2495	0.16	332.5	6.815
S26/0398	2719488	6011761	9.5	6.5	9.5	1	8	0.8	6	2	26.5	6	2	0.02		39.5	7.05
S26/0399	2718570	6011343	9.7	7.7	9.7	1	5	1.2	6.5	1	22.5	4.5	5.5	0.19		72.5	
S26/0400	2718695	6015416	16	13	16	6	17.75	1.81	11	6	74	13.85	4.2	0.03	0.7745	180	6.95
S26/0401	2715910	6011920	12	?	?	1	4	0.9	6	1.5	21	4	5.5	0.235		69.5	
S26/0403	2718830	6012850	7.5	7.5	10.5	1	5	0.7	5	1	21	5	4	0.05		70	
S26/0429	2719620	6013450	23	?	?	4						10		0.1	0.32		6.13
S26/0437	2715480	6014900	16.18	16.18	0	6			8	5	60	3				264	6.23
S26/0439	2717510	6016900	11.5	?	?	6	13.6	1.14	10.8	4.92	35	14.85	10.45	3.565	<0.01	164	6.25
S26/0449	2719240	6013925	9	?	?	2								0.003		242	3
S26/0457	2717675	6012051	6.06	?	?	1	5.4	0.82	7.91	1.52	20.7	5.85	5.3	0.83	<0.01	81	6.065
S26/0467	2719290	6015570	6.2	?	?	6	15	1.715	7.14	2.74	27	12.15	8.95	3.04	<0.01	135	6.03
S26/0471	2719700	6013400	30	?	?	5	25	1.6	13.1	4.3	89.1	11.9	1	<0.002	1.346	254.48	
S26/0480	2718200	6010100	3	?	?	1			6	10	44	37		0.36		223	6.6
S26/0481	2718400	6017000	8	?	?	6			11	3	24	10		4.2		134	6.9
S26/0500	2717265	6010718	3.4	?	?	1	6.5	1.25	8.5	2.5	23.156	6	4.5	1.15		94.5	6.445
S26/0515	2716910	6010925	5.5	?	?	1					34	10					6.3
S26/0520	2716450	6012250	7	?	?	1	5.5	0.9	6	2	16.467	5.5	5	0.99		69	6.375
S26/0529	2715970	6011219	7.3	?	?	1	6	1.25	7	2.5	24.476	5	3.5	0.44		89	6.875
S26/0540	2715297	6012774	6.8	?	?	1	5	0.75	6	1	18.033	4	3	0.34		64.5	6.5
S26/0545	2719501	6013110	18	?	?	2	18.5	1.3	10	4.5	62.64	14.5	3.5	0.025		179	6.56
S26/0547	2719471	6011895	4.3	?	?	1	6.2	0.65	6.15	2.15	25.985	5.75	1.7	0.06	0.16	76.5	6.28
S26/0550	2719300	6015950	5	?	?	6	37.5	1.55	10.5	6	83	53.5	3.2	0.05	0.07	236.5	6.4
S26/0552	2719300	6015700	6	?	?	6			5	2	37	12		1.5		145	7.3
S26/0563	2718710	6017500	5	?	?	6			7	2	23	11		0.7		102	7
S26/0568	2723504	6013642	45	40.9	43.9	5	21.9	1.21	21.3	9	122.1	11.75	0.002	<0.002	0.47	269	7.09

Notes:

1. Depth listings correspond to total bore depth and the top and bottom of the screened or open interval. "?" indicates data not available

* Tabulated results are for "combined" fields based on reported values for both dissolved and total concentrations, or "combined" fields based on reported values for both laboratory and field measurements of conductivity and pH.

Table A1. Continued (page 3 of 5).

Site	Easting	Northing	Depth (m)			GWRC Unit	Na*	K*	Ca*	Mg*	HCO3	Cl	SO4	NO3	NH4	Cond*	pH*
			Total	Scrn Top	Scrn Bot		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg N/L	mg N/L	uS/cm	pH
S26/0573	2720970	6012190	48.5	46.3	48.3	7	35.4	1.34	25	10.8	146	44	<0.5	<0.002	0.82	375	7.07
S26/0574	2721655	6014955	1.92	?	?	2								0.12	1.79		
S26/0575	2721583	6015015	1.79	?	?	2								0.01	4.07		
S26/0576	2723479	6014255	31	27	31	4	20.5	1	14.85	5.59	79.2	16.75	2	0.0004	0.34	212.5	6.84
S26/0580	2720900	6013500	15	?	?	2	20	1.15	11.5	6.5	69.648	16	3.5	0.015		191	7.175
S26/0582	2724530	6013410	2	?	?	2	28	1.5	9	7	70	32	1	0.05	0.49	233	6.6
S26/0591	2724067	6013676	18	?	?	4	16.5	1.7	10	4	53.115	16	1	0.47		170	6.63
S26/0614	2721000	6012643	34.7	32.7	34.7	7	52.5	1.44	24	10.6	147	65.9	5	<0.002	0.82	408	6.79
S26/0615	2724072	6013694	15	?	?	4	20.2	0.95	14.4	5.14	76	27	7.7	<0.002	2.29	265	6.53
S26/0621	2723280	6012560	20	16	20	4	21.3	1.11	16.2	6.36	99	20	4	<0.002	1.4	264	6.75
S26/0622	2723000	6010900	46	?	?	7	97.5	2	34.5	14.5	132.02	161.5	1	0.04		749	6.975
S26/0624	2723020	6016480	9.5	?	?	4	22	1.2	7	6	52	20	11	0.8	0.04	185	6.5
S26/0629	2722200	6011800	6	?	?	2	25.5	1.5	18.5	8.5	105.13	14	2.5	0.175		254	7.225
S26/0632	2724644	6013731	14.3	?	?	2	18.05	0.9	12.85	5	71	16.5	0.1	0.02	0.76	187	6.73
S26/0637	2722119	6016295	12	?	?	2	19	1	11	6	17	17	5	2.2		184	6.4
S26/0642	2721762	6011581	16.5	?	?	4	31	1.5	18	9	112	24	5.3	0.0425	1.48	282	7
S26/0643	2720400	6015900	5	?	?	6										183	5.9
S26/0644	2720700	6016550	4	?	?	6	11	1.4	6	4	28	9	11	0.48		123	6.15
S26/0646	2721100	6017000	4	?	?	6			8	3	20	11		1.1		100	6.9
S26/0649	2722630	6016010	18	?	?	4	24	1.15	14	7	89.664	13	4	0.025		217	6.79
S26/0651	2720600	6015100	5	?	?	2			10	5	15	16		9.3		187	6.9
S26/0657	2724881	6013103	62	?	?	7	280	4.1	68.1	20.6	167.46	545	1	0.05	1.55	1830	6.825
S26/0658	2720650	6016480	8	?	?	6	14	4.4	9	4	19.672	11	11	3.2		165	6.35
S26/0659	2722460	6010120	6	?	?	3	20	2.75	27	8	78.836	24.5	27	0.625		296.5	6.23
S26/0660	2724319	6014098	4.17	?	?	2	13.8	16.8	6.59	3.81	32	21	28.6	0.159	<0.01	191	5.87
S26/0661	2724300	6015500	9	?	?	2	14	11	16	6.5	20.5	19.5	20	28.9	0.02	288.5	6.45
S26/0662	2721069	6012270	5.21	?	?	1	19.9	2.2	10.4	5.53	64	22.1	10.5	0.014	0.29	203	6.19
S26/0663	2722300	6015500	26.6	23.3	26.6	4	29	1.5	17	9	107	16	1.5	0.04		265	7.3
S26/0664	2720560	6013250	25.5	22.51	25.51	4	28		17	9	89	24		0.02		238	6.8
S26/0666	2721985	6015675	21.65	18.45	21.65	4	18	0.9	10	5	60	12	6	1.08	0.01	162	7.4
S26/0667	2720420	6016100	10.8	9	11	2	13	1.1	9	4	23	12	8	5.8		156	

Notes:

1. Depth listings correspond to total bore depth and the top and bottom of the screened or open interval. “?” indicates data not available

* Tabulated results are for “combined” fields based on reported values for both dissolved and total concentrations, or “combined” fields based on reported values for both laboratory and field measurements of conductivity and pH.

Table A1. Continued (page 4 of 5).

Site	Easting	Northing	Depth (m)			GWRC Unit	Na*	K*	Ca*	Mg*	HCO3	Cl	SO4	NO3	NH4	Cond*	pH*
			Total	Scrn Top	Scrn Bot		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg N/L	mg N/L	uS/cm	pH
S26/0668	2722527	6016969	25	23	25	4	15	3	11	6	31	12	10	6		185	5.9
S26/0669	2722630	6016950	11.5	9.5	11.5	2	16	1.25	10	5	31	13	9	7.3	0.01	187	6.6
S26/0672	2721000	6012500	9	?	?	2	28		17	9	89	24		0.02		238	6.8
S26/0675	2722941	6014309	31.5	27.5	31.5	4	23.65	1.175	15.05	8.825	106.5	15.35	4	0.05	0.335	211.5	6.84
S26/0677	2722180	6011930	14.1	10.9	14.1	4											
S26/0693	2720546	6017019	4	?	?	6			6	3	20	11		1.1		100	6.9
S26/0705	2720489	6015999	27.4	25.9	27.4	4	17	1.1	9.4	4	32	12.3	9.1	5.0185	<0.01	166.5	6.265
S26/0708	2724548	6013150	3.4	?	?	2	21.9	10	16.9	6.47	75	23.6	34.4	0.709	0.62	287	6.38
S26/0709	2724632	6016432	6	?	?	2	13	1.77	9.19	4.37	22	14.9	15	6.51	<0.01	165	5.79
S26/0721	2725800	6015600	5	?	?	2	19	1.2	10	6	51	27	7	0.1	0.15	202	6.5
S26/0726	2726000	6016600	11	?	?	2			14	3	34	26		0.16		242	7.3
S26/0730	2727800	6016000	33	?	?	7	5	1.4	7	1	15.574	4	5	0.05		66	
S26/0732	2729200	6017100	3	?	?	2			8	2	20	30	2.5	9.3		232	7.2
S26/0734	2725411	6015545	6.33	?	?	2	19	3.2	11.6	2.9	19	18.5	18.9	5.276	<0.005	193	5.8
S26/0736	2725200	6010200	8	?	?	3	13	1.9	20	5	70.058	14	4.5	0.14		204.5	6.52
S26/0738	2725320	6015300	5.4	?	?	2	17	2.1	7.245	3.945	26	23	14.15	1.86	0.07	173	5.73
S26/0739	2727766	6014016	5.6	?	?	2	411	4.9	48	10.7	252	640	24.8	<0.002	0.34	2250	7.57
S26/0740	2726765	6014999	24.4	?	?	4	31	1.33	23	10.3	148	29.2	<0.5	0.007	0.5	356	6.88
S26/0743	2725045	6013506	33	31	33	5	60.7	1.79	31.7	11.7	140	110	<0.5	<0.002	0.96	588	6.95
S26/0744	2725645	6014231	33	28.4	32.4	4	40	1.38	16.2	8.01	95	53.4	6.2	<0.002	0.53	370	6.37
S26/0752	2727820	6010150	8.5	7.5	8.5	3					215	116	50			520	7.06
S26/0753	2726532	6016215	27	?	?	4	21	1.06	15.1	6.19	94	20.8	<0.5	<0.002	0.65	235	6.92
S26/0756	2725937	6010018	19	17	19	3	17.9	1.56	26.75	5.79	96	18.2	8.1	0.003	0.08	248	6.505
S26/0758	2724909	6013034	11.82	?	?	2	40.2	1.39	16.9	8.3	84	75.5	1.3	0.005	0.87	377	6
S26/0762	2725720	6011070	9.5	8.5	9.5	3	36.15	2.05	22.35	6.75	104.2	47.05	0.3298	0.003	0.545	359	6.455
S26/0768	2726180	6015400	47	41.5	47.5	7	139	1.96	48.6	15.4	216	243	0.6	<0.002	0.93	1001	7.07
S26/0774	2725368	6014960	15	?	?	2	19.6	1.01	11.4	4.52	66	25.3	0.8	<0.002	0.5	211	6.6
S26/0779	2726000	6016400	3	?	?	2	27	2.8	10	7	31.967	44	13	0.02		270	
S26/0780	2729500	6013500	10	?	?	4	12.5	1.5	6.5	3	29.517	14.5	5	0.465		129	6.27
S26/0781	2729100	6012800	9	?	?	3	10	5.65	10	3.5	18.377	8.5	2.5	6.57		157	5.68
S26/0793	2725595	6014321	73.2	64.2	73.2	7	944	9.3	146	48.8	217	1690	<0.5	0.004	3.1	5100	7.23

Notes:

1. Depth listings correspond to total bore depth and the top and bottom of the screened or open interval. “?” indicates data not available

* Tabulated results are for “combined” fields based on reported values for both dissolved and total concentrations, or “combined” fields based on reported values for both laboratory and field measurements of conductivity and pH.

Table A1. Continued (page 5 of 5).

Site	Easting	Northing	Depth (m)			GWRC Unit	Na*	K*	Ca*	Mg*	HCO3	Cl	SO4	NO3	NH4	Cond*	pH*
			Total	Scrn Top	Scrn Bot		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg N/L	mg N/L	uS/cm	pH
S26/0824	2720564	6016101	20.6	14	15	4	15.6	1.2	10.6	4.755	30.75	13.1	9.55	6.037	0.0009	174	6.1
S26/0830	2727168	6018462	4.97	?	?	2	11.1	1.05	6.31	3.03	26	13.6	6.9	1.86	<0.01	118	5.92
S26/0846	2717921	6011212	39.3	33.3	39.3	5	7.855	0.75	8.29	2.09	31	6.1	3.4	0.644	<0.01	91	6.51
S26/0877	2722074	6021486	12	?	?	6						17.4		10.7	<0.01	216	58.5
S26/0879	2723838	6024226	5	?	?	6						12.5		0.55	<0.01	196	70.5
S26/0911	2717612	6012423	8.8	7	9	1	5.55	1.06	7.79	1.61	22	7.3	5	1.15	<0.01	83	6.07
S27/0185	2717320	6009845	6.4	5.8	6.4	1			9	2	22	8	5	2		105	6.4
S27/0248	2723076	6009725	7.9	?	?	3	28.5	2	19	6	77.976	30	17	0.08		275.5	
S27/0249	2723620	6009420	13	11	13	3	21	1.8	31	9	113	35	3	0.05		341	
S27/0250	2723490	6009500	16	?	?	3			30	8	103	31		0.04		246	6.46
T26/0302	2730165	6020895	8.98	?	?	2					107	30.5		0.06	0.06	295	6.62
T26/0326	2730876	6017526	10	?	?	2	23.5	1.25	10.85	8.3	68.3	19.85	7.4	<0.002	1.191	223	6.56
T26/0332	2732246	6019123	13.4	11.4	13.4	2	20	1.08	11.45	4.78	38	29.05	12.4	1.073	0.005	202	5.89

Notes:

1. Depth listings correspond to total bore depth and the top and bottom of the screened or open interval. "?" indicates data not available

* Tabulated results are for "combined" fields based on reported values for both dissolved and total concentrations, or "combined" fields based on reported values for both laboratory and field measurements of conductivity and pH.

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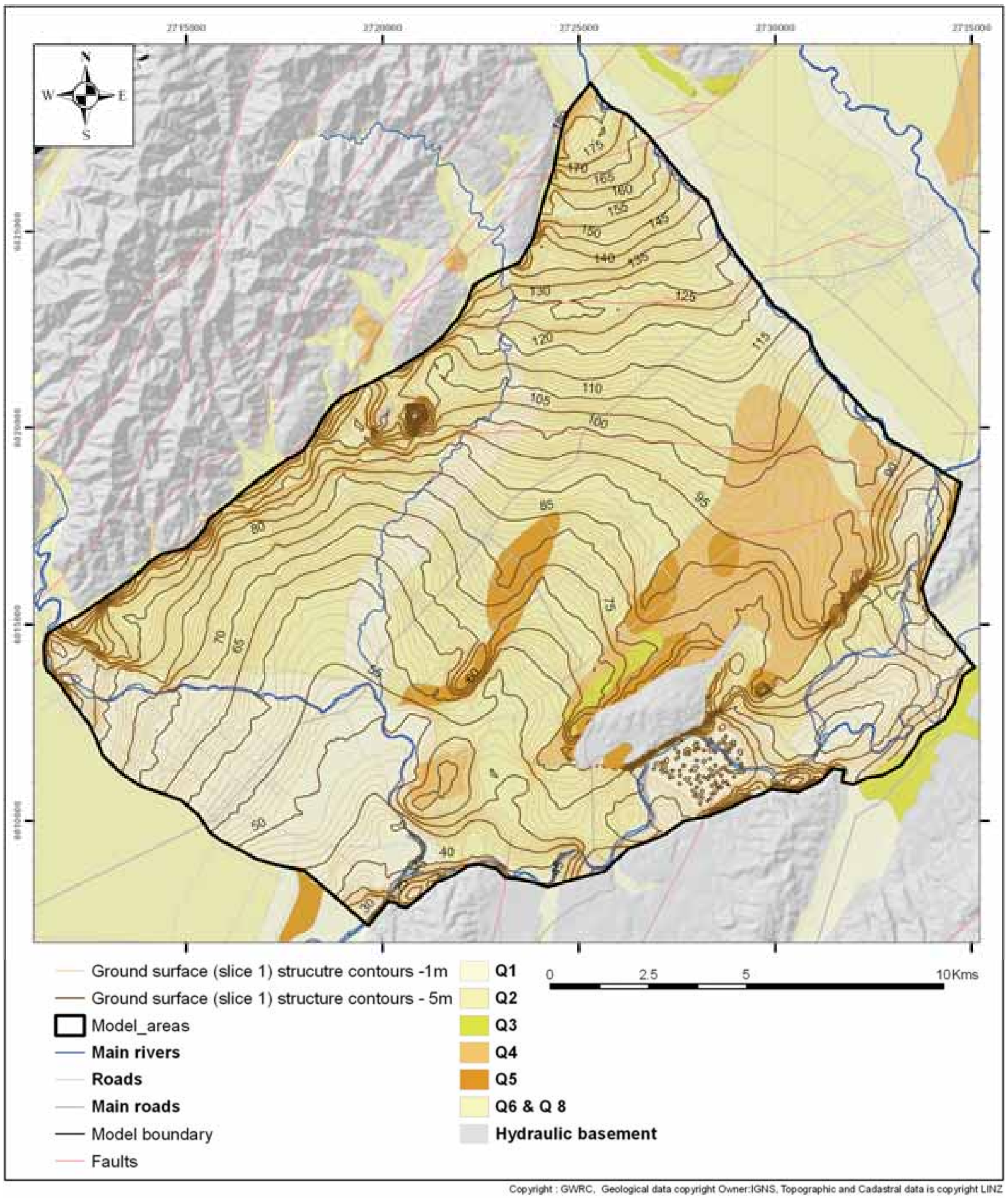
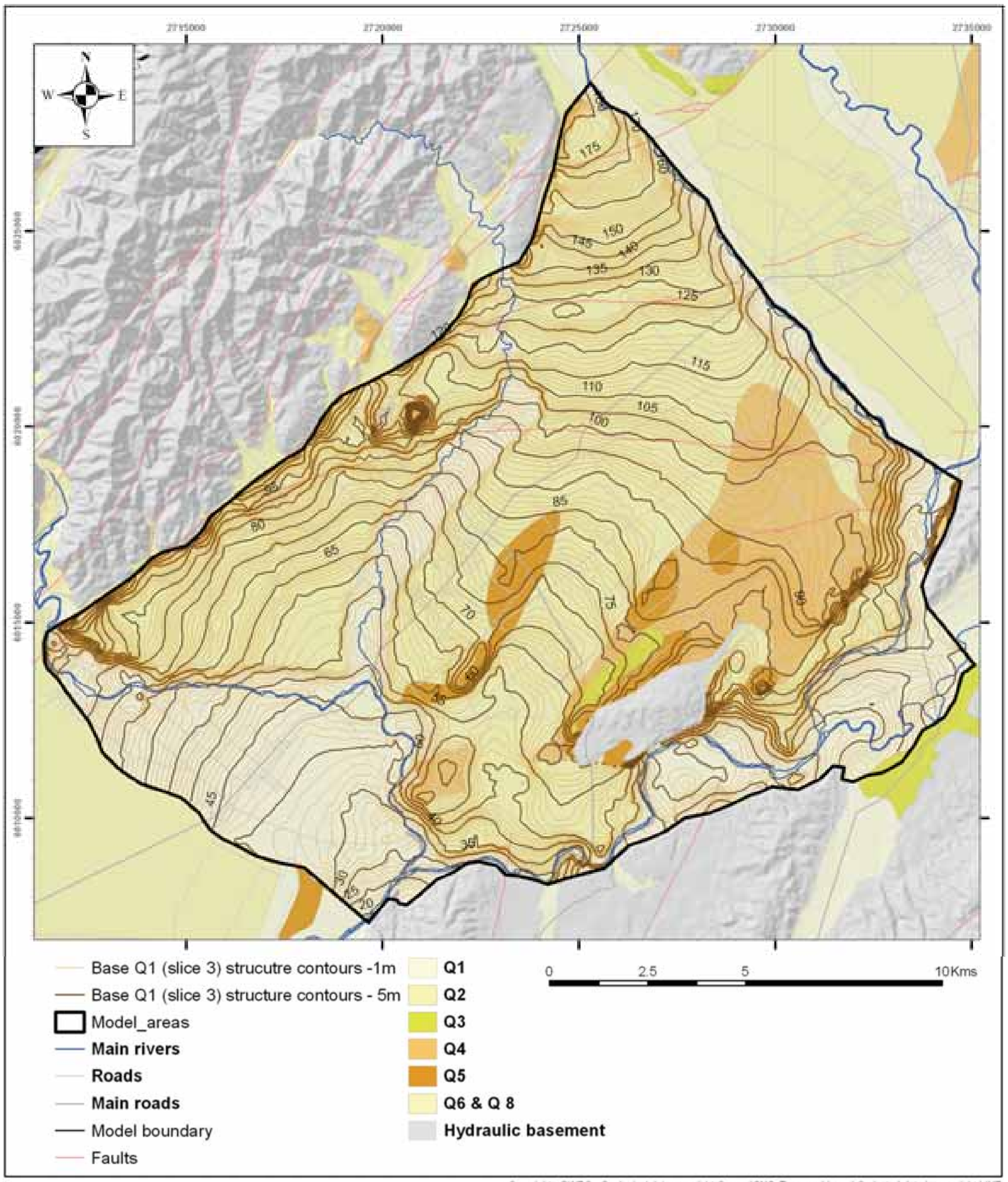
Appendix 7:

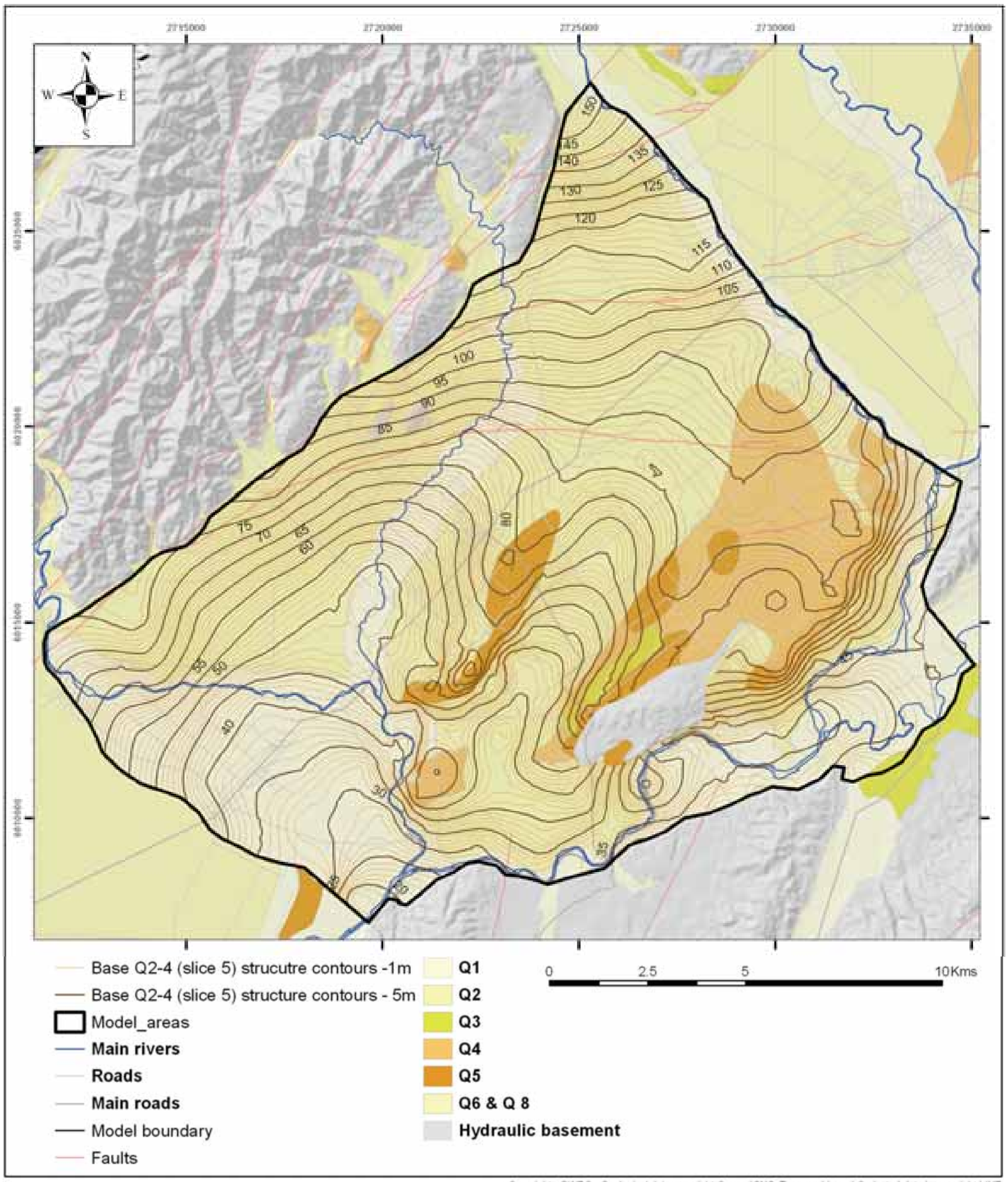
Model slice structure contours (main layers)



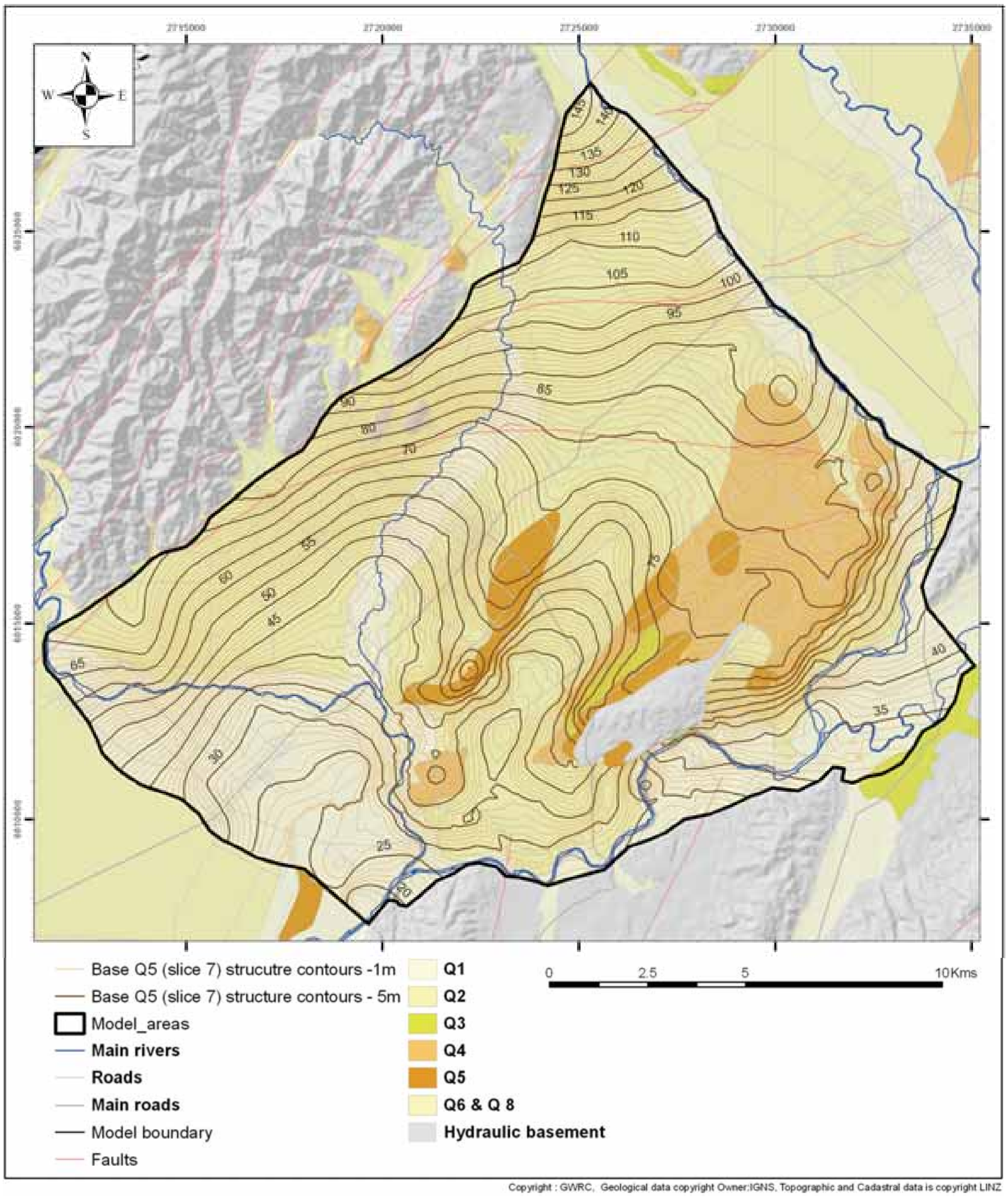
Structure contours – FEFLOW SLICE 1



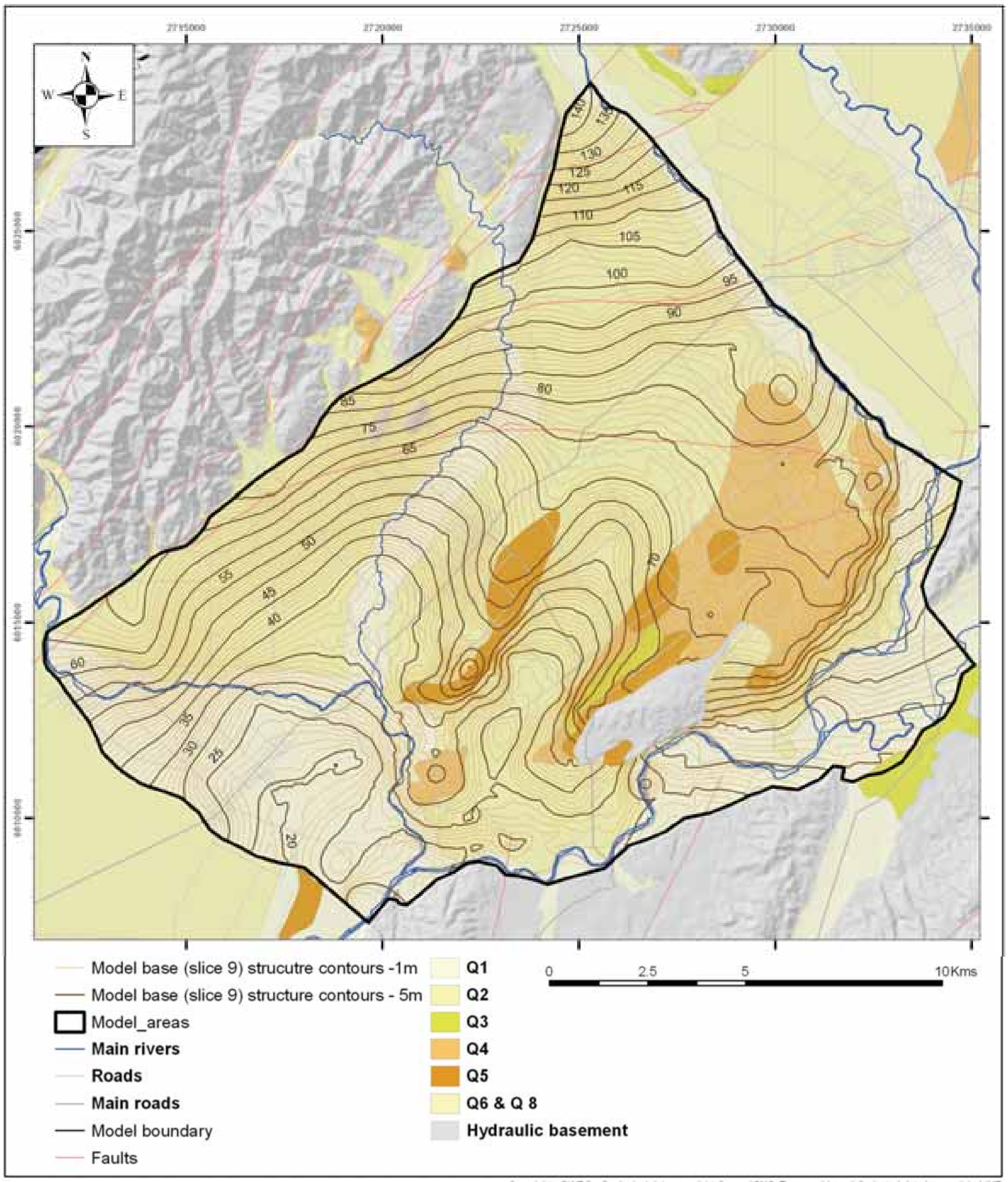
Structure contours – FEFLOW SLICE 3



Structure contours – FEFLOW SLICE 5



Structure contours – FEFLOW SLICE 7



Structure contours – FEFLOW SLICE 9

Appendix 8:

Mike11 surface water model for the Middle Valley catchment

A MIKE11 surface water model was developed for the Middle Valley catchment to provide time-varying river stage data to the FEFLOW groundwater flow model. FEFLOW simulates river boundary conditions using Transfer (Cauchy/3rd kind) boundary nodes which describe a time-varying reference hydraulic head (river stage).

Model software

The modelling software used was the Danish Hydraulic Institute (DHI) hydraulic modelling package MIKE11 (version 2004)[1] which simulates flow, water quality and sediment transport in rivers, estuaries, irrigation systems, and channels. MIKE11 uses the Saint-Venant one-dimensional unsteady flow equations to model open channel flow. It is a one-dimensional modelling tool for the detailed analysis, design, management and operation of simple or complex river systems.

MIKE11 produces flow, velocities and water levels throughout the river system based upon the surveyed river cross sections and a longitudinal grid system. MIKE11 accounts for the dynamic effects of catchment inflows and channel storage.

Modelled river systems

The Middle Valley surface water model incorporates the Waingawa and Waiohine rivers, the Mangatarere Stream, and the Ruamahanga River between its confluences with the Waingawa and Waiohine rivers. This area matches that used in the Middle Valley groundwater model developed in FEFLOW.

Input flow data

Flow data were available at a number of recorder sites within the catchment and are archived on Greater Wellington hydrological database (Hilltop) as detailed in Table A8.1. The flow data cover the period June 1992 to May 2007 (the FEFLOW model calibration period).

Because the Mangatarere Stream at Gorge site only commenced operation in 1999, a synthetic flow record was produced to fill the record gap prior to 1999 based on a correlation developed from two nearby gauging sites (Atiwhakatu River at Mt Holdsworth and Waingawa River at Kaituna). For the period 1 July 1992 to 22 August 1997 flow data for the Mangatarere Stream were synthesised using a correlation based on the flow at the Atiwhakatu site at Mt Holdsworth Rd (Harkness 2005):

Mangatarere Stream at Gorge (L/s) = 0.5652 (Atiwhakatu River at Mt Holdsworth Rd (L/s)) – 124.37

For the period 22 August 1997 to 8 February 1999 flow data were synthesised using a correlation based on all Mangatarere gaugings and the rated flow at the Waingawa River at Kaituna site for the period 1999–2007:

*Mangatarere Stream at Gorge (m^3/s) = 0.1526 * Waingawa River at Kaituna* $(m^3/s)^{1.0792}$

[1] An earlier version of the original Middle Valley MIKE 11 model was developed by MWH Ltd, but later refined by Greater Wellington.

After 8 February 1999, the site Mangatarere Stream at Gorge was fully rated for flow at all stages, therefore data from that date on are from the actual record.

Table A8.1: Flow data

Site	Site No.	Map Reference
Ruamahanga at Wardells	29201	T26:347192
Waingawa at Upper Kaituna	29246	S26:227324
Mangatarere at Gorge	29243	S26:209274
Waiohine at Gorge	29224	S26:117183

Averaging of data

The FEFLOW model runs on a 7-day time step. In order to speed up run times and attempt to increase the stability of the MIKE11 models the flow data were averaged on a 7-day moving mean basis with the output time step being the last time step of the 7-day period. That is, each data point in the averaged data file represents the mean flow for the previous 7 days. This averaging was done using virtual measurements in Hilltop and then exported in a format suitable for MIKE11.

Integration of water takes

Those river flow gauging sites used in the MIKE11 model are all located at or just before the rivers exit from the Tararua Range onto the Wairarapa plain. Therefore the flow record does not take into account any water removed from the channels for water supply and irrigation downstream of the flow gauges. This may result in an artificially high flow in the rivers downstream of the flow gauges. Unfortunately, continuous records of the water being taken from the rivers by consent holders, including the large water supply and irrigation takes, are not readily available. As a way of estimating the effect of these takes on the model outcomes, a version of the MIKE11 flow data sets was developed that assumed all the major consented water takes were abstracting at their maximum consented rates during the model period. This is discussed further for each river below.

Waingawa River

There are two major consented water takes on the Waingawa River: the Masterton Water Treatment Plant (WAR940080) and the Taratahi Water Race (WAR010227). Both of these consents run on a stepped regime based on gauged flows at the Waingawa River at Kaituna.

The Masterton Water Treatment Plant is somewhat unique in that at most times more water is extracted from the Waingawa River than is actually used, with the remainder being returned to the river further downstream. There is just one step-down level on this take. This is shown in Table A8.2.

Table A8.2: Masterton Water Treatment Plant–Waingawa River abstraction regime

Waingawa R flow at Kaituna (L/s)	>1,900	<1,900
Maximum abstraction (L/s)	463	324
Maximum consumption (L/s)	405	324
Return to Waingawa (L/s)	58	0

Abstraction for the Taratahi Water Race has two step-down levels. This is shown in Table A8.3.

Table A8.3: Taratahi Water Race–Waingawa River abstraction regime

Waingawa R flow at Kaituna (L/s)	>1,900	1,700-1900	<1,700
Maximum abstraction (L/s)	482	410	337

The combined allowable take, based on the flow at Waingawa River at Kaituna and the step-down regime, were subtracted from the flow record at the flow gauge. This was then converted into a 7-day mean flow record as described above.

Waiohine River

There are two major consented water takes on the Waiohine River below the flow gauge in the Waiohine Gorge: the Greytown Water Treatment Plant (WAR990142) and the Moroa Water Race (WAR010200). The separate and combined regimes are shown in Table A8.4.

Table A8.4: Greytown Water Treatment Plant and Moroa Water Race–Waiohine River abstraction regime

Waiohine R flow at Gorge (L/s)	<2,300	2,300-3,040	3,040-4,000	>4,000
Greytown Water Treatment Plant (L/s)	60	100	180	180
Moroa Water Race (L/s)	350	400	450	500
Total abstraction (L/s)	410	500	630	680

Note: When flow at Waiohine River at Gorge is less than 3,040L/s the combined take of the Water Treatment Plant and Water race must be less than 500L/s.

Mangatarere Stream

On the Mangatarere Stream, there is one significant take for the Carrington Water Race (WAR010202). However there is another take for the Carterton Water Supply (WAR020050) on the Kaipaitangata Stream, a tributary of the Mangatarere Stream. As the Kaipaitangata Stream was not included in the MIKE11 model, the take was also not considered. There is a single step-down abstraction regime for the Carrington Water Race based on the flow in the Mangatarere Stream at Gorge, as shown in Table A8.5.

Table A8.5: Carrington Water Race–Mangatarere Stream abstraction regime

Mangatarere S flow at Gorge (L/s)	>150	<150
Maximum abstraction (L/s)	113	50

It should be noted that there are times when the maximum allowable take of 50 L/s (when Mangatarere Stream at Gorge is flowing at less than 150 L/s) is more than the total flow in the stream. For the model purposes it was assumed that in this situation all water is removed from the stream and flow was set to 0 L/s.

Cross section data

River cross sections are surveyed by Greater Wellington as part of its flood protection role. A total of 171 cross sections with corresponding level data and location co-ordinates were incorporated into the MIKE11 model – the most recent cross section data for the rivers in the model are detailed in Table A8.6. Because not all cross sections can be surveyed at one time there is sometimes a range of dates that cover each branch. Cross sections were imported directly into MIKE11 from the Hilltop database.

Table A8.6: Cross section data

River	Survey date	Number of sections
Ruamahanga River	2000-2007	49
Waingawa River	2001	30
Mangatarere Stream	2001	47
Waiohine River	2004-2004	45

The level data were supplied in the Wairarapa Catchment Board Datum. The groundwater model was developed based on level data using the L&S Datum. Therefore, all the river cross section data were converted to the L&S Datum by subtracting 9.22 m from all cross section data.

Hydrodynamic modelling

MIKE11 produces flow, velocities and water levels at Hnodes based upon the surveyed river cross sections and a longitudinal grid system. MIKE11 also accounts for the dynamic effects of catchment inflows and channel storage.

The MIKE11 model of the Middle Valley catchment consists of four branches (Ruamahanga, Waingawa, Waiohine and Mangatarere) that replicate the drainage system. A total of 178 Hnode points were used in the model corresponding to the 171 surveyed cross sections plus interpolated sections at river confluences and at the FEFLOW model boundaries.

The only inflows to the current model set up came from the flow recorders sites at the upstream boundary of the four branches as described above. The downstream boundary condition at the last cross section on the Ruamahanga River is a simple Q-h (discharge-water level) relationship. The relationship is shown in Table A8.7.

The frictional effect of the river channels on flows are represented by the Manning's n channel roughness coefficient. A Manning's n channel roughness parameter of 0.045 was applied globally to all branches of the model.

Table A8.7: Discharge-water level relationship at the downstream end of the Middle Valley model

Stage height, h (m, L&S Datum)	Discharge, Q (m^3/s)
33.36	0
33.86	7.5
33.87	7.8
33.88	8
33.9	8.6
33.934	9.6
33.982	11.3
34.04	14.3
34.16	21.6
34.36	38.4
34.56	59
34.76	87
34.96	125
35.26	193
35.76	343
35.96	420
36.76	625
37.76	920
38.76	1220
39.76	1500
40.76	1790
41.76	2080
42.76	2360
44.76	2920
46.76	3500

Model files

The MIKE11 model consists of a number of files linked by a simulation file. When the model runs it produces a results file that contains the water level and discharge results for all or selected nodes within the model.

Appendix 9:

Groundwater flow model for the Middle Valley catchment of the Wairarapa Valley: PEST interface script for FEFLOW

APPENDIX B

GROUNDWATER FLOW MODEL FOR THE MIDDLE VALLEY CATCHMENT OF THE WAIRARAPA VALLEY

A PEST INTERFACE TO PERFORM AUTOMATED FEFLOW MODEL CALIBRATION

Introduction

A numerical groundwater flow model for the Middle Valley Catchment of the Wairarapa Valley has been developed by coupling a surface water model (MIKE11 code) and a groundwater model (FEFLOW code) using the IFMMIKE11 interface in the FEFLOW model. The objective of the groundwater model is to evaluate the groundwater system and to predict groundwater levels under different abstractions and climate stress scenarios in order to manage the water resource sustainably in the Middle Catchment of the Wairarapa Valley.

In terms of the MDBC modelling guideline (MDBC, 2001), the FEFLOW model of the Middle Valley Catchment of Wairarapa is best categorised as an aquifer simulator of high complexity. As such, the prediction reliability of the groundwater model is the major issue in the model calibration. Figure 1 indicates the GWRC registered groundwater bores (abstraction and monitoring bores) within the model area. Figures 2 to 4 provide comparisons of observed and simulated hydrographs after the GWRC manual calibration.

Questions on prediction reliability are difficult to address using manual calibration procedures. Use of inverse models such as PEST (Doherty, 2008) are becoming increasingly popular in groundwater modelling because PEST provides not only parameter estimates and heads and flows simulated for the stresses of interest, but also confidence intervals for both the estimated parameters and heads and flows. These confidence intervals are convenient for conveying the reliability of the results to end-user.

Appendix B provides a guidance to implement an automated calibration procedure using PEST for groundwater model calibration for the Middle Valley Catchment of Wairarapa.

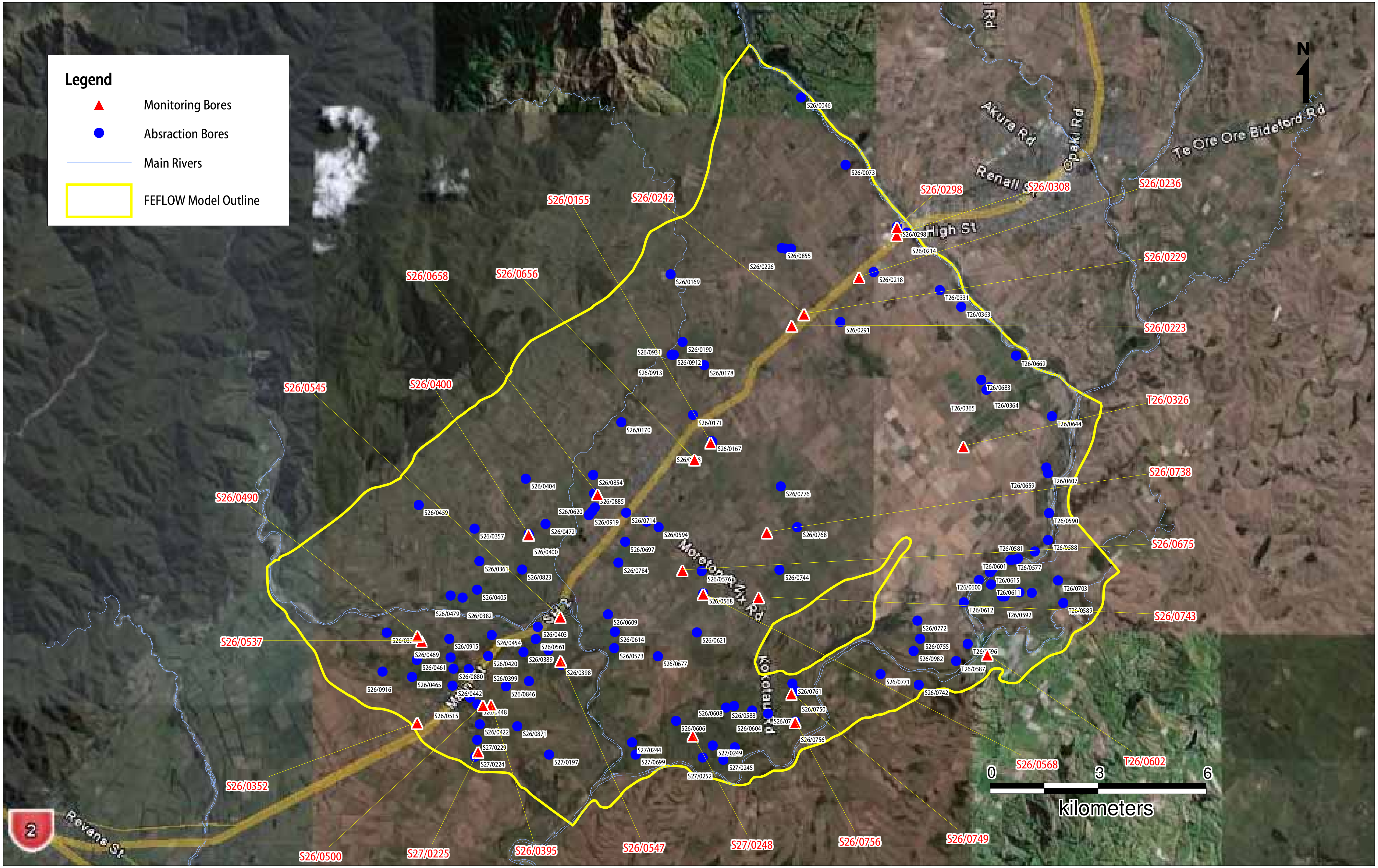


Figure 1
GWRC REGISTERED GROUNDWATER BORES

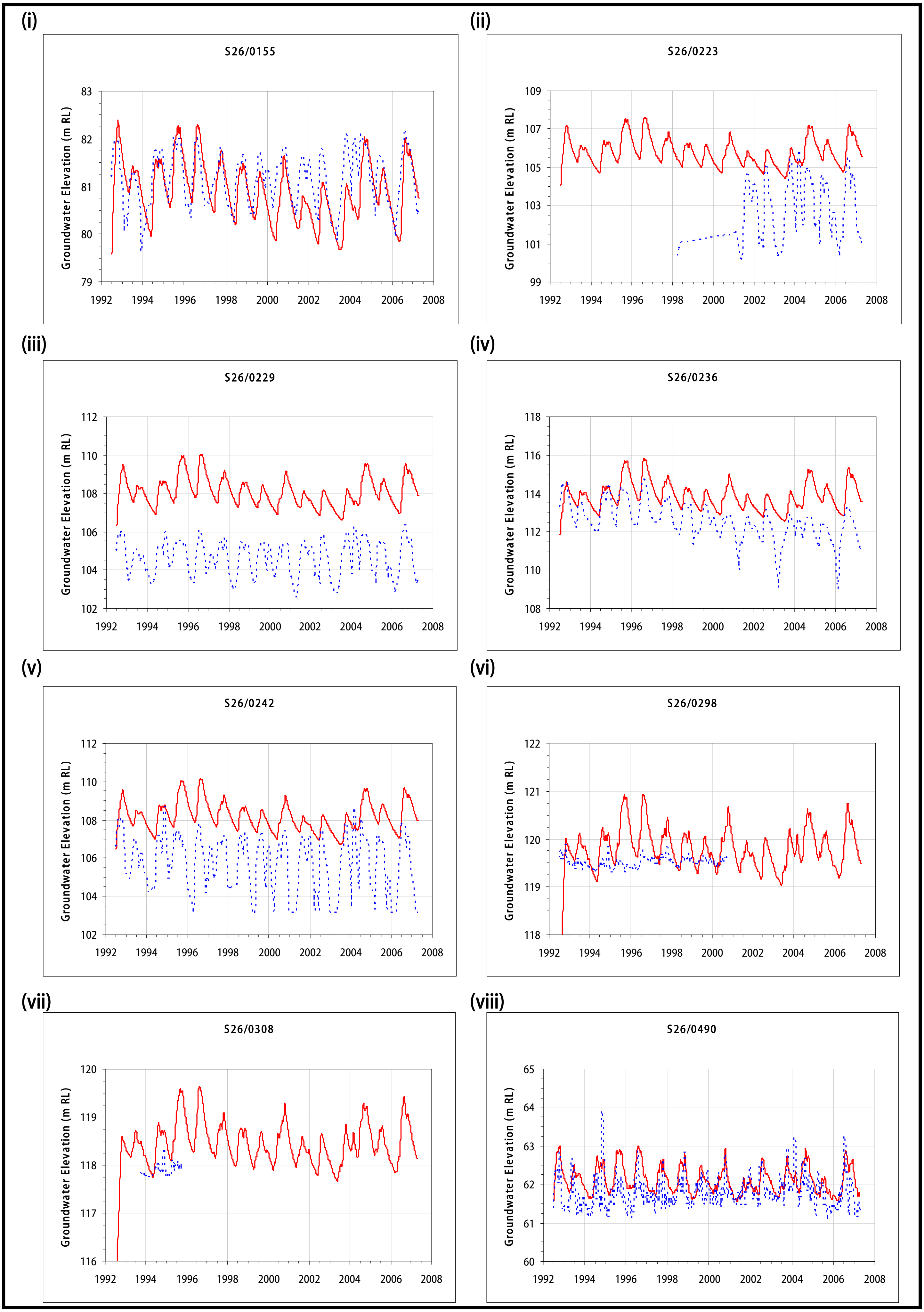


Figure 2
COMPARISON OF OBSERVED & SIMULATED HYDROGRAPHS (AFTER GWRC MANUAL CALIBRATION)

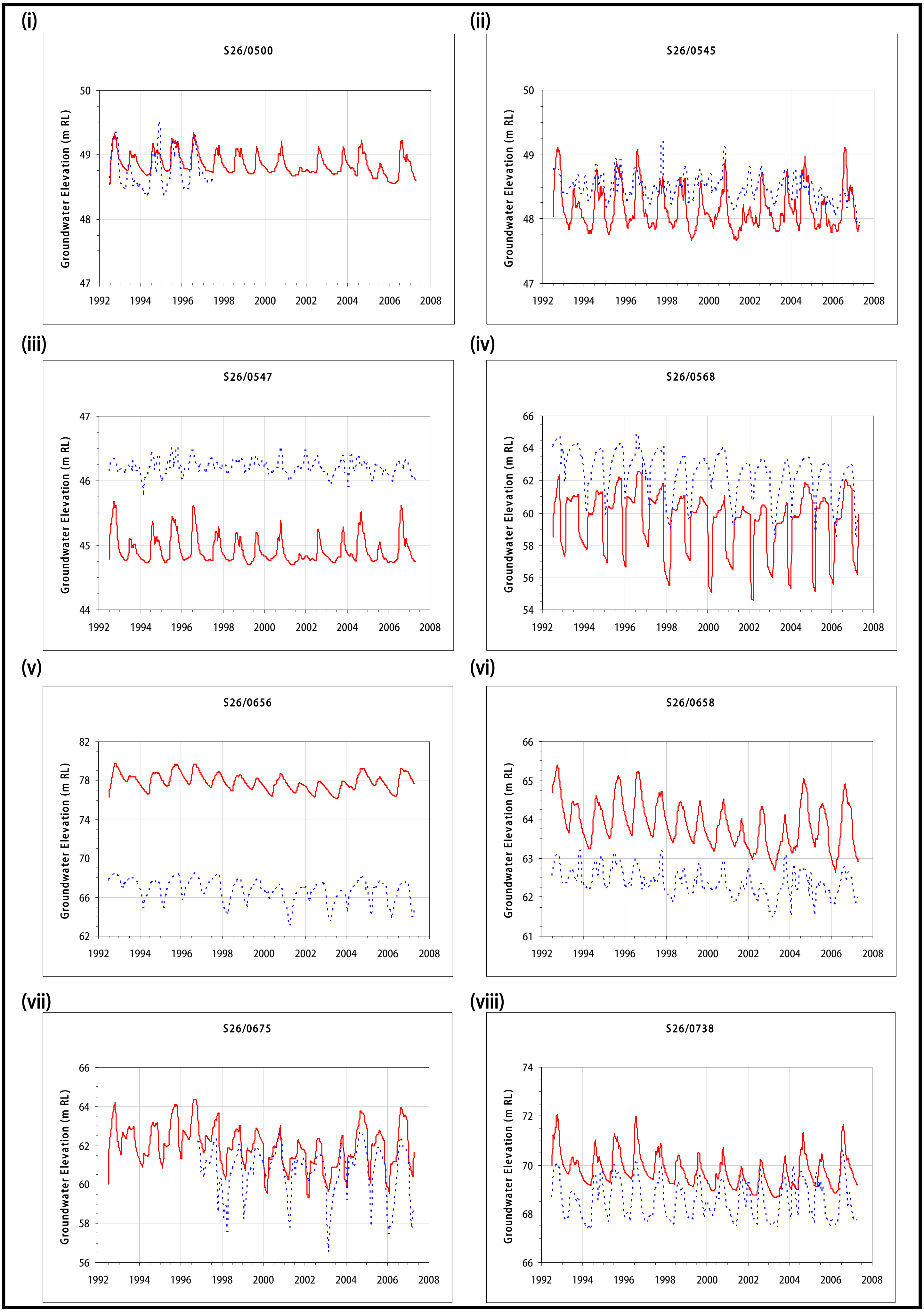
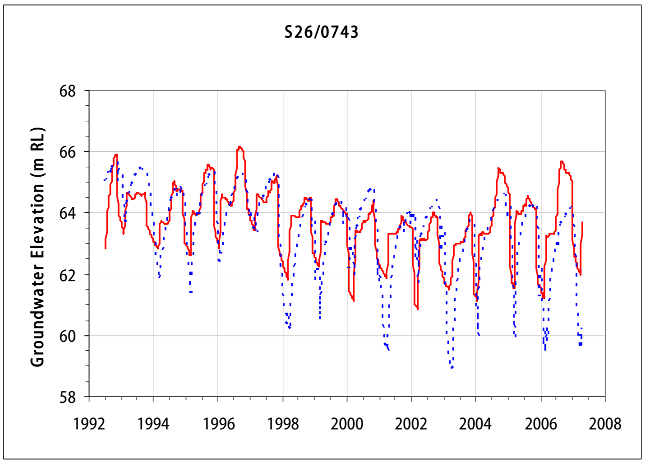
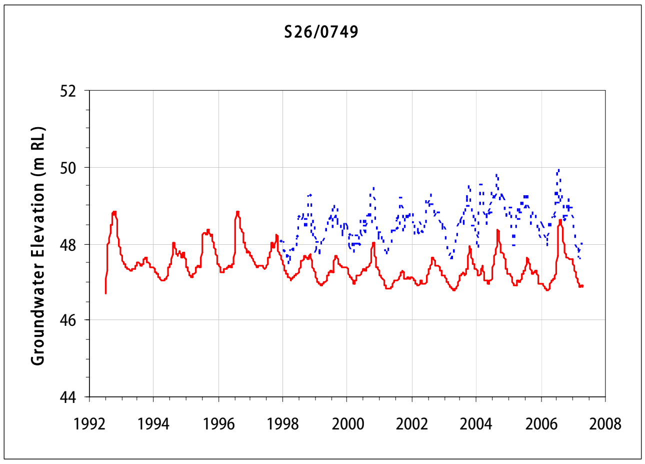


Figure 3
COMPARISON OF OBSERVED & SIMULATED HYDROGRAPHS (AFTER GWRC MANUAL CALIBRATION)

(i)



(ii)



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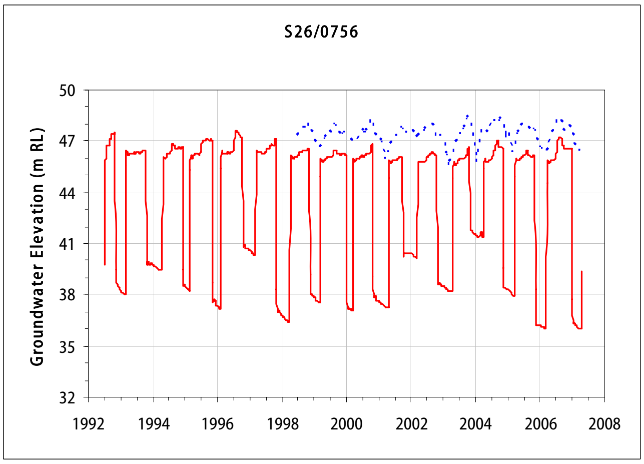
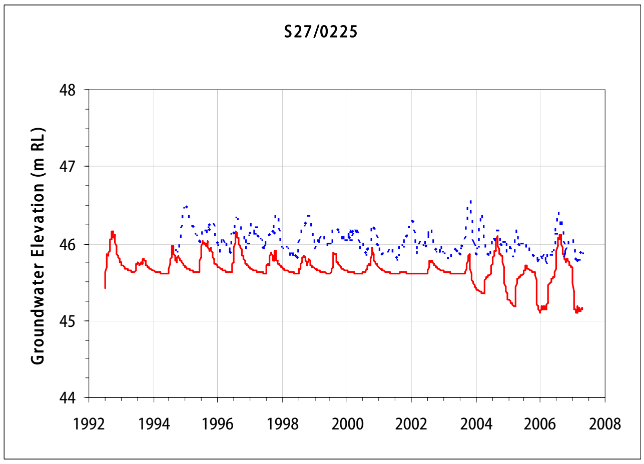


(iv)



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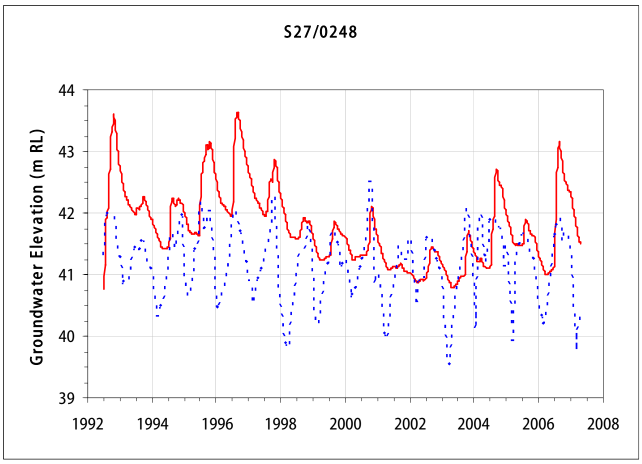

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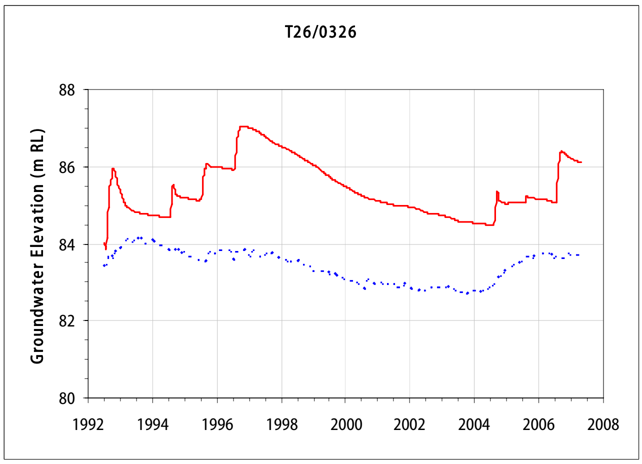

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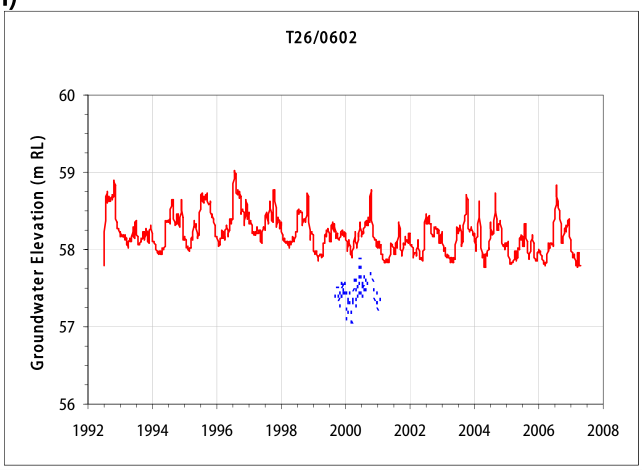

(viii)

Figure 4
COMPARISON OF OBSERVED & SIMULATED HYDROGRAPHS (AFTER GWRC MANUAL CALIBRATION)

2. FEFLOW-PEST Interface

The latest version of PEST, and all of its utility software, is available from the following web site:

http://www.sspa.com/Pest/index.shtml

The latest groundwater data utilities are also available from the following web site and the compressed groundwater data utilities have to be expanded (unzipped) to a directory of your choice (add this directory to "environment system variable – PATH").

http://www.sspa.com/Pest/utilities.shtml

PEST requires three types of input file. These are:

- Template files - one for each model input file on which parameters are identified;
- Instruction files - one for each model output file on which model-generated observations are identified; and
- An input control file, supplying PEST with the names of all template and instruction files, the names of the corresponding model input and output files, the problem size, control variables, initial parameter values, measurement values and weights, etc.

2.1. Template file

PEST provides a set of parameter values which it wants the model to use for a particular model run. The only way that the model can access these values is to read them from its input file(s). PEST achieves this through a template file which contains parameters requiring optimisation.

There are two groups of parameters (hydraulic conductivity and storativity) that are to be initially calibrated in the FEFLOW model. Figure 5 provides 11 hydraulic conductivity zones identified in the groundwater model and uniform values for specific yield and specific storage are assigned in the model. The hydraulic conductivity for each zone and the storativity values for the model domain are provided in a look-up table (i.e. the template file). Table B.1 provides that template file:

Table B.1 Template for FEFLOW model parameters

ptf # zone ID		Value	
1	#	HY01	#
2	#	HY02	#
3	#	HY03	#
4	#	HY04	#
5	#	HY05	#
6	#	HY06	#
7	#	HY07	#
8	#	HY08	#
9	#	HY09	#
10	#	HY10	#
11	#	HY11	#
12	#	SYD1	#
13	#	SST1	#

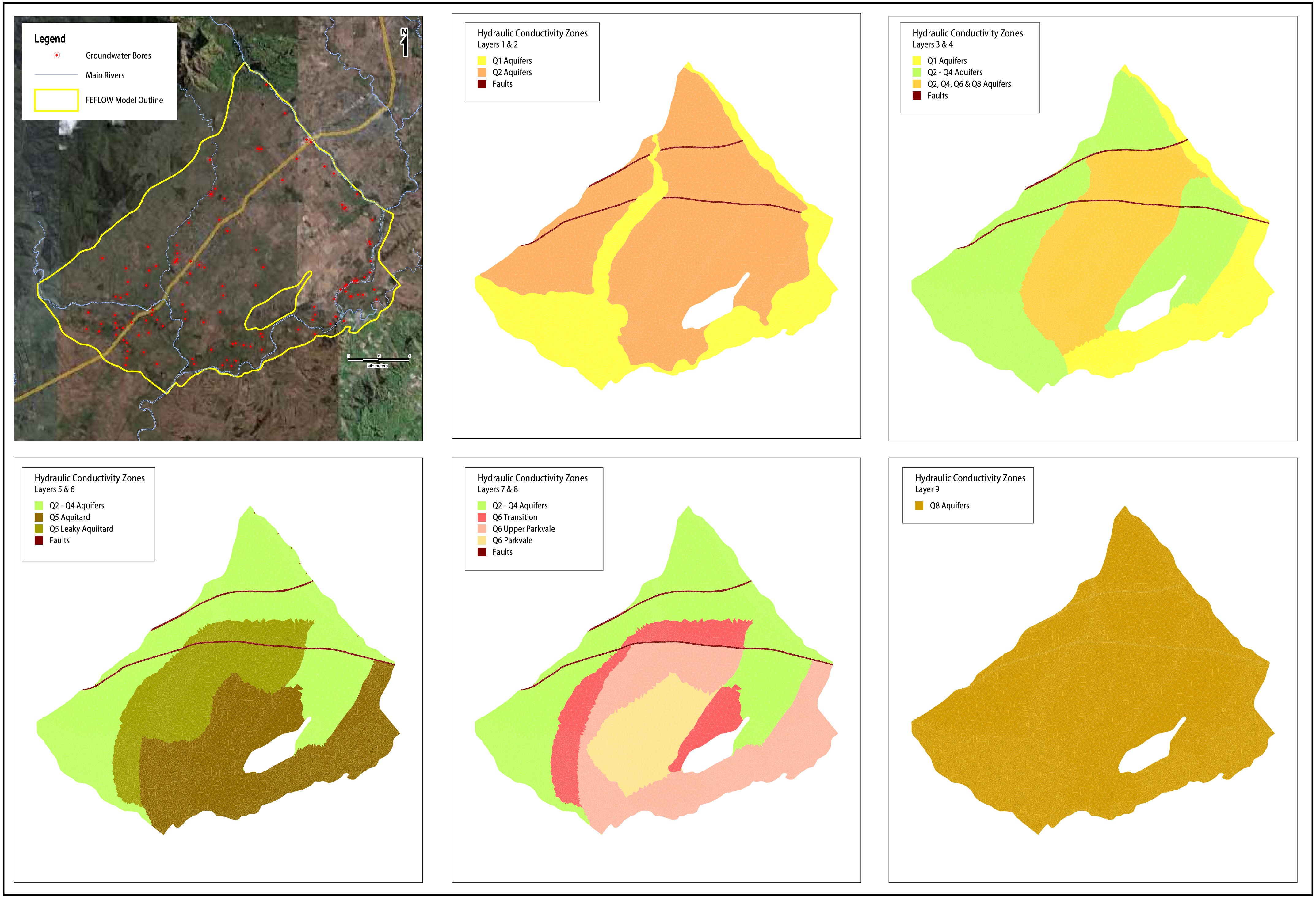

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Figure 5
HYDRAULIC CONDUCTIVITY ZONATION

There are 21,074 finite elements in each FEFLOW model layer and Figure 6 indicates the finite element mesh of the FEFLOW model (N.B. in Figure 6 the inset provides the element number for part of Layer 1). The relationship between the FEFLOW model elements and their respective hydraulic conductivity zones are provided in Table B.2.

Table B.2 FEFLOW model element number and hydraulic conductivity zone

FEFLOW Element ID	Hydraulic Conductivity Zone ID								
	Layer 01	Layer 02	Layer 03	Layer 04	Layer 05	Layer 06	Layer 07	Layer 08	Layer 09
1	1	1	2	2	2	2	2	2	11
2	4	4	3	3	5	5	9	9	11
3	4	4	3	3	5	5	9	9	11
4	1	1	2	2	2	2	2	2	11
5	1	1	2	2	2	2	2	2	11
-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-
21070	4	4	2	2	2	2	2	2	11
21071	4	4	2	2	2	2	2	2	11
21072	4	4	2	2	2	2	2	2	11
21073	4	4	2	2	2	2	2	2	11
21074	4	4	2	2	2	2	2	2	11

The FEFLOW model ASCII file (*.fem) has a general structure with a variable number of statements necessary to describe a FEFLOW model. The flow material data in the ASCII file are provided under the following sub-headings:

- 101 Conductivity in x-direction for 3D (m/d);
- 103 Conductivity in y-direction for 3D (m/d);
- 105 Conductivity in z-direction for 3D (m/d);
- 110 Storativity (drain- or fillable) or density ratio (1); and
- 112 Storage compressibility (1/m) (2D unconfined / 3D) (1) (2D confined).

The flow material data are stored in the following format:

material_value node_list (The elements where the material_value is to overwrite the default value.)

Once, PEST has identified a new set of parameters as described in the template file, the material value in the FEFLOW ASCII file (*.fem) will be replaced with the new set of parameters and subsequently the FEFLOW model run will be performed. Table B.3 indicates the part of the master ASCII file which will be used to create new FEFLOW model file (*.fem) once PEST has identified a new set of parameters (i.e. @@HYX, @@HYY, @@HYZ, @@SYD and @@SST in Table B.3 will be replaced with new flow material data).

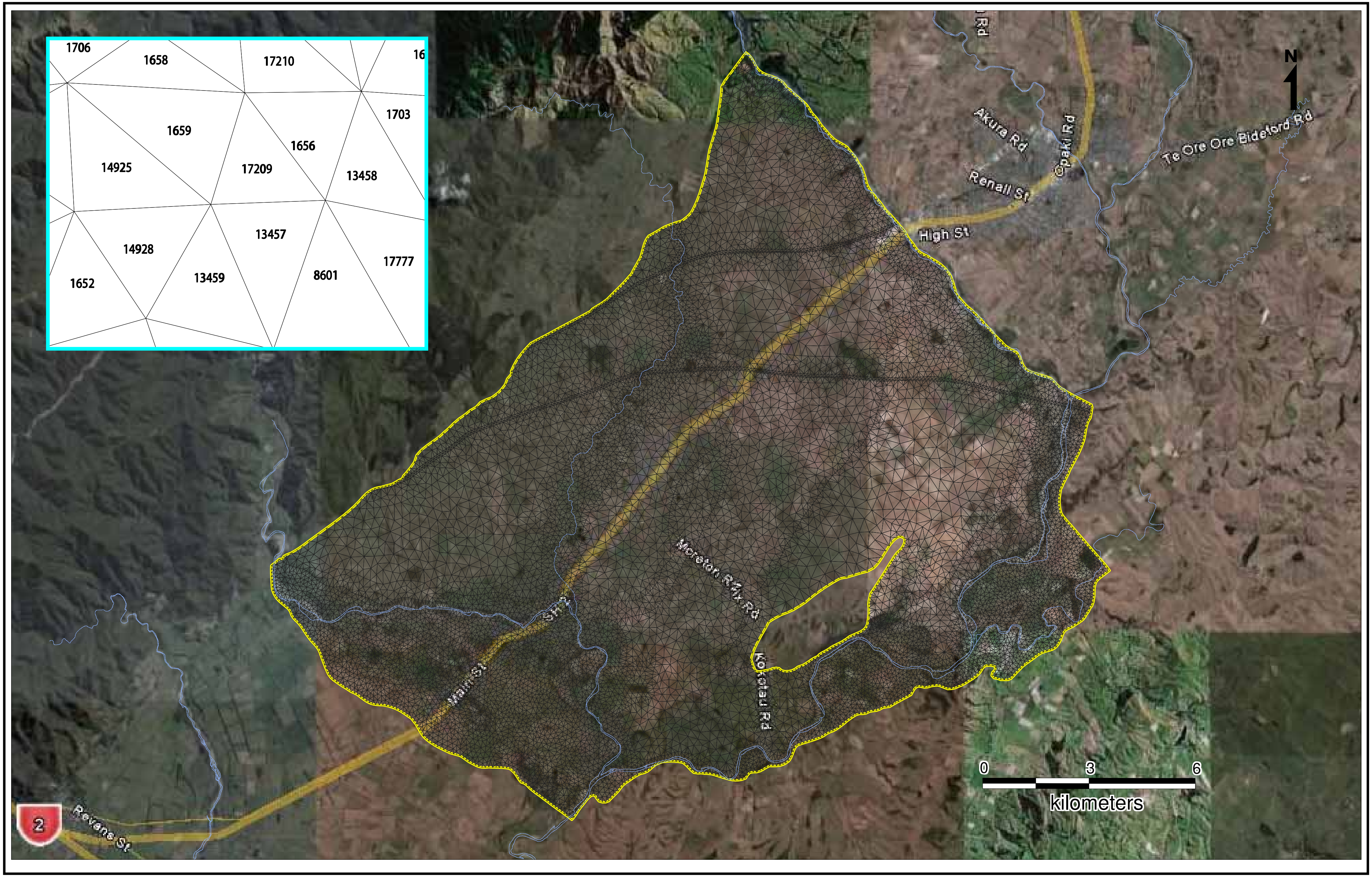

Figure 6
FEFLOW MODEL GRID AND ELEMENT NUMBERS IN LAYER 1

Table B.3 Flow material data in the master FEFLOW ASCII file

```
MAT_I_FLOW
101 0.000000e+000 "Conductivity in x-direction for 3D"
@@HYX
103 0.000000e+000 "Conductivity in y-direction for 3D"
@@HYY
105 0.000000e+000 "Conductivity in z-direction for 3D"
@@HYZ
110 0.000000e+000 "Storativity (drain- or fillable) or density ratio"
@@SYD
112 0.000000e+000 "Storage compressibility"
@@SST
```

2.2. Instruction file

The FEFLOW model ASCII output file (*.dar) contains voluminous amount of data, however PEST requires only the model simulated head at the monitoring bore locations to compare with the historical observed data. The instruction file provides information regarding how to find the FEFLOW simulated water levels /heads at the monitoring bore locations. One of the Groundwater Data Utility (GDU) programs (DAR2SMP) reads the FEFLOW ASCII output file (*.dar) and then writes simulated groundwater levels / heads at the model time steps (7 days) in the "bore sample format" (Doherty, 2008). Then another GDU program (SMP2SMP) reads the simulated bore sample file and writes the simulated groundwater levels / heads corresponding to observed time steps. PEST compares the observed groundwater levels / heads against the simulated groundwater levels / heads using the instruction file. Table B.4 provides part of the instruction file (first column) and the corresponding bore sample file.

Table B.4 Instruction file & bore sample file

pif #				
l1 (O0001)38:55	s26_0155	01/07/1992	12:00:00	81.195667
l1 (O0002)38:55	s26_0155	08/07/1992	12:00:00	81.226657
l1 (O0003)38:55	s26_0155	15/07/1992	12:00:00	81.348257
l1 (O0004)38:55	s26_0155	22/07/1992	12:00:00	81.483057
l1 (O0005)38:55	s26_0155	29/07/1992	12:00:00	81.617857
l1 (O0006)38:55	s26_0155	05/08/1992	12:00:00	81.816000
- -		- -		
- -		- -		
l1 (O5170)38:55	t26_0326	11/03/1998	12:00:00	83.514686
l1(O5171)38:55	t26_0326	18/03/1998	12:00:00	83.502671
l1 (O5172)38:55	t26_0326	25/03/1998	12:00:00	83.490057
l1 (O5173)38:55	t26_0326	01/04/1998	12:00:00	83.477043

2.3. PEST control file

The PEST control file provides information necessary to carry out the automated model calibration by supplying PEST with the names of the template file and the instruction file together with the corresponding model input/output files. It also provides PEST with the model execution file (model.bat), parameter initial estimates with the range, observed groundwater levels to which model simulated groundwater levels are to be matched. Table B.5 provides a part of the pest control file.

Table B.5 Part of PEST control file

```
pcf
* control data
restart  estimation
13     5173     02  0    21
1      1     single point  1    0    0
--
* parameter groups
hy      relative 0.01  0.0  switch  2.0 parabolic
ss      relative 0.01  0.0  switch  2.0 parabolic
* parameter data
hy01  log factor    350.000        1.500000E+01   4.000000E+03   hy   1.0000   0.0000   1
hy02  log factor    150.000        1.000000E+00   6.000000E+02   hy   1.0000   0.0000   1
hy03  log factor    200.000        1.000000E+01   8.000000E+02   hy   1.0000   0.0000   1
hy04  fixed factor  40.0000        1.000000E+01   1.000000E+02   hy   1.0000   0.0000   1
hy05  log factor    5.000000E-03   1.000000E-03   1.000000E-02   hy   1.0000   0.0000   1
hy06  log factor    5.000000E-02   1.000000E-02   1.000000E+00   hy   1.0000   0.0000   1
hy07  log factor    50.0000        2.000000E+00   2.000000E+02   hy   1.0000   0.0000   1
hy08  log factor    100.000        5.000000E+00   4.000000E+02   hy   1.0000   0.0000   1
hy09  log factor    100.000        1.000000E+01   8.000000E+02   hy   1.0000   0.0000   1
hy10  log factor    0.05000        1.000000E-02   2.000000E+00   hy   1.0000   0.0000   1
hy11  fixed factor  5.00000        1.000000E+00   1.000000E+02   hy   1.0000   0.0000   1
syd1  log factor    0.100000       1.000000E-02   3.000000E-01   ss   1.0000   0.0000   1
sst1  log factor    1.000000E-03   1.000000E-05   1.000000E-02   ss   1.0000   0.0000   1
* observation groups
s26_0155
--
s27_0248
t26_0326
* observation data
O0001      81.195667   0.75   s26_0155
O0002      81.226657   0.75   s26_0155
O0003      81.348257   0.75   s26_0155
O0004      81.483057   0.75   s26_0155
O0005      81.617857   0.75   s26_0155
- -
O5170      83.514686   0.75   t26_0326
O5171      83.502671   0.75   t26_0326
O5172      83.490057   0.75   t26_0326
O5173      83.477043   0.75   t26_0326
* model command line
model.bat
* model input/output
par.tpl  par.txt
out.ins  intsimlvl.smp
* prior information
```

As indicated in Table B.5, the "parameter data" section of the pest control file contains 13 parameters (hy01 – hy11, syd1 & sst1) along with their initial parameter values and their upper and lower bounds. The two hydraulic conductivity parameters for zones 4 and 11 are fixed with 40 and 5 m/d respectively. These parameters will not take part in the optimising process.

There are 21 observation groups (monitoring bores) and the "observation data" section of the pest control file contains 5,173 observations and their respective groups with the weight attached to each residual in the calculation of the objective function. If the assigned observation weight is zero, that observation will not contribute in the calculation of the objective function.

The "model command line" of the pest control file supplies the command that will be called by PEST to run the model once PEST has identified a new set of parameters. The following section details the model execution file.

2.4. Model execution file

Once PEST has identified a new set of parameters, it calls a batch file (model.bat) to run the FEFLOW model. The batch file contains the following sequence of steps:

- Transfer the PEST identified parameters into the FEFLOW model ASCII file (*mvcw*);
- Execution of the FEFLOW model (*feflow54c*);
- Separation of the simulated groundwater levels/heads from the FEFLOW ASCII output file (*dar2smp*); and
- Selection of the simulated groundwater levels/heads to the corresponding observed values (*smp2smp*).

Table B.6 provides the contents of the model execution file. Due to voluminous nature of model input/output files, "program wait" is introduced to make sure that the input/output files are written completely before the execution of the following program.

Table B.6 PEST model execution file

```
@echo off
wait > NUL
mvcw > NUL
wait > NUL
wait > NUL
"C:\program files\wasy\feflow 5.4\bin32\feflow54c.exe" -run -work C:\GWRC\FEFLOW\ -steps tstep.pow -dar temp.dar -log mvcw.log mvcw.fem > NUL
wait > NUL
wait > NUL
copy ..\results\temp.dar  simlvl.dar > NUL
wait > NUL
wait > NUL
dar2smp < dar2smp.inp > NUL
wait > NUL
wait > NUL
smp2smp < smpsmp.inp > NUL
```

3. PEST Calibration

3.1. PEST setup

The FEFLOW groundwater model has been developed for the period from 1 July 1992 to 1 May 2007 and simulates transient groundwater system behaviour at weekly time step. The groundwater model has nine layers (189,666 elements) and takes an execution time of 4 hours on a Microsoft WINDOWS XP platform with 3 GB of RAM. A limited calibration period from 1 July 1992 to 1 April 1998 was adopted to allow reasonable computing run times whilst leaving the balance of the available period of observed data for model verification purposes.

If a longer period is desired for model calibration, the additional observations can be easily included in the "observation data" in the PEST control file with the addition of instructions to PEST to obtain corresponding simulated groundwater levels/heads. Table B.7 provides initial parameter values and their lower and upper bounds with the parameter hy04 and hy11 fixed at 40 and 5 m/d respectively.

Table B.7 Parameter data for PEST

Parameter	Transformation	Initial Value	Lower Bound	Upper Bound
hy01	log factor	350	1.50E+01	4.00E+03
hy02	log factor	150	1.00E+00	6.00E+02
hy03	log factor	200	1.00E+01	8.00E+02
hy04	fixed factor	40	1.00E+01	1.00E+02
hy05	log factor	5.00E-03	1.00E-03	1.00E-02
hy06	log factor	5.00E-02	1.00E-02	1.00E+00
hy07	log factor	50	2.00E+00	2.00E+02
hy08	log factor	100	5.00E+00	4.00E+02
hy09	log factor	100	1.00E+01	8.00E+02
hy10	log factor	0.05	1.00E-02	2.00E+00
hy11	fixed factor	5	1.00E+00	1.00E+02
syd1	log factor	0.1	1.00E-02	3.00E-01
sst1	log factor	1.00E-03	1.00E-05	1.00E-02

There are 21 observation groups (monitoring bores) in the PEST control file. Table B.8 provides the weights assigned to each monitoring bore and the number of observations in each monitoring bore included in the PEST control file.

Table B.8 outline of observation data used in PEST

Monitoring Bore	Weights	7 day mean of observed data (m RL)		Range of fluctuations (m)	Number of observed data
		Minimum	Maximum		
s26_0155	0.75	79.633	82.044	2.412	301
s26_0223	0.00	100.410	100.421	0.011	3
s26_0229	1.00	102.977	106.130	3.153	301
s26_0236	1.00	111.940	114.771	2.831	301
s26_0242	1.00	103.133	108.729	5.596	301
s26_0298	0.50	119.298	119.891	0.593	301
s26_0308	1.00	117.737	118.360	0.623	109
s26_0490	1.00	61.131	63.930	2.799	301
s26_0500	1.00	48.343	49.536	1.193	263
s26_0545	1.00	48.176	49.210	1.034	301
s26_0547	1.00	45.769	46.540	0.771	301
s26_0568	0.75	59.056	64.907	5.850	301
s26_0656	0.00	64.180	68.492	4.312	301
s26_0658	0.75	61.872	63.223	1.351	301
s26_0675	1.00	57.597	62.337	4.739	77
s26_0738	0.75	67.368	70.095	2.727	301
s26_0743	0.75	60.188	65.685	5.496	301
s26_0749	1.00	47.472	48.072	0.600	18
s27_0225	1.00	45.838	46.481	0.643	188
s27_0248	0.75	39.813	42.300	2.487	301
t26_0326	0.75	83.402	84.144	0.742	301

3.2. PEST control files

The initial PEST control file (HY12300.PST) was generated using the PEST utility program (PESTGEN) and Tikhonov regularisation constraints were added to the HY12300.PST PEST control file using the following command:

addreg1 HY12300.PST REG12300.PST

The REG12300.PST PEST control file was run till the first optimisation (11 FEFLOW model runs) to obtain the corresponding Jacobian matrix file. Once the Jacobian matrix was written, a single value decomposition (SVD) functionality was introduced using the PEST utility program (SVDAPREP). The main advantage of introducing the SVD functionality is that it combines the model parameters into fewer super parameters and substantially reduces the PEST run time. The SV12300.PST PEST control file which contains four super parameters, was used for the PEST optimisation.

3.3. PEST output

Table B.9 provides summary of PEST optimisation results. The overall objective function reduced from 17,114 to 4,057 (i.e. 76 % reduction) during the PEST optimisation.

Table B.9 Summary of PEST optimisation

```
Objective function ----->

 Sum of squared weighted residuals (ie phi)           =  4057.
 Contribution to phi from observation group "s26_0155"   =  275.5
 Contribution to phi from observation group "s26_0223"   =  0.000
 Contribution to phi from observation group "s26_0229"   =  271.9
 Contribution to phi from observation group "s26_0236"   =  584.9
 Contribution to phi from observation group "s26_0242"   =  320.1
 Contribution to phi from observation group "s26_0298"   =  28.48
 Contribution to phi from observation group "s26_0308"   =  36.05
 Contribution to phi from observation group "s26_0490"   =  93.62
 Contribution to phi from observation group "s26_0500"   =  8.273
 Contribution to phi from observation group "s26_0545"   =  25.00
 Contribution to phi from observation group "s26_0547"   =  371.2
 Contribution to phi from observation group "s26_0568"   =  622.8
 Contribution to phi from observation group "s26_0656"   =  0.000
 Contribution to phi from observation group "s26_0658"   =  262.2
 Contribution to phi from observation group "s26_0675"   =  517.5
 Contribution to phi from observation group "s26_0738"   =  55.73
 Contribution to phi from observation group "s26_0743"   =  339.5
 Contribution to phi from observation group "s26_0749"   =  8.847
 Contribution to phi from observation group "s27_0225"   =  18.16
 Contribution to phi from observation group "s27_0248"   =  149.7
 Contribution to phi from observation group "t26_0326"   =  67.10

Correlation Coefficient ----->

 Correlation coefficient                  =  0.9993

Analysis of residuals ----->

 All residuals:-
   Number of residuals with non-zero weight                =  4869
   Mean value of non-zero weighted residuals               =  0.1572
   Maximum weighted residual [observation "o2784"]         =  4.204
   Minimum weighted residual [observation "o3741"]         =  -5.175
   Standard variance of weighted residuals                 =  0.8350
   Standard error of weighted residuals                    =  0.9138
```

Table B.10 indicates the PEST optimised values for the model parameters.

Table B.10 PEST optimised FEFLOW model parameters

Zone ID	Parameter Value		Comments
hy01	1536.37	m/d	Q1 aquifers
hy02	13.23	m/d	Q24 Aquifers
hy03	144.18	m/d	Q2468 Aquifers
hy04	40.00	m/d	Fix Q234 Layer 1 & 2
hy05	1.0000E-02	m/d	Q5 Aquitard
hy06	1.0000E+00	m/d	Q5 Leaky Aquitard
hy07	61.29	m/d	Q6 transition
hy08	100.86	m/d	Q6 Upper Parkvale
hy09	152.04	m/d	Q6 Parkvale
hy10	7.0745E-02	m/d	Faults
hy11	5.00	m/d	Fix Q8 Layer 9
syd1	9.1237E-02		Specific Yield
sst1	6.2056E-04	1/m	Specific Storage

Table B.11 provides average RMS error at each monitoring bore before and after PEST optimisation. The overall RMS error has been reduced from 1.88 m to 1.12 m; however it was noted for some of the bores individual RMS error has been increased during the PEST optimisation.

Table B.11 Calibration performance analysis

Monitoring Bore	Weights	Average fluctuation (m)	Number of observed data	Objective function (m^2)		Average RMS Error (m)		Error Reduction
				Initial	Final	Initial	Final	
s26_0155	0.75	2.41	301	188.66	275.46	0.7917	0.9566	-20.8%
s26_0223	0.00	0.01	3					
s26_0229	1.00	3.15	301	331.08	271.86	1.0488	0.9504	9.4%
s26_0236	1.00	2.83	301	5388.00	584.89	4.2309	1.3940	67.1%
s26_0242	1.00	5.60	301	400.98	320.09	1.1542	1.0312	10.7%
s26_0298	0.50	0.59	301	958.42	28.48	1.7844	0.3076	82.8%
s26_0308	1.00	0.62	109	1861.10	36.05	4.1321	0.5751	86.1%
s26_0490	1.00	2.80	301	76.90	93.62	0.5055	0.5577	-10.3%
s26_0500	1.00	1.19	263	59.62	8.27	0.4761	0.1774	62.8%
s26_0545	1.00	1.03	301	49.51	25.00	0.4056	0.2882	28.9%
s26_0547	1.00	0.77	301	401.64	371.21	1.1551	1.1105	3.9%
s26_0568	0.75	5.85	301	685.98	622.83	1.5096	1.4385	4.7%
s26_0656	0.00	4.31	301					
s26_0658	0.75	1.35	301	486.79	262.20	1.2717	0.9333	26.6%
s26_0675	1.00	4.74	77	1636.80	517.49	4.6105	2.5924	43.8%
s26_0738	0.75	2.73	301	163.78	55.73	0.7376	0.4303	41.7%
s26_0743	0.75	5.50	301	865.85	339.52	1.6960	1.0621	37.4%
s26_0749	1.00	0.60	18	6.02	8.85	0.5783	0.7011	-21.2%
s27_0225	1.00	0.64	188	120.06	18.17	0.7991	0.3108	61.1%
s27_0248	0.75	2.49	301	31.02	149.74	0.3210	0.7053	-119.7%
t26_0326	0.75	0.74	301	3402.20	67.10	3.3620	0.4722	86.0%
Over all performance			4869	17114.4	4056.6	1.8748	0.9128	51.3%

The results indicated in Table B.11 do not indicate that the achieved overall reduction in the objective function has reflected a uniform improvement in prediction across the model domain. While this is a relatively disappointing outcome, it may simply reflect that some aspect of the overall conceptualisation of the system may require revision. For example it may ultimately prove to be the case that the zonation of aquifer hydraulic conductivity adopted for the calibration requires reconsideration and amendment.

To this end it is recommended that a systematic process be undertaken to review the data in Table B.11 and then re-examine the key elements of the hydrogeological conceptualisation for the areas of the model where improvement to prediction has not been achieve (or in fact prediction has worsened).

Table B.12 provides a summary of quantitative measures of calibration performance after the automated calibration procedure. Ideally the scaled errors should be a low value (< 5%) and the coefficient of determination should be closer to 1. The measures of calibration performance indicated in Table B.12 indicate that even though the difference between the observed and simulated groundwater levels lie within the acceptable norms, the scale errors and coefficient of determination suggests that the calibration performance at some of bores (e.g. S26_0298, S26_308, S26_0547, S26_0658, S26_0749, t26_0326) are not acceptable.

Table B.12 Measures of calibration performance

Monitoring Bore	Error (m)				Scaled Error			Coefficient of Determination
	Minimum	Maximum	Absolute Mean	Root Mean Square	Scaled Mean Sum of Residuals	Scaled Root Mean Square of Residuals	Scaled Root Mean Fraction Square of Residuals	
s26_0155	-0.3455	1.7003	0.8519	0.9566	35.3%	39.7%	39.6%	0.19
s26_0223								
s26_0229	-2.4183	0.9676	0.7690	0.9504	24.4%	30.1%	30.3%	0.64
s26_0236	0.3381	2.4734	1.3153	1.3940	46.5%	49.2%	49.1%	0.27
s26_0242	-1.8663	2.9758	0.8249	1.0312	14.7%	18.4%	18.4%	2.22
s26_0298	-0.7866	2.2112	0.2188	0.3076	36.9%	51.9%	51.8%	0.03
s26_0308	-1.3845	0.4715	0.4390	0.5751	70.5%	92.4%	92.3%	0.03
s26_0490	-0.1787	2.6312	0.4997	0.5577	17.9%	19.9%	19.8%	0.47
s26_0500	-0.3584	0.6708	0.1438	0.1774	12.0%	14.9%	14.8%	3.15
s26_0545	-0.1212	0.7730	0.2528	0.2882	24.4%	27.9%	27.8%	0.34
s26_0547	0.8406	1.3890	1.1066	1.1105	143.4%	144.0%	143.9%	0.01
s26_0568	-0.4333	4.2041	1.2227	1.4385	20.9%	24.6%	24.3%	0.52
s26_0656								
s26_0658	-1.5943	-0.1784	0.9031	0.9333	66.8%	69.1%	69.1%	0.05
s26_0675	-5.1751	-1.0854	2.3923	2.5924	50.5%	54.7%	55.5%	0.25
s26_0738	-0.9826	1.1680	0.3307	0.4303	12.1%	15.8%	15.7%	1.46
s26_0743	-2.3097	1.7857	0.9040	1.0621	16.4%	19.3%	19.7%	1.08
s26_0749	0.4608	0.9059	0.6927	0.7011	115.5%	116.9%	116.8%	0.08
s27_0225	-0.5517	0.1595	0.2847	0.3108	44.3%	48.3%	48.4%	0.23
s27_0248	-0.1204	1.3106	0.6617	0.7053	26.6%	28.4%	28.2%	0.34
t26_0326	-1.1697	-0.0754	0.4048	0.4722	54.6%	63.7%	63.6%	0.06

The estimated high scaled errors are of some concern. In response to this closer scrutiny of the construction details of the monitoring bores used for calibration is warranted to confirm that the bores used truly represent the groundwater levels in the correct layers in the FEFLOW model. For example the FEFLOW model under predicts the groundwater levels at bore S26_0547 by approximately 1.0 m. The FEFLOW model contains the following data at bore S26_0547:

- Slice 1 elevation 49.8 m RL
- Slice 2 elevation 45.4 m RL
- Slice 3 elevation 40.4 m RL
- Minimum observed groundwater elevation 45.8 m RL
- Maximum observed groundwater elevation 46.5 m RL
- Average observed groundwater elevation 46.2 m RL
- Assigned initial groundwater level in FEFLOW model 44.8 m RL
- Maximum simulated groundwater elevation 45.4 m RL
- Minimum simulated groundwater elevation 44.8 m RL
- Average simulated groundwater elevation 45.1 m RL

Close inspection of the aforementioned data indicates that the likely origin of the under prediction of the groundwater elevations for this bore is an incorrect assignment of the initial model conditions. And, Layer 1 at bore S26_0547 remains dry throughout the FEFLOW model simulation.

This problem may be able to be readily rectified through reassignment of the initial model conditions.

It is possible that numerous similar issues exist with the model and a process of review and revision is likely to tease these out and result in an improved model. Once these reviews and revisions have been carried out, the following processes should be undertaken to further improve model calibration:

- Using PEST, formulate the objective function to reflect temporal differences in groundwater elevations such as the amplitude of variation around the mean observed groundwater elevation for each monitoring bore; and then
- Rather than rely parameter zonation using a LOOKUP type table, introduce PEST pilot points to distribute the parameters. It should be noted that this process is likely to exacerbate FEFLOW model run times with the current model architecture (i.e. 9-layers).

To improve the model run times whilst using PEST pilot points, consideration should be given to some rationalisation of the model configuration to aggregate some of the model layers. For example model layers 1 & 2 could be potential aggregated as could model layers 3 & 4, 5 & 6, and 7 & 8 to produce an overall 5 layer model. It is likely that the predictive power of such a rationalised / simplified model will not substantially decrease as it would be expected that there would be a paucity of data values to support determination of vertical leakage within the current 9-layer configuration.

Water, air, earth and energy – elements in Greater Wellington's logo that combine to create and sustain life. Greater Wellington promotes **Quality for Life** by ensuring our environment is protected while meeting the economic, cultural and social needs of the community

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