



Wairarapa Valley groundwater resource investigation

Lower Valley catchment hydrogeology and modelling

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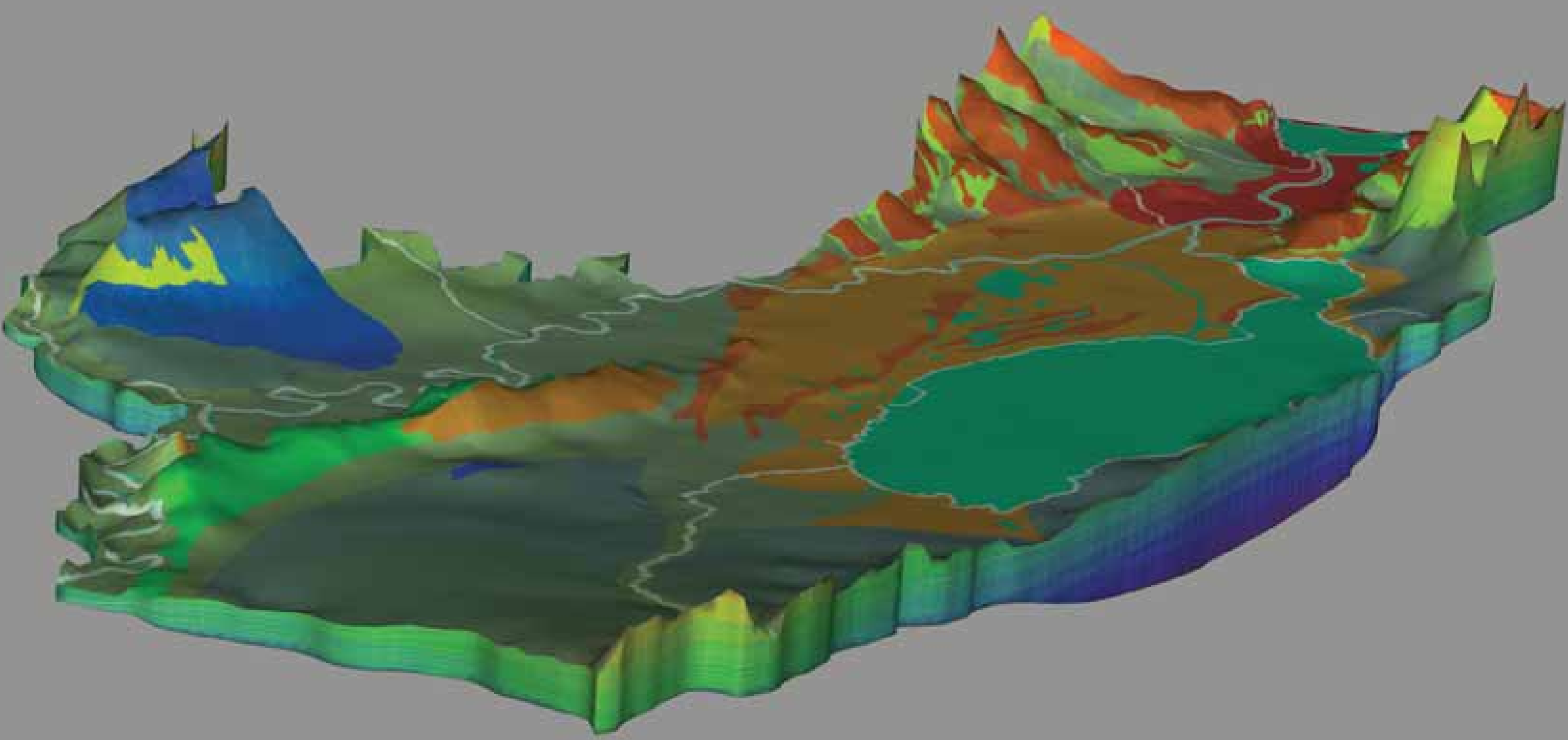

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Executive summary

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 sustainable aquifer 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 Lower Valley catchment. This 643 km^2 catchment encompasses Lake Wairarapa, Lake Onoke, the Martinborough terraces and the Tauherenikau fan. The catchment contains the lower reaches of the Ruamahanga River and its main tributary, the Huangarua River. Smaller tributaries draining the Aorangi Range near the coast include the Dry, Tauanui and Turanganui rivers. The Tauherenikau River is another major drainage system which is sourced in the Tararua Range and flows into Lake Wairarapa.

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 gauging, 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 Lower Valley groundwater environment. The tectonically complex groundwater basin contains a heterogeneous sequence of late Quaternary fluvio-glacial sediments. Major fault and fold structures have influenced the drainage patterns and depositional environments of the alluvium sequences. Faulted blocks of older, less permeable sediments and basement greywacke rock have been uplifted and displaced against younger water-bearing strata around Te Maire ridge and the Martinborough terraces. Structural deformation is also responsible for the creation of a large subsiding basin centred on Lake Wairarapa. Here muliple sequences of thin reworked confined gravel aquifers are confined by extensive lacustrine and estuarine fine-grained deposits.

Conceptually, the Lower Valley groundwater catchment is characterised as a largely 'closed' groundwater system in which the dominant water balance components are rainfall recharge, fluxes between surface water and groundwater and abstraction. Geological constraints at the coast permit only a very limited connection between the groundwater system and the sea.

On a broad scale, the groundwater environment consists of a shallow unconfined flow system which is connected to rivers and streams wherever permeable Holocene alluvium occurs, in particular along the Ruamahanga and Tauherenikau rivers. On the eastern side of the valley the Ruamahanga River has carved a shallow channel between Te Maire ridge and the eastern hills where groundwater and surface water are virtually indistinguishable. Relatively low permeability, poorly-sorted fan gravels occur on the western side of the valley against the Tararua Range. These are graded distally and segregate into a sequence of discrete re-worked permeable confined aquifers in the depression of Lake Wairarapa (lake basin). Intervening poorly sorted gravels and fine grained interglacial aquitards confine and separate reworked gravel intervals.

The groundwater head distribution in the northern part of the Lower Valley catchment reflects a surface water drainage pattern. In the Lake Wairarapa area the groundwater system becomes confined, the regional groundwater gradient flattens and flow vectors converge on the lake. This implies slow discharge through leakage from deep confined aquifers.

High seasonal variability in groundwater level and flow dynamics is attributable to a combination of rainfall recharge, river/steam flow conditions and, in some areas, abstraction stresses. Inter-seasonal variability in rainfall recharge reflects temporal rainfall patterns driven by the El Nino Southern Oscillation. Longer-term climate-driven hydrographic trends are particularly evident in confined aquifers (Martinborough and lake basin).

Rainfall recharge also exhibits a very pronounced spatial pattern due to the very steep rainfall gradient across the valley (1,800 mm in the west to 800 mm in the east). Recharge was calculated on a 500 m^2 grid using a soil moisture balance model. The average annual recharge volume over a 16-year period between 1992 and 2008 was 47.3 x 10^6 m^3 (130,000 m^3/day). Up to 40-50% of rainfall becomes recharge over the upper Tauherenikau fan but less than 10% of rainfall reaches groundwater over the Lake Wairarapa area where low permeability soils and near-surface geological conditions inhibit rainfall infiltration.

Fluxes between shallow groundwater and surface water are a dominant component of the groundwater balance for the Lower 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 principal river systems – the Ruamahanga and Tauherenikau – exhibit complex patterns of flow gain and loss with respect to underlying shallow aquifers.

Groundwater abstraction in the catchment has more than doubled over the last decade primarily due to demand for seasonal pasture irrigation. At the time of initial groundwater model development in 2008, there were 142 consented bores with a combined allocation of 202,000 m^3/day and 40.3 x 10^6 m^3/year. Annual meter readings show that in general resource consent holders do not exceed 10-30% of their annual allocation. Modelling of actual abstraction using soil moisture demands indicates that peak current usage is about 100,000 to 130,000 m^3/day. This is equivalent to about 65% of the consented daily rate. Groundwater abstraction currently constitutes more than about 25% of the total catchment recharge from surface water during the summer months and appears to have an impact on aquifer discharge (base flow) quantities.

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 assisted with stratigraphic correlation work and the identification of aquifer flow paths.

The conceptual hydrogeological model for the Lower 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.

Simulated catchment water balances show that the major rivers recharge groundwater, and that groundwater discharges in low-lying areas provide base flow to spring-fed streams and lakes. During summer aquifer recharge from river bed leakage almost equals aquifer discharge to springs, wetlands and lakes.

Temporal changes in the dynamics of the groundwater system were simulated and attributed to a combination of natural climatic variability and the rapidly developing resource utilisation. Aquifers that do not have stable base levels and are controlled by surface water, such as in the lake basin and Kahutara areas, show clear evidence of climate- and abstraction-related seasonal and long-term declines in groundwater level. Abstractions impact the base flow to surface water systems, or else directly deplete flows, particularly in the Ruamahanga River.

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. In addition, the model could not be calibrated to the deep Martinborough confined aquifer because of inadequacies in the geological conceptualisation in this area. This shortcoming does not impact on other parts of the model or on the shallow Martinborough aquifers. 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 Lower Valley catchment.

Contents

Figures

Appendix 1: Monitoring bore drill logs

Appendix 2: Rainfall recharge modelling

Appendix 3: Groundwater abstraction modelling

Appendix 4: Assessment of groundwater and surfacewater chemistry in the Upper and Lower Wairarapa Valley

Appendix 5: Model slice structure contours

Appendix 6: MIKE11 surface water model for the Lower Valley catchment

Appendix 7: Parameter zonation framework for the Lower Valley catchment model

Appendix 8: A PEST interface to perform automated FEFLOW model calibration

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 third 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 Middle and Upper 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 Lower Valley. It comprises the following sections:

- Section 2 – Physical setting: Briefly describes the Lower 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 Lower 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 Lower 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 Lower 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. Lower Valley environment and climate

2.1 Physical setting and landuse

The Lower Valley catchment of the Wairarapa Valley (Figure 2.1) covers an area of about 64,300 ha (643 km^2) and encompasses Lake Wairarapa, the Martinborough terraces and Lake Onoke. The catchment is bounded to the northwest by the Tararua Range and the southeast by the dry eastern hill country. From the northern boundary, coinciding with the terrace edge of the Waiohine Plains near Greytown, the catchment extends some 46 km to the south coast at Lake Onoke. The towns of Featherston and Martinborough are the two largest population centres in the catchment.

The Lower Valley catchment generally has a low relief (Figure 2.2) and slopes gently from alluvial fan areas in the west and north to Lake Wairarapa and the Ruamahanga flood plain. Te Maire ridge represents an elongate topographic feature separating the Ruamahanga River and Martinborough terraces in the east from the Tauherenikau plains in the west.

Lake Wairarapa is the dominant surface water feature in the catchment covering an area of 78.4 km^2. The Ruamahanga and the Tauherenikau rivers are the two principal surface water systems which drain into Lake Onoke and Lake Wairarapa respectively. Numerous smaller streams and spring systems occur on the eastern side of the catchment draining the eastern hill country. Important spring discharge areas occur around the edge of the Tauherenikau fan.

Agriculture is the dominant land use in the catchment. Dairy is the dominant form of farming (28% of the catchment area), followed by sheep and beef (19%), sheep (18%) and beef (14%) farming. Lake Wairarapa occupies 14% of the catchment area, while urban land uses occupy just 3% (Figure 2.3).

2.2 Soils

The distribution of soil groups in the Lower 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 of the northern and western parts of the catchment being widespread on the Tauherenikau fan. They also occur in patches around Lake Wairarapa coinciding with wind-blow sand deposits. These are mainly yellow-brown shallow silt loams on a gravel (or sand) substrate which are well, to excessively, drained.

Recent Well Drained Soils occur on the recent alluvial floodplains of the Ruamahanga, Tauherenikau and Huangarua rivers. This soil group comprises of stony sands that are well, to excessively, drained.

Recent Poorly Drained Soils are silt loams occurring on river floodplains where they represent overbank deposits. They also occur extensively around

Lake Wairarapa and through to Lake Onoke. In these areas they are associated with underlying lacustrine and estuarine low-permeability sediments.

Gley Soils are organic rich, poorly drained and very poorly drained soils generally occurring where the water table is high. In their un-drained state oxygen is limited and reducing conditions occur. These soils occur on the lower Tauherenikau fan in a wide belt against Te Maire ridge – areas which, before widespread drainage, were formerly swamps.

Pallic Soils occur on much older surfaces such as Te Maire ridge, the Pirinoa terraces to the north and south of the Onoke-Narrows 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 and intensity of El Nino and La Nina. Three phases of the IPO have been 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.
- 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 as yet, 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 2.5 shows the locations of the rain gauges in the Lower Valley catchment. 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.

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 2.6 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, refer Figure 2.5) is significantly different to the other two sites and this may in fact relate to the shorter monitoring record for this site.

Figure 2.6 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 7.1.4).

3. Surface water environment

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

3.1 Rivers

3.1.1 Channel systems and flow characteristics

The Lower Valley catchment contains the lower reaches of the Ruamahanga River and its main tributary the Huangarua River. Smaller tributaries draining the Aorangi[3] Range near the coast include the Dry, Taunui and Turanganui rivers (Figure 2.2). The Tauherenikau River is another major drainage system which is sourced in the Tararua Range and flows into Lake Wairarapa.

(a) Ruamahanga River

The Ruamahanga River is the principal drainage system on the Wairarapa plains. The river is about 162 km long and 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 used to naturally discharge directly to Lake Wairarapa but was diverted in the 1960s via the Ruamahanga Diversion, so that low flows now by-pass the lake and flow directly into Lake Onoke at the coast.

Downstream from the Waiohine River confluence, the Ruamahanga River has a strongly meandering single channel form, with extensive gravel beaches developing on the river bends. River control works confine the river between stop banks downstream of Pahautea. From Tuhitarata to Lake Onoke high stop banks further confine the river, meanders have been cut off, and gravel beaches are largely absent.

(b) Huangarua River

The most significant tributary of the Ruamahanga River within the Lower Valley catchment is the Huangarua River which joins the Ruamahanga near Martinborough. The Huangarua River starts at the confluence of two other tributary rivers – Ruakokoputuna River and Makara River – which are sourced in the eastern Aorangi Range. These two rivers flow in a northerly direction for about 20 km through sedimentary hill country to join and become the Huangarua River at the Hautotara Bridge. The river continues to flow north through a wide valley in a channel that is actively degrading into Holocene gravels. At Hikawera the valley narrows and the river is joined by another tributary, the Whangaehu River. The Huangarua River then flows northwest to join the Ruamahanga River about 1.8 km north of Martinborough. In this reach the river has a single-thread channel with broad gravel beaches and varies in width from about 20 to 100 m. The total catchment area of the Huangarua River is 311 km^2.

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[3] Also known as Haurangi Range.

(c) Other rivers draining the Aorangi Range

Several small streams and rivers flow off the Aorangi Range to join the lower section of the Ruamahanga River. The most significant of these are Dry River near Martinborough and Tauanui and Turanganui rivers in the Onoke area. The Tauanui River joins the Ruamahanga River about 9 km upstream of Lake Onoke. The Turanganui River once flowed into the Ruamahanga River through a broad gravel delta but has now been diverted south for about 1.5 km and flows directly into Lake Onoke.

The Tauanui and Turanganui rivers both carry a relatively high gravel load and display a narrow form with long shingle beaches in their upper reaches. In its middle reaches, the Tauanui River widens to around 80m and displays a semi-braided form in places before returning to a narrow single-thread form upstream from the Martinborough-Lake Ferry Road. Many of the lower reaches of both rivers are stop-banked, confining the flow to relatively narrow channels. In their lower reaches both rivers frequently run dry during low-rainfall periods, although small sub-surface flows probably continue within their gravel beds.

The Dry River drains a small catchment (36 km^2) in the northern Aorangi Range and joins the Ruamahanga River about 6 km southwest of Martinborough. Dry River also carries a high gravel load and lives up to its name, often flowing below bed level during dry periods.

The catchments of these rivers – southeastern tributaries of the Ruamahanga River – have different rainfall patterns and geological characteristics to catchments in the Tararua Range, which means the rivers tend to have lower flows (during dry periods), lower gravel loads, and generally poorer water quality (with higher suspended sediment and nutrient concentrations) than western tributaries (see Section 8 for further discussion on the distinctive hydrochemical characteristics of the eastern catchment rivers).

(d) Tauherenikau River

The Tauherenikau River is the only major drainage system in the Wairarapa Valley which is not a tributary of the Ruamahanga River. The river rises in the main Tararua Range near Mt Hector and emerges onto the Wairarapa plain north of Featherston. It then flows across the alluvial plain to discharge into Lake Wairarapa. The river has a catchment area of 144 km^2 of which 112 km^2 is mountainous in the Tararua Range.

The Tauherenikau River is relatively steep and takes a short and direct course to Lake Wairarapa. On the plains it is initially a steep, semi-braided river with a wide channel partly bounded by terraces. Downstream of SH 2 the gradient levels out and the river is less confined but also less braided. Below the Featherston–Martinborough Road (SH 53) bridge the river has a single-thread form that actively wanders across the gravel bed. The river carries a high sediment load and gravel is extracted from both the SH 2 and SH 53 bridge reaches.

In the mid-1950s the lower section of the Tauherenikau River between the Martinborough Road bridge and Lake Wairarapa was straightened. The new channel is confined within stop banks and the bed is elevated above the surrounding plains.

3.1.2 Hydrology

Flow statistics for the lower Ruamahanga River (measured at Waihenga), the Tauherenikau River (measured at the Gorge) and the Huangarua River (measured at Hautotara) are listed in Table 3.1. The gauge locations are shown in Figure 3.1.

Table 3.1: Flow statistics for major waterways in the Lower Valley catchment

	Catchment area above gauge (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 Waihenga	2,340	85.34	50.3	8.77	1,903
Tauherenikau River at Gorge	112	9.17	4.94	1.1	670
Huangarua River at Hautotara	140	*	*	0.19	514

* Statistics unavailable.

3.2 Lakes Wairarapa and Onoke

Lake Wairarapa is the dominant feature of the Lower Valley catchment covering an area of about 78 km^2 (Figure 3.2). The lake is shallow (mostly less than 2.5 m deep) and about 18 km long by 6 km wide. It receives the majority of its inflow from the Tauherenikau River with small contributions from several small streams along the western shores and occasional flood flows from the Ruamahanga River. There is anecdotal evidence that the lake also receives inflows via discrete springs on the lake bed and it seems probable that groundwater also discharges to the lake through the Tauherenikau River delta gravels. The hydrochemical characteristics of the lake provide evidence that it may also receive discharge from deep confined aquifers (see Section 8). Ongoing water conductivity profiling investigations by Greater Wellington have also shown evidence of lake bed spring discharge.

Between 1964 and 1974 major flood control works around the lake involved the diversion of the Ruamahanga River away from the lake under normal flow conditions and the construction of the Oporua spillway and barrage floodgates at the outlet to the lake (Figure 3.2). Over 1,200 ha of wetlands around the lake shore were drained at this time.

The exit from Lake Wairarapa to Lake Onoke is regulated by six barrage gates operated by Greater Wellington under a resource consent provided for under the National Water Conservation Order for Lake Wairarapa. As a result of these works, the lake level is now artificially regulated by the barrage gates.

Some natural fluctuations in lake level are caused by rainfall and the effects of wind. The mean lake level is 0.64 m amsl (recorded at Burlings).

Lake Onoke is a 650 ha brackish barrier lake at the mouth of the Ruamahanga River. It is separated from Palliser Bay by a 3 km long gravel spit which is breached by rising lake levels or, now more commonly, cut artificially to reduce the danger of flooding to nearby farmland. For long periods the lake is tidal, but in southerly conditions during a low river flow, the exit to the sea becomes blocked. The level of Lake Onoke can rise to such a height that there can be backflow through the barrage gates into Lake Wairarapa.

3.3 Springs and wetlands

Figure 3.2 shows the locations of principal springs and wetlands in the Lower Valley catchment based upon documented records held by Greater Wellington. There are complex interactions between "natural" spring fed streams and the artificial water race systems which make the analysis of the groundwater component of some springs difficult to characterise.

3.3.1 Otukura–Battersea system

The hydrology, ecology, water quality and instream values of the Otukura Stream and Battersea Drain have been described by Watts (2007). Instream flow requirements were subsequently documented by Watts (2008). The following description of the system is taken from these reports.

The Otukura Stream has a small lowland catchment abutting the western side of Te Maire ridge on the Tauherenikau alluvial fan (Figure 3.2). The fan alluvial deposits in this area may also be attributable to the Waiohine River when it may have historically flowed in a more southerly directly. Major tributaries to the Otukura Stream include the Battersea Drain, Stonestead Creek and various channels associated with the Moroa Water Race.

Both the Otukura Stream and Battersea Drain are part of the Battersea Drainage Scheme which was created with the purpose of lowering water tables in winter. The Battersea Drain is a highly modified and possibly totally man-made channel and the Otukura Stream, although largely natural, was highly modified in the 1950s to enhance drainage. It is probable that groundwater forms a significant proportion of the flow in both drainage systems, particularly in winter given that the function of the drainage scheme is to lower the water table. The low flows in summer could be entirely groundwater derived.

There were, until recently, six consents to abstract a total of 56 L/s from both systems but all have expired and await renewal. Three of the takes from the Battersea Drain were for sub-surface irrigation (via a tile drain system beneath adjacent farmland which is flooded by raising the level in the drain). Wellington Fish and Game Council also hold a resource consent to divert up to 100 L/s from the Otukura Stream near the shore of Lake Wairarapa to maintain levels in the JK Donald wetland reserve.

The Otukura Stream has been monitored at the weir since 1997 (see Figure 3.1 for gauge location). The flow data (Figure 3.5) provide a naturalised 7-day mean annual low flow (MALF) of 107 L/s after abstraction has been taken into account. The lowest recorded flow is 3 L/s. However, it must be borne in mind that the flows are also affected by inputs from the Moroa Water Race. During summer there are possibly no gains from groundwater to the Otukura Stream, and it is probable that the system is entirely fed by the water race. During winter, spring flow gains were detected between Cross Road and Wards Line. The seepage face was also observed to extend during winter to include low lying ephemeral wetland in the Fabians Road area.

3.3.2 Stonestead Creek

Stonestead Creek (also known as Dock Creek) is a tributary of the Otukura Stream but has quite different flow characteristics. This stream is sustained by a high volume spring discharge derived from the adjacent Tauherenikau River via a shallow highly permeable aquifer. The mean low flow of the creek is about 500 L/s.

Stonestead Creek comprises two main tributary channels on either side of Kahutara Road (Figure 3.2; refer also to Figure 7.3.3). The western tributary has a measurable water race inflow that can easily be separated from spring flow. Water races also contribute some inflow to the eastern tributary although the volume is considerably less and is more difficult to separate from spring flow. Flow in the western tributary is fairly consistent through the year. However, increased winter flow in the eastern tributary is probably related to the expansion of leakage pathways from the Tauherenikau River. Most of the flow in both tributaries emerges near SH 53. During summer the seepage face is approximately 500 m north of SH 53 and during winter the seepage face is situated further to the north of Duddings Line – although this position may be influenced by increased inflows from the water race.

3.3.3 Donalds/Abbotts creeks

A system of drainage channels around the Featherston area are collectively termed the Donalds/Abbotts creek system (Figure 3.2). There is relatively sparse information on this drainage system but some of the flows are thought to be groundwater discharge from the fan alluvium. Spot gauging data suggest that the total summer base flow is in the order of 50-100 L/s.

3.3.4 Lake margin wetlands

Remnant wetland and lagoon areas occur around the periphery of Lake Wairarapa (Figure 3.2). These were once part of an extensive wetland/swamp/lacustrine environment covering much of the Lower Valley catchment. Prior to the flood control works around the lower Ruamahanga River the level of Lake Wairarapa could be seasonally very low. Exposure of the lake bed to sandstorms resulted in the deposition of a series of low dunes along the eastern lake shore. These dunes trap a series of lakes and wetlands between the Tauherenikau River and the former entrance of the Ruamahanga River into the lake at Willow Island. The largest of these wetlands are Boggy Pond and Matthews Lagoon, and several lagoons in the J. K. Donald Block. The Lake Wairarapa wetlands have significant ecological, cultural and recreational values.

3.4 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[4]. Water races were constructed in the first half of the 20th century by local government authorities 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 receive spring discharges in low-lying areas.

Figure 3.4 shows the two water race systems in the Lower Valley catchment – the Moroa (sourced from the Waiohine River) and the Longwood (sourced from the Tauherenikau River). The complex network of race channels often link in with existing natural waterways, agricultural drainage systems, springs and wetlands.

Water race take points are below all stream gauges on related rivers. The amount of water taken through water races is discussed in more detail later in this report as it significantly influences the flow in rivers at low flow. This is pertinent to the accurate analysis of flows in rivers and their interaction with groundwater systems.

The largest and most extensive water race in the Lower Valley catchment is the Moroa Water Race. The race diverts water from the Waiohine River upstream of the Railway Bridge at a maximum consented rate of 450 L/s. A minor amount of the take flows north into the Greytown area springs in the Middle Valley catchment.

The Moroa Water Race links into the Battersea Drain system and the Otukura Stream both of which are partially spring-fed and partially sustained by the water race and surface runoff.

The Longwood Water Race has an extensive channel network between Featherston and the Tauherenikau River (Figure 3.4). The water is sourced from the Tauherenikau River at the foot of the Tararua Range at a maximum consented rate of 200 L/s.

[4] 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.

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 Lower Valley catchment – these are listed in Table 4.1 along with their individual previously defined safe yield estimates and current status of water allocation. Several zones are fully allocated, or approaching full allocation status: Lower Valley (Aquifer 2), Riverside, Tawaha, the Martinborough terraces (eastern and western) and the Huangarua lower terraces.

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 Lower Valley catchment, as defined in Greater Wellington's Regional Freshwater Plan (RFP) and associated safe yield planning documents

Groundwater zone	RFP safe yield (m^3/year x 10^6)	Safe yield allocated* (%)	Resource potential
Woodside	16.0	4	Poor
Moroa	0.8	30	Poor-moderate
Battersea	2.4	77	Moderate-good
Tauherenikau	20	26	Good
South Featherston	5.3	30	Poor-moderate
Lower Valley			
Tauanui 1	0.8	1	Moderate-good
Turanganui 1	1.1	59	Moderate-good
Whangaehu 1	0.5	36	Moderate-good
Aquifer 2	13.5	98	Good
Aquifer 3	7.7	46	Good
Riverside	3.9	100	Very good
Tawaha	11.0	100	Very good
Martinborough eastern terraces	0.31	135	Poor-moderate
Martinborough western terraces	1.5	84	Poor-moderate
Huangarua lower terraces	1.2	96	Moderate-good
Huangarua upper terraces	0.5	17	Moderate-poor
Pirinoa Terraces	18.1	0	Poor

* Percentage safe yield allocated as at 2009.

Several of the more important and heavily used groundwater zones have been described together with the basis of the safe yield estimates in a series of reports prepared by Professional Groundwater and Environmental Services Limited (Butcher 1996a–b and Butcher 2001a–c). These zones are summarised in turn below.

4.2.1 Battersea groundwater zone

The Battersea zone was defined as the lower portion of the Tauherenikau fan where Recent or Holocene alluvial deposits overlie older fan sediments (Butcher 2001a). A shallow unconfined to semi-confined aquifer was identified (Aquifer 1) at 15-20 m deep which was further subdivided into three sub-aquifers (1a – 1c). Four deeper aquifers were also thought to occur down to about 90 m depth but with poor ability to transmit groundwater. The zone was regarded to be rainfall recharged. A large proportion of groundwater discharges into the Battersea and Otukura drainage systems.

4.2.2 Martinborough terraces groundwater zone

The Martinborough terraces were recognized as a separate groundwater zone occupying the area of uplifted alluvial terraces associated with the Harris anticline (Butcher 2001b). Groundwater abstraction commenced in earnest in this zone in the early 1990s for vineyard irrigation. Two semi-confined sand and gravel aquifers were identified, plunging to greater depth off the Harris anticline. A more productive Aquifer 2 was identified between 15 and 35 m depth (subdivided into three sub units) sustaining bore yields of between 1 and 15 L/s. Groundwater quality was also noted to generally improve with distance from the Harris anticline. Rainfall recharge was regarded to be the sole recharge mechanism on the terraces and groundwater levels appear susceptible to variations in annual rainfall recharge.

4.2.3 Huangarua groundwater zone

This zone was delineated as the area south east of Martinborough, between the Harris anticline and the Tertiary hill country to the east (Butcher 2001c). This is an area where historically there has been very little groundwater use until very recently due to the expansion of viticulture. The zone was divided spatially into the recent floodplain of the Huangarua River where most groundwater abstraction occurs, and older uplifted terraces of limited groundwater potential. Two aquifers were identified beneath the floodplain: a shallow unconfined aquifer (Aquifer 1) which is potentially connected to the Huangarua River but also receives rainfall recharge, and a deeper confined aquifer (Aquifer 2) to the south of Hikawera bridge that is considered to be rainfall-recharged and subdivided into two levels.

4.2.4 Lower Wairarapa Valley

A study by Butcher (1996a) focussed on the area around Lake Wairarapa and the narrow valley outlet to Lake Onoke and the coast. Four (and possibly up to seven) artesian aquifers were identified in this area to a depth of about 180 m, with Aquifer 1 being the most utilised and best understood. The aquifers were described as thin and separated by substantial silty/clayey aquicludes of marine or estuarine origin. Variations in aquifer properties and water quality across the valley were described. Groundwater quality was observed to improve towards the sides of the valley towards postulated recharge areas where younger isotopic ages occur. Rainfall infiltration around the margins of the basin was perceived to be the main recharge mechanism with older possibly connate, waters occupying the deepest parts.

4.2.5 Ruamahanga River Floodplain – Martinborough to Pukio

This zone was described by Butcher (1996b) and comprises recent and later Quaternary alluvial aquifers associated with the Ruamahanga River floodplain between Martinborough and Pukio. An upper Aquifer 1 progressively deepens down-valley from Morrisons Bush where the aquifer sequence is very thin 10-20 m) to become confined by later lacustrine sediments to a depth of 20-30 m in the Pukio basin area. A deeper Aquifer 2 is postulated at greater depth. Only Aquifer 1 is utilised and has been subdivided on the basis of aquifer properties and water quality. Recharge to Aquifer 1 is thought to occur via a combination of rainfall and river leakage.

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 Lower Valley catchment to support and fill critical gaps in existing data sets. The work programme comprised the following activities:

- Construction of two groundwater monitoring bores
- Water meter surveys of selected groundwater takes
- Groundwater sampling and analysis
- Low flow river concurrent gauging
- Springs surveys
- Piezometric surveys
- Differential GPS surveying.

5.1 Monitoring bore construction

Two shallow monitoring bores (S27/0884 and S27/0885) were constructed in the Lower Valley catchment over May to June 2008 (Table 5.1, Appendix 1). These bores are located in the Ruamahanga valley near the northern catchment boundary (refer to Figure 7.1 for locations). In this area, the valley-fill alluvium is very thin (<15 m or so) and there is good connection between the shallow groundwater environment and the river. Since there is a large demand on the groundwater resource in this area, it was considered necessary to construct these monitoring bores to help characterise the groundwater-surface water dynamics of the valley and quantify river depletion effects. In addition, one of the new monitoring bores (S27/0885 – Didsbury) is located on the boundary of the catchment and will provide useful information on aquifer throughflows from the adjoining Middle Valley catchment.

Table 5.1: Summary details of monitoring bores constructed in the Lower Valley catchment over May to June 2008

Description	Bore No.	Easting	Northing	Depth drilled (m)	Aquifer base (m)	Screen interval (m)	Casing material
Tucker (GW) Morrisons Bush	S27/0884	2718498	6002962	18.9	9.8	4.5 – 7.5	50 mm ID PVC, 3m pre-slotted screen
Didsbury (GW) Fabians Road	S27/0885	2719015	6007384	14.3	13.8	7 – 10	50 mm ID PVC, 3m pre-slotted screen

5.2 Water meter study

Historical groundwater abstraction data are inadequate for the Lower 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 in the Lower and Middle Valley catchments was implemented during 2006/07. Data loggers were also installed in nine of the 21 bores in the programme. A further nine abstraction bores were added to the weekly meter reading programme late in the 2006/07 irrigation season. In all, 18 meters were installed in the Lower Valley catchment (Riverside, Tawaha and Lower Valley groundwater zones). The locations of these are shown in Figure 5.1.

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, 65 of which were located in the Lower Valley catchment (as shown in Figure 5.1). 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 5.2), 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;
- Major ion analysis at River State of the Environment (RSoE) sites; and
- Stable and major ion testing at selected spring locations.

5.4 River gauging

Concurrent river flow gaugings during low flows were used to characterise gain and loss patterns in major river systems in the Lower Valley catchment. Several concurrent gauging surveys were carried out on the Ruamahanga and Tauherenikau rivers between the summer of 2006 and 2007 as detailed in Table 5.2.

Table 5.2: Concurrent gauging runs carried out during 2006-2008 in the Lower Valley catchment

River	Dates for concurrent gauging
Lower Ruamahanga	16/03/2006, 22/02/2006
Tauherenikau	22/02/2006, 21/02/2007, 19/2/2008 (partial)
Stonestead (Dock) Creek	19/02/2008

5.5 Springs survey

Numerous springs occur in the Lower 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 Otukura Stream, Battersea Drain and Stonestead (Dock) Creek systems.

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. A winter survey was carried out between 17 and 26 September 2008.

5.7 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 Upper 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 Lower Valley Catchment groundwater model. The work involved a spring bed level survey and river water level survey (summer low flow and winter stable flow). Figure 5.3 shows the survey locations.

6. Geology and hydrostratigraphy

A review of the geology of the Lower 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).

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.

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 (e.g. Martinborough terraces at depth).

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, Waiohine, Waingawa and Tauherenikau rivers). The gravels represent high energy, poorly sorted alluvial fan depositional environments. These are interdigitated with fine-grained overbank, swamp, lacustrine or estuarine deposits.

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 re-worked, 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.

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.

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

The units shown in Table 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 at 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 loess horizons. 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 Lower Valley geology

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

The depositional environments of the late Quaternary sequence have been strongly influenced by subsidence, uplift and sea level changes. 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. This 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 have 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.

The principal structural and sedimentological features of the Lower Valley catchment are shown in Figure 6.2. These are:

- The regionally active Wairarapa Fault bounding the western side of the basin.
- A series of long-valley faults concentrated along the eastern side of the basin, including the Martinborough and Huangarua faults. These faults are responsible for the occurrence of Te Maire ridge, the Martinborough terraces, and elevated eastern terrace deposits bounding the basin.

- The northeast-southwest oriented fault-bounded uplifted basement block comprising the elongate Te Maire ridge located between the Ruamahanga River and the Tauherenikau fan.

- Uplifted terraces of older Quaternary sediments beneath Martinborough and the associated Harris anticline.

- Lake Wairarapa depression (lake basin) – a deep, actively subsiding basin centred on the lake and the area to the east. The basin is filled with fine-grained lacustrine and estuarine sediments to several hundred metres depth. Thin gravel deposits associated with the Tauherenikau and Ruamahanga rivers protrude into the subsiding fine-grained deposits.

- The Tauherenikau alluvial fan system occupying the north part of the basin between Te Maire ridge and the Wairarapa Fault, merging into the subsiding basin to the south beneath the lake.

- The Lake Onoke uplifted valley mouth area.

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

A number of long-valley faults are concentrated particularly along the eastern side of the Lower Valley catchment (Figure 6.2). These are thought to have significant vertical displacement (down to the west) and continue through the gap at Lake Onoke.

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

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

Lake Wairarapa lies in a shallow, elongate depression which has historically been the focus for the main drainage systems in the valley. The Ruamahanga River, before it was artificially diverted, used to loop back up-valley into the lake after clearing Te Maire ridge.

The lake is impounded to the south by the uplifted coastal area, and to the north by the Tauherenikau fan and Te Maire ridge. Rapid subsidence is occurring beneath the lake (Begg et al. 2006) and bore log data show that the area is underlain by thick (20-40 m) post-glacial estuarine muds. These marine sediments are the product of deposition during the Holocene between the sea level rise at the end of the last glaciation (the Otiran Glaciation, 14,000 years BP) and 6,500 years BP when the present sea level was attained. A prominent gravel aquifer at the base of the muds is regarded to represent Waiohine Gravel (Q2). This is the principal aquifer in this area.

Shells from a drillhole at Pouawha have been dated from four levels in the Holocene mud unit, yielding ages of 4-5,000 years old. The lowest was from 35 m below sea level. Because the shells are of estuarine origin, this is a clear indication that this area has subsided during the Holocene.

In contrast to the subsidence around Lake Wairarapa, towards the coast the south-eastern part of the Rimutaka Range is thrusting south-eastwards across the mouth of the Wairarapa Valley. Evidence for this active deformation is exhibited by marine benches at the mouth of the valley which rise up to 130 m above sea level. These benches have been dissected during the last interglacial period when the sea was within a few metres of its current level.

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

6.3 Hydrostratigraphy of the Lower Valley catchment

The geologic framework as described above provides a basis for the characterisation of the groundwater environment and the identification of a hydrostratigraphic sequence. The late Quaternary sequence (Table 6.1) comprises a large spectrum of sediment types which have been subject to variable degrees of sorting, reworking, compaction and deformation by faulting and folding. The basin-fill sequence is therefore highly heterogeneous; laterally continuous units rarely occur outside the lake basin area. Although all units are saturated below the water table, enhanced transmissivities in the coarser-grained sand and gravel units have locally developed as a result of better sediment sorting and reworking by drainage systems. These constitute a complex series of aquiferous units within an overall leaky aquifer system.

The Lower Valley catchment contains six broadly defined sub-areas which exhibit distinctive geological and hydrogeological characteristics (Figure 6.3):

- Sub-area 1: Tauherenikau fan and northern lake margin
- Sub-area 2: Ruamahanga valley down to the Pukio area
- Sub-area 3: Martinborough terraces and Dry River
- Sub-area 4: Lake basin
- Sub-area 5: Onoke/Narrows
- Sub-area 6: Huangarua valley and eastern side valleys

The sub-areas are characterised by one or a number of hydrostratigraphic units which have been recognised on the basis of the observed sedimentological sequences, well yields and aquifer properties, as well as the interpreted geological history of the catchment .

Table 6.2 lists the hydrostratigraphic units, their spatial distributions and the general nature of their hydrogeology.

Table 6.2: Principal hydrostratigraphic units (HSU) of the Lower Valley catchment

HSU	General hydrogeological nature	Sub-area
A: Alluvial fan gravels (Q2 – Q8)	Poor-moderate aquifers: generally low hydraulic conductivity, poorly sorted gravels with silts/clay and organic lenses. Improved sorting distally where higher bore yields are obtained such as in the Kahutara area. Poor bore yields on the upper fan areas. Includes the side fans in the Onoke/ Narrows area.	Tauherenikau fan Huangarua valley Onoke/Narrows
B: Unconfined aquifer (Q1 +)	Good aquifer: generally high hydraulic conductivity, reworked gravels, strong connection with rivers.	Ruamahanga valley Tauherenikau fan Huangarua valley
C: Q2, Q4 and Q6 (+Q8?) lake basin confined aquifers	Aquifers: medium-high hydraulic conductivity, discreet, highly confined units (<10 m thick)	Lake basin Ruamahanga valley (south) Onoke/Narrows
D: Q1, Q3, Q5 + Q7 Silt/clay aquitards	Aquitards: very low hydraulic conductivity, silty/clay estuarine and swamp deposits.	Lake basin Ruamahanga valley (south) Onoke/Narrows
E: Martinborough terrace deposits	Low hydraulic conductivity, compact, clay-bound alluvial terrace sequences with silt aquitards.	Martinborough terraces
F: Flow barriers	Uplifted fault or terraces features of very low permeability forming regional flow barriers.	Te Maire ridge, Harris anticline, Martinborough Fault (at depth).

The hydrogeological characteristics of four principal aquifer units (A, B, C and E) are described below.

6.3.1 Unit A: Alluvial fan gravels (Q2-8)

The Tauherenikau fan complex in sub-area 1 takes the form of a wedge of heterogeneous fluvial and glacial outwash sediments rapidly deposited mainly during galcial periods. The fans prograde towards Te Maire ridge and the lake basin.

The fan sequence is commonly poorly sorted, coarse and matrix-rich. It becomes quite compact and matrix-bound with depth and therefore tends to exhibit a low hydraulic conductivity capable of supporting only low-yielding wells. Bores in this unit tend to be less than about 30 m deep and obtain moderate yields of generally less than 10 L/s. Locally enhanced hydraulic conductivities are the product of sediment reworking sometimes enabling wells to yield larger quantities of water.

The upper 40 m or so of the fan deposits is considered to be of Q2-Q4 age (last glacial outwash gravels), and mapped as Q2 age at the surface – except in the vicinity of the Tauherenikau River and adjacent to Te Maire ridge where Q1 deposits are mapped.

Older glacial and interglacial late Quaternary deposits are considered to occur to a depth of about 60-70 m. Each major cold-climate phase is assumed to have accumulated 10-15 m of fan gravel (John Begg, GNS Science, pers. comm.). Interglacial warm periods (Q1, Q3, Q5, Q7) are associated with thin laterally extensive silt/clay/peat –rich deposits.

The western upper fan areas closest to the Wairarapa Fault appear to have a lower hydraulic conductivity. There also seems to be an absence of laterally traceable permeable zones in the fan sequence in this area but local reworking is evident through the occurrence of sporadic higher well yields.

In the distal fan areas towards the lake basin and against Te Maire ridge, progressive downstream reworking of the cold-phase (glacial) outwash gravels has resulted in the development of a moderately productive aquifer sequence which sustains numerous higher-yielding bores (the Kahutara area). These bores abstract from Q6 cold phase deposits at depths of 30-50 m. However, most bores in the lower Tauherenikau fan area abstract from last glacial Q2 or Q4 deposits (< c. 30 m deep). Near Te Maire ridge, the fan sequence has been influenced by complex structural deformation.

The fan sequence (Unit A) is therefore extremely heterogeneous and is essentially a single leaky aquifer system. As it approaches the edge of the lake basin, reworked cold-phase gravels with enhanced hydraulic conductivity become distinguishable within the distal fan sequence. These continue into the basin to form the confined Unit C aquifers.

6.3.2 Unit B: Unconfined aquifers (Q1+)

Holocene age (Q1) gravels represent a shallow (<15 m deep) dynamic unconfined aquifer which generally has a strong interaction with the surface water environment. The gravels are associated with present-day river channels and postglacial flood plains of the Ruamahanga and Tauherenikau rivers.

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. Many large groundwater abstractions in the Lower Valley catchment occur from this unit along the Ruamahanga River (the Riverside and Tawaha groundwater zones).

The Q1 unconfined aquifer also occurs along the Huangarua River where the gravels have a different eastern catchment provenence (marine sediments) and are therefore likely to exhibit different hydraulic properties. The Tauanui and Turanganui rivers in the Onoke/Narrows area are also associated with relatively narrow deposits of Q1 gravels.

6.3.3 Unit C: Q2, Q4 and Q6 confined aquifers

The Unit C confined aquifers are most clearly distinguishable as discrete gravel rich layers (no more than 10-15 m thick) separated by thick aquitard layers in the lake basin. However they also extend back up valley to the distal Tauherenikau fan (sub-area 1) and up into the Ruamahanga valley (sub-area 2) where they merge and are recharged from rainfall or river bed leakage.

The youngest Unit C aquifer (Q2 age) is the most widespread and is confined by a Holocene aquitard. This laterally persistent gravel-rich layer (5-10 m thick) can be traced at a depth of between 30 and 50 m into the lake basin. It extends from the Tauherenikau fan and Ruamahanga valley through to the Onoke area at the coastline. The Q2 aquifer exhibits artesian conditions and is widely utilised for irrigation purposes in the lake basin and Onoke/Narrows areas. It is possible that this aquifer is the product of an amalgamation of glacial outwash gravels from both the Ruamahanga and Tauherenikau rivers, the former being restricted to the south-eastern side of the valley and the central lower lake (Te Hopai) area. It is therefore probable that the aquifer is recharged both from the Ruamahanga River and from the Tauherenikau fan. Evidence for this is provided by water chemistry characteristics (see Section 8).

Beneath the Q2 aquifer, two similar (Unit C) deeper thin gravel layers occur – termed the ‘Q4’ and ‘Q6’ aquifers (both are the product of cold climate phases). The Q4 aquifer seems to merge with the Q2 aquifer in the Ruamahanga valley (Tawaha area) and eventually connect with the shallow alluvium. However, it separates out from the Q2 aquifer by a thickening aquitard (Unit D) as it enters the lake basin to become a distinct confined unit which is utilised by a small number of irrigation bores.

The Q4 aquifer peters out in the lower lake area and the silt/clay aquitard (unit D) separating the Q2 and Q4 aquifers in the lake basin progressively increases in thickness. The aquitard is regarded to be of Q3 age (an interglacial, warm climate interval).

A further aquifer (Unit C) can be identified beneath the Q4 aquifer, separated from it by a third (thought to be Q5 age) aquitard. This is the Q6 aquifer, although its extent and spatial delineation is rather more speculative than the overlying aquifer units. There is little evidence in the bore logs that Q6 extends beyond the centre of the lake basin and it probably fades out in a similar manner to the Q4 aquifer.

6.3.4 Unit E: Martinborough terrace deposits

The Martinborough terraces (sub-area 3) are interpreted to be comprised of two distinct geological sequences:

Deeper bores intercept older, less permeable terrace alluvium which is interpreted to be of mid Quaternary age (mQa) outcropping to the east on the Harris ridge (Unit E, Tables 6.1 and 6.2). This deeper mQa aquifer sequence is confined by a thick aquitard of possible interglacial Ahiaruhe age and has a groundwater head some 10 m higher than overlying aquifers. It also exhibits a distinct hydrochemical signature (Section 8). The maximum depth of the aquifer sequence has been estimated to be about 70-80 m on the downthrown eastern side of the Martinborough Fault, thinning towards the anticline axis to the east.

Lying above the deeper confined mQa aquifer, a shallow aquifer (20-30 m depth) is intercepted by the majority of bores on the Martinborough terraces. The alluvium comprising this aquifer is interpreted to be of late Quaternary age (Q4 or Q6 age). This aquifer is regarded to be in hydraulic continuity with the Ruamahanga valley sequence whereas the deep confined mQa aquifer is interpreted to be isolated from the down-valley groundwater environment by displacement along the Martinborough Fault.

6.4 Cross sections and three-dimensional model

To assist in the three dimensional characterisation of the Lower Valley groundwater system data from bore logs were used to construct a series of hydrogeological cross sections. Figure 6.4 shows the locations of nine cross sections constructed using well log data and the positions of bores having reliable geological log data, and Figures 6.5 to 6.13 contain the cross sections.

The cross sections show the interpreted aquifer sequences and the way that they have been affected by structural deformation. Interpretation of the catchment geology and the cross sections involved significant input from John Begg of GNS Science who was responsible for the recent 1:250,000 scale geological map for the Wairarapa Valley. It should however be appreciated that the geological environment is very complex and difficult to interpret unequivocally. In many of the sections, since most bores do not penetrate the entire aquifer sequence, the base of the groundwater system is estimated on the basis of the interpreted geological structure, feasible unit thickness and depth, and style of structural deformation. This was done through an iterative process of preparing unit isopach maps and unit boundary contour maps then referring back to the sections to develop a three-dimensional interpretation.

The salient features and interpretation of the sections relevant to the hydrogeological environment are summarised as follows:

6.4.1 Tauherenikau Fan – Te Maire ridge

Section 1

Cross section 1 (Figure 6.5) shows the principal features of sub-area 1 (Tauherenikau fan) and the upstream part of sub-area 2 (Ruamahanga valley). The dominating feature on the NNE-SSW orientated section is the Te Maire ridge structure. The block effectively forms the edge of a Tauherenikau fan groundwater system to the west (sub-area 1). The Ruamahanga River has eroded a shallow notch into the older Tertiary and early Quaternary sequence on the east side of the ridge (as far south as the Huangarua River confluence) where the total aquifer thickness is probably less than 20 m (Unit B).

Cross section 1 depicts the heterogeneous nature of the gravel, sand and silt Tauherenikau fan deposits (Unit A). The entire fan sequence is designated unit A in this study and is essentially a single heterogeneous leaky aquifer system.

Section 1 also shows the lower-lying Otukura-Battersea spring discharge zone where greater proportions of clay and silt are evident in the bore logs. Historically, this area may well have been a low-energy swamp/wetland environment and may have suffered structural subsidence.

6.4.2 Lower Tauherenikau fan – Te Maire – Martinborough

Cross-valley sections 2 and 3; Long-valley section 8

Cross-valley sections 2 and 3 (Figure 6.6 and 6.7) characterise the geological structure and groundwater environment of the lower Tauherenikau fan (Kahutara groundwater zone) between the Wairarapa Fault and the Te Maire ridge barrier (sub-area 1). To the east of the Te Maire ridge, the deepening Ruamahanga River alluvium (sub-area 2; Tawaha groundwater zone) and the adjacent Martinborough terraces (sub-area 3) are depicted.

The mid-Quaternary Tauherenikau fan sequence deepens to about -80 m amsl by cross section 3 (Figure 6.7). The fan sequence (Unit A) has also been deformed by the active Te Maire structures resulting in up-warping against the ridge. This configuration is supported by the outcrop on a small hill of older Q3 deposits within the Q2 surface just west of Te Maire ridge on cross section 3 (see also Figure 6.2). In reality, a complex series of folds rather than a simple up-warping is likely to occur in this area, in a manner similar to that shown by the geophysical surveys on the edge of Tiffen Hill in the Middle Valley catchment.

In addition to deformation, the Quaternary sequence is also interpreted to lap onto the ridge structure so that the deposits thin and deflect upwards as they approach the ridge. Bores beside the ridge in the Kahutara-Battersea area therefore probably intercept older sequences at relatively shallow depths. This may also explain the development of confined and artesian-flowing conditions in this area in shallow bores.

Greywacke basement is intercepted at the base of deep bore S27/0737 (Nicolls, 109 m) on cross section 2 (Figure 6.6). The base of the late Quaternary sequence has been placed at about 75 m deep in this bore, above thick peat and clay sequence which has been tentatively correlated to the Ahiaruhe formation (mQa).

Many irrigation bores in the lower Tauherenikau fan area near to the ridge (Kahutara groundwater zone) are interpreted to abstract from the stratigraphically lower Q6 deposits at depths of 30-50 m. However, elsewhere most bores in the lower Tauherenikau fan area abstract from either the younger Holocene (Q1) or last glacial (Q2, Q4) deposits (< c. 30 m deep).

Cross sections 2 and 3 also show the deepening nature of the Ruamahanga valley, bounded by the Te Maire ridge on the west, and the Martinborough Fault to the east. By cross section 3, the alluvium has deepened to about 40-50 m from the very shallow system further north. The alluvium rapidly thickens south of the Huangarua confluence.

Cross section 8 (Figure 6.12) is oriented along the axis of the Ruamahanga valley and shows a distinctive deepening of the system towards the lake basin. Between cross sections 2 and 3, all bores tap gravels within a 10-15 m thick zone located at 15-20 m depth. These gravels are thought to be of Q2-Q4 age (Unit C) and are overlain by an irregularly developed silt-rich Holocene sequence (Unit D). The Q2-Q4 gravel aquifer merges up-valley with the shallow unconfined Holocene alluvium (Unit B) indicating a direct hydraulic connection to the Ruamahanga River.

The geological characteristics of the Martinborough terraces in sub-area 3 are shown on in cross sections 2 and 3 (Unit C and Unit E). The gently westward-sloping terraces lie on the flank of the Harris Anticline – the axis of which forms the prominent hills to the east.

The Martinborough Fault forms the western boundary of the Terraces and is downthrown to the east. However, in the upper part of the sequence at least, the fault probably does not significantly hinder the flow of groundwater from the Terraces to the adjacent Ruamahanga valley.

The surface of the Martinborough terraces is mapped as Q2 age in the Martinborough area and as Q4 age further to the south indicating a northward-tilting structure (Unit C). In the Dry River area these older deposits are covered by a mantle of Q1 Holocene alluvium. Mid Quaternary sediments (mQa) are mapped on the Harris ridge together with a thin wedge of older Tertiary mudstone (Pea). The Harris ridge therefore forms a distinct boundary to the groundwater system.

6.4.3 Lake basin

Cross-valley sections 4 to 6; long-valley sections 8 and 9

The term *lake basin* refers to the subsiding depositional basin centred on Lake Wairarapa and the surrounding area between the lake and eastern hills. Lines of Holocene dunes mark former lake shorelines and wind deposition of exposed lake bed sediments prior to the construction of the flood control scheme.

Long-valley cross section 9 (Figure 6.13) reveals the morphology of the lake basin and its transition into the Tauherenikau fan (sub-area 4). Cross section 8 (Figure 6.12) shows the northerly transition from the lake basin into the Ruamahanga valley.

The base of the aquifer sequence in the lake basin has been placed at an interpreted boundary between late Quaternary and mid Quaternary sediments. The basin aquifer sequence is estimated to attain a thickness of about 150 m (140 m below current sea level) in the Te Hopai area (cross section 6). At least three distinct gravel units, no more than about 10 m thick, can be traced descending from the Tauherenikau and Ruamahanga fans into the basin (Unit C). It appears that the upper unit only (Q2) extends further into the Onoke area to the coast.

From near the intersection with cross sections 3 and 4, cross section 9 show the development of a near-surface clay aquitard thickening towards the centre of the lake basin (Unit D). This aquitard unit is interpreted to be of Holocene age (Q1) and represents an accumulation of estuarine and lacustrine muds within the sinking basin. It attains a maximum thickness of about 50 m around the lower lake area and has a variable thin cover layer of wind-blown sands or more permeable recent alluvium.

Beneath the Holocene aquitard, the laterally persistent Q2 gravel-rich layer about 5-10 m thick can be traced on all cross sections at a depth of between 30 and 50 m into the lake basin (cross section 9). The unit extends from the Tauherenikau fan and Ruamahanga valley through to the Onoke area at the coastline (cross section 8).

The deeper Q4 and Q6 thin gravel aquifers can also be identified from the cross sections. The Q4 aquifer merges with the Q2 aquifer in the Ruamahanga valley (Tawaha area) and connects with the shallow alluvium as shown in Section 9. As it enters the lake basin it separates from the Q2 aquifer by a thickening aquitard (Unit D).

The Q4 aquifer terminates somewhere beneath the lower lake area and is identifiable no further than cross section 6. The silt/clay aquitard (Unit D, Q3) separating the Q2 and Q4 aquifers in the lake basin progressively increases in thickness from about 20 m near the end of Te Maire ridge, to about 50 m in the lower lake area.

A further Q6 aquifer (Unit C) occurs beneath the Q4 aquifer, separated from it by a third (thought to be Q5 age) aquitard. There is little evidence in the bore logs that Q6 extends beyond about cross section 5, and it probably fades out in a similar manner to the Q4 aquifer.

6.4.4 Valley mouth: Onoke – Narrows – Barrage

Cross sections 7 and 9

Cross section 9 (Figure 6.13) shows the salient features of the valley mouth area (sub-area 5) where the base of the aquifer system rises steeply to near-sea level at the coast. There is an abrupt and distinct transition from the lake basin to this area. The coastal area has experienced significant uplift resulting in a condensed or truncated aquifer sequence. At the coast, the depth to basement (probably Tertiary marine mudstone) is interpreted to be less than 10 m on the basis of coastal bore logs and by extrapolation of the sloping Q5 marine terraces on either side of Lake Onoke. This means there is very little coastal outflow of groundwater from the Wairarapa basin and therefore a very limited connection between aquifers in the Onoke/Narrows area and the sea.

The Q2 aquifer (Unit C) appears to extend into this area where it occurs under highly confined conditions. Above the Q2 level, there are lensoid gravel bodies which are probably associated with the fans of side valleys such as the Turanganui and Tauanui rivers (Unit A). It is probable that recharge enters the aquifers through these fans via bed losses from the side rivers. This may also be a principal recharge mechanism for the Q2 aquifer.

Cross section 7 (Figure 6.11) provides an interpretation of the morphology of the aquifer system across the valley mouth area. The Q2 aquifer is identifiable at a depth of 30-40 m, being slightly deeper in the central part of the valley. Above this the sediments are regarded to be of Holocene age, mostly silts and clays with clay-bound gravels (Unit D). Wedges of gravel also extend into the sequence from the east – those shown on cross section 7 are probably associated with the Turanganui fan. The base of the aquifer system is tentatively estimated to be about 60 m on this section line, rising to about 10 m at the coast.

7. Hydrogeology

7.1 Groundwater flow system and level monitoring

7.1.1 Lower Valley groundwater level monitoring network

Greater Wellington currently operates a network of 33 automatic and manual groundwater level monitoring bores in the Lower Valley catchment. The locations of the monitoring sites are shown in Figure 7.1 while Table 7.1 provides the details for each monitoring bore (including the two new monitoring bores drilled as part of the project field programme).

7.1.2 Regional groundwater flow pattern

Regional groundwater flows in the Lower Valley catchment were characterised using groundwater level measurements collected over two decades from the monitoring bore network. Figure 7.2 shows the piezometric surface for March 2007 and September 2008 using only those monitoring bores which are shallower than 20 m depth (to avoid incorporating higher heads associated with deep confined aquifers, particularly in the lake basin).

The general regional flow pattern in the northern part of the catchment reflects the regional topography. Here, groundwater flows in a southerly direction down the Tauherenikau fan to Lake Wairarapa. Close to Te Maire ridge, the flow turns parallel to the ridge which forms a regional hydraulic barrier.

The groundwater flow gradient on the Tauherenikau fan is steepest on the upper and middle fan area being about 0.008. Levels drop from over 80 m amsl at the top of the fan, to about 10-15 m amsl in the river delta zone close to the lake.

On the other side of Te Maire ridge, groundwater flows follow the Ruamahanga River where much lower gradients of about 0.002 reflect both the topographic gradient and the high transmissivity of the river alluvium. Flow off the Martinborough terraces occurs in a westerly direction and merges with the Ruamahanga flow system.

In the lake basin, the groundwater flow gradient abruptly flattens to about 0.0005 and the flow vectors converge on Lake Wairarapa. The piezometric data show heads of about 5 m amsl in the lake basin, and imply that there is very little horizontal flow in the lake area. A small flow gradient from the lower lake/barrage area back up-valley towards the lake flats is also apparent. The observed head pattern indicates regional groundwater discharge to the lake but no throughflow from the lake basin to the coast. Comparison of the chemistry of lake basin aquifers with the lake water concurs that groundwater discharge to the lake is probable (see Section 8.3).

In the Onoke/Narrows area the gradient is relatively flat with levels ranging from about 5 m amsl to about 2 m amsl near the coast. The deflection of contours around the side valleys (of the Turanganui and Tauanui rivers) is also suggestive of lateral groundwater flow recharge inputs from the valleys.

Table 7.1: Lower Valley catchment groundwater level monitoring sites

Bore ID	Owner/Name	Auto/Manual	Depth (m)	Top screen (m)	Bottom screen (m)	Screen type	Use	Groundwater zone	Sub-area
S27/0148	Carlisle	Manual	8.77	0.00	0.00	Unknown	Not used	Woodside	1
S27/0202	Croad, JR & WJ	Automatic	4.80	3.68	4.88	Concrete liners	Irrigation	Moroa	1
S27/0099	Simmonds, John	Automatic	16.76	0.00	0.00		Domestic	Battersea	1
S27/0035	South Featherston School	Manual	6.50	0.00	0.00	Unknown	Not used	Tauherenikau	1
S27/0009	Dondertman, A 'Windy Farm Ltd'	Manual	10.50	9.50	10.50	Stainless steel	Domestic	South Featherston	1
S27/0012	Dondertman, A 'Windy Farm Ltd'	Manual	66.50	63.90	71.00	Slotted casing	Irrigation	South Featherston	1
S27/0330	Burt & Co.	Automatic	20.00	16.00	20.00	Stainless steel	Not used	Tauherenikau	1
S27/0317	Simmonds, J	Automatic	17.52	0.00	0.00	Slotted casing	Irrigation	Kahutara	1
S27/0271	Simmonds, J	Manual	29.20	0.00	29.20	Slotted casing	Stock	Kahutara	1
S27/0309	Simmonds, J	Automatic	28.20	0.00	0.00	Slotted casing	Irrigation	Kahutara	1
S27/0346	W.C.B./Smith, K	Automatic	9.50	0.00	0.00	No screen	Not used/monitoring	Tawaha West	2
S27/0381	W.C.B./Herrick, A	Automatic	20.95	0.00	0.00	No screen	Not used	Tawaha East	2
S27/0542	Butcher	Manual	19.00	0.00	0.00	No screen	Not used/monitoring	Tawaha	2
S27/0481	Dry River Beef Ltd	Automatic	23.10	19.60	23.10	Stainless steel	Not used	Pukio	2
S27/0485	Greater Wellington	Manual	20.00	0.00	0.00	No screen	Not used	Pukio	2
S27/0484	Ness/Greater Wellington	Manual	43.00	0.00	0.00	No screen	Not used	Pukio	2
S27/0884	Tucker/Greater Wellington	Automatic	10.00	7.00	10.00	Slotted pvc	Monitoring	Riverside	2
S27/0885	Didsbury/Greater Wellington	Automatic	7.5	4.5	7.5	Slotted pvc	Monitoring	Riverside	2
S27/0517	Stuart	Manual	19.40	0.00	0.00	Unknown	Not used	Pukio	3
S27/0522	Duggan, J	Automatic	21.00	19.00	21.00	Stainless steel	Domestic	Martinboro' W Terraces	3
S27/0640	Te Kairanga Wines Ltd	Manual	69.00	62.00	68.00	Stainless steel	Irrigation	Martinboro' E Terraces	3
S27/0571	Martinborough Golf Club	Automatic	32.00	31.00	32.00	Stainless steel	Irrigation	Martinboro' E Terraces	3
S27/0403	Wall, J.G.	Manual	41.50	39.50	41.50	Stainless steel	Not used	Martinboro' E Terraces	3
S27/0560	MacCullum/Paul Collins FA	Manual	39.00	36.50	38.50	Stainless steel	Irrigation	Martinboro' E Terraces	3
S27/0467	Green, R	Automatic	30.10	27.10	30.10	Stainless steel	Irrigation	Kahutara	4
S27/0446	Landcorp 'Awaroa'	Manual	60.80	35.00	60.80	Open hole	Not used	Kahutara	4
S27/0465	Vavasour - Awaroa	Manual	38.48	0.00	0.00	Open hole	Not used	Kahutara	4
S27/0428	W.C.B./Landcorp 'Wairio'	Automatic	43.56	40.26	43.56	Stainless steel	Not used	Wairio	4
S27/0434	Wairoria Partnership	Automatic	45.20	0.00	0.00		Not used	Te Hopai	4
S27/0442	Robinson Transport	Automatic	177.70	0.00	0.00		Domestic	Te Hopai	4
S27/0587	Luttrell, I	Automatic	34.00	0.00	0.00	Unknown	Not used	Onoke	5
S27/0576	Luttrell, I	Manual+Automatic	55.53	0.00	0.00	Unknown	Stock	Onoke	5
S27/0594	Warren, H	Manual	44.00	40.80	44.09	Stainless steel	Irrigation	Narrows	5
R28/0002	Annear, L	Manual	17.00	0.00	0.00	No screen	Domestic	Turanganui	5
S27/0618	Atkinson, B	Manual	47.27	0.00	0.00	Unknown	Domestic	Whangaehu	5

7.1.3 Depth to water table

Figure 7.3 shows the depth to water table or piezometric surface (derived from the numerical model). This map essentially represents groundwater level minus the water table/piezometric surface level (a negative value therefore means the groundwater level lies above the ground surface – represented by brown shading). Where unconfined aquifers occur – the Tauherenikau fan, upper part of the Ruamahanga valley, Te Maire ridge, Huangarua valley and raised Quaternary terraces in the Onoke (southern) area – a water table depth of between about 2 m and 10 m is evident. There is therefore potential for groundwater recharge in these areas. On the lower parts of the Tauherenikau fan, the lake basin and Onoke areas the depth to water table becomes negative (i.e., is above ground surface), indicating groundwater discharge and artesian conditions.

7.1.4 Temporal groundwater level trends and vertical flow gradients

(a) Sub-area 1: Tauherenikau fan

Figures 7.4 to 7.8 show the groundwater level hydrographs for monitoring bores in sub-area 1 of the Lower Valley catchment. Rainfall infiltration is the dominant recharge process over the relatively permeable soils of fan and this is reflected in the highly seasonal nature of the hydrographs. However, groundwater levels are clearly influenced by surface water levels – especially near the Tauherenikau River.

The drainage pattern over much of the fan is intensively managed by an extensive network of drains and interlinked water races (the Moroa Water Race being the largest and also the Longwood Water Race, see Section 3.4). The Battersea-Otukura/Moroa area was probably once a large swamp/wetland as evidenced by the presence low permeability peaty soils.

The artificial drain and water race systems remove groundwater during the winter months but are probably a recharge source during the summer months when groundwater levels drop. Locally, shallow groundwater levels are therefore highly influenced by the drain-water race system.

Shallow groundwater level records for the northern part of the Tauherenikau fan are shown in Figure 7.4 for three shallow monitoring bores (S27/0148 – 9 m, S27/0202 – 5 m, and S27/0099 – 17 m). Bore S27/0148 has a relatively large seasonal level fluctuation of about 3–5 m which varies from year to year depending upon rainfall patterns. In contrast, such variation is largely absent in S27/0202 (5 m deep) – but since this observation site is a large diameter concrete lined well, groundwater level fluctuations may be suppressed or, alternatively, shallow groundwater levels in this area may be influenced by nearby drainage channels.

The deepest of the three bores in Figure 7.4 – S27/0099 (17 m deep) – shows the drawdown effects from pumping. This becomes more pronounced from about the mid-1990s. This bore also shows a consistent long-term maximum winter water level at about 34.5m amsl compared to a ground level of 34.6m amsl, although there is a deepish drain nearby which may also provide a buffering influence (i.e., the water level is within 100 mm of the ground surface at this site).

The groundwater level hydrograph for a continuously monitored bore adjacent to the Tauherenikau River is shown in Figure 7.5. Bore S27/0035 (6 m deep) shows a seasonal fluctuation in level of up to about 2 m and, although it is highly probable that there is a close correlation between the shallow groundwater and the river, it is not possible to demonstrate this using the manual monthly monitoring data. The groundwater level at this site does, however, appear to be correlated to the long-term rainfall pattern as shown by the cusum plot for the Bannockburn monitoring site (see Section 2.3.2 for a discussion on the cusum plot).

Figure 7.6 shows the monitoring record for another bore located close to the Tauhernikau River – S27/0330 (20 m deep) – together with the flow in the Tauherenikau River for a 12-month period from October 2006. There is very little time lag between river flow peaks and groundwater level response even though the bore is screened in a semi-confined aquifer. A water sample from this bore was dated using tritium, SF6 and CFC methods (see Section 8) at about 30-40 years old. This would indicate the presence of a high-transmissivity aquifer linking the semi-confined aquifer to the upstream recharge zone of the river. The longer-term seasonal fluctuations are also consistent with the river flow regime and declining levels beginning in 2006 may reflect changes in the bed level of the river.

Near the edge of the Tauherenikau fan in the Kahutara area a cluster of three monitoring bores (Figure 7.7) show an upward vertical flow gradient as confined aquifer conditions develop towards the lake basin area. The winter groundwater head in bore S27/0309 (30 m deep) is about 12 m amsl, but is about 9 m amsl in bore S27/0317 (17 m deep). The pronounced seasonal irrigation drawdowns in groundwater levels of 3-4 m can be observed in all three monitoring bores in this area. Bore S27/0271 shows a long-term declining trend in winter levels between 1992 and 2004, followed by a gentle recovery. The trend appears to reflect both the long-term climatic cycle and increasing abstraction trends – as shown by the superimposed cumulative deviation from the monthly mean rainfall plot for Bannockburn.

Figure 7.8 shows the other two monitoring bores in sub-area 1 located close to Featherston at Windy Farm. These bores measure groundwater levels at 66 m depth (S27/0012) and 10 m depth (S27/0009). Although both bores show large pumping-induced seasonal drawdowns (up to 6 m in the deeper bore) it is evident that there is a significant downwards hydraulic gradient here in the order of 4-5 m over a 50 m vertical distance. This indicates a high recharge potential in this area.

In summary, groundwater level monitoring shows the aquifers in sub-area 1 are influenced by both rainfall and river/stream recharge processes. The controlling influences of widespread drainage and water race systems in regulating shallow groundwater levels across much of the area are also evident.

(b) Sub-area 2: Ruamahanga valley

Groundwater levels close to the Ruamahanga River are controlled by river stage due to the high degree of groundwater-surface water connectivity. Monitoring bores in this zone tend to have a well-defined summer base-level below which the aquifer level will not fall. This is demonstrated by the data obtained over a one-year period from the two new Greater Wellington monitoring bores (S27/0884 and S27/0885) shown in Figures 7.9 and 7.10. Both monitoring bores are situated about 300 m from the Ruamahanga River and are screened in the top 10 m of the unconfined aquifer. The direct correlation between river flow and seasonal river flow patterns is also displayed in Figure 7.11 by comparing the groundwater hydrograph for bore S27/0885 (Didsbury) with the flow record for the Waihenga gauging site on the Ruamahanga River (Figure 3.1).

Monitoring data for two automatic monitoring sites further down the valley near the Huangarua confluence – bore S27/0346 (Smith, 9.5 m deep and 750 m from the Ruamahanga River) and bore S27/0381 (Herrick, 21 m deep and 250 m from the river) – are shown in Figure 7.12. In addition, Figures 7.13 and 7.14 show the correlation between flow in the Ruamahanga River (measured at Waihenga bridge) and the two monitoring bores. Both figures show a strong connection between groundwater levels and river flows but bore S27/0346, located further away from the river, shows a considerably more smoothed response and a much larger seasonal variation in water levels than the deeper bore S27/0381. This suggests that at greater distance from the river, the aquifer has a delayed interaction with the river and that aquifer storage is utilised to a greater degree during the summer. This is further supported by the observation that groundwater levels measured in bore S27/0381 (closer to the river) show a stable summer base level controlled by the river. The more distant bore S27/0346 shows a decreasing summer base level as abstraction in the area increases, indicating less of a connection to the river at a distance of 750 m.

Continuing down-valley in sub-area 2, a cluster of four monitoring bores provide information on the aquifers as they become progressively more confined towards the lake basin (Figures 7.15 to 7.17). Manually monitored bores S27/0484 and S27/0485 are nested piezometers adjacent to the Ruamahanga River and are screened at 43 m and 20 m depth respectively. Figure 7.15 shows that both monitoring bores have identical water levels – similar to the river level although they do not have a summer base level controlled by the river (probably because they are relatively deep so there is not a direct hydraulic connection). Seasonal level declines of about 3 m are indicative of a single aquifer system with some connection to the river to a depth of at least 43 m. Figure 7.15 also shows a marked decline in recovered winter levels from about 1998 which corresponds with increased summer drawdowns associated with a significant increase in groundwater abstractions over the last decade in this area of the Ruamahanga valley (Tawaha groundwater zone). The trend does not appear to correlate with the long-term rainfall trend after 2004; the cusum plot shows rainfall has tended to be above average since 2004, yet there is no corresponding increase in groundwater levels.

Bore S27/0542 (19 m deep) and bore S27/0481 (23 m deep) have a similar range in groundwater levels of about 2-3 m (Figure 7.16). There is generally no long-term change in average level in these bores, but lower summer levels are noticeable in recent years. The higher head registered in S27/0481 (Dry River Beef) is suggestive of inflow through the fan of the Dry River. Figure 7.17 shows a detailed part of the hydrograph for this bore (for the summer period December 2008 to March 2009) against Ruamahanga River flow. The influence of river recharge on the deeper confined or semi confined aquifers in this area is evident.

In summary, the temporal groundwater level characteristics observed in sub-area 2 are dominated by the flow conditions in the Ruamahanga River, demonstrating a strongly connected groundwater and surface water environment.

(c) Sub-area 3: Martinborough terraces

Monitoring bores on the Martinborough terraces fall into two distinctive depth categories:

- A shallow system to about 30 m depth that has groundwater levels showing it to be part of the Ruamahanga valley (sub-area 2) groundwater environment.

- A deep groundwater system beneath a thick aquitard unit that has heads 10-20 m higher than the shallow system.

Hydrochemical data provide evidence for the existence of two groundwater systems within the Martinborough terraces with distinctive chemical signatures (see Section 8).

Bores S27/0571 (32 m) and S27/0522 (21 m) allow the monitoring of levels in the shallow system (Figure 7.18). Located on the eastern terraces near Martinborough, bore S27/0571 (Martinborough Golf Club) has a highly variable hydrograph showing long-term seasonal trends in groundwater level characteristic of a low permeability aquifer dominated by rainfall recharge. The long-term trend reflects the climatic cycles shown on the cusum rainfall plot for the Bagshot rainfall station (see Section 2.3.2 for an explanation of the cusum plot). As this monitoring bore is pumped for irrigation, sharp annual drops in level are mostly pumping-related. The shallower monitoring bore S27/0522 is located on the Martinborough western terraces but has a more subdued hydrograph than bore S27/0571. This is probably because there is no irrigation in the vicinity and it is only pumped for domestic supply. The record for this well is too short to discern any long-term trends.

Monitoring bore S27/0560 (39 m deep, Figure 7.19) in the deep confined aquifer is screened at the same depth as the Martinborough Golf Club monitoring bore (S27/0571, located 700 m due east in the shallow system). However, bore S27/0560 has a groundwater head some 20 m higher than bore S27/0571. An explanation for this could be the occurrence of inclined strata between the two bores (striking approximately northeast to southwest) and the presence of an intervening very low permeability aquitard separating two different aquifers with different recharge sources but accessible at the same depth. Another explanation is the presence of geological structures in this area which compartmentalise the aquifer.

Monitoring data for two other bores screened in the deep system (S27/0403 – 41 m, and S27/0640 – 69 m) are shown in Figure 7.19. Interestingly, the deeper of the two bores has a similar head to bore S27/0560 (39 m). However, bore S27/0403 (41 m) is of a similar depth to S27/0560 (39 m) and is located about 500 m due south but has a head some 10 m lower. Steeply inclined strata and the presence of a highly layered aquitard-aquifer sequence could account for the head differences between bores in such close proximity (as discussed above).

In summary, sub-area 3 groundwater levels are influenced primarily by rainfall recharge and in the deeper confined aquifers, by long-term rainfall trends.

(d) Sub-area 4: Lake basin

The lake basin defines a sub-area with radically different hydrogeological characteristics than sub-areas 1 to 3 where a series of thin confined aquifers occurs in a predominantly silt-dominated lacustrine/estuarine sequence.

There are six monitoring bores in the lake basin sub-area recording groundwater levels in a number of the confined aquifers. The most extensive, utilised and traceable aquifer unit is the Q2 aquifer. Monitoring bores S27/0465 (38 m), S27/0428 (44 m) and S27/0434 (45 m) are screened in this aquifer. All show a similar winter head of 5–5.5 m amsl and seasonal declines in level of 1–3 m as exhibited by the hydrographs in Figure 7.20. The progressive decrease in summer levels relates to increasing abstraction from this aquifer since the early 1990s. There is also a gradual long-term decline in winter levels which could be related to increasing groundwater abstraction and/or long-term rainfall trends in the recharge area on the Tauherenikau fan (as shown by the cusum monthly rainfall plot for Bagshot, Figure 7.20).

Also shown on Figure 7.20 is the hydrograph for monitoring bore S27/0467 (green line, 27 m deep). The lower groundwater head measured at this site signifies that it must be screened within a shallower gravel aquifer located within the Q1, predominantly fine-grained cover sequence capping the Q2 aquifer. In the north-eastern part of the lake basin, the thick Q1 aquitard characteristically contains discrete gravel lenses associated with former drainage courses of either the Ruamahanga or the Tauherenikau rivers.

Monitoring bore S27/0446 (61 m) is screened in the underlying Q4 aquifer. It records a slightly higher head of about 6.5 m amsl than the Q2 aquifer (Figure 7.21). The hydrograph for this bore also shows a much higher seasonal variation of 4–5 m, much of which is probably related to the drawdown effects of nearby irrigation bores.

The Robinsons Transport monitoring bore (S27/0442, 177 m) is the deepest bore in the Lower Valley and is used to record groundwater pressures in a deep low-permeability aquifer below the main groundwater environment considered in this study. It is probable that this bore intercepts either middle or early Quaternary sediments. As a consequence, the head in this bore is much higher than other lake basin bores as shown in Figure 7.21, sitting at about 21 m amsl – about 15 m higher than the Q2 aquifer. The hydrograph shows little seasonal fluctuation but the drawdowns associated with pumping from this bore are evident.

In summary, monitoring of the confined aquifers within sub-area 4 (lake basin) show a subdued response to distal long-term rainfall recharge trends. Groundwater abstractions, particularly within the Q2 aquifer, cause widespread seasonal drawdowns that appear to propagate widely across much of the basin.

(e) Sub-area 5: Onoke/Narrows

The aquifers occurring in this sub-area are confined beneath a low permeability cover sequence.

Two monitoring sites on the northern side of this sub-area have almost identical hydrographs (Figure 7.22). Bores S27/0587 (34 m) and S27/0576 (55 m), also know as the Luttrell bores, are shown in Figure 7.1. Groundwater levels in these bores recover seasonally to about 6 m amsl (i.e. above the lake basin Q2 aquifer level). They exhibit a very high seasonal drawdown of 5-6 m in response to nearby irrigation abstraction from a relatively low transmissivity formation.

Bore S27/0594 (44 m) is located on the eastern side of the valley within the fan zone of the Turanganui River. This bore has a less seasonally variable hydrograph (Figure 7.23, green line) and a consistent head of about 8 m amsl (higher than the monitoring bores of similar depth on the other side of the Ruamahanga River). Larger summer drawdowns in recent years can be attributed to the commencement of irrigation from a nearby irrigation bore (S28/0008). Bore S27/0618 (5 km northeast of S27/0594) shows a higher winter head (12 m) than monitoring bores to the west of similar depth. These have a winter level of about 6 m amsl (see Figure 7.22). Bore S27/0618 is possibly screened within older mid or early Quaternary sediments on the edge of the valley and may be under a higher confining pressure than bores to the west. A long-term declining trend in groundwater levels (Figure 7.23) is evident in this bore which, because of the effects of general irrigation in the area, also has a large seasonal drawdown of up to 5 m.

The Onoke/Narrows sub-area appears to be relatively complex geologically with groundwater levels apparently lower close to the Ruamahanga River (bores S27/0587 and S27/0576).

(f) Sub-area 6: Huangarua valley and eastern hills

There are no monitoring bores in this sub-area to enable a characterisation of temporal groundwater level trends and vertical flow gradients.

7.2 Rainfall recharge

7.2.1 Occurrence and spatial variability

A principal groundwater recharge process in the Lower 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 seeps through the ground.

The steep rainfall gradient across the valley from the Tararua Range to the eastern hills results in considerable spatial variability in recharge. The highest average annual rainfall of 1,800-1,900 mm occurs against the Tararua Range, reducing to 800-900 mm on the eastern side of the valley (Section 2.3, Figure 2.5). Because of this high rainfall gradient, rainfall recharge is expected to demonstrate a large spatial variability across the catchment. Soil type and the underlying shallow geology also exert a significant influence on rainfall recharge processes.

Figure 7.24 shows the location of likely rainfall recharge zones based upon underlying soil and geological conditions. Rainfall recharge potential is highest in areas with the lowest runoff coefficient (i.e. where the most permeable soils occur) – the Tauherenikau fan, northern part of the Ruamahanga valley and the Martinborough terraces. This map is consistent with the depth to water table map presented in Figure 7.3 which shows those areas where rainfall recharge is most likely to occur based on the relative difference between ground level and groundwater level. Recharge occurring in the areas identified is considered to infiltrate to deeper aquifer levels and flow into downgradient confined aquifers of the lake basin.

In the lake basin area, the shallow geology consists of large thicknesses of lacustrine and estuarine silts. Rainfall infiltration is therefore not regarded to provide a recharge source to the confined aquifers in this area – where significant upwards vertical gradients are observed. However, localised rainfall recharge to shallow more permeable superficial deposits, such as the Holocene dune sands, will occur. Very shallow groundwater within these sands will tend to discharge relatively quickly into streams, rivers and drains, or into Lake Wairarapa.

A similar situation to that in the lake basin is observed within the Onoke/Narrows sub-area. Upwards or neutral head gradients in the aquifers suggest that groundwater discharges to the surface or to horizontal flows in this area. However, rainfall recharge along side-valleys such as those of the Turanganui, Tauanui and Dry rivers may provide a recharge source for aquifers occupying the main valley in this area. This concept is supported by groundwater chemistry and isotope data.

7.2.2 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 2 provides details of the recharge model and input parameters for the Lower 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).

7.2.3 Spatial recharge pattern

Outputs from the recharge model are shown in Figures 7.25 to 7.30.

Figure 7.25A shows the modelled annual average recharge for the Lower Valley catchment. The recharge pattern is strongly influenced by the annual rainfall distribution (Figure 7.25B) and ranges from 700-940 mm/year along the northern edge over the upper Tauherenikau fan area, to less than 100 mm/year on the Martinborough terraces. Considerably lower recharge occurs over the lake basin and Onoke areas due to low permeability soils and the prevalence of groundwater discharge conditions.

Figure 7.26 shows recharge as a percentage of rainfall on an average annual basis. Over the upper fan areas, up to about 50% of rainfall becomes groundwater recharge. On the drier southern side of the valley along the Ruamahanga valley and on the Martinborough terraces, less than 10–20% of rainfall becomes recharge due to higher proportional losses to evapo-transpiration.

Figures 7.27 and 7.28 show representative recharge maps for 29 June 2005 and 25 June 2008 derived from the distributed soil moisture balance recharge model to illustrate regional recharge patterns. Recharge is restricted to the northern parts of the catchment – over the Tauherenikau fan, Ruamahanga valley, Martinborough terraces and Huangarua valley. There is no recharge over the southern part of the catchment due to the existence of confined aquifer conditions, upwards flow gradients and shallow low permeability sediments. The recharge pattern in the north reflects the rainfall gradient and, for the 25 June 2008 example, is highest in the northern-most part of the catchment at 3–4 mm/day and lowest over the Martinborough terraces at <1 mm/day.

7.2.4 Simulated recharge trends 1992–2008

Recharge modelling enables the analysis of recharge trends for the modelled period (1992–2008). The calculated recharge records for three representative cells from the distributed model are shown in Figure 7.29 and the locations and soil properties for each of the cells are shown in Table 7.2.

Table 7.2: Representative cells from the distributed recharge model for the Lower Valley catchment

Cell ID	Location	Col.	Row	FC	Wilt	SCS	Fract
38445	Featherston	149	113	120	40	89	0.4
40522	Battersea area/ Tauherenikau fan	157	118	110	40	86	0.4
43391	Martinborough	168	138	330	180	91	0.4

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

Figure 7.29 shows a plot of the annual recharge depth for each of the three cells to demonstrate the spatial variation in recharge across the valley, and to illustrate trends over the last 16 years. The plots show a progressive decrease in annual recharge between 1996 and 2001 in the Tauherenikau fan/Featherston area. The recharge pattern on the eastern side of the valley and the Martinborough terraces reflects the significantly lower rainfall and elevated potential evapo-transpiration rate, and also the prevalence of low-permeability soils on the loess-covered terraces.

On the Martinborough terraces, a prolonged dry period began in 1997 and extended into 2003 resulting in virtually no modelled recharge for the years 2000, 2001 and 2002. Again, little or no recharge occurs in 2003, 2005 and 2007. This recharge pattern is noticeably reflected in groundwater level trends in the Martinborough sub-area (Section 7.1.4(c)).

The calculated daily volumetric recharge rates derived from the soil moisture balance model for the entire Lower Valley catchment for the period 1992–2008 are shown in Figure 7.30. The long-term variability pattern mirrors the modelled recharge outputs for individual model cells (Figure 7.29) showing significantly lower annual recharge between 1997 and 2003, in 2005 and 2007. The driest years in the 16-year record were 2001 and 2007 and the wettest were 1996 and 2008. The polynomial regression line on Figure 7.30 shows long-term declining recharge rates from 1992 to about 2003, followed by a rising trend from 2004 to 2008. Moving 30-day averages are also shown to clarify inter-year variability.

Long-term variability in recharge is reflected in groundwater levels and aquifer discharge rates (such as spring flows). Figure 7.31 shows the monitoring hydrographs for the period 1992-2008 for two representative bores located in the Q2 confined aquifer in the Kahutara groundwater zone (S27/0271) and in the lake basin (S27/0428). The aquifer is regarded as being recharged from rainfall over the Tauherenikau fan. Both of these hydrographs show a long-term gentle recession up until 2003/04 when the recession flattens before declining again at an even steeper rate up until the end of the monitoring record in 2008. The early decline is reflective of the recharge trend and could be explained by reducing aquifer recharge rates, rather than abstraction which started to increase dramatically from about 2003 (see Section 7.5). The more recent decline in groundwater levels is, however, opposite to the long-term recharge pattern and could be more plausibly explained by rapidly increasing seasonal irrigation abstraction from the catchment.

7.2.5 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 soil moisture balance model has been verified by comparing calculated recharge with lysimeter data from 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 2. 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 is considered to be a recharge area for deeper 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 within sub-area 1 show an average seasonal level rise in the unconfined aquifer of about 3 m (see Section 7.1.4(a)).

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.

7.3 Groundwater–surface water interaction

7.3.1 Background

Large components of the groundwater balance for the Lower 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. Natural groundwater discharges occur as river base flow, spring flow and diffuse seepage into wetlands and lakes. 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. For this reason, developing new policy to sustainably manage the surface water and groundwater resources in the Lower 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.

Figure 7.32 illustrates the concentration of large shallow abstractions located within the Q1 unconfined aquifer adjacent to major drainage systems, particularly along the Ruamahanga River. Many of these groundwater abstractions source water through depletion of surface water flow.

7.3.2 Connected surface water environments

The principal surface water environments which are connected to groundwater are as follows:

- Tauherenikau River (above SH 53)
- Huangarua River (relatively little information is available for this river)
- Main eastern side-valleys – the Dry, Tauanui and Turanganui rivers all lose flow to groundwater
- Springs – Stonestead (Dock) Creek, Otukura/Battersea system, Abbotts/ Featherston system
- Water races – the Moroa Water Race is considered to both recharge groundwater and receive groundwater discharge
- Ruamahanga River – upstream of Huangarua confluence
- Lake Wairarapa – gains inflow from Tauherenikau fan gravels and seepage from deeper aquifers.

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 or stream 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.

Figures 7.33A–C provide an analysis of the concurrent gauging surveys as a series of longitudinal profile plots for three rivers and streams in the Lower Valley catchment (the Tauherenikau River, Stonestead (Dock) Creek and the lower Ruamahanga River). Each plot shows the observed losing and gaining reaches of the waterways. In a losing reach the river loses flow to the aquifer and in a gaining reach the river gains water from the underlying aquifer.

The same data are represented geographically in Figure 7.34 with losing, gaining or neutral (neither gaining nor losing) reaches highlighted in different colours. A river can therefore have simultaneous gaining, losing and neutral reaches along its length in a seasonally varying pattern. It is important to recognise that these plots represent the groundwater–surface water interaction during low flow and low groundwater level conditions. It is probable that the pattern is somewhat different under different flow regimes (i.e. high flows).

7.3.3 Tauherenikau River

Figure 7.33A shows the analysis of the concurrent gauging surveys for the Tauherenikau River. The locations of the gauging sites are shown on Figure 7.34. The plot shows an observed losing reach between the gorge and the Tauherenikau Racecourse–SH 53 bridge area. Over this reach, the river consistently loses between 800 L/s and 1,100 L/s to groundwater. Most of this disappears over a 3 km section between the SH 2 bridge and the SH 53 bridge. The reason for the high bed-loss over this reach is probably due to the occurrence of channels filled with highly permeable gravel along a former course of the river. These gravels allow flow to be diverted to groundwater from the true left bank of the Tauherenikau River. The channels link into the Stonestead (Dock) Creek spring system and a large proportion of the loss from the river probably re-emerges in this vigorous spring system which flows consistently at more than 400 L/s in its lower reaches (see Figure 7.33B). Some of the loss may also re-emerge in springs and drains on the northern side of the river as it enters the delta area at Lake Wairarapa.

Downstream of SH 53 the flow in the Tauherenikau River remains stable, showing neither significant loss nor gain. Along this reach and down to the shore of Lake Wairarapa, the river is generally elevated above the surrounding land and therefore the bed must have a relatively low hydraulic conductivity to prevent losses.

7.3.4 Groundwater discharge on the Tauherenikau fan

Several extensive spring systems and diffuse groundwater discharge areas occur on the Tauherenikau fan. The most extensive discharge area is the Otukura/Battersea spring/drain system covering the eastern part of the fan, down to Te Maire ridge (Figures 3.2 and 7.35). The Battersea drainage system is highly modified and linked to the Moroa Water Race network making it very difficult to distinguish groundwater discharge from water race flows. The discharge area may extend as far up the fan as SH 2 with much of the flow being channelled to the south. The flows in this spring system have not been quantified for this study, but it is likely that the water race system recharges the shallow groundwater during summer, whilst draining the water table during high winter levels.

The Otukura spring system is also highly modified and is integrated with the agricultural drainage network. The main Otukura Stream channel (Figure 7.35) is fed by the Moroa Water Race at the northern end of Cross Line. Any groundwater gains downstream can thereby be attributed to groundwater inflow. During summer it appears that there are no gains from groundwater and that the very small flows observed at the Otukura Stream weir of 30–50 L/s (sometimes less) are entirely water race-derived. The flow record for the Otukura Stream is shown in Figure 3.3; this shows the influence of surface water runoff during the winter months. It should also be remembered that during summer, groundwater seepage may be strongly influenced by evapotranspiration and, although no flow is measured, there is probably a portion which is evaporated.

The other major spring discharge on the Tauherenikau fan is associated with the Stonestead (Dock) Creek system (see Figure 7.33B) which is closely linked to the Tauherenikau River (as discussed previously).

There is relatively sparse information on the Donalds/Abbotts Creek system around Featherston but some of the flow is thought to be groundwater discharge from the fan alluvium. Spot gauging data suggest that the total summer base flow is in the order of 50–100 L/s.

7.3.5 Ruamahanga River

The relatively large rates of flow in this river mean that it is not possible to confidently identify losing and gaining patterns because the standard gauging error is too high at +/- 10%. However, Table 7.3 lists the data derived from a concurrent gauging survey carried out on 22 February 2006, and another less detailed one on 16 March 2006, which serve to provide an indication of the interaction between the Ruamahanga River and the groundwater environment. The locations of the gauging sites are shown on Figure 7.34 and the data in Table 7.3 are plotted in Figure 7.33C.

Table 7.3: Summary data from concurrent gauging surveys of the lower Ruamahanga River on 22 February 2006 and 16 March 2006 (L/s)

Gauging site	22 Feb 2006	16 Mar 2006	Loss/gain (22 Feb 2006)	Loss/gain (16 Mar 2006)
Morrisons Bush	10,930	12,917	*No data*	*No data*
Moiki	10,702	*No data*	Loss 228	*No data*
Tributary input Huangarua R @ Ponatahi*	*263*	*258*	No data	*No data*
Waihenga bridge	10,299	*No data*	Loss 403	*No data*
Walls	9,613	12,806	Loss 686	Loss 110
Pukio	10,218	13,388	Gain 605	Gain 582
Awaroa Sill	9,536	13,101	Loss 682	Loss 287
Otaraia	10,978	13,007	Gain 1,442	Loss 94

* Flows measured downstream are normalised to the input.

The two gauging runs show quite different results, which may be attributed to gauging error, although both show consistent loss and gain patterns between Morrisons Bush and Awaroa Sill. The February survey showed very large losses of about 1,300 L/s between Morrisons Bush and Walls, taking into account inflow from the Huangarua River. This recorded loss is likely to be outside the gauging error. The March survey shows only a small loss of about 100 L/s for the same reach.

The gauged loss between Morrisons Bush and Walls is consistent with the conceptual understanding that this reach of the Ruamahanga River recharges both shallow and deeper aquifers and is a recharge source for deeper confined aquifers in the lake basin. Aquitard layers develop and thicken downstream from the Walls area and therefore the Ruamahanga River is not likely to recharge deep aquifers downstream of there. Towards Walls there are also recent gravel-filled palaeochannels of the Ruamahanga River which may divert some flow from the river westwards towards Lake Wairarapa.

Both gauging surveys showed a large gain in flow of about 500–600 L/s between Walls and Pukio. The consistency between the sets of data suggests that the gain is real. The Dry River enters the Ruamahanga River between these sites and, although there is no flow in the tributary during the summer at its confluence, it is probable that there is a significant shallow groundwater through-flow in the gravel fan deposits emanating from the eastern hills catchment. Together with shallow groundwater flowing off the Martinborough terraces, these through-flows could account for the gaining flow in the Ruamahanga River between Walls and Pukio.

Losses from the river in the reach below Pukio could relate to diversions from the river towards Lake Wairarapa via old gravel channel deposits. Gauging errors towards Otaraia are, however, likely to increase due to the higher flows and tidal influences on the flow.

7.3.6 Lake Wairarapa

Very little information exists (other than anecdotal) with which to characterise the connection between Lake Wairarapa and groundwater. It seems highly likely that the lake receives groundwater inflow from the shallow Tauherenikau fan deposits and from groundwater stored in the superficial deposits around the lake, as well as from agricultural drains which are used to manage the water table in former lake margin wetland areas. Whether there is input from deep confined aquifers via seepage or discreet springs is unknown, although there are anecdotal reports of spring up-wellings in the lake bed. Piezometric contour lines for deeper aquifers in the lake basin converge on the lake (Figure 7.2) suggesting that there must be discharge from the deep aquifers (most probably as diffuse leakage) into the lake.

Because the lake level is managed at the barrage and surface water inflows into the lake (principally the Tauherenikau River) and out of the lake have not be gauged to date, it is not possible to undertake water balance calculations for the lake. However, the groundwater flow model has proven very useful in terms of determining the functioning of the lake as a regional groundwater sink.

7.4 Groundwater abstraction

7.4.1 Abstraction trends and current allocation status (2008)

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

The locations of consented groundwater abstractions are shown in Figure 7.32, with abstraction bores grouped into nine areas to assist spatial analysis. As at the commencement of groundwater model development in 2008, there were 142 bores in the Lower Valley catchment consented to take up to 201,700 m^3/day and 40.3 x 10^6 m^3/year of water – the highest total take of any of the three Wairarapa Valley groundwater catchments.

Figure 7.36 shows the trend in groundwater allocation for the Lower Valley catchment over the 16-year modelling period (1992–2008). Also shown on this plot is the estimated (or modelled) abstraction for the entire Lower Valley catchment using the methodology described below in Section 7.4.3. The daily abstraction rate from the catchment for the three years up to 2008 was estimated to be between 100,000 and 130,000 m^3/day (up to about 65% of the consented abstraction rate).

Table 7.4 summarises data (also shown in Figure 7.37) relating to the quantity of consented allocation from bores groups associated with the six groundwater sub-areas.

Figure 7.32 and Table 7.4 show that the highest concentrations of groundwater abstraction in the Lower Valley catchment occur around the lower edge of the Tauherenikau fan (Battersea-Kahutara-Lake Domain zones) and along the shallow permeable alluvium of the Ruamahanga River (Riverside-Tawaha-Pukio zones).

Table 7.4: Groundwater allocation in the Lower Valley catchment (2009)

Sub-area	Bore group/location	No. of consented abstractions	Consented vol. (m^3/day)	Consented vol. (m^3/year)
1	Group 1: Tauherenikau fan	23	14,480	3,647,969
	Group 2: Kahutara / Tauherenikau delta	20	38,454	8,053,165
	Subtotal	*43*	*52,934*	*11,701,134*
2	Group 3: Ruamahanga valley above Huangarua confluence (Riverside Zone)	13	22,813	3,003,598
	Group 4: Ruamahanga valley, Huangarua to Pukio (Tawaha Zone)	13	32,747	8,316,699
	Group 5: Pukio area	11	33,571	5,992,800
	Subtotal	*37*	*89,131*	*17,313,097*
3	Group 6: Martinborough terraces	26	6,546	1,263,914
4	Group 8: Lake basin	17	33,738	6,033,020
5	Group 9: Onoke/Narrows	7	12,417	2,638,640
6	Group 7: Huangarua valley	12	6,946	1,344,285
	Total	**142**	**201,712**	**40,294,090**

Table 7.4 also shows that the most heavily consented areas are the Kahutara/Tauherenikau delta (Bore group 2), Tawaha (Bore group 4) and Pukio (Bore group 5). The Ruamahanga valley has fewer bores but these are generally shallow and higher yielding, reflecting higher transmissivities than in the Kahutara area.

7.4.2 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 7.38 provides a broad evaluation of the proportion of the consented annual abstraction volume which was used over the period 2002/03 to 2008. About 378 reliable annual meter readings were compared against the consented take for their associated bore. 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 7.39 is 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 about 35% or less of the consented annual volume and that only 10% of readings show an actual annual use of greater than 50% the allocated volume.

Weekly meter readings were taken during the 2006/07 irrigation season from 21 large takes in Tawaha and Riverside groundwater zones (sub-area 2). These readings showed that annual use during the irrigation season was on average 27% of the annual allocated volume (the range 11-40%).

During the following 2007/08 irrigation season all abstractions of 10 L/s or more were metered on a weekly or fortnightly basis. The combined data for all metered bores are shown in Figure 7.40. The combined consented daily volume for the metered bores is 154,130 m^3 and the peak actual abstraction during February 2008 was 87,400 m^3/day – which is about 60% of the total allocated daily volume. On an annual basis, the combined consented abstraction from these bores is 33,966,842 m^3, whilst the total metered consumption for wells pumping at 10 L/s or more was 11,041,900 m^3. This represents 32.5% of the allocated annual volume.

The 2007/08 metering exercise demonstrated that resource consent holders tend to abstract groundwater at a rate approaching the maximum 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.

7.4.3 Abstraction modelling

Analysis of the Lower Valley catchment requires a reasonably good knowledge of groundwater use, particularly the timing of irrigation abstraction, short-term (weekly) abstraction rates, and the 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 (when available) was developed to model historic groundwater abstractions on a weekly basis for the period 1992 to 2008 (the numerical model calibration period). A variable soil moisture, deficit-linked, 'adjustment factor' was also applied to consented daily 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 is likely to start and stop 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 3 contains a detailed methodology of abstraction simulation developed for this study. Figure 7.36 shows the results of the abstraction modelling as a combined daily volumetric basis for the entire Lower Valley catchment.

7.4.4 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 Lower Valley catchment was estimated from the location of known bores, associated land use (using the 'Agribase' database) and the assumed abstraction rates in Table 7.5.

The distribution of permitted takes is shown in Figure 7.41 and indicates high bore densities on the Tauherenikau fan (particularly in the Featherston, Battersea and Kahutara areas) and on the Martinborough terraces. There is an estimated total of 590 permitted takes in the catchment cumulatively abstracting an estimated volume of 11,400 m^3/day, or approximately 5.6% of the consented groundwater abstraction volume. Cumulatively, the volume of permitted takes is therefore not significant in relation to consented takes, although there may be localised effects from permitted groundwater abstraction in some areas.

Table 7.5: Assumed daily water demand in relation to land use applied in the estimation of groundwater taken in the Lower Valley catchment as a permitted activity

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

7.5 Aquifer hydraulic properties

The hydraulic properties of the hydrostratigraphic units within the Lower 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 *Type 2* basic yield tests (transmissivity derived using a simple yield-drawdown calculation). The more reliable Type 1 tests were preferentially used to characterise the hydraulic properties of the various hydrostratigraphic units in the project area.

Figure 7.42 shows the spatial distribution of the observed transmissivity data. The map shows a pattern that reflects the distribution of the principal hydrostratigraphic zones. Particularly apparent is the lower hydraulic conductivity of the Tauherenikau fan deposits, Martinborough terraces and alluvium in Onoke/Narrows area. The enhanced transmissivity of shallow Q1 gravels located along the Ruamahanga River and in the confined lake basin aquifers is also evident.

Table 7.6 contains a summary of the Type 1 aquifer test data – segregated into the hydrostratigraphic units and groundwater sub-areas described previously in Section 6.3:

- Sub-area 1: Tauherenikau fan and northern lake margin
  Mid-Tauherenikau fan between 20 and 80 m contours (alluvial fan gravels)
  Lake Domain and Kahutara (transitional alluvial fan–lake basin confined aquifers)
- Sub-area 2: Ruamahanga valley
  Q1 unconfined aquifer (<20 m) and transitional Q2-Q4 semi confined/confined aquifers.

- Sub-area 3: Martinborough terraces
  Mid Quaternary terrace deposits
  Q1 unconfined aquifer and Q2 or older deposits
- Sub-area 4: Lake basin
  Q2-Q4 lake basin confined aquifers
- Sub-area 5: Onoke/Narrows
  Q2-4 confined aquifers
- Sub-area 6: Huangarua valley
  Q1 unconfined aquifer
  Q2+ terraces

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. The geometric mean values in Table 7.6 are regarded to be representative of the areas and associated hydrostratigraphic units.

Table 7.6: Analysis of transmissivity and storage values derived from Type 1 groundwater pump tests in the Lower Valley catchment

Sub-area	No. of *Type 1* tests	Mean T (m²/day)	Geomean T (m²/day)	Std Dev T	Mean S	Geomean S	St
1 – Tauherenikau fan	18	700	420	570	5E-4	3.6E-4	0.1
1 – Lake Domain/ Kahutara	24	1880	1,200	1500	7.5E-3	3.4E-4	
2 – Ruamahanga valley >20 m	11	4,150	2,900	3,150	5E-4	4E-4	
2 – Tawaha & Ruamahanga valley <20 m	20	5,200	4,500	2,600	0.034	0.016	
3 – Martinborough & Dry River Aqs 1+2 10-60m	26	700	530	520	3.7E03	8E-4	0.15
3 – Martinborough & Dry River Aq 3+ >60m	3	35	34	10	3E-4	2E-4	
4 – Lake basin Q2 confined aquifers	11	2,750	1,150	3,380	2E-4	1.5E-4 6E-5 (Q4)	
5 – Onoke/ Narrows	5	320	290	140	1.4E-4	1.3E-4	
6 – Huangarua valley <10 m	3	1,100	900	820			0.15
6 – Huangarua valley >10 m	10	760	580	470	5E-3	7E-4	

Note: T = transmissivity, S = storage and St = specific yield.

Table 7.6 demonstrates the increasing sorting with distance down the Tauherenikau fan and into the lake basin by the progressively increasing transmissivity between sub-areas 1 and 4. This is coupled with a decrease in storativity into the deeply confined lake basin aquifers.

Highest transmissivities occur in the Ruamahanga valley (sub-area 2) within the shallower aquifers (<20 m depth), generally of Q1 or Q2 age. The geometric transmissivity mean for these deposits is 4,500 m^2/day (hydraulic conductivity = 3-400 m/day).

The Martinborough terraces (sub-area 3) have a distinctively different hydraulic property characteristic consistent with the geology of this area – being an older uplifted terrace sequence. The upper sequence (to about 60 m depth) exhibits transmissivities similar to the Tauherenikau fan of about 4-500 m^2/day. Both the Tauherenikau fan and upper Martinborough terrace sequences are considered to be contemporaneous. The deeper aquifers of the Martinborough terraces have significantly lower hydraulic conductivity reflected by transmissivity values of about 50 m^2/day.

8. Hydrochemistry

8.1 Introduction

Water chemistry data for the Lower 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 et al. 2009) on the groundwater and surface water chemistry of the Lower Valley catchment. It also summarises the results of groundwater age dating and isotope testing. The analysis builds on previous work undertaken for the Middle Valley catchment by Daughney (2007) and 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

Using both groundwater and surface water chemistry data, a multivariate statistical analyses was undertaken by GNS Science (Daughney 2009) for the entire Wairarapa Valley. A full account of the work is contained in Appendix 4. Hierarchical cluster analysis (HCA) was used to define water quality 'clusters' (i.e. hydrochemical groups or categories) and then assign monitoring sites to a group. HCA was performed purely on the basis of groundwater chemistry (conductivity and major ions[5]), and did not explicitly account for any factors such as bore location, depth or aquifer lithology. Thus, HCA can provide a simple summary of the variation in groundwater chemistry across the Lower Valley catchment without any prior assumptions regarding the conceptualised hydrogeology.

The HCA investigation used chemistry data (provided by Greater Wellington) from about 6,000 water samples collected from 602 groundwater monitoring sites and 31 surface water monitoring sites. The analysis identified two major hydrochemical categories, termed clusters A and B, which are very different in terms of their 'average' hydrochemistry.

Category A waters include most of the surface water sites as well as 40% of groundwater sites. These are oxygen-rich dilute waters with Ca and HCO_3 as the dominant cation. Category A waters are typical of river waters and groundwater falling in this category would be expected to have been recharged recently from rivers or from rainfall in areas of low intensity landuse. Category A waters were further subdivided into two subclusters:

- A1: very dilute waters associated with rivers that drain the Tararua Range and shallow groundwater near to rivers; and
- A2: waters with higher concentrations of total dissolved solids (TDS) associated with shallow groundwater within alluvial fan deposits predominantly recharged from rainfall.

[5] 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 B waters comprise about 60% of groundwater sites and are dominated by Na and HCO_3. The concentrations of most ions are considerably higher than for Category A and are characteristic of more evolved (or reduced) groundwaters. This type of chemistry probably indicates older groundwaters. Category B waters were further subdivided into four smaller clusters termed B1, B2, B3 and B4 as they become progressively more evolved.

B1 waters are more evolved and reduced, being characterised by a considerable increase in all major ions and conductivity, higher concentrations of NH_4-N, Fe and Mn and low concentrations of NO_3-N. Surface water sites assigned to B1 are associated with rivers draining the eastern catchments (such as the Huangarua River) and are probably influenced by the different catchment geology (Miocene-Pliocene marine deposits) compared with Tararua Range-sourced rivers. Groundwater of B1 type may therefore be recharged from B1-type streams and rivers.

B2 waters are more oxygen-poor and typical of shallow to moderate depth bores (Q4-Q6?). Cluster B3 waters tend to have higher concentrations of most major ions than B1 and B2 waters and lower concentrations of SO_4. B3 type groundwaters are therefore slightly older and more chemically evolved than B1 and B2 sites and are characteristic of relatively deep bores in the lake basin (Q8+). Cluster B4 sites have the highest conductivity and concentrations of major ions inidicating that the groundwater is very old and possibly stagnant. Low SO_4 and NO_3-N concentrations indicate a highly anoxic environment. Cluster B4 sites tend to occur only in the lake basin at depth.

8.3 Interpretation of Lower Valley hydrochemistry

The HCA analysis of Wairarapa groundwater and surface waters provided the following observations with regard to the Lower Valley catchment (refer also to Figure 8.1):

- Rivers that drain the Tararua Range such as the Tauherenikau are typically oxygen-rich with low TDS and are assigned to Cluster A1.
- Rivers that drain the eastern side of the valley (e.g. the Huangarua River) are oxygen-rich but have a higher concentration of dissolved solids compared with Tararua Range-fed rivers (B1-type waters). The geology of the eastern catchments (predominantly marine sediments) appears to impart a distinctive chemical signature to the rivers that drain them.
- The Ruamahanga River has an A2 signature which is consistent with a significant proportion of its base flow being derived from rainfall-recharged groundwater. However, in the lake basin area, there is no evidence that local groundwaters are of A2 type and it was therefore concluded that the river does not interact with groundwater in this area (downstream of Pukio). This observation is consistent with concurrent flow gaugings and the geological model for this area.
- Lake Wairarapa has a B1-type chemical signature even though the rivers that drain into it have A1 or A2 signatures. Deeper groundwaters in the

vicinity of Lake Wairarapa are assigned to clusters B1 to B4. Hence the hydrochemistry of the lake may indicate that it receives some inflow via seepage from deep aquifers.

- Oxygen-rich A1-type groundwater is found in shallow bores in the Q1 gravels near the losing reaches of the Tauherenikau River. This pattern is observed across the Wairarapa Valley and indicates a hydraulic connection between rivers and the shallow groundwater environment.

- Tauherenikau fan deposits contain shallow groundwater which is oxygen-rich (Cluster A2) and has a chemical signature consistent with rainfall recharge.

- The chemical signature of B2 waters from moderate depth bores in the Tauherenikau delta (Kahutara) and lake basin could have been acquired by evolution from A2 type groundwater as it moves along a flow path to the lake basin at depth. This implies that the B2 groundwaters are recharged by rainfall and that a hydraulic connection occurs between the A2-type waters in the Tauherenikau fan and the deeper lake basin aquifers.

- Most bores to the south of Lake Wairarapa are deep and contain groundwater that is oxygen-poor with high concentrations of dissolved solids (clusters B3 and B4). This is consistent with strongly reducing conditions and old groundwaters that are flowing very slowly.

8.4 Groundwater age dating

Groundwater residence times and flow pathways in the Lower Valley catchment were examined using tritium, CFC, SF6 and C14 data. A detailed description of this work is discussed in Morgenstern (2006). 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.

The estimated age dates shown in Figure 8.2 provide a pattern which is consistent with the conceptual groundwater flow system. The youngest waters occur in shallow aquifers on the Tauherenikau fan and are mostly around 40 years old, with occasional younger waters probably associated with recharge from neaby rivers or streams. As the aquifer becomes confined downgradient into the lake basin (through the Kahutara transition zone), there is a marked increase in residence time to about 150 years for the upper confined Q2 aquifer. Clearly, there must be active leakage or throughflow from this aquifer in order to maintain such a relatively young age. The age of 180 years in the Onoke area suggests that the lake basin Q2 aquifer continues through to the coast. A very deep bore (178 m – Robertson Transport) screened within a deep, low yielding formation in the lake basin returned an age of 6,000 years suggesting a very restricted flow system at this depth.

Down through the Ruamahanga valley there is also a clear evolution in groundwater age along the regional groundwater flow path – from about 50 years in the Huangarua confluence area – through to 80 years in the Pukio area, then to about 150 years in the centre of the lake basin. This pattern therefore provides good evidence for a continuous flow path from the unconfined Ruamahanga valley aquifers through to the lake basin confined (Q2) aquifer.

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. This 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 analysis.

The Murray Darling Basin Commission (MDBC) modelling guidelines (Middlemis 2001) provide succinct statements on the purpose, form and significance of a conceptual model:

- *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 hydrogeological 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 6.5 to 6.13 are a series of cross sections which describe the conceptual model developed for the Lower Valley catchment. The various boundaries, physical geological framework, hydrological features and water balance components are discussed separately below.

9.2 The Lower Valley groundwater environment characteristics

The Lower Valley catchment covers an area of approximately 643 km^2 and incorporates the catchments of the Ruamahanga and Tauherenikau rivers, and also Lakes Wairarapa and Onoke. The tectonically complex groundwater basin contains a heterogeneous sequence of late Quaternary fluvio-glacial sediments. Major fault and fold structures have influenced the drainage patterns and depositional environments of the alluvium sequences. Blocks of older less permeable sediments and basement greywacke rock have been uplifted and displaced against younger water-bearing strata around Te Maire ridge and the Martinborough terraces. Structural deformation is also responsible for the creation of a large subsiding basin centred on Lake Wairarapa where muliple sequences of thin re-worked gravel aquifers are confined by extensive lacustrine and estuarine fine-grained deposits.

On a broad scale the Lower Valley catchment groundwater environment comprises a shallow, unconfined, flow system which is connected to rivers and streams where permeable Holocene alluvium occurs. Large areas of relatively low permeability, poorly-sorted fan gravels occur on the western side of the valley against the Tararua Range and on the Tauherenikau fan. The fan sequences grade distally and segregate into a sequence of discrete re-worked permeable confined aquifers in the lake basin. Intervening poorly sorted gravels and fine grained interglacial aquitards confine and separate reworked gravel intervals. On the eastern side of the valley, the Ruamahanga River has carved a shallow channel between Te Maire ridge and the eastern hills. Here, groundwater flowing in the relatively thin permeable alluvium is intimately associated with the river. The Martinborough terraces represent a geologically distinct uplifted area of low permeability alluvium. Structurally complex older terrace deposits (mid Quaternary +) occur at depth in the Martinborough area.

9.3 Groundwater system boundaries

The model domain boundaries for the Lower Valley groundwater catchment are shown in Figure 9.1 and are described as follows:

Western: 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: this boundary separates the Lower Valley from the Middle Valley catchment. It is placed along a groundwater flow divide between the two systems but also coincides with a geological boundary between younger Q1 age gravels of the Waiohine plains to the north and the older Q2 surface of the Tauherenikau fan to the south. Where this boundary crosses the Ruamahanga River no through-flow is assumed to occur from the adjoining Middle Valley catchment due to the very shallow depth of the valley-fill alluvium at this locality. In reality there is probably a small amount of throughflow, but it is considered insignificant in terms of the catchment water budget.

Eastern: 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. In the coastal area (Onoke/Narrows), the boundary encompasses a wedge of early Quaternary terraces which host a series of incised river valleys containing younger alluvium – a probable source of recharge to the main valley.

Southern boundary: the short coastline section at Lake Onoke is represented as a fixed head condition at 0 m amsl - which is part of the Lake Onoke boundary condition (also assumed fixed head at sea level).

Internal physical boundaries: The Te Maire ridge represents a faulted block of greywacke basement mantled with an older alluvial terrace sequence. The ridge represents an elongate low-permeability barrier within the flow system which plunges into the lake basin. Likewise, the Harris ridge to the east of

Martinborough represents the core of the anticline containing Tertiary mudstone and separates the Huangarua valley from the Martinborough terraces.

9.4 Geological framework

9.4.1 Hydrostratigraphy and groundwater sub-areas

Table 6.2 lists the principal hydrostratigraphic units identified in the Lower Valley catchment. The principal features of the five groundwater sub-areas (see Section 6.3) have been distinguished using the geological analysis, in particular the cross sections discussed in Section 6, and the hydrogeological and hydrochemical assessments (Sections 7 and 8 respectively). They are summarised below.

(a) Sub-area 1: Tauherenikau fan (alluvial fan gravels and Q1 unconfined aquifer)

- A large fluvio-glacial low-angle outwash fan system occupying the northern part of the Lower Valley catchment between the Wairarapa Fault and Te Maire ridge, and extending into Lake Wairarapa.

- The fan deposits are a highly heterogeneous mixture of gravels, sands and silts.

- Abstraction bores in the fan sequence tend to be no more than about 30 m deep and provide moderate yields, generally less than 10 L/s.

- The upper fan area to the west (the former Woodside groundwater zone), closest to the Wairarapa Fault, seems to have a lower hydraulic conductivity.

- There are no laterally traceable aquifer zones in the fan sequence – local reworking is, however, evident through the occurrence of sporadic higher bore yields.

- Tauherenikau fan deposits develop better groundwater potential towards the base of the fan in the Battersea and Kahatara zones where moderate-yielding irrigation bores are located.

- Reworked gravels extend off the fan and into the lake basin merging with deep confined aquifers (Q2, Q4, Q6). The aquifers are separated by low permeability silt aquitards which lap on to the fan and are associated with palaeo lacustrine or estuarine environments.

- The modern Tauherenikau River has built a broad distributary delta where it enters Lake Wairarapa periodically spreading well-sorted gravel deposits into the silt-dominated lacustrine/estuarine environment of the lake basin. At a shallow level, recent

Tauherenikau River delta gravels are probably a source of groundwater inflow into Lake Wairarapa.

- At some time in the recent past the Tauherenikau River has cut into the fan re-working the gravels and re-depositing them as Q1 (Holocene age) alluvium. Although never more than about 10 m thick these Q1 deposits constitute a local aquifer that is higher-yielding than the surround fan sequence, with which it is in hydraulic connection.

- Groundwater is recharged principally through rainfall infiltration over the fan, although river bed leakage (and water race leakage) is an important additional recharge source.

- Groundwater discharges into widespread spring and wetland systems distributed across the lower fan areas.

- The fan system is connected to confined lake basin aquifers and provides some of the recharge to the lake basin aquifers.

(b) Sub-area 2: Ruamahanga River valley (Q1 unconfined aquifer, Q2+Q4 aquifers; Q1, Q3 and Q5 aquitards)

- A shallow (<15 m deep) unconfined aquifer occupies the Ruamahanga valley which is defined by the occurrence of postglacial Holocene age (Q1) gravels and older glacial Q2-4 age alluvium around present-day river channels and flood plains.

- The uplifted Te Maire ridge forms the western boundary of the Ruamahanga groundwater system and effectively separates it from the Tauherenikau fan. The eastern boundary is represented by a greywacke basement or mid-Quaternary older low-permeability terraces.

- North of the Huangarua confluence, the valley fill behaves as a single shallow, linear, unconfined (to semi-confined) aquifer which has a relatively free hydraulic connection to the Ruamahanga River. The aquifer is only 10-20 m thick and underlain either by basement greywacke or Tertiary mudstone.

- Groundwater probably moves between the aquifer and river freely in a complex manner, continually leaving and re-joining the meandering river.

- To the south of the Huangarua confluence towards the lake basin, the Ruamahanga valley remains bounded by the Te Maire ridge on the west, but is now also bounded by the Martinborough Fault on the east side. The base of the groundwater system rapidly deepens to about 40-50 m from the very shallow system further north.

- Q2 and Q4 aquifers segregate out as intervening wedges of silt-rich aquitard develop and progressively thicken down-valley as they enter the lake basin (see cross-section 8, Figure 6.12).

- The segregated Q2 and Q4 aquifers enter the lake basin and merge with similar age deposits associated with the Tauherenikau drainage system.

- Near-surface lower permeability Holocene lake sediments extend up-valley into the Tawaha area and form an upper semi-confining layer thickening towards the lake basin (Q1 aquitard).

- The Q1 gravels of the Ruamahanga River exhibit medium to high hydraulic conductivities. Most large groundwater abstractions in the Lower Valley catchment occur from the Q1 aquifer along the Ruamahanga River (Riverside and Tawaha zones) where highly transmissive aquifers occur.

- The Ruamahanga River is a recharge source for the deepening Q2 and Q4 confined aquifers where they merge with shallow Holocene alluvium upstream of confining lake sediments in the Tawaha area.

(c) Sub-area 3: Martinborough terraces (mid-early Quaternary terraces)

- Below a relatively thin mantle (30-40 m) of late Quaternary sediments (Q2-Q6), the Martinborough terraces are underlain by a much older sediment sequence which has been elevated on the flanks of the Harris Anticline. Early Quaternary (eQa) deposits are also mapped on the crest of the anticline together with Tertiary mudstone.

- These deposits consist mainly of alluvial gravel and sand with minor silt and swamp deposits. Most of the gravel deposits are clay-bound and have low hydraulic conductivities. Early Quaternary beds may be lacustrine and the sequence is subject to tilting, folding and faulting. The lower sequence has a relatively poor groundwater potential but bores in it can yield a sufficient quantity of groundwater for low-demand irrigation.

(d) Sub-area 4: Lake basin (Q2, Q4, Q6 and Q8 lake basin aquifers; Q1, Q3, Q5, Q7 aquitards)

- The lake basin is the dominant feature of the Lower Valley catchment. It is an actively subsiding depositional basin containing multiple, thin (<10 m), permeable, gravel aquifers within a predominantly fine-grained estuarine/lacustrine sequence.

- The aquifers are a product of both the Tauherenikau and Ruamahanga rivers which have periodically spread coarse sediments into the lake area during cold intervals. At least three thin gravel cycles can be recognised – Q2, Q4 and Q6 and deeper (unidentified) units undoubtedly exist.

- The aquifers extend back up-valley to recharge areas in the Tauherenikau fan and Ruamahanga valley.

- There is a distinction with respect to aquifer properties and water quality between gravels associated with the Ruamahanga River along the southern side of the lake basin and those deposited by the Tauherenikau River which occupy the central part of the basin. The Ruamahanga-sourced gravels have better hydraulic conductivity and water quality.

- Most of the gravel aquifers do not reach the basin outlet at Onoke but generally dissipate upstream of the Pouawha area. The exception to this appears to be the youngest Q2 (last glacial) aquifer which does seem to extend to the coast.

- Thick silt and clay aquitards occur in the lake basin where subsidence has resulted in alternative periods of estuarine and lacustrine environments

- The aquitards appear to attain 35-40 m or more in thickness in the deepest part of the lake basin, thinning to less than 10m towards the basin edges. They also appear to extend into the Onoke/Narrows area and are separated by thin gravel aquifers, except closer to the coast where the deeper gravel layers appear to fade out.

- Discharge from the confined aquifer in the lake basin occurs via vertical leakage through the aquitards and into Lake Wairarapa.

(e) Sub-area 5: Onoke/Narrows

- The Q2 aquifer from the lake basin appears to extend into this area where it occurs under a highly confined condition. Above Q2 there are lensoid gravel bodies which are probably associated with the fans of tributaries such as the Turanganui and Tauanui rivers. It is probable that significant recharge enters the aquifers through these fans via bed losses from the side rivers. This may also be a principal recharge mechanism for the Q2 aquifer.

- At the coast the depth to basement (probably Tertiary mudstone) is interpreted to be less than 10 m meaning there is very little coastal outflow of groundwater from the Wairarapa Basin and therefore a very limited connection between aquifers in the Onoke/Narrows area and the sea.

- Early Quaternary terraces occur on either side of the narrowing Wairarapa Valley in the Onoke/Narrows area.

(f) Sub-area 6: Huangarua Valley and eastern side valleys

- Gravels of Q1 age derived from the eastern hill country occur along the smaller Huangarua, Dry, Tauanui and Turanganui river systems. Thin deposits of later Quaternary alluvium (Q5) sometimes mantle these terraces, while gullies and valleys contain younger Holocene alluvium. The largest of these are the Turanganui and Tauanui rivers draining the eastern hills in the Onoke area.

- The fans of the side valleys obtrude into the main valley fill sequence and may provide a recharge source to deeper confined aquifers.

- On the southern side of the valley, older mid- to early Quaternary terraces occur against which the younger valley sequence fill has been deposited. It is probable that the surface of the older, less permeable, terrace deposits extends at a low angle northwards towards the Ruamahanga River (cross section 6, Figure 6.3). Most bores on the southern side of the valley probably intercept older aquifers than bores of the same depth on the northern side. This would account for differences in groundwater head in bores of the same depth on different sides of the valley (see Section 6.4.4).

9.4 Internal flow barriers

Te Maire ridge represents a prominent structural feature comprising a complex series of sub-parallel faults and folds in the Lower Valley catchment. The ridge forms a linear low-permeability barrier between the Tauherenikau fan gravels to the west and the confined Ruamahanga River to the east and constitutes a prominent aquifer boundary The presence of greywacke bedrock near the Ruamahanga River on its eastern flank suggests that the ridge is associated with a large vertical uplift component. Thin Quaternary cover sequences on the ridge are not regarded as being hydraulically connected to more permeable sequences on either side of the valley.

9.5 Hydrological framework and water balance estimation

A conceptual model for the Lower Valley catchment is required to describe 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 are as follows:

Inputs: Rainfall recharge

Runoff recharge – surface water inflow from rivers, streams, water races

Irrigation returns*

Outputs: Discharge to river beds

Diffuse seepage to wetlands and ET loss

Discharge to Lake Wairarapa

Discharge to Lake Onoke*

Spring flow

Abstraction from bores (or, more strictly, supply to bores)

Outflow to the sea*

* Water balance components 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 9.1 summaries the estimated water balance for the Lower Valley groundwater catchment.

Table 9.1: Estimated steady-state water balance for the Lower Valley catchment

	In (m^3/day)	Out (m^3/day)
Rainfall recharge	130,000	
River flow loss/gw recharge	210,000	
Water race recharge	10,000	
River flow gain/ gw discharge		120,000
Springs and diffuse ET		130,000
Abstraction		40,000
Lake Wairarapa discharge (+Onoke)		60,000
Total	*350,000*	*350,000*

Bearing in mind the limitations of an equilibrium water balance, it is interesting to note that on a catchment scale, river recharge dominates rainfall recharge. However, the balance indicates that about half the river recharge quantity returns back to surface water in downstream reaches (although the return is likely to be a mix of rainfall and river sources recharge). Discharge from the system is largely through connections to the surface water environment (rivers and springs).

The sources of the various balance quantities presented in Table 9.1 are as follows:

Rainfall recharge:	soil moisture balance model (annual average)
River inflow:	concurrent gaugings average losses (Tauherenikau and Ruamahanga rivers 100,000 m^3/day each; 20,000 m^3/day estimated for Huangarua River and side valleys)
Water race recharge:	estimated 25% loss of consented race take
River discharge:	concurrent gauging/estimate 120,000 m^3/day (Ruamahanga River)
Springs/ET:	combination of gauging data and evapotranspiration estimate (Dock Creek – 50,000 m^3/day; Otukura/Battersea – 60,000 m^3/day; Abbotts/Featherston – 30,000 m^3/day)
Abstraction:	annual average independently modelled abstraction 2008–40,000 m^3/day
Lake discharge:	assumed from water balance calculation (unknown).

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 Lower 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 Lower 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) and 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.

The Phase 2 model for the Lower 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 Lower 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 Model domain

The model domain was defined using the geological analysis presented in Section 6, in particular, the cross sections in Figures 6.5 to 6.13. The groundwater system is defined by the three-dimensional occurrence of late Quaternary and Holocene alluvial sediments.

The model domain (Figure 10.1) covers an area of 643 km^2 and incorporates the lowland catchments of the Tauherenikau and Ruamahanga rivers, Lake Wairarapa and Lake Onoke. Te Maire ridge consists of an uplifted greywacke basement block and is represented as an area of very low permeability. The domain is 42.5 km in length, extending from the southern edge of the Waiohine plains to the coast at Lake Onoke. The maximum width of the modelled catchment is approximately 20 km, extending from the base of the Tararua Range to the eastern hills and Martinborough terraces, also taking in the Huangarua valley.

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 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 hydro-geologically distinct areas defined by physical aquifer boundaries (such as geological boundaries, faults and rivers). Figure 10.2 shows the super-element mesh created for the model domain. 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 coarser 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 10.3. 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 numbers 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 176,868 elements, 97,650 nodes, and 17 layers. The distance between the nodes varies from about 500 m over the alluvial fan areas down to about 300 m in the vicinity of rivers.

10.4.3 Model configuration

Table 10.1 summarises the model configuration settings.

Table 10.1: Lower Valley catchment model configuration

Type of model	3-D saturated flow
Type of aquifer	Unconfined top layer with phreatic surface
Model layers	17 layers (18 slices)
Type of simulation	Steady state and transient flow
Type of elements	6-node, triangular prisms
Number of elements	176,868
Number of nodes	97,650
Equation solver	Iterative
Time stepping	AB/TR predictor-corrector

10.4.4 Model layers

The model has 17 layers (18 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: Lower Valley catchment model layer configuration and corresponding hydrostratigraphic units

LOWER VALLEY FEFLOW MODEL LAYER SCHEDULE

LAYER	SLICE	Hydrogeological unit layer groups
1, 2	1, 2, 3	**Q1 Unconfined aquifer** (Ruamahanga, Huangarua, Tauherenikau) **Q1 aquitard** (Holocene lake sediments – lake basin) Q2-8 Alluvial fan gravels (Tauherenikau fan, Huangarua valley) mid Quaternary terraces (Martinborough, Onoke/Narrows)
3, 4, 5	4, 5, 6	**Q1 aquitard** (Holocene lake sediments – lake basin) Q2-8 Alluvial fan gravels (Tauherenikau fan, Huangarua valley) mid Quaternary terraces (Martinborough, Onoke/Narrows)
6, 7	7, 8	**Q2 aquifer** (Ruamahanga, lake basin, Onoke/Narrows) Q2-8 Alluvial fan gravels (Tauherenikau fan, Huangarua valley) Mid Quaternary terraces (Martinborough, Onoke/Narrows)
8, 9, 10	9, 10, 11	**Q3 aquitard** (Ruamahanga, lake basin, Onoke/Narrows) Q2-8 Alluvial fan gravels (Tauherenikau fan, Huangarua) mid Quaternary terraces (Martinborough, Onoke/Narrows valley side)
11	12	**Q4 aquifer** (Ruamahanga, lake basin) Q2-8 Alluvial fan gravels (Tauherenikau fan, Huangarua) mid Quaternary terraces (Martinborough, Onoke/Narrows valley side)
12, 13, 14	13, 14, 15	**Q5 aquitard** (Ruamahanga, lake basin, Onoke/Narrows) Q2-8 Alluvial fan gravels (Tauherenikau fan, Huangarua) mid Quaternary terraces (Martinborough, Onoke/Narrows valley side)
15	16	**Q6 aquifer** (lake basin) Q2-8 Alluvial fan gravels (Tauherenikau fan, Huangarua) mid Quaternary terraces (Martinborough, Onoke/Narrows valley side)
16, 17	17, 18	**Q7+ aquitard** (lake basin) Q2-8 Alluvial fan gravels (Tauherenikau fan, Huangarua) mid Quaternary terraces (Martinborough, Onoke/Narrows valley side)

Layers 6–7, 11 and 15 are aquifer; all other layers are aquitard.

key:
- aquifer
- aquitard
- slices

total slices = 18
total layers = 17

The layer surfaces were modelled using bore log data and were based upon the geological cross sections shown in Figures 6.5 to 6.13. 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 5 contains the structure contours for each of the model slices.

Slice 1 represents the ground surface and was modelled using a combination of LIDAR data (lake basin, Tauherenikau floodplain, and Ruamahanga flood plain) and, where LIDAR were unavailable, the 20 m contour topographic map.

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 with the centre of deepening at Lake Wairarapa. The influence of structural uplift at Te Maire ridge and at the coast in the Onoke/Narrows area is clearly visible. The base of the groundwater system rises in the Tauherenikau fan area and through the Ruamahanga valley. Figure 10.5 shows the total thickness of the groundwater system estimated by subtracting the groundwater surface from the model base elevation.

Figure 10.6 shows a series of cross sections through the model to illustrate the layer geometry. The locations of the section lines are shown on Figure 10.1.

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 16-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 boundary

The external model boundary coincides with the catchment boundaries which were defined during the conceptual model development (Section 9.2) and are shown in Figures 10.2 and 10.3. All external model boundaries are of no-flow type except at the coast at Lake Onoke where a fixed head boundary at sea level was placed.

10.5.2 Rivers and spring-fed streams

Transfer boundary conditions (Cauchy/3rd kind) were assigned along the full lengths of the Tauherenikau, Ruamahanga and Huangarua rivers to simulate the interaction between the river and the aquifer system. This kind of boundary condition was also used to simulate the eastern side-valley rivers: Dry, Tauanui and Turanganui rivers. The Stonestead (Dock) Creek and Abbotts/ Featherston spring-fed streams were also simulated using this transfer boundary type.

Diffuse groundwater discharges associated with the Otukura/Battersea spring system and the Featherston fan–Lake Domain springs were simulated using transfer boundary condition as well, but in a slightly different manner as discussed below.

The locations of transfer boundary nodes for main river and stream channels are shown in Figure 10.7.

The transfer boundary condition describes a time-varying or constant reference hydraulic head (river stage or drain/spring level) 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 a transfer area across which flux is calculated. In a regional 3-D model this is achieved by assigning the lines of boundary nodes to two or more neighbouring slices to create a saturated vertical exchange area which approximates the river width. The exchange area in an unconfined aquifer will naturally vary depending upon the saturated thickness of the layer. For the designation of groundwater discharge over a wider area, such the Otukura-Battersea spring discharge zone, transfer nodes were applied to the top slice only to define an areal transfer area.

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 Tauherenikau River and the Ruamahanga rivers between the Waingawa and Waiohine rivers. Appendix 6 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 (H-nodes) 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 226 cross sections with corresponding level data and location co-ordinates were incorporated into the MIKE11 model. Channel cross section surveys were available at approximately 100 m intervals down each of the rivers. Measured river flow data for each of the rivers were derived from a number of continuous recorder sites within the model area (Table 10.3).

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

Site	Site No.	Map Reference
Ruamahanga River at Waihenga bridge	29202	S27:146-982
Huangarua River at Hautotara	29222	S27:173-871
Ruakokopatuna River at Iraia	29250	S28:084-782
Tauherenikau River at Gorge	29251	S26:081-127
Lake Wairarapa at Burlings (stage)	29209	S27:918-948
Lake Onoke at Lake Ferry (stage)	29237	R28:892-770

10.5.4 Transfer of MIKE 11 modelled stage data to FEFLOW

Transient river stage heights required by the FEFLOW transfer boundary nodes were 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 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 between the river and aquifer. Large values of transfer rate allow a 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 contains the values used in the model which were derived through model calibration.

Table 10.4: Calibrated transfer rates for 3rd kind (Cauchy) boundary conditions

River/stream	Transfer rate (1/d)
Ruamahanga River	3
Tauherenikau River	3
Stonestead (Dock) Creek	3
Otukura/Battersea spring system	0.001
Huangarua River	3
Side valleys: Dry, Tauanui and Turanganui rivers	0.1

10.5.6 Diffuse spring discharge boundaries

For the Otukura/Battersea and Lake Domain diffuse spring discharge areas, transfer boundary nodes were assigned as an areal mesh on a single slice (slice 1) to create a horizontal exchange area. Figure 10.7 shows the transfer boundary locations for the diffuse spring discharge areas. The stage heights for these boundary networks were derived using ground elevation data LIDAR (where available) and streambed or 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 2. Recharge was calculated on a daily time step for the 16-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 a ArcGIS polygon shape file and then tying each of the grid polygons/cells (2,381 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 2,381 polygons, each having a unique 7-day average recharge record for the 16-year run period.

10.5.8 Groundwater abstractions

Appendix 3 describes the methodology used to create synthetic abstraction data for the calibration period. Each 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 Lower Valley groundwater system has maintained consistency with the conceptual hydrogeological model presented in Section 9. The adopted framework was used by the inverse parameter estimation model (PEST).

Figures A7.1 to A7.7 in Appendix 7 show the parameter zones for hydraulic conductivity, horizontal, (Kx) and vertical (Kz), specific storage (Ss), specific yield (St) and transfer rate (in and out – It and Ot respectively). Most hydrostratigraphic units are represented by several zones to account for anticipated spatial variations in each of the properties. The table in Appendix 9 lists the parameter zones, locations and the associated model layers.

10.6.1 Horizontal hydraulic conductivity (kx,y)

Figures A7.1 to A7.3 show the horizontal hydraulic conductivity (Kx) parameter zonation for each of the 17 model layers. The top five layers are almost identical – representing Q1 age sediments in the lake basin and Ruamahanga valley. These layers also correspond to either the Q2+ fan deposits of the Tauherenikau fan, or the recent alluvium associated with the Tauherenikau River and its delta area as it enters Lake Wairarapa. The latter delta deposits merge with the lake sediments as shown by the parameter zonation in layers 1 to 3. Zone Kx13 in layers 2 to 5 represent the uppermost Q1 age aquitard which extends across the lake basin and through to the Onoke area. The zonation down the Ruamahanga valley (Kx4-Kx69-Kx79) represents the gradual mergence of the permeable river alluvium with the lake basin aquitard. Zone Kx4 extends through all model layers (1-17) representing the relatively thin alluvium occupying the Ruamahanga valley to the east of Te Maire ridge.

The low permeability older terrace sequences to the north and south (Pirinoa terraces) of the Onoke-Narrows area and Te Maire ridge correspond to zones Kx5 and Kx7 and extend through all model layers. The more permeable surficial side-valley alluvium in the Onoke area is represented by zone Kx78 (layers 1 and 11) to allow recharge to flow into the main valley aquifers.

Layers 6 and 7 are important for the representation of the first confined aquifer in the lake basin – the Q2 confined aquifer. In the lake basin, the aquifer is represented by two zones (Kx15 and Kx34) to simulate the dual Tauherenikau-Ruamahanga provenance of the gravels comprising this aquifer. The extension of the Q2 confined aquifer through to the coast is also facilitated by zones Kx16 and Kx102 – the latter zone enabling the representation of side valley fan gravels entering the main valley.

Zone Kx18 in Layers 8 to 10 represent the second major aquitard in the lake basin (Q3 aquitard), extending through to the coast. The aquitard extends up the Ruamahanga valley where, as it diminishes, it allows vertical leakages to occur between Q2 and Q4 aquifers. Below layer 7, the Tauherenikau fan is represented as a single leaky aquifer by zones Kx1, Kx92 and Kx93 to allow a degree of spatial and vertical variability in hydraulic conductivity).

Layer 11 coincides with the Q4 confined aquifer in the lake basin (zones 20 and 35) and a tenuous extension of this aquifer into the Onoke area (Kx21 and Kx103).

Zone 18 in layers 12-14 also corresponds with the Q5 aquitard. The underlying Q6 aquifer in the lake basin is more limited in extent than the overlying Q4 and

Q2 aquifers. It is represented by three zones of distally diminishing hydraulic conductivity (Kx25, Kx26 and Kx27). This aquifer does not extend into the Onoke area.

10.6.2 Vertical hydraulic conductivity (K_z)

Figures A7.4 to A7.6 show 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 Storage

The unconfined storage parameter (St) is only relevant to upper model layers (1-4) which may become partially saturated during the simulation. Figure A7.7 shows the St zones assigned to layers 1 to 4. Most of the catchment is covered by zone St52, but additional zones have been used for the Ruamahanga and Huangarua valleys (St76), Tauherenikau River (zone St75) and the Tauherenikau fan (zone St77). Zone St53 has been arbitrarily set for layers 5-17 – even though a St value is not used by FEFLOW when layers are saturated.

Specific storage (Ss) zones are also shown in Figure A7.7. The zonation is simple – Layers 1-5 have one zone (Ss51) to allow a decreased confined storage coefficient at shallower depth. Layers 6-10 and Layers 11-17 have a dual zonation (Ss47 and 48 and Ss49 and 50 respectively) to distinguish between the Tauherenikau fan and lake basin deposits.

10.6.4 Transfer rate

Transfer rate zones (relating to 3rd kind, transfer boundary nodes) are shown in Figure A7.7. Each area has a transfer in zone (It) and a transfer out zone (Ot). The zones are only applicable where transfer nodes have been set on rivers, springs and on the lakes.

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 a spring flows and measured river flow losses/gains). As such, the calibration process has an inverse approach through the adjustment of 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 parameter estimation algorithms (such as PEST) removes some of the subjectivity of manual trial-and-error process and provides an insight to the 'non-uniqueness' of a model.

Manual calibration under steady state conditions was initially undertaken as a first step for the Lower 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 and boundary conditions and to tune the 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 16-year period (1992–2008).

11.2 Minimising 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 (Middlemis 2001) modelling guidelines suggest that the following methods should be conjunctively employed 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 climatic conditions plus induced stresses such as abstraction).

c) When 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 Lower Valley catchment model as far as the available data would allow.

With reference to requirement a), hydraulic conductivity ranges were evaluated using pumping test data (Table 7.6) for the main aquifer units which were referenced during the calibration process as constraints.

To address requirement b), the transient model calibration and verification period covers a 16-year period over which both climate stresses and abstraction stresses experienced a large variation. Figures 7.29 and 7.30 illustrate the range in both calculated recharge (reflecting climatic conditions) and abstraction over the 16-year calibration period.

In terms of requirement c), Section 7.3 provided a description of the surface water–groundwater connection characteristics and also provides quantification of some of the fluxes between the two systems (such as spring discharges, spatial patterns and amounts of river flow losses and gains). These data were assigned a relatively high weighting during the calibration process to ensure that the simulated water balance is 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 7.1) 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 7.3) 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 (Middlemis 2001) modelling guidelines 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 (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 heads 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 evapo-transpiration 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 at Waiorongomai 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 16-year model calibration period (1992-2008) shows that this period had a high variability in climate and is not biased towards any particular climatic phase.

11.5 Preliminary 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 consistent with the estimated fluxes (discussed in Section 7). The steady state process additionally serves to check on the 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 to an equilibrium condition that 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 September 2008. The latter was used for the steady state calibration to represent stable late winter groundwater conditions. Figure 7.2 shows the measurement sites and contoured groundwater levels associated with this survey.

There is a need to determine an appropriate recharge condition for late winter. A condition representing the average daily recharge over the 16-year period 1992–2008 was calculated on a volumetric basis for the entire Lower Valley catchment using the Rushton recharge model (Section 7).

Steady state calibration was achieved by manually calibrating the model to head targets measured in 54 bores for all aquifer depths in the Lower Valley catchment. The only excluded monitoring sites are for the deep confined aquifers in the Martinborough area (insufficient data currently exist to conceptualise this aquifer – which is regarded to be isolated from the main valley catchment).

11.5.1 Results

The results of the steady state calibration run are shown in Figure 11.3 and the calibration statistics are listed in Table 11.3. The overall residual mean of the calibration was encouragingly low (2.4 m) for the 2008 calibration data-set. The highest residual of 11 m is for a bore situated high on the Tauherenikau fan (S27/0148) indicating that some adjustment in the model parameter zonation may be required in this area since the modelled levels are too low.

Table 11.3: Steady-state calibration statistics for the Lower Valley catchment model

Statistical performance measure	Calibration statistic	Unit
Absolute residual mean	2.40	m
Min residual	-8.33	m
Max residual	11.22	m
Sum of residuals	146.13	m
Residual standard deviation	3.33	m
Observed range in head	58.08	m
Mean sum of residuals	2.71	m
Scaled mean sum of residuals	0.09	%
Sum of residual squares	663.12	m^2
Root mean square (RMS) error	3.50	m
Scaled RMS	6.03	%

The root mean square (RMS) statistic is an absolute measure of the calibration that is problem specific (its value is affected by the measured values). It is a good error indicator, along with the scaled RMS. The scaled RMS of 6% shows that the ratio of error to total head differential is small and indicative of a good match between measured and observed groundwater levels, flow gradients and flow patterns.

Figure 11.4 shows the modelled steady state head distribution over the model domain for the unconfined aquifer layer 1. Comparison with Figure 7.2, which was constructed using observed data, shows a good agreement with the simulated regional flow pattern.

At a regional scale, in a heterogeneous aquifer system, the calibration is regarded as a good initial simulation and provides confidence in the conceptualisation of the flow system, and the assumptions that have been adopted.

11.5.2 Steady state mass balance

The steady state mass balance (inflow and outflow rates) is shown in Table 11.4. Inflows are river recharge (117 million litres per day or ML/d), and rainfall recharge (325 ML/d). Outflow from the groundwater system is dominated by three mechanisms: discharge back into the rivers (178 ML/d), discharge to springs (105 ML/d) and discharge into Lake Wairarapa (133 ML/d).

Table 11.4: Modelled steady state mass balance for the Lower Valley groundwater model

Flow component	Inflows (m^3/day)	Outflows (m^3/day)
Rivers Springs/ET	180,000	110,000 144,000
Lake Wairarapa Lake Onoke		50,000 8,000
Abstraction		7,000
Rainfall recharge	139,000	
Total	*319,000*	*319,000*

Comparison between the steady state model output and the estimated water balance for the catchment presented in Table 9.1 shows that the simulated flows agree relatively well with the estimated flow budget and that there is an order of magnitude agreement. 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 4.5 years of data for the period 25 June 2003 to 10 January 2007. 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 (both very dry and wet years) and covers a period over which groundwater abstraction significantly increased. It therefore represents a window of time in which there was a large range in system stresses to facilitate a more robust calibration.

Following the automated PEST calibration using the 4.5 year data-set, a verification run was performed using monitoring data covering the period 1 July 1992 to 1 October 2008 (16.2 years) – i.e. both prior to, and after, the calibration data-set. The transient groundwater model was run with a weekly stress period, 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 PEST automated calibration process was undertaken for the period 25 June 2003 to 10 January 2007 using groundwater level observation targets and also 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 8 contains a description of the PEST interface developed for FEFLOW.

PEST utilises the parameter zonation framework described in Section 10.6 (see Appendix 7). 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 45 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 pumping test data and plausible ranges for the type of material contained within the zone. As parameters reached their bounds or became insensitive during the PEST inversion process, additional zones were fixed (or tied to other zones) by manual intervention of the PEST run. A total of 38 zones were fixed and 10 were tied, including river boundary transfer rate zones, although additional zones were fixed near to the end of the parameter estimation process. 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: Lower 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 in m/day. All PEST-estimated parameters are log-transformed.

Unknown parameters	Initial value	Lower bound	Upper bound	Fixed parameters	Value	Tied parameters	Tied to
Kx01	8.6	5	20	it54	3.0	Kx11	Kx08
Kx02	15.9	10	30	it56	2.0	Kz40	Kz37
Kx04	315.2	100	330	it58	0.1	Kz41	Kx34
Kx08	50.2	40	60	it60	0.001	Kx35	Kx34
Kx10	5.8	1	100	it62	0.001	Kx72	Kx34
Kx12	110.0	5	110	it94	0.5	Kz39	Kx34
Kx14	31.2	5	1000	it96	0.0004	Kx80	Kx34
Kx15	102.7	10	200	it100	0.07	Kz83	Kx34
Kx16	41.4	5	150	Kx03	500.0	Kz84	Kx34
Kx17	6.3	1	50	Kx05	0.004	Kx87	Kx86
Kx20	96.8	10	2000	Kx06	8.6		
Kx21	28.2	1	500	Kx07	0.1		
Kx22	9.5	1	150	Kx09	0.1		
Kx25	77.1	1	80	Kx13	0.9		
Kx29	24.5	1	50	Kx18	0.1		
Kx32	1.0	1	40	Kx19	6.0		
Kx34	77.0	50	200	Kx23	8.6		
Kx65	7.9	1	200	Kx24	0.01		
Kx68	7.7	1	50	Kx26	20.0		
Kx69	70.0	15	70	Kx27	3.0		
Kx70	22.7	10	50	Kx28	0.1		
Kx71	10.7	1	6	Kx30	0.0		
Kx73	39.2	10	40	Kx31	0.1		
Kx74	250.8	100	300	Kx33	86.4		
Kx79	8.7	5	50	Kx64	0.001		
Kx81	3.1	1	50	Kx78	10.0		
Kx86	80.0	80	200	Kx88	20.0		
Kx92	15.9	10	30	Kx89	60.0		
Kx93	20.0	10	30	Kx90	100.0		
Kx102	40.0	5	150	Kx91	20.0		
Kx103	28.4	1	50	Kz43	8.6E-05		
Kz36	0.8	0.05	1	Kz67	2.6E-02		
Kz37	2.6E-04	5E-06	5E-04	ot55	3.0		
Kz38	7.0E-04	1E-05	5E-03	ot57	2.0		
Kz42	5.3E-05	1E-05	1E-04	ot59	0.1		
Kz44	7.2E-05	5E-06	5E-04	ot61	0.001		

Table 11.5 *cont.*: Lower 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 in m/day. All PEST-estimated parameters are log-transformed.

Unknown parameters	Initial value	Lower bound	Upper bound	Fixed parameters	Value	Tied parameters	Tied to
Kz45	3.0E-03	1E-05	5E-03	ot63	0.001		
Kz66	6.5E-04	1E-05	1E-03	ot95	0.5		
Kz82	3.3E-02	5E-04	5E-02	ot97	0.001		
Kz85	2.2E-05	1E-05	1E-03	ot101	0.07		
Kx98	6.5E-4	1E-05	1E-03	St52	0.017		
Kz99	6.5E-4	1E-05	1E-03	St53	1E-05		
Ss46	2.8E-04	1E-06	1E-02	St75	0.07		
Ss47	1.0E-05	1E-07	1E-03	St76	0.06		
Ss48	1.3E-05	1E-07	1E-03				
Ss49	4.8E-06	1E-07	1E-03				
Ss50	8.6E-06	1E-07	1E-03				
Ss51	7.4E-06	1E-06	1E-03				
St77	7.8E-02	3E-02	2E-01				

11.6.3 Calibration targets, observation data processing and weighting

Figure 7.1 shows the locations of long-term groundwater monitoring bores and those used in the PEST calibration are listed in Table 11.6. The sites are distributed across the Lower Valley catchment and measure groundwater levels at various depths ranging from 5 m to 66 m. Deep monitoring bores on the Martinborough terraces were not included in the calibration dataset because the deep confined aquifer in this area has not been satisfactorily characterised due to lack of geological information. In addition, monitoring bores which have no data within the PEST calibration window are not listed in Table 11.6.

The data were processed to provide a representative value every seven days resulting in 5,234 head observations at 29 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.

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 have unreliable bore construction information were assigned a weighting of 0.75 (reasonable) or 0.5 (poor).

Table 11.6: Groundwater level targets used in the Lower Valley catchment model transient PEST calibration (refer to Figure 7.1 for locations)

Sub-area & monitoring Well No.	Depth (m)	Manual or Continuous/ Dedicated or Pumped monitoring site	Calibration weighting	Model slice
Sub-area 1 – Tauherenikau fan				
S27/0148 (Carlisle)	8.77	M / D	0.75	5
S27/0202 (Croad)	4.80	C / P	0.75	7
S27/0099 (Simmonds)	16.76	C / P	0.75	7
S27/0035 (F'ston School)	6.50	M / D	0.75	3
S27/0009 (Windy Farm)	10.50	M / P	0.75	7
S27/0012 (Windy Farm)	66.50	M / P	0.6	17
S27/0330 (Burt)	20.00	M / P	1.0	7
S27/0317 (Simmonds)	17.52	C / P	0.75	7
S27/0271 (Simmonds)	29.20	M / P	0.75	11
S27/0309 (Simmonds)	28.20	C / P	0.75	11
Sub-area 2 – Ruamahanga valley				
S27/0346 (WCB/Smith))	9.50	C / D	1.0	6
S27/0381 (WCB/Herrick)	20.95	C / D	1.0	11
S27/0542 (Butcher)	19.00	M / D	0.75	7
S27/0481 (Dry River Beef)	23.10	C / D	1.0	7
S27/0485 (GW/Ness)	20.00	M / D	0.75	7
S27/0484 (GW/Ness)	43.00	M / D	0.75	11
Sub-area 3 – Martinborough terraces and Dry River				
S27/0517 (Stuart)	19.4	M / D	0.75	9
S27/0522 (Duggan)	21.00	C / P	1.0	9
S27/0571 (Mart. Golf Club)	32.00	M / P	0.75	11
Sub-area 4 – Lake basin				
S27/0467 (Green)	30.10	C / P	0.75	6
S27/0446 (Landcorp)	60.80	M / D	0.75	11
S27/0465 (Vavasour)	38.48	M / D	0.75	7
S27/0428 (Landcorp)	43.56	C / D	1.0	7
S27/0434 (Wairoria P'ship)	45.20	C / D	1.0	7
Sub-area 5 – Onoke/Narrows				
S27/0587 (Luttrell)	34.00	C / D	0.5	6
S27/0576 (Luttrell)	55.53	M+C / P	0.5	11
S27/0594 (Warren)	44.00	M / P	0.5	7
R28/0002 (Annear)	17.00	M / P	0.5	7
S27/0618 (Atkinson)	47.27	M / P	0.5	11

Note: calibration weighting: 1.0 = reliable, 0.75 = reasonable, 0.5 = poor

The transient calibration was also assisted by concurrent river flow gauging data (see Section 7.4) which provided valuable information regarding the quantities of water moving between surface water and groundwater for specific river reaches. Spring flow measurements provided additional calibration targets for the various spring systems in the Lower Valley catchment (see Section 3.3).

Concurrent river flow data and the spring gauging data were therefore used as explicit 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 that are sensitive to surface water interactions (hydraulic conductivity near 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. 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 provides a summary of quantitative measures for the calibration quality following the automated PEST calibration procedure. The overall objective function (phi) reduced from about 13,000 to a value of 7,736 (i.e. a 40% reduction). The model calibration has a high correlation coefficient (R) of 0.992. This is a measure of the overall un-weighted goodness-of-fit between modelled outputs and observations. Ideally, R should be above 0.9. The contribution to the total phi from each of the monitoring bores is also listed in Table 11.7.

Table 11.8 provides more detail on the model to measurement fit for each of the observation bores and presents their weighted error statistics. 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. For a regional-scale groundwater model which has a high degree of geological complexity and heterogeneity, scaled errors of up to about 40-50% 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 although some have higher scaled errors as discussed below.

Table 11.7: Summary of PEST optimisation of groundwater head calibration for the Lower Valley transient groundwater flow model

Objective function -----> Sum of squared weighted residuals (ie phi)		7736
SUB-AREA 1 (Tauherenikau fan)		
Contribution to phi from observation group	S27/0009	167.1
Contribution to phi from observation group	S27/0012	981.5
Contribution to phi from observation group	S27/0035	120.1
Contribution to phi from observation group	S27/0099	81.9
Contribution to phi from observation group	S27/0148	965.6
Contribution to phi from observation group	S27/0202	34.3
Contribution to phi from observation group	S27/0271	79.3
Contribution to phi from observation group	S27/0309	221.6
Contribution to phi from observation group	S27/0317	258.4
Contribution to phi from observation group	S27/0330	149.7
Total contribution sub-area 1 (1,860 residuals)		*3,059*
SUB-AREA 2 (Ruamahanga valley)		
Contribution to phi from observation group	S27/0346	174.3
Contribution to phi from observation group	S27/0381	35.9
Contribution to phi from observation group	S27/0481	431.8
Contribution to phi from observation group	S27/0484	40
Contribution to phi from observation group	S27/0485	46
Contribution to phi from observation group	S27/0542	150.2
Total contribution sub-area 2 (1,116 residuals)		*878.2*
SUB-AREA 3 (Martinborough terraces and Dry River)		
Contribution to phi from observation group	S27/0517	42.1
Contribution to phi from observation group	S27/0522	1321
Contribution to phi from observation group	S27/0571	318.6
Total contribution sub-area 3 (398 residuals)		*1,681*
SUB-AREA 4 (Lake basin)		
Contribution to phi from observation group	S27/0428	402.6
Contribution to phi from observation group	S27/0434	385.5
Contribution to phi from observation group	S27/0446	29.5
Contribution to phi from observation group	S27/0465	63
Contribution to phi from observation group	S27/0467	64.5
Total contribution sub-area 4 (930 residuals)		*945.1*
SUB-AREA 5 (Onoke/Narrows)		
Contribution to phi from observation group	R28/0002	151.2
Contribution to phi from observation group	S27/0576	30.6
Contribution to phi from observation group	S27/0587	49.7
Contribution to phi from observation group	S27/0594	133
Contribution to phi from observation group	S27/0618	807
Total contribution sub-area 5 (930 residuals)		*1,171.5*
Correlation coefficient (R)		0.992
Analysis of all residuals ----->		
Number of residuals with non-zero weight		5234
Mean value of non-zero weighted residuals		0.252
Maximum weighted residual		4.44
Minimum weighted residual		-5.92
Standard variance of weighted residuals		1.49
Standard error of weighted residuals		1.22

Table 11.8: Measures of calibration performance for the Lower Valley transient groundwater flow model (head residuals). There are no calibration targets in sub-area 6 (Huangarua valley).

Monitoring bore	Error (m)					Scaled error (%)	
	No. of residuals	Minimum weighted residual	Maximum weighted residual	Absolute mean weighted residual	Root mean square (RMS)	Scaled mean sum of residuals (SMSR)	Scaled RMS (SRMS)
SUB-AREA 1(Tauherenikau fan)							
S27/0009	186	-2.12	0.47	0.8	0.95	22.68	25.89
S27/0012	186	-3.77	-1.7	2.2	2.3	49.28	50.11
S27/0035	186	-1.1	-0.15	0.77	0.8	47.84	49.38
S27/0099	186	-1.7	1.13	0.15	0.66	14.36	17.28
S27/0148	186	0.6	4.44	2.1	2.28	39.96	43.68
S27/0202	186	-1.15	0.46	0.26	0.43	41.15	51.81
S27/0271	186	-0.66	1.6	0.34	0.65	13.75	17.06
S27/0309	186	-0.52	2.12	0.92	1.09	23.49	26.85
S27/0317	186	-0.39	1.75	1.06	1.18	32.56	35.54
S27/0330	186	0.15	1.86	0.83	0.9	99.56	108.43
SUB-AREA 2 (Ruamahanga valley)							
S27/0346	186	-1.78	-0.3	0.91	0.97	30.46	32.33
S27/0381	186	-0.53	0.95	0.36	0.44	17.11	19.30
S27/0481	186	0.21	2.46	1.45	1.52	39.42	41.30
S27/0484	186	-1.34	0.48	0.27	0.46	13.63	17.56
S27/0485	186	-1.35	0.37	0.31	0.49	14.75	18.49
S27/0542	186	-0.32	1.52	0.8	0.9	28.31	31.36
SUB-AREA 3 (Martinborough terraces – upper and Dry River)							
S27/0517	26	-2.7	0.06	0.91	1.27	119.53	16.82
S27/0522	186	-5.92	-1.0	2.43	2.66	157.81	172.73
S27/0571	186	-2.82	3.04	0.8	1.3	22.16	25.54
SUB-AREA 4 (Lake basin)							
S27/0428	186	0.89	2.28	1.43	1.17	83.88	68.82
S27/0434	186	0.45	2.8	1.31	1.44	59.63	65.45
S27/0446	186	-1.14	0.86	0.07	0.4	7.87	9.93
S27/0465	186	0.3	0.98	0.54	0.58	21.73	23.11
S27/0467	186	-1.2	-0.13	0.55	0.59	23.03	24.69
SUB-AREA 5 (Onoke/Narrows)							
R28/0002	186	0.65	1.4	0.89	0.9	91.63	92.78
S27/0576	186	-1.05	0.28	0.3	0.4	7.92	9.78
S27/0587	186	-1.44	0.94	0.19	0.52	6.80	8.19
S27/0594	186	0.23	1.5	0.81	0.84	28.39	29.58
S27/0618	186	1.53	2.67	2.06	2.08	66.10	66.45

11.6.6 Calibration validation run

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 dataset 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 16.2 years duration was performed for the period 1 July 1992 to 1 October 2008. The PEST calibration data-set for 25 June 2003 to 10 January 2007 was incorporated within the run and therefore the validation data-set comprised additional monitoring data dating both prior to and after the period of the PEST calibration data-set. The full transient model validation run had 848 7-day stress periods and a run duration of 5,936 days.

11.6.7 Discussion: model-to-measurement head fit

The information presented in Tables 11.7 and 11.8 should be considered in conjunction with the model-to-measurement fit plots provided in Figures 11.5 to 11.9. These show the simulated and observed groundwater levels for the 16-year calibration period for the head calibration targets (grouped into the five sub-areas discussed in Section 6.3). The model to measurement calibration is discussed for each area below.

(a) Sub-area 1: Tauherenikau fan

Observation sites located in the northern area of the Tauherenikau fan (bores S26/0148, S26/0202 and S26/0099) have reasonable head calibration statistics with SMSR and SRMS scaled errors of between 15 and 50%. Figure 11.5 shows that although the simulated head magnitudes for these bores are reasonable, there is a deviation in the middle of the validation run where the modelled heads dip down and recover between about 1998 and 2003. This reflects the long-term recharge variation that is not apparent in the observation data, which could be due to the buffering influence of surface water drains and the Moroa Water Race in close proximity to the observation bores – an influence which is not simulated in the model because it represents average regional-scale head conditions. It is probable that the long-term recharge trend is a real phenomena masked by the influence of buffering surface water features as shown, for instance, by bore S27/0271 (also in sub-area 1 further to the southwest in the Kahutara area).

Bores S27/0035 and S27/0030 are both located close to the Tauherenikau River. Both have large scaled errors (Table 11.8), particularly S27/0330 (100-108%) primarily because the observation data have a very small range, although the mean weighted residual for both these sites is only about 0.8 m. The simulated heads at both sites are reasonably close to measured values.

In the Featherston area the two sites S27/0009 and S27/0012 provide head values for 10 m and 66 m depth in the fan sequence. The model is simulating the head in the shallower system reasonably well (SRMS=25%), but is over-predicting the head in the feeder system and therefore does not accurately simulate the downwards head gradient in this area. Attempts to simulate the vertical gradient were not successful and a localised highly heterogeneous condition in the fan alluvium could be responsible. The poor calibration in vertical head gradient at this particular site is not of concern since it is not experienced in any other areas of the fan system.

The remaining plots in Figure 11.5 relate to three head targets (S27/0317, S27/0271 and S27/0309) in the Kahutara area at the edge of the Tauherenikau fan before it enters the lake basin. There is an upwards head gradient in this area which is simulated by the model. All three head targets have scaled errors of between 13 and 35% (Table 11.8). Abstraction drawdowns evident on all three sets of observation data are not accurately simulated by the model. Because the model mesh is relatively coarse, localised pumping drawdowns cannot be accurately simulated – the monitoring sites are abstraction bores (or are close to abstraction bores).

(b) Sub-area 2: Ruamahanga valley

Figure 11.6 shows the calibration hydrographs for sub-area 2. Groundwater levels in this area generally exhibit a strong correlation with the Ruamahanga River which exerts a consistent summer base level condition in the unconfined aquifer. Table 11.8 and 11.9, and the visual comparison of the observed and modelled heads in Figure 11.6, show that there is a very good calibration in this sub-area indicating that the coupled groundwater–surface water environments are accurately simulated.

(c) Sub-area 3: Martinborough terrace and Dry River

Head calibration plots for six monitoring targets in the Martinborough terrace-Dry River area are shown in Figure 11.7. There is close agreement between the simulated and observed head in the shallow (upper) aquifers of the Martinborough terrace (above about 35 m depth) as shown by bores S27/0522 (21 m deep) and S27/0571 (Martinborough Golf Club, 32 m deep). At both sites, and at the Dry River bore (S27/0517), the model predicts a more seasonally volatile groundwater head than the monitoring data suggests indicating that recharge may be overestimated in wetter years.

The three deeper monitoring bores on the Martinborough terrace (as discussed previously) show that the model does not predict the head very well below about 35 m. The poor-yielding deeper aquifers are confined beneath a thick aquitard sequence (see Section 6.3.4) within a possibly much older terrace sequence (mQa or earlier) which is structurally complex. The model does not simulate the considerably higher heads in the deep system as shown by the calibration plots for bores S27/0640 (69 m), S27/0403 (41 m) and S27/0560 (39 m). Since the deeper Martinborough aquifer is confined and largely isolated from the shallow sequence, it is apparent that only the shallow aquifer sequence (to about 35 m depth) can be simulated accurately at this stage. As further data become available refinement of the model structure and layer configuration for the deeper system will be necessary. This limitation is not expected to impact on the predictive capability of the model for the shallow aquifer system.

(d) Sub-area 4: Lake basin

Figure 11.8 shows the calibration plots for the lake basin confined aquifers. The northern cluster of monitoring sites (bores S27/0467, S27/0446 and S27/0465) are in both the Q2 and Q4 aquifers and show a very good model-to measurement groundwater level fit. Seasonal abstraction drawdowns are also simulated relatively well. The remaining two more southerly sites are bores S27/0428 and S27/0434. Both are considered to be in the upper Q2 aquifer and the model tends to under-predict the head consistently by about 1 m. This is nevertheless considered to represent a good calibration considering the paucity of data with which to characterise the aquifers in this area. It is probable that the model is too simple in this area and that the overlying aquitard changes and becomes less permeable towards the distal southern end of the basin.

(e) Sub-area 5: Onoke/Narrows

A good head correlation is apparent for the two observation sites to the north of the Ruamahanga River (bores S27/0576 and S27/0587) as shown in Figure 11.9. Bore S27/0595, located in the fan of the Turanganui River, also shows a reasonably good correlation. The remaining two head observation targets are both probably located within older Quaternary terrace deposits on the edge of the main valley-fill alluvium and both have simulated heads some 2-3 m lower than the observed data. The higher observed groundwater levels in these valley-edge bores probably relate to the significantly lower hydraulic conductivity of the older terrace sequence. The model does not simulate these deposits but rather predicts a head for the main valley aquifer system.

(f) Sub-area 6: Huangarua valley

As noted in Section 7.1.4, there are no monitoring bores in this sub-area.

11.6.8 Water balance calibration

(a) Global water balance

Figure 11.10 illustrates the simulated water balance dynamics on a bulk (global) 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 135,000 m^3/day over the 16-year calibration period (note that although the Lower Valley catchment is significantly larger than the Middle Valley catchment, the average global recharge quantities are smaller due to large areas of low permeability sediments in the lake basin area which limit the infiltration of rainfall recharge). The annual average recharge for the model calibration period is 47.3 x 10^6 m^3 – although there is considerable inter-seasonal variability as shown by Figure 11.10B.

Figure 11.10C shows the modelled total groundwater abstraction for the Lower Valley catchment between 1992 and 2008. The peak abstraction rate during the 2007/08 irrigation season was about 130,500 m^3/day (130.5 ML/d) – over three times the early 1990s rate.

The simulated global interaction between groundwater and the surface water environment is represented by Figure 11.10D. The plot depicts, as a positive flux, the total amount of water discharging from groundwater to surface water – in other words, the base flow discharge to rivers, streams and springs. Negative fluxes indicate a net loss of surface water to groundwater. Also shown is the running mean for net base flow discharge to rivers which reveals the long-term trend for the 16-year calibration period. Modelled base flow discharge declines between 1996 and 2003, after which the trend flattens and then slowly rises. The trend reflects the long-term rainfall, represented by the cumulative deviation from the monthly rainfall mean (cusum) plot, and therefore may be largely climate driven. However, the failure of the system to fully recover after 2003 even though rainfall recharge increased substantially during 2004, 2006 and 2008 indicates that groundwater abstraction may also influence base flow discharge in the catchment. This will be explored further during Phase 3 of the Wairarapa Valley groundwater resource investigation.

Figure 11.10E shows the simulated cumulative change in storage over the model calibration period (and the running mean for this data). The plot shows the same long-term trend as Figure 11.10D and displays a marked drop in groundwater storage between 1996 and 2003 during which a decline in groundwater levels occurred (as discussed previously in Section 7.1.4). The trend reverses in late 2004 in response to increased recharge, but flattens off in 2006 despite the exceptionally high recharge during this year (Figure 11.10B). Again, significantly increased abstraction rates over the past five years or so may also influence the cumulative storage trend – in addition to climatic control.

At any particular time the global water balance for the Lower Valley catchment is very different. This is shown in Table 11.9 which displays the modelled global water balances for two stress periods in summer (5 February) and winter (8 July) 2008 – an average rainfall year (see Figure 11.10B).

During summer, Table 11.9 shows that the rivers provide the sole groundwater recharge source which is balanced by discharge back into lowland rivers, spring-fed streams and the lakes. There is also a large loss from storage (recorded as a flux in as water is released from storage) which results in falling groundwater levels. During summer, groundwater abstraction represents about 25% of the total water balance for the catchment.

The winter 2008 balance shows that rainfall recharge was the dominant input to the groundwater system – significantly higher than river recharge. Comparison of the two balances shows the significant storage replenishment occurring during winter when groundwater levels recover from summer lows. Note that storage increase is shown as an out component in the mass balance indicating water passing into storage. About 40% of the recharge from rainfall and rivers contributes to the storage replenishment.

Table 11.9: Representative global transient water balances for summer and winter 2008 from the Lower Valley catchment transient groundwater model

	Flux in (m^3/day)	Flux out (m^3/day)
5 February 2008 – summer		
Rainfall recharge	0	
River recharge	383,000	
Abstraction		130,000
River + spring base flow		380,000
Change in storage	127,000	
Total	*510,000*	*510,000*
8 July 2008 – winter		
Rainfall recharge	508,000	
River recharge	314,000	
Abstraction		6,000
River + spring base flow		506,000
Change in storage		310,000
Total	*822,000*	*822,000*

(b) Sub-area water balances

Figure 11.11 shows simulated surface water discharge, abstraction and recharge water balance components for the five sub-areas where data are available. Surface water discharge dominates sub-areas 1 and 2, which contain the Tauherenikau and Ruamahanga rivers respectively (Figure 11.11A). The long-term climatic trend of reducing base flow discharge is evident in these two areas. The relatively constant discharge in sub-area 4 is dominated by groundwater leakage into Lake Wairarapa.

Figure 11.11B shows that the groundwater resource in sub-area 2 (Ruamahanga valley) is the most heavily developed (currently over 60,000 m^3/day). The next, in terms of abstraction volume, is sub-area 1 (Tauherenikau fan) which has a current estimated abstraction rate of 30,000 m^3/day, and then sub-area 4 (lake basin) at about 20,000 m^3/day. Abstraction from the remaining sub-areas is small by comparison.

Rainfall recharge is depicted in Figure 11.11C over a short period of time in order that the detail can be discerned. Sub-area 1 accommodates the bulk of rainfall recharge in the Lower Valley catchment, with relatively minor quantities supplied by sub-areas 2 (Ruamahanga valley) and 3 (Martinborough terraces). Recharge over the lake basin and Onoke sub-areas is minor in comparison with sub-area 1 due to the occurrence of thick lacustrine sequences near the surface which prevent the infiltration of rainfall. The vertical hydraulic gradient is also upwards in these areas.

(c) Simulated river and spring boundary fluxes

Spatial patterns of river flow losses and gains discussed in Section 7.3 and quantitative observations of river/spring losses and gains (Figures 7.31 and 7.32) 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: 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 11.12 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 7.32 shows that the simulated pattern of gains and losses along the main river courses, particularly around the main fault structures, is consistent with observed patterns and the conceptual hydrogeological model.

From a quantitative perspective, model calibration relied on measured flow losses and gains for specific river reaches (or transfer node Groups) and spring discharge zones as delineated in Figure 11.13. The observed fluxes represent irregular 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 at the time of measurement.

Figures 11.14 to 11.18 show transient water balance outputs for each of the transfer node groups with reference to target fluxes. The outputs are discussed below.

Tauherenikau River

Figure 11.14 shows the modelled fluxes between the Tauherenikau River and groundwater over three reaches (observation groups 10, 11, 12, see Figure 11.13). The river is observed to consistently lose flow between the gorge (permanent gauging site) and the Tauherenikau Racecourse–SH 53 bridge area (see Section 7.3.3 and Figure 7.31). Over this reach, the river loses between 800 and 1,100 L/s to groundwater during the summer period. Most of the loss occurs over a 3 km section between the SH 2 bridge and the SH 53 bridge. Downstream of SH 53, the flow in the Tauherenikau River remains stable, showing neither a significant loss nor gain. The simulated flow losses shown in Figure 11.4 show a good correlation with the observed fluxes, mostly out of the river to groundwater upstream of SH 53. During the winter months, the model predicts a small base flow contribution from groundwater upstream of SH 2 in the order of 100-200 L/s.

Tauherenikau fan spring-fed streams

Simulated flows from groundwater to the Stonestead (Dock) Creek, Featherston streams and the Otukura-Battersea stream system are shown in Figure 11.15.

The simulated flux from groundwater to the Stonestead (Dock) Creek shows a declining base flow from about 750 to 600 L/s over the calibration period (Figure 11.5A). The simulated base flow is consistent with the estimated mean low flow of the creek of about 500-600 L/s (Section 3.3.2).

The Otukura/Battersea spring/drain system occupies the eastern part of the Tauherenikau fan (Figure 3.4). A naturalised 7-day mean annual low flow (MALF) of 107 L/s was estimated for this system (see Section 3.3.1) – much of which is probably derived from the Moroa Water Race. The groundwater discharge component is therefore regarded to be relatively minor during the summer months. The lowest recorded flow is 3 L/s and during very dry summer periods it appears that there is a very minor (or zero) gain from groundwater. Figure 11.15B shows the simulated groundwater discharge to this system which maintains a close consistency to the observed flow conditions. During the summer months, the flux from groundwater is generally less than 20 L/s, and remains low during the dry 2000-2004 period.

Figure 11.15C shows the simulated discharge to the Donalds–Abbotts streams in the Featherston area. Spot gauging data suggest that the total summer base flow (groundwater discharge) is in the order of 50-100 L/s; this is corroborated by the model. Again, a declining groundwater discharge from this system is indicated over the model calibration period.

Simulated spring discharges on the Tauherenikau fan closely match measured flows. All three spring-fed systems (Stonestead, Otukura and Abbotts/Donalds) show a declining base flow over the model calibration period which continues through to 2008. The cause of this appears to be a combination of climatic variation and increased groundwater abstraction. The latter option is advocated since the base flow reductions persist even though recharge has increased to above average levels in recent years (see Figure 11.10).

Ruamahanga River

Figure 11.16 shows the modelled fluxes between the Ruamahanga River and groundwater over four reaches which correspond to concurrent river gauging survey (see Table 7.3). The first reach extends from the northern model boundary to the Huangarua confluence and contains the section of river which is confined between Te Maire ridge and the eastern hills (the so-called Riverside area). Table 7.3 shows that this reach (down to about Waihenga bridge) may lose about 600 L/s in summer (based on one concurrent gauging). Figure 11.16A shows that simulated river flow loss for this reach is about 500–800 L/s during summer, dropping to less than 400 L/s in winter when the hydraulic gradient between the river and the adjacent aquifer is lowest.

Figure 11.16B shows the simulated aquifer-river flux between the Huangarua confluence and the Tawaha area (Walls gauging site) which has a gauged loss of 110–690 L/s (Table 7.3). The model simulates a fairly neutral gain-loss flux on this reach, peaking at about a 200 L/s loss to the aquifer in summer. This is consistent with the gauging data, given the large error inherent in the gaugings (200–300 L/s).

The succeeding short section of river between Walls and Pukio (Figure 11.16C) has a simulated river flow gain of 500–700 L/s; this is substantiated by concurrent gauging data which measured a gain of 582–605 L/s (Table 7.3).

The simulated river-aquifer flux for lower section of the Ruamahanga River between Pukio and Lake Onoke is shown in Figure 11.16D. The model predicts a consistent gain in flow in the lower reaches of the catchment of between 600 and 1,000 L/s. Concurrent gauging data for the last two stations in Table 7.3 are somewhat contradictory due to the difficulty in gauging the lower part of the river and due to tidal effects. The gauging of 22 February 2006 does, however, indicate a large gain of about 1,500 L/s which is offset by a loss upstream (between Pukio and Awaroa Sill) of about 700 L/s. The balance would therefore be about an 800 L/s gain which is consistent with the range predicted by the model.

Eastern rivers

The simulated water balance for the Huangarua River is divided into upper and lower sections and shown in Figures 11.17A and B. There are no concurrent gauging data for this river with which model predictions can be compared. Each channel segment shows a small loss of flow to groundwater during the summer of about 100 L/s and larger gains during winter of >200 L/s.

Figure 11.17C shows the modelled loss of flow from Dry River into the adjacent aquifer which peaks at about 150 L/s in summer when the hydraulic gradient between the river and the adjacent aquifer is highest. The Tauanui River has a similar response to the Dry River and consistently loses about 250 L/s to groundwater (Figure 11/17D). There are no concurrent flow data for these rivers to verify the model predictions. However, it is known that both rivers lose a substantial proportion of their flows into the fan gravels and the magnitude of simulated flow loss is consistent with observed flows in the rivers.

Lakes Wairarapa and Onoke

There was no prior information relating to the interaction of groundwater with either Lake Wairarapa or Lake Onoke and, to date, no accurate water balance studies have been undertaken for these water bodies. The model, calibrated to groundwater heads in the vicinity of Lake Wairarapa in particular, can therefore supply valuable information on the nature of its groundwater dependence.

Figure 11.18A shows the modelled flux into the Lake Wairarapa from aquifers underlying and surrounding it. The flux represents both leakage from deep confined aquifers and lateral inflow from surrounding shallow unconfined aquifers (such as Tauherenikau delta gravels). The model simulates a relatively narrow range in groundwater discharge to the lake of between about 350 and 470 L/s. The mean simulated discharge over the model calibration period is 430 L/s (about 37,000 m^3/day, or 37 ML/day). Approximately half of this quantity appears to be derived from shallow aquifers around the Tauherenikau delta area. The groundwater discharge rate to the lake varies by about 50 L/s seasonally and is lowest during late summer.

Figure 11.18B shows the modelled groundwater input to Lake Onoke at a relatively consistent 70–90 L/s.

11.6.9 Calibrated parameter values

Tables 11.10 to 11.14 show the calibrated values for the final PEST optimisation run for adjustable (unknown) and fixed model parameters for each of the hydrostratigraphic units. 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).

The tables also show the 95% confidence intervals for the adjustable parameters. Although the confidence limits are highly dependent upon the assumptions underpinning the model, the confidence limits provide a useful means of comparing the certainty with which the parameters have been estimated by PEST.

Figure 11.19 presents a graphical comparison of the measured ranges of horizontal hydraulic conductivity for the various hydrostratigraphic units (refer to Table 7.6) with the calibrated parameter values. It is clear that the calibrated model hydraulic conductivity values are consistent with the observed ranges 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 hydrostratigraphic unit A (alluvial fan deposits) of the Lower 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)

Zone	Parameter	Location	Layers	Adjustable, fixed or tied parameter in final PEST run	Calibrated value with upper and lower 95% confidence limits for adjustable parameter
Horizontal hydraulic conductivity (Kx) unit: m/day					
1	Kx	Upper Tauherenikau fan	1–10	adjustable	9.8 (9.37 – 10.2)
2	Kx	Mid-lower Tauherenikau fan	1–7	adjustable	16.8 (16.4 – 17.3)
92	Kx	Tauherenikau fan	8–11	adjustable	15.35 (14.8 – 15.9)
93	Kx	Tauherenikau fan	12–17	adjustable	13.35 (13.0 – 13.7)
Vertical hydraulic conductivity (Kx) unit: m/day					
0	Kz	All areas	1–17	fixed	0.01 * Kx
Specific storage (Ss) unit: dimensionless					
48	Ss	Tauherenikau fan, Ruamahanga valley and Martinborough	6–10	adjustable	1.3E-5 (1.2E-5 – 1.3E-5)
50	Ss	Tauherenikau fan, Ruamahanga valley and Martinborough	11–17	adjustable	2 E-5 (1E-5 – 2E-5)
51	Ss	Whole domain	1–5	adjustable	6 E-6
Specific yield (St) unit: percent/100					
53	St	Whole domain	5–17	fixed	1E-5
75	St	Tauherenikau fan	1–4	fixed	0.07
77	St	Tauherenikau fan	1–4	adjustable	0.078 (0.076 – 0.08)
Transfer rate in and out (It and Ot) unit: d^{-1}					
96	It	Tauherenikau delta	12–17	fixed	1E-4
97	Ot	Tauherenikau delta	12–17	fixed	1E-4
100	It	Tauherenikau fan – Featherston	1–17	fixed	0.07
101	Ot	Tauherenikau fan – Featherston	1–17	fixed	0.07

Table 11.11: Calibrated parameters for hydrostratigaphic unit B (unconfined Q1 gravels) of the Lower 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)

Zone	Parameter	Location	Layers	Adjustable, fixed or tied parameter in final PEST run	Calibrated value with upper and lower 95% confidence limits for adjustable parameter
Horizontal hydraulic conductivity (Kx) unit: m/day					
3	Kx	Tauherenikau Holocene	1–3	fixed	350
4	Kx	Upper Ruamahanga; Huangarua valley	1–1 7	adjustable	330 (317–343)
6	Kx	Recent Lake Wairarapa sediments	1	fixed	8.64
8	Kx	Lake basin /Onoke Holocene cover; side valley fans	1	fixed	60
11	Kx	Onoke/Narrows Holocene	2	fixed	70
12	Kx	Side-valley fans	2	fixed	110
14	Kx	Lower Tauherenikau fan	6–7	adjustable	46.2 (37.3–57.1)
74	Kx	Tauherenikau fan	1–2	adjustable	178.5 (165.5–192.7)
78	Kx	Side river alluvium – Onoke	1–11	fixed	10
89	Kx	Tauherenikau delta transition zone	1–2	fixed	60
90	Kx	Tauherenikau delta transition zone	3	fixed	100
91	Kx	Tauherenikau delta transition zone	3	fixed	20
104	Kx	Upper Dry River fan	1–17	fixed	5
Vertical hydraulic conductivity (Kx) unit: m/day					
0	Kz	Tauherenikau delta	1–17	fixed	0.01 * Kx
Specific storage (Ss) unit: dimensionless					
46	Ss	Ruamahanga valley	1–5	fixed	3.5E-4
51	Ss	Whole domain	1–5	adjustable	6E-6
Specific yield (St) unit: percent/100					
53	St	Whole domain	5–17	fixed	1E-5
76	St	Ruamahanga valley and Huangarua valley	1–4	fixed	0.056
Transfer rate in and out (It and Ot) unit: d^{-1}					
54	It	Tauherenikau floodplain/Dock Ck	1–17	fixed	3
55	Ot	Tauherenikau floodplain/Dock Ck	1–17	fixed	3
56	It	Ruamahanga valley	1–17	fixed	2
57	Ot	Ruamahanga valley	1–17	fixed	2
58	It	Lake basin – Ruamahanga R.	1–17	fixed	0.1
59	Ot	Lake basin – Ruamahanga R.	1–17	fixed	0.1
60	It	Onoke side valleys	1–17	fixed	0.001
61	Ot	Onoke side valleys	1–17	fixed	0.001
62	It	Lake basin – Lake Wairarapa	1–17	fixed	0.001
63	Ot	Lake basin – Lake Wairarapa	1–17	fixed	0.001
94	It	Dry River	1–17	fixed	0.5
95	Ot	Dry River	1–17	fixed	0.5

Table 11.12: Calibrated parameters for hydrostratigaphic unit C (Q2, Q4 and Q6 confined/semi-confined aquifers) of the Lower 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)

Zone	Parameter	Location	Layers	Adjustable, fixed or tied parameter in final PEST run	Calibrated valuewith upper and lower 95% confidence limits for adjustable parameter
Horizontal hydraulic conductivity (Kx) unit: m/day					
15	Kx	Q2 aquifer – Tauherenikau delta/Kahutara area, and N. lake basin	6–7	adjustable	131.3 (106.2 – 162.4)
16	Kx	Q2 aquifer – N. Onoke area (zone 102 in S.)	6–7	adjustable	28.2 (26.9 – 29.6)
20	Kx	Q4 confined aquifer Tauherenikau zone	11	fixed	100.5
21	Kx	Q4 aquifer, Onoke N. zone	11	adjustable	11.7 (11.5 – 12.0)
23	Kx	Huangarua Valley, deep	11	fixed	8.64
25	Kx	Q6 aquifer lake basin – proximal	15	adjustable	100 (96.9 – 103.2)
26	Kx	Q6 aquifer lake basin – intermediate	15	fixed	20
27	Kx	Q6 aquifer lake basin – distal	15	fixed	3
34	Kx	S. lake basin	6-7	fixed	77.3
35	Kx	S. lake basin	11	fixed	77.5
70	Kx	Dry River	6–7	adjustable	31.1 (30.3 – 31.9)
73	Kx	Dry River	11	adjustable	40.0 (38.6 – 41.5)
86	Kx	Ruamahanga valley – Tawaha	6–7	fixed	80
87	Kx	Ruamahanga valley –Tawaha	11	fixed	80
88	Kx	Onoke	6–7	fixed	20
102	Kx	Onoke	6–7	adjustable	41.1 (39.9 – 42.5)
103	Kx	Onoke (south)	11	adjustable	46.9 (39.1 – 56.1)
Vertical hydraulic conductivity (Kx) unit: m/day					
0	Kz	All areas	1–17	fixed	0.01 * Kx
Specific storage (Ss) unit: dimensionless					
47	Ss	Lake basin and Onoke	6–10	adjustable	1.1E-5 (1.1E-5 – 1.2E-5)
48	Ss	Tauherenikau fan, Ruamahanga valley and Martinborough	6–10	adjustable	1.3E-5 (1.2E-5 – 1.3E-5)
49	Ss	Lake basin and Onoke	11–17	adjustable	5.3E-6 (5.1E-6 – 6.3E-6)
50	Ss	Tauherenikau fan, Ruamahanga valley and Martinborough	11–17	adjustable	1.7E-5 (1.5E-5 – 1.9E-5)
51	Ss	Whole domain	1–5	adjustable	6.1E-6 (5.9E-6 – 6.3 E-6)
Specific yield (St) unit: percent/100					
53	St	Whole domain	5–17	fixed	1E-5

Table 11.13: Calibrated parameters for hydrostratigaphic unit D (Q1, Q3, Q5, Q7 aquitards) of the Lower 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)

Zone	Parameter	Location	Layers	Adjustable, fixed or tied parameter in final PEST run	Calibrated value with upper and lower 95% confidence limits for adjustable parameter
Horizontal hydraulic conductivity (Kx) unit: m/day					
13	Kx	Holocene lacustrine aquitard	2	fixed	0.86
18	Kx	Q3 aquitard lake basin	8–10	fixed	0.08
19	Kx	Ruamahanga valley – Tawaha	12–14	fixed	6.0
28	Kx	Q6 aquitard Onoke	15	fixed	0.08
31	Kx	Q7 aquitard lake basin	16–17	fixed	0.08
33	Kx	Huangarua valley	9–10	fixed	86
68	Kx	Dry River	3–5	adjustable	12.7 (12.3 – 13.0)
69	Kx	Ruamahanga valley – Tawaha	3–5	fixed	63.7
71	Kx	Dry River	8–10	adjustable	5.9 (5.7 – 6.0)
72	Kx	Ruamahanga valley – Tawaha	8–10	fixed	77.5
79	Kx	Ruamahanga valley – Pukio	3–5	fixed	8.6
80	k x	Ruamahanga valley – Tawaha	3–5	fixed	29
81	k x	Ruamahanga valley – Pukio	12–14	fixed	3.1
Vertical hydraulic conductivity (Kx) unit: m/day					
36	Kz	Ruamahanga valley – Tawaha	3–5	adjustable	0.085 (0.03 – 0.21)
37	Kz	Lake basin	8–10	adjustable	2.9E-4 (2.5E-4 – 3.4E-4)
38	Kz	Tauherenikau fan	8–10	adjustable	4.9E-4 (4.8E-4 – 5.1E-4)
39	Kz	Ruamahanga valley – Tawaha	8-10	fixed	0.77
40	Kz	Lake basin	12–14	tied	0.0013
41	Kz	Ruamahanga valley – Tawaha	12–14	fixed	5.2E-4
43	Kz	Onoke side valleys	3–5	fixed	8.6E-5
44	Kz	Lake basin	3–5	adjustable	7E-5 (6.8E-5 – 7.3E-5)
45	Kz	Tauherenikau fan	3–5	adjustable	7.2E-3 (7E-3 – 7.5E-3)
82	Kz	Ruamahanga valley – Pukio	3–5	adjustable	0.01 (1E-3 – 0.05)
83	Kz	Ruamahanga valley – Pukio	8–10	fixed	0.39
84	Kz	Ruamahanga valley – Pukio	12–14	fixed	6.7E-4
85	Kz	Tauherenikau fan – Featherston	8–10	adjustable	3E-5 (2E-5 – 3E-5)
98	Kz	Dry River	3–5	adjustable	2.8E-4 (2E-4 – 3E-4)
99	Kz	Dry River	8–10	adjustable	1.3E-4
Specific storage (Ss) unit: dimensionless					
47	Ss	Lake basin and Onoke	6–10	adjustable	1.1E-5 (1.1E-5 – 1.2E-5)
48	Ss	Tauherenikau fan, Ruamahanga valley and Martinborough	6–10	adjustable	1.3E-5 (1.2E-5 – 1.3E-5)
49	Ss	Lake basin and Onoke	11–17	adjustable	5.3E-6 (5.1E-6 – 6.3E-6)
50	Ss	Tauherenikau fan, Ruamahanga valley and Martinborough	11–17	adjustable	1.7E-5 (1.5E-5 – 1.9E-5)
51	Ss	Whole domain	1–5	adjustable	6.1E-6 (5.9E-6 – 6.3 E-6)
Specific yield (St) unit: percent/100					
52	St	Lake basin – Onoke	1–4	fixed	0.017
53	St	Whole domain	5–17	fixed	1E-5

Table 11.14: Calibrated parameters for hydrostratigaphic units E and F (Martinborough terrace sequence and flow barriers) of the Lower Valley transient groundwater flow model (Kx – horizontal hydraulic conductivity, Kz – vertical hydraulic conductivity, Ss – specific storage, It – transfer rate in, Ot – transfer rate out)

Zone	Parameter	Location	Layers	Adjustable, fixed or tied parameter in final PEST run	Calibrated value with upper and lower 95% confidence limits for adjustable parameter
UNIT E (Martinborough terrace sequence)					
Horizontal hydraulic conductivity (Kx) unit: m/day					
10	Kx	Martinborough terraces	1–9	adjustable	6.2 (6.0 – 6.4)
17	Kx	Dry River	1–2	adjustable	16.8 (16.5-17.2)
22	Kx	Martinborough terrace, confined	10–12	adjustable	9.6 (9.3 – 10.0)
24	Kx	Martinborough and Dry River – deep aquitard	13–14	fixed	0.01
29	Kx	Martinborough terraces – deep confined	15	adjustable	24.6 (23.7 – 25.5)
32	Kx	Martinborough and Dry River – deep confined	16–17	adjustable	1.3 (0.05 – 29.3)
65	Kx	Martinborough terrace – Harris anticline edge	1–14	adjustable	11.9 (11.3 – 12.6)
Vertical hydraulic conductivity (Kx) unit: m/day					
42	Kz	Martinborough terraces – Dry River	12–14	adjustable	4.7E-5 (4.6-4.8E-5)
66	Kz	Martinborough terraces	1–9	adjustable	6.6E-4 (6.4 – 6.8E-4)
67	Kz	Martinborough terraces – Harris anticline edge	1–15	fixed	0.026
Specific storage (Ss) unit: dimensionless					
51	Ss	Whole domain	1–5	adjustable	6.1E-6 (5.9E-6–6.3 E-6)
UNIT F (flow barriers)					
7	Kx	Coastal terraces (Pirinoa & N)	1–17	fixed	0.086
9	Kx	Harris anticline core	1–17	fixed	0.086
30	Kx	Martinborough Fault	15–17	fixed	8.6E-5
0	Kz	All areas	1–17	fixed	0.01 * Kx

11.6.10 Parameter sensitivity

Parameter sensitivities are listed in Table 11.15 for those parameters which were 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 log of 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 11.15: Parameter composite and relative sensitivity for the Lower Valley transient groundwater flow model (final optimisation adjustable parameters). Kx – horizontal hydraulic conductivity, Kz – vertical hydraulic conductivity, St – specific yield, Ss – specific storage.

Parameter	Hydrostratigraphic unit(s) and area	Composite sensitivity	Relative sensitivity
Kx01	A: Upper Tauherenikau fan	0.081	0.081
Kx02	A: Mid-lower Tauherenikau fan	0.094	0.115
Kx04	B: Upper Ruamahanga; Huangarua valley	0.051	0.128
Kx10	E: Martinborough terraces	0.078	0.062
Kx14	B: Lower Tauherenikau fan	0.071	0.118
Kx15	C: Q2 aquifer – Tauherenikau delta/Kahutara area, and N. lake basin	0.064	0.135
Kx16	C: Q2 aquifer – N. Onoke area	0.031	0.045
Kx17	E: Dry River	0.078	0.095
Kx21	C: Q4 aquifer, Onoke N. zone	0.087	0.093
Kx22	E: Martinborough terrace, confined	0.072	0.071
Kx25	C: Q6 aquifer lake basin – proximal	0.077	0.155
Kx29	E: Martinborough terraces – deep confined	0.091	0.126
Kx32	E: Martinborough and Dry River	0.0005	0.0005
Kx65	E: Martinborough terrace – Harris anticline edge	0.075	0.081
Kx68	D: Dry River	0.080	0.088
Kx70	D: Dry River	0.085	0.127
Kx71	D: Dry River	0.124	0.096
Kx73	D: Dry River	0.057	0.091
Kx74	B: Tauherenikau channel	0.071	0.160
Kx92	A: Tauherenikau fan	0.052	0.062
Kx93	A: Tauherenikau fan	0.062	0.070
Kx102	C: Onoke	0.076	0.123
Kx103	C: Onoke (south)	0.063	0.105
Kz36	D: Ruamahanga valley – Tawaha	0.001	0.001
Kz37	D: Lake basin	0.064	0.225
Kz38	D: Tauherenikau fan	0.085	0.282
Kz42	E: Martinborough terraces – Dry River	0.093	0.402
Kz44	D: Lake basin	0.080	0.333
Kz45	D: Tauherenikau fan	0.080	0.172
Kz66	E: Martinborough terraces	0.069	0.219
Kz82	D: Ruamahanga valley – Pukio	0.001	0.001
Kz85	D: Tauherenikau fan – Featherston	0.073	0.335
Kz98	D: Dry River	0.072	0.255
Kz99	D: Dry River	0.001	0.002
Ss47	C + D: Lake basin and Onoke	0.081	0.402
Ss48	A, C, D: Tauherenikau fan, Ruamahanga valley and Martinborough	0.102	0.501
Ss49	C, D: Lake basin and Onoke	0.073	0.386
Ss50	A, C, D: Tauherenikau fan, Ruamahanga valley and Martinborough	0.012	0.058
Ss51	Whole domain, all units	0.067	0.350
St77	A: Tauherenikau fan	0.082	0.090

The relative sensitivities listed in Table 11.15 are also graphically displayed in Figure 11.20. This helps to identify those parameters which most affect the calibration, and to identify any parameters which may degrade the performance of the parameter estimation process. This includes 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 11.20 shows that the horizontal hydraulic conductivity parameters all have about the same relative sensitivity (around 0.1) but are not overly insensitive such that they would result in a poor calibration. Very insensitive parameters were progressively fixed during the PEST run to prevent problematic parameters dominating the optimisation process. There is, however, one very insensitive Kx parameter (Kx32) representing the very deep Martinborough area aquifers in layers 16 and 17. The insensitivity probably relates to the lack of observation data at this level. The parameter will not have been accurately estimated (see discussion in Section 11.7 on the calibration status of the deep Martinborough system).

Immediately apparent from Figure 11.20 is the high relative sensitivity associated with most of the vertical hydraulic conductivity parameters – these were consequently estimated with a higher degree of certainty. These highly sensitive parameters relate to hydrostratigrahic unit D (aquitard units) in the lake basin area. There are three vertical hydraulic conductivity parameter zones which are very insensitive (Kz36, Kz82, and Kz99) – all are aquitard units (D) in the Ruamahanga valley/Dry River area and were consequently estimated with a lower degree of certainty.

The calibration was also highly sensitive to most of the confined storage parameters (Ss), except for Ss50. Confidence in the estimation of these parameters by PEST is therefore good.

11.7 Summary

The Lower Valley catchment transient-flow groundwater model was calibrated for the period 1992–2008 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 model does not predict the groundwater head in the deep confined Martinborough aquifers accurately – the model remains uncalibrated in this area due to unresolved inadequacies in the model structure. This shortcoming is not expected to impact on other parts of the model, including the modelling of the shallow Martinborough aquifers.

The importance of accurately incorporating surface water–aquifer fluxes in the calibration process is stressed. Since the Lower Valley groundwater system is essentially ‘closed’ (there is very minor groundwater discharge to the sea), the modelled fluxes out of the system (principally via discharges to springs and rivers) are highly correlated to the inputs – rainfall recharge and river bed losses. Calibration of the model to observed surface water fluxes (both in and out) 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 and those which are insensitive and therefore were not estimated accurately. The sensitivities are partly related to the uneven spread of observation sites 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 aquifers along the Ruamahanga and Tauherenikau rivers and the confined aquifers of the lake basin and lower Tauherenikau fan areas.

11.8 Model limitations

There are a number of limitations and assumptions associated with the Lower 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 Tauherenikau River). 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 have been 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 Lower 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 2) and the water balance calibration of the model serve to verify the accuracy of the recharge calculations.

- *Martinborough terrace deep aquifer*: the model is not calibrated to the deep Martinborough confined aquifer due to unresolved inadequacies in the model structure. This shortcoming is not expected to impact on other parts of the model or the shallow Martinborough aquifers. Further work on the geological configuration of the deep terrace deposits is required to resolve this limitation.

- *Aquifers associated with the eastern rivers:* there was no information with which to confirm the model accuracy in the Huangarua River catchment or the aquifers associated with other minor eastern rivers. Low confidence should therefore be placed in any model predictions made in these areas.

Despite the above limitations and assumptions, the calibration outputs provide confidence that the transient numerical FEFLOW model provides a good representation of the Lower 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 'Lower Valley catchment' of the Wairarapa Valley. Filled with Late Quaternary alluvium and glacial outwash deposits to depths of up to 150 m, the basin hosts a highly heterogeneous groundwater system containing a sequence of discontinuous water-bearing strata. Major faulting and folding, both historical and contemporary, add considerable complexity to the hydrogeological functioning of the basin. The principal structural features of the catchment are the subsiding depositional lake basin centred on Lake Wairarapa, the uplifted areas of Te Maire ridge and the Martinborough and Wairarapa south coast terraces.

The most important hydrogeological characteristic of the northern part of the Lower 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). These aquifers provide recharge to down-gradient confined aquifers in the lake basin area.

The Lower 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). The two major rivers – the Ruamahanga and the Tauherenikau – are both recharge sources for groundwater in the northern part of the catchment. There is no significant connection between groundwater and the sea in the Onoke area and therefore seawater intrusion is not considered to be of concern.

Climate and recharge modelling suggest that around 50-60% of rainfall becomes groundwater recharge over the western area 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, although they are also overprinted by the effects of increasing trends in groundwater abstraction.

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 2008 was in the order of 130,000 m^3/day, whilst the total maximum allocation was about 202,000 m^3/day. Groundwater abstractions now constitute more than 25% of the daily catchment water balance during the summer months and appear to impact aquifer discharge (base flow) quantities.

Temporal changes in the dynamics of the groundwater system are attributable to a combination of natural climatic variability and rapidly developing abstraction stresses. Aquifers which do not have stable base levels controlled by surface water, such as in the lake basin and Kahutara areas, show clear evidence of climate- and abstraction-related seasonal and long-term declines in groundwater level. Cumulatively, it is highly probable that abstractions impact the base flow to surface water systems or else directly deplete flows, particularly in the Ruamahanga River. These effects will be explored in detail in Phase 3 of the Wairarapa Valley groundwater resource investigation.

The conceptual hydrogeological model was verified and transformed into a numerical transient flow model using FEFLOW. The model was then 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.

Simulated catchment water balances show that the major rivers recharge groundwater, and that groundwater discharges in low-lying areas provides a base flow to spring-fed streams and lakes. During summer, aquifer recharge from river bed leakage almost equals aquifer discharge to springs, wetlands and lakes.

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. The deep Martinborough confined aquifers were also not accurately simulated. 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 lower 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

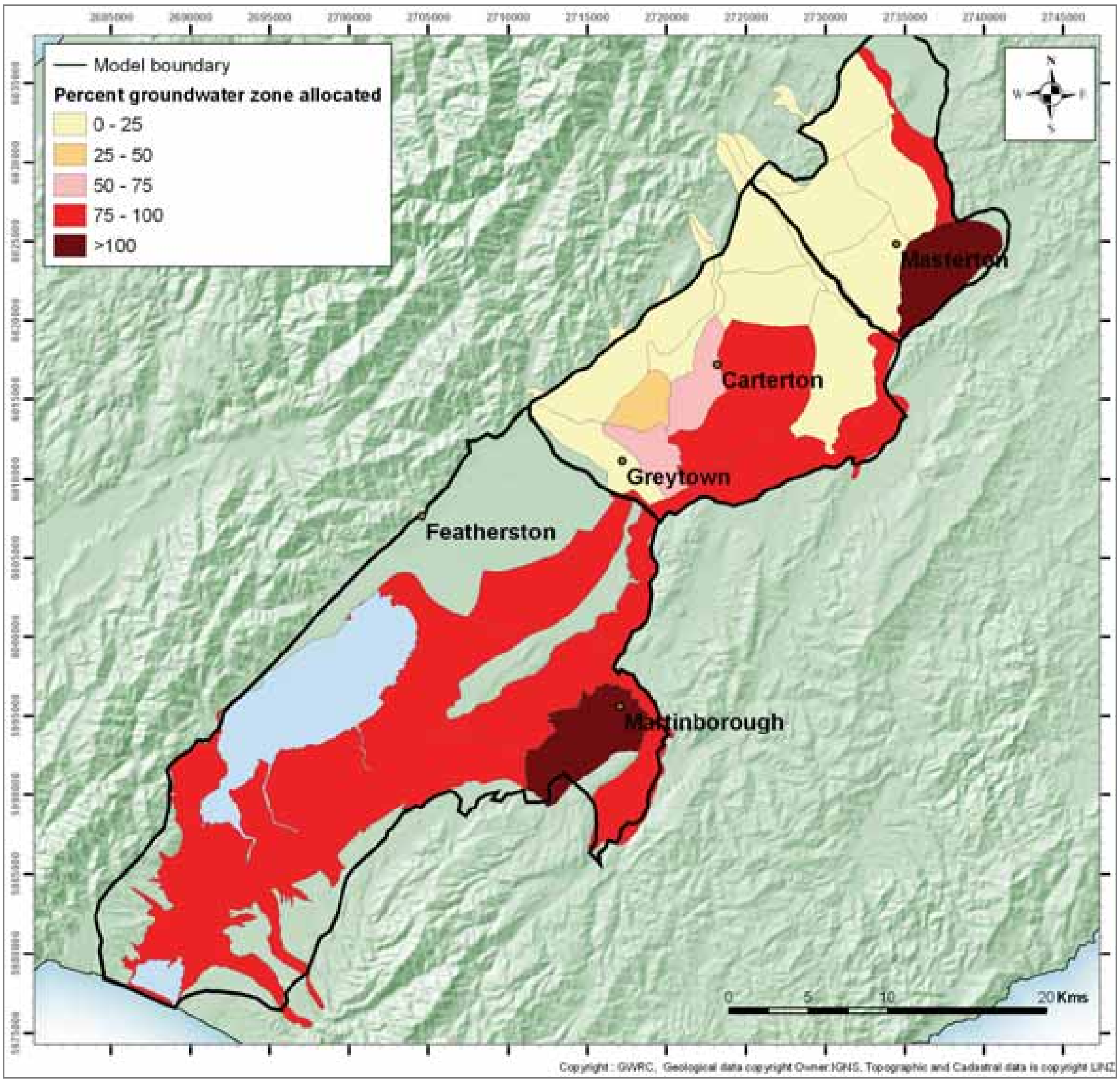
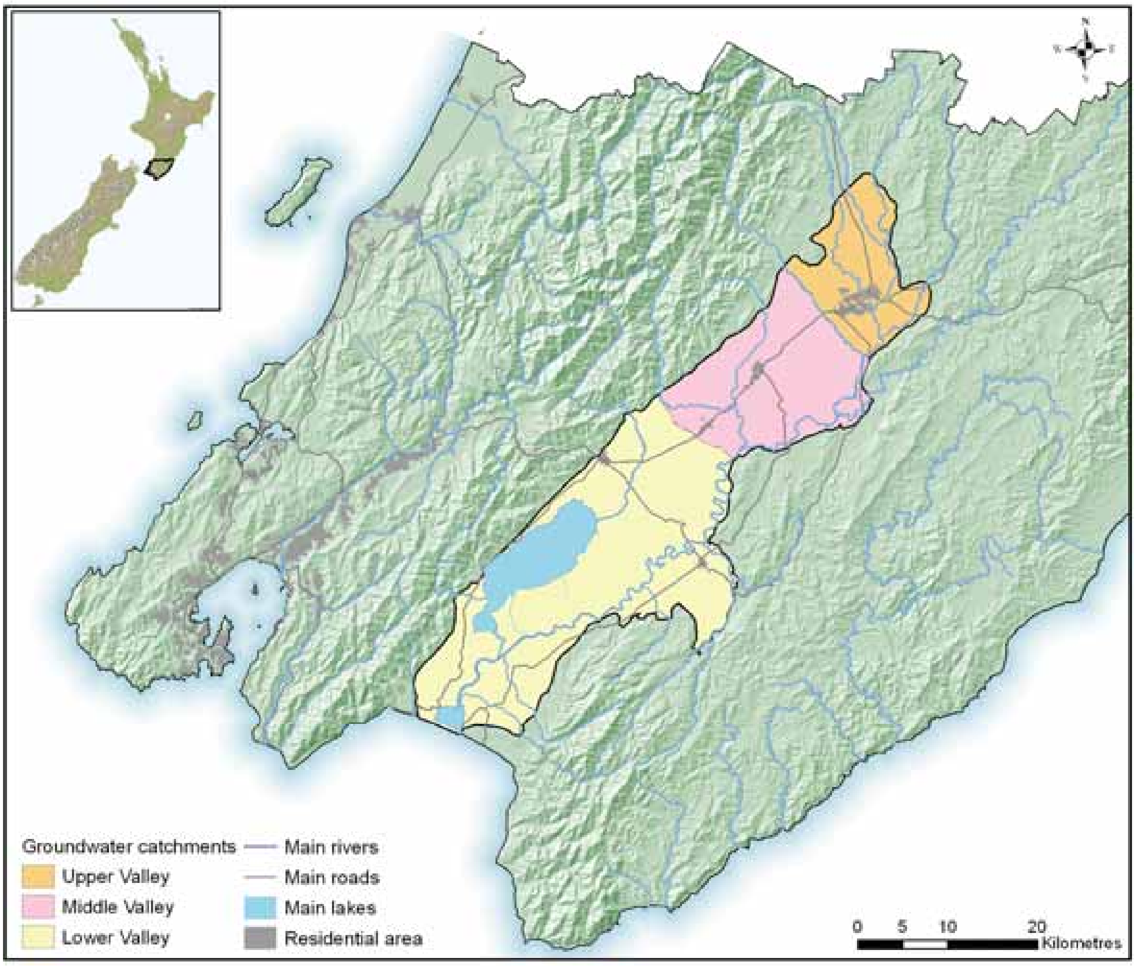


Figure 1.1: Allocation (%) of Wairarapa Valley groundwater zones as at June 2008



(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

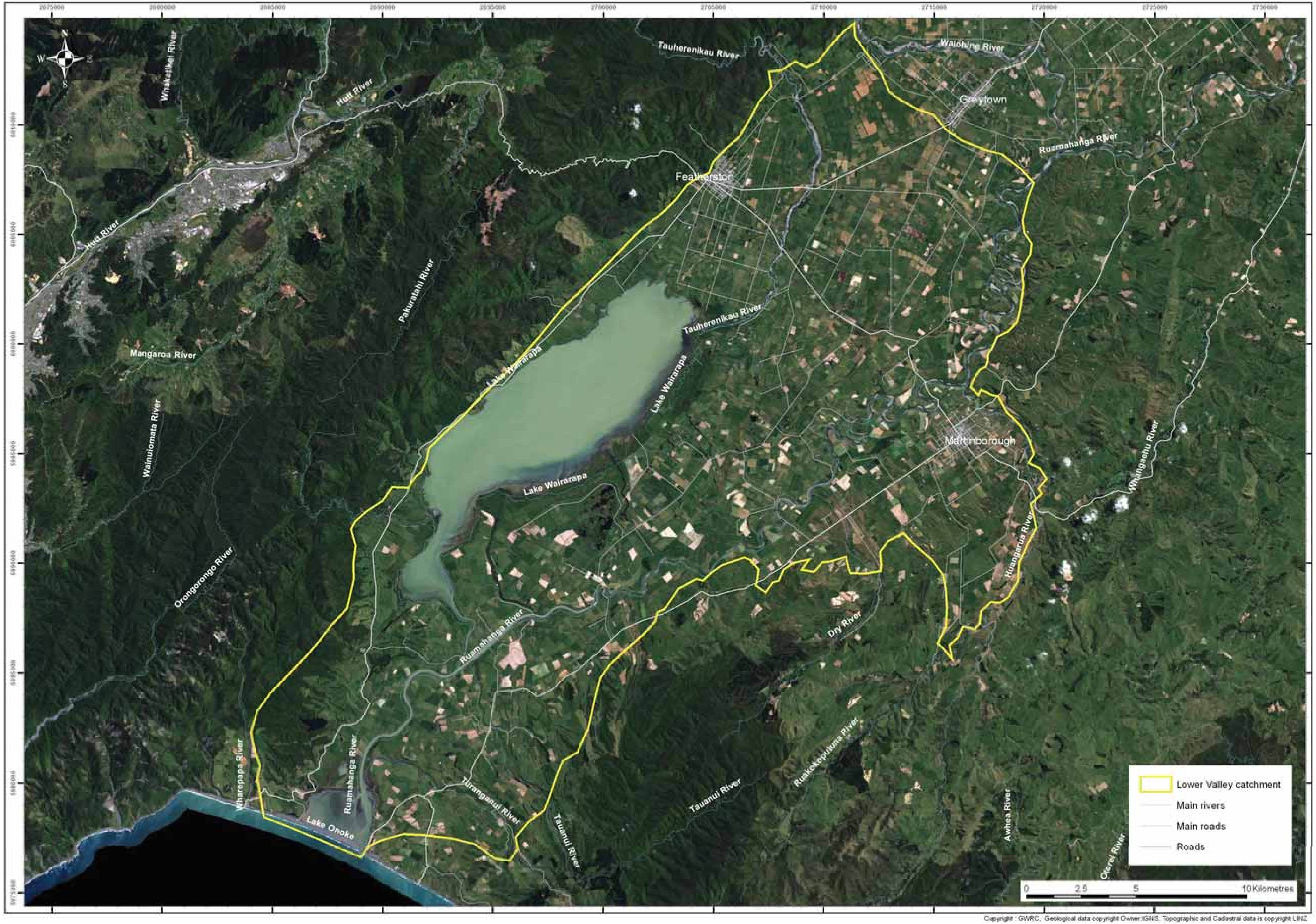


Figure 2.1: Satellite image showing the Lower Valley sub-catchment boundary and principal geomorphological features. The active Wairarapa Fault forms the linear north-westerly boundary against the Tararua Range – associated tectonic subsidence is responsible for Lake Wairarapa.

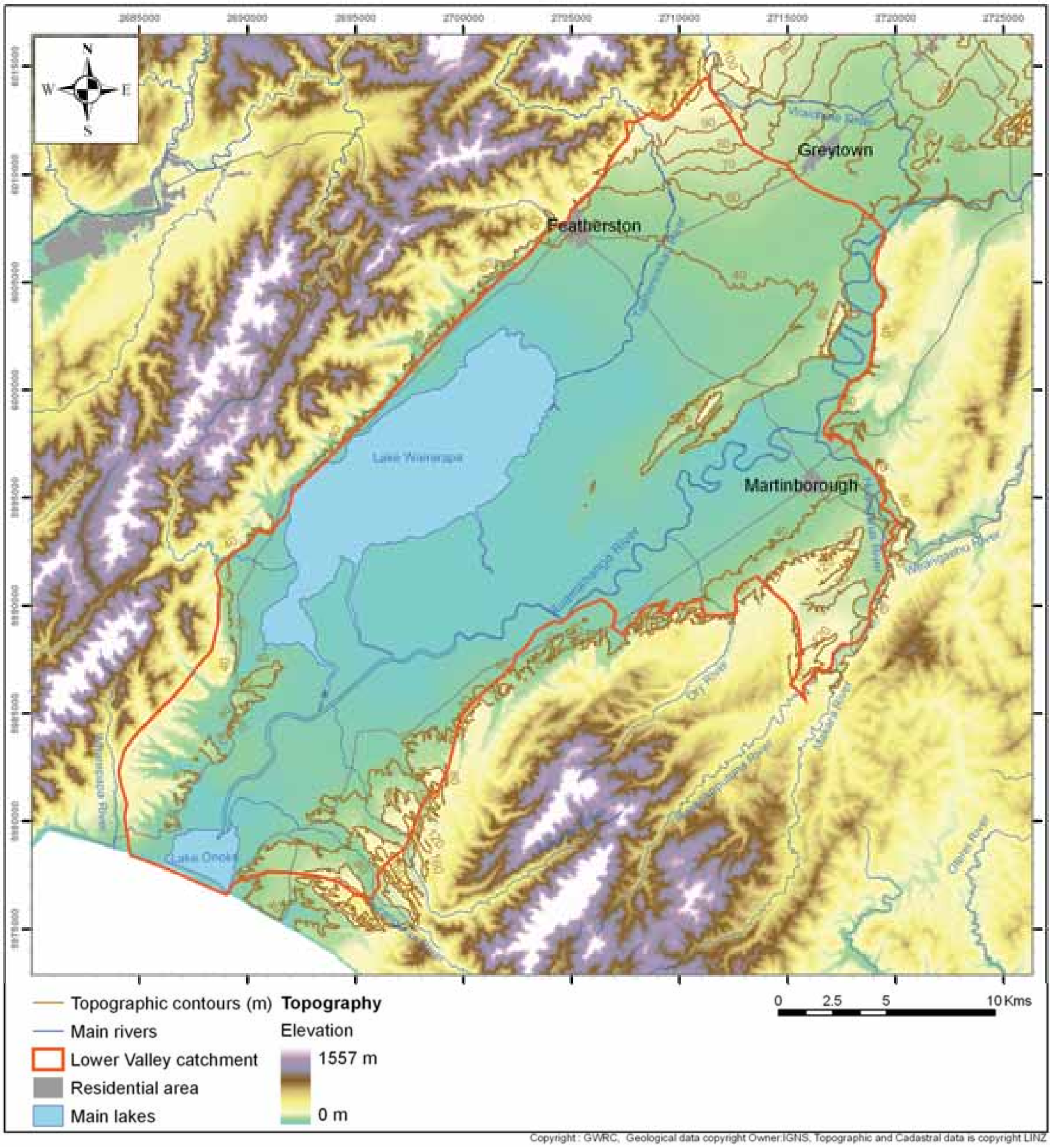


Figure 2.2: Topographic contours for the Lower Valley catchment (contours within the catchment boundary are for 40, 80, 120 and 160 m amsl)

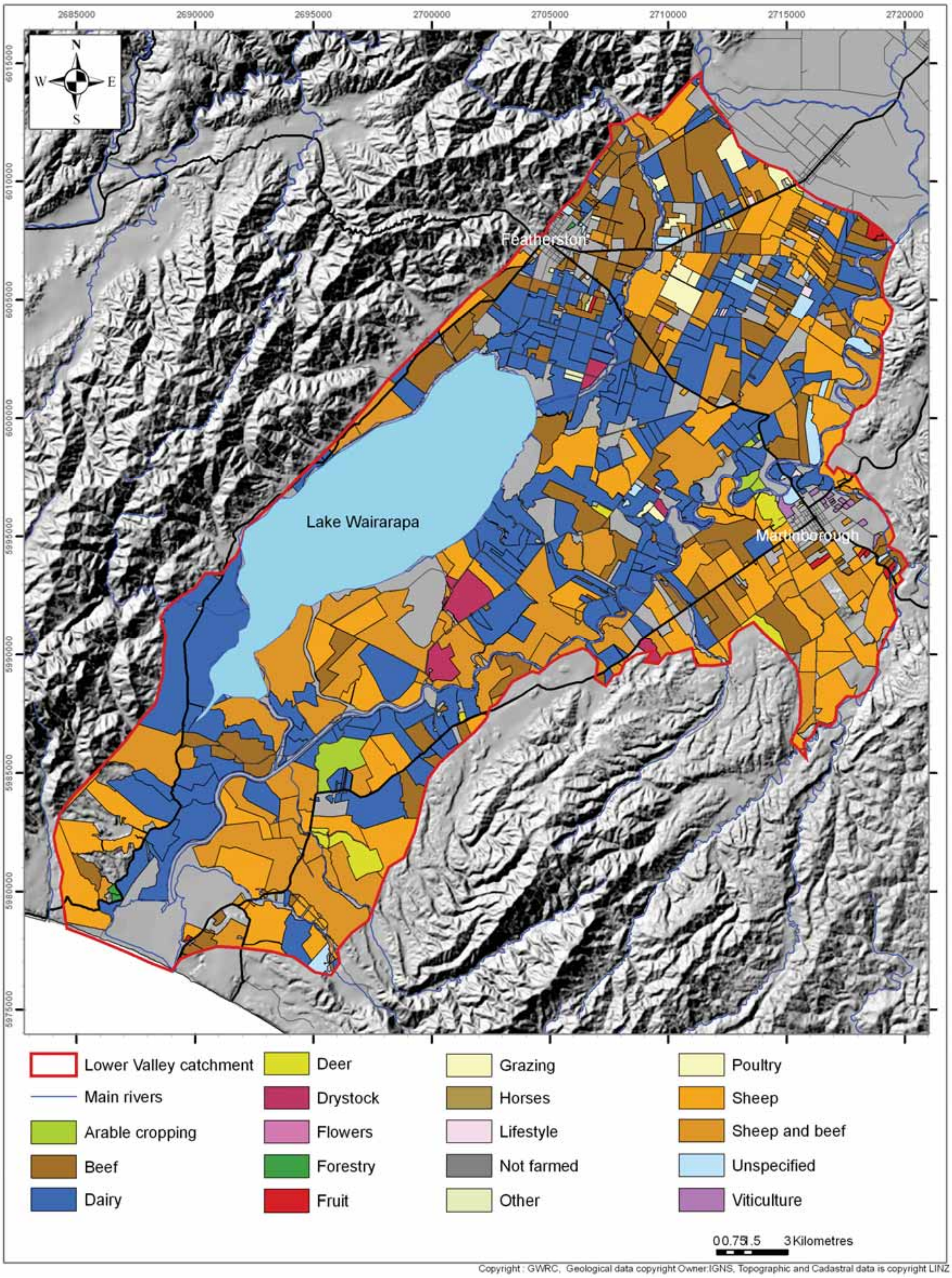


Figure 2.3: Landuse map for the Lower Valley catchment, derived from Agribase (2001 version). Note the dominant dairy, sheep and beef landuses.

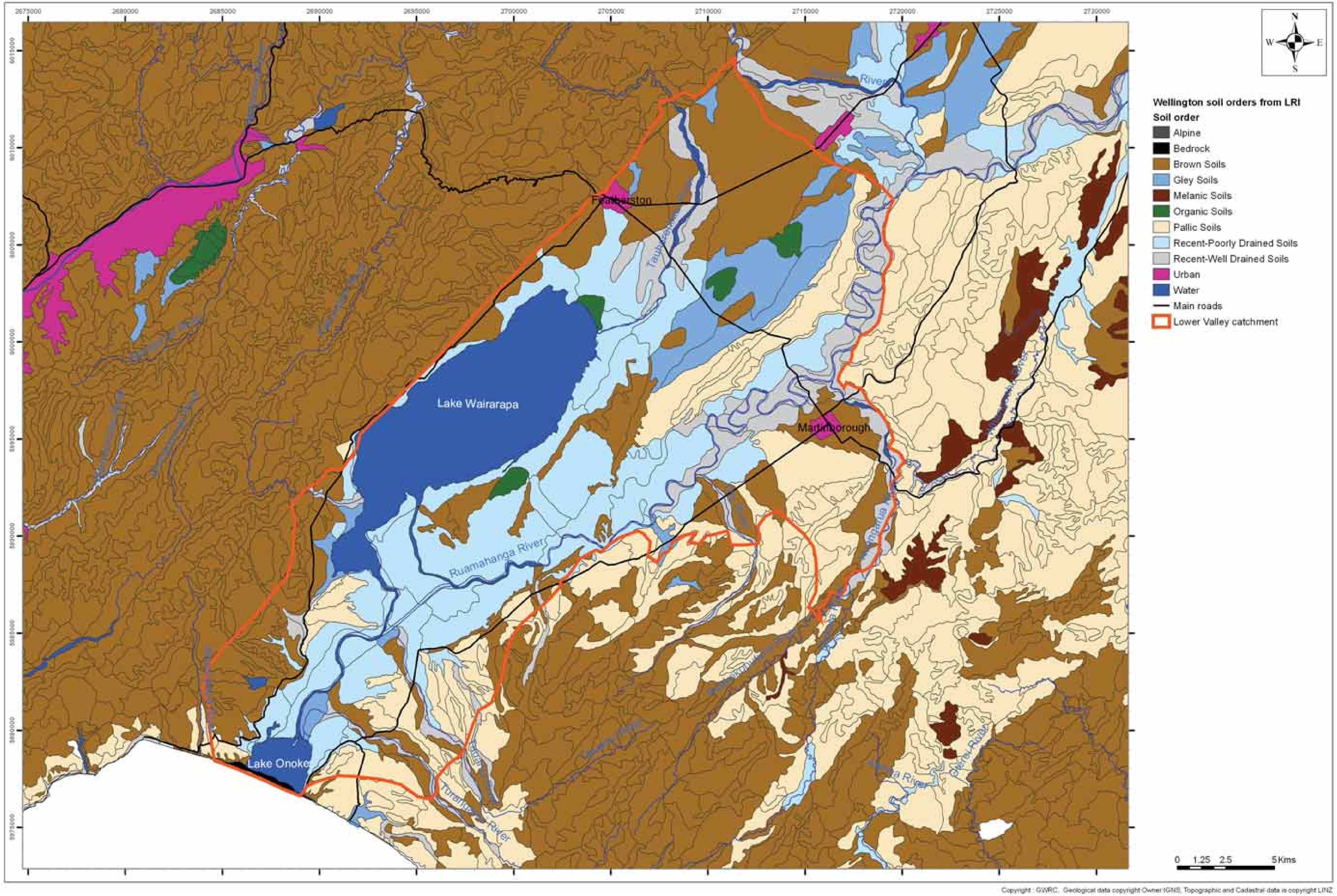


Figure 2.4: Soils of the Lower Valley catchment (Source: NZLRI)

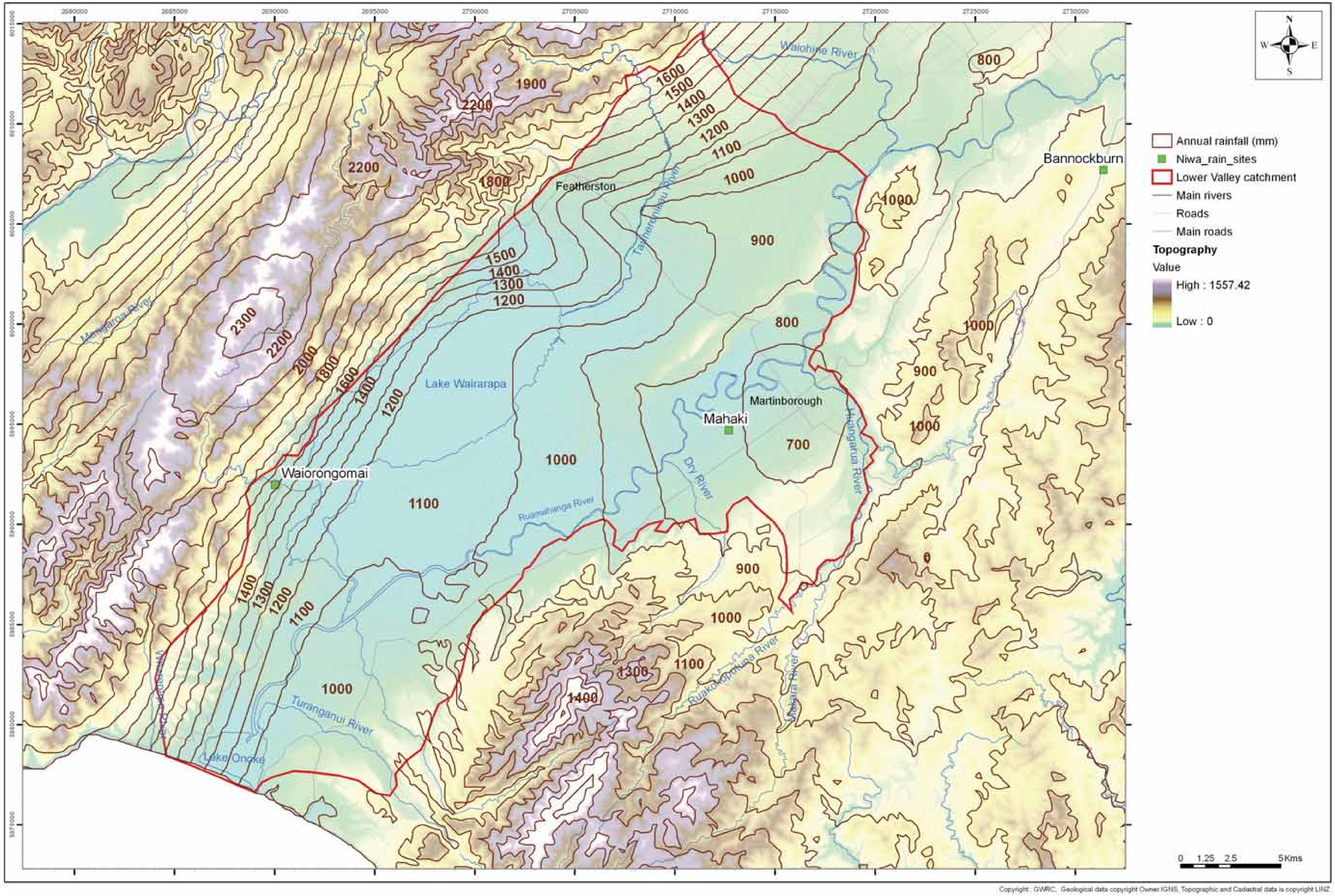


Figure 2.5: Annual average rainfall for the Lower Valley catchment (Source: LENZ). Also shown are long-term NIWA rainfall monitoring stations.

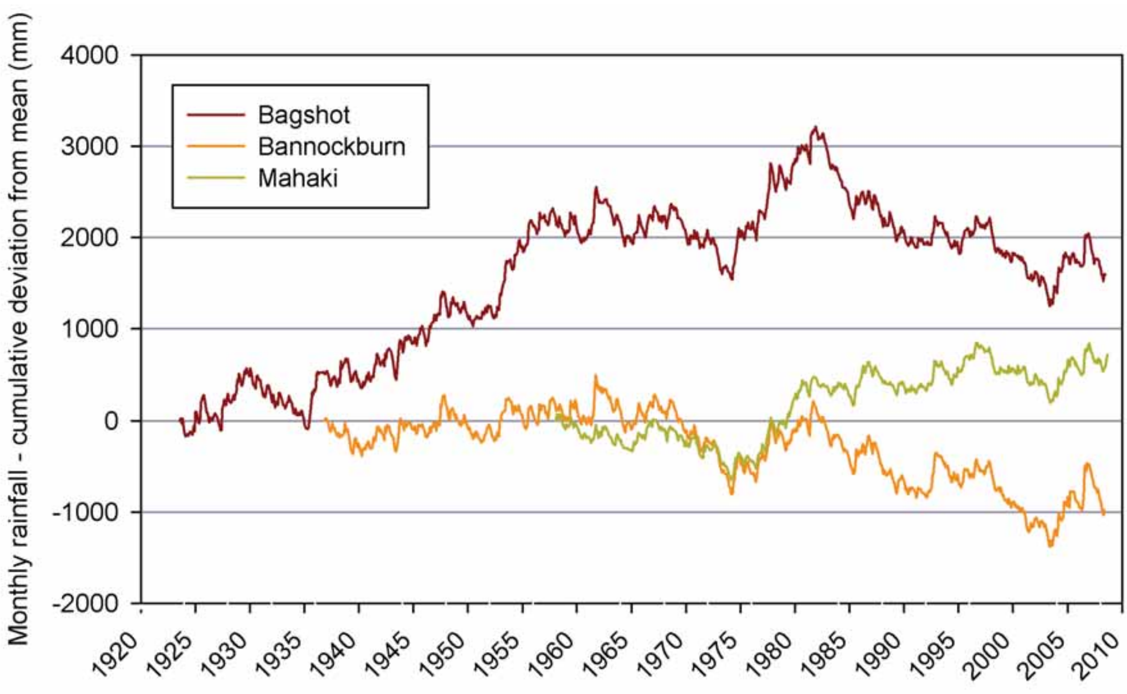


Figure 2.6: Cumulative deviation from the monthly mean rainfall ('cusum') trends at three long-term rainfall stations in the Wairarapa Valley

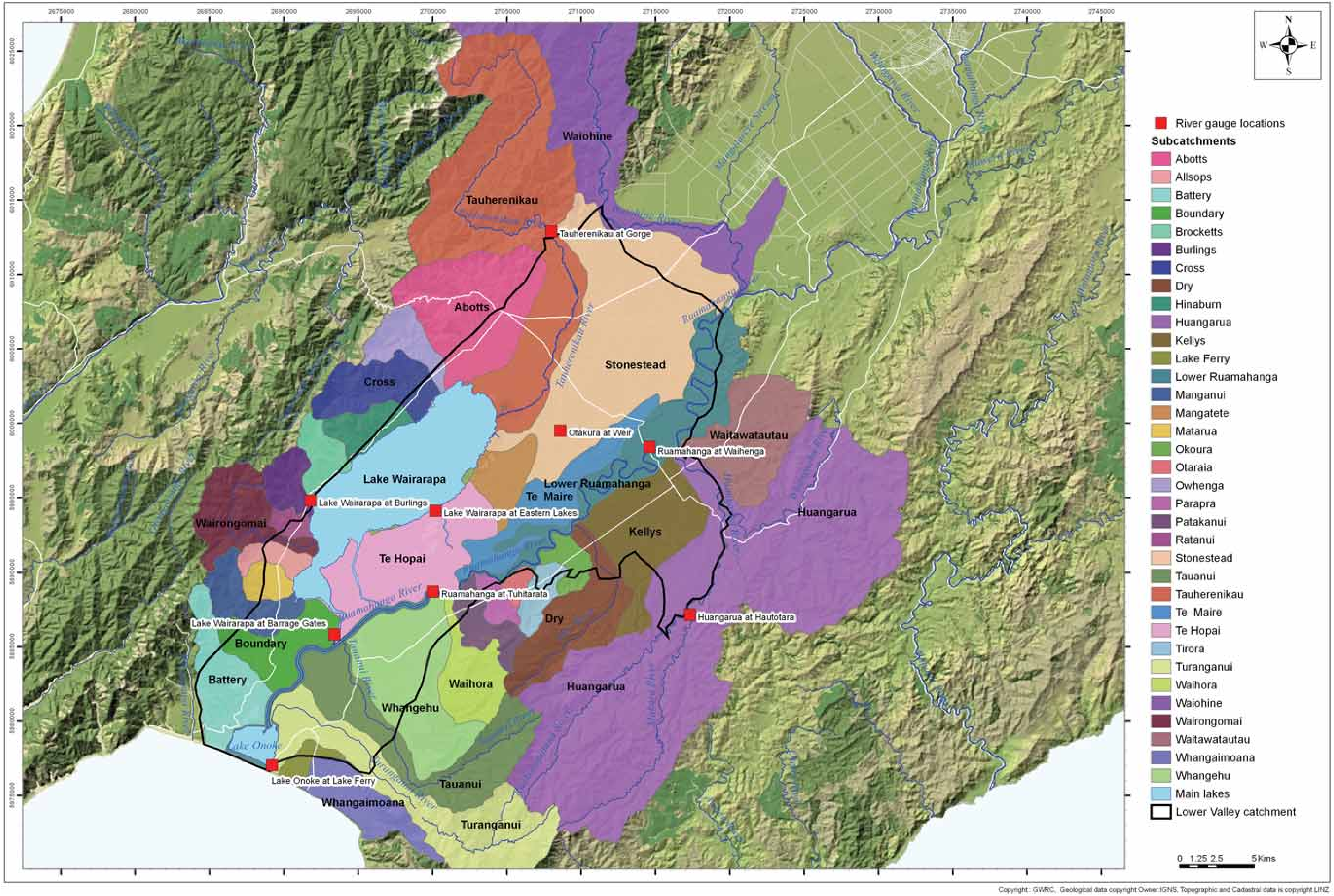


Figure 3.1: Surface water gauge locations and catchment boundaries compared to the Lower Valley catchment boundary (only larger sub-catchments have been labelled in the map)

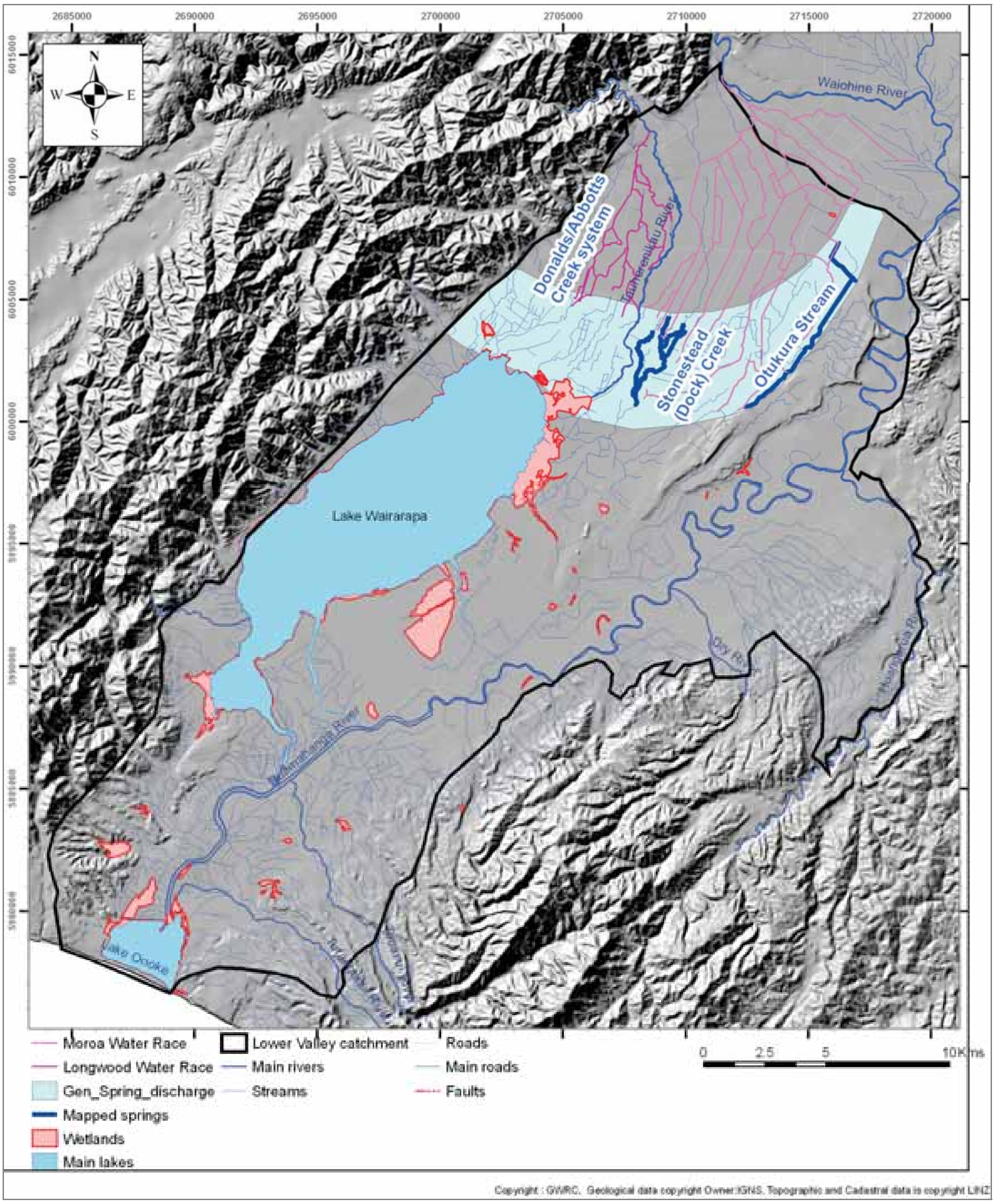


Figure 3.2: Groundwater discharge areas in the Lower Valley catchment. The general discharge area on the lower Tauherenikau fan is highlighted together with principal spring systems. Water race channels are also shown (pink lines).

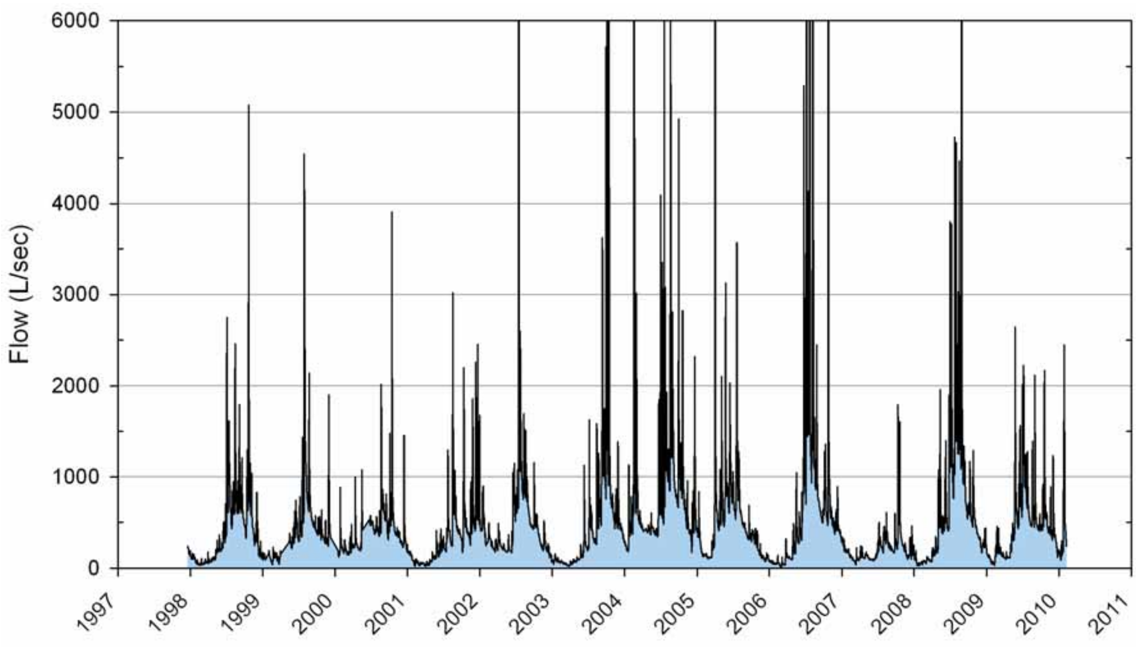


Figure 3.3: Flow in the Otukura Stream (at Weir) between 1998 and 2010

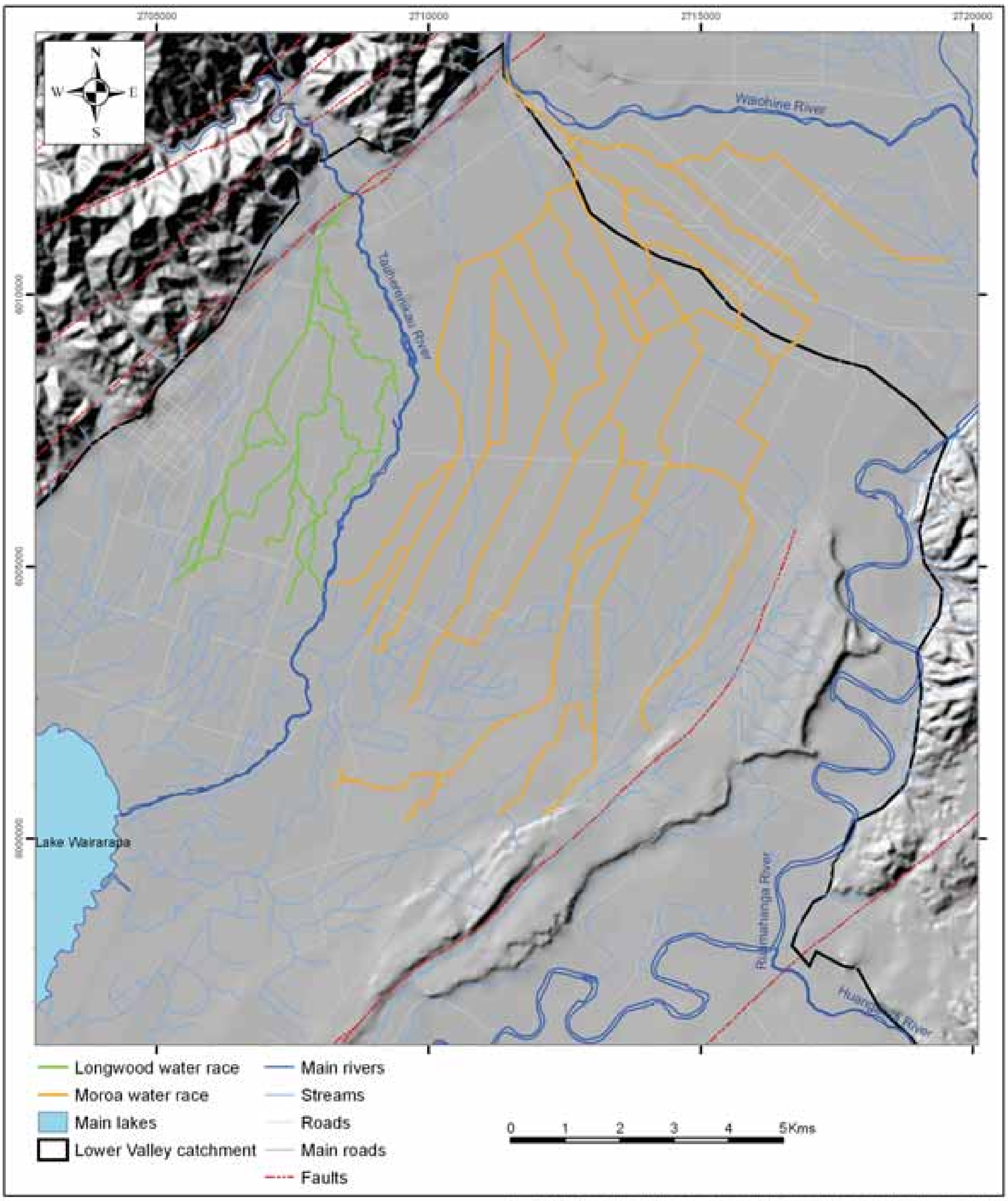


Figure 3.4: Longwood and Moroa Water Race networks on the Tauherenikau fan

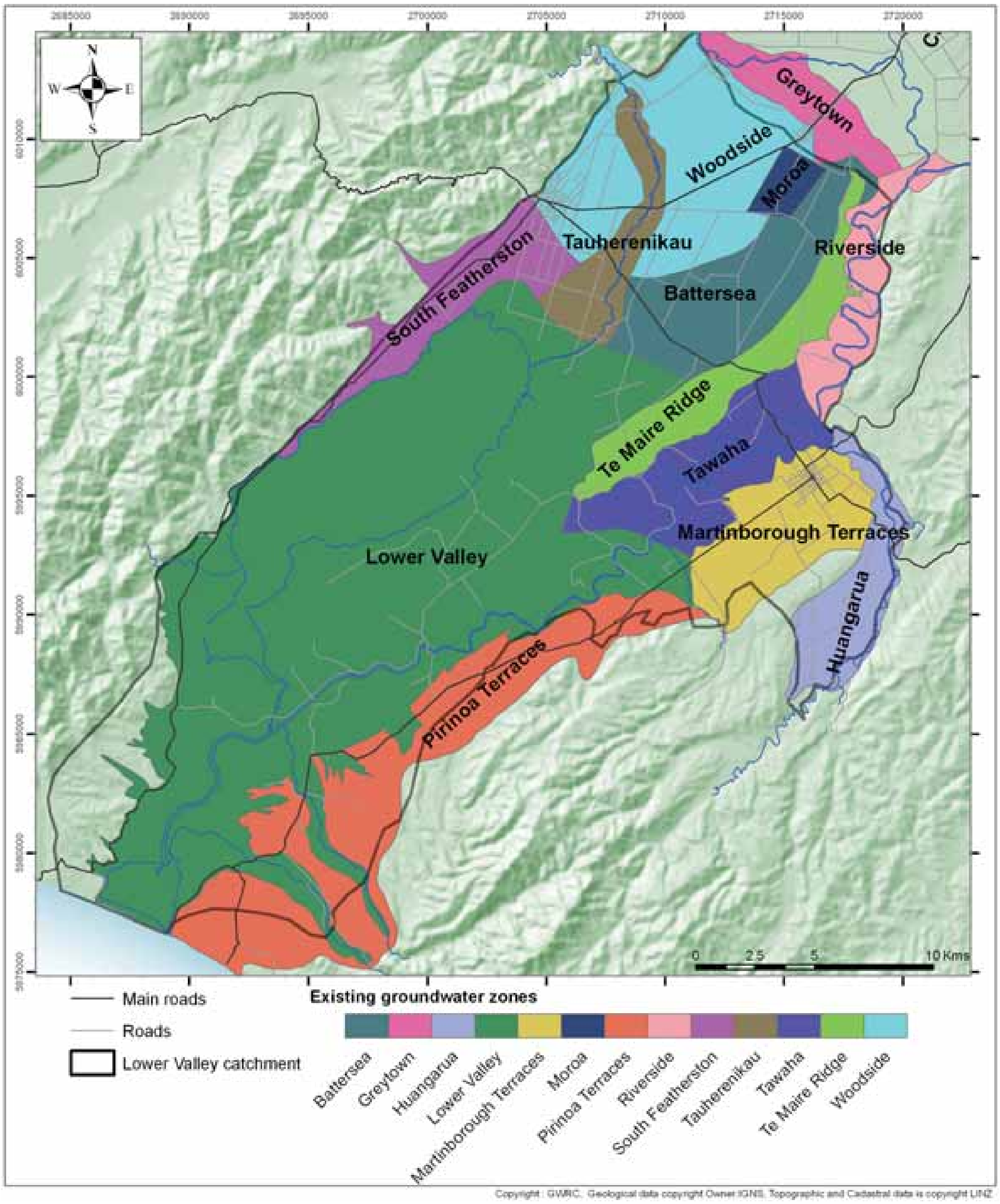


Figure 4.1: Existing groundwater zones identified in Greater Wellington's Regional Freshwater Plan (WRC 1999). Note that some groundwater zones are partially within the Middle Valley catchment.

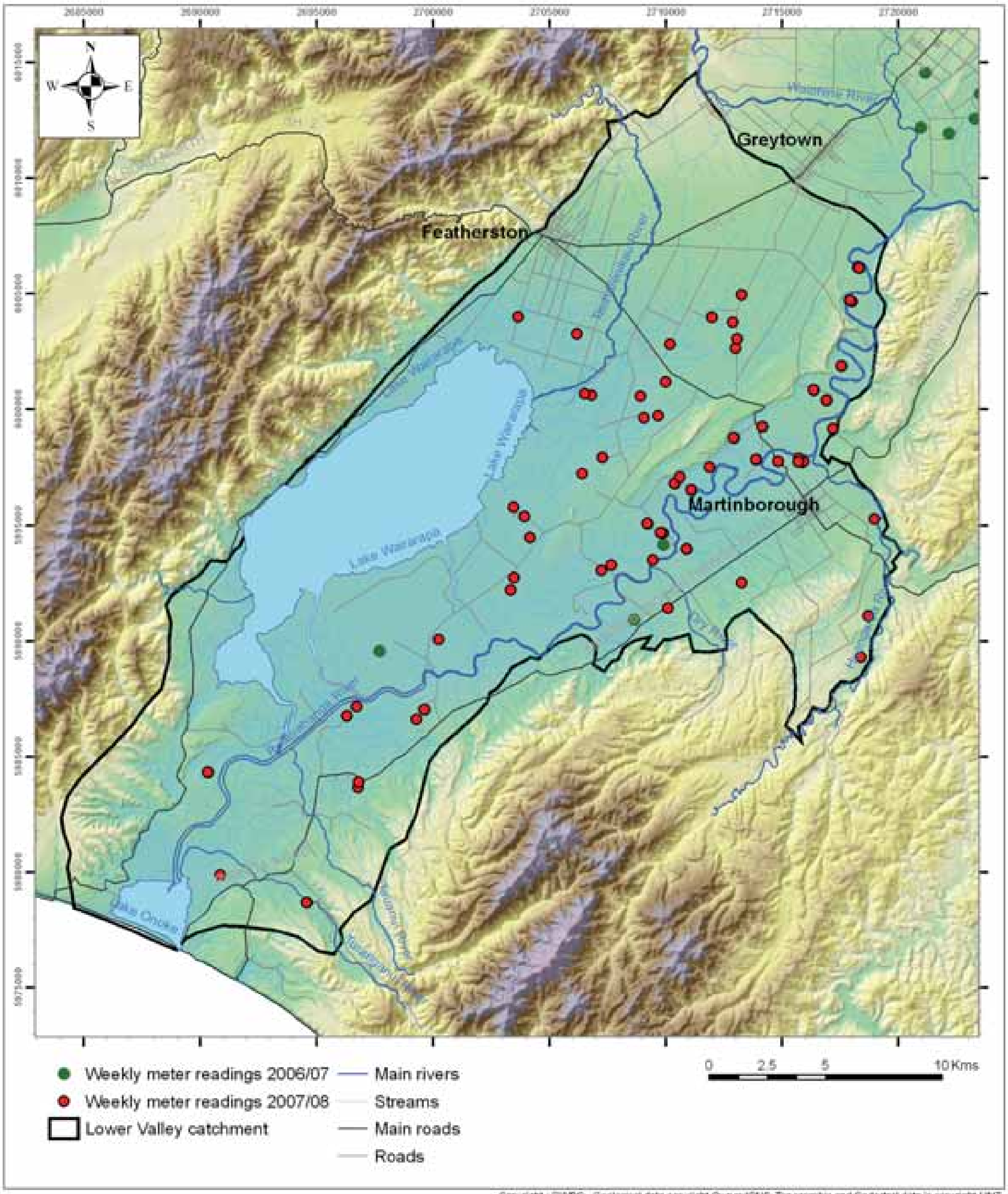
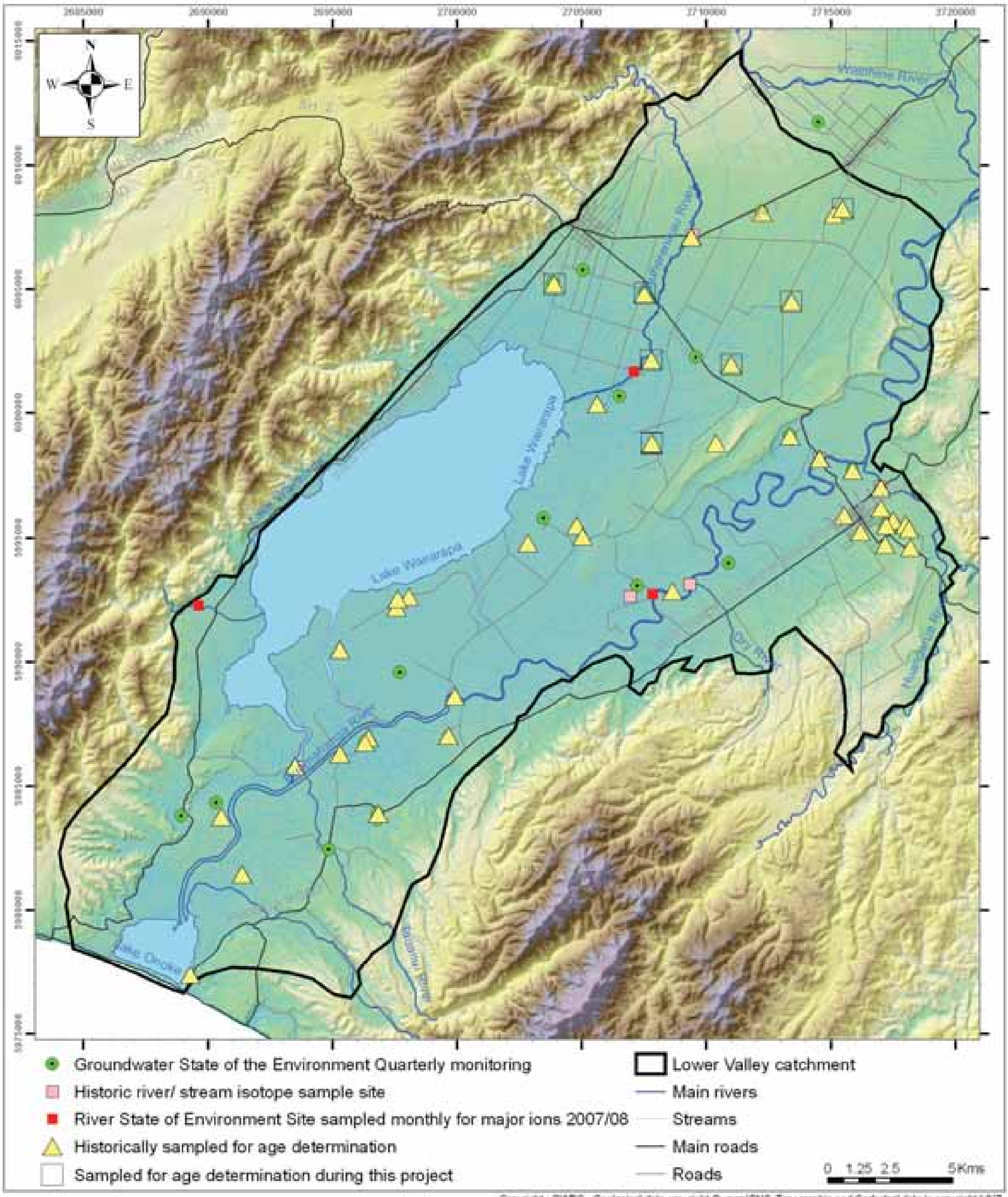


Figure 5.1: Water meter survey locations (2006/07 and 2007/08) in the Lower Valley catchment



5.2: Lower Valley catchment groundwater bores with hydrochemistry data

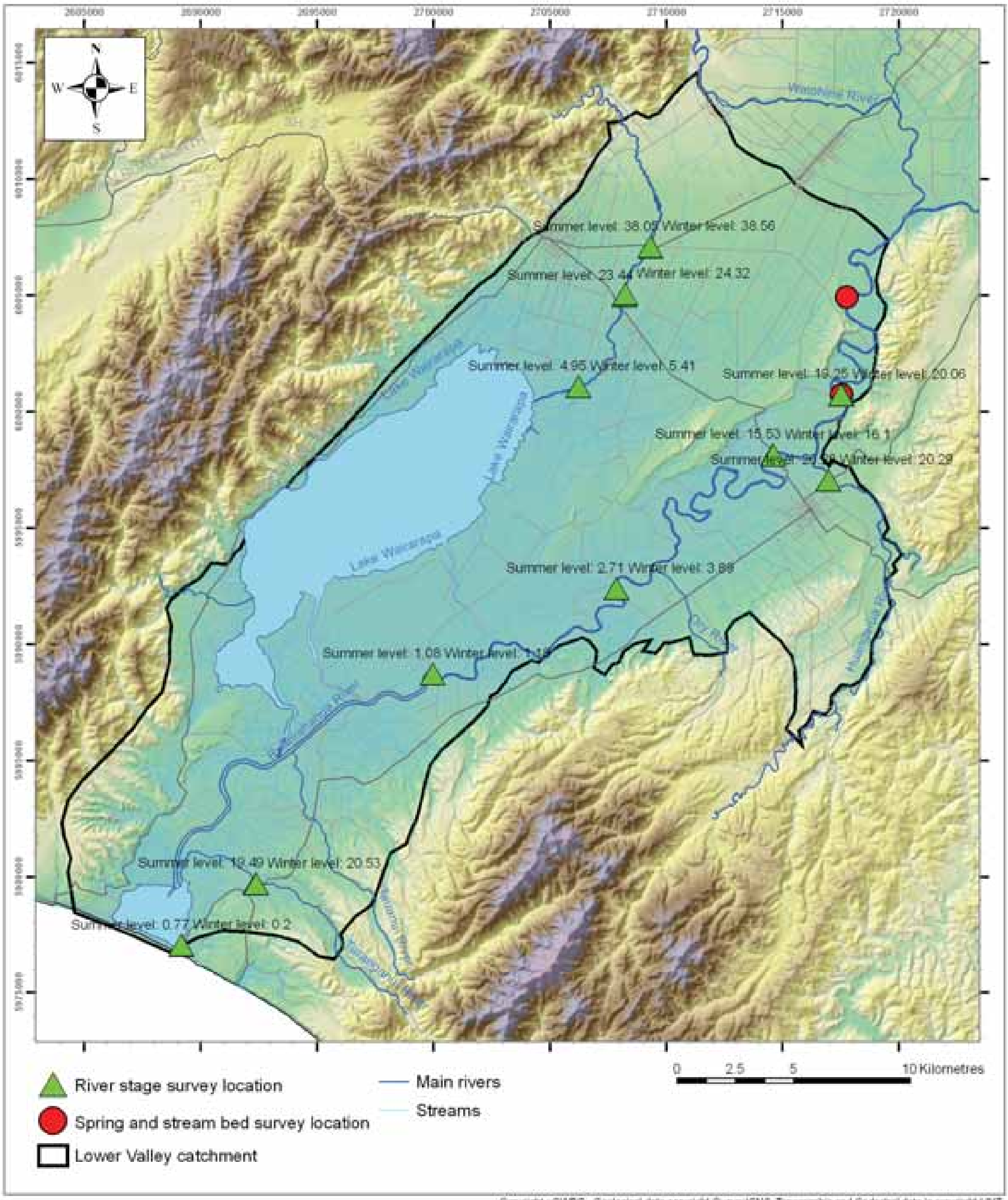
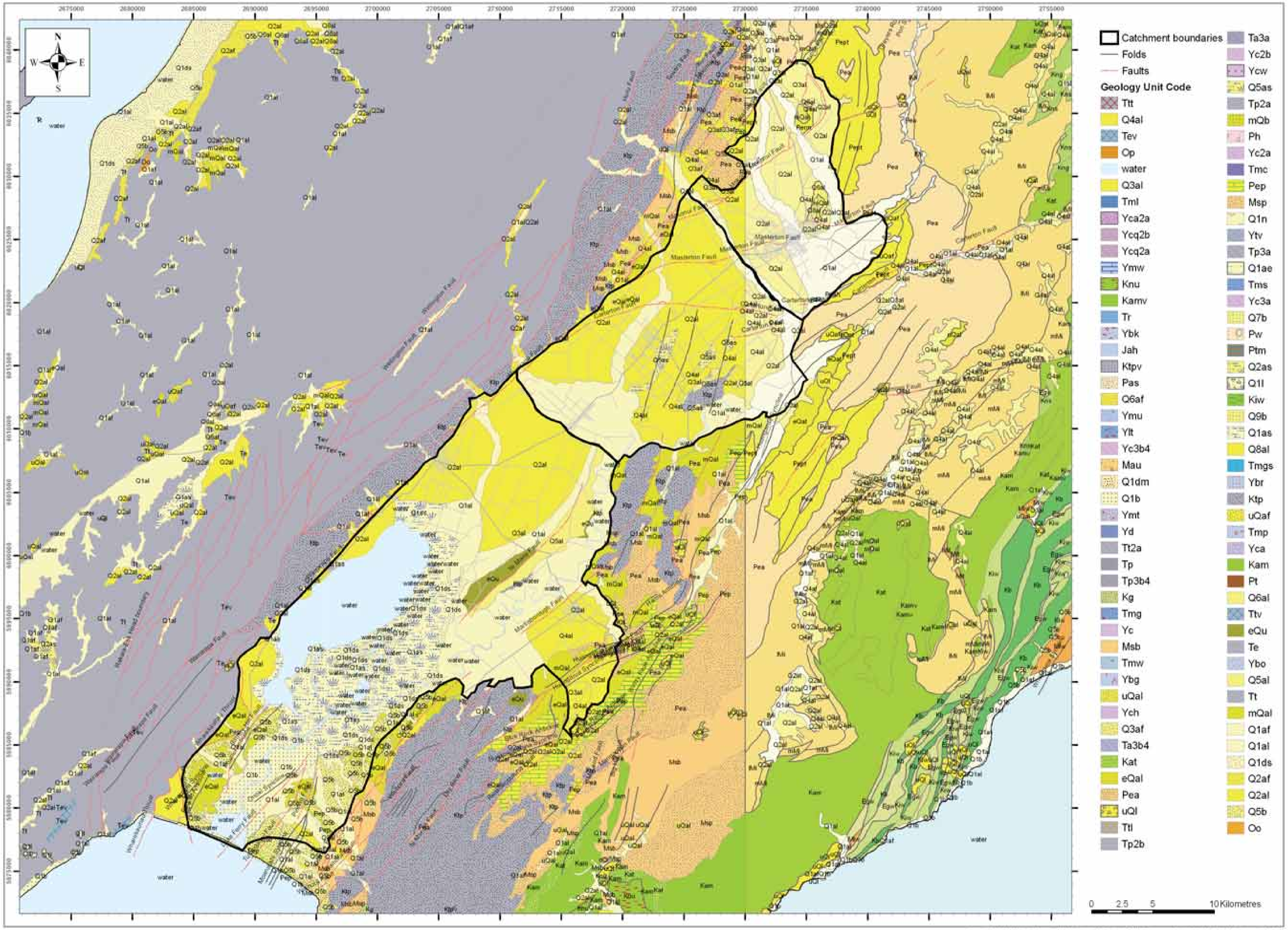


Figure 5.3: Surface water GPS survey locations in the Lower Valley catchment



(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

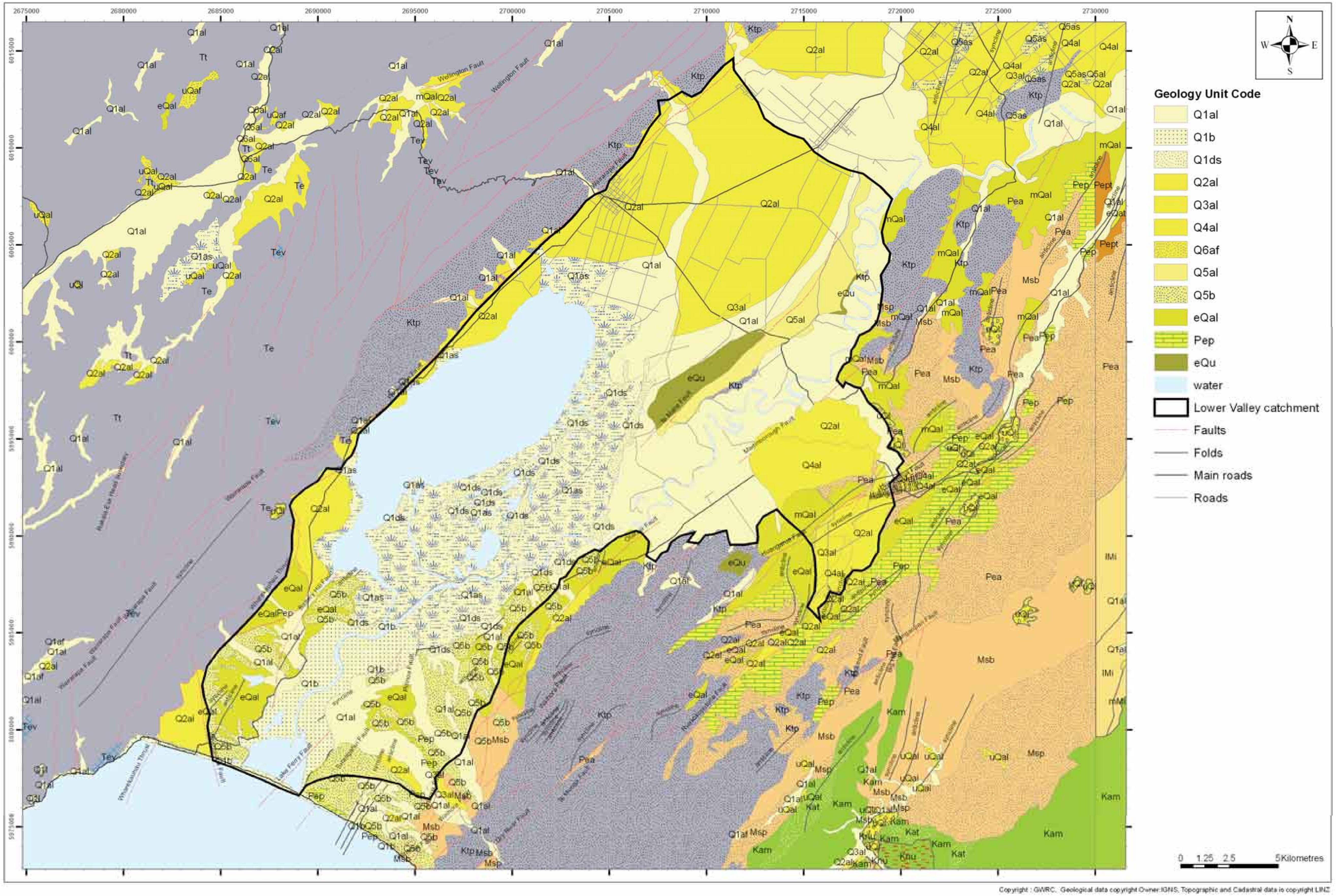


Figure 6.2: Detailed geology of the Lower Valley catchment (Source: GNS 2001)

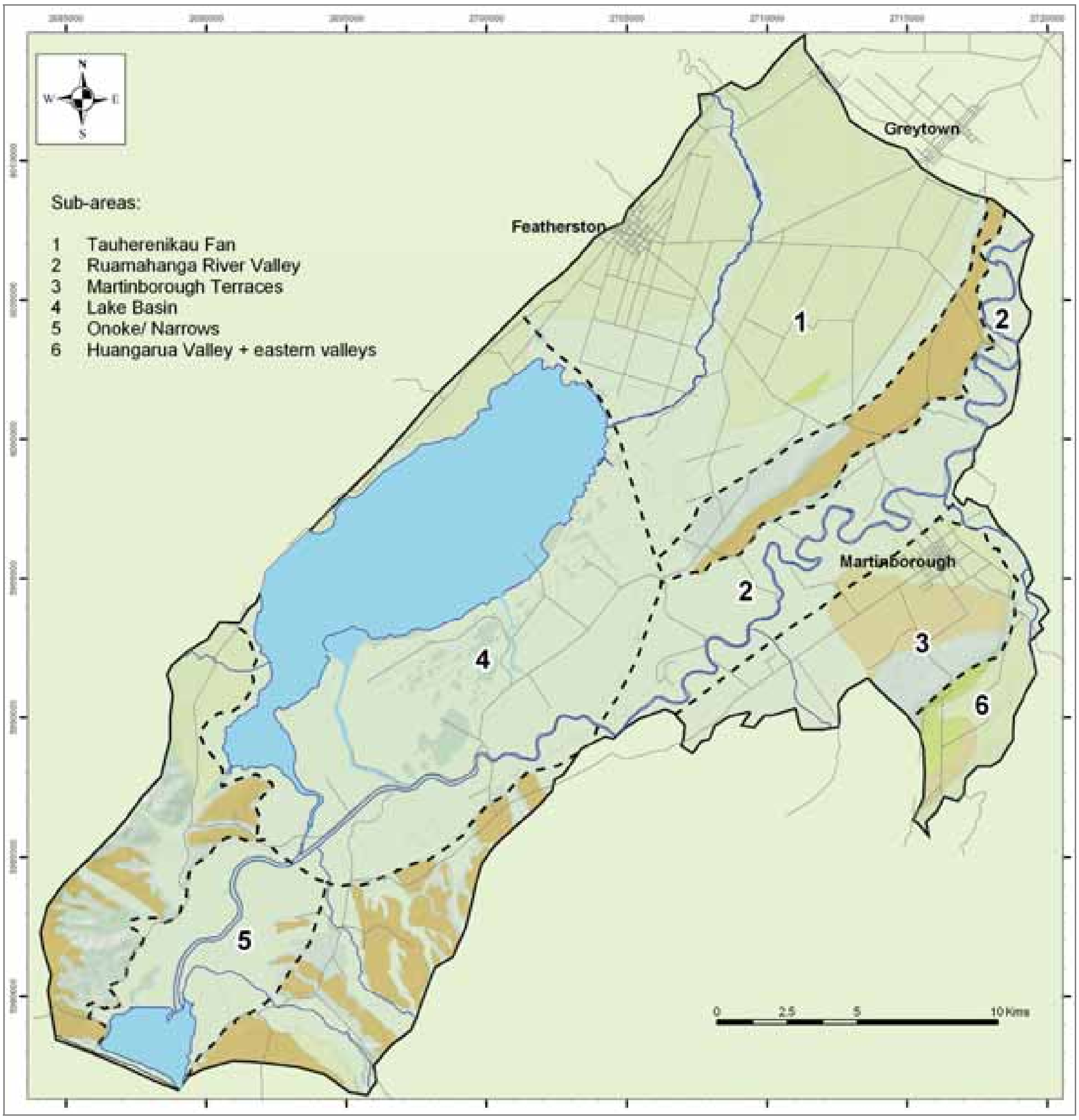


Figure 6.3: Hydrostratigraphic sub-areas of the Lower Valley catchment

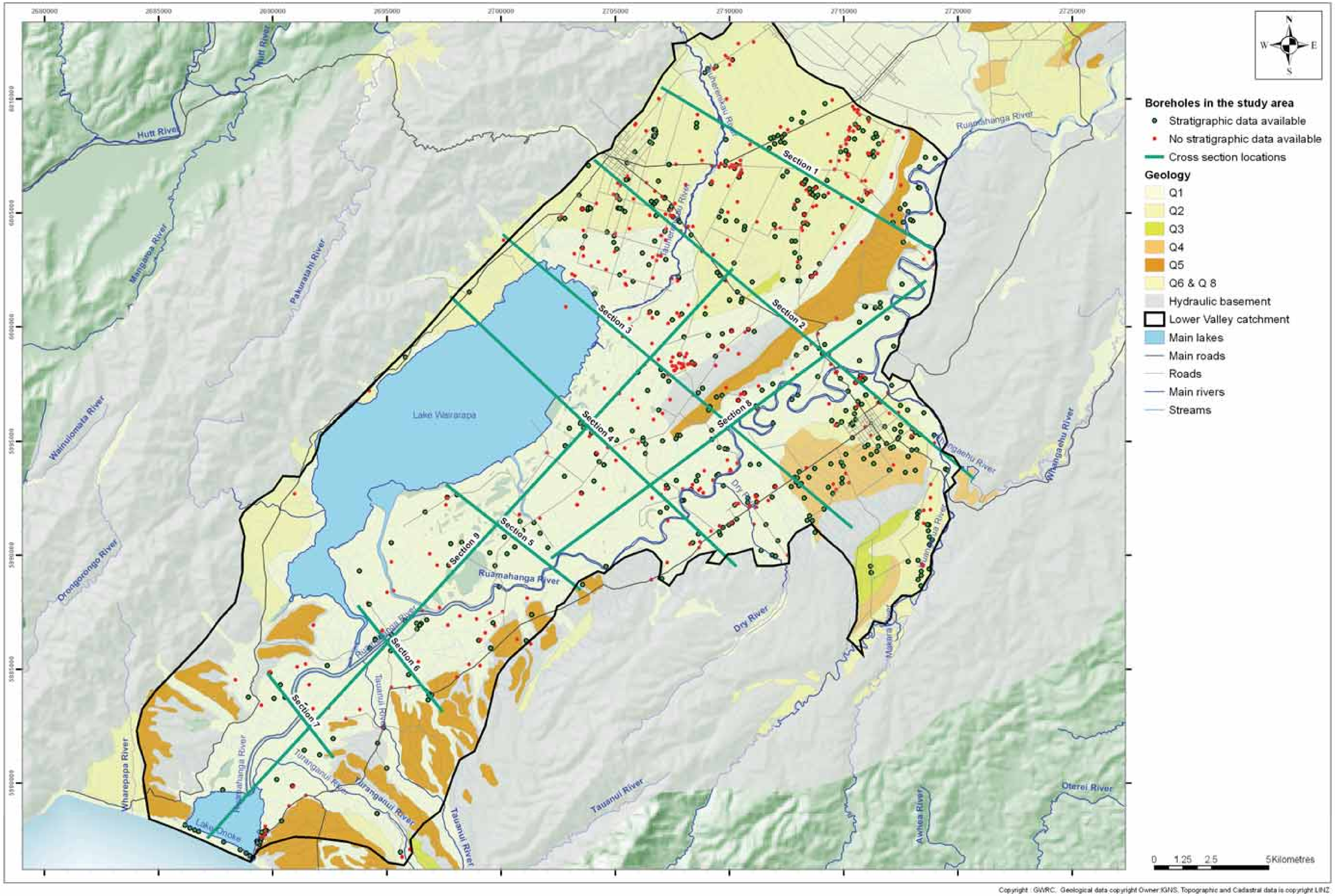


Figure 6.4: Locations of geological cross sections and bores in the Lower Valley catchment. Late Quaternary geology is also shown.

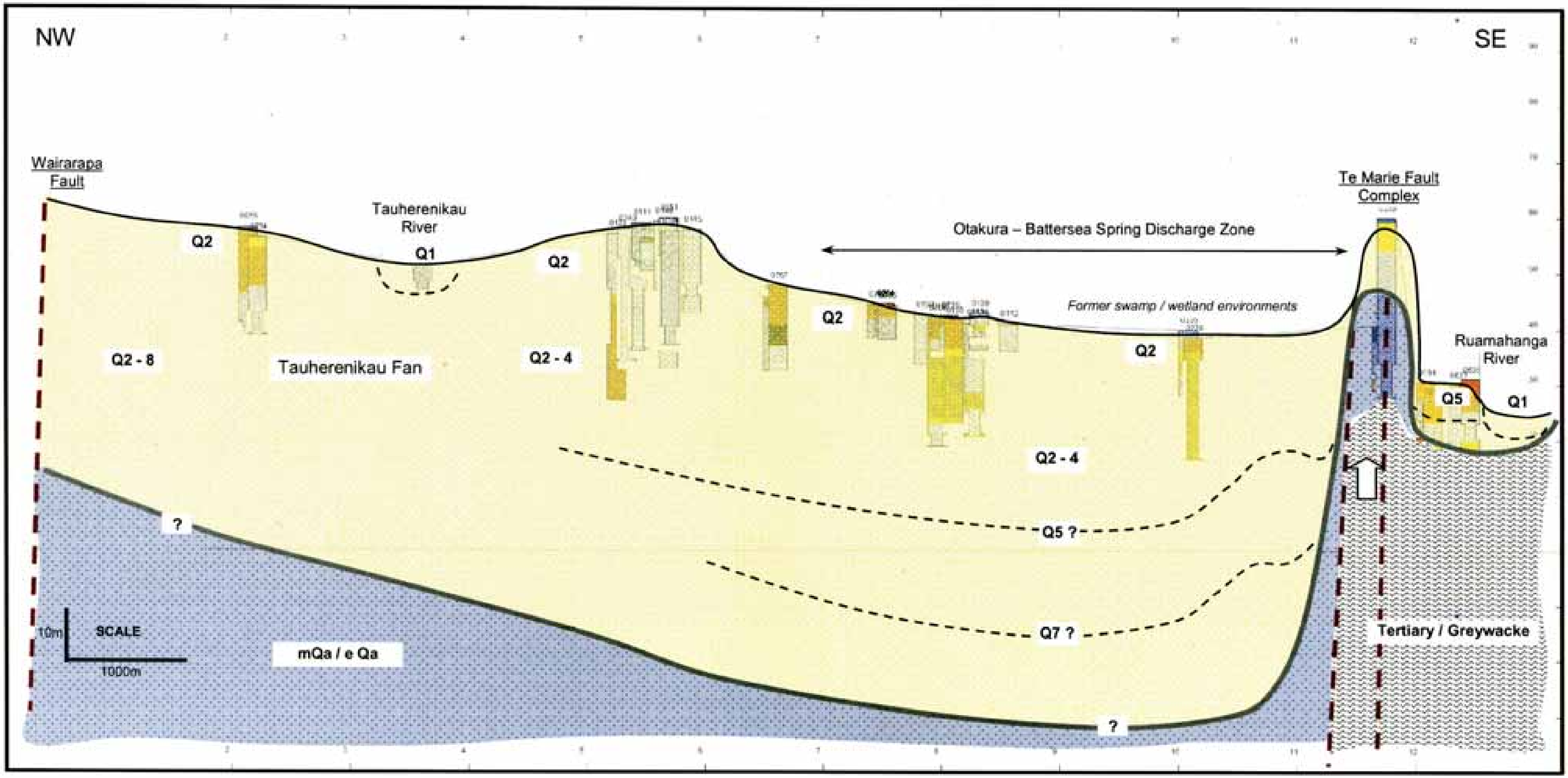


Figure 6.5: Geological cross section – Line 1, Lower Valley catchment

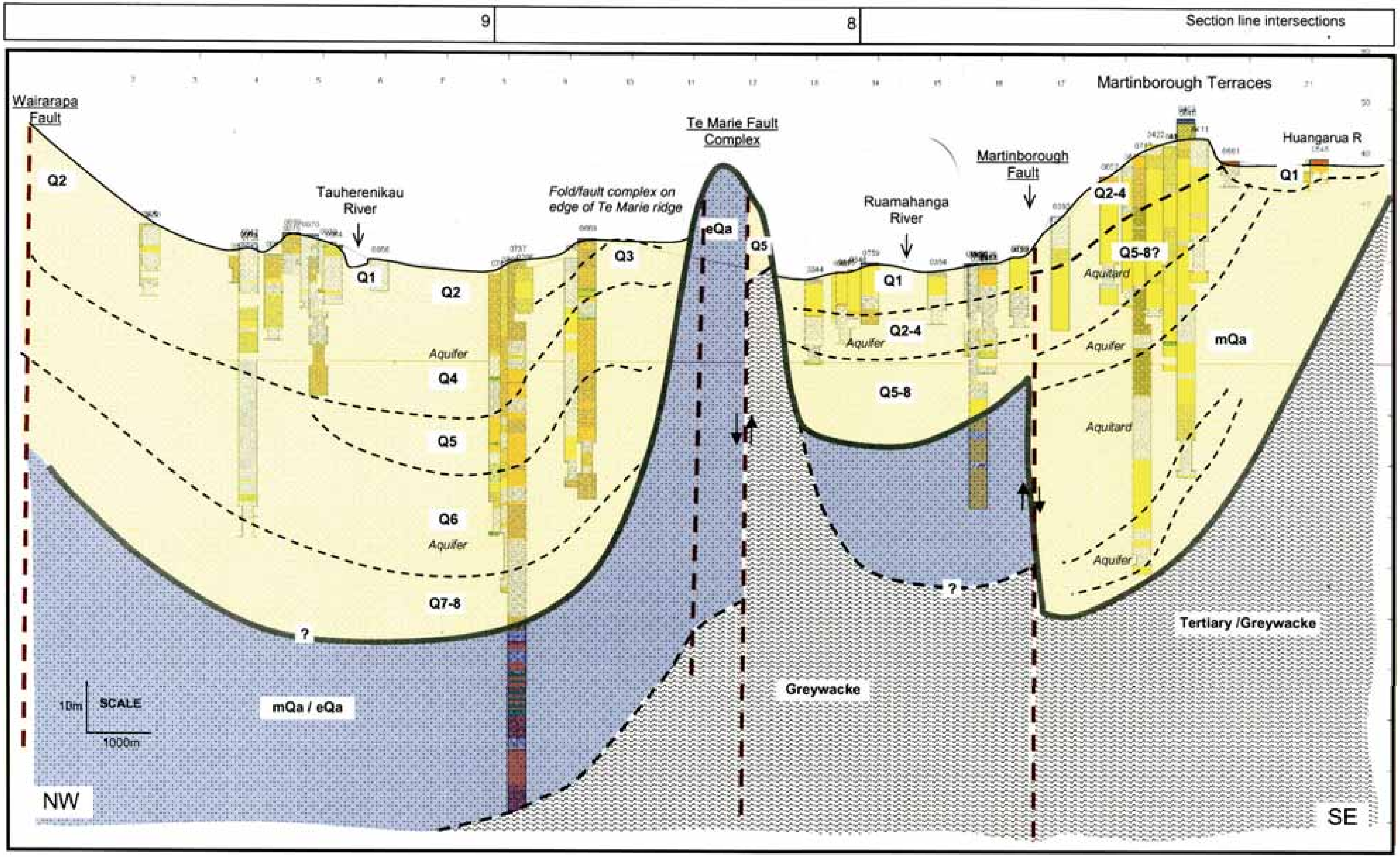


Figure 6.6: Geological cross section – Line 2, Lower Valley catchment

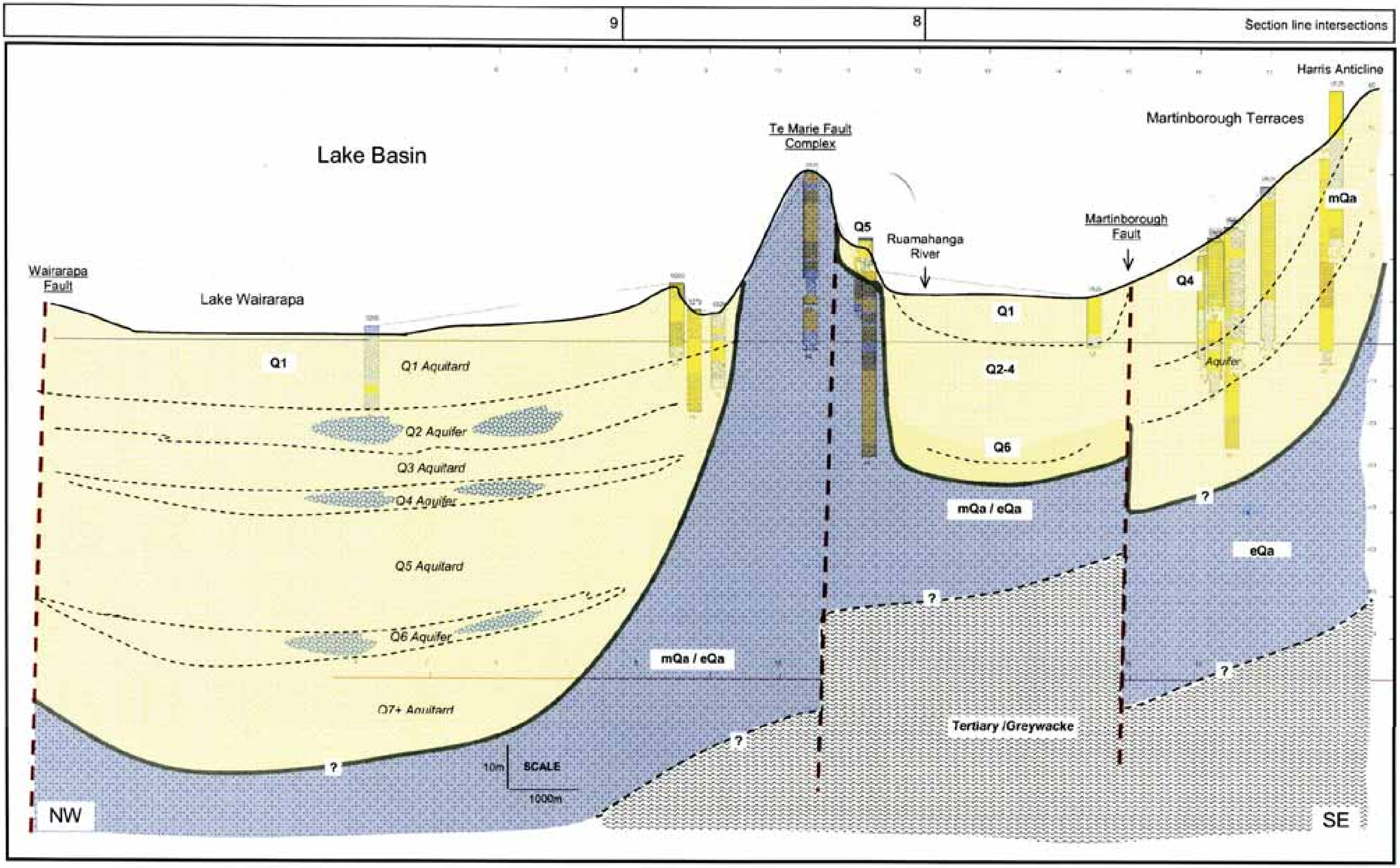


Figure 6.7: Geological cross section – Line 3, Lower Valley catchment

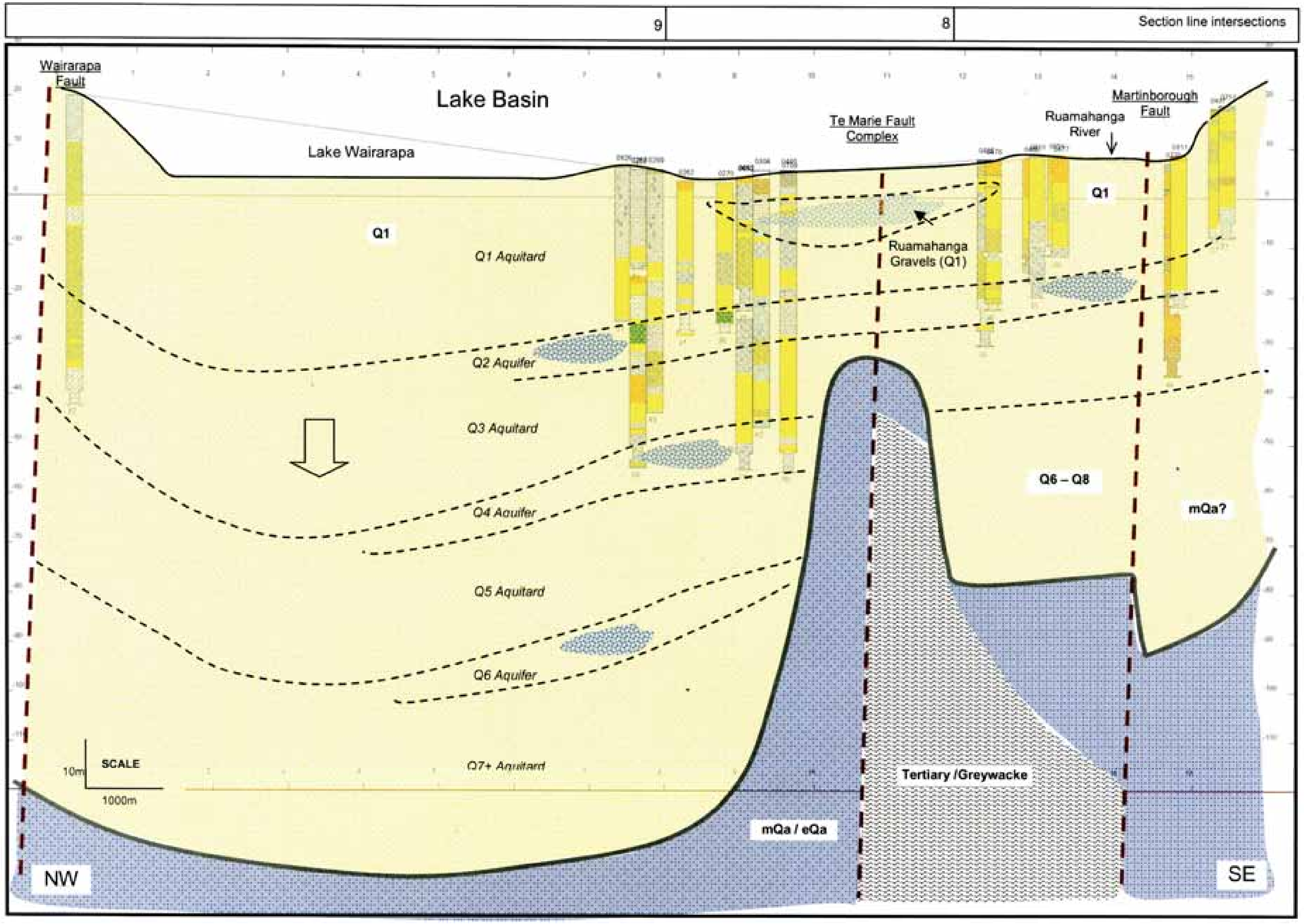


Figure 6.8: Geological cross section – Line 4, Lower Valley catchment

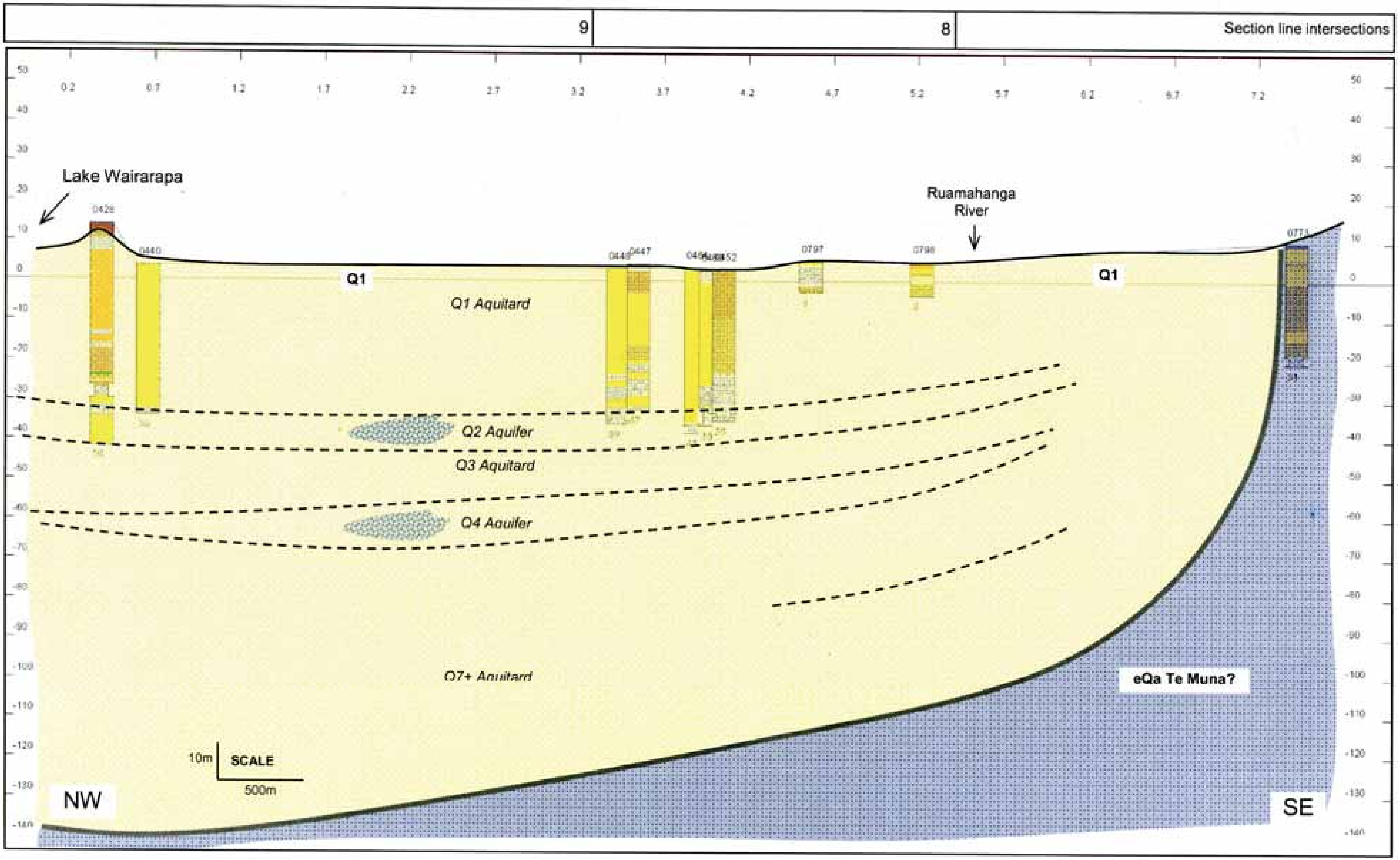


Figure 6.9: Geological cross section – Line 5, Lower Valley catchment

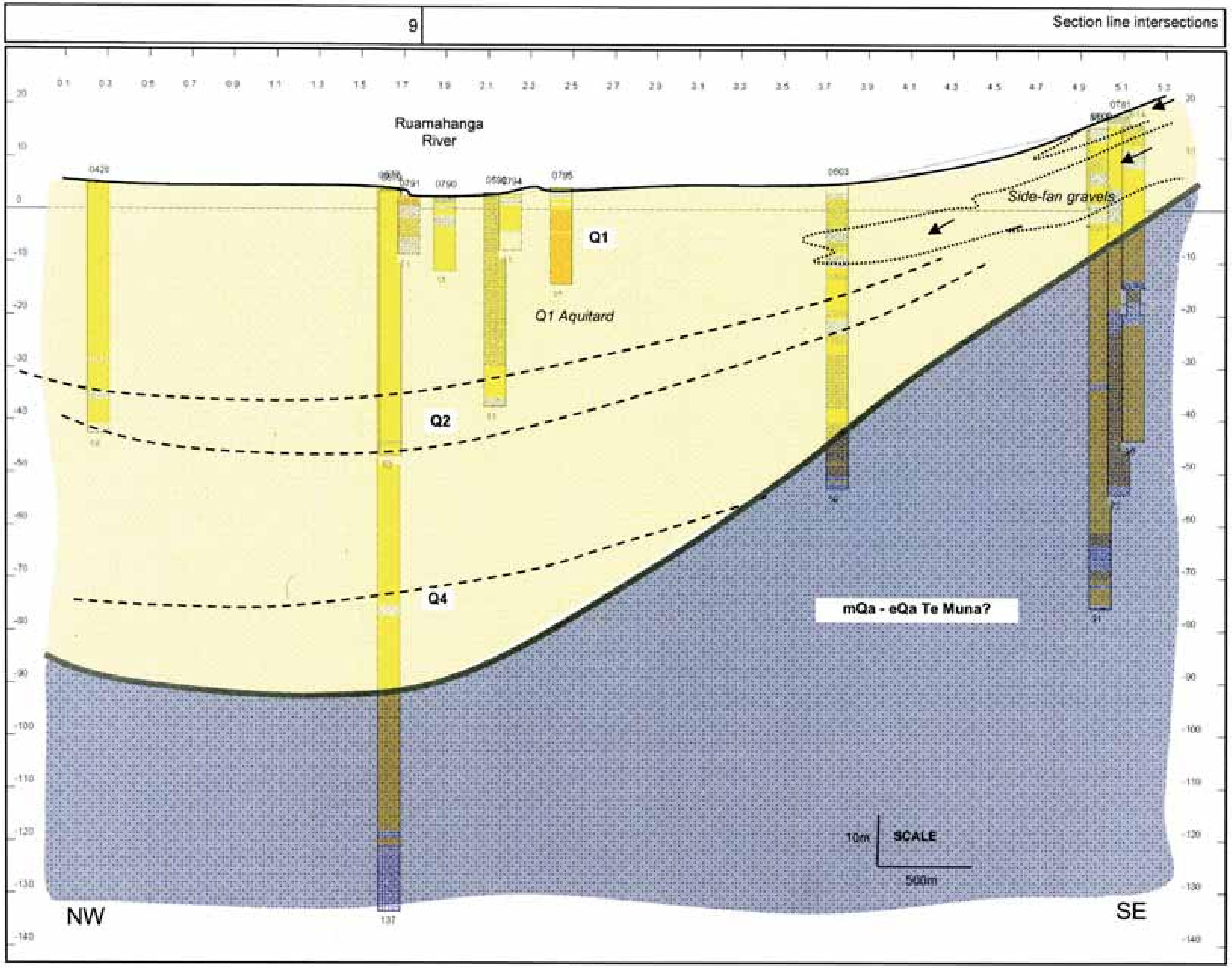


Figure 6.10: Geological cross section – Line 6, Lower Valley catchment

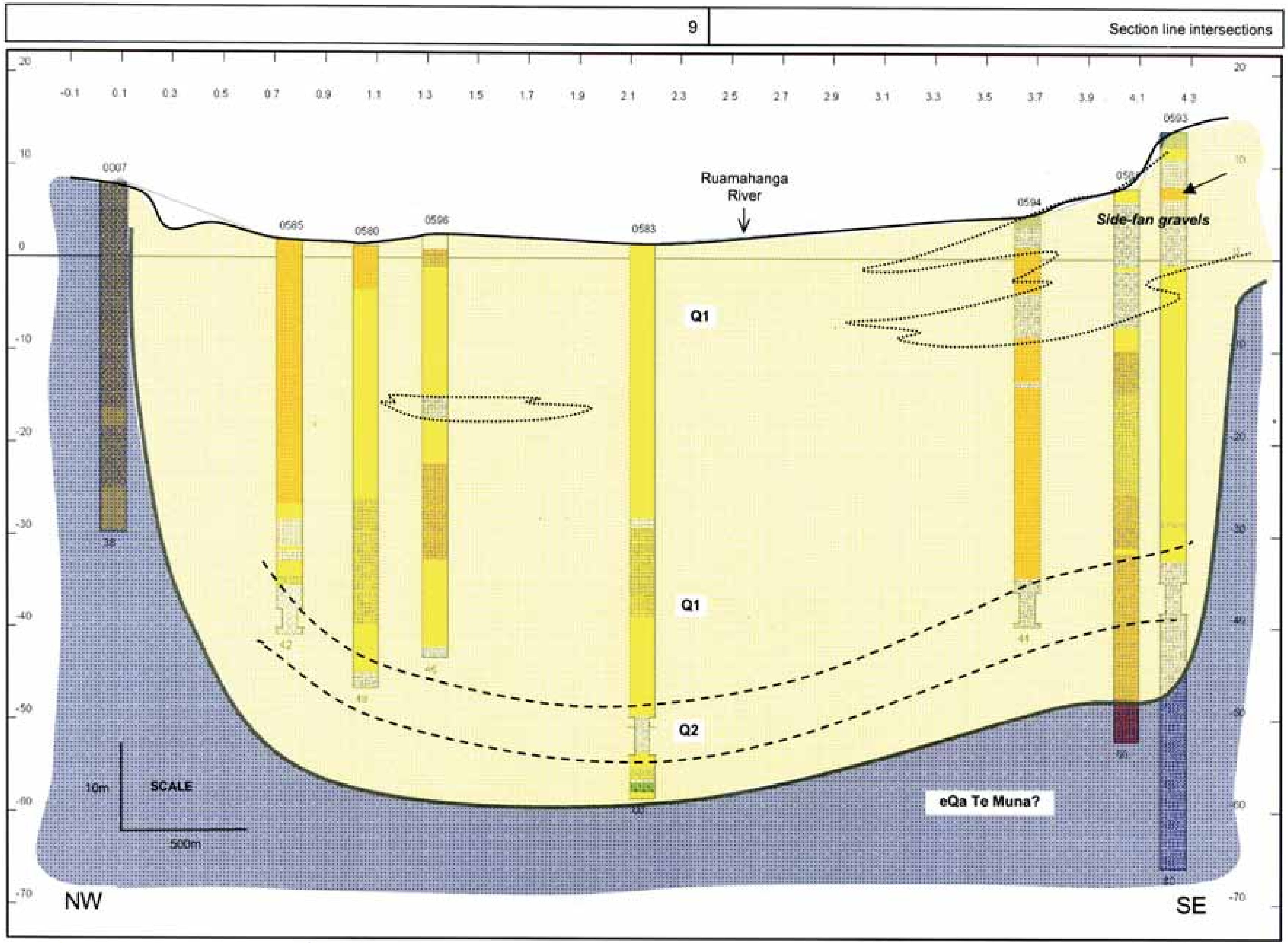


Figure 6.11: Geological cross section – Line 7, Lower Valley catchment

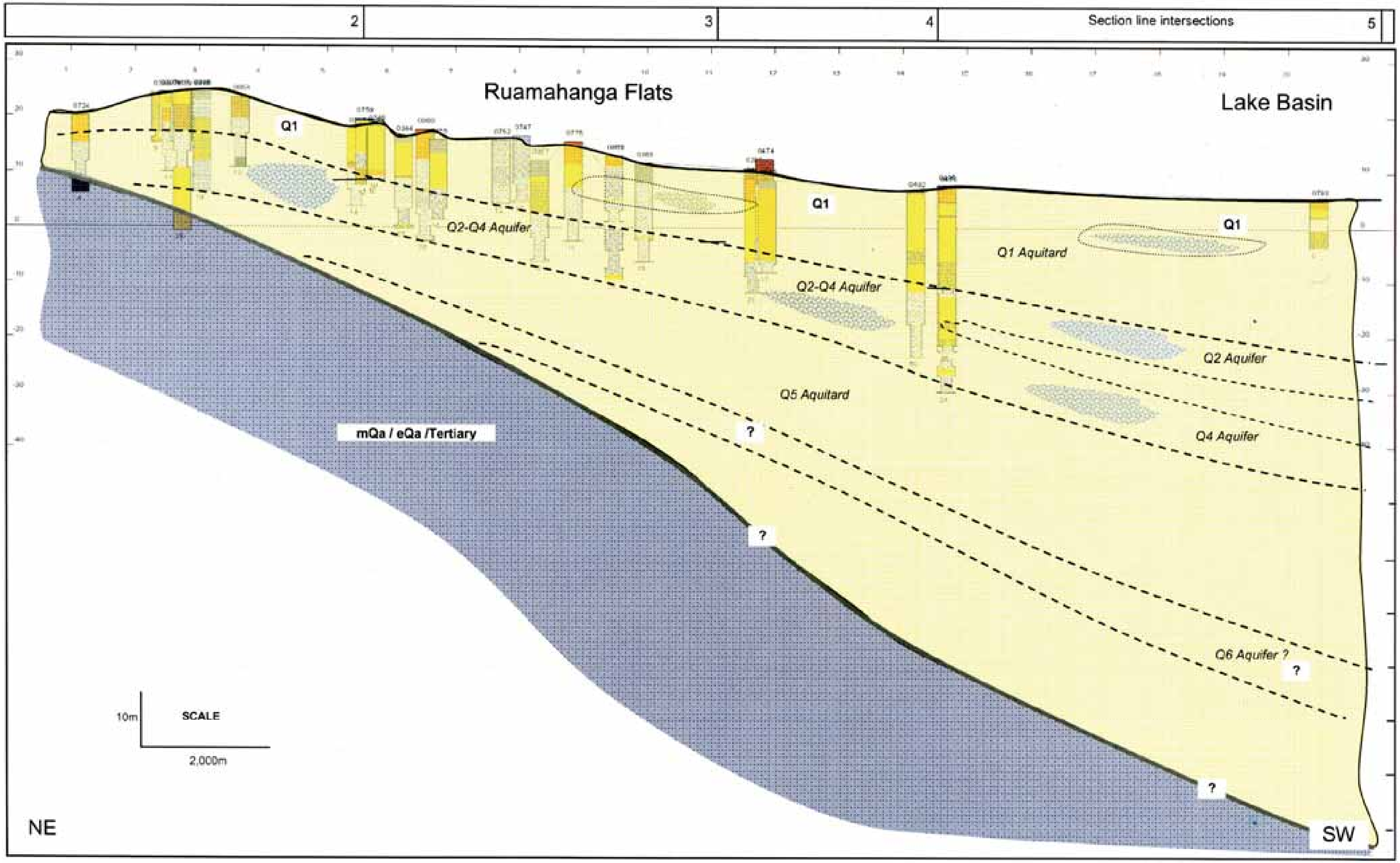


Figure 6.12: Geological cross section – Line 8, Lower Valley catchment

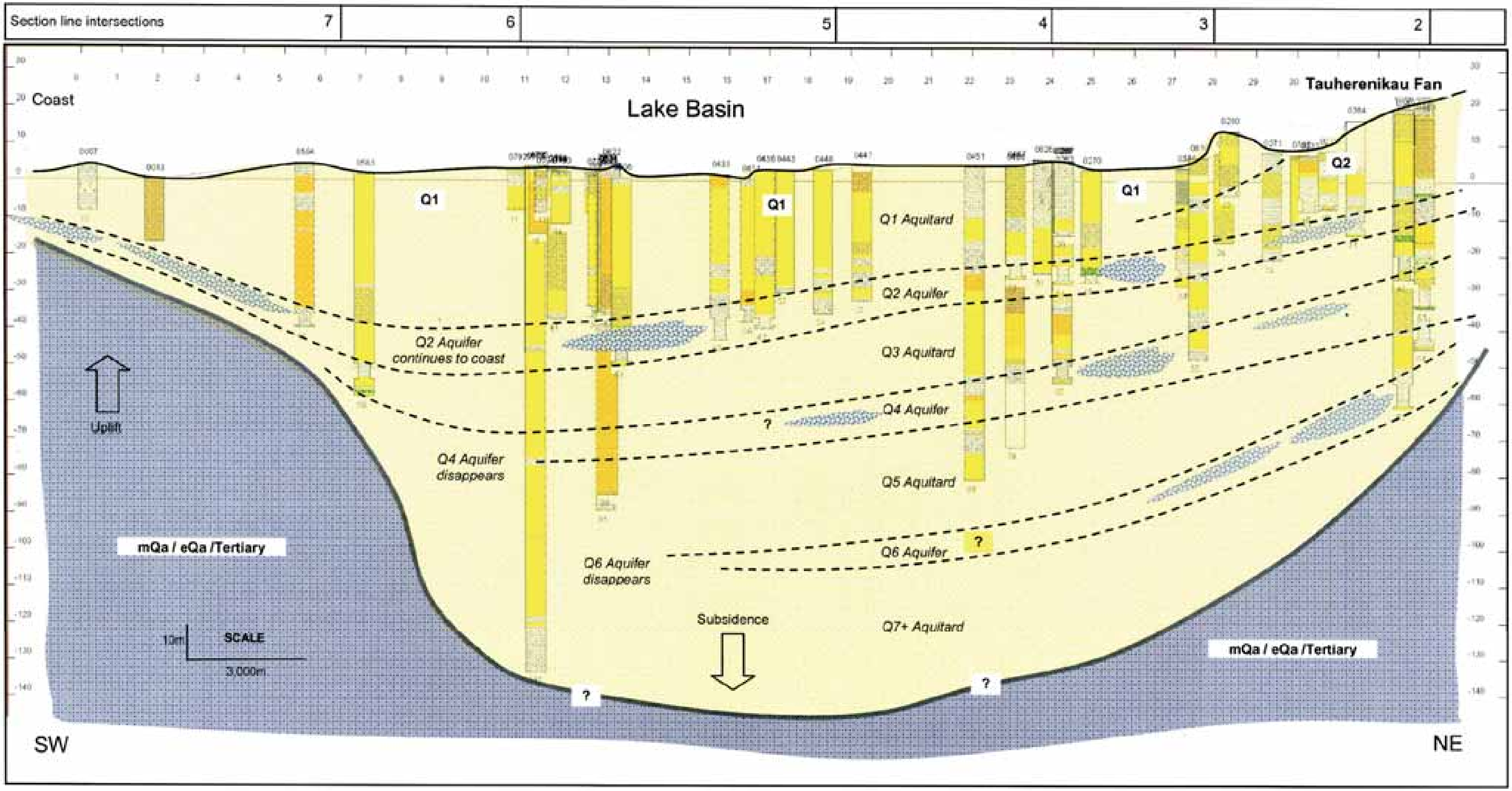


Figure 6.13: Geological cross section – Line 9 (long valley), Lower Valley catchment

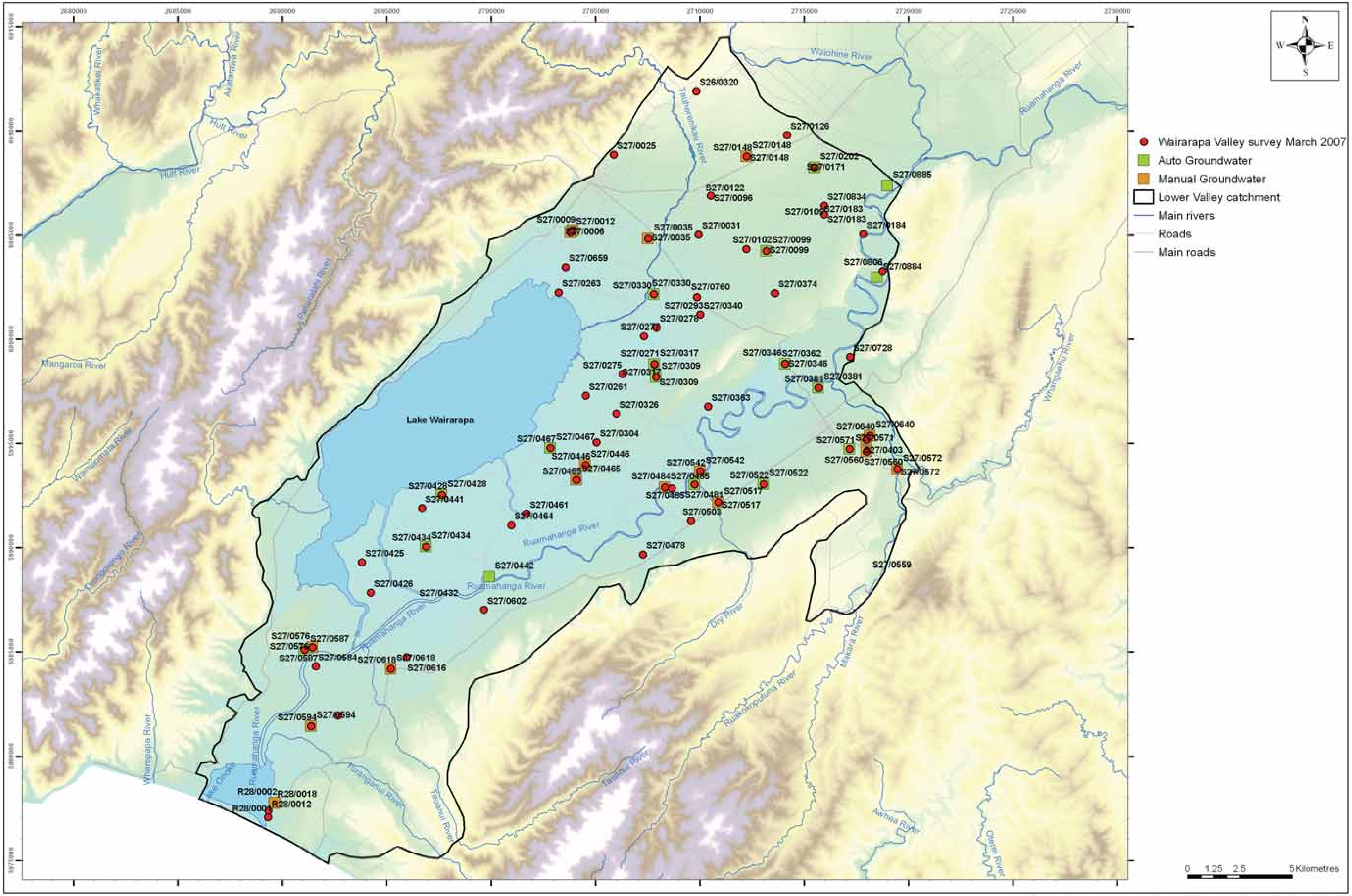


Figure 7.1: Groundwater level monitoring sites within the Lower Valley catchment

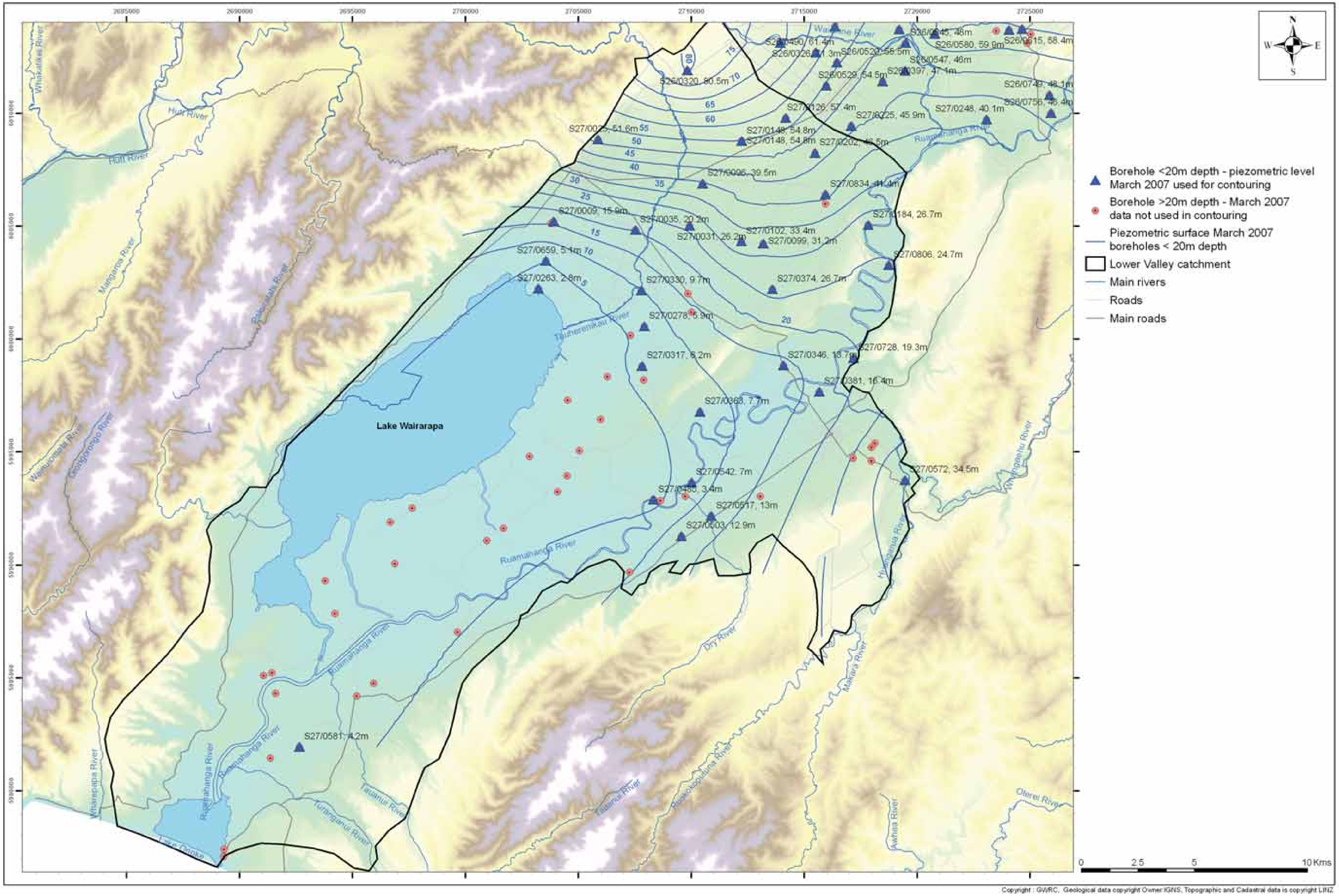


Figure 7.2A: Piezometric contours (March 2007) for the Lower Valley catchment based on data from bores <20 m in depth. Data points used to develop the contours are shown.

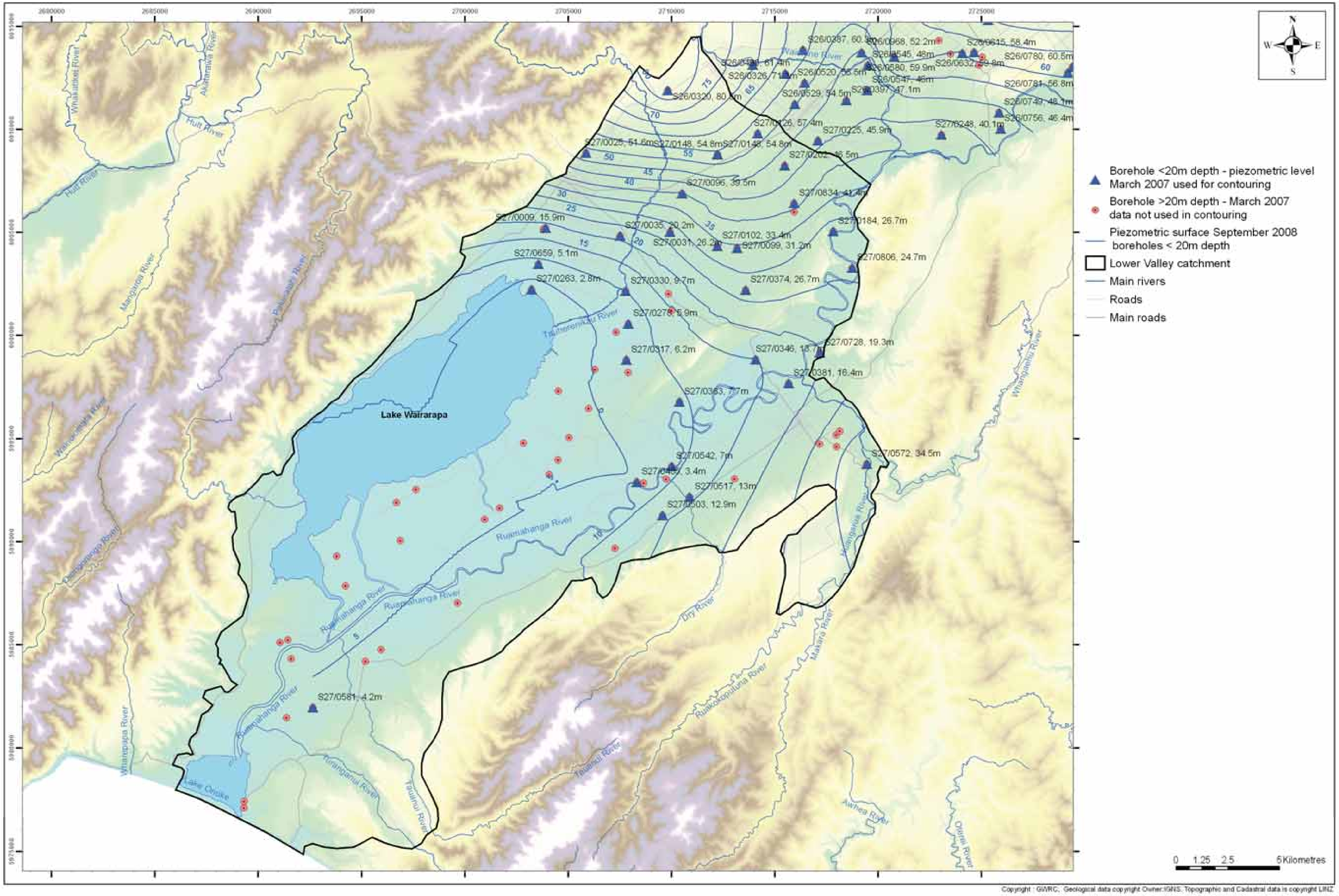


Figure 7.2B: Piezometric contours (September 2008) for the Lower Valley catchment based on data from bores <20 m in depth. Data points used to develop the contours are shown.

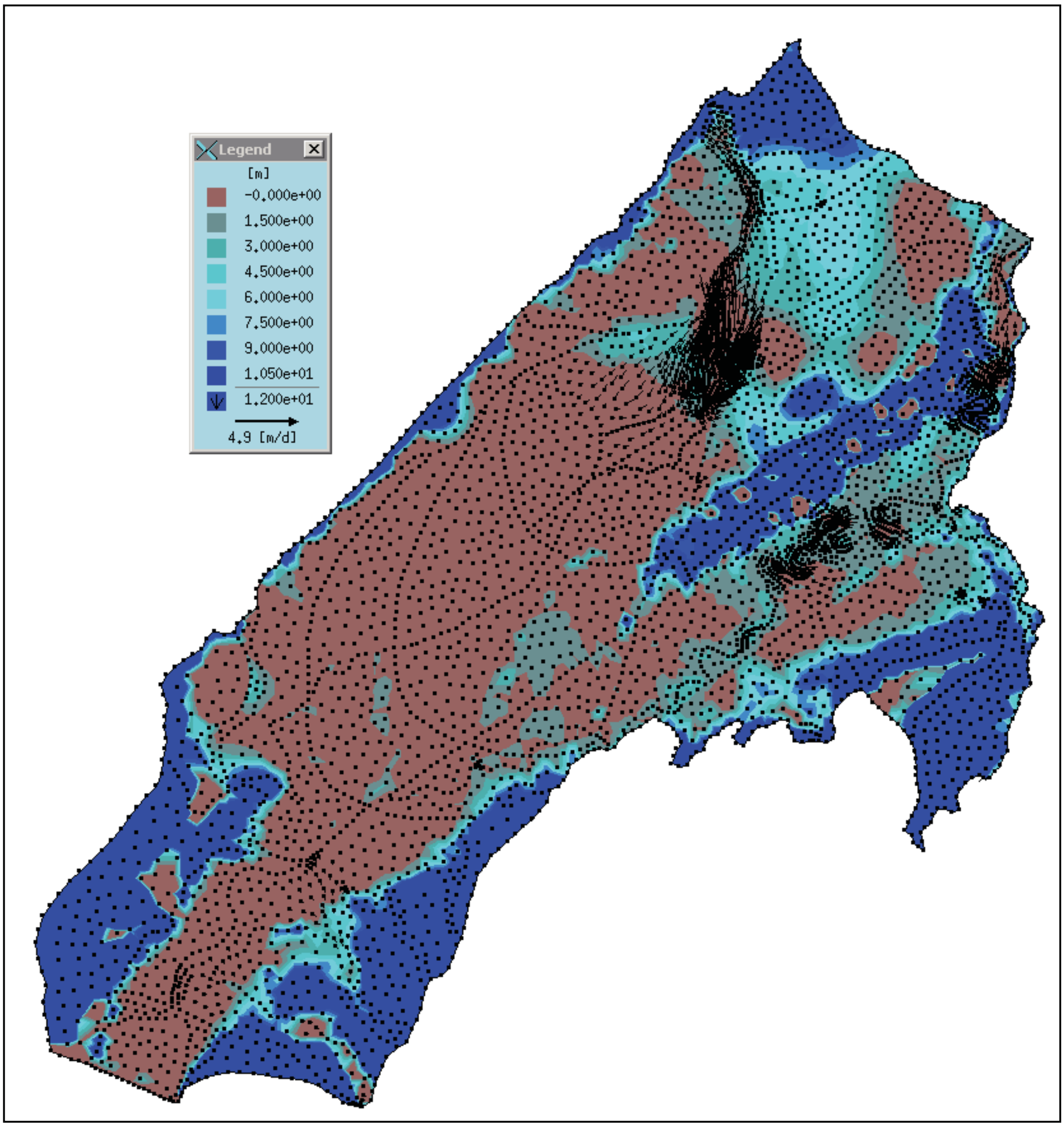


Figure 7.3: Depth to groundwater level map to help identify general recharge areas where groundwater level is below ground level – shown by a positive value in the map (grey-blue). The upper parts of the Tauherenikau fan, Te Marie Ridge, the Harris anticline and the Onoke/Pirinoa terraces are potential recharge areas. The brown shading shows areas where groundwater level is above ground surface and therefore indicates either groundwater discharge (Otukura and lower Tauherenikau – Featherston areas) or confined artesian conditions (Lake basin, Onoke and Martinborough terrace areas).

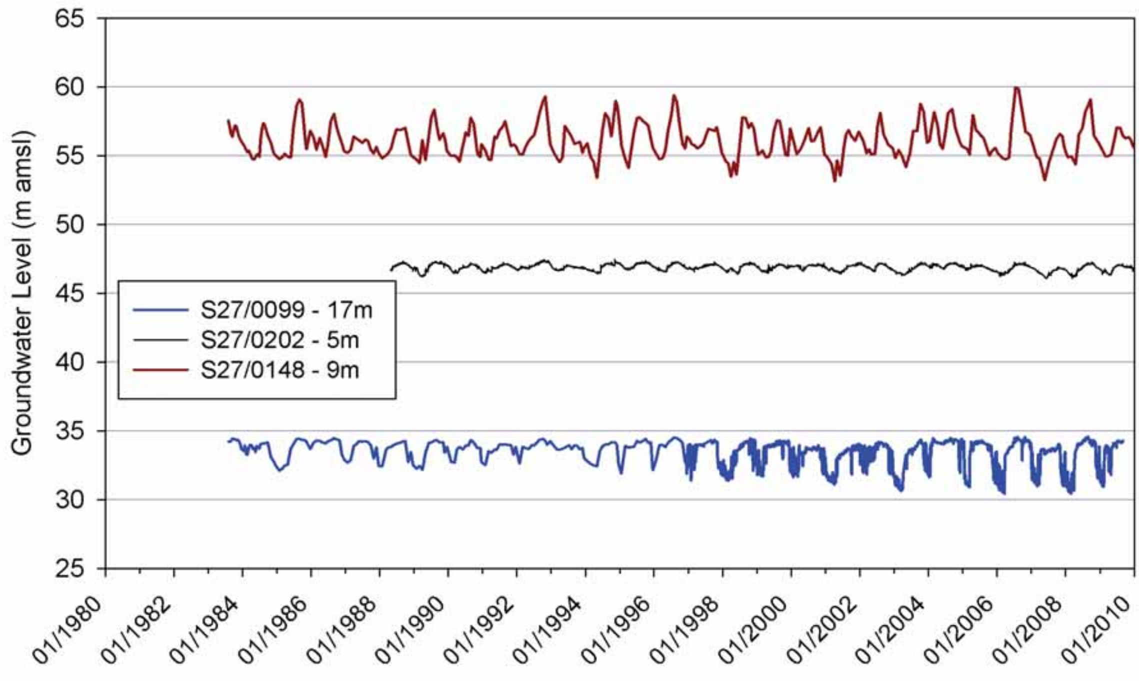


Figure 7.4: Groundwater level hydrographs for sub-area 1 (Tauherenikau fan) – bores S27/0099, S27/0202 and S27/0148

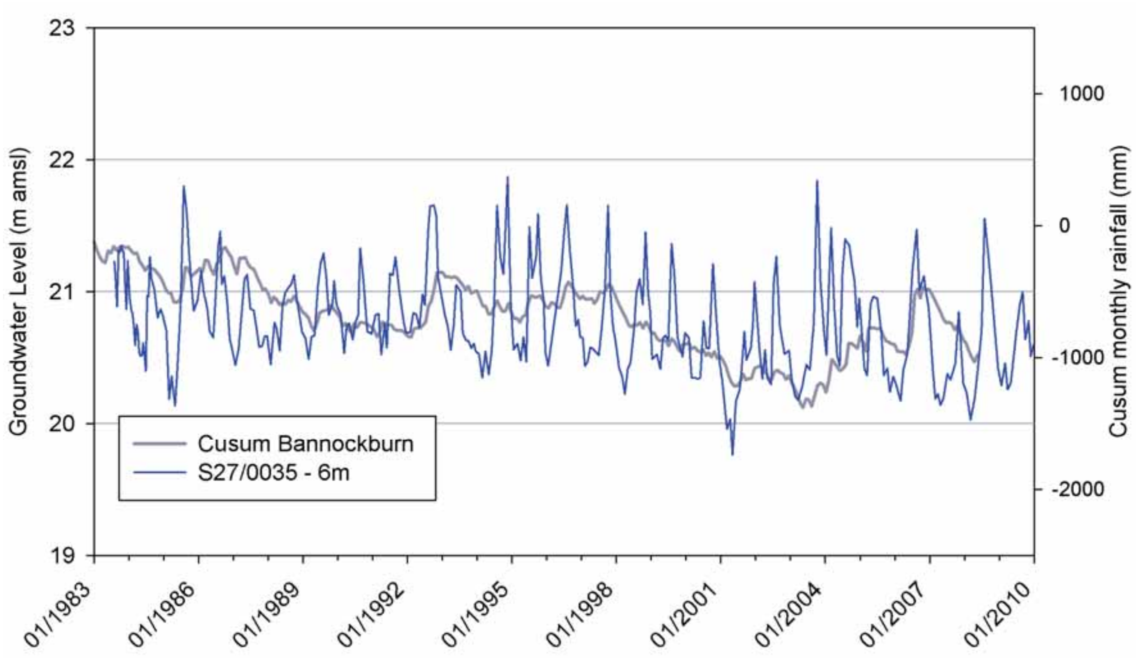


Figure 7.5: Groundwater level hydrograph for sub-area 1 (Tauherenikau River) – bore S27/0035

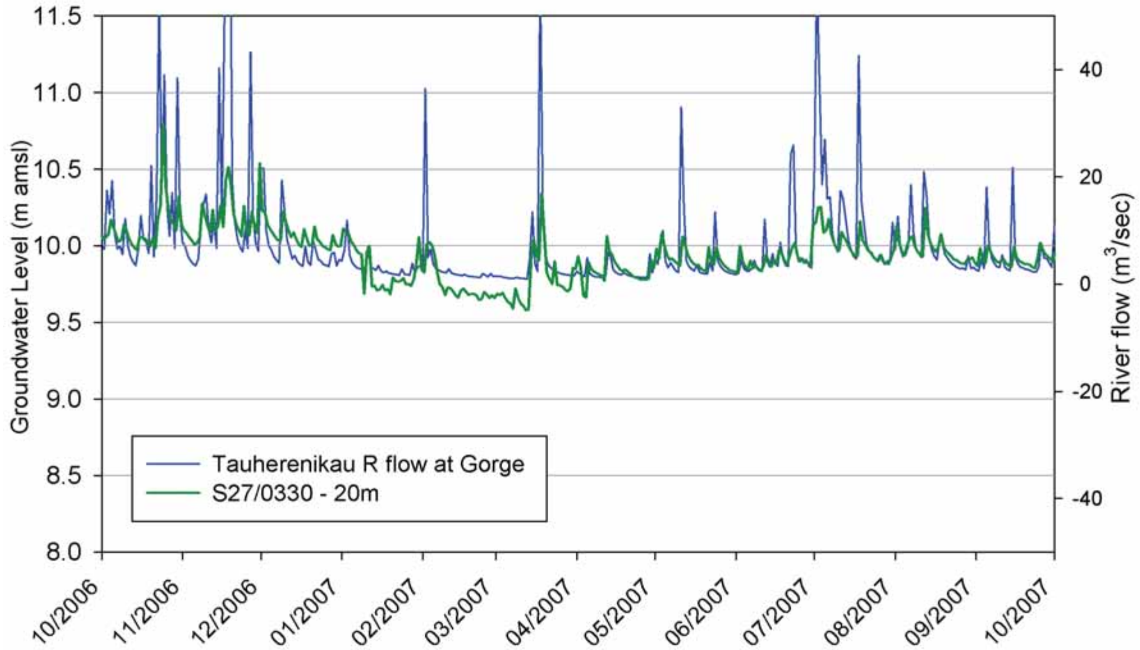


Figure 7.6: Detail of bore S27/0330 hydrograph and Tauherenikau River flow for the period October 2006 to October 2007

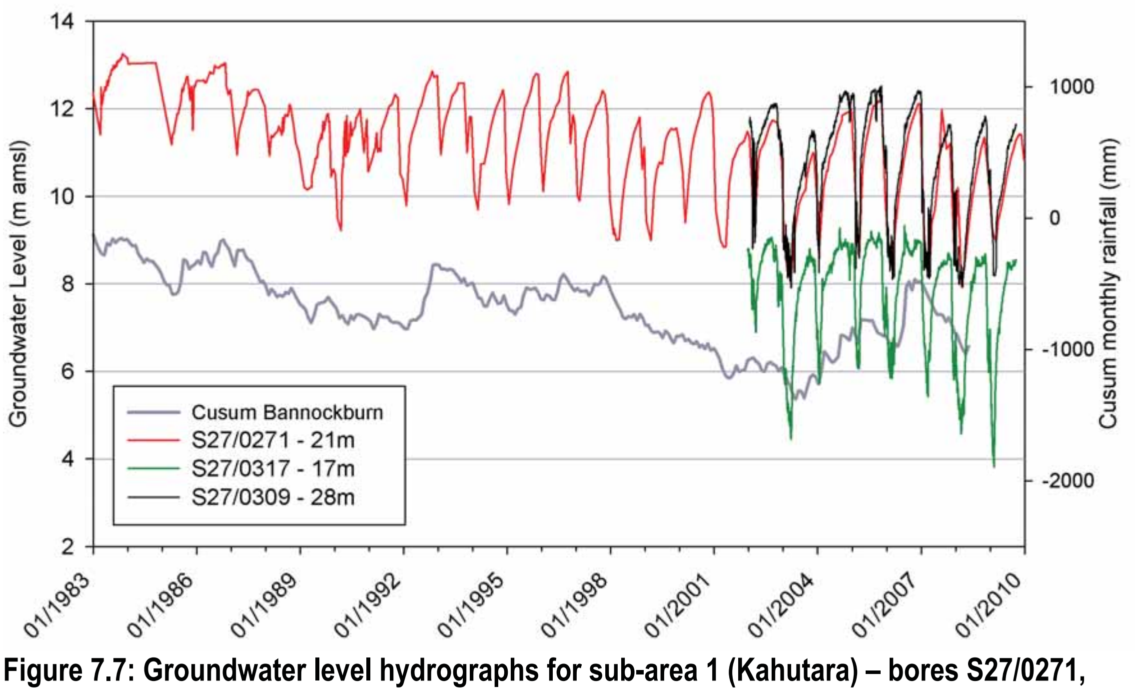


Figure 7.7: Groundwater level hydrographs for sub-area 1 (Kahutara) – bores S27/0271, S27/0317 and S27/0309

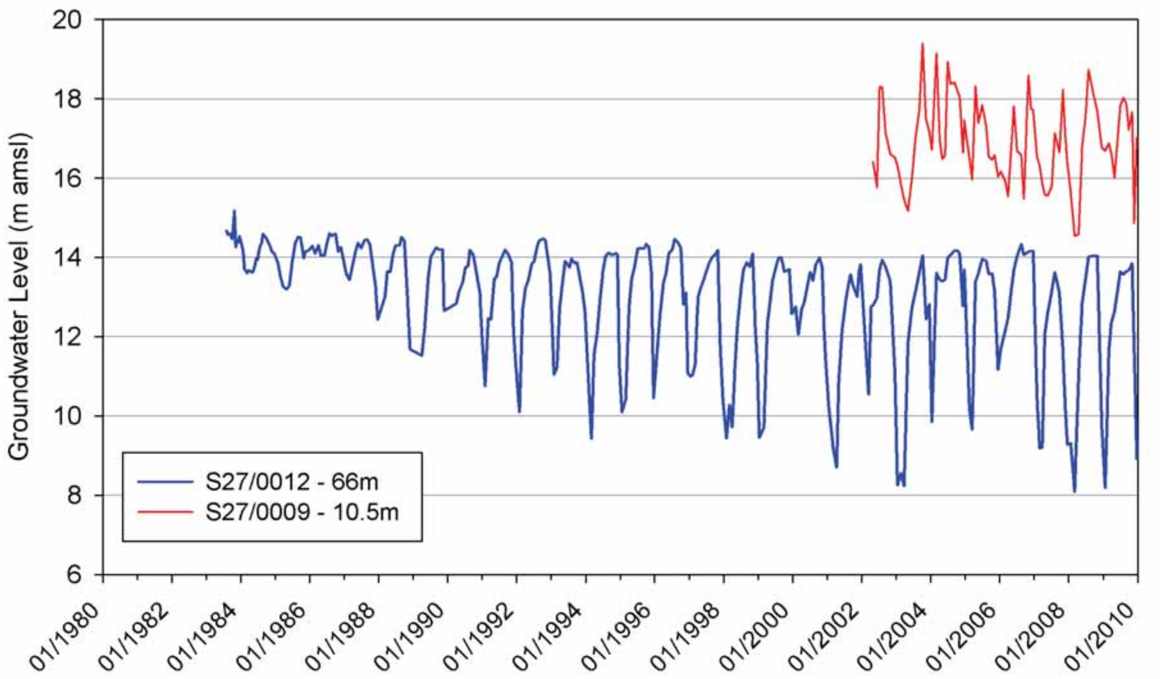


Figure 7.8: Groundwater level hydrographs for sub-area 1 (Windy Farm) – bores S27/0012 and S27/0009

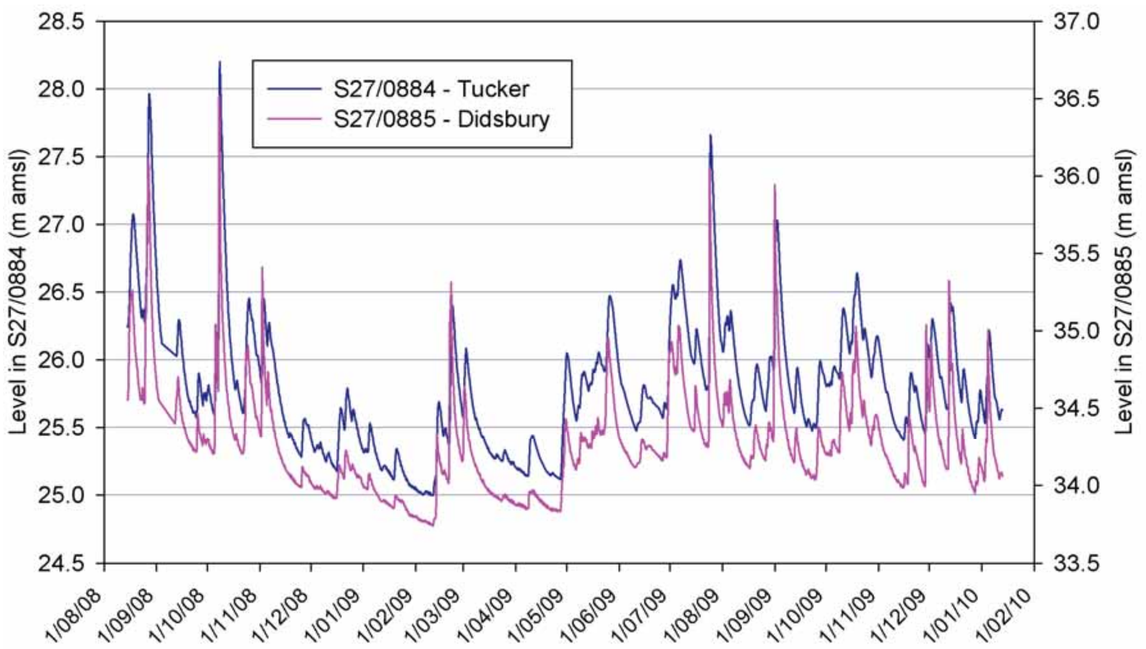


Figure 7.9: Groundwater level hydrographs for sub-area 2 (Ruamahanga River) – bores S27/0884 and S27/0885

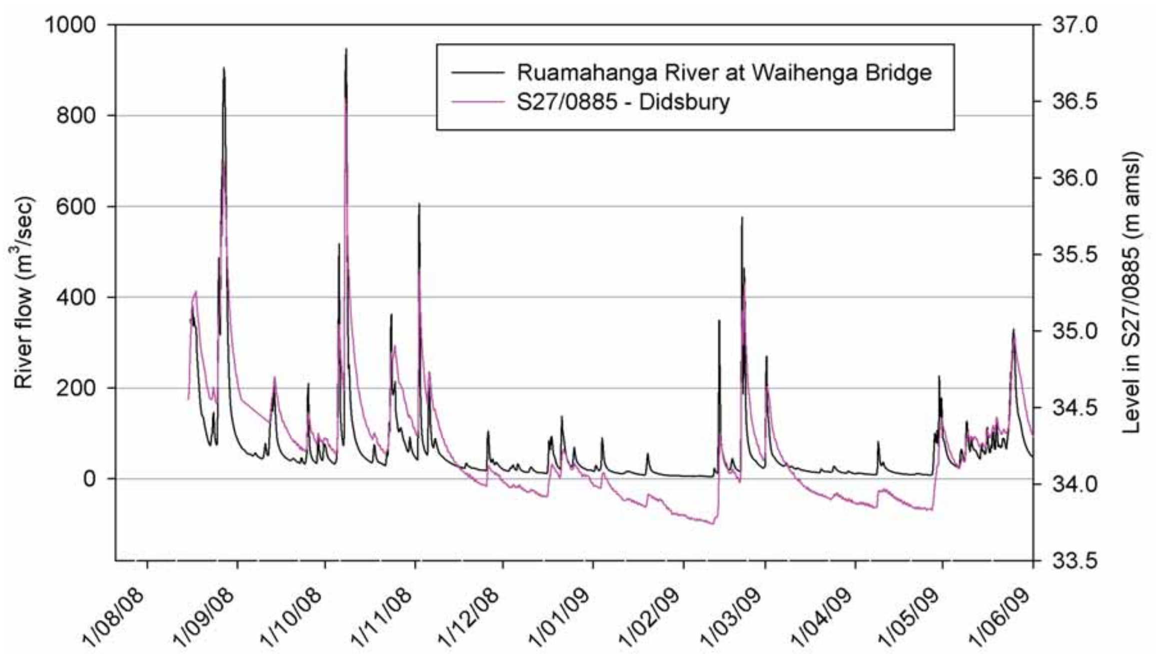


Figure 7.10: Groundwater level hydrograph for sub-area 2 – bore S27/0885 – and Ruamahanga River flow at Waihenga Bridge

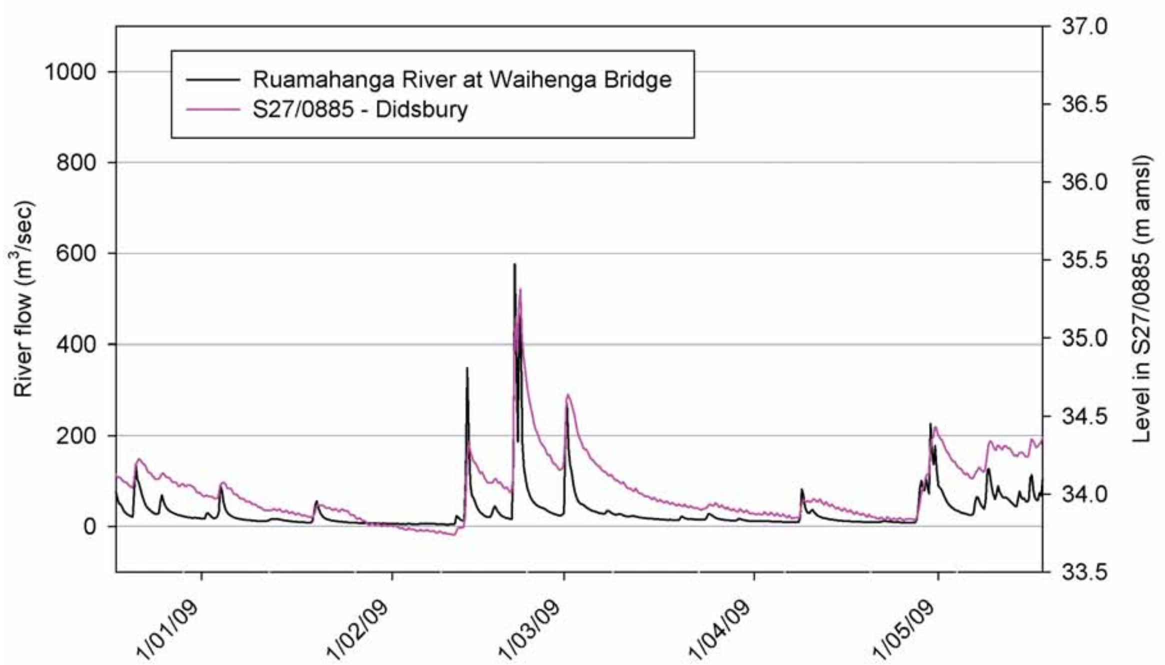


Figure 7.11: Groundwater level hydrograph for sub-area 2 – bore S27/0885 – and Ruamahanga River flow at Waihenga Bridge (detail)

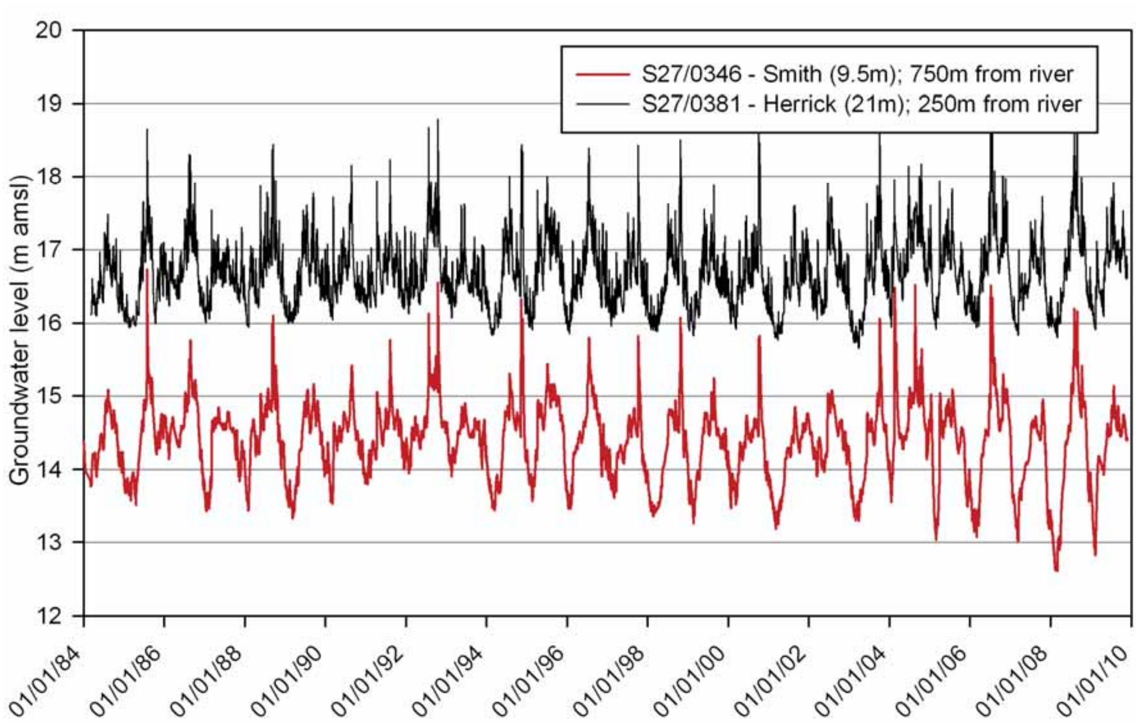


Figure 7.12: Groundwater level hydrographs for sub-area 2 (Pukio area) – bores S27/0346 and S27/0381

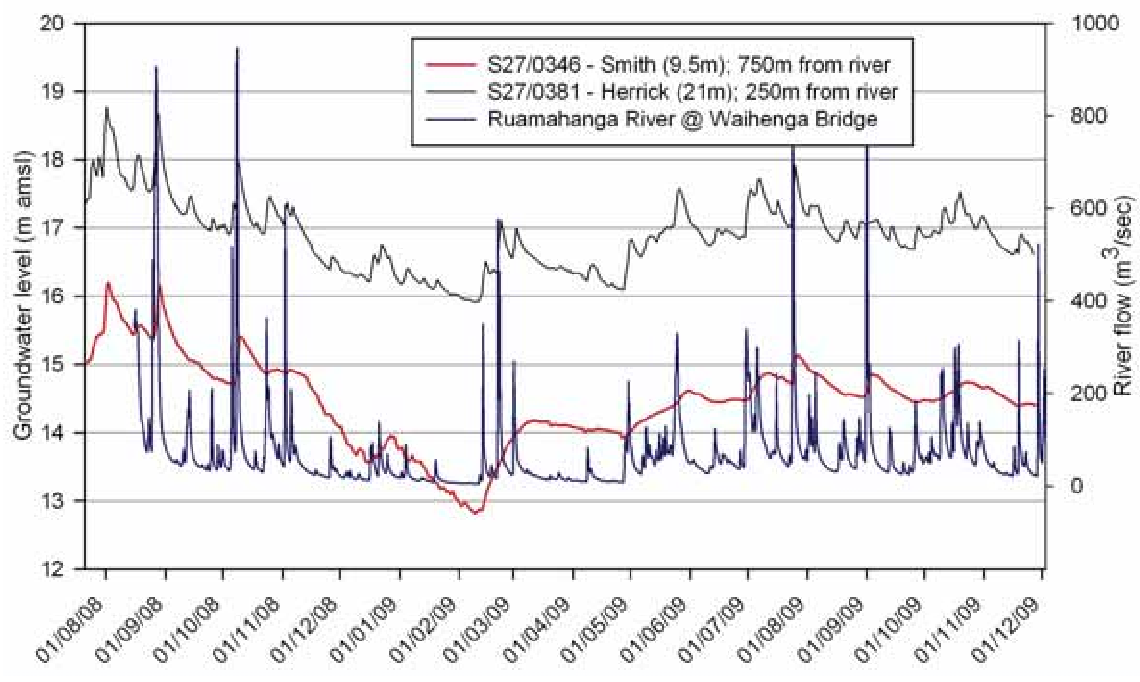


Figure 7.13: Groundwater level hydrographs for sub-area 2 – bores S27/0346 and S27/0381, July 2008 to December 2009

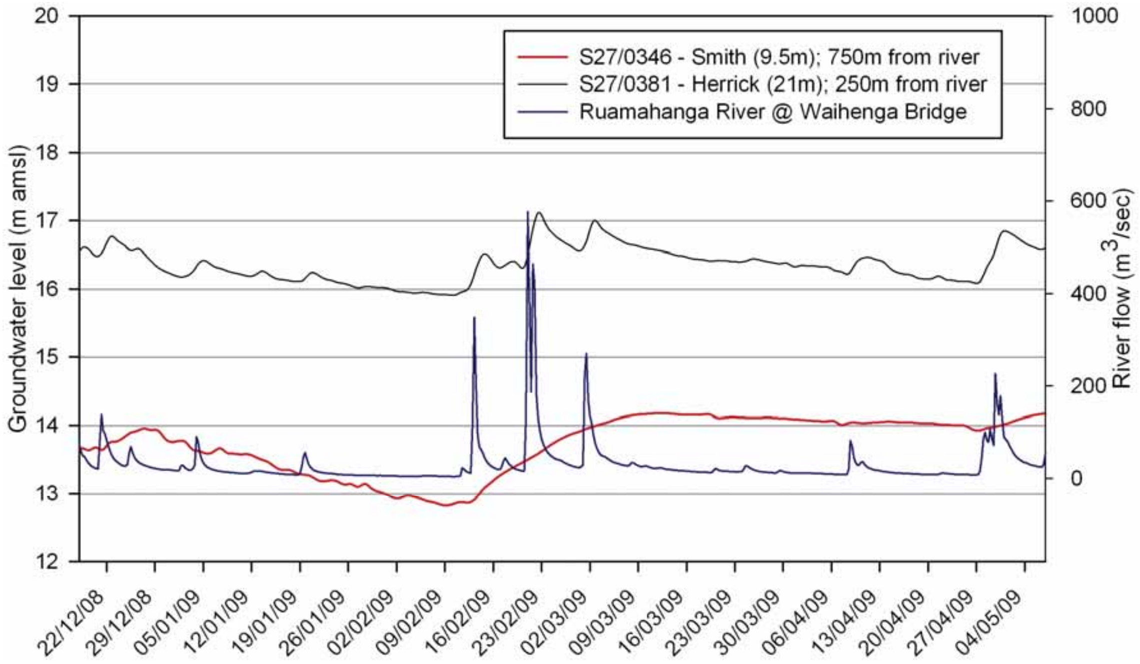


Figure 7.14: Groundwater level hydrographs for sub-area 2 (Ruamahanga valley) – bores S27/0346 and S27/0381, December 2008 to May 2009

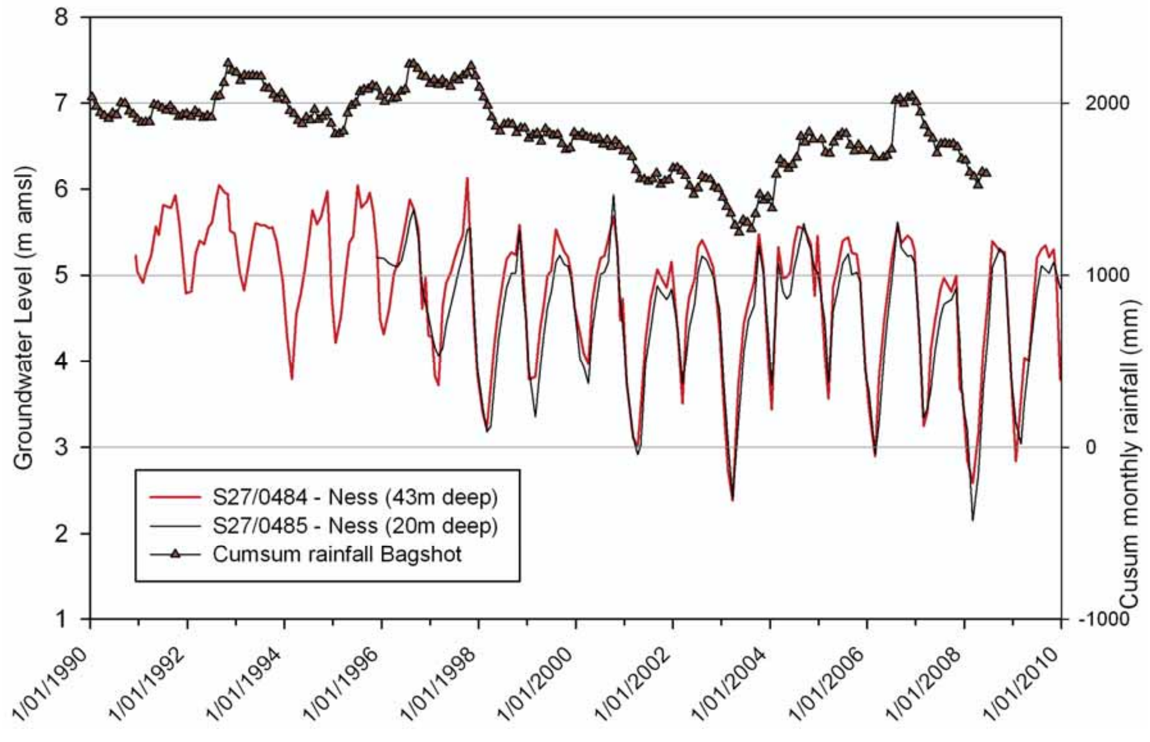


Figure 7.15: Groundwater level hydrographs for sub-area 2 (Ruamahanga valley) – bores S27/0484 and S27/0485

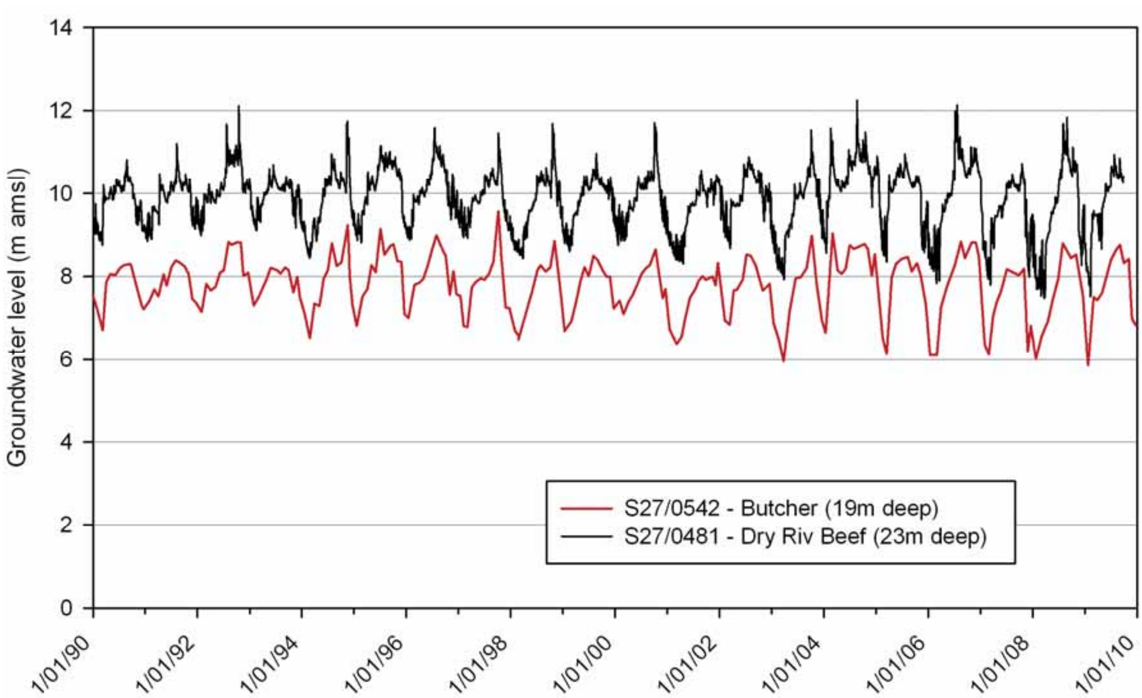


Figure 7.16: Groundwater level hydrographs for sub-area 2 (Ruamahanga valley) – bores S27/0542 and S27/0481

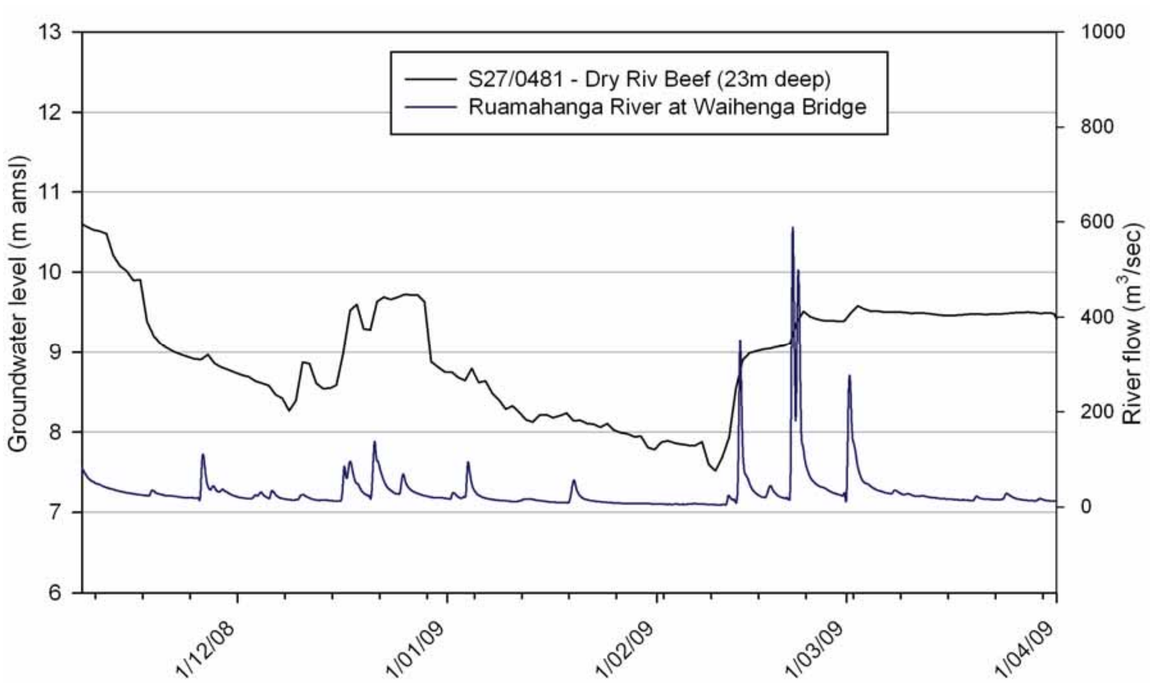


Figure 7.17: Groundwater level hydrograph for sub-area 2 (Ruamahanga valley) – bore S27/0481 – and Ruamahanga River flow at Waihenga Bridge, December 2008 to April 2009

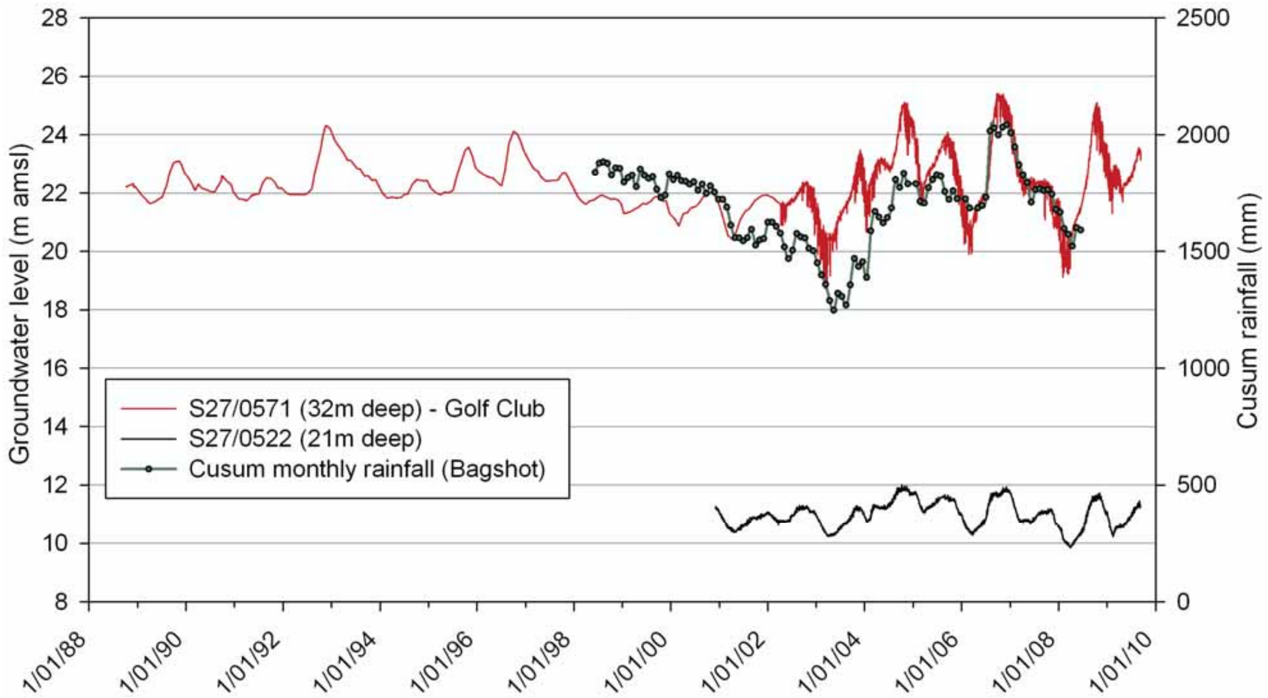


Figure 7.18: Groundwater level hydrographs for sub-area 3 (Martinborough terraces) – bores S27/0571 and S27/0522

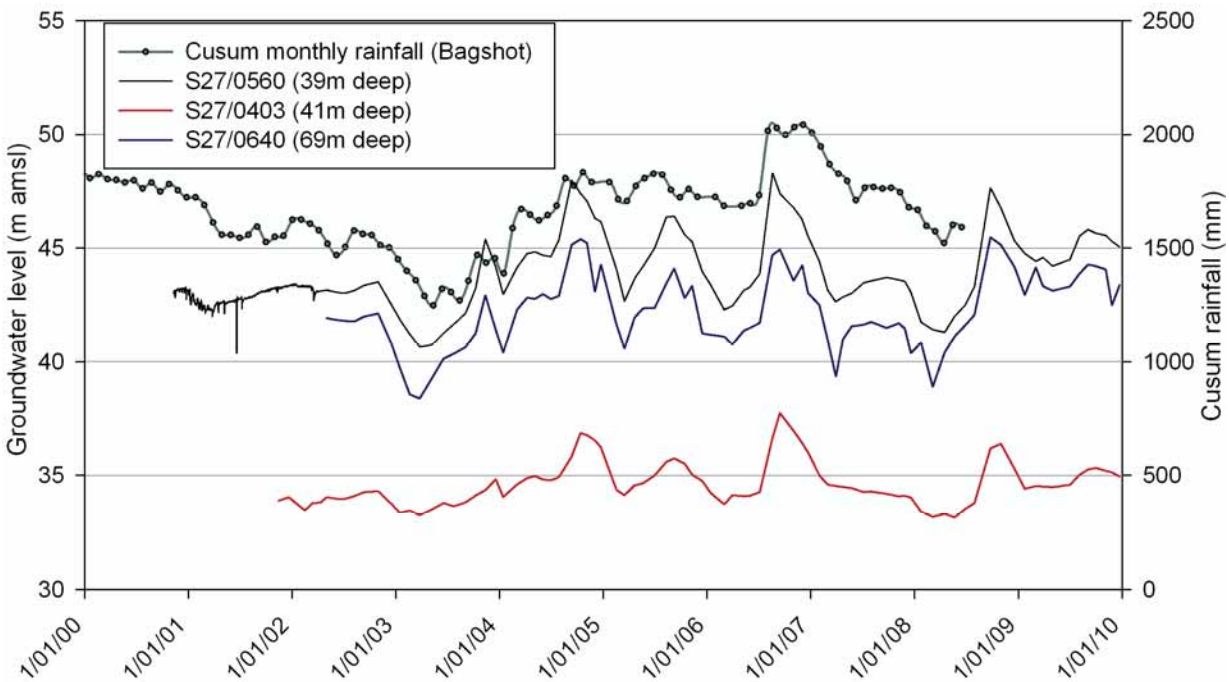


Figure 7.19: Groundwater level hydrographs for sub-area 3 (Martinborough terraces) – bores S27/0560, S27/0403 and S27/0640

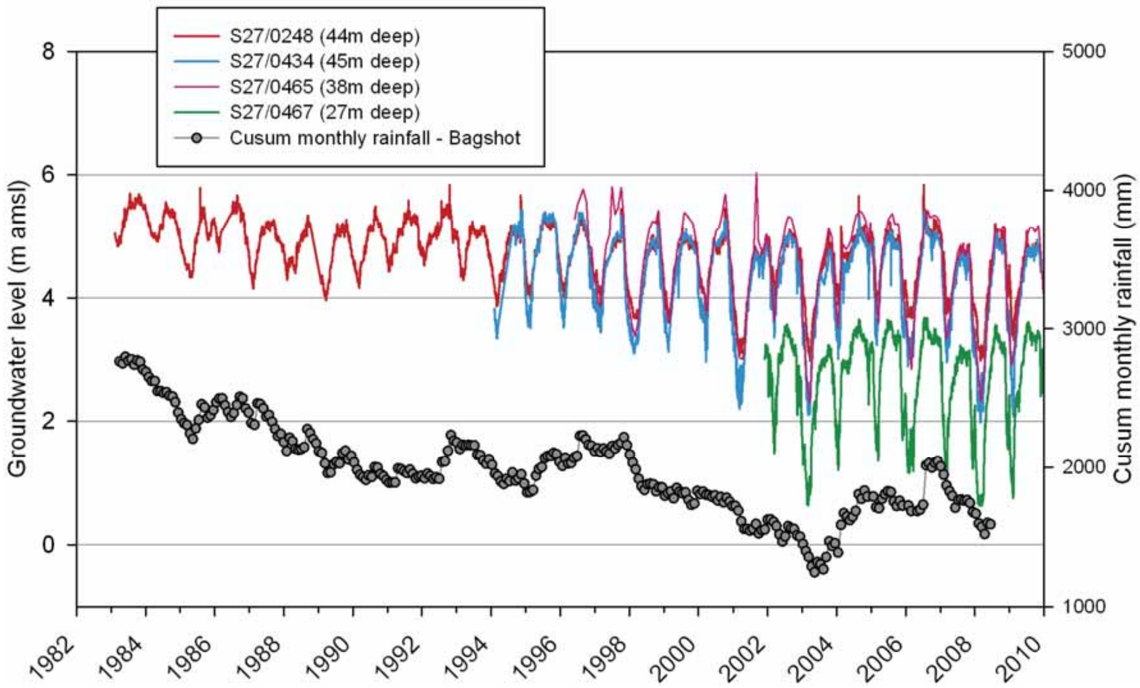


Figure 7.20: Groundwater level hydrographs for sub-area 4 (Lake basin) – Q2 aquifer monitoring bores

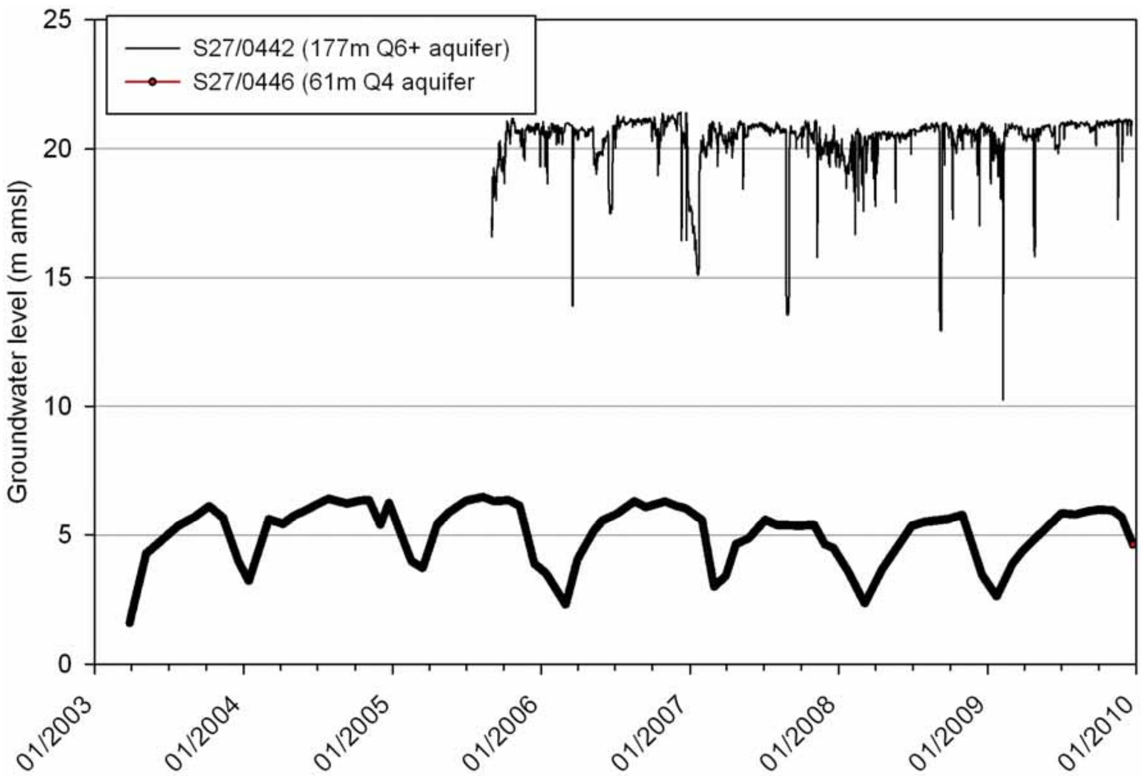


Figure 7.21: Groundwater level hydrographs for sub-area 4 (Lake basin) – Q4 and deeper aquifers (bores S27/0442 and S27/0446)

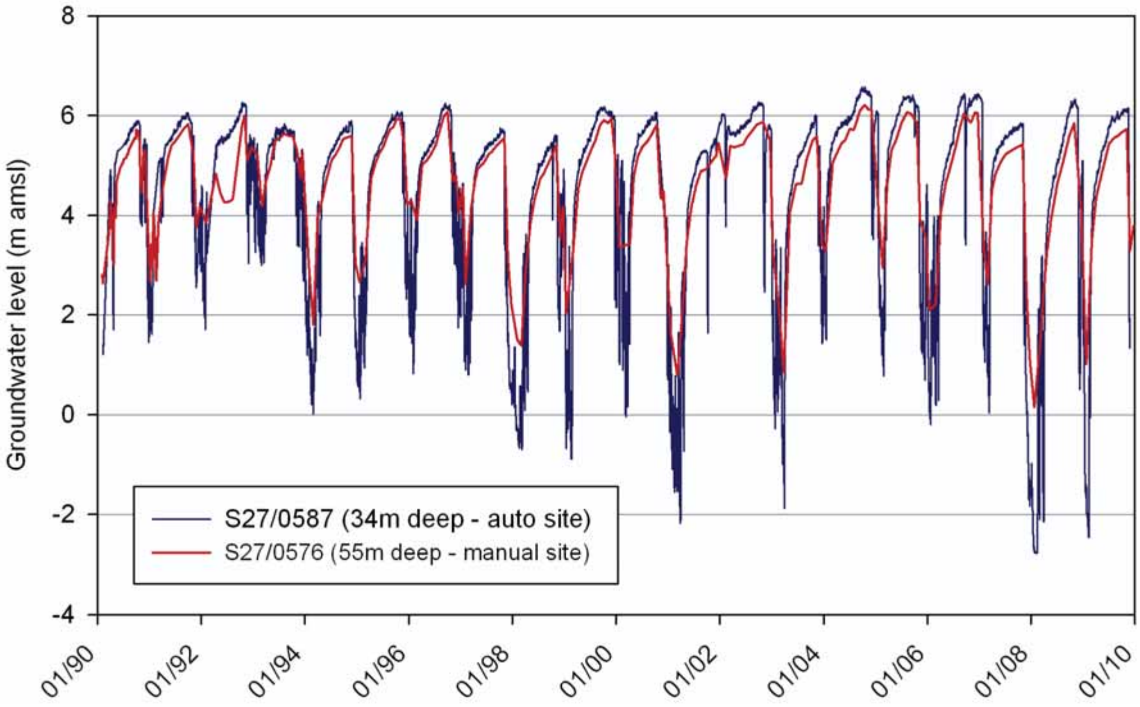


Figure 7.22: Groundwater level hydrographs for sub-area 5 (Onoke) – 'Luttrell bores'

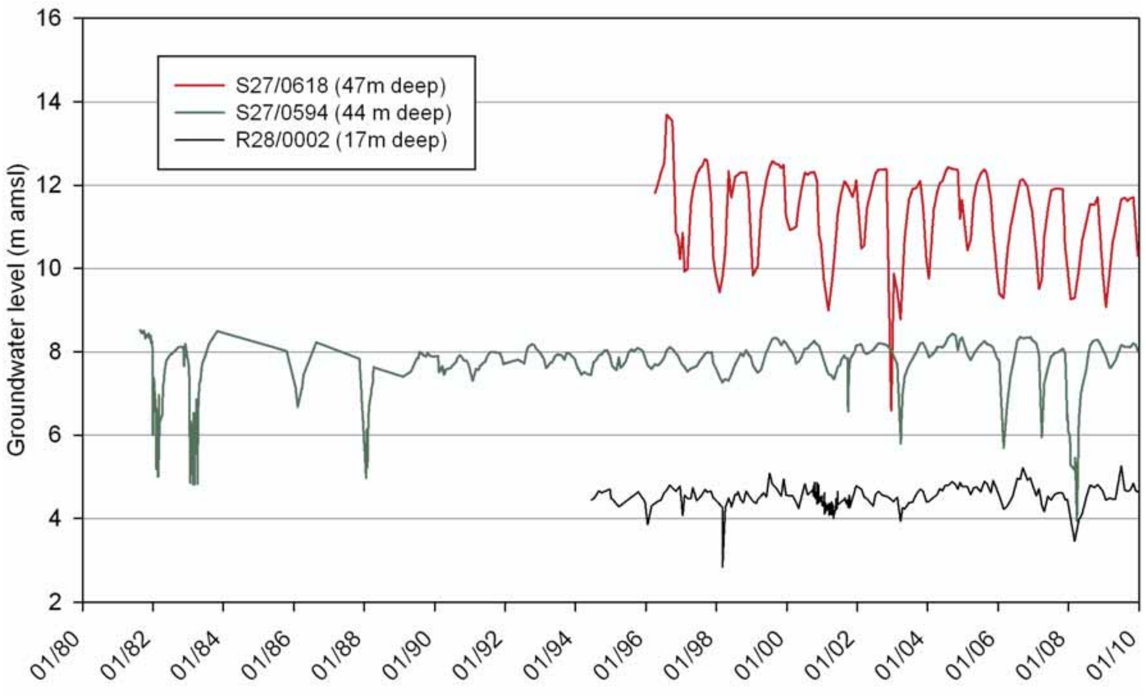


Figure 7.23: Groundwater level hydrographs for sub-area 5 (Onoke) – bores S27/0618, S27/0594 and R28/0002

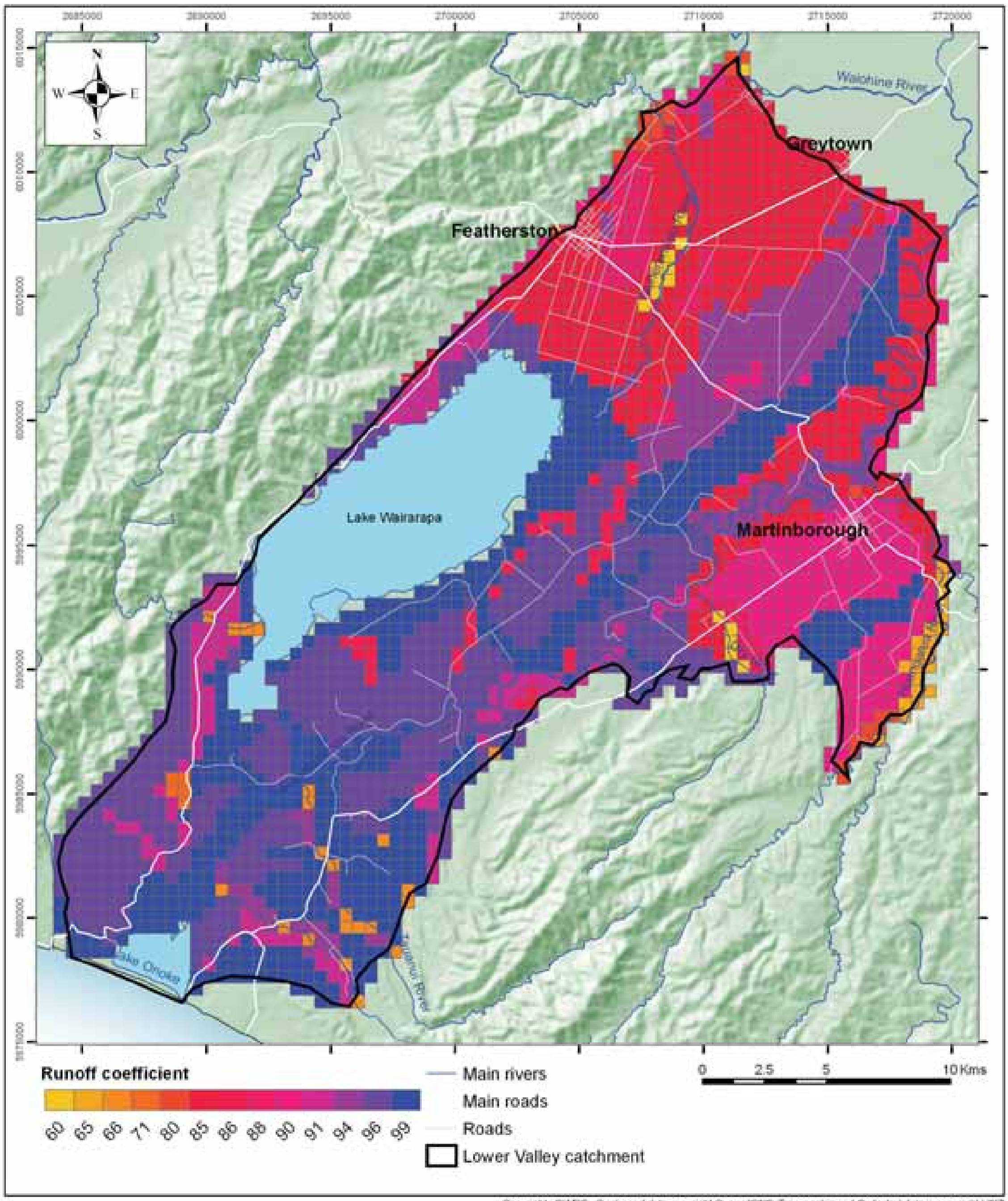


Figure 7.24: Rainfall recharge areas in the Lower Valley catchment. Rainfall recharge is highest in areas with low runoff coefficient values.

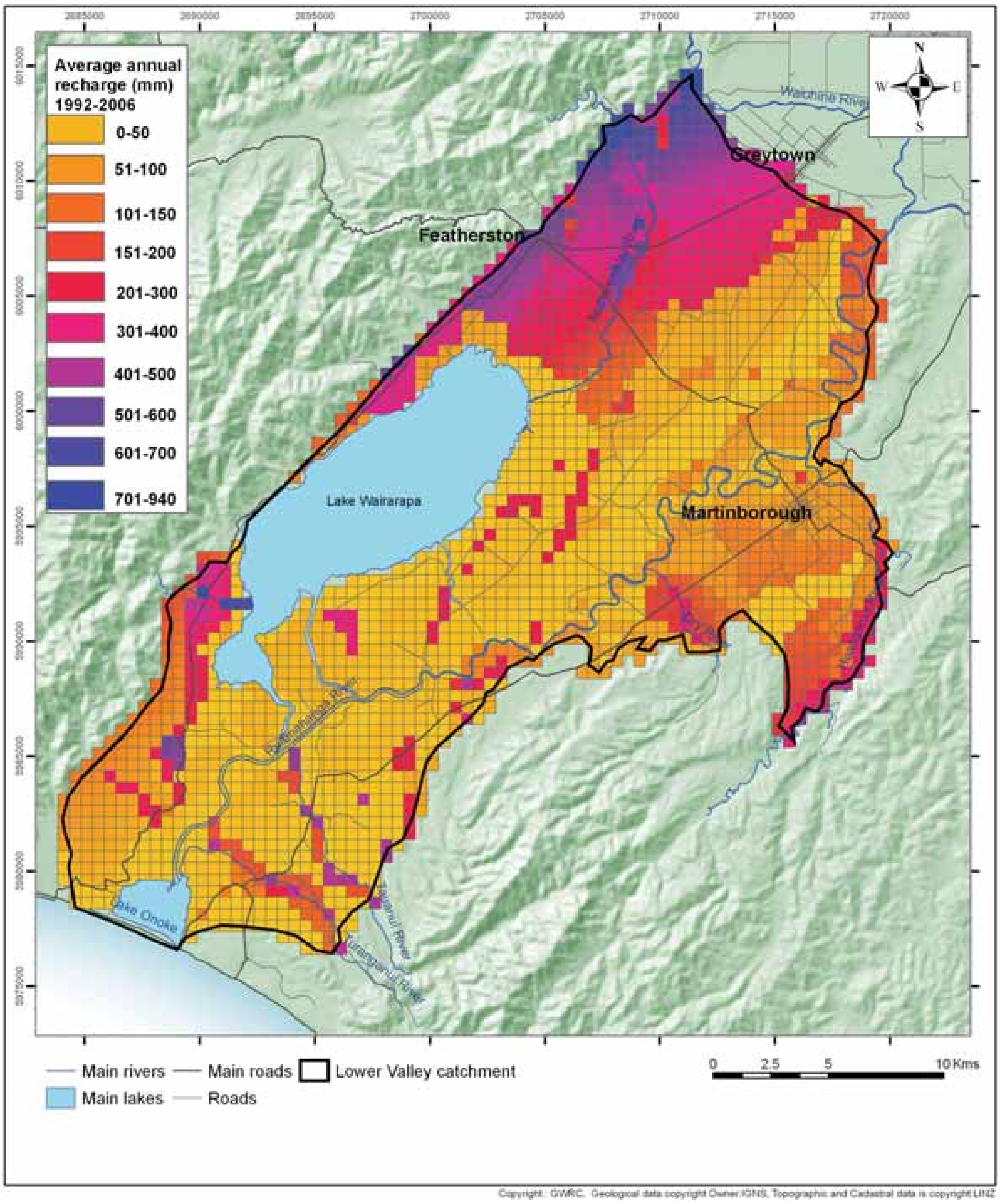


Figure 7.25A: Average annual recharge for the Lower Valley catchment over the modelling period 1992-2008, calculated using a soil moisture balance model

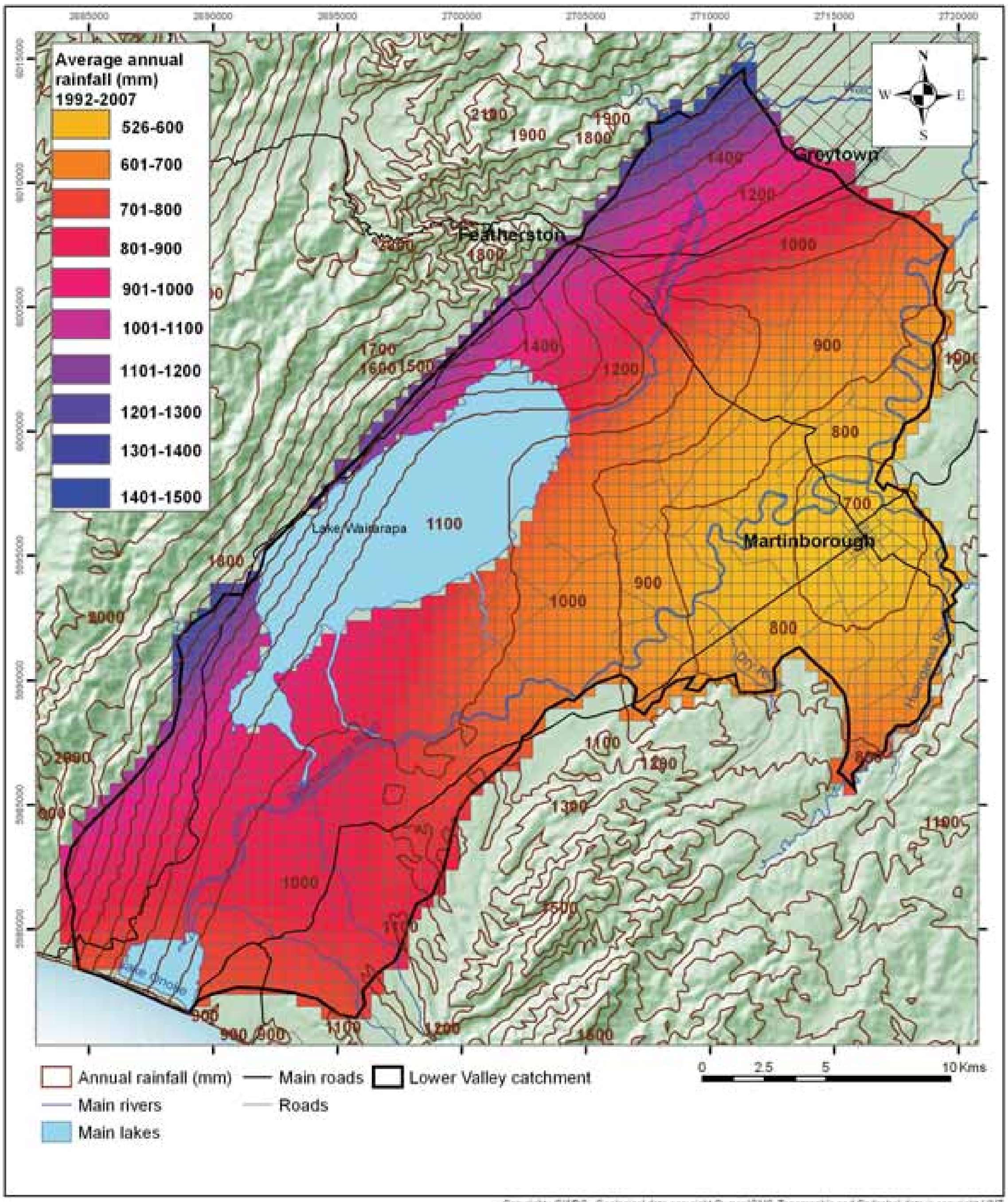


Figure 7.25B: Average annual rainfall data sourced from NIWA modelling for the Lower Valley catchment. Mean (1920–1970) rainfall isohyets are overlaid in the figure for comparison.

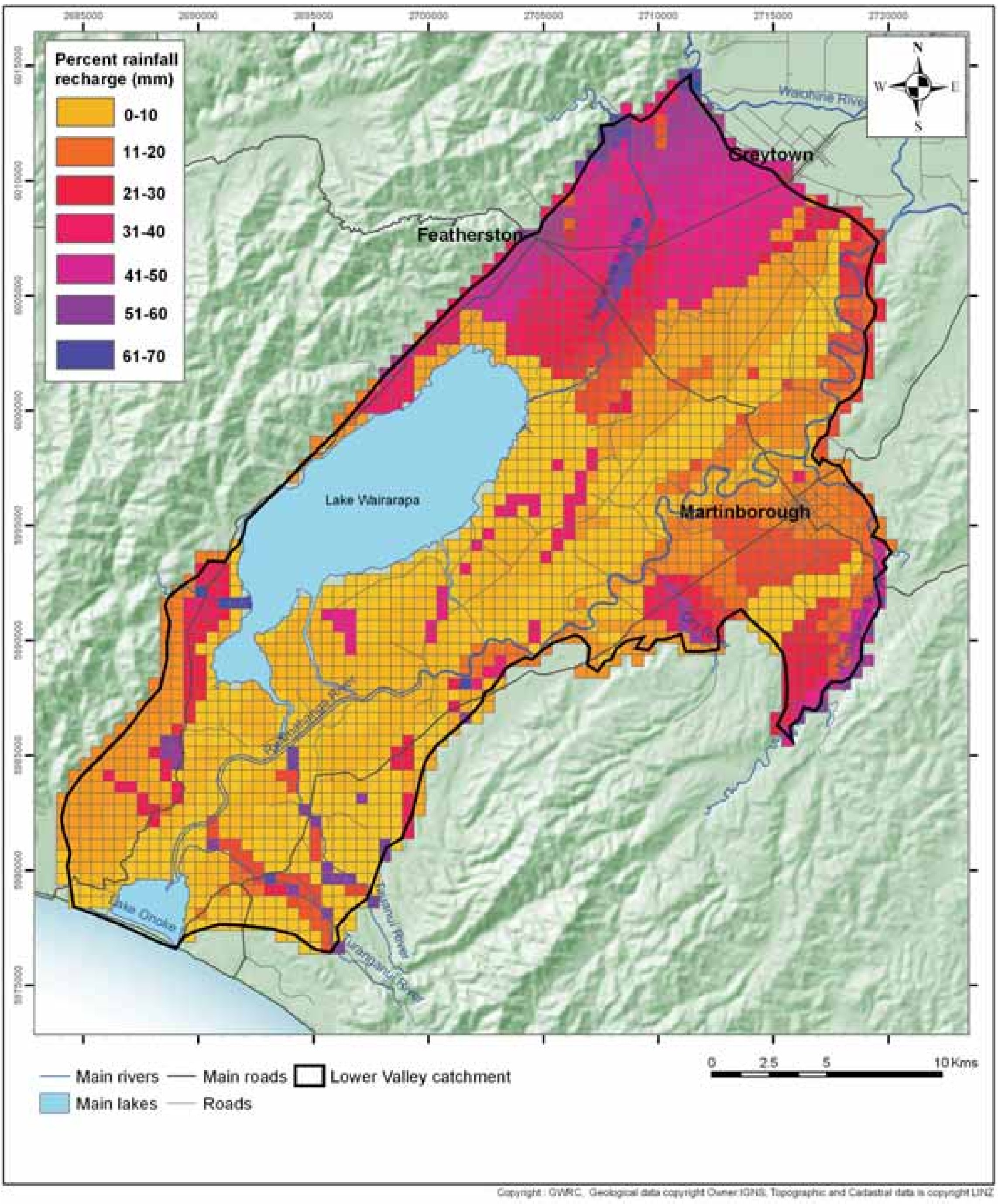


Figure 7.26: Percentage of rainfall that recharges the Lower Valley catchment

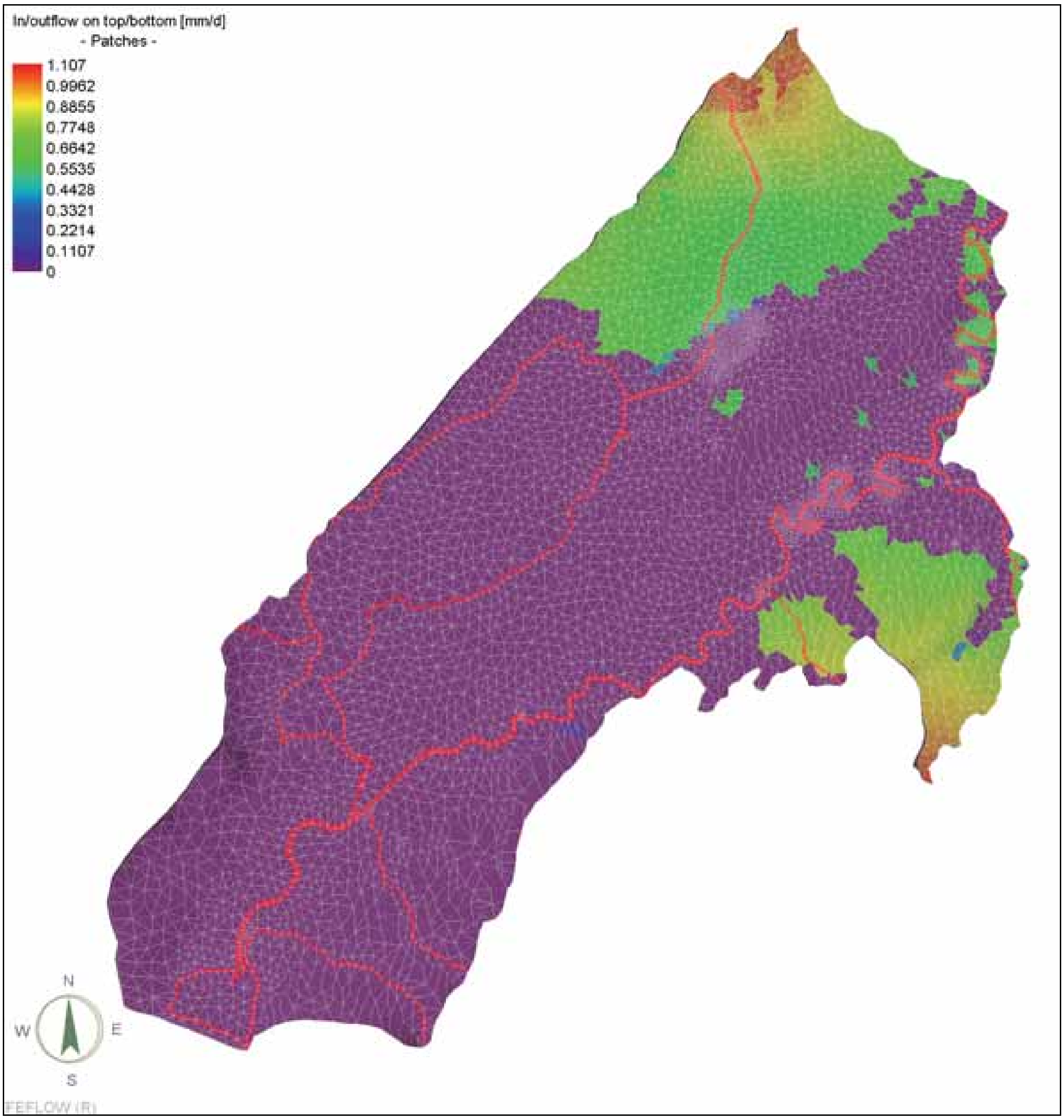


Figure 7.27: Modelled spatial rainfall recharge pattern across the Lower Valley catchment for the week of 29 June 2005 (7-day average). At this time there is only recharge on the upper Tauherenikau fan and also over the upper Martinborough terraces and Huangarua valley.

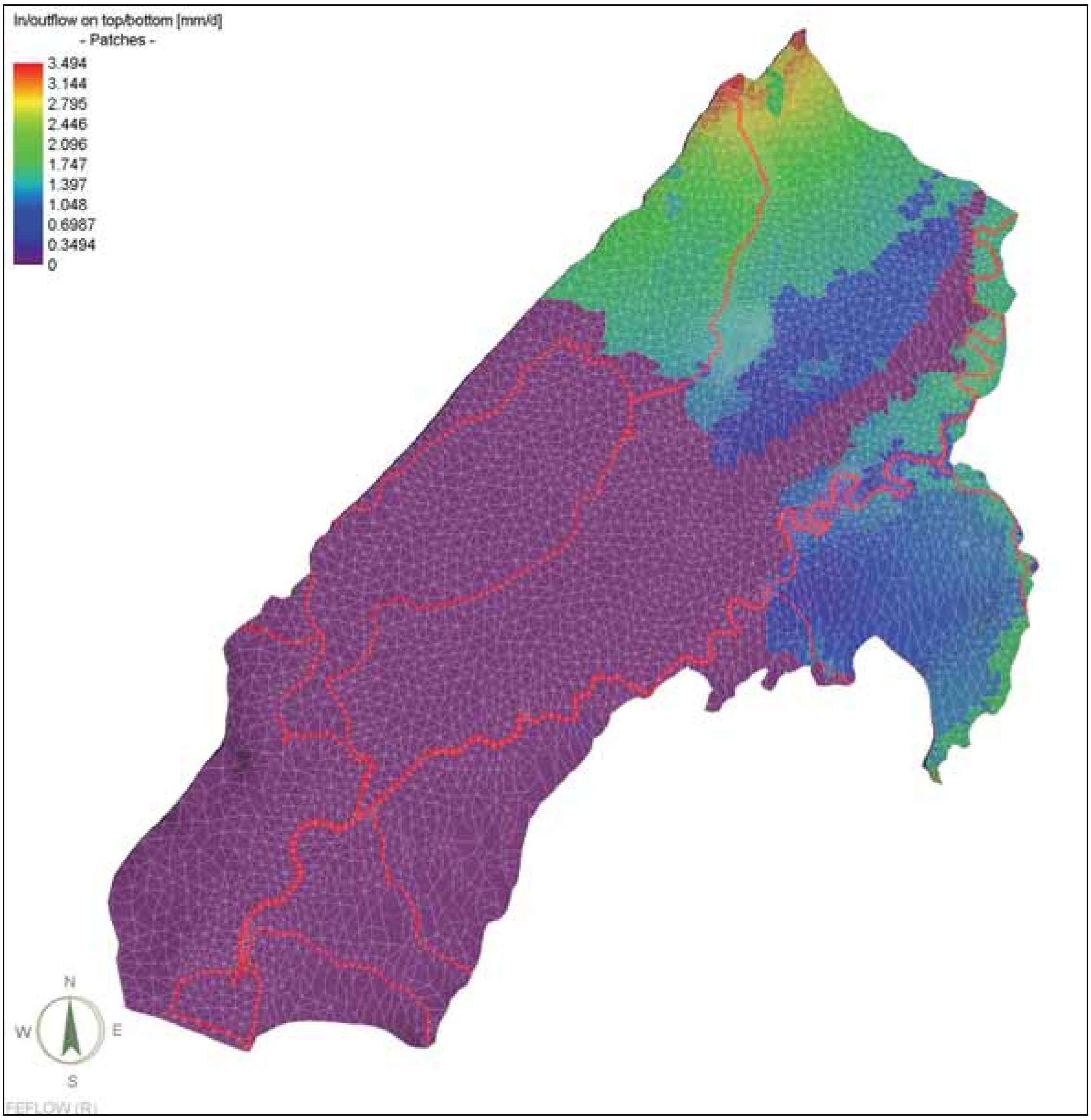


Figure 7.28: Modelled spatial rainfall recharge pattern across the Lower Valley catchment for the week of 25 June 2008 (7-day average). At this time there is recharge over the Tauherenikau fan, Ruamahanga valley, Martinborough terraces and the Huangarua valley. There is no recharge over the Lake basin and Onoke areas as confined aquifers and upwards flow gradients dominate these areas.

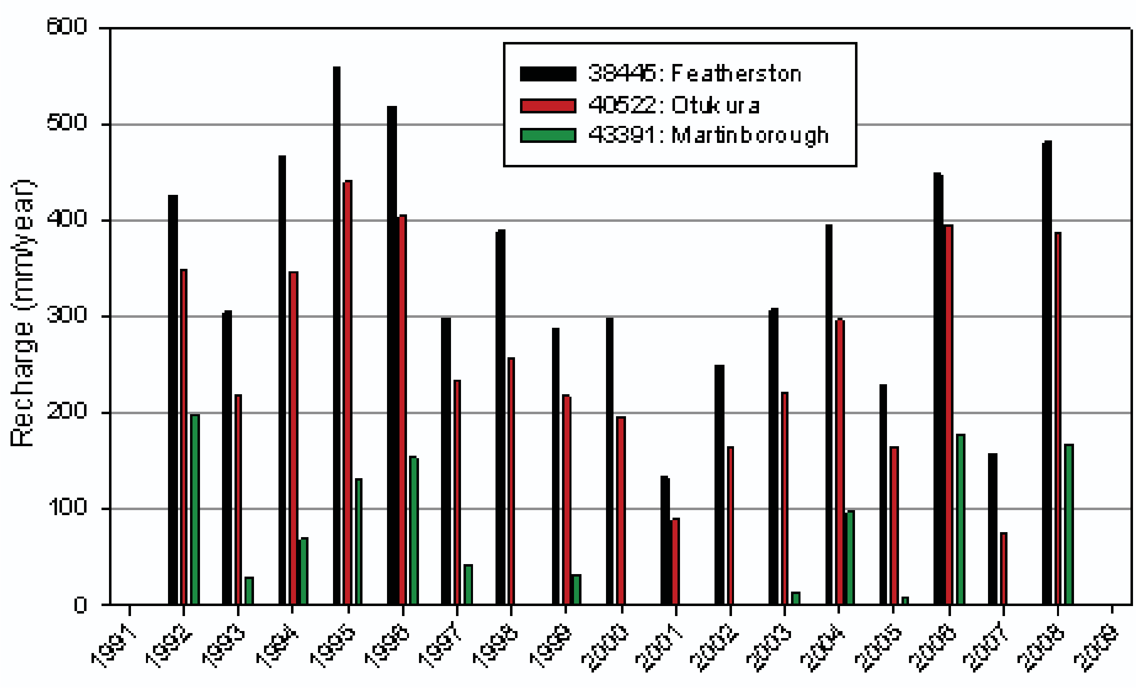


Figure 7.29: Annual recharge calculated for three representative recharge model cells across the Lower Valley catchment for the period 1992 to 2008

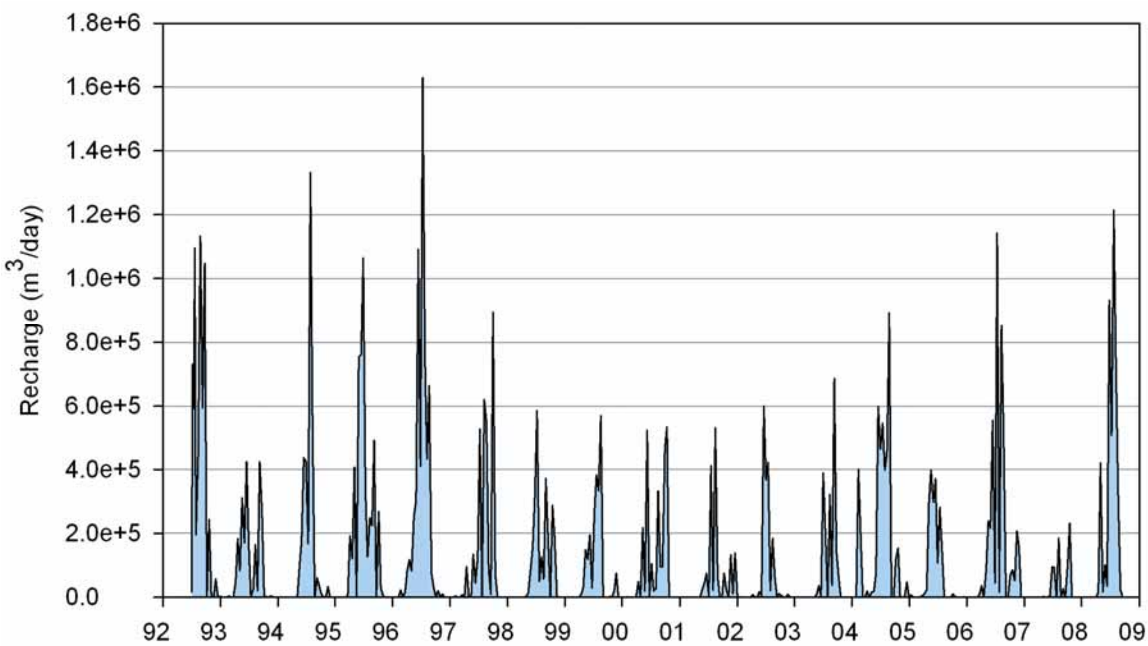


Figure 7.30: Modelled rainfall recharge for the Lower Valley catchment for the period 1992 to 2008

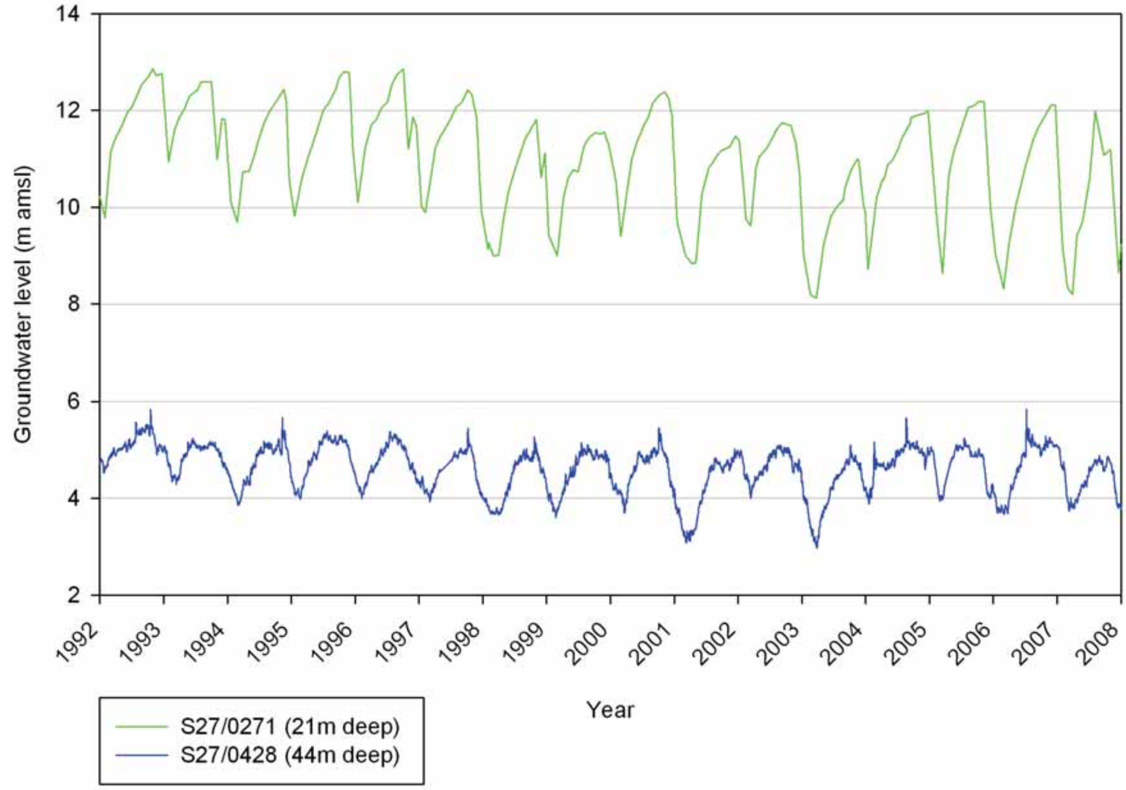


Figure 7.31: Groundwater levels in two bores located in the Q2 confined aquifer in the Kahutara groundwater zone (S27/0271) and in lake basin (S27/0428), 1992–2008

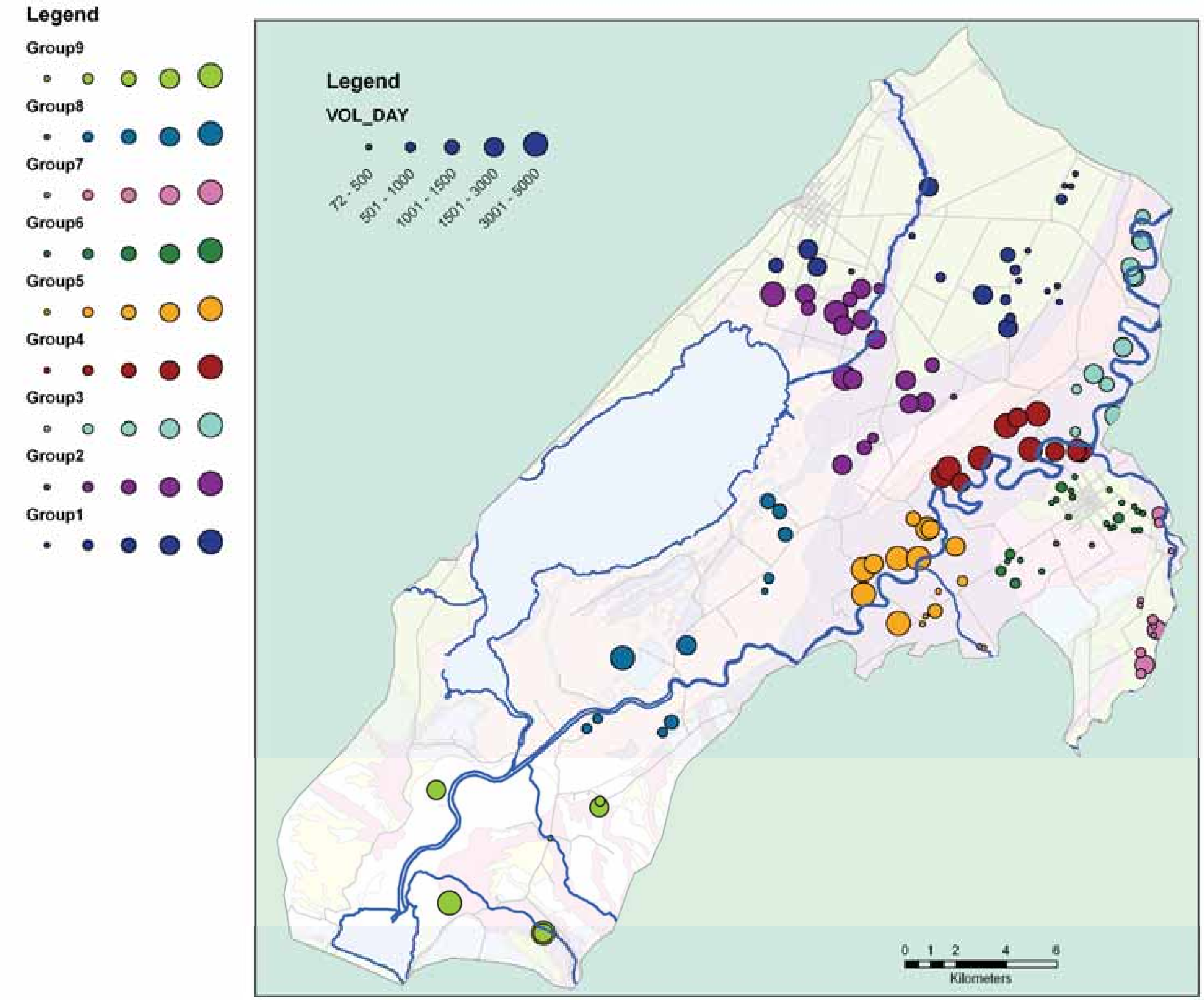


Figure 7.32: Consented bores in the Lower Valley catchment showing daily allocation magnitude (m^3/day) and abstraction bore groups 1- 9

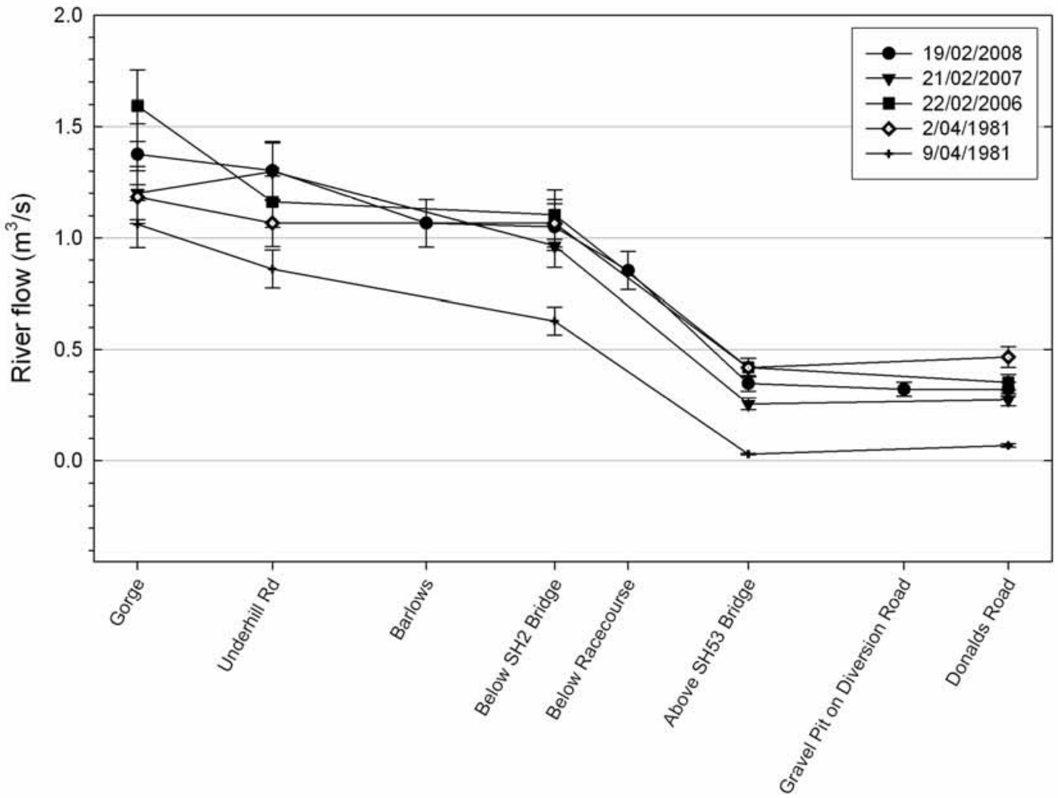


Figure 7.33A: Concurrent flow gauging surveys on the Tauherenikau River. Error bars show the expected maximum standard flow gauging error (+/- 10%)

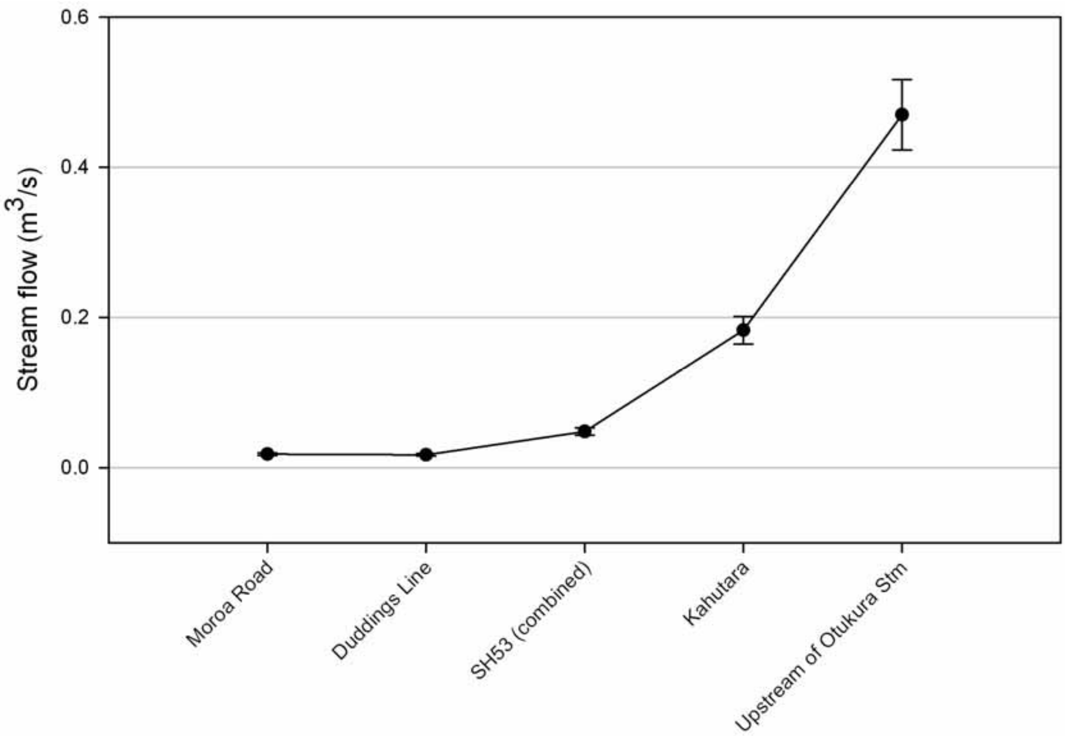


Figure 7.33B: Concurrent flow gauging survey undertaken on Stonestead (Dock) Creek on 19 February 2008. Error bars show the expected maximum standard flow gauging error (+/- 10%)

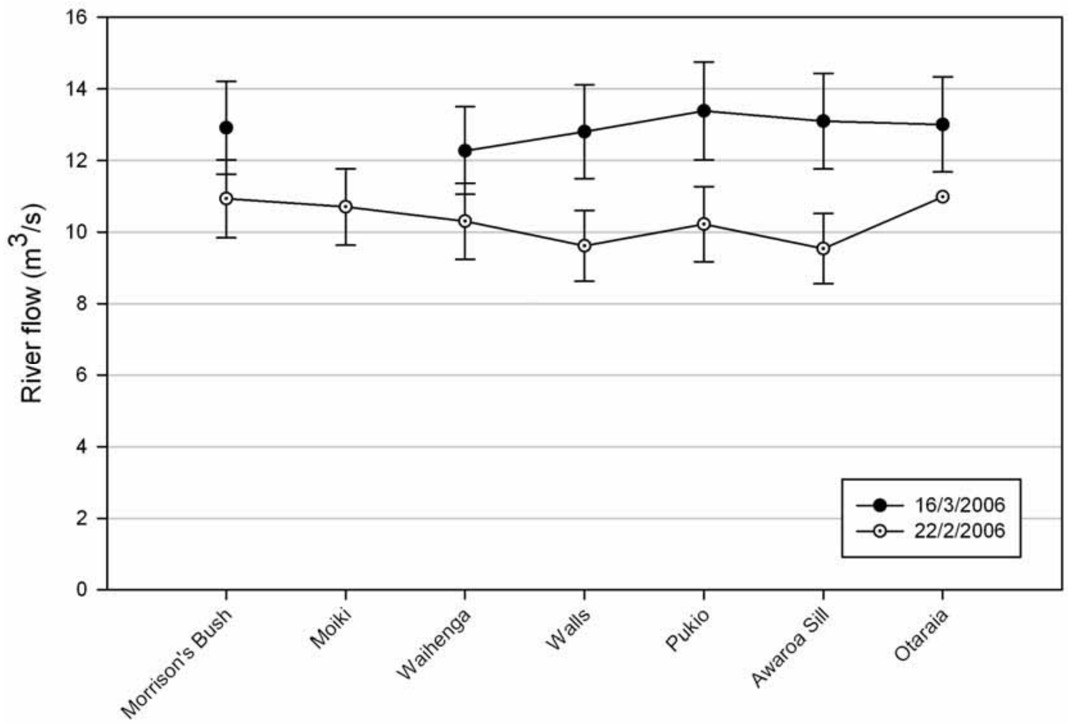


Figure 7.33C: Concurrent flow gauging surveys on the lower Ruamahanga River. Error bars show the expected maximum standard flow gauging error (+/- 10%)

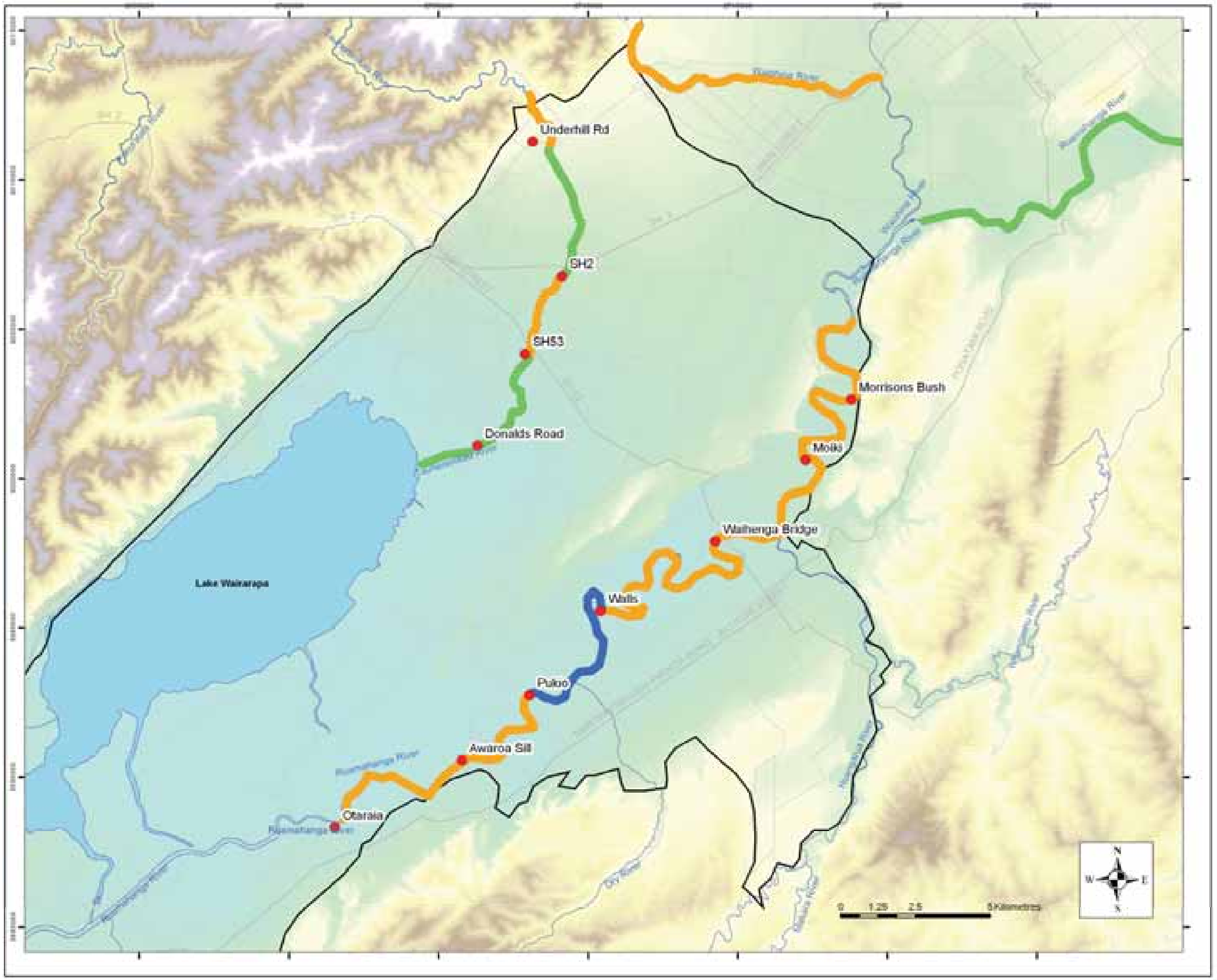


Figure 7.34: Concurrent flow gauging sites on the Tauherenikau and Ruamahanga rivers. Also shown are the flow loss and gaining patterns (orange = loss, blue = gain, green = neutral)

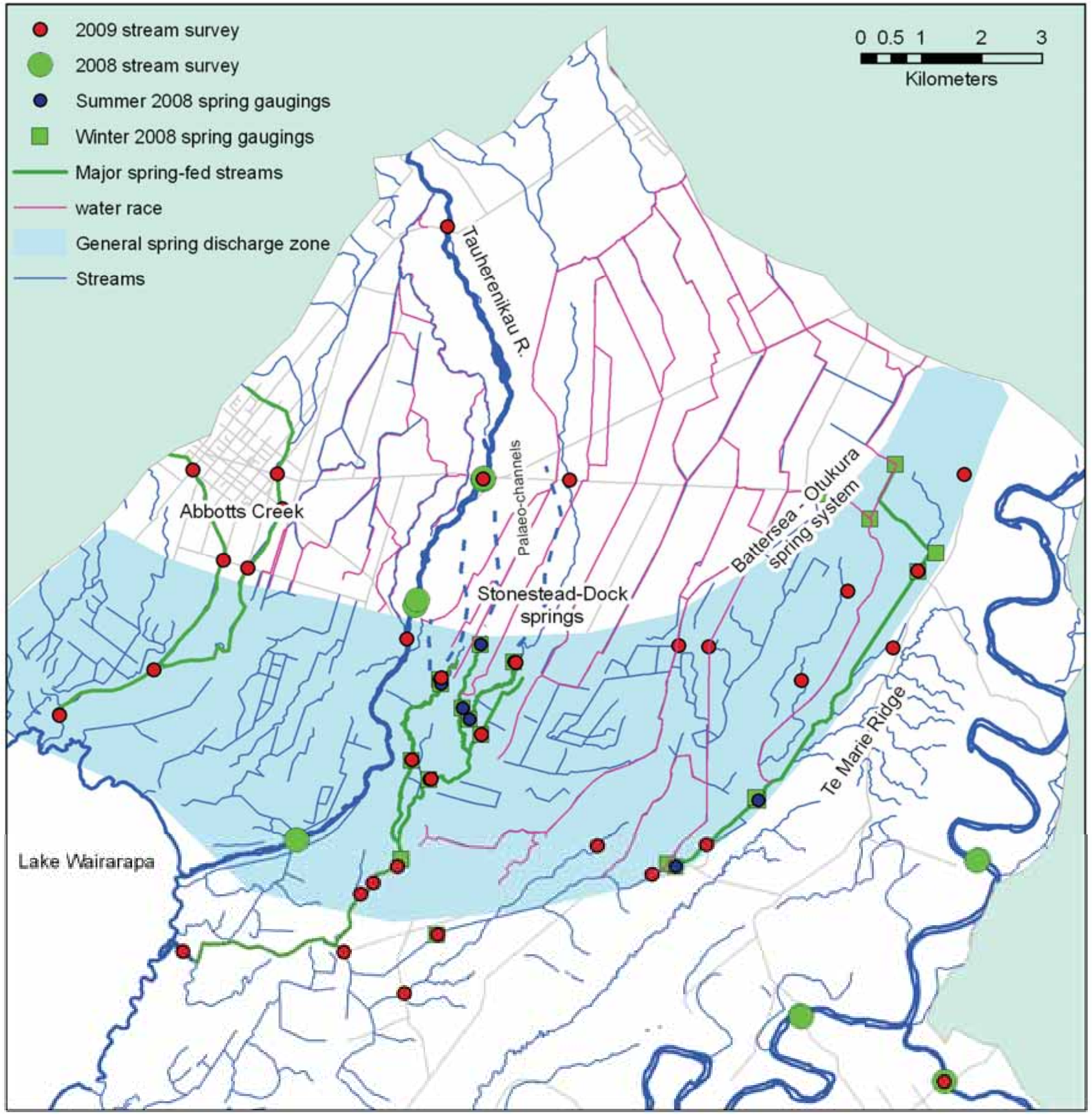


Figure 7.35: Groundwater discharge on the Tauherenikau fan – locations of stream and spring surveys, principal spring-fed streams and the general groundwater discharge zone

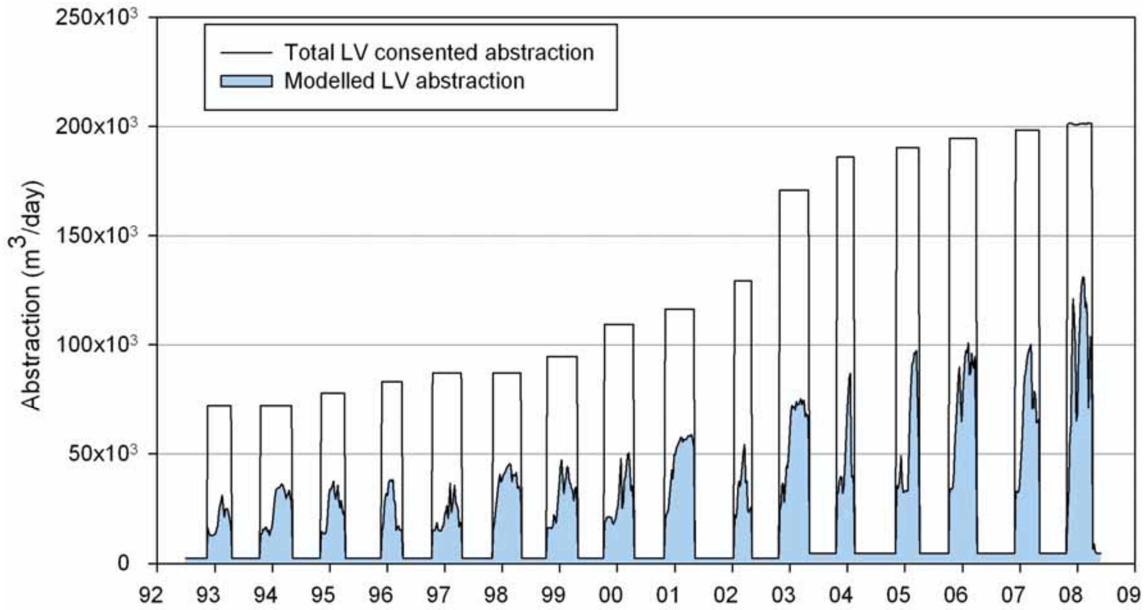


Figure 7.36: Consented and modelled (actual) groundwater abstraction in the Lower Valley catchment, 1992 and 2008

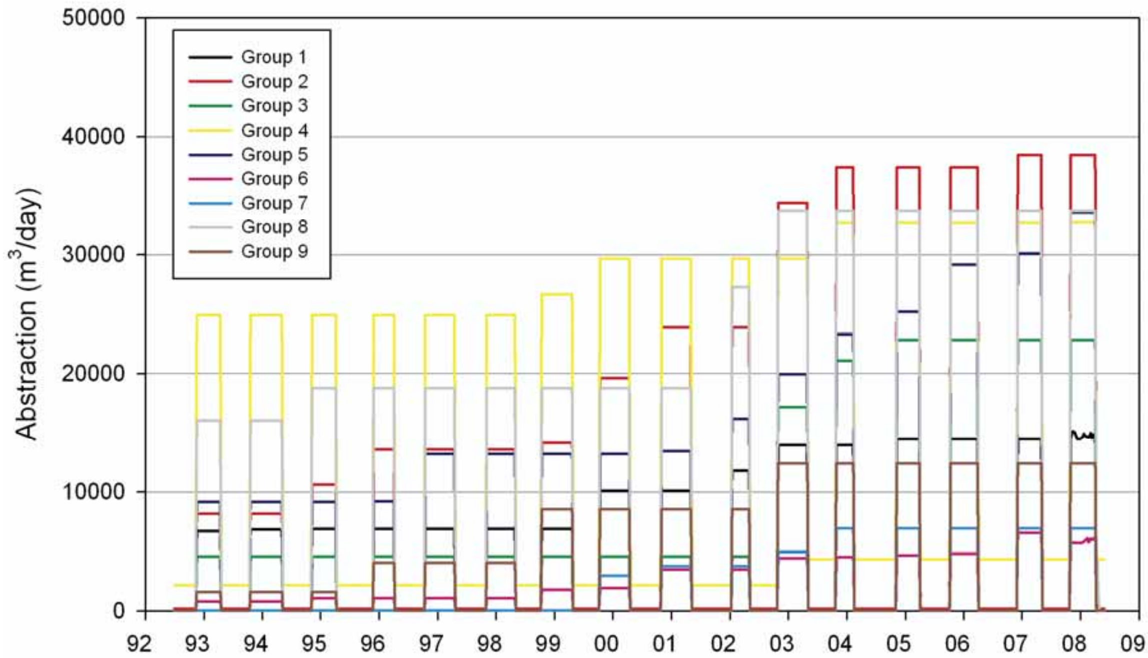


Figure 7.37: Consented groundwater abstraction for the nine well groups (see Figure 7.34) for the period 1992 to 2008

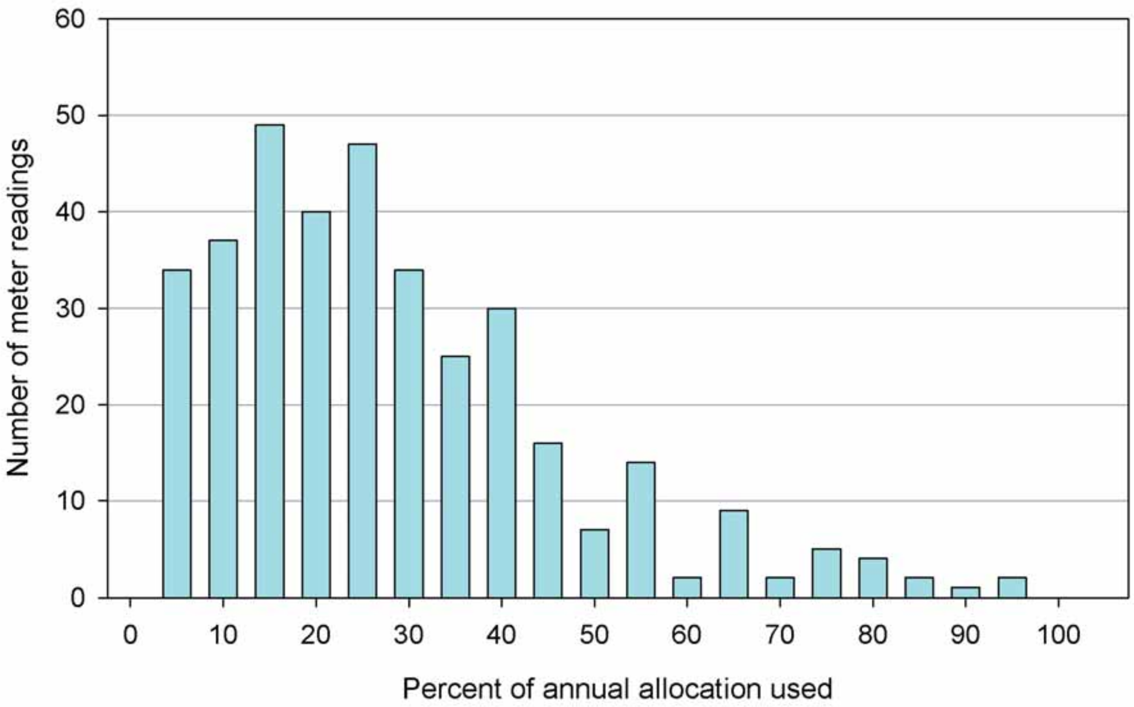


Figure 7.38: Frequency distribution of metered annual use (as a percentage of annual allocation) in the Wairarapa Valley over the period 2002 to 2008

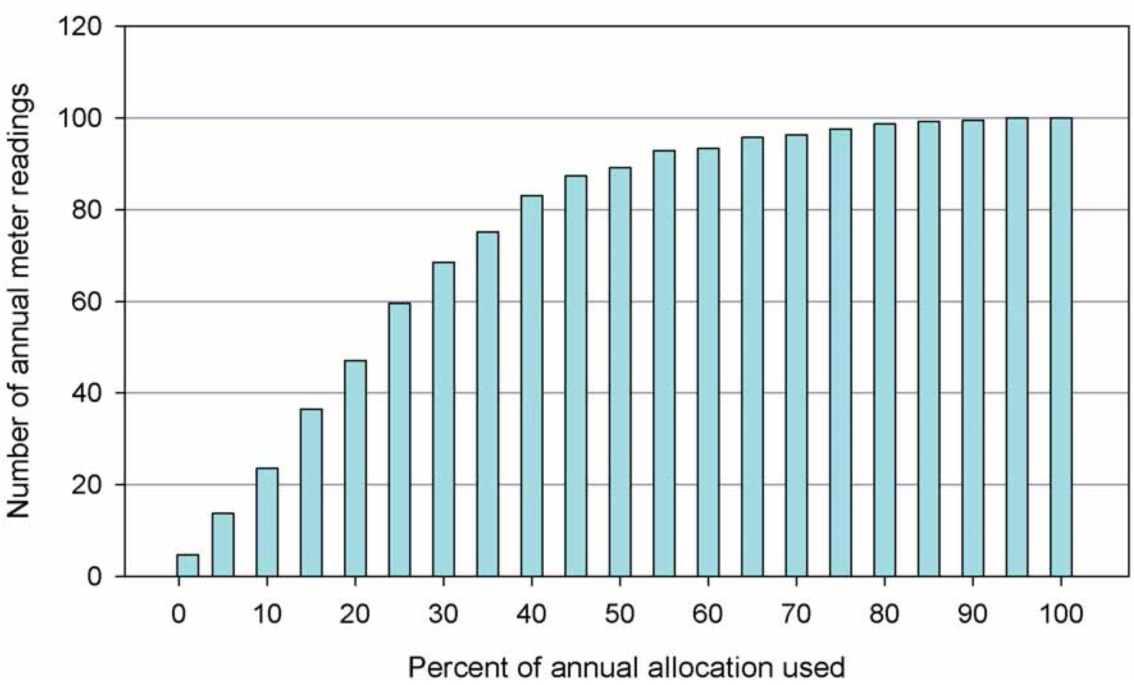


Figure 7.39: Cumulative frequency plot for percentage allocation used (based on all annual meter readings for the Wairarapa Valley over 2002-2008)

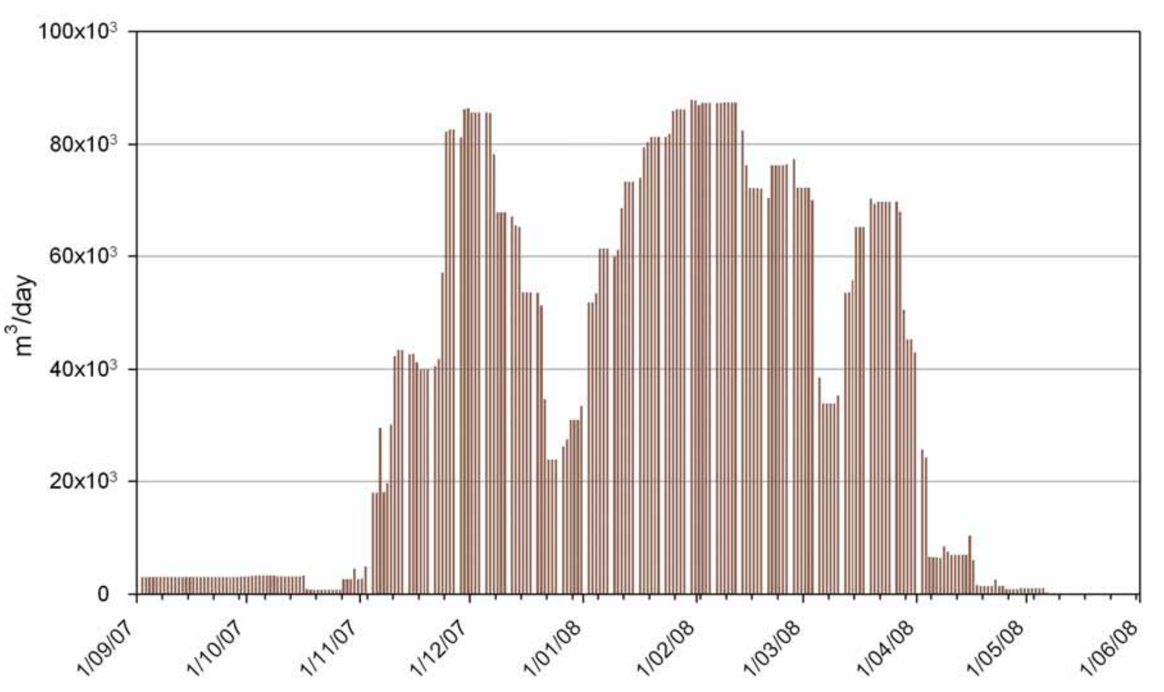


Figure 7.40: Meter reading data for the 2007/08 irrigation season for all groundwater takes of >10 L/s in the Lower Valley catchment

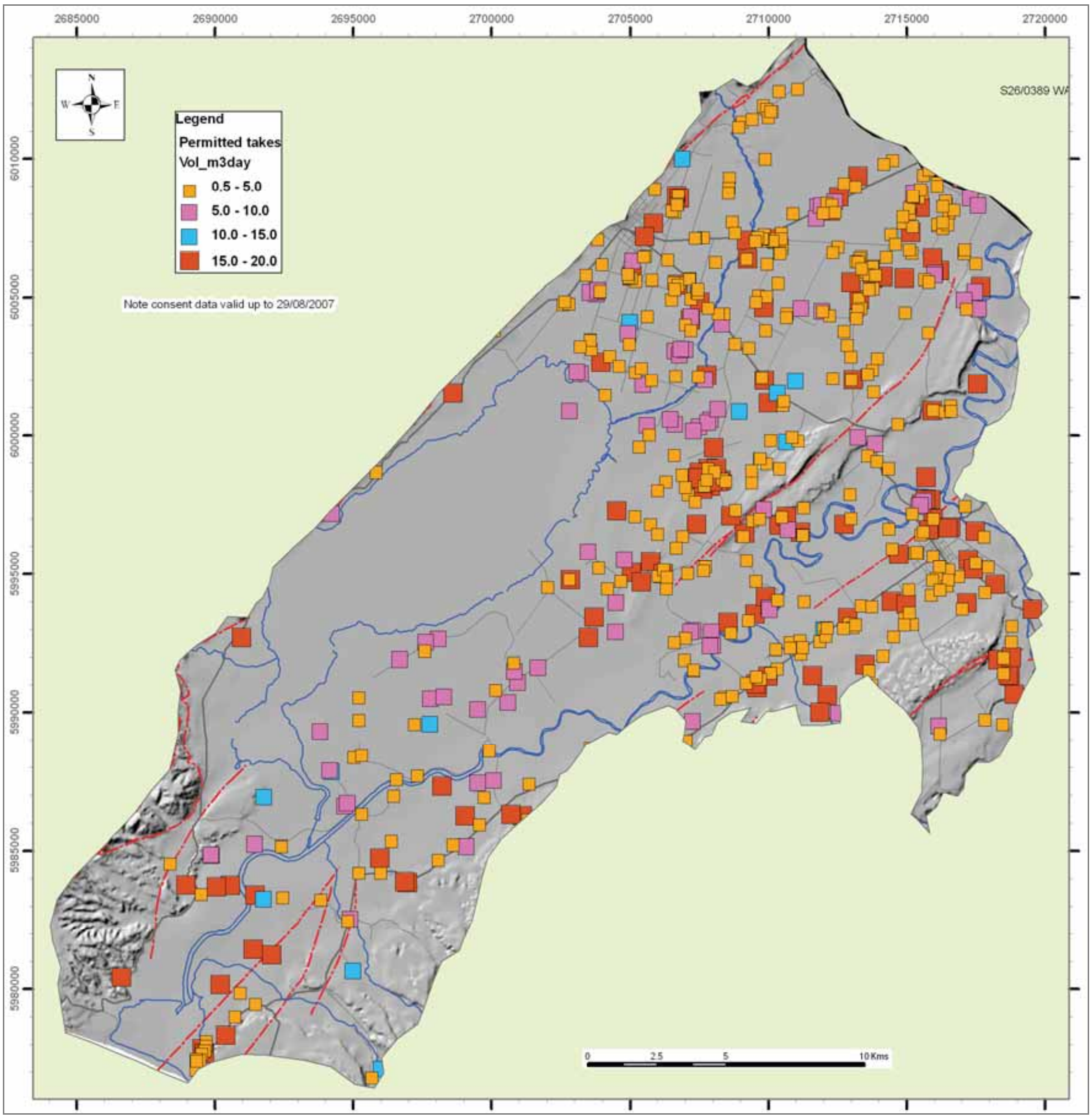


Figure 7.41: Estimated permitted (non-consented) groundwater abstractions in the Lower Valley catchment based on land use and Greater Wellington's Wells database. Abstractions of less than 20m^3/day do not require a resource consent. It is estimated that there are some 590 permitted groundwater takes in the catchment abstracting at an estimated mean rate of 11,400m^3/day.

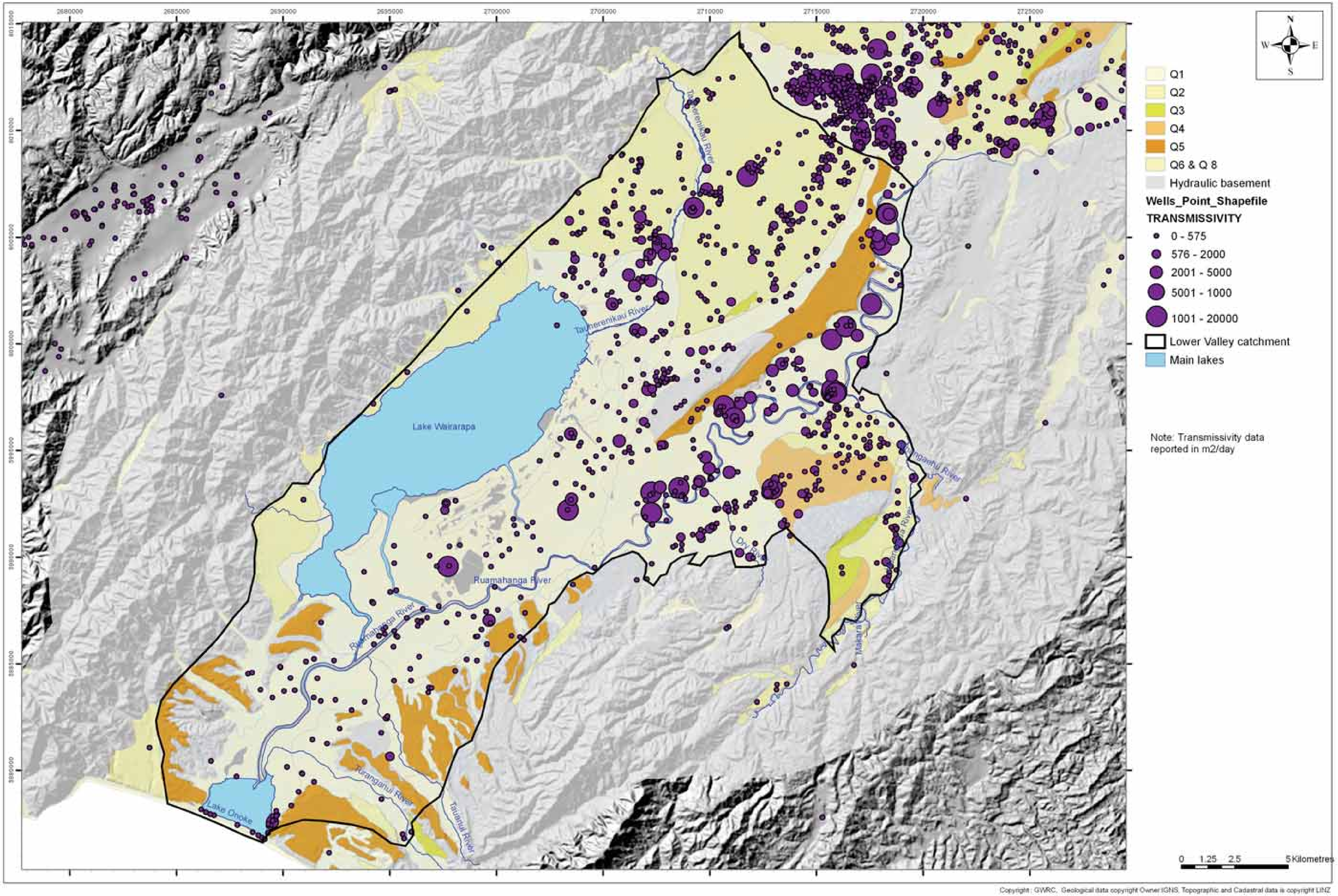


Figure 7.42: Transmissivity distribution in the Lower Valley catchment using aquifer test data derived from Greater Wellington's Wells database. Note the high transmissivity values associated with shallow Q1 alluvium along the Ruamahanga valley and around the Tauherenikau River.

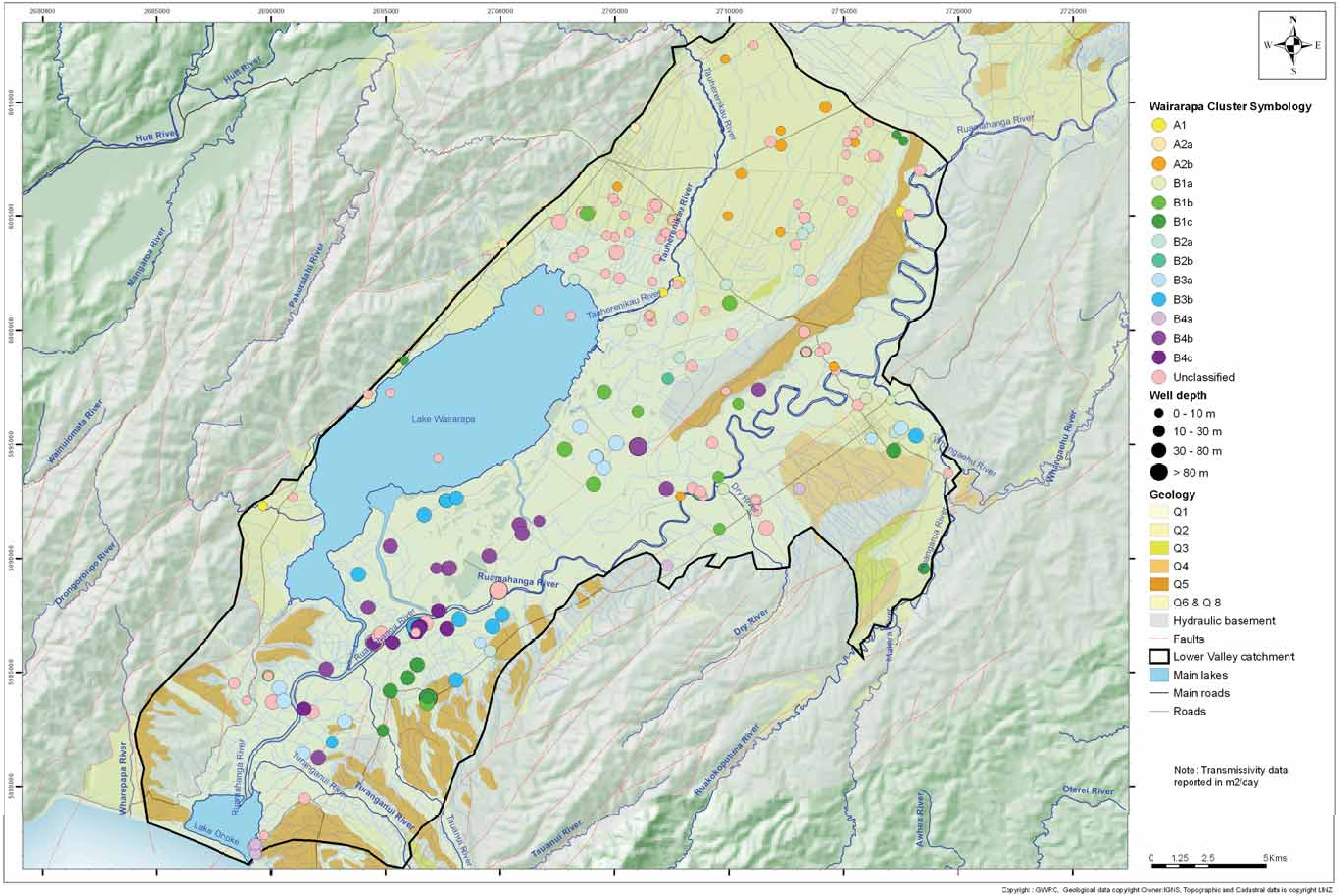


Figure 8.1: Results from hierarchical cluster analysis (HCA) of groundwater and surface water chemistry data in the Lower Valley catchment

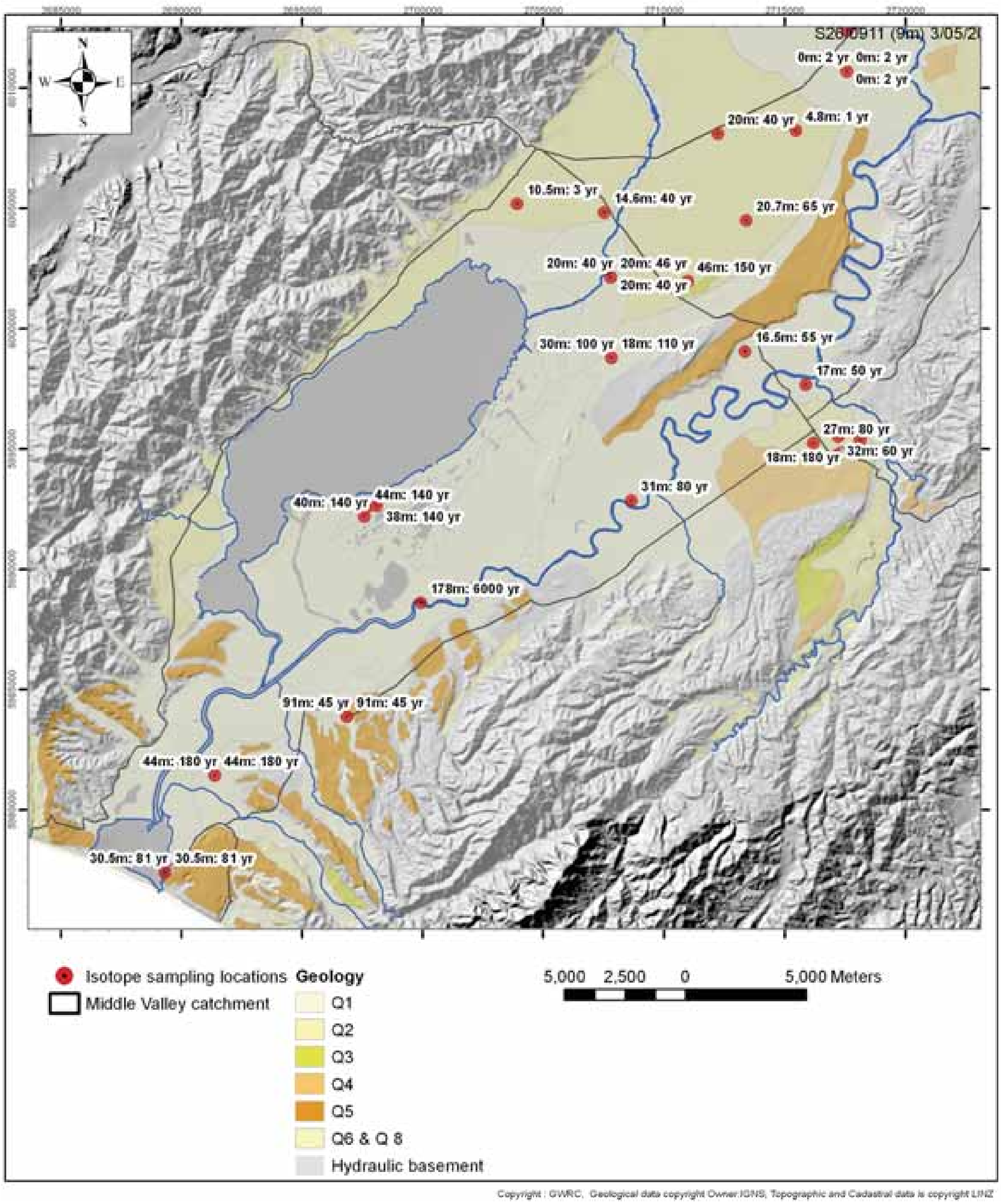


Figure 8.2: Groundwater residence times derived from a compilation of tritium, CFC, SF6 and C14 dating techniques

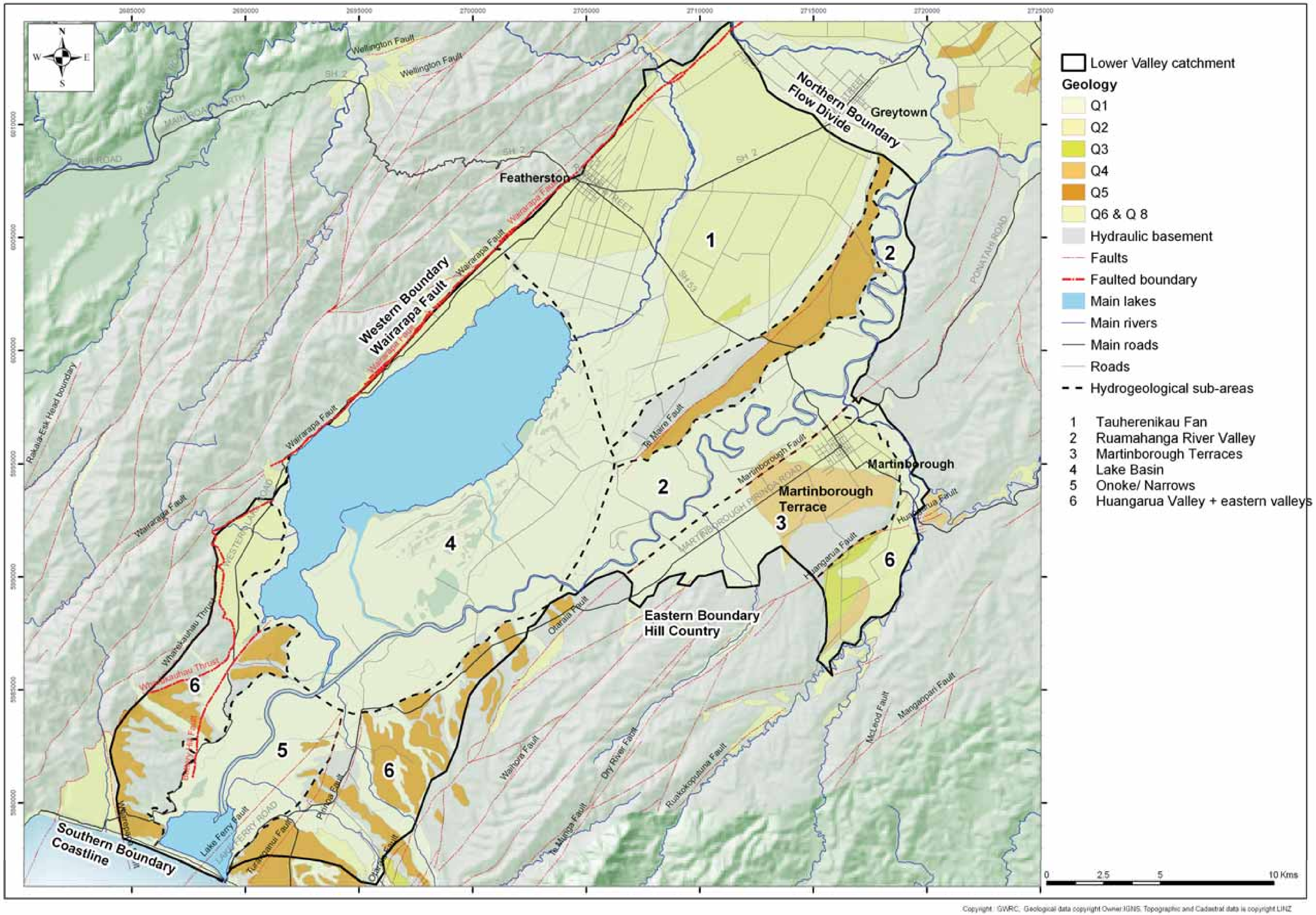


Figure 9.1: The Lower Valley catchment showing model domain boundaries and hydrogeological sub-areas

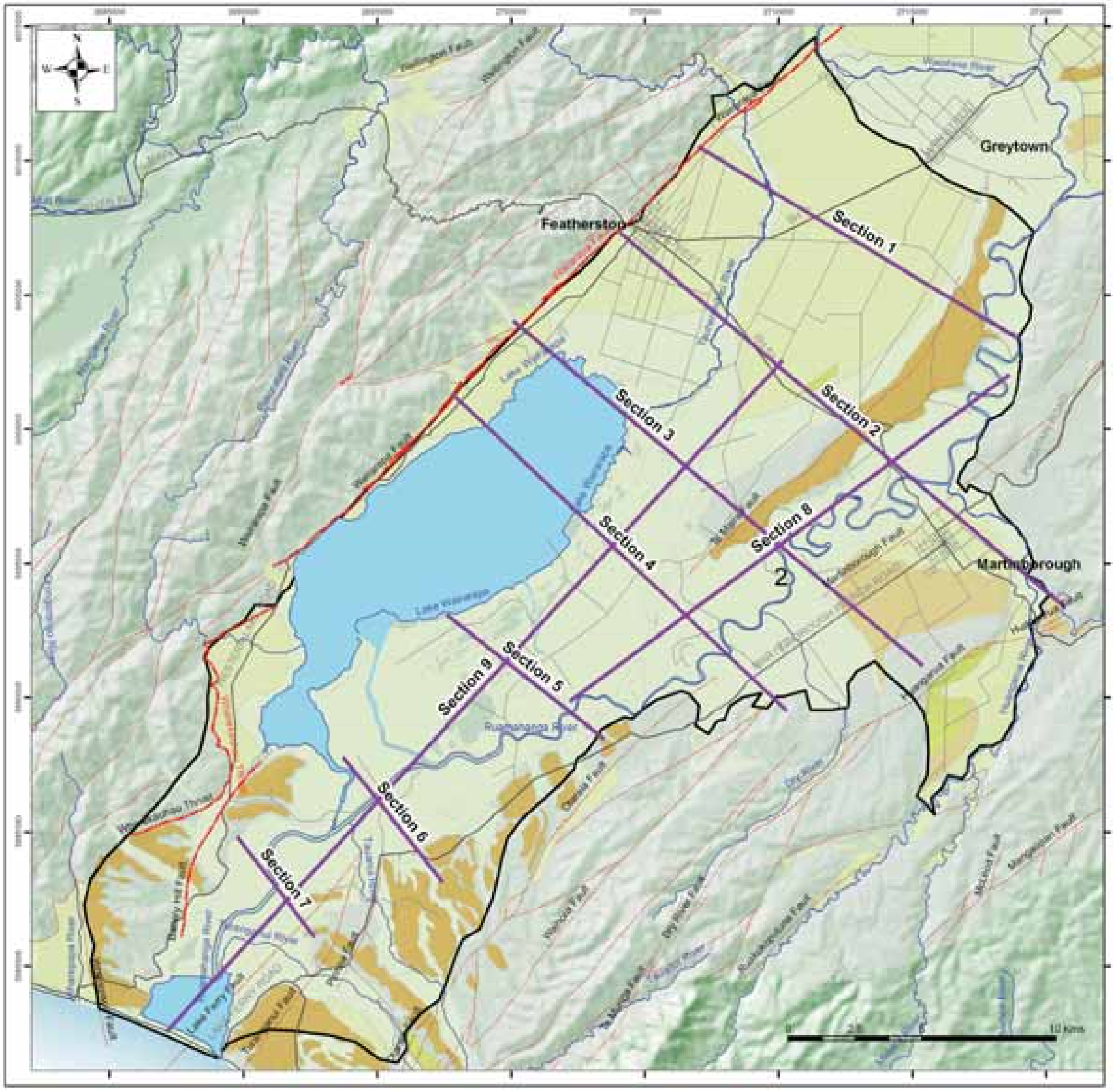


Figure 10.1: Cross section locations in the Lower Valley catchment model domain

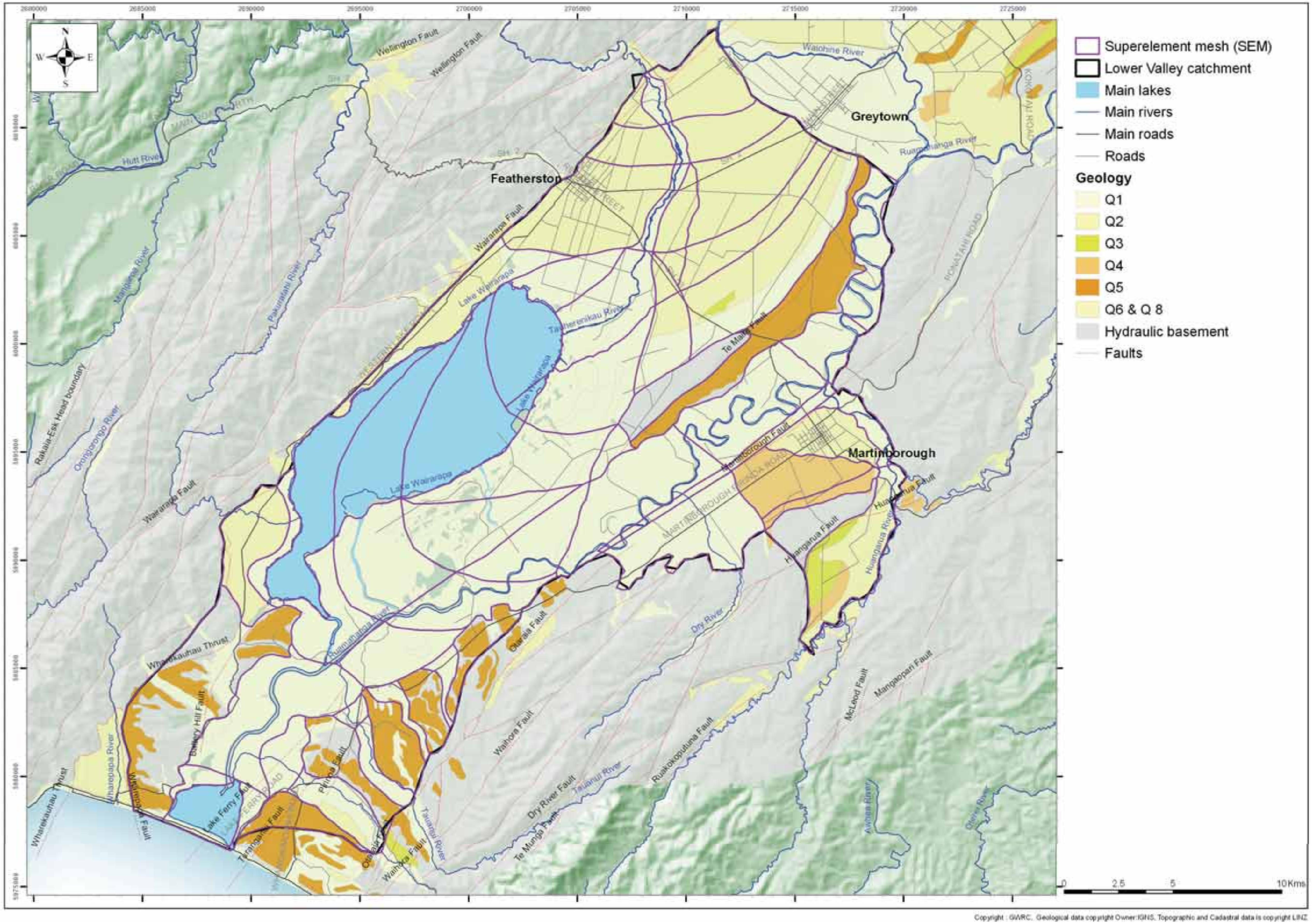


Figure 10.2: Super element mesh (SEM) used for generating the finite element mesh for the Lower Valley catchment FEFLOW groundwater model

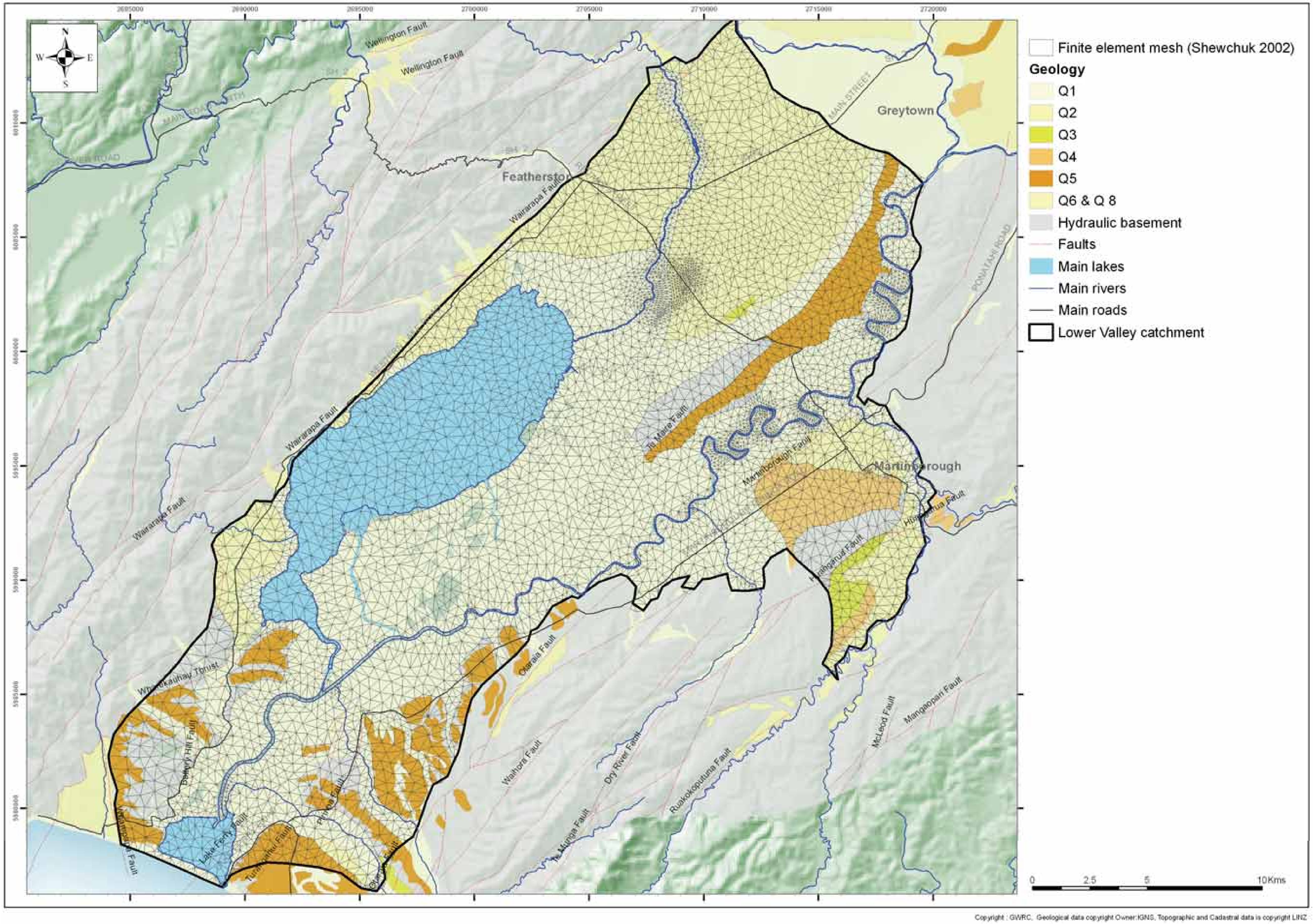


Figure 10.3: Finite element mesh for the Lower Valley catchment groundwater model generated using "Triangle" (Shewchuk 2002)

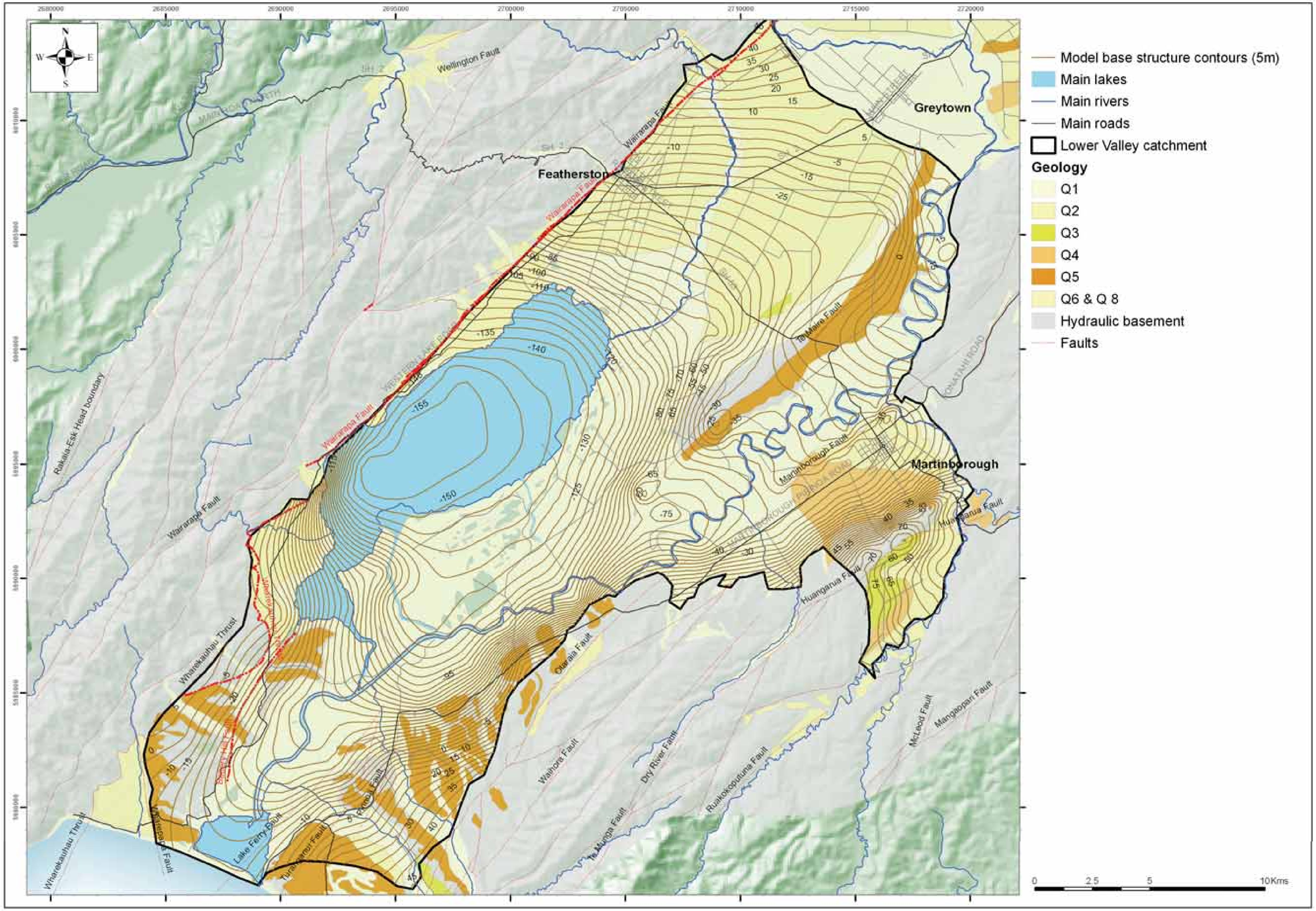


Figure 10.4: Model base structure contours, Lower Valley catchment

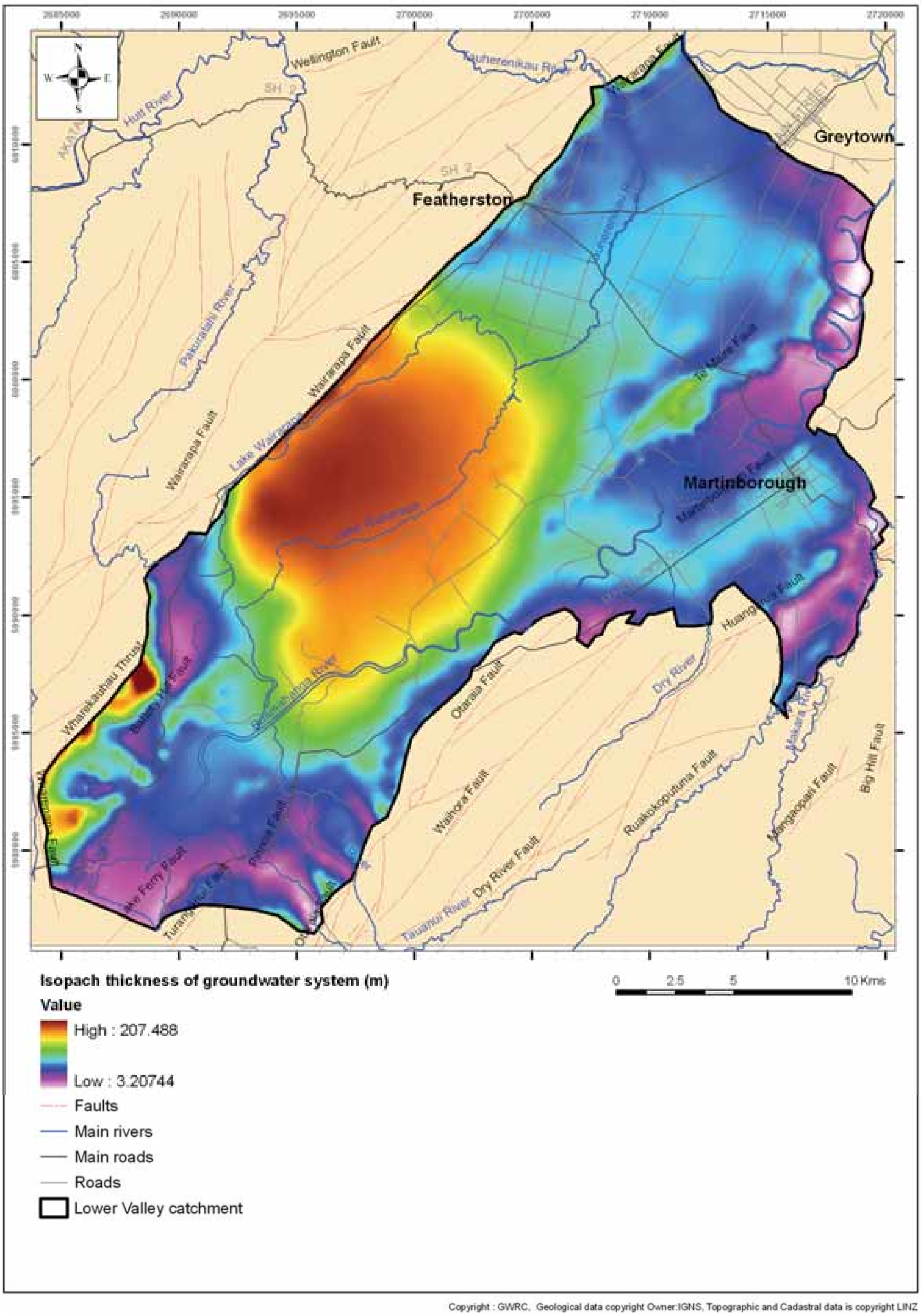


Figure 10.5: Thickness (isopach) of the groundwater system in the Lower Valley catchment model

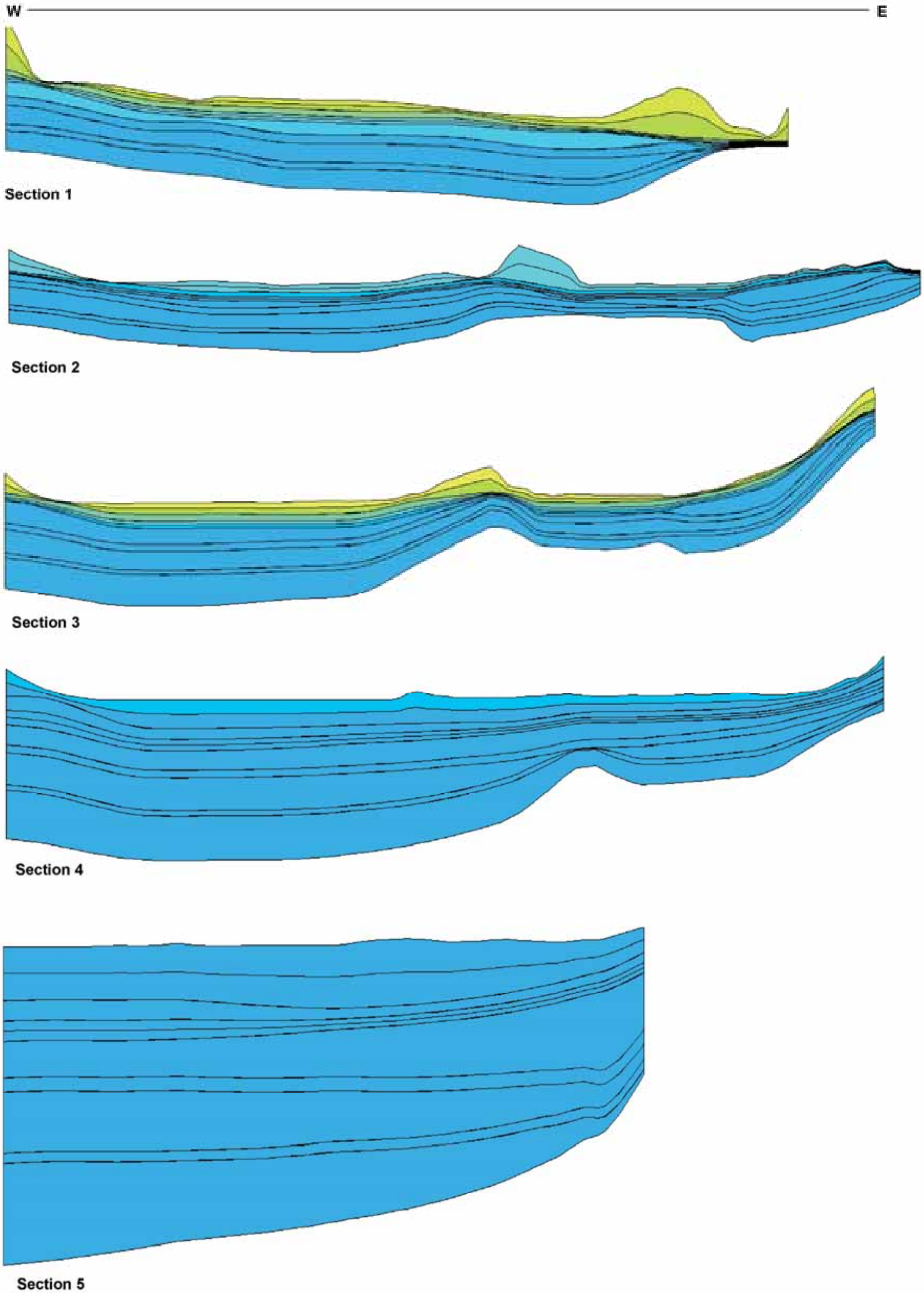


Figure 10.6A: Model cross sections 1–5 showing three-dimensional layer configuration. Section locations are shown in Figure 10.1. Vertical scales are consistent, horizontal scales are approximate.

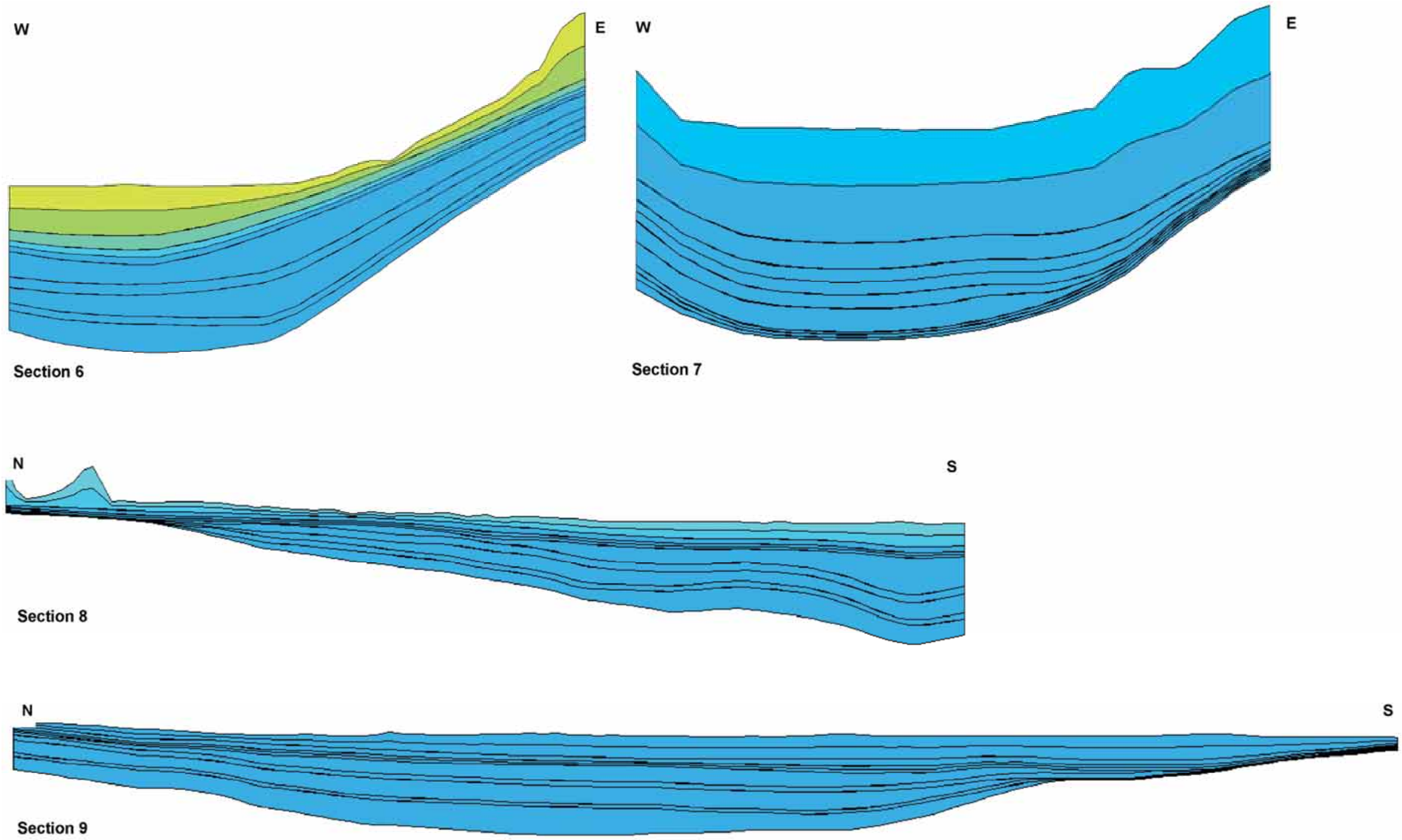


Figure 10.6B: Model cross sections 6–9 showing three-dimensional layer configuration. Section locations are shown in Figure 10.1. Vertical and horizontal scales are not consistent.

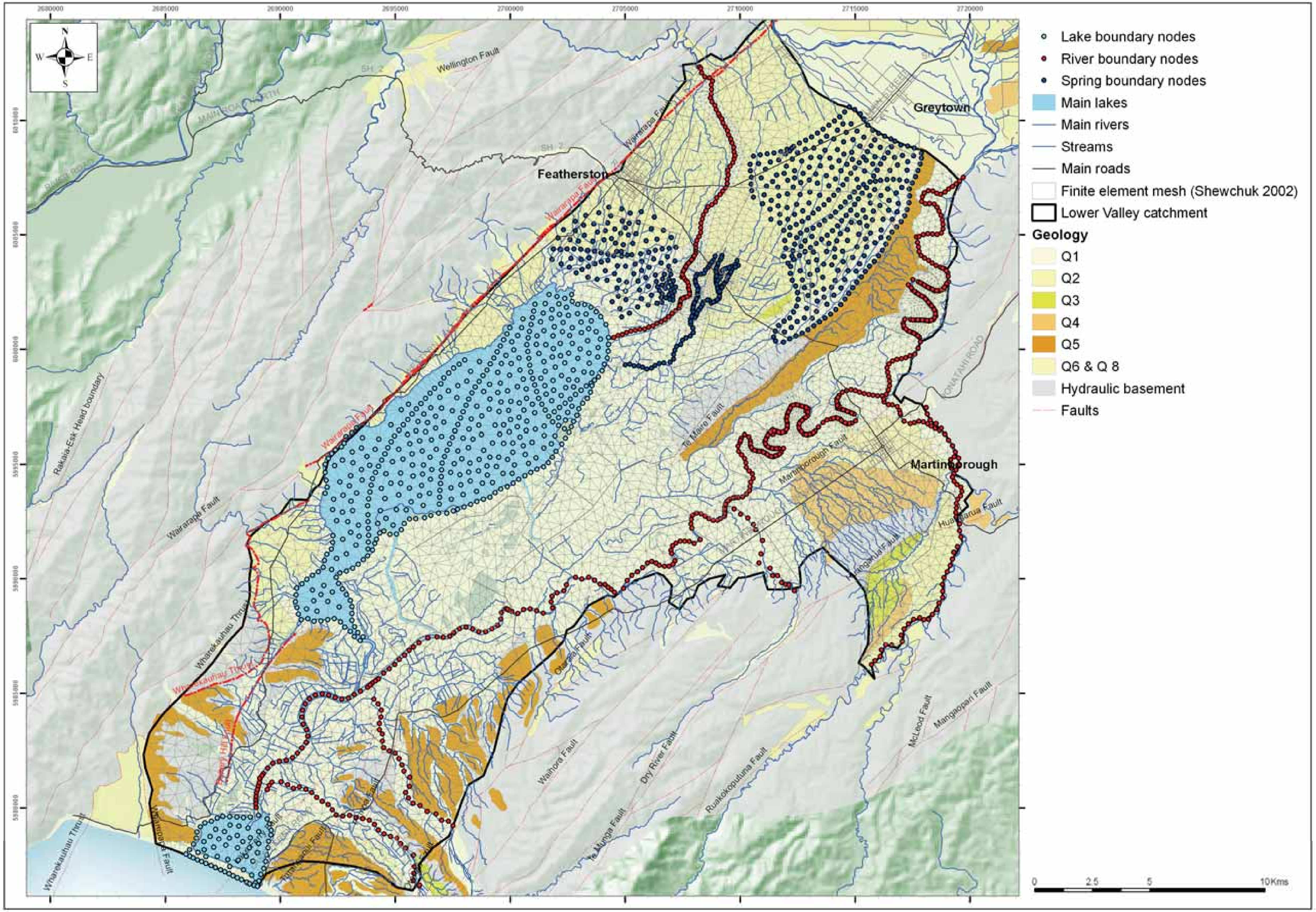


Figure 10.7: River, spring, and lake transfer boundary nodes for the Lower Valley catchment model (all layers)

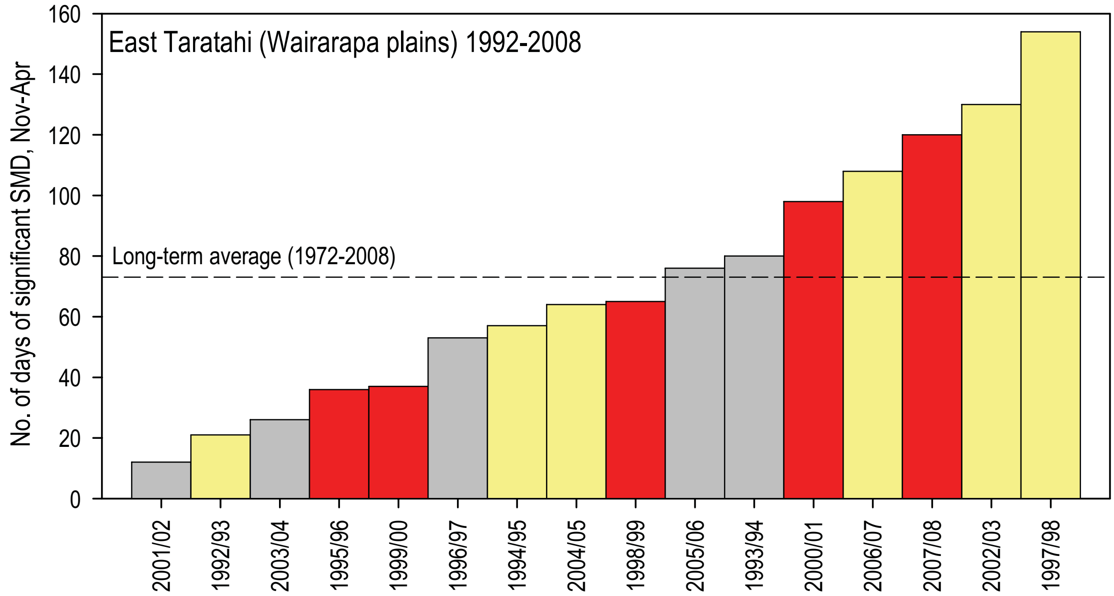


Figure 11.1: Number of days per growing season (November to April) with significant soil moisture deficit (greater than 110 mm) at East Taratahi near Masterton during the model calibration period, 1992–2008. Yellow bars indicate El Nino, red indicate La Nina, and grey indicate neutral years. Soil moisture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

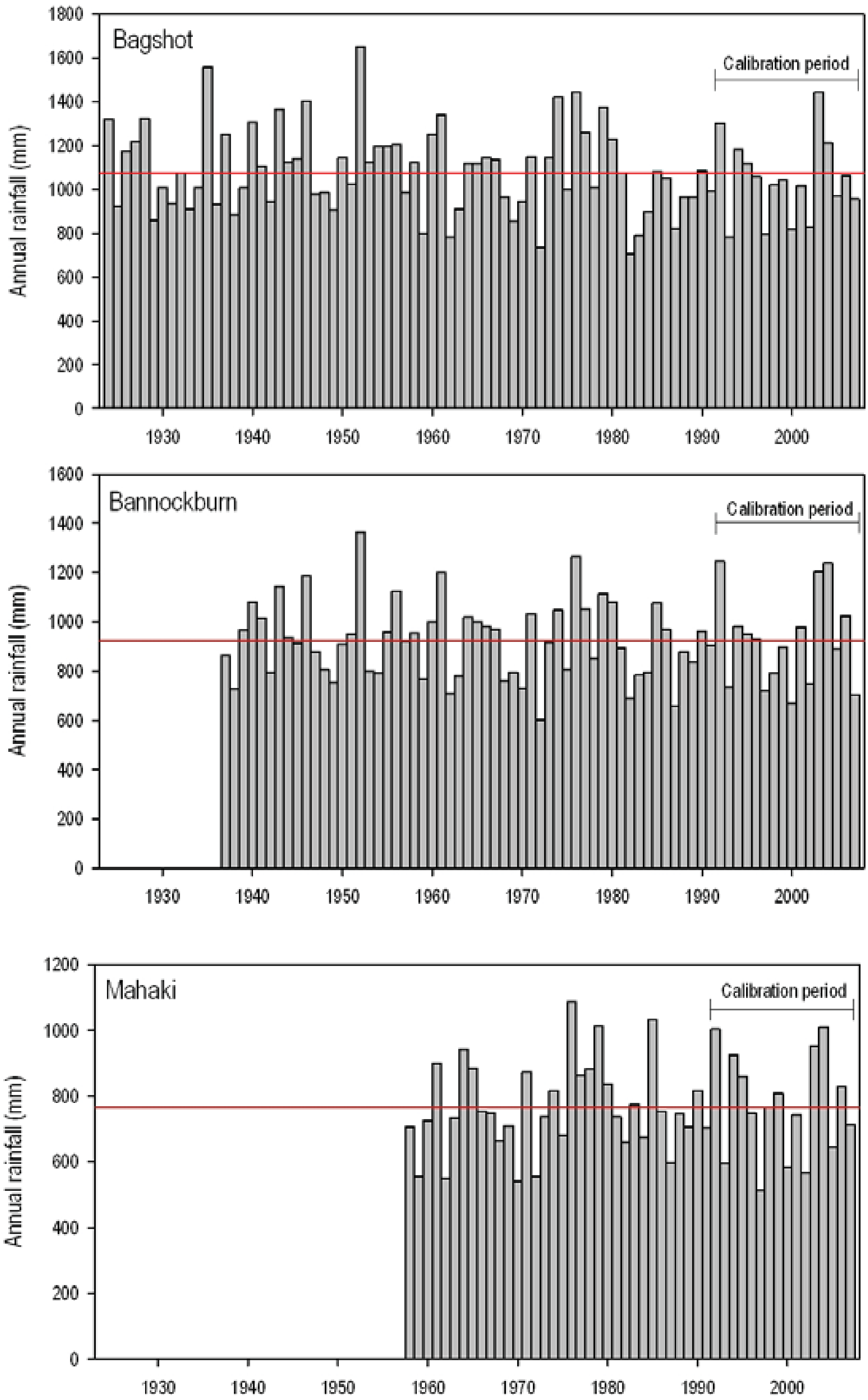
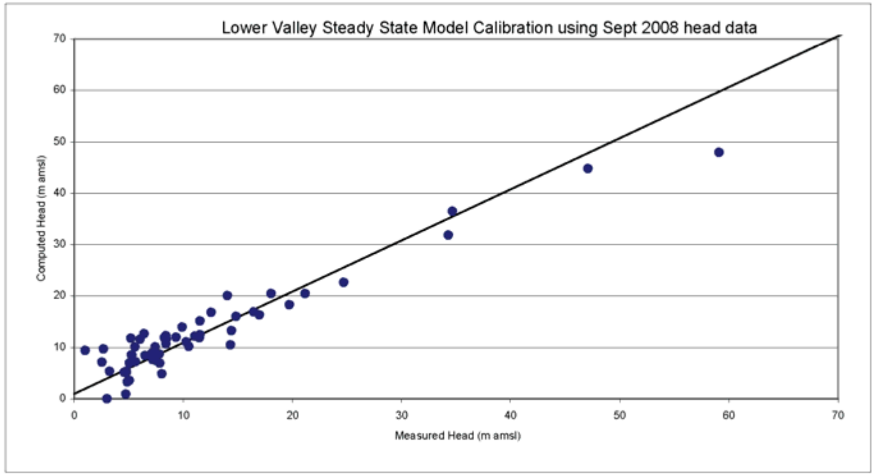


Figure 11.2: Annual rainfall at three long-term monitoring sites in the Wairarapa. The red line indicates the long-term mean at each site. Note the annual rainfalls shown are for a July to June year (data provided by NIWA).

Steady-state model calibration

Well No	Depth	Measured Head m	Computed Head m	Residual m	Abs residual m	Squared residual m2	Weight
S27/0584	49	1.01	9.34	-8.33	8.33	69.47	1
S27/0621	42	2.55	7.14	-4.58	4.58	21.00	1
S27/0263	19	2.70	9.71	-7.01	7.01	49.16	1
R28/0001	28	3.01	0.05	2.96	2.96	8.79	1
S27/0467	30	3.27	5.37	-2.10	2.10	4.41	1
S27/0464	40	4.60	5.11	-0.51	0.51	0.26	1
R28/0002	17	4.74	0.85	3.89	3.89	15.14	1
S27/0434	45	4.81	5.04	-0.24	0.24	0.06	1
S27/0461	24	4.81	5.35	-0.54	0.54	0.29	1
S27/0428	44	4.89	3.21	1.68	1.68	2.82	1
S27/0441	40	5.05	3.51	1.54	1.54	2.36	1
S27/0465	39	5.08	6.89	-1.81	1.81	3.29	1
S27/0581	14	5.22	11.72	-6.50	6.50	42.31	1
S27/0484	25	5.25	8.53	-3.28	3.28	10.74	1
S27/0485	26	5.29	8.53	-3.24	3.24	10.48	1
S27/0576	56	5.61	10.06	-4.45	4.45	19.80	1
S27/0446	60	5.62	7.18	-1.57	1.57	2.45	1
S27/0587	34	6.07	11.51	-5.44	5.44	29.60	1
S27/0278	15	6.40	12.66	-6.26	6.26	39.18	1
S27/0478	24	6.53	8.42	-1.90	1.90	3.61	1
S27/0502	30	7.15	8.89	-1.74	1.74	3.02	1
S27/0304	52	7.20	7.58	-0.38	0.38	0.14	1
S27/0275	28	7.46	10.03	-2.57	2.57	6.62	1
S27/0261	41	7.54	7.39	0.15	0.15	0.02	1
S27/0326	30	7.81	8.72	-0.91	0.91	0.82	1
S27/0602	61	7.86	6.95	0.91	0.91	0.82	1
S27/0425	49	8.05	4.85	3.20	3.20	10.27	1
S27/0594	44	8.27	11.80	-3.53	3.53	12.48	1
S27/0317	18	8.42	12.19	-3.77	3.77	14.24	1
S27/0542	19	8.45	10.63	-2.19	2.19	4.78	1
S27/0277	28	8.49	11.58	-3.09	3.09	9.54	1
S27/0363	18	9.35	11.95	-2.60	2.60	6.76	1
S27/0330	20	9.91	13.96	-4.05	4.05	16.37	1
S27/0603	58	10.29	11.10	-0.81	0.81	0.66	1
S27/0481	23	10.51	10.13	0.38	0.38	0.14	1
S27/0271	30	11.08	12.18	-1.10	1.10	1.20	1
S27/0309	30	11.47	11.85	-0.38	0.38	0.14	1
S27/0522	21	11.53	15.15	-3.62	3.62	13.12	1
S27/0618	47	11.53	12.48	-0.95	0.95	0.90	1
S27/0340	45	12.56	16.82	-4.26	4.26	18.16	1
S27/0012	66	14.04	20.01	-5.97	5.97	35.65	1
S27/0503	14	14.35	10.47	3.89	3.89	15.10	1
S27/0517	19	14.41	13.22	1.18	1.18	1.40	1
S27/0346	9	14.85	15.97	-1.13	1.13	1.27	1
S27/0293	22	16.48	16.89	-0.41	0.41	0.17	1
S27/0381	23	16.97	16.31	0.66	0.66	0.43	1
S27/0009	10	18.08	20.47	-2.39	2.39	5.71	1
S27/0728	12	19.75	18.30	1.45	1.45	2.10	1
S27/0035	6	21.16	20.48	0.68	0.68	0.47	1
S27/0571	32	24.69	22.62	2.07	2.07	4.29	1
S27/0099	17	34.30	31.76	2.54	2.54	6.43	1
S27/0572	3	34.67	36.41	-1.74	1.74	3.01	1
S27/0202	5	47.12	44.72	2.40	2.40	5.75	1
S27/0148	9	59.09	47.87	11.22	11.22	125.92	1



Calibration Statistics

Absolute residual mear	2.40 m
Min residual	-8.33 m
Max residua	11.22 m
Sum of residuals	146.13 m
Residual Standard deviatio	3.33 m
Observed range in heac	58.08 m
Mean sum of residuals	2.71 m
Scaled mean sum of residuals	0.09 %
Sum of residual squares	663.12 m^2
Root mean square (RMS error	3.50 m
Scaled RMS	6.03 %

Figure 11.3: Results for the preliminary steady-state calibration of the Lower Valley model showing model-to-measurement scatter plot

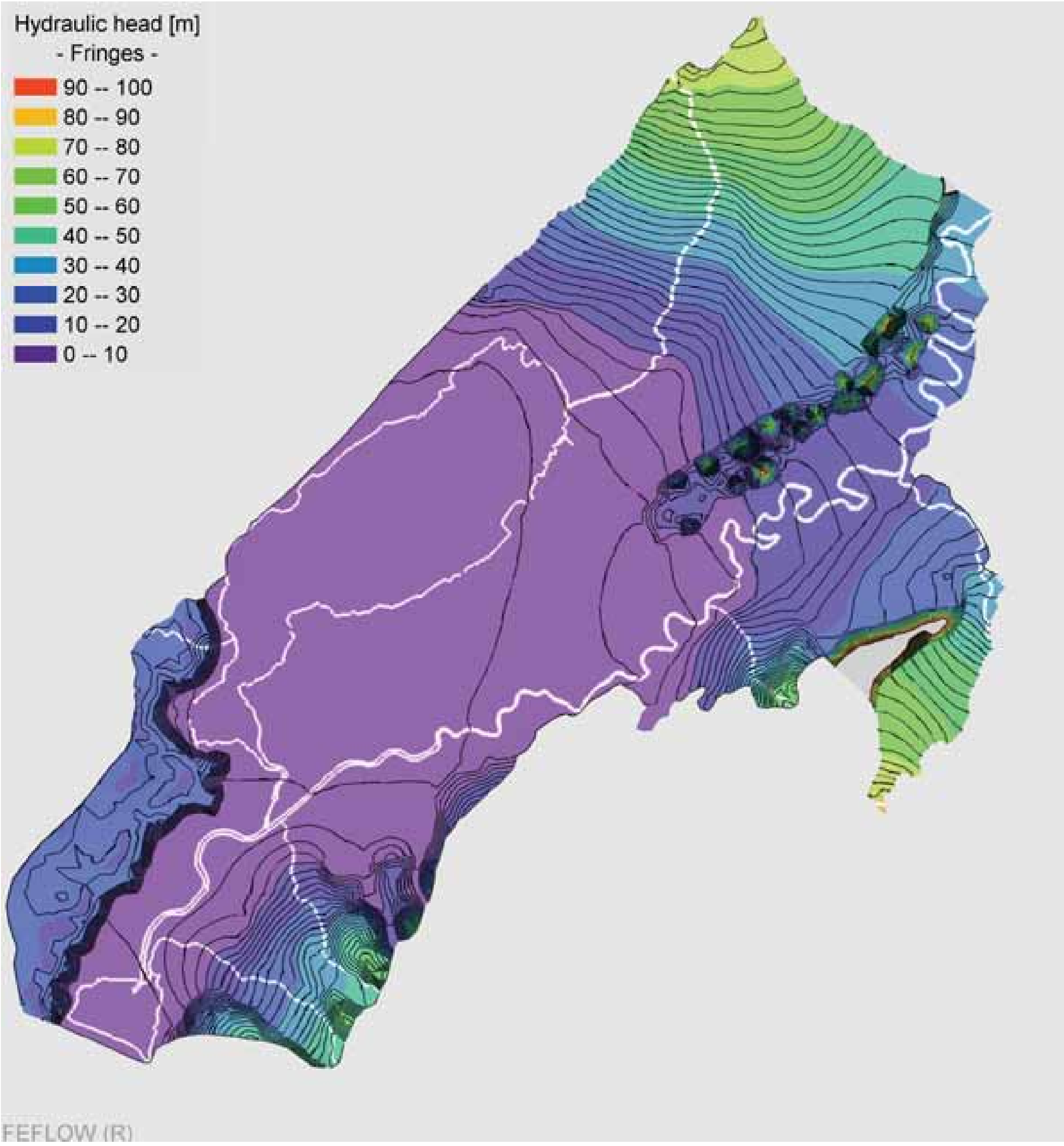


Figure 11.4: Modelled steady state head distribution (summer conditions) in the Lower Valley catchment

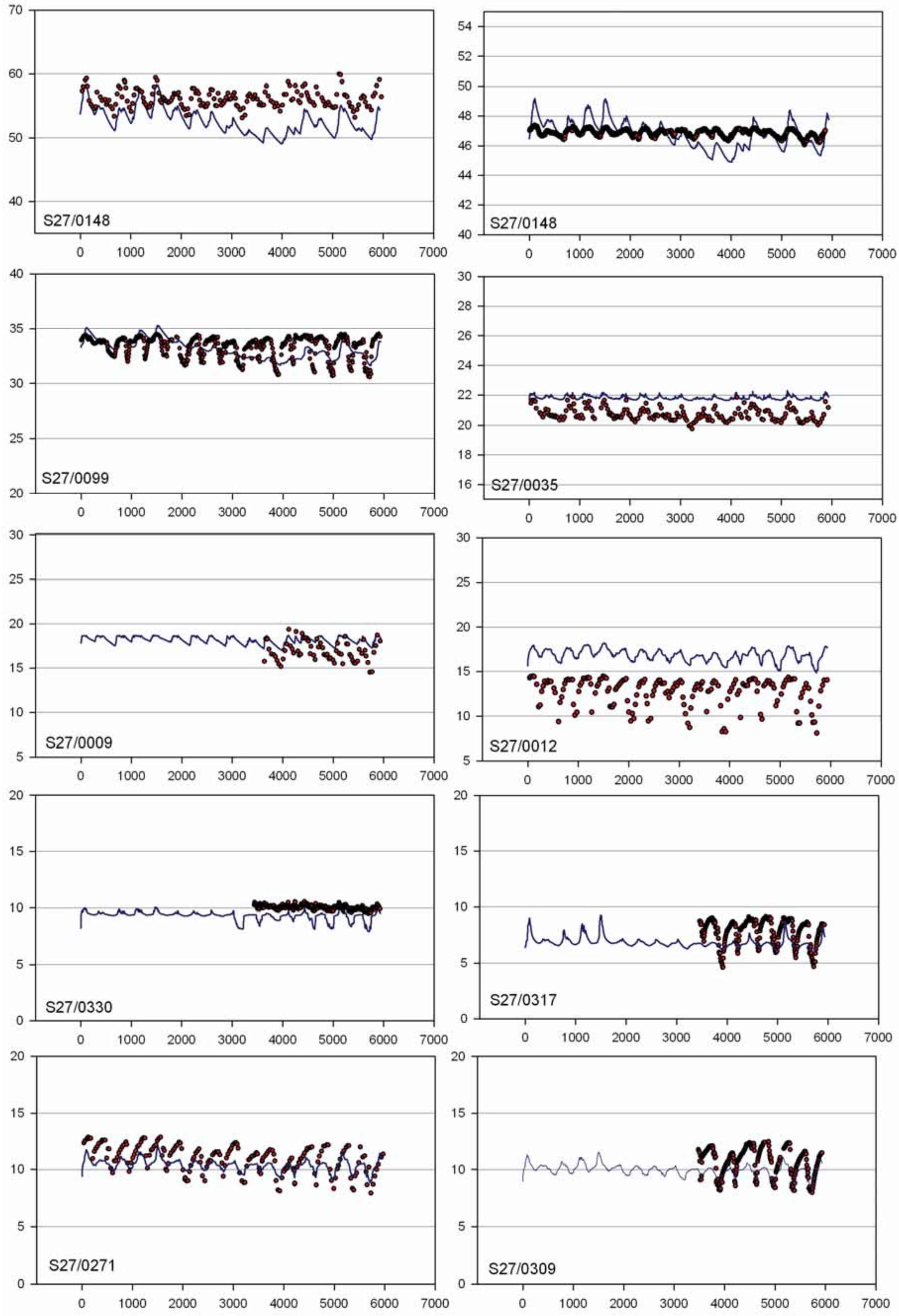


Figure 11.5: Transient model groundwater head calibration plots for sub-area 1 (Tauherenikau fan). Red circles = observed data, solid blue line = simulated head. The vertical scale is in metres amsl.

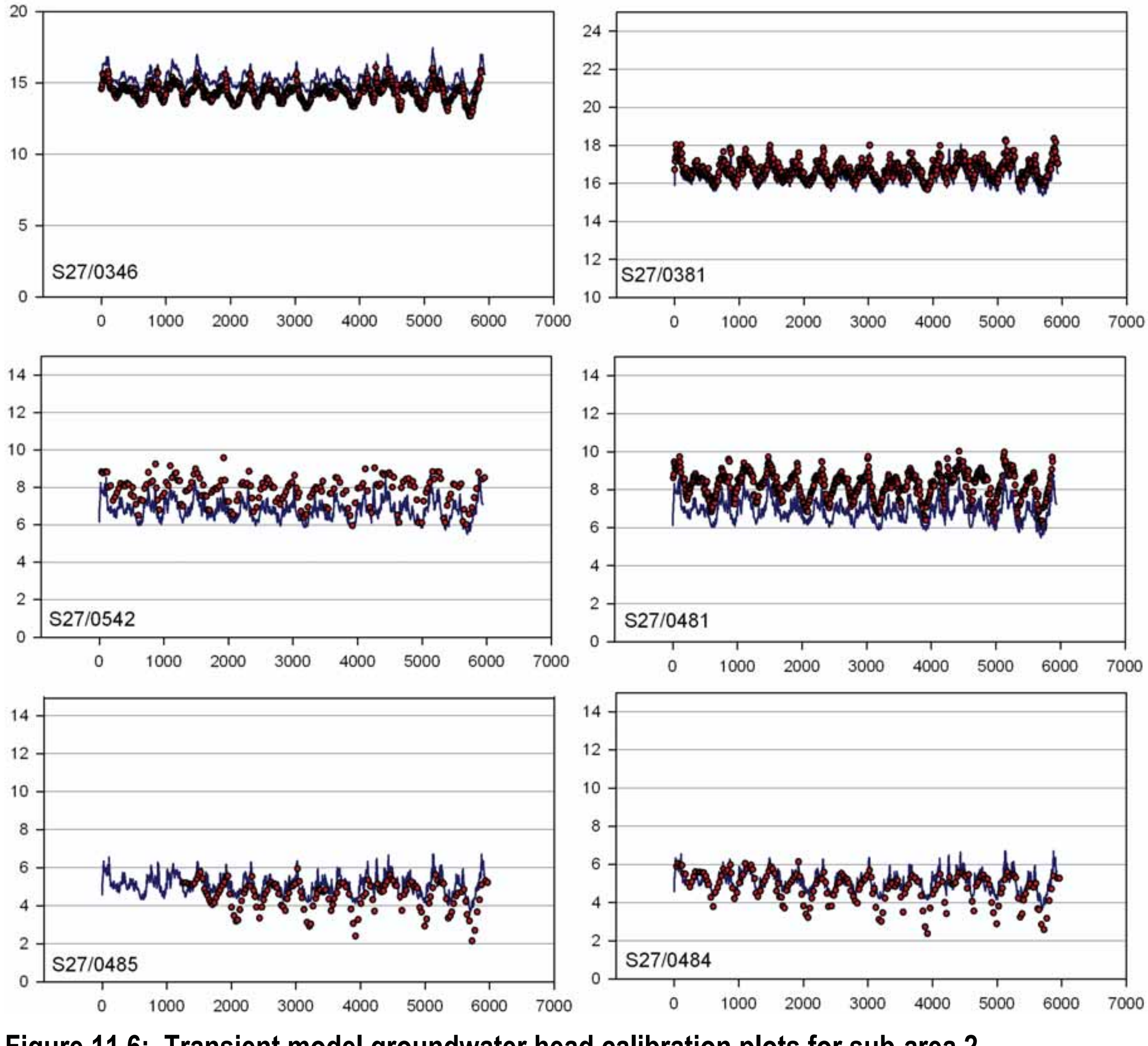


Figure 11.6: Transient model groundwater head calibration plots for sub-area 2 (Ruamahanga valley). Red circles = observed data, solid blue line = simulated head. The vertical scale is in metres amsl.

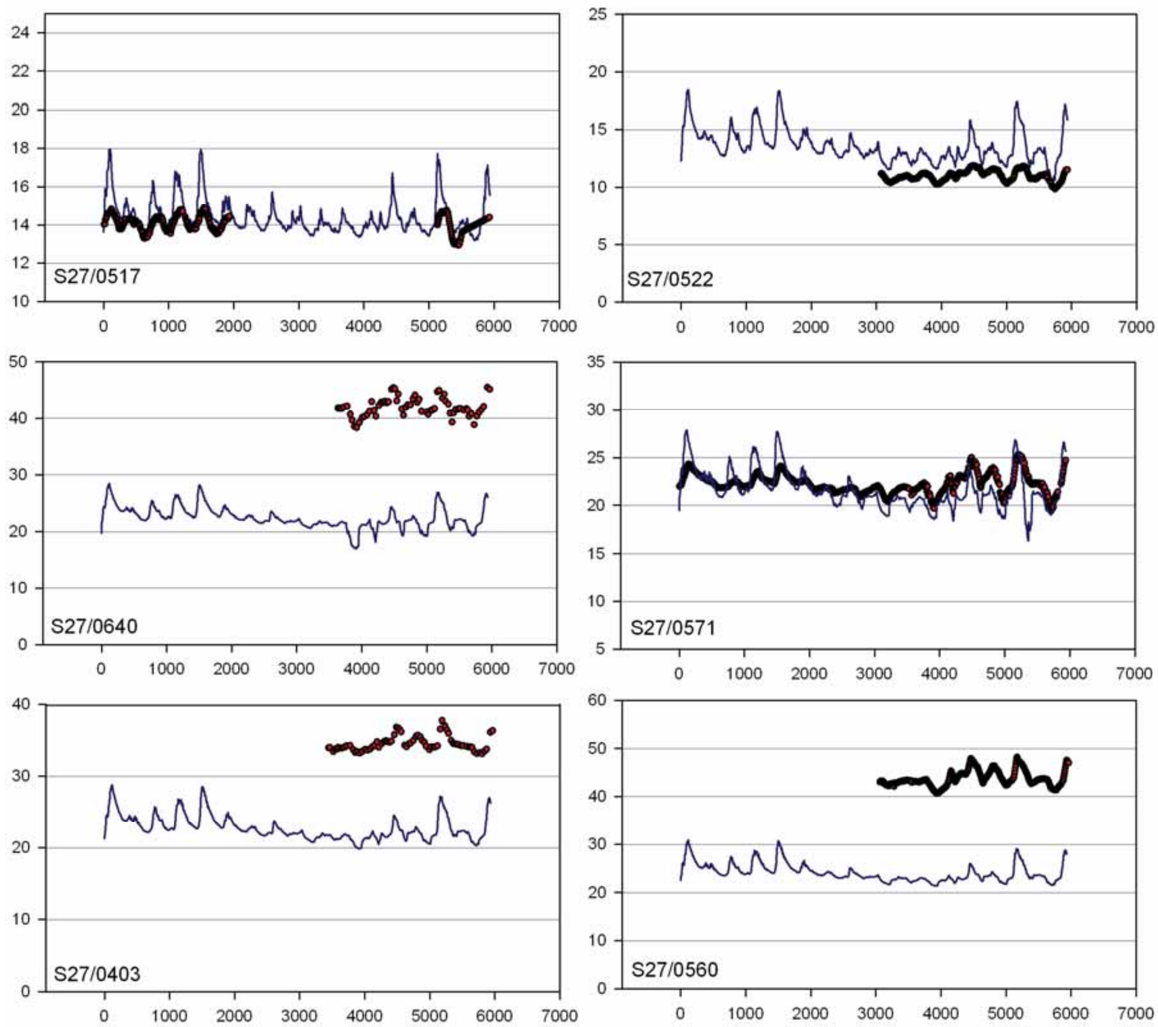


Figure 11.7: Transient model groundwater head calibration plots for sub-area 3 (Martinborough/Dry River). Red circles = observed data, solid blue line = simulated head. The vertical scale is in metres amsl.

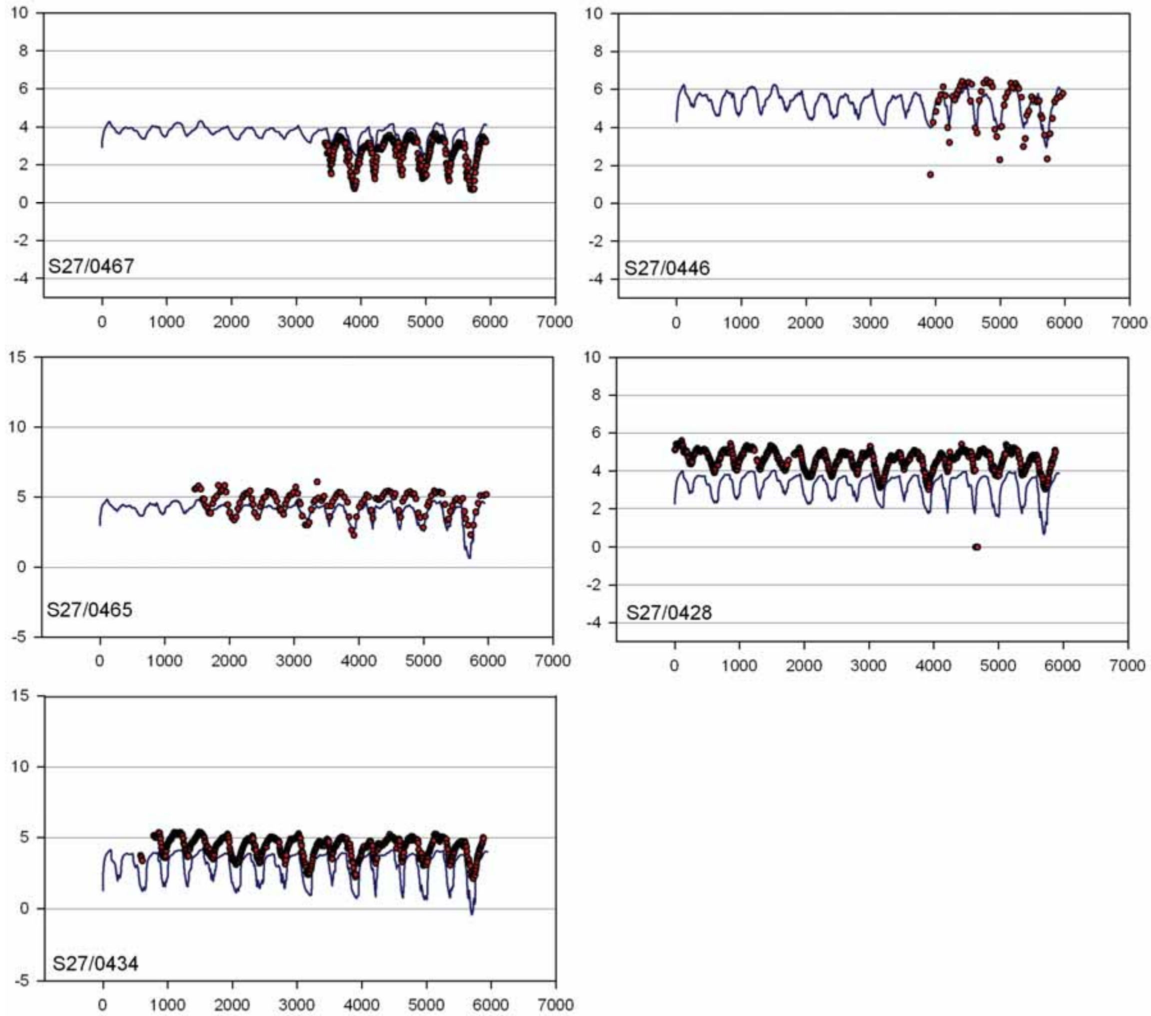


Figure 11.8: Transient model groundwater head calibration plots for sub-area 4 (Lake basin). Red circles = observed data, solid blue line = simulated head. The vertical scale is in metres amsl.

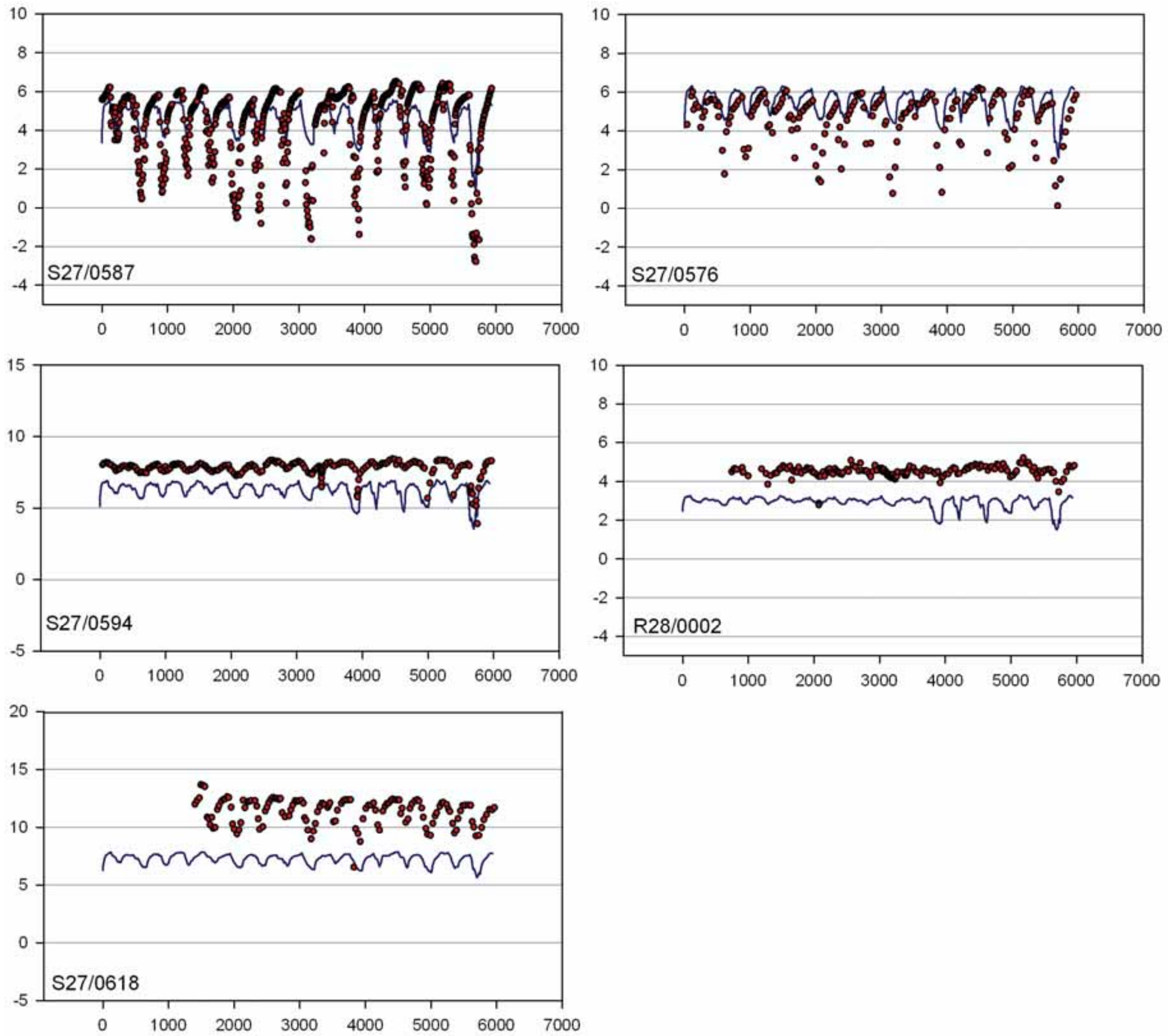


Figure 11.9: Transient model groundwater head calibration plots for sub-area 5 (Onoke). Red circles = observed data, solid blue line = simulated head. The vertical scale is in metres amsl.

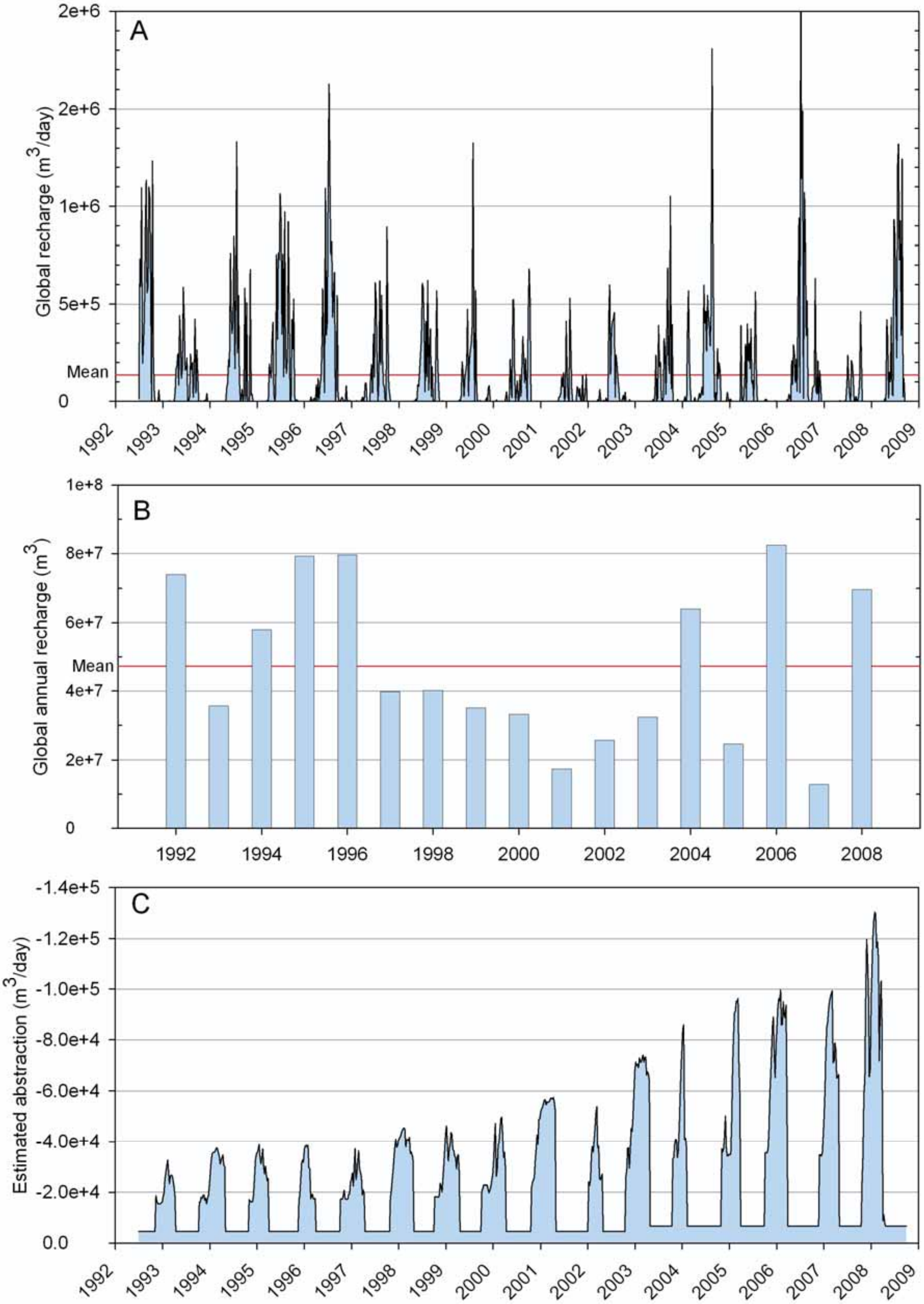


Figure 11.10 (A–C): Transient model calibration simulated global water balances
A – Daily recharge
B – Annual recharge
C – Modelled daily abstraction

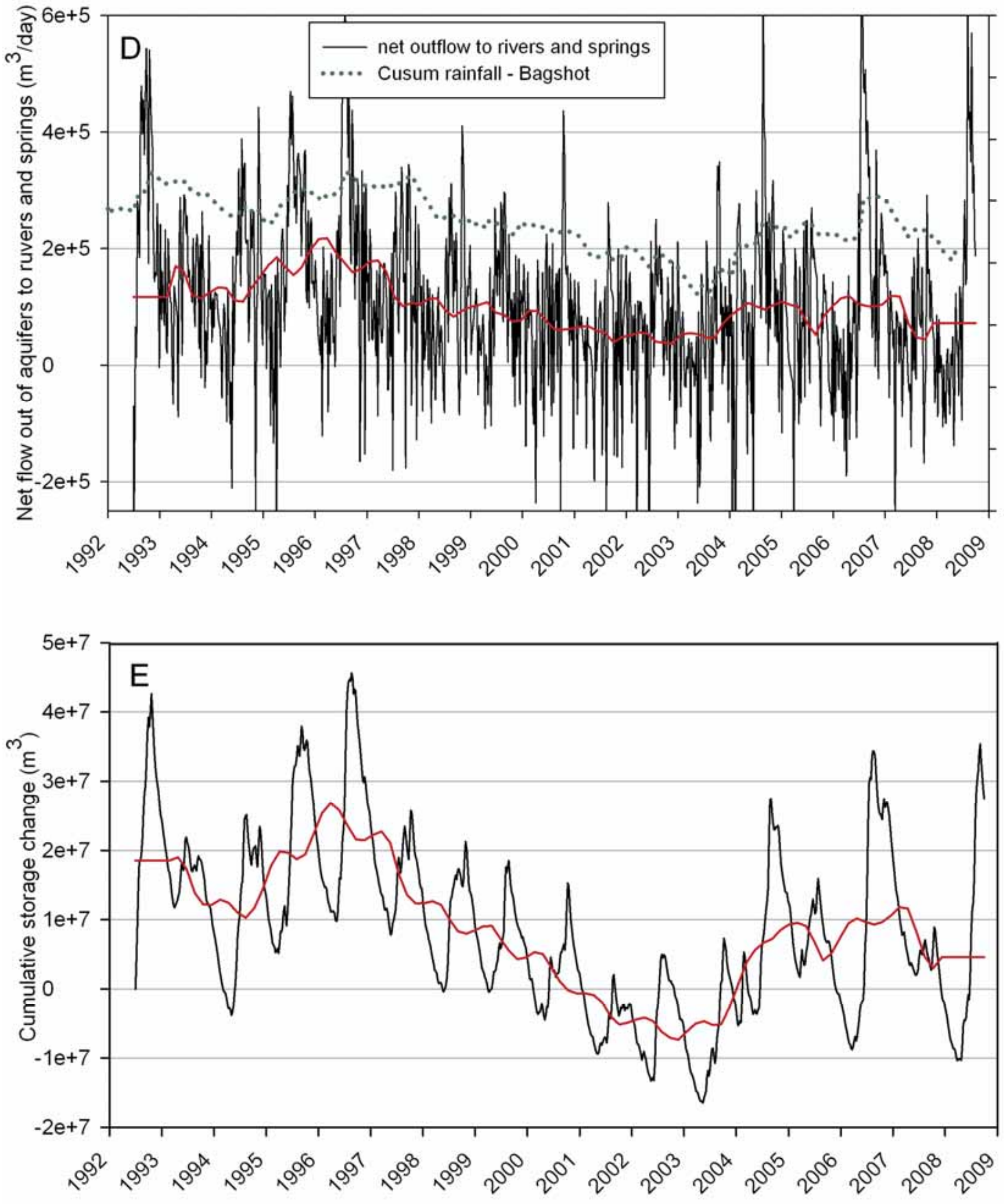


Figure 11.10 (D–E): Transient model calibration simulated global water balances
D – Simulated net flux to surface water
E – Cumulative aquifer storage change over calibration period

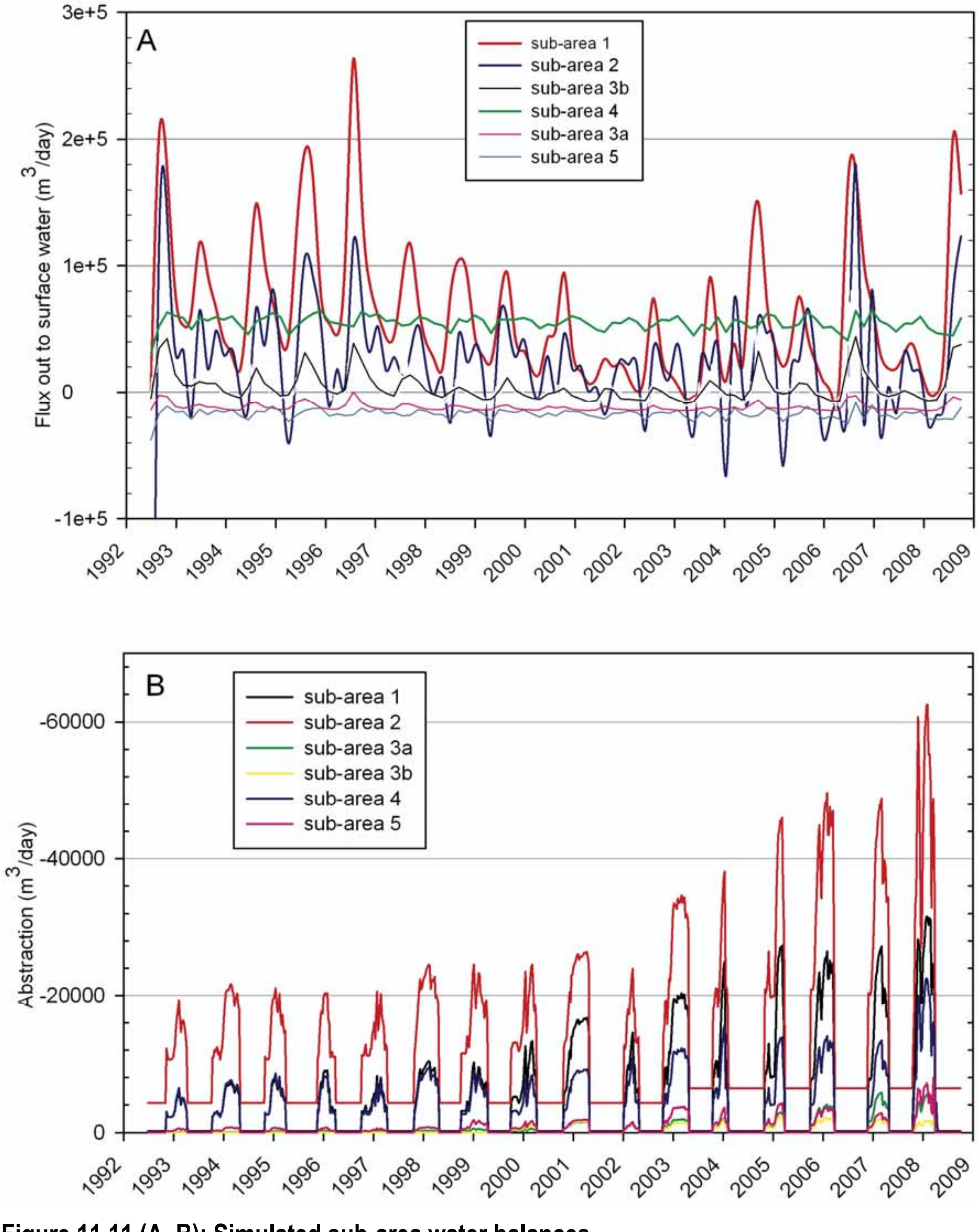


Figure 11.11 (A–B): Simulated sub-area water balances
A – Flux to surface water
B – Daily abstraction

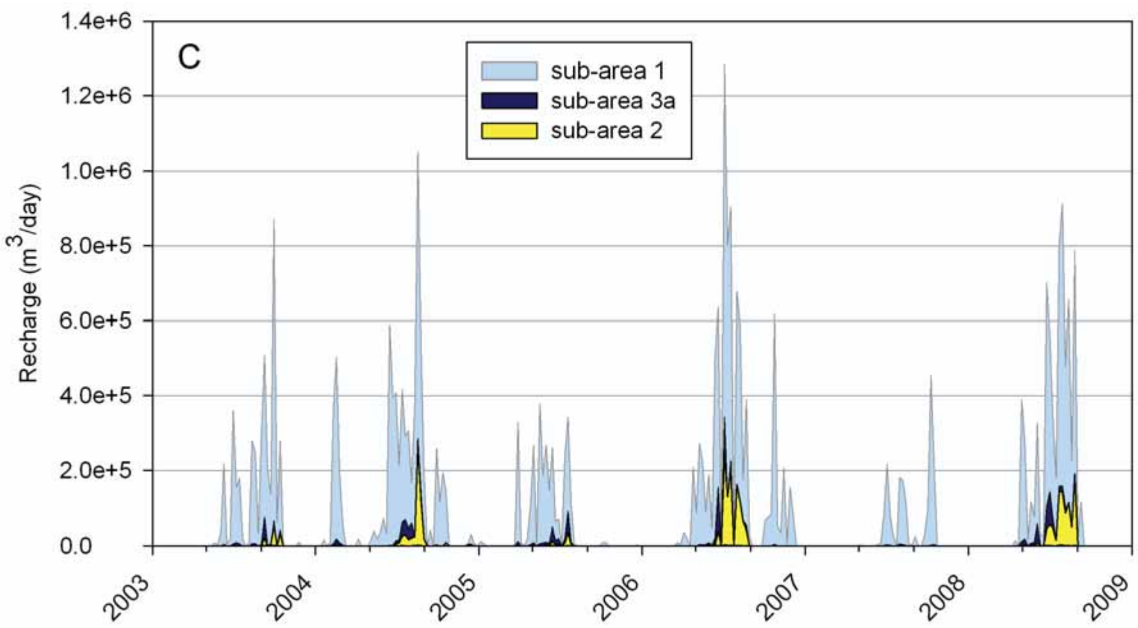


Figure 11.11 (C): Simulated recharge in sub-areas 1 (Tauherenikau fan), 2 (Ruamahanga valley) and 3a (Martinborough terraces)

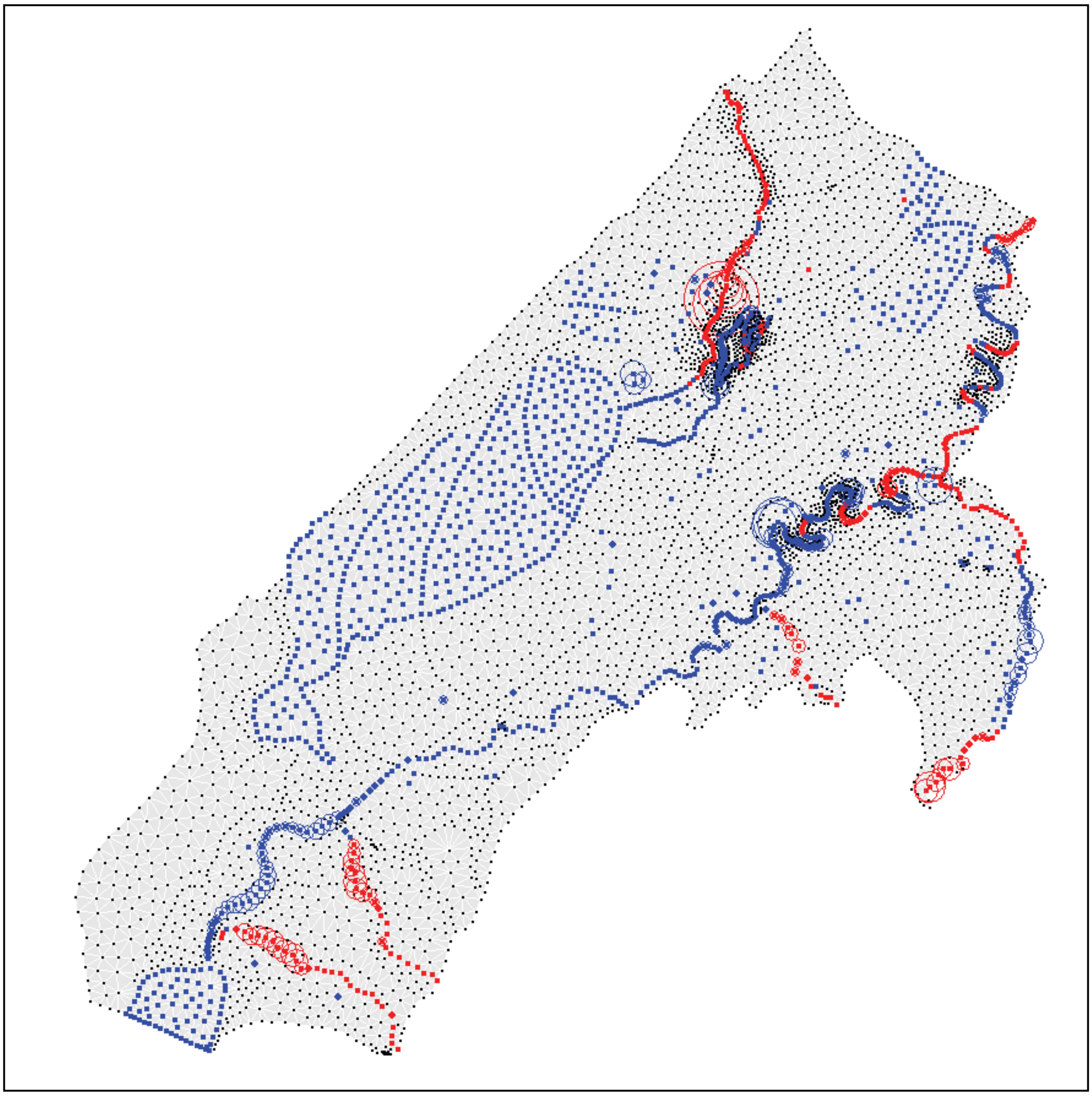


Figure 11.12: Simulated summer river, spring and lake gain and loss pattern for the Lower Valley catchment on model day 4585 (25 January 2005). The blue markers show a groundwater discharge and the red markers show a loss from surface water to groundwater. The size of the marker is proportional to flux magnitude.

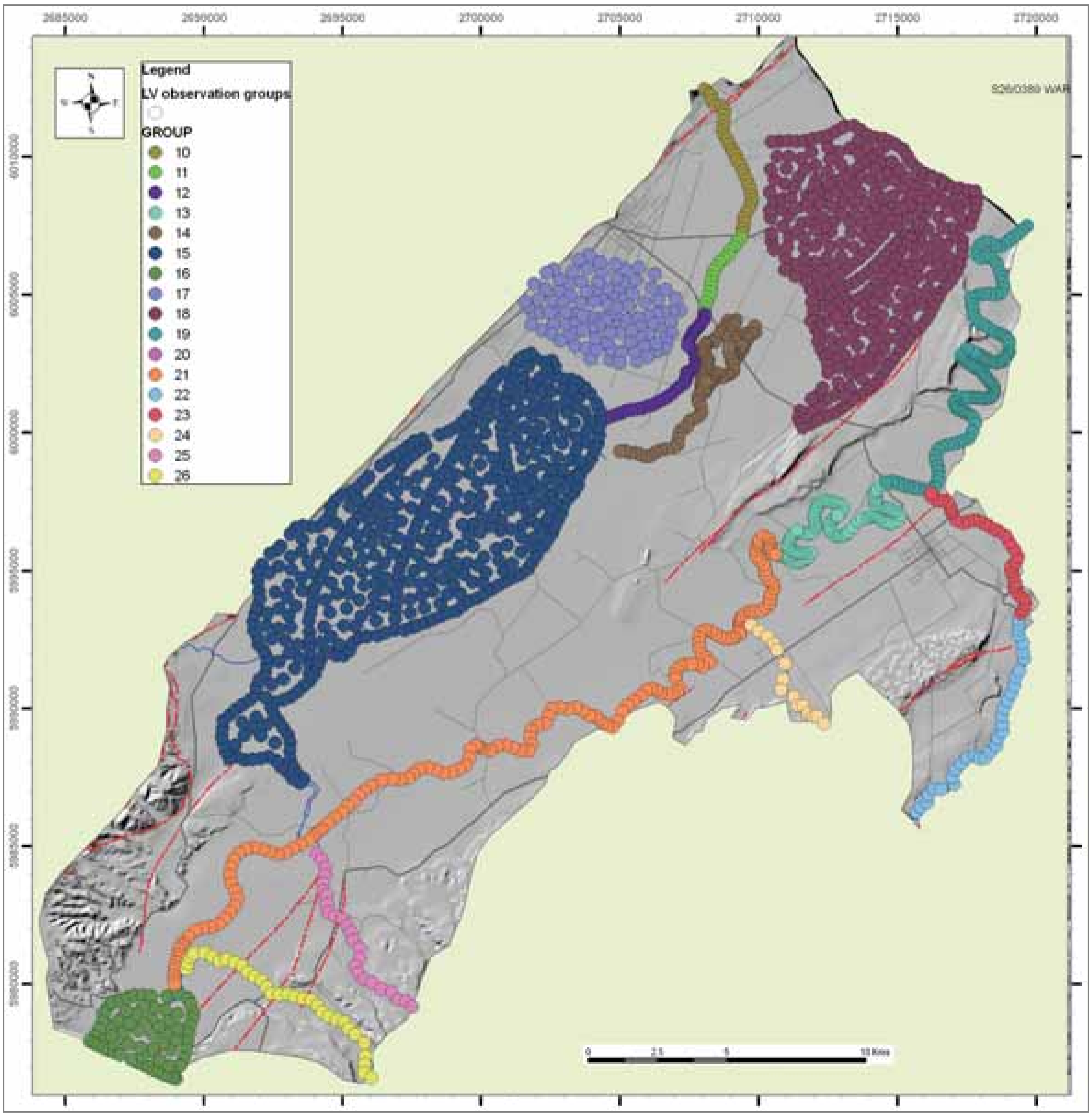


Figure 11.13: Transfer node observation groups used to analyse surface water – groundwater fluxes in the Lower Valley catchment model

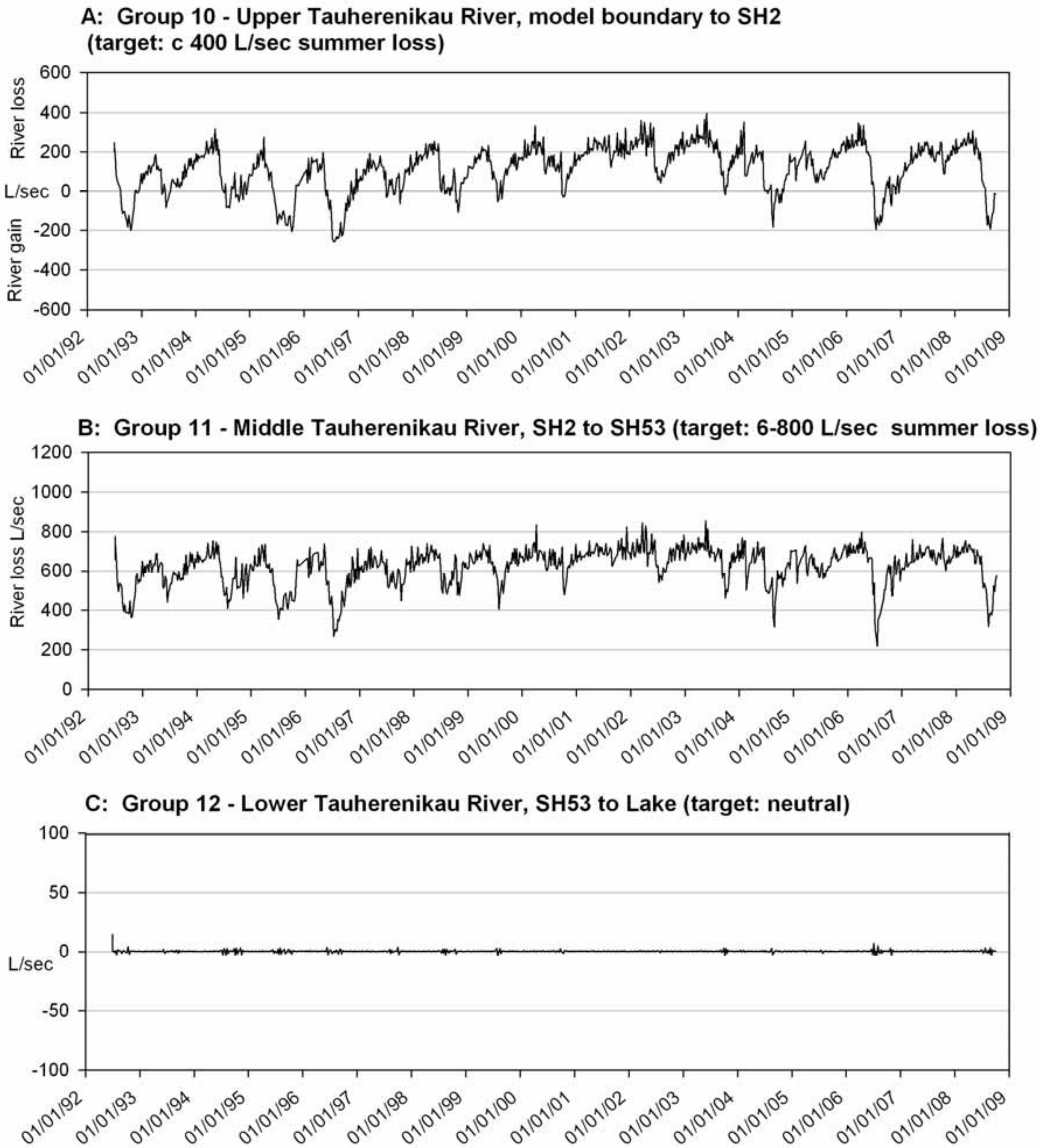


Figure 11.14 (A-C): Simulated transient water balances for three reaches of the Tauherenikau River for the model calibration period, 1992–2008

A – Upper Tauherenikau River

B – Middle Tauherenikau River

C – Lower Tauherenikau River

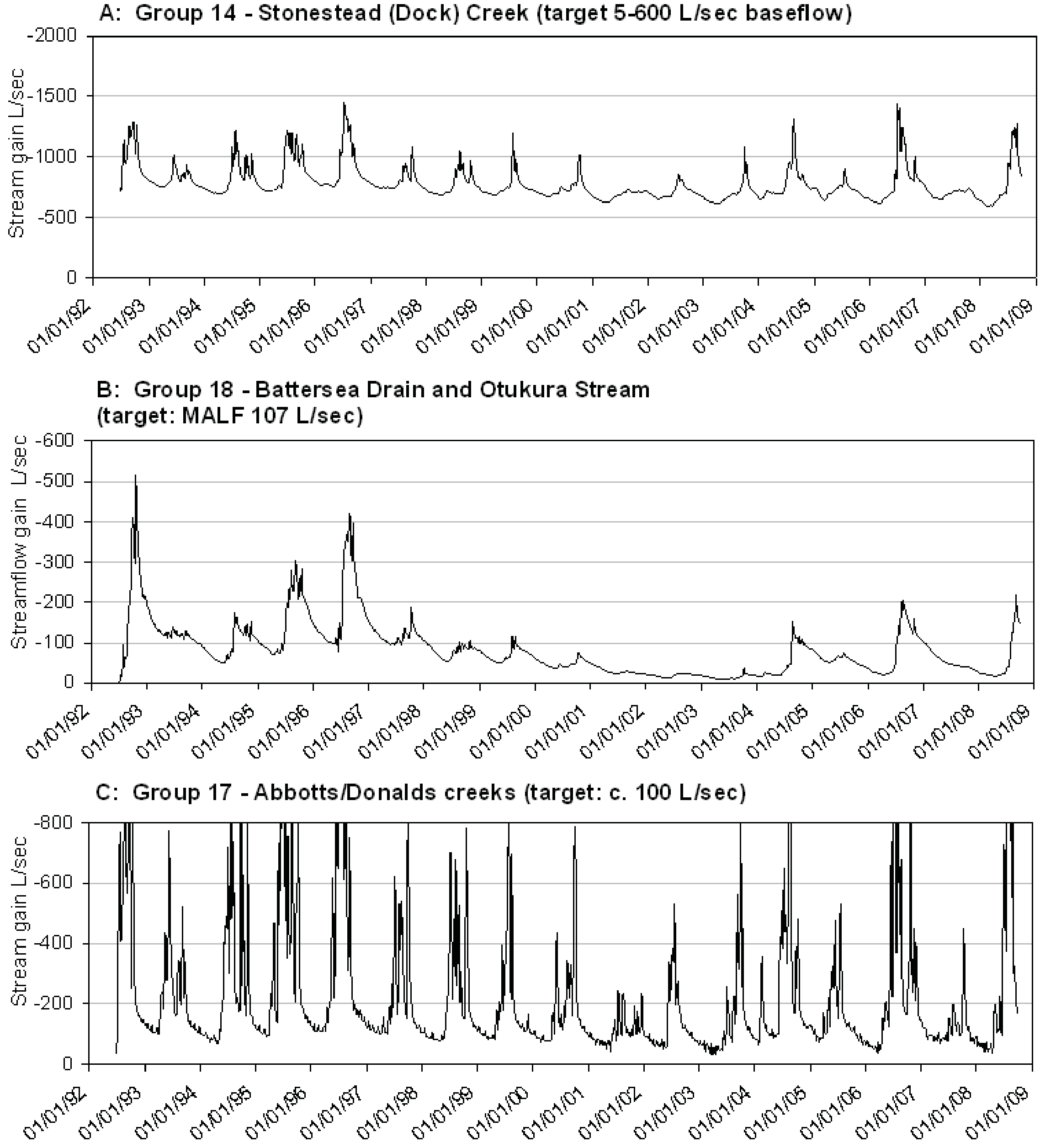


Figure 11.15 (A-C): Simulated transient water balances for spring discharge areas on the Tauherenikau fan for the model calibration period, 1992–2008

A – Stonestead (or Dock) Creek

B – Battersea Drain and the Otukura Stream

C – Abbotts/Donalds creeks in the Featherston area

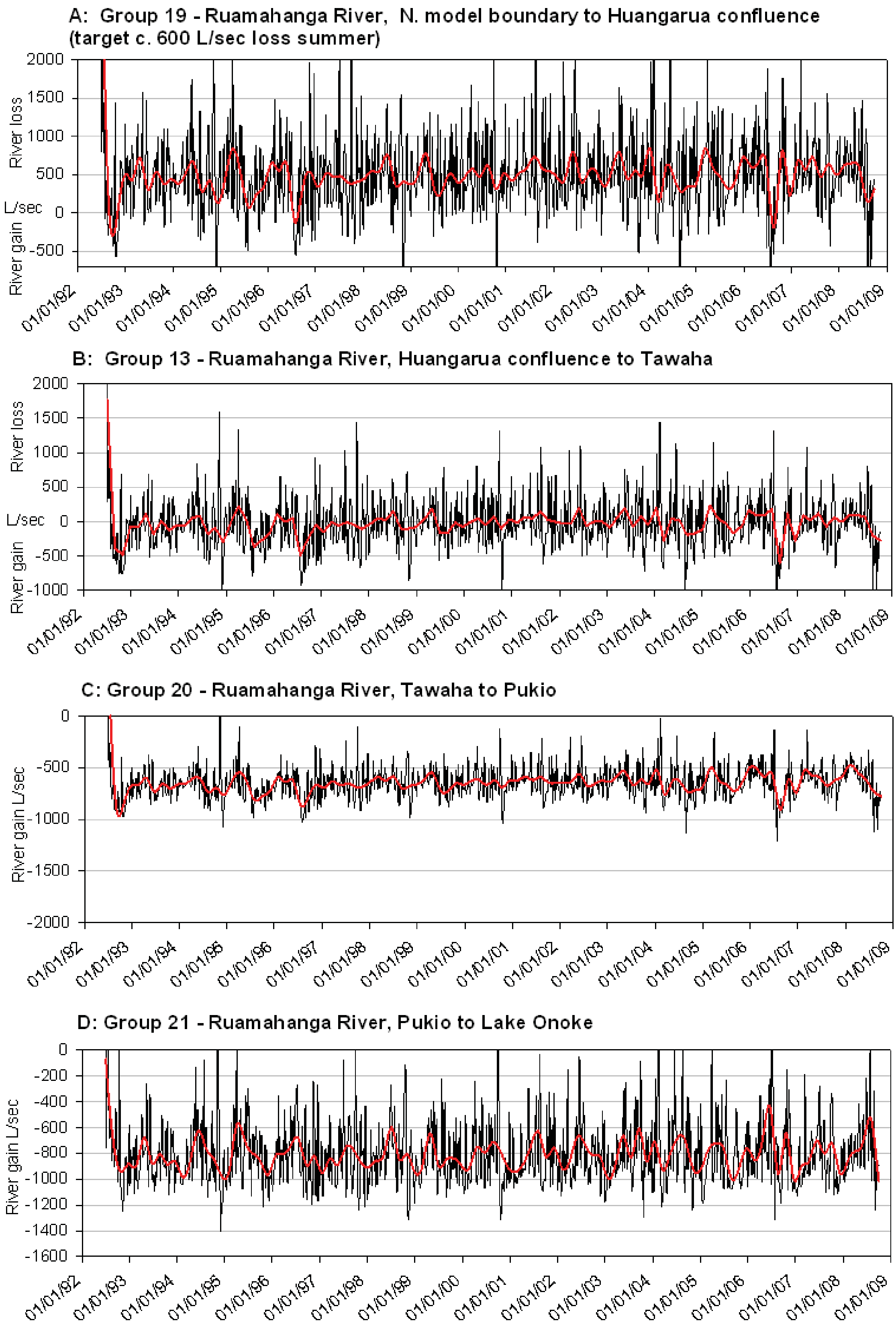


Figure 11.16 (A-D): Simulated transient water balances along four reaches of the Ruamahanga River for the model calibration period, 1992–2008. Note a negative flux means a discharge from the aquifer to the river and a positive flux means a loss of river flow to the aquifer. The red lines are a 4-week moving average.

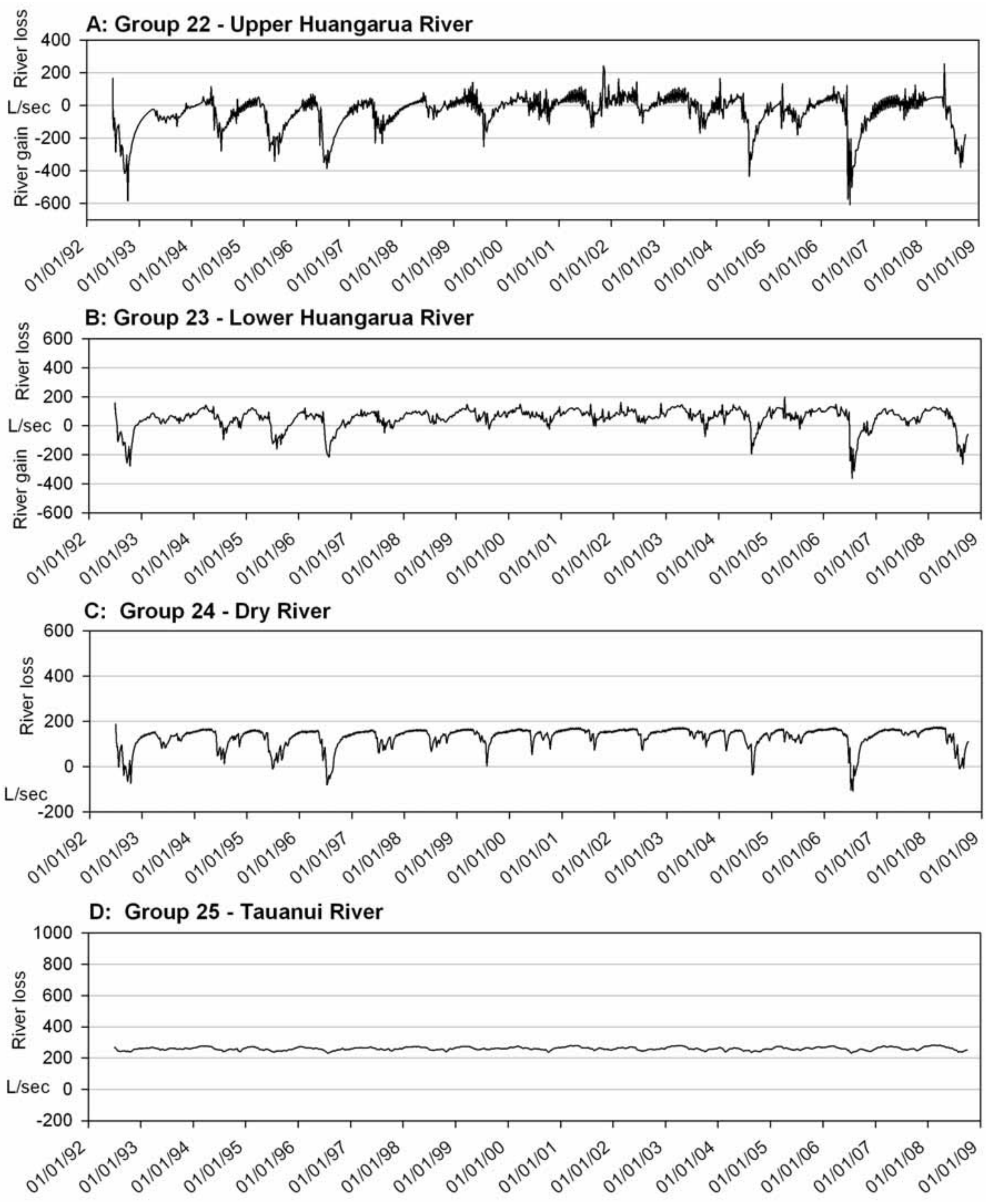


Figure 11.17 (A-D): Simulated transient water balances for eastern catchment rivers for the model calibration period, 1992–2008. Note a negative flux means a discharge from the aquifer to the river and a positive flux means a loss of river flow to the aquifer.

A – Upper Huangarua River

B – Lower Huangarua River

C – Dry River

D – Tauanui River

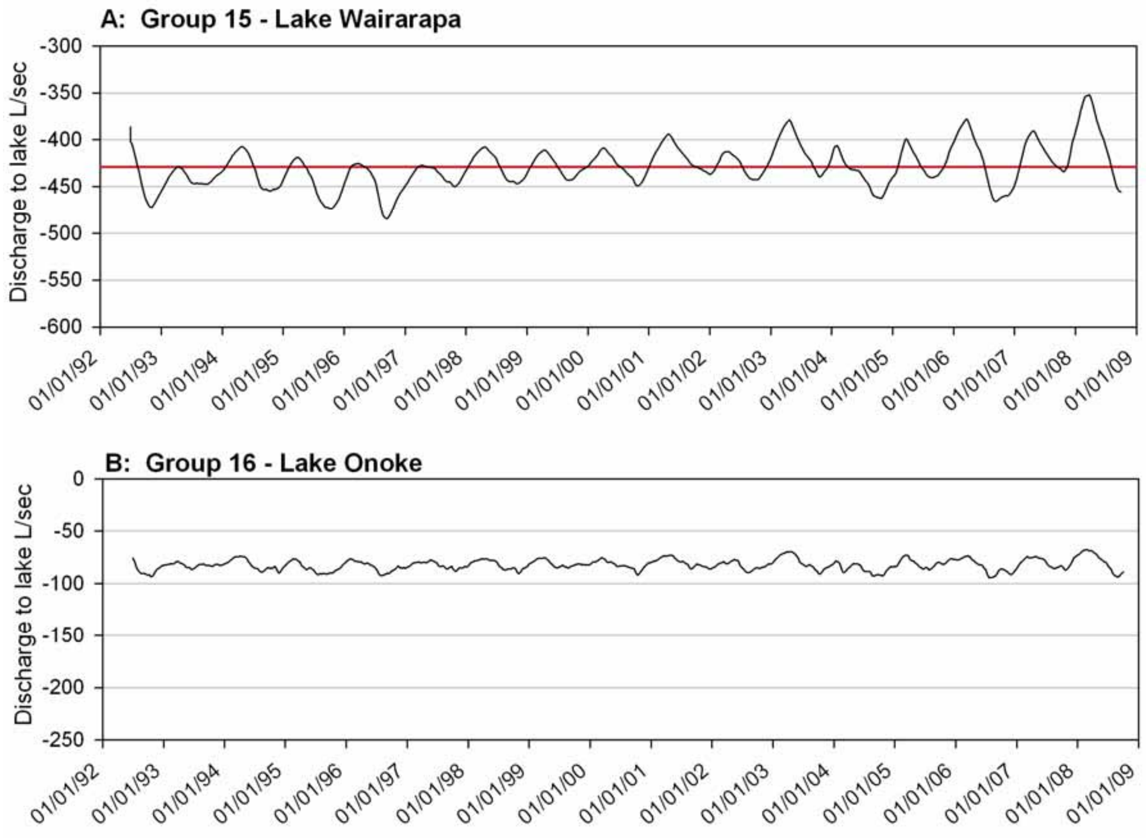


Figure 11.18 (A-B): Simulated discharge to lakes Wairarapa (A) and Onoke (B) in the Lower Valley catchment for the model calibration period, 1992–2008

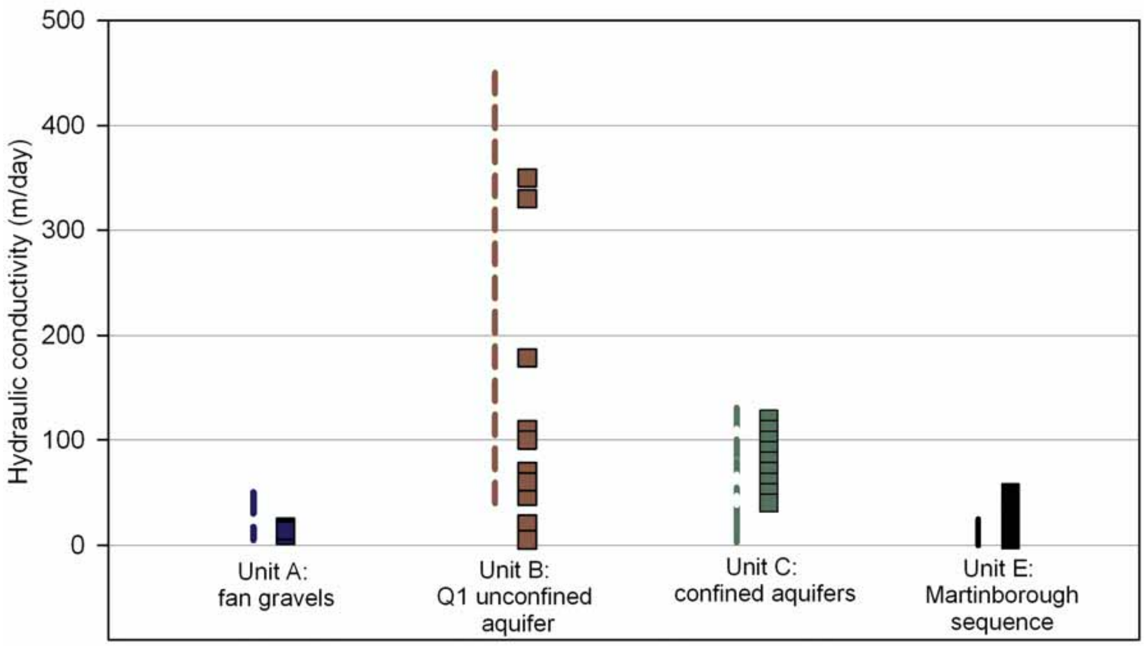


Figure 11.19: Comparison of calibrated model hydraulic conductivity parameter values (square symbols) with the range of observed values derived from aquifer testing (dashed lines)

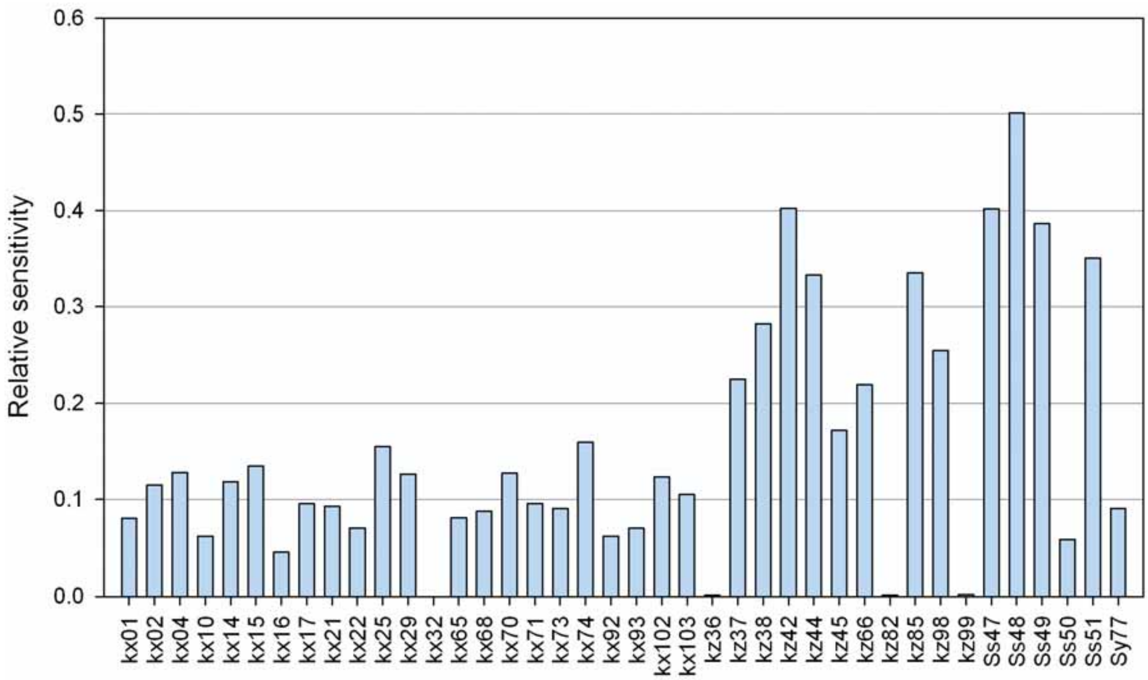


Figure 11.20: Relative parameter sensitivities for adjustable parameters estimated by PEST

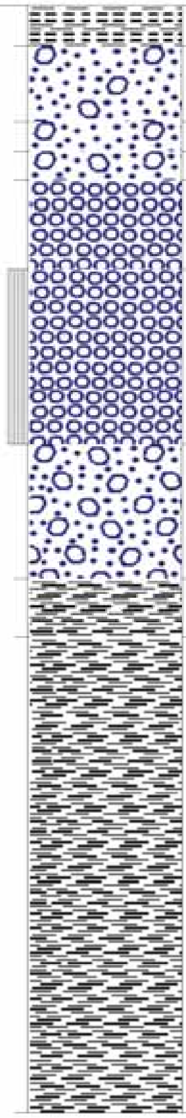
Appendix 1:

Monitoring bore drill logs

Borelog for well S27/0884 - GWRC / TUCKER

Gridref: 2718498.6002962
Ground Level Altitude +MSD
Driller : GRIFFITHS DRILLING COMPANY LTD
Drill Method: Rotary/Percussion
Drill Depth : 18.9m Drill Date :

greater WELLINGTON
REGIONAL COUNCIL



Scale	Depth	Drillers Description	Formation
		Brown SILTY clay Soil	
	-0.70m	Brown SANDY GRAVEL (sub angular gravel 6 to 8mm)	
	-2.00m	Brown SANDY GRAVEL (rounded gravel)	
	-2.50m	Brown SANDY GRAVEL - angular 15mm with fine to medium sand (Damp sandy layer at ~ 2.5m. w/l -2.5m bgl at 3.0m)	
	-3.00m	Brown GRAVEL SANDY increasing gravel size with depth 15 to 20mm (more water. w/l -2.5m bgl)	
	-4.50m	Light Brown GRAVELS - loose rounded gravels increasing in size with depth (up to 25mm) Wood fragments between 6 to 7.0m	
-5			
	-7.50m	Brown SANDY GRAVEL - sub angular gravel 10mm . Fine to medium sand with slit	
	-9.80m	Grey CLAY - firm & sticky semi plastic	
-10			
	- 10.8m	Grey Clay - Dry, Fizzed with acid	
-15			
	- 18.9m		

Borelog for well S27/0885 - GWRC / DIDSBURY

Gridref: 2719015.6007384
Ground Level Altitude 35.89 +MSD
Driller : GRIFFITHS DRILLING COMPANY LTD
Drill Method: Rotary/Percussion
Drill Depth : 14.3m Drill Date : 1/05/2008

greater WELLINGTON
REGIONAL COUNCIL

Depth	Drillers Description	Formation
-3.00m	Brown silty CLAY, damp very soft non-cohesive.	
-4.40m	Blue grey CLAY, damp soft non-cohesive.	
-4.80m	Grey CLAY- Hard drillling, not as moist as above	
-5.20m	Grey fine to medium sub-angular GRAVEL, minor silt, water level at 5.2 mbgl -2.9m and still recovering	
-6.40m	Grey sandy fine to medium rounded GRAVEL, large proportion angular fine to coarse grey sand, small amount of grey silt	
-7.80m	Grey sandy fine to coarse rounded GRAVEL, medium to coarse sub-angular grey sand, good water level recovery water level at 7.5 mbgl -1.9m	
-9.20m	Grey sandy fine to coarse rounded to sub-angular GRAVEL, medium to coarse sub-angular grey sand (less than above), brownish grey silt, possibly less water than above.	
- 11.2m	Grey gravelly fine to coarse SAND, with fine sub-rounded gravel, minor course gravel, possible brown silt, water level at 10.5mbgl -1.9m.	
- 11.5m	Light brown / grey clay, dry and hard	
- 12.6m	Blue grey sandy fine GRAVEL, fine to coarse cemented sand, water level at 12.5 mbgl -2.00m	
- 13.8m	Blue grey gravelly fine to medium SAND, minor angular gravel, dark grey water at 13 mbgl	
- 14.3m	Grey clay cohesive	

Scale: -5, -10

Appendix 2:

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 Lower 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 A2.1. 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 A2.2 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 A2.3. 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.

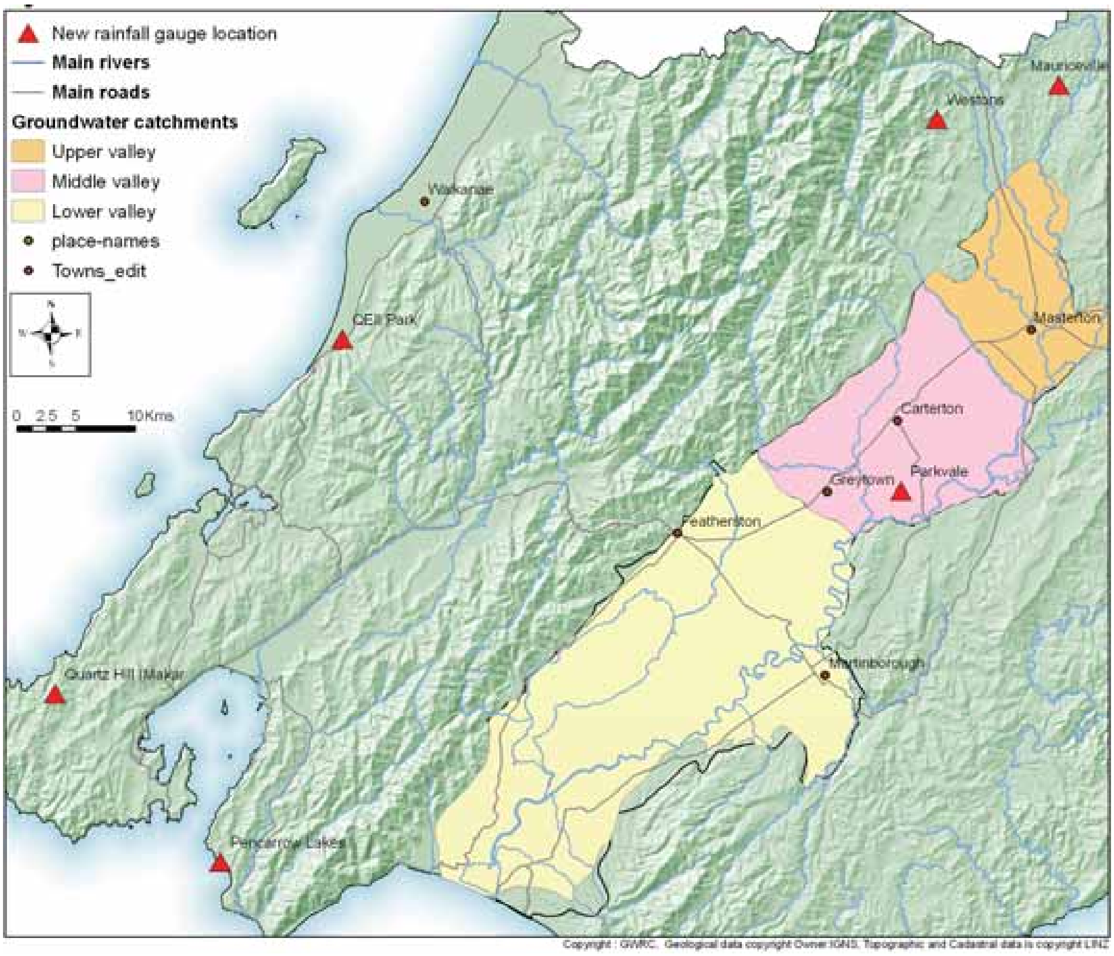


Figure A2.1: Location of "new" rainfall stations used to verify the NIWA model

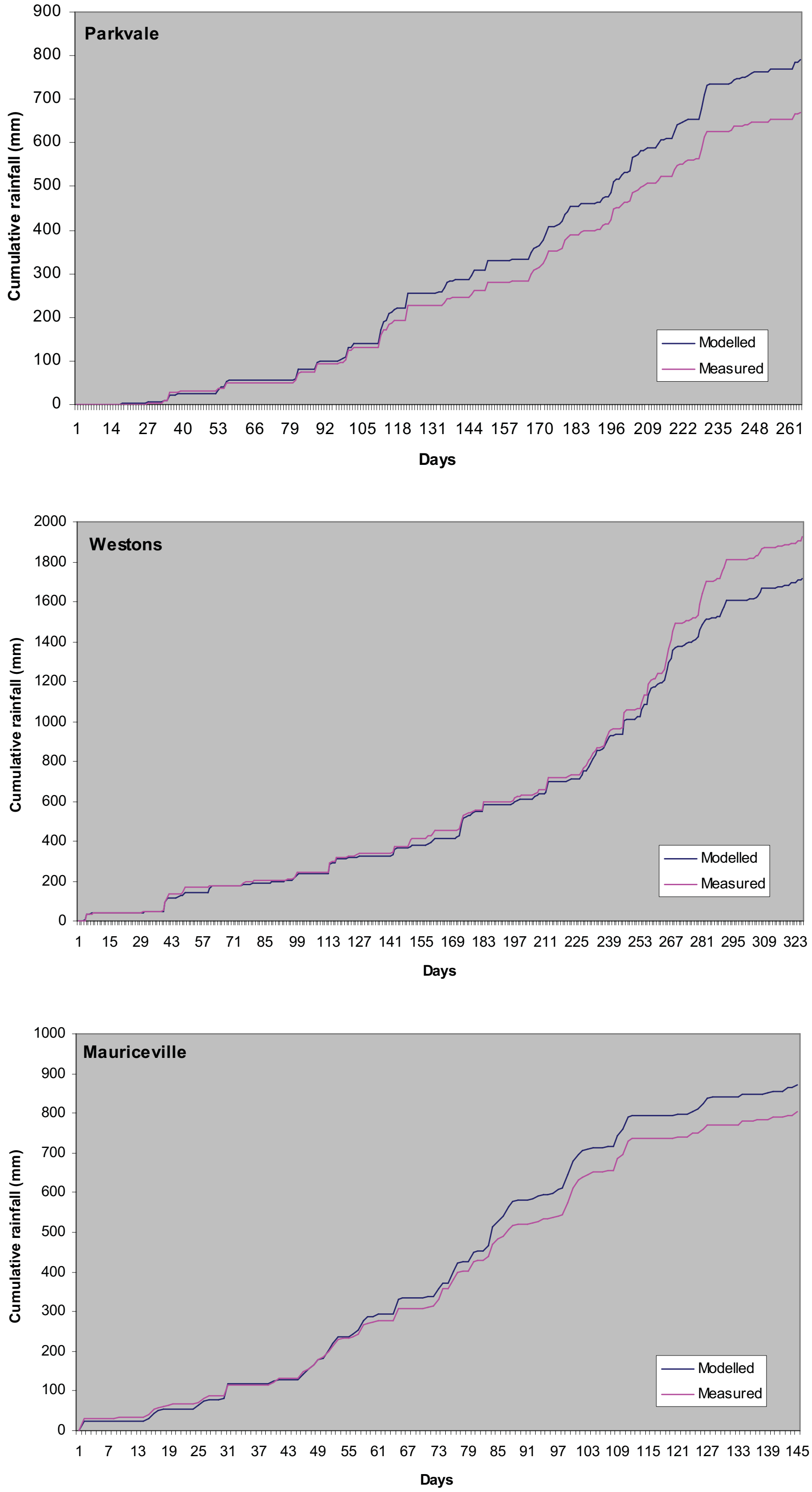


Figure A2.2: Cumulative measured and modelled daily rainfall graphs for three rainfall stations within or close to the Wairarapa Valley using available data (2007/08)

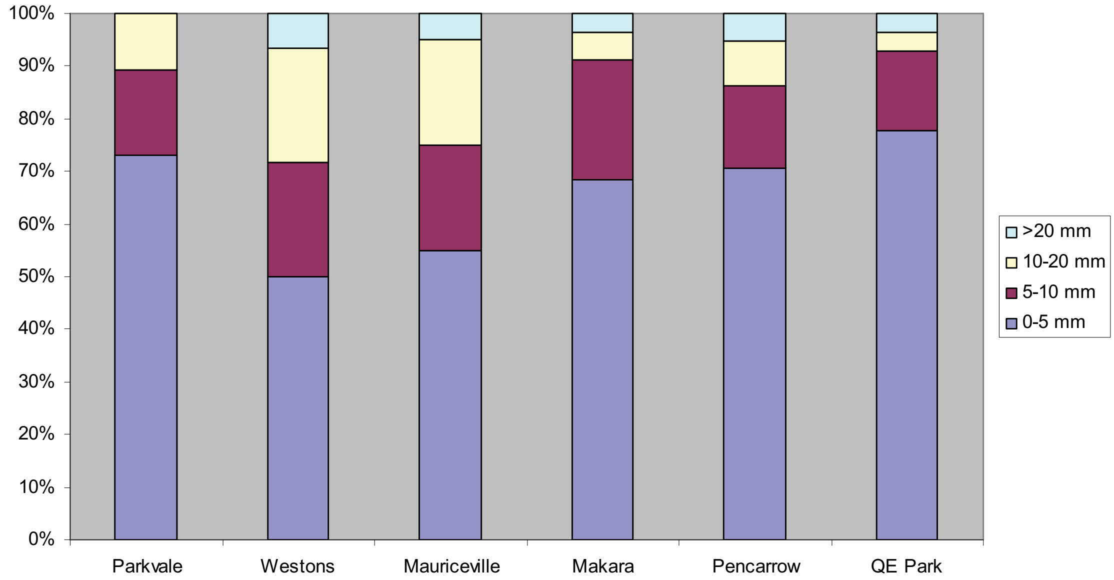


Figure A2.3: Weekly prediction errors for the NIWA 500 m² grid rainfall interpolation model for the Wellington region using supplementary data from six independent rainfall stations (excluded from the groundwater model)

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 A2.1 provides a summary of properties assigned to the dominant soil classes in the model area.

Table A2.1: Soil properties used in the Rushton soil moisture balance model for the Lower 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	60-66	0.5
2	o1c/o23/o78a	Ruamahanga stony sand/ Manihera sand/Kohinui stony loam	Recent soils/ Yellow-brown sands/Yellow-brown shallow soils	80	26	54	32	Well	45-60	71-86	0.5
3	o1c	Ruamahanga stony sand	Recent soils	90	26	64	38	Well	45	60-65	0.5
4	o75b/o78a	Tauherenikau stony silt loam/ Kohinui stony loam	Yellow-brown shallow soils	110	40	70	42	Well	60-65	80-85	0.5
5	o75/o75a/o75b/ o76b	Tauherenikau silt loam/ Tauherenikau shallow silt loam/Tauherenikau stony silt loam/Opaki brown stony loam	Yellow-brown shallow soils	120	40	80	48	Well	65-68	85-94	0.5
6	o23b	Kumenga mottled sand	Yellow-brown sand	200	80	120	60	Poor	74	99	0.5
7	o29/o29e/o13a/ o13b/o13c	Pirinoa silt loam/Bideford loam/Wharekaka mottled fine sandy loam/Wharekaka fine sandy loam/Tawaha siltloam	Intergrades between yellow-grey earths and yellow-brown earths/Yellow-grey earths	220	120	100	45	Imperfect-Poor	70-74	90-99	0.5
8	o1b/o76c	Ruamahanga sand/Carterton shallow silt loam	Recent soils/ Yellow-brown shallow soils	280	110	170	70	Well	65	85-91	0.5
9	o1	Greytown silt loam and sandy loam	Recent soils	310	120	190	80	Well-Poor	65	91	0.5
10	o2/o1/o106/ o1b/o12/o23b	Ahikouka silt loam/Greytown silt loam and sandy loam/ Otukura silt loam/ Ruamahanga sand/ Martinborough loam/ Kumenga mottled sand	Recent soils/Gley soils/Yellow grey-yellow brown earths/Yellow-brown sand	330	120-180	150-210	60-90	Well-Poor	65-74	85-96	0.5
11	o2	Ahikouka silt loam	Recent soils	350	150	200	80	Poor	74	94	0.5
12	o35b/o41a	Kaikouta silt loam/Tuhitarata hill soils	Yellow-brown earths	400	240	160	72	Imperfect	70	90-96	0.5
13	o99/o107c/o2/ o2a/o3	Moroa loam and stony loam/Taratahi peat, loamy peat and peaty loam/ Ahikouka silt loam/Pukio clay loam	Gley soils/ Organic soils/ Recent soils/ Saline recent soils	450	250-260	190-200	50-100	Poor	74-82	85-99	0.5

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 A2.2) and are the same values as those used by White et al. (2003). No surface runoff was incorporated in these simulations.

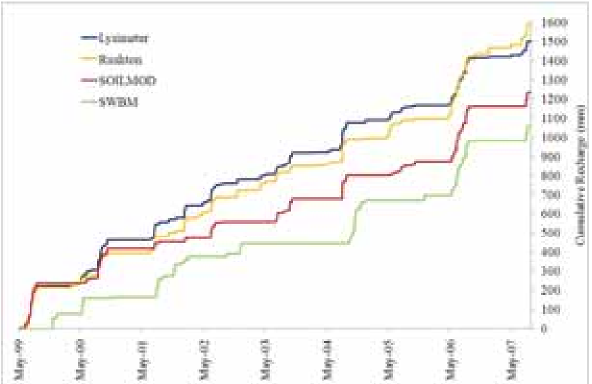
Table A2.2: Soil properties used for Canterbury recharge simulations

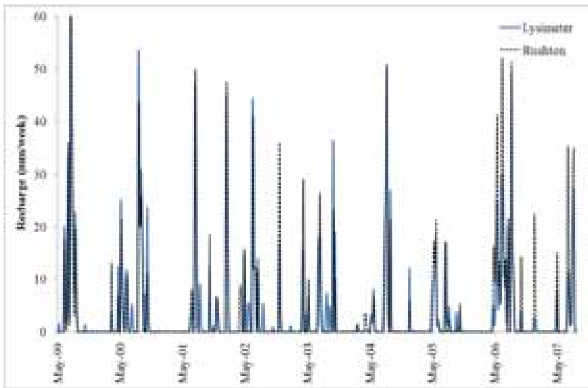
	Christchurch Airport	Lincoln University	Hororata
Soil Series	Waimakariri	Templeton	Hororata
Soil Type	V stony sandy loam	Silt loam on sand	Stony silt loam
Drainage	Excessively drained	Well drained	Well drained
Profile Depth (mm)	300	650	300-400
PAW (mm)	45	170	75
FC (mm)	115	253	189
Rooting Depth (mm)	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 A2.4. Statistics to compare the three models are provided in Table A2.3. 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.

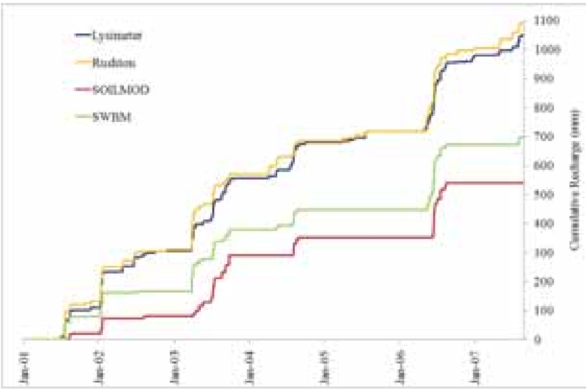
The period of record for this simulation is longer than reported in White et al. (2003), which only simulated from May 1999 to March 2001. Conditions were drier than normal from 2003 to 2005 and this led to an overall reduction in the percentage of rainfall recharge recorded at the three sites. SOILMOD 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.

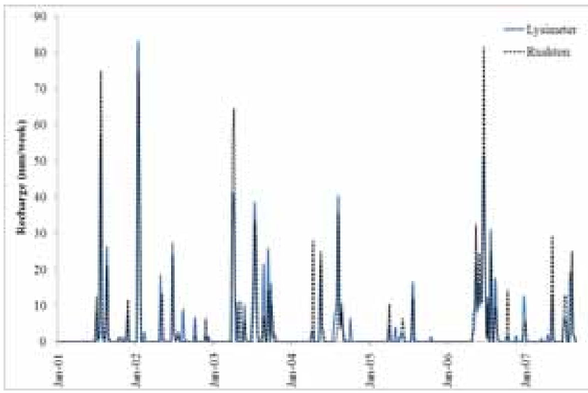
Airport



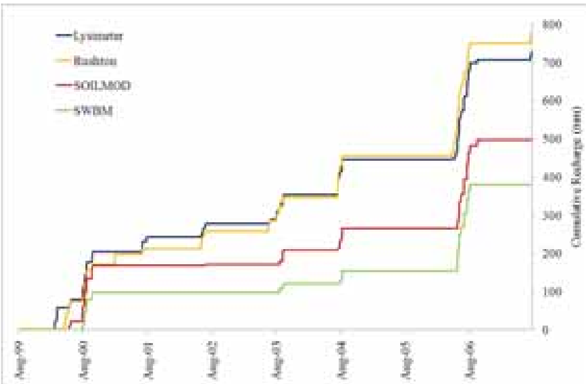


Hororata





Lincoln



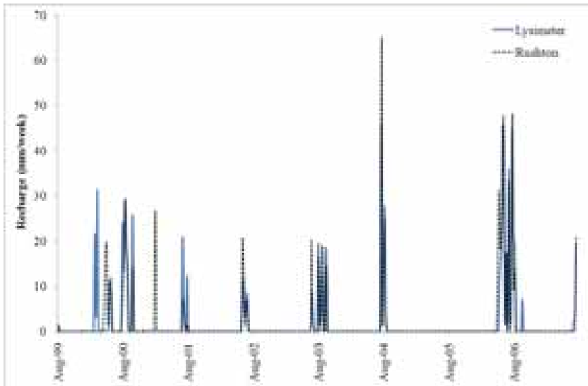


Figure A2.4: Hydrographs of cumulative recharge calculated by three soil moisture balance models (Rushton, SOILMOD and SWBN) compared to lysimeter data (left). Weekly recharge for the Rushton model compared with lysimeter recharge (right)

Table A2.3: 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 3:

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. The abstraction records available for this study are limited to annual usage records since about 2002 for some bores, and weekly usage records for 65 bores for the 2007/08 irrigation season.

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

Underlying assumptions: that irrigators begin pumping when the soil moisture deficit (SMD) reaches some critical threshold value; that SMD conditions are uniform across the catchment; that all irrigators behave consistently; that irrigators stop pumping for the season at a higher SMD prior to anticipated wetter winter conditions, but always prior to the end of April according to resource consent conditions (most consents allow pumping between October and April).

Metering data collected from 65 bores during the 2007/08 irrigation season were used to determine a relationship between SMD and irrigation abstraction. Figure A3.1(A) shows the metered weekly abstraction for this period (for all takes of >10 L/s). Daily SMD was calculated for the same period using the Rushton et al. (2006) soil moisture balance model and is shown in Figure A3.1(B) as a weekly average. The soil moisture deficit was calculated for a designated Lower Valley climate and soil reference site (this reference site was used for all three sub-catchment studies). The reference site is Alloa, close to the Tauherenikau River in the central part of the Wairarapa Valley where soil moisture is also monitored. Soil moisture monitoring data for the 2007/08 irrigation season are shown, for comparison, in Figure A3.1(C).

The location and soil properties at Alloa considered representative of a typical irrigated soil in the Wairarapa Valley:

- Grid reference: 2709806 / 6007150
- NIWA Grid Square: i = 133; j = 146
- Moderate drainage soils
- Field capacity = 330mm
- Wilting point = 120mm
- Drainage: Imperfect
- Root constant = 600mm

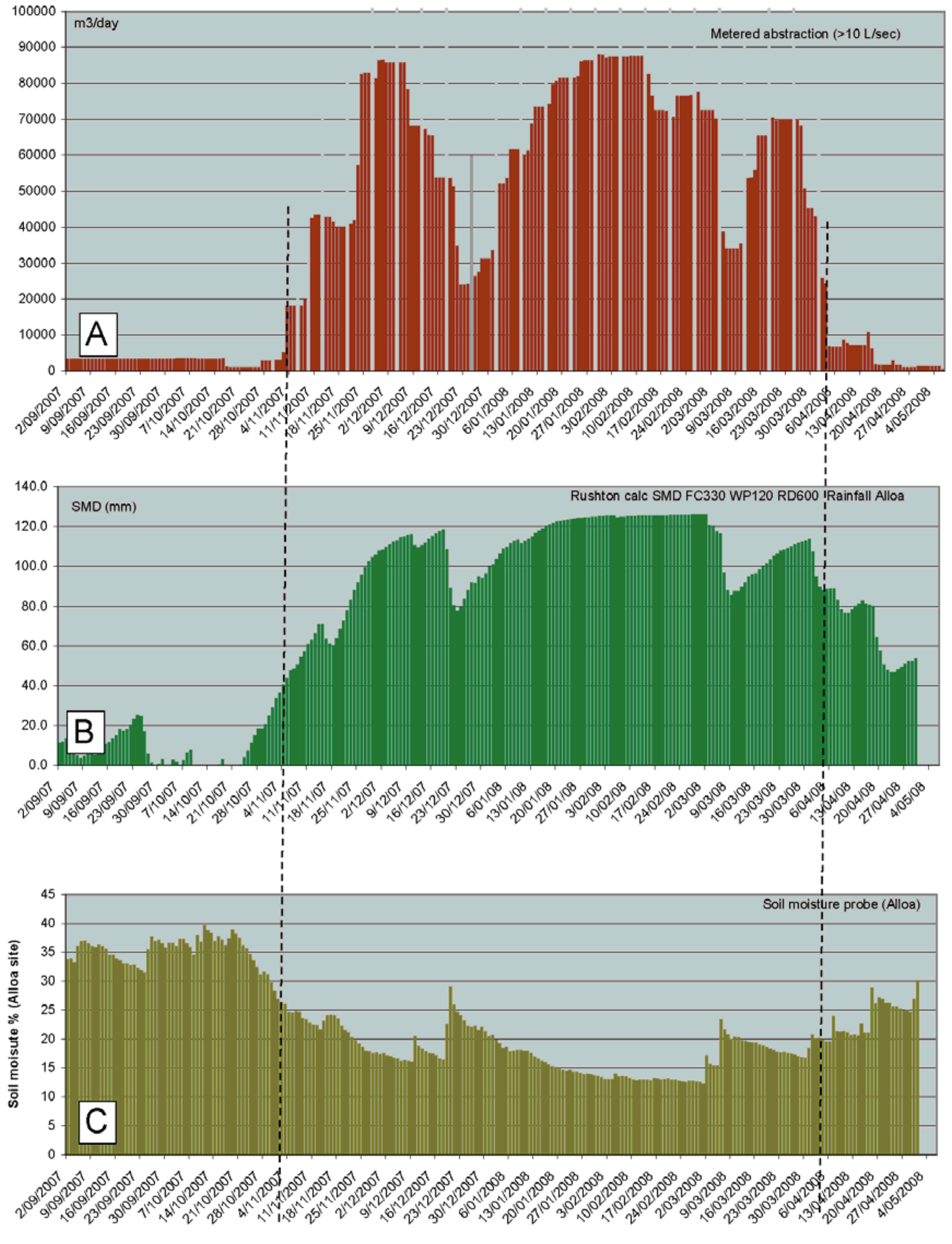

Figure A3.1: (A) Metered Lower valley catchment abstraction, (B) calculated soil moisture deficit, and (C) soil moisture monitoring data at Alloa, for the 2007/08 irrigation season

The information presented in Figure A3.1 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) shows 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.

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 in the Wairarapa 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, well before SMD levels recovered to 20 mm. This may have been in anticipation of winter rainfall, to avoid creating water-logged soils.

Table A3.1 shows the estimated irrigation season intervals for the period 1992 to 2008 based upon SMD modelling, using an irrigation commencement trigger of 20 mm SMD and cessation trigger of 80 mm SMD. The irrigation season intervals are used in the numerical groundwater model, together with the total annual metered water quantity (where available) which is applied over the irrigation season in proportion to SMD level (the apportionment methodology is described in Step 2 below).

Table A3.1: Estimated irrigation season intervals using modelled soil moisture deficit at Alloa

Irrigation season	Season length (days)	Season length (weeks)	Start date	Stop date
1992/93	155	22	10/11/1992	13/04/1993
1993/94	204	29	12/10/1993	03/05/1994
1994/95	155	22	11/11/1994	04/04/1995
1995/96	134	19	21/11/1995	02/04/1996
1996/97	190	27	08/10/1996	15/04/1997
1997/98	183	26	28/10/1997	28/04/1998
1998/99	197	28	06/10/1998	20/04/1999
1999/00	190	27	05/10/1999	11/04/2000
2000/01	159	22	24/10/2000	01/05/2001
2001/02	113	16	08/01/2002	30/04/2002
2002/03	190	27	22/10/2002	29/04/2003
2003/04	113	16	21/10/2003	10/02/2004
2004/05	148	21	02/11/2004	29/03/2005
2005/06	176	25	04/10/2005	28/03/2006
2006/07	155	22	28/11/2006	01/05/2007
2007/08	162	23	23/10/2007	01/04/2008

Step 2: Calculation of weekly pumping rates

Weekly meter data collected over the 2007/08 irrigation season for all groundwater takes of 10 L/s and greater were used to establish a relationship between the proportion of the consented daily abstraction rate used and SMD. This relationship was then used to produce a synthetic abstraction record within the bounds of the seasonal irrigation interval defined in Table A3.1.

This approach was adopted because it is not possible to calculate a theoretical irrigation demand based on crop evaporation needs since there was little information on the irrigated land areas and crop types in the Greater Wellington consents database. Also, the high rainfall gradient across the Wairarapa Valley would mean that each individual property would need to be modelled separately – a task that would be exceedingly time consuming and impractical.

The broader approach of relating water use to soil moisture conditions and consented daily abstraction rate on an average basis across the Lower Valley catchment was therefore used. The exception to this is where weekly or monthly use data were available (2006-08) in which case the actual metered use data were used in the model for the corresponding years.

Using the metering and estimated SMD data for the 2007/08 irrigation season, an 'Abstraction Fraction' (AF) was developed for specific soil moisture deficits (i.e. at a particular SMD the AF relates the consented total daily abstraction rate to the actual metered abstraction rate). The AF represents an average for the region. Therefore, the AF increases to >0.5 (0.5*consented daily rate) when the SMD is high. Using this method, the abstraction rate increases through the season as SMD increases thus avoiding the unrealistic constant rate block pumping used if the annual take is distributed evenly throughout the irrigation season. The resulting estimated annual takes correspond well to the anticipated 20-50% of consented annual rates.

The following equation was developed to relate SMD to AF by plotting the SMD and corresponding proportion (fraction) of consented daily take actually used (on a catchment wide basis):

$$\mathbf{AF = 3E\text{-}05 * SMD^2 - 0.0009 * SMD + 0.1449}$$

where: AF = abstraction factor
SMD = soil moisture deficit, calculated for each stress period (i.e. week)

For each modelled stress period, the SMD was calculated using the Rushton model. The abstraction factor was then calculated using the above equation. The AF is then applied to the daily consented pumping rate for each pumping bore to provide a synthetic seasonal irrigation take of variable length (season length is calculated using the method above).

The AF is also a good way of apportioning an annual metered take (if available) over the irrigation season. This is done by dividing the sum of the AFs over the irrigation season by the annual meter quantity. The AF/7 for a specific stress period is then multiplied by this figure.

Appendix 4:

Assessment of groundwater and surfacewater chemistry in the Upper and Lower Wairarapa Valley

Assessment of groundwater and surface water chemistry in the Upper and Lower Wairarapa Valley

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CONTENTS

FIGURES

TABLES

APPENDICES

ABSTRACT

This investigation employed hierarchical cluster analysis (HCA) to provide insight into the groundwater chemistry in the Upper Wairarapa Valley (the area north of the Waingawa River) and the Lower Wairarapa Valley (the area south of the Waiohine River). The aim was to assist with development and substantiation of the transient groundwater flow models for the Upper and Lower Wairarapa Valley currently being developed by Greater Wellington Regional Council. This study complements the assessment of hydrochemistry in the Middle Wairarapa Valley (the area between the Waingawa and Waiohine Rivers) made by Daughney (2007).

HCA conducted using all available surface water and groundwater chemistry data for the entire Wairarapa Valley allowed for the definition of two, six or thirteen hydrochemical clusters, depending on the separation threshold employed. The hydrochemistry and spatial positioning of sites assigned to these various clusters provides insight into the hydrology of the Wairarapa Valley. For example, differences in catchment geology cause the rivers draining the Tararua Ranges to have markedly different hydrochemistry compared to the rivers draining the eastern hills, and these hydrochemical signatures can be traced into the aquifers in the vicinity of losing river reaches. Shallow rainfall-recharged groundwaters are found throughout the Wairarapa Valley, generally where alluvial fan deposits are mapped at the surface. Deeper groundwaters are commonly oxygen-poor, especially in the Lower Valley. Lake Wairarapa has a hydrochemical signature that suggests that it receives some inflow from deeper groundwater in addition to surface drainage. Overall, this investigation has shown that HCA can be valuable for the conceptualisation of hydrology and hydrogeology at the basin scale.

KEYWORDS

Groundwater chemistry, groundwater quality, hierarchical cluster analysis, multivariate statistics, Wairarapa, Wellington

1. INTRODUCTION

Greater Wellington Regional Council (GWRC) is in the process of developing three separate numerical transient groundwater flow models for the Lower, Middle and Upper portions of the Wairarapa Valley. These transient groundwater flow models are 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).

The first of the three transient groundwater flow models was constructed for the Middle Wairarapa Valley, covering the area south of the Waingawa River and extending to just south of the Waiohine River. To support the development of the flow model, Daughney (2007) applied multivariate methods to provide insight into the spatial variations in groundwater chemistry in the Middle Valley. Overall, Daughney (2007) showed that multivariate assessment of groundwater chemistry can improve the conceptual understanding of the local and regional hydrogeology and hence can be valuable for the development and validation of a hydrogeological model.

This study applies multivariate statistical methods to provide insight into the groundwater chemistry across the entire Wairarapa Valley. The aim is to assist with the development and substantiation of the transient groundwater flow models currently in development for the Upper and Lower portions of the Wairarapa Valley, defined as those parts of the valley north of the Waingawa River and south of the Waiohine River, respectively.

Hierarchical cluster analysis (HCA) is the primary method applied in this investigation. HCA can be used to define water quality “clusters” (i.e. groups or categories) and assign monitoring sites to these clusters on the basis of groundwater quality. The HCA approach has been previously applied to understand variations in groundwater chemistry in the Middle Wairarapa Valley (Daughney, 2007). HCA has also been applied to data collected through the National Groundwater Monitoring Programme (NGMP), to understand spatial variations in hydrochemistry across all of New Zealand (Daughney and Reeves, 2005; Daughney 2007). HCA is performed purely on the basis of groundwater chemistry and does not explicitly consider any factors such as well location, well depth or aquifer lithology. Thus HCA can potentially provide a simple summary of the variation in groundwater chemistry across the entire Wairarapa Valley without any prior assumptions about which parts of the Wairarapa should be dominated by which particular groundwater quality categories.

2. METHODS

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 50 analytes in ca. 6000 water samples collected from 633 monitoring sites. The set of monitoring stations considered in this study was comprised of 31 surface water monitoring stations, including three stations in the National River Water Quality Monitoring Network operated by NIWA (Larned et al., 2004) and several stations on rivers and streams draining into the Wairarapa Valley, and 602 groundwater monitoring sites, five of which are included in the National Groundwater Monitoring Programme operated by GNS Science (Daughney and Reeves, 2005).

Analytical data were prepared for HCA as described in Appendix 1, by 1) combination of results fields, 2) calculation of median parameter values on a per-site basis, 3) calculation of charge balance error (CBE) using the median parameter values, and 4) estimation of missing results.

HCA was then performed using only the sites with CBE between -10% and +10%, on the basis of log-transformed site-specific 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 (cf. Daughney and Reeves, 2005; Daughney, 2007). Parameters such as Fe, Mn, NO_3-N and NH_4-N were excluded from HCA because their concentrations are probably controlled more by redox potential than by aquifer lithology. Three categorisation methods were employed:

- First, HCA was conducted using the Nearest Neighbour linkage rule. The Nearest Neighbour method identifies sites that have unusual chemistry compared to the other sites in the dataset (these unusual sites are termed “residuals”) and which should be excluded from further analysis due to their possible biasing influence.
- Second, HCA was conducted using Ward’s linkage rule, after the exclusion of sites identified as residuals. Ward’s method is typically the most appropriate for hydrochemical assessments (Güler et al., 2002).
- Third, cluster assignments were “predicted” for those sites that had not been considered in the HCA, i.e. those sites with CBE outside the acceptable limits of -10% to +10%, and for which median values were not available for between one and three of the required eight input variables. The square of the Euclidean distance was calculated between each site’s median parameter values and the centroid of each of the clusters defined using Ward’s method. The predicted cluster for each site was determined on the basis of minimum site-to-centroid separation distance.

Note that in this study, HCA was conducted by considering all river and groundwater monitoring stations in the Wairarapa Valley together as a single group. The approach used in this study is distinct from the approach of Daughney (2007), in which HCA was applied only to groundwater monitoring sites (surface water monitoring stations were not included) and only for sites in the Middle Wairarapa Valley.

3. WAIRARAPA SURFACE WATER AND GROUNDWATER CHEMISTRY

Results from HCA are presented in the form of dendrograms in Figures 1 and 2. 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.

Cluster "centroids" defined using Ward's method are compiled in Table 1. The centroid for a particular cluster gives the average value of each variable considered in the HCA algorithm. Parameters such as Fe, Mn, NO_3-N, NH_4-N, etc. were not included in the definition of the clusters, but average values within each cluster were determined (after the clusters had been defined on the basis of the other variables) and are listed in Table 1. Table 1 also includes information pertaining to the average global and national values of selected water quality parameters in rivers and groundwaters.

Results from HCA are also presented using complementary graphical methods such as a Piper diagram (Figure 6), and box-whisker plots (Figures 7 and 8) are used to assess the variation of each parameter between the clusters defined at a selected separation threshold. A summary of the significant hydrochemical variations between pairs of clusters is provided in Table 2. A "membership list" is compiled in Table 3, in which each site is unequivocally assigned to one cluster at each separation threshold. Table 4 lists the "predicted" cluster assignment for those sites that could not be considered in the HCA, i.e. those sites with CBE outside the acceptable limits of -10% to +10%, and for which median values were not available for between one and three of the required eight input variables. Finally, Figure 9 shows a simple graphical summary of the characteristics of each cluster.

The clusters defined in this investigation are based on data from surface water and groundwater monitoring stations across the entire Wairarapa Valley, but are highly comparable to the clusters defined by Daughney (2007) for the groundwater monitoring stations in the Middle Wairarapa Valley. The correspondence of clusters defined in the two studies is shown in Figure 10.

3.1 Identification of sites with unusual hydrochemistry

The Nearest Neighbour clustering algorithm was performed for the 276 sites (22 surface water monitoring stations and 254 groundwater monitoring stations) that had information for all eight of the required input parameters and also had CBE within the acceptable limits of ±10%. Eight residual sites were detected (Figure 1), most of which have higher proportions of Na and Cl (relative to other cations and anions) when compared to the other sites considered in this study (Figure 6). The eight residuals are all groundwater monitoring sites, but their locations do not appear to be spatially related:

- **S26/0001** (Upper Valley): Na-Cl type water with moderate conductivity (330 μS/cm)
- **T26/0540** (Upper Valley): Unusually high SO4 (210 mg/L) relative to other anions
- **S26/0045** (Upper Valley): very low ion concentrations and low conductivity (10 μS/cm)
- **S26/0657** (Middle Valley): Na-Cl type water with low conductivity (183 μS/cm)
- **S26/0739** (Middle Valley): Na-Cl type water with high conductivity (2250 μS/cm)
- **S26/0793** (Middle Valley): Na-Cl type water with high conductivity (5180 μS/cm)
- **S27/0442** (Lower Valley): Na-HCO3-Cl type water with low Ca (7.9 mg/L)
- **S27/0577** (Lower Valley): Na-Cl type water with high K (11 mg/L)

3.2 Cluster definitions

The eight residual sites with unusual hydrochemistry were excluded, and then the remaining 268 sites (22 surface water monitoring stations and 246 groundwater monitoring stations) could be divided into two[1] major hydrochemical categories at a separation threshold of ca. 1300 (Figure 2). These two clusters, termed Clusters A and B,[2] are very different in terms of "average" hydrochemistry, which is confirmed in the listing of centroids in Table 1. Indeed, the differences in the hydrochemistry are so large that the partitioning of sites into Clusters A and B provides little insight into spatial variability of groundwater quality across the Wairarapa Valley. Hence only a brief commentary on the distinction between Clusters A and B is warranted before focussing on the distinctions between clusters defined at lower separation thresholds:

- **Category A** (40.7% of sites): groundwaters (91 sites) and surface waters (18 sites) that are relatively dilute (median TDS is 81 mg/L) with Ca and HCO_3 as the dominant cation and anion, respectively. Median ion concentrations for Category A are comparable to the global average for river waters (Table 1), and accordingly most of the surface water monitoring sites in the Wairarapa are assigned to this category. For groundwater monitoring sites, this type of chemistry might be expected for aquifers that have been recently recharged from rivers, or for aquifers recently recharged from rainfall in areas with low intensity land use (cf. "pristine, unimpacted" groundwater category defined by Daughney and Reeves, 2005). Sites assigned to Category A are typified by oxygen-rich water, as evidenced by measurable concentrations of substances such as NO_3-N and SO_4 that tend to exist in oxygenated water, and low concentrations of substances such as NH_4-N Fe and Mn that are generally only present in oxygen-poor water.
- **Category B** (59.3% of sites): groundwaters (155 sites) and surface waters (4 sites) with Na and HCO_3 as the dominant cation and anion, respectively. The concentrations of most ions are higher than for Category A and are more similar to the global expectation for groundwater or for "reduced, evolved" groundwater in New Zealand (Table 1). For groundwater monitoring sites, this type of chemistry might indicate that the groundwaters are slightly older and/or that the aquifers receive a greater proportion of recharge from rain (salts are accumulated during passage through the soil zone). For surface water monitoring points, this type of chemistry might indicate that a substantial proportion of the water is derived from an aquifer, e.g. via seepage. Sites assigned to Category B are likely to exhibit oxygen-poor water, as evidenced by measurable concentrations of substances such as NH_4-N Fe and Mn that are generally only present in oxygen-poor water, and low concentrations of substances such as SO_4 and NO_3-N that tend to exist only in oxygen-rich water.

If the HCA separation threshold is lowered to roughly 600, Cluster A is partitioned into two smaller clusters (arbitrarily termed Clusters A1 and A2), and Cluster B is partitioned into four

[1] In any application of HCA, the minimum "resolution" results in the definition of two clusters. Technically, HCA can be performed to define just one cluster, but this is generally not very useful, because by definition this one cluster would include the entire dataset (i.e. in this study, all of the sites), and hence nothing would be learned about what makes certain sites different from others in terms of groundwater quality.

[2] All of the cluster names used in this report are completely arbitrary and are not chosen to relate to the location or hydrogeology of the sites included within each cluster.

smaller clusters (arbitrarily termed Clusters B1, B2, B3 and B4). If the separation threshold is further lowered to ca. 300, there are 13 subclusters defined: Cluster A1 remains undivided, Clusters A2, B2 and B3 are partitioned into two subclusters each, and Clusters B1 and B4 are partitioned into three subclusters each (Figure 2, Table 1). The actual separation thresholds employed are somewhat arbitrary and are based on the desired resolution of the investigation. The definition of six clusters (instead of just two) provides much more insight into the spatial variation of groundwater quality across the Wairarapa Valley, and the definition of 13 subclusters is really just the maximum that can be manageably interpreted and presented clearly (Figures 3 to 5). It is important to bear in mind that there may be substantial differences in the value of any single parameter at different sites within any single cluster or subcluster; these within-cluster and between-cluster parameter variations are displayed graphically on the Piper diagram in Figure 6 and the box-whisker plots in Figures 7 and 8.

To summarise, the hydrochemical differences between the six clusters and 13 subclusters are related to redox potential, TDS, water type and NO_3-N concentration. These hydrochemical differences appear to be driven by well depth, spatial variations in aquifer lithology and the degree of human impact (see summary diagram in Figure 9). Further distinctions amongst the various clusters and subclusters are described below.

- **Cluster A1** (34 sites, of which 8 are surface water sites): Sites assigned to Cluster A1 are typified by low concentrations of major ions, in many cases even lower than the global expectation for rivers (Table 1). Surface water sites assigned to Category A1 are associated with rivers that drain the Tararua Ranges, e.g. the Waiohine, Waingawa and Tauherenikau Rivers (Table 3). Groundwater monitoring sites assigned to Category A1 are usually wells less than 10 m deep that are heavily grouped in proximity to the losing reaches of rivers such as the Waiohine, Waingawa, Waipoua and Tauherenikau. This likely indicates a hydraulic connection by which the aquifers (likely Q1 gravels) are recharged directly from the rivers. Cluster A1 groundwaters tend to have low concentrations of substances such as NH_4-N, Fe and Mn, suggesting that they are oxygen-rich.
- **Cluster A2** (75 sites, of which 10 are surface water sites): Cluster A2 hydrochemistry is differentiated from Cluster A1 by slightly higher TDS and higher proportions of Na relative to Ca and of Cl relative to HCO_3. Similar to Cluster A1, Cluster A2 has measurable SO_4, coupled with low Mn, Fe and NH_4-N, indicating that aerobic water is the norm. Groundwater monitoring sites assigned to Cluster A2 are typically shallow and are found in association with Q2, Q3 and Q4 alluvial fan deposits adjacent to the Tararua Ranges. The hydrochemistry suggests that Cluster A2 groundwaters receive recharge from rainfall instead of or as well as from rivers (a conclusion also reached by Morgenstern, 2005). As another indicator of the importance of rainfall recharge, the A2 groundwaters tend to have higher NO_3-N than A1 sites (salts and NO_3-N are accumulated during passage of water through the soil zone). Surface water sites assigned to Cluster A2 are located on the Ruamahanga, Mangatarere, Waipoua and Tauanui Rivers (Table 3). This may indicate that the baseflow of these rivers is supplied by groundwater that has been recharged primarily via rainfall. It appears that the Ruamahanga River has relatively little interaction with groundwater in the Lower Valley, because the river maintains an A2 signature whereas the nearby groundwaters are hydrochemically quite different.

- **Subcluster A2a** (32 sites, of which 4 are surface water sites): Sites assigned to subcluster A2a are differentiated from other sites in Cluster A2 by higher conductivity and slightly higher concentrations of major ions. The higher concentrations of NO_3-N, K, Cl and SO_4 may indicate that subcluster A2a sites are recharged primarily from rainfall, possibly in areas with more intensive land use impact compared to sites assigned to subcluster A2b. Most sites assigned to subcluster A2a are located in the Middle and Upper portions of the Wairarapa Valley.
- **Subcluster A2b** (43 sites, of which 6 are surface water sites): Sites assigned to subcluster A2b are differentiated from other sites in Cluster A2 by lower conductivity and slightly lower concentrations of major ions. Sites assigned to subcluster A2b may receive a portion of recharge from rivers, or may be recharged in areas with less intense land use compared to sites assigned to subcluster A2a. Most sites assigned to subcluster A2b are located in the Middle and Upper portions of the Wairarapa Valley, typically interspersed with sites assigned to subcluster A2a.

- **Cluster B1** (54 sites, of which 4 are surface water sites): Relative to sites assigned to Clusters A1 and A2, sites assigned to Cluster B1 are characterised by a considerable increase in all major ions and conductivity, higher concentrations of NH_4-N, Fe and Mn, and relatively low concentrations of NO_3-N. These hydrochemcial characteristics suggest perhaps older more evolved groundwater, more oxygen-poor conditions at some sites, and/or the influence of local geology. With respect to the possible influence of geology, it is noteworthy that surface water sites assigned to Cluster B1 are predominantly associated with the rivers and streams that drain the hills on the eastern margin of the Wairarapa Valley, such as the Whangaehu and Huangarua Rivers and the Kopuaranga Stream (Table 3). The geology in the catchments of these rivers and streams includes Miocene-Pliocene marine deposits that may be allow for greater or more rapid accumulation of dissolved substances, relative to the chemically more resistant Mesozoic greywacke that forms the Tararua Ranges. Groundwater sites assigned to Cluster B1 may receive a significant portion of their recharge from B1-type streams or be hosted by aquifer materials that include some alluvium derived from the Miocene-Pliocene marine deposits in the eastern hills. Groundwater sites assigned to Cluster B1 are found in several locations, including the Te Ore Ore sub-basin in the Upper Valley, the shallower aquifers in the vicinity of Carterton and Greytown and near the coast.
  - **Subcluster B1a** (16 sites, of which 4 are surface water sites): Sites assigned to subcluster B1a are differentiated from other sites in Cluster B1 by having higher concentrations of Ca (conductivity and TDS are the same across all subclusters of B1). The low concentrations of NH_4-N, Fe and Mn indicate that most sites assigned to subcluster B1a are typified by oxygen-rich conditions. Concentrations of NO_3-N are typically low and similar to Cluster A1, indicating that human/agricultural impact is generally limited, and/or that recharge is derived primarily from river seepage. Sites assigned to subcluster B1a are predominantly found on the eastern side of the valley, e.g. in the Te Ore Ore sub-basin and proximal to rivers and streams that drain the hills on the eastern side of the Wairarapa Valley.
  - **Subcluster B1b** (17 sites, none of which are surface water sites): Sites assigned to subcluster B1b are differentiated from other sites in Cluster B1 by having higher

concentrations of Mg and Na and lower concentrations of SO_4 (conductivity and TDS are the same across all subclusters of B1). Sites assigned to subcluster B1b also have higher concentrations of NH_4-N, Fe and Mn compared to other sites in Cluster B1, which indicates that many B1b-type sites exhibit oxygen-poor conditions. Concentrations of NO_3-N are typically low and similar to Cluster A1, indicating that human/agricultural impact is generally limited, and/or that recharge is derived primarily from river seepage. Most sites assigned to subcluster B1b are found along the centre of the valley, for example in the Carterton sub-basin in the Middle Valley and just east of Lake Wairarapa in the Lower Valley. The prevalence of oxygen-poor conditions is consistent with deeper aquifers that are isolated from the atmosphere.

  - **Subcluster B1c** (21 sites, none of which are surface water sites): Sites assigned to subcluster B1c are differentiated from other sites in Cluster B1 by having lower concentrations of HCO_3 (conductivity and TDS are the same across all subclusters of B1). The low concentrations of NH_4-N, Fe and Mn indicate that most sites assigned to subcluster B1c are typified by oxygen-rich conditions. Concentrations of NO_3-N are typically low and similar to Cluster A1. Sites assigned to subcluster B1c are grouped together in certain areas of the valley, including the Te Ore Ore sub-basin and the Lower Valley near the Huangarua River.

- **Cluster B2** (44 sites, all of which are groundwater sites): The hydrochemistry at sites in Cluster B2 is generally similar to Cluster B1, but the B2 sites typically have slightly lower concentrations of major ions and higher concentrations of NH_4-N, Fe and Mn, These higher concentrations, coupled with the observed low SO4 concentrations, suggests that B2-type waters are more oxygen-poor, with sulphate reduction occurring at some sites. Groundwater sites assigned to Cluster B2 are of shallow to moderate depth and are found in both the Carterton and Parkvale sub-basins, possibly in confined Q6 deposits.

  - **Subcluster B2a** (34 sites, none of which are surface water sites): Sites assigned to subcluster B2a are differentiated from other sites in Cluster B2 by slightly lower concentrations of NH_4-N, Fe and Mn. This hydrochemical pattern suggests that while most sites assigned to Cluster B2 are typified by oxygen-poor water, the sites in subcluster B2a may not be as anoxic as the sites assigned to subcluster B2b.

  - **Subcluster B2b** (10 sites, none of which are surface water sites): Sites assigned to subcluster B2b are differentiated from other sites in Cluster B2 by their higher concentrations of NH_4-N, Fe and Mn. Many sites assigned to subcluster B2b are relatively shallow, which implies that the accumulation of NH_4-N, Fe and Mn is not necessarily controlled by the age of groundwater but instead by the availability of a reductant like organic carbon.

- **Cluster B3** (30 sites, all of which are groundwater sites): The hydrochemistry at sites in Cluster B3 is generally similar to Clusters B1 and B2, but Cluster B3 sites tend to have higher concentrations of most major ions and lower concentrations of SO_4. This suggests that B3-type groundwaters are slightly older, more chemically evolved or that groundwater flow conditions may be more stagnant than at B1 or B2 sites. B3-type groundwaters are derived from relatively deep bores, perhaps screened in Q8 deposits, and are scattered in the Lower Valley and the Parkvale and Carterton sub-basins.

- **Subcluster B3a** (18 sites, none of which are surface water sites): Sites assigned to subcluster B3a are differentiated from other sites in Cluster B3 by slightly higher concentrations of Ca and Mg relative to Na, although Na is in general the dominant cation. Sites assigned to subcluster B3a are found in the Middle and Lower Valley.
- **Subcluster B3b** (12 sites, none of which are surface water sites): Sites assigned to subcluster B3b are differentiated from other sites in Cluster B3 by significantly higher concentrations of K and slightly lower concentrations of Ca and Mg relative to Na, although Na is in general the dominant cation. The high concentration of K may indicate the importance of ion exchange. Sites assigned to subcluster B3b are found in the Lower Valley.

- **Cluster B4** (31 sites, all of which are groundwater sites): Cluster B4 groundwaters are differentiated from others in this classification scheme by the highest conductivity and concentrations of major ions, indicating groundwater that is likely old and possibly stagnant. The low SO_4 and NO_3-N concentrations indicate a highly anoxic environment, with little connection to the atmosphere. Sites assigned to Cluster B4 are all moderate to deep wells, the majority of which are located in the Lower Valley, with a small group in the Parkvale sub-basin (i.e. just west of Tiffen Hill). It is assumed that these bores tap into sediments older than oxygen isotope stage Q8, and that aquifer recharge is derived via seepage from overlying units.
  - **Subcluster B4a** (5 sites, none of which are surface water sites): Sites assigned to subcluster B4a are differentiated from other sites in Cluster B4 by their higher concentrations of SO_4 (the highest of any subcluster defined in this study) and lower concentrations of NH_4-N, Fe and Mn. This hydrochemical pattern suggests that many sites assigned to subcluster B4a are typified by oxygen-rich conditions. Wells assigned to subcluster B4a tend to be shallower than other B4-type sites, but are still relatively deep compared to the sites assigned to other clusters defined in this study. This may indicate that oxygen depletion at sites assigned to subcluster B4a is limited by the absence of a suitable reductant such as organic carbon.
  - **Subcluster B4b** (16 sites, none of which are surface water sites): Sites assigned to subcluster B4b are differentiated from other sites in Cluster B4 by having lower concentrations of Na and Cl and higher concentrations of HCO_3 and NH_4-N. Concentrations of SO_4 are low, indicating strongly reducing conditions (sulphate reduction is occurring). An abundance of B4b-type sites is found in the Lower Valley.
  - **Subcluster B4c** (10 sites, none of which are surface water sites): Sites assigned to subcluster B4c are differentiated from other sites in Cluster B4 by having higher conductivity and higher concentrations of Na, K and Cl. Concentrations of SO_4 are generally low, indicating strongly reducing conditions (sulphate reduction is occurring). Most B4c-type sites are found in the Lower Valley.

4. FOCUS ON HYDROCHEMISTRY IN THE UPPER WAIRARAPA VALLEY

This section of the report provides a focus on the spatial variations in hydrochemistry in the Upper Wairarapa Valley (Figure 3). The following observations can be made:

- Rivers that drain the Tararua Ranges on the western side of the valley (e.g. Waingawa, Waipoua upstream of Masterton, Ruamahanga upstream of Kopuaranga confluence) typically have oxygen-rich water with relatively low concentrations of dissolved solids. As elsewhere in the Wairarapa Valley, the waters of rivers that drain the Tararua Ranges are assigned to Cluster A1. The implication is that the rocks of the Tararua Ranges are resistant to chemical erosion (perhaps because the rocks are well lithified), and/or that the contact time between the water and rock is brief, such that only limited accumulation of dissolved ions in the river water occurs.
- Rivers that drain the eastern side of the valley (e.g. Whangaehu, Kopuaranga) are typically have oxygen-rich water with higher concentrations of dissolved solids and more Na relative to Ca compared to the rivers that drain the western side of the valley. The catchments on the eastern side of the valley contain Miocene-Pliocene rocks of marine origin, and the difference in geology (compared to the Mesozoic Tararura greywacke) appears to lead to a distinct hydrochemical signature in the rivers that drain the eastern hills (Cluster B1).
- Oxygen-rich groundwater with “Tararura-like” hydrochemistry (Cluster A1) is found in shallow wells in Q1 gravels near the losing reaches of rivers that drain the Tararua Ranges, such as the Waignawa, Waipoua and Ruamahanga. This very likely indicates a hydraulic connection between the losing reach of these rivers and the shallow Q1 alluvial gravel aquifers.
- Away from the rivers, with the exception of the Te Ore Ore sub-basin, shallow groundwater is oxygen-rich and has a hydrochemical signature that is consistent with rainfall recharge (Cluster A2). The implication is that rainfall supplies the majority of recharge to aquifers in the alluvial fan deposits (predominantly Q2) that outcrop across much of the Upper Valley.
- There is an intermixed group of A1-type and A2-type groundwaters adjacent to the Waingawa River where it crosses the Masterton Fault. In this particular area, some portions of the aquifer may receive recharge primarily from river seepage (the Waingawa is a “Tararua-like river assigned to Cluster A1), perhaps via preferential flow pathways in Q1 gravels. In contrast, the hydraulic connection to the river is not as strong elsewhere, and the aquifers are recharged by rainfall, perhaps through Q2 fan materials.
- There are several deeper wells in the centre of the Upper Valley where groundwater is oxygen-poor (Cluster B2). The hydrochemistry at these sites could be acquired by evolution from A1- or A2-type groundwater as it moves along a flow path. The implication is that B2-type groundwater might be recharged by rainfall and that hydraulic connections may exist between sites assigned to Cluster A1 or A2 and Cluster B2, although this hypothesis would need to be verified through aquifer testing.
- The groundwater wells assigned to Cluster B2 tend to be relatively deep in the central part of the Upper Valley, but are shallower further east. This spatial pattern may indicate that B2-type groundwater is moving upward from depth and nearing the surface in the vicinity of the Ruamahanga River. This hypothesis cannot be verified with hydrochemical

data alone, but is consistent with the geological interpretation of the Upper Valley, by which aquifers are assumed to dip towards the northwest.

- The groundwater in the Te Ore Ore sub-basin is chemically similar to the rivers that drain the eastern hills (Cluster B1). This may indicate that groundwater in the Te Ore Ore sub-basin is recharged by seepage from a B2-type river, such as the Whangaehu or the Kopuaranga. Alternatively or in addition, it is possible that the Te Ore Ore sub-basin contains some alluvial material derived from erosion of the Miocene-Pliocene rocks of marine origin known to be present for example in the catchments of the Whangaehu and Kopuaranga Rivers. In the latter case, it is possible that the B1-type hydrochemical signature could be acquired through rainfall recharge, as the infiltrating water reacts with the Miocene-Pliocene alluvium. It is not possible from the hydrochemical data alone to determine whether river or rainfall recharge is dominant in the Te Ore Ore sub-basin.

5. FOCUS ON HYDROCHEMISTRY IN THE LOWER WAIRARAPA VALLEY

This section of the report provides a focus on the spatial variations in hydrochemistry in the Lower Wairarapa Valley (Figure 5). The following observations can be made:

- Rivers that drain the Tararua Ranges on the western side of the valley (e.g. Tauherenikau) are typically oxygen-rich with relatively low concentrations of dissolved solids. As elsewhere in the Wairarapa Valley, these rivers that drain the Tararua Ranges are assigned to Cluster A1. The implication is that the rocks of the Tararua Ranges are resistant to chemical erosion, and/or that the contact time between the water and rock is brief, resulting in only limited accumulation of dissolved ions in the river water occurs.
- Rivers that drain the eastern side of the valley (e.g. Huangarua) are typically oxygen-rich with higher concentrations of dissolved solids and higher concentrations of Na relative to Ca compared to the rivers that drain the western side of the valley. The catchments on the east side of the valley contain Miocene-Pliocene rocks of marine origin, and the difference in geology (compared to the Mesozoic Tararura greywacke) appears to lead to a distinct hydrochemical signature in the rivers that drain the eastern hills (Cluster B1).
- The Ruamahanga River has an A2-type hydrochemical signature along much of its course, from the Upper Valley to the Lower Valley. This hydrochemical signature is consistent with a significant portion of baseflow being derived from rainfall-recharged groundwater. While rainfall recharged groundwater is evident in the Upper and Middle Valley, such groundwater is not found in proximity to the Ruamahanga River in the Lower Valley. This implies that the Ruamahanga River does not gain or lose a significant volumetric proportion of its flow from aquifers in the Lower Valley. This assumption is consistent with the concurrent gauging data (Figure 5) and with isotope data for the Lower Valley (Morgenstern, 2005).
- Lake Wairarapa has a B1-type chemical signature, even though the rivers and streams that drain into it (e.g. Tauherenikau) have A1 or A2 signatures. Deeper groundwaters in the vicinity of Lake Wairarapa are assigned to Clusters B1, B2, B3 and B4. Hence the hydrochemistry of the lake may indicate that it receives some inflow via seepage of deep groundwater.

- Oxygen-rich groundwater with “Tararura-like” hydrochemistry (Cluster A1) is found in shallow wells in Q1 gravels near the losing reaches of rivers that drain the Tararua Ranges, such as the Tauherenikau. This pattern is observed elsewhere in the Wairarapa Valley and very likely indicates a hydraulic connection between the losing reach of the river and the shallow Q1 alluvial gravel aquifers.
- In areas northeast of Lake Wairarapa, particularly in the centre and at the western margin of the valley, Q2 fan deposits are exposed at the surface and shallow groundwater is oxygen-rich and has a hydrochemical signature that is consistent with rainfall recharge (Cluster A2). This spatial pattern is observed in the Middle and Upper Wairarapa Valley as well, implying that rainfall supplies the majority of recharge to aquifers in these alluvial fan deposits.
- There are several moderately deep wells in the centre of the Lower Valley, north and east of Lake Wairarapa, where groundwater is oxygen-poor and total dissolved solids concentrations are moderate (Cluster B2). The hydrochemistry at these sites could be acquired by evolution from A2-type groundwater as it moves along a flow path. The implication is that these B2-type groundwaters might be recharged by rainfall and that hydraulic connections may exist between sites assigned to Cluster A2 and Cluster B2 in the Lower Valley, although this hypothesis would need to be verified through aquifer testing.
- The majority of wells south of Lake Wairarapa are relatively deep and contain groundwater that is oxygen-poor with relatively high concentrations of total dissolved solids (Clusters B3 and B4). This hydrochemical signature is consistent with moderately to strongly reducing conditions (sulphate reduction is evident at many sites assigned to Cluster B4). The implication is that the groundwater in this part of the Lower Valley is relatively old, aquifers are probably confined, and groundwater is perhaps flowing slowly. The sites assigned to Cluster B3 and Cluster B3 are spatially intermixed, so it is unclear whether they represent isolated aquifers or instead are hydraulically linked.

6. SUMMARY

This investigation employed hierarchical cluster analysis (HCA) to provide insight into the groundwater chemistry in the Upper Wairarapa Valley (the area north of the Waingawa River) and the Lower Wairarapa Valley (the area south of the Waiohine River). The aim was to assist with development and substantiation of the transient groundwater flow models for the Upper and Lower Wairarapa Valley currently being developed by GWRC. This study complements the assessment of hydrochemistry in the Middle Wairarapa Valley (the area between the Waingawa and Waiohine Rivers) made by Daughney (2007).

HCA conducted using all available surface water and groundwater chemistry data for the entire Wairarapa Valley allowed for the definition of two, six or thirteen hydrochemical clusters, depending on the separation threshold employed. The hydrochemistry and spatial positioning of sites assigned to these various clusters provides insight into the hydrology of the Wairarapa Valley:

- The chemistry of the rivers draining into the Wairarapa Valley is controlled by geology. The Tararua Ranges on the west side of the Wairarapa Valley are composed of chemically resistant greywacke. Rivers draining the Tararua Ranges, and groundwaters fed from losing reaches of these rivers, are of a particular chemical signature typified by the presence of oxygen and relatively low concentrations of dissolved ions. In contrast, rivers draining the catchments in the eastern hills have a different chemical signature, usually with higher concentrations of dissolved ions, which is probably controlled by the presence of Miocene-Pliocene rocks of marine origin.
- Rainfall-recharged groundwaters are found in shallow wells throughout the Wairarapa Valley where Q2 alluvial fan deposits are mapped at the surface. The passage of recharge water through the soil zone allows for the accumulation of dissolved salts and, in some places, also nitrate.
- Where rainfall-recharged groundwater supplies the baseflow of a river, that river may display a chemical signature similar to that of the groundwater. The Mangatarere and Ruamahanga Rivers appear to be of this type.
- Lake Wairarapa has a hydrochemistry that implies that it is fed to some degree by seepage from deeper, oxygen-poor groundwater.
- Most groundwater sites in the Lower Valley are oxygen-poor, often with relatively high concentrations of total dissolved solids. The implication is that the groundwater in the Lower Valley is relatively old, aquifers are probably confined, and groundwater is perhaps flowing slowly.

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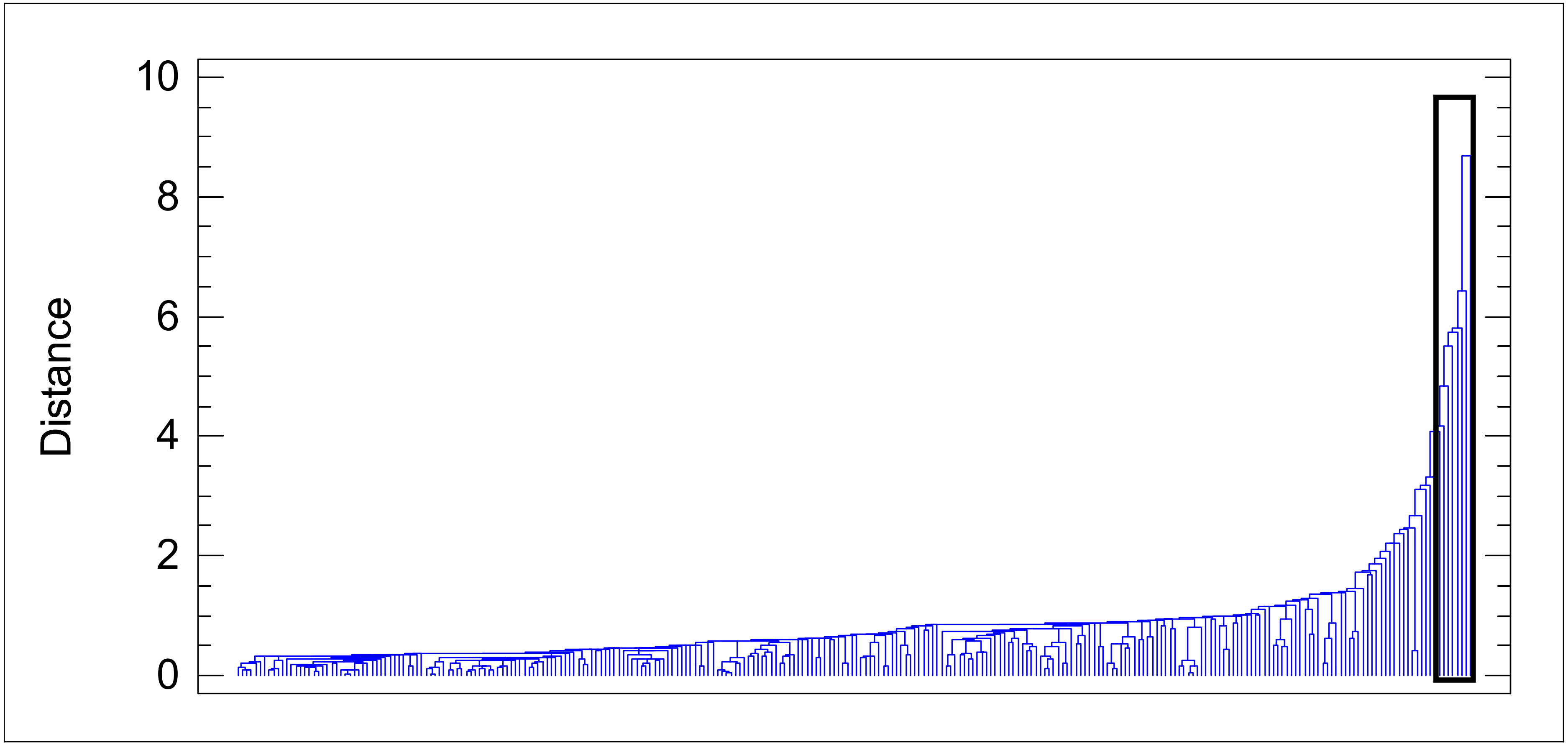

Figure 1. Hierarchical cluster analysis dendrogram, Nearest Neighbour linkage rule. The terminus of each vertical blue line represents a single monitoring site. Marked box identifies eight outlier (residual) sites.

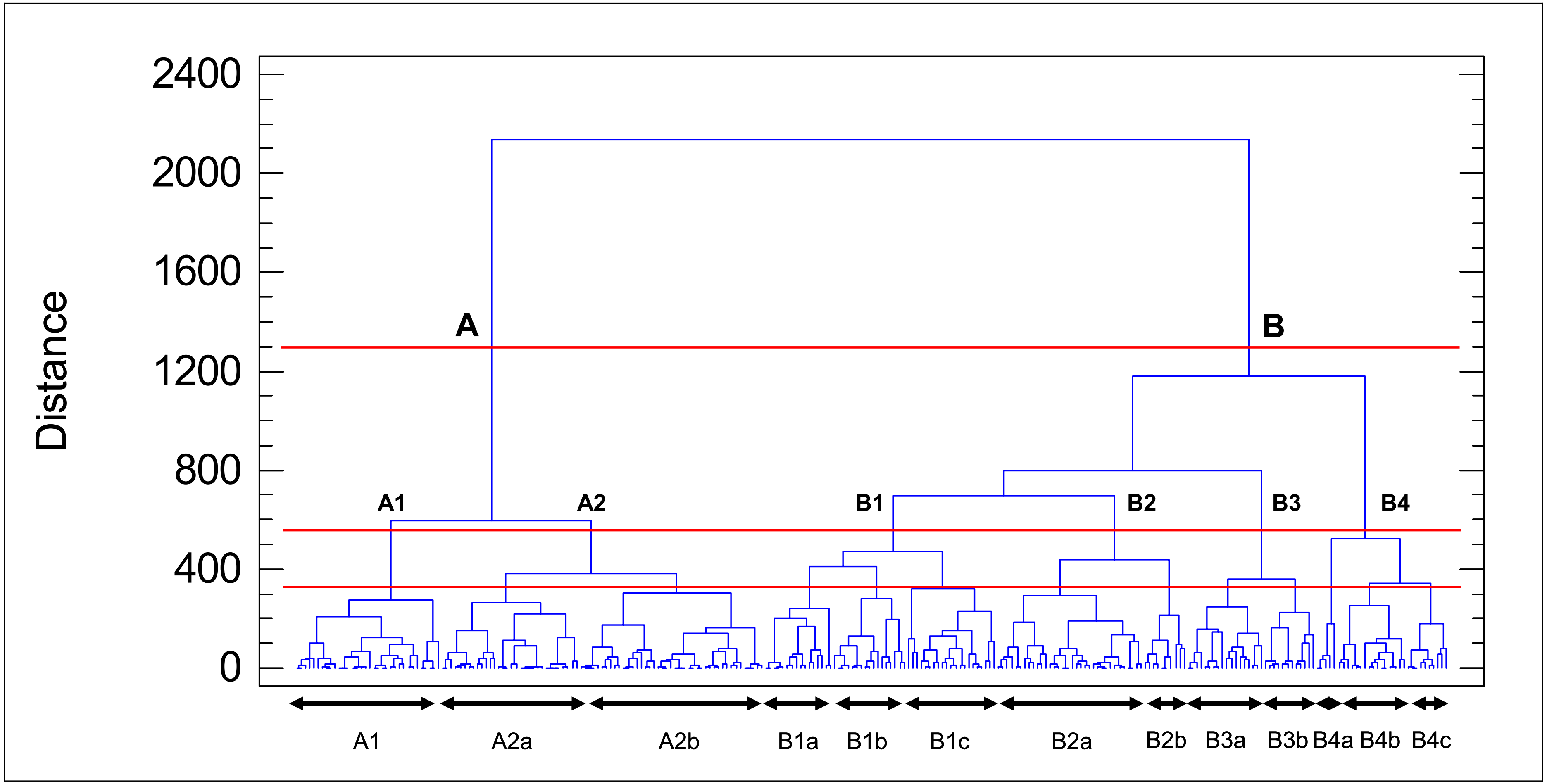

Figure 2. Hierarchical cluster analysis dendrogram, Ward's linkage rule. identifying two main clusters (A and B) at a separation threshold of ca. 1300, six subclusters (A1 to B4) at a separation threshold of ca. 550, and thirteen subclusters (A1 to B4c) at a separation threshold of ca. 350. The terminus of each vertical blue line represents a single monitoring site.

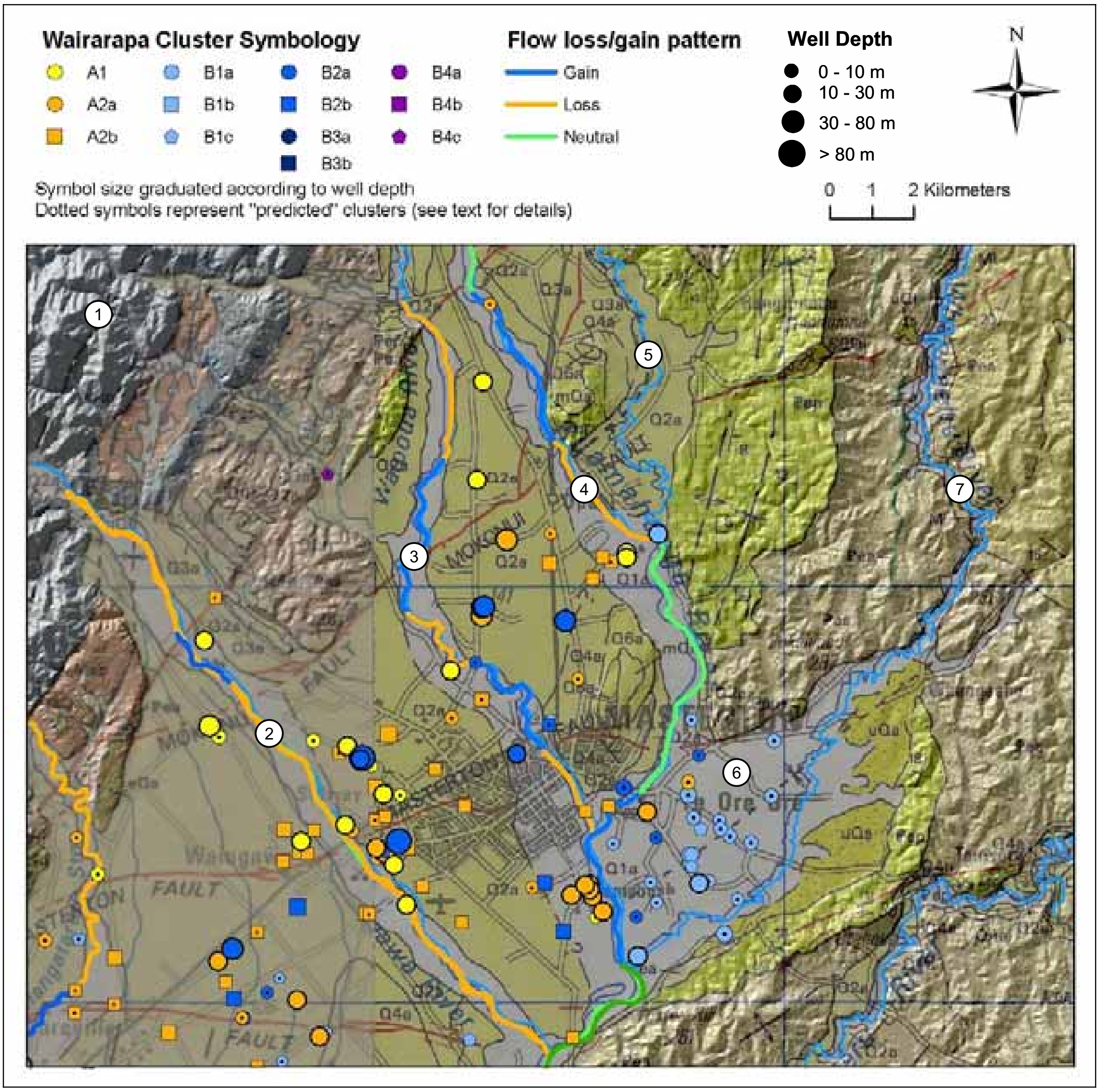

Figure 3. Cluster assignments, Upper Wairarapa Valley. Map base layer shows a digital terrain model in combination with surficial geology (Begg and Johnston, 2000; Lee and Begg, 2002). Circled numbers denote geographic features described in the text: 1) Tararua Ranges, 2) Waingawa River, 3) Waipoua River, 4) Ruamahanga River, 5) Kopuaranga River, 6) Te Ore Ore subbasin, 7) Whangaehu River.

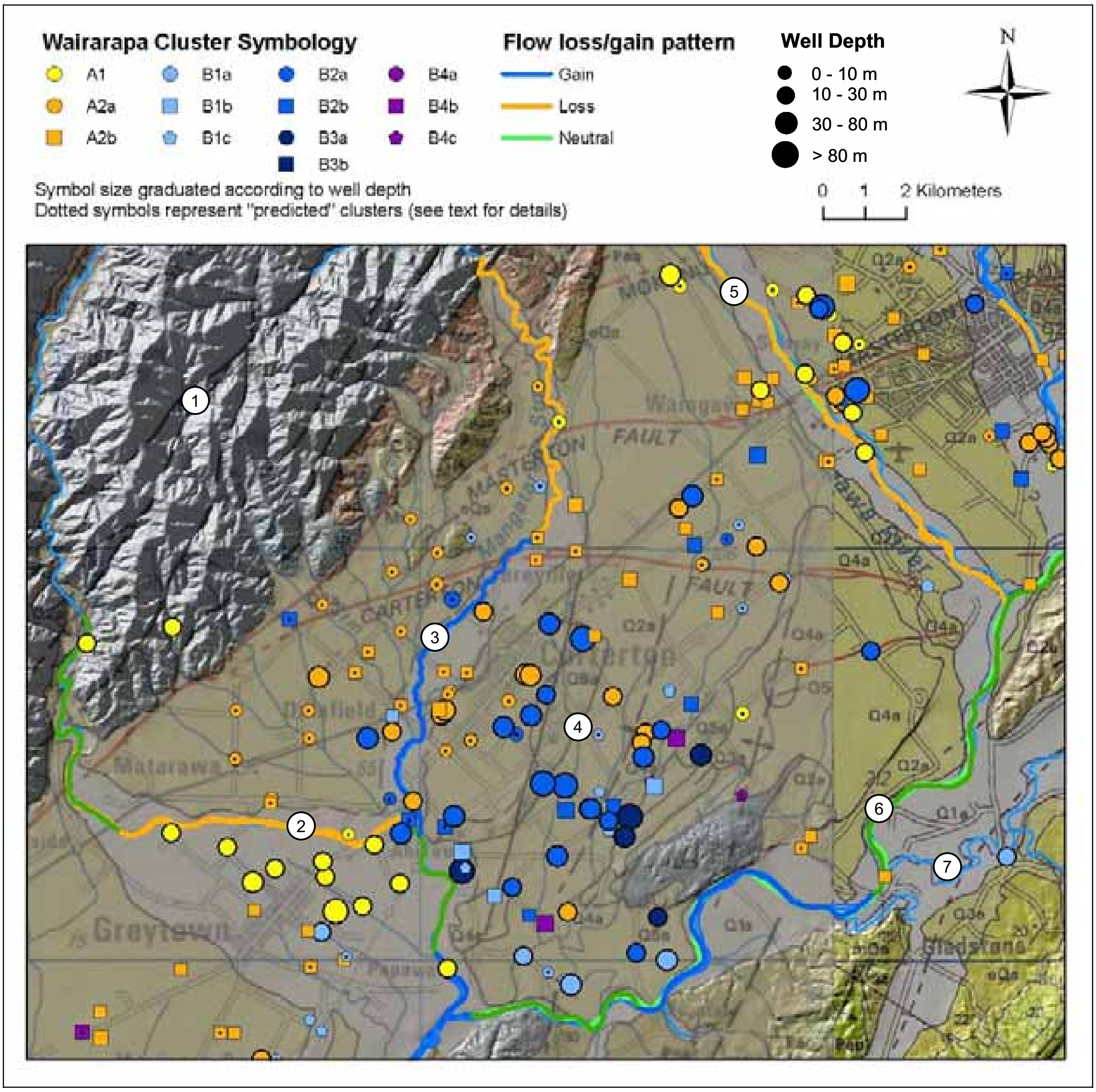

Figure 4. Cluster assignments, Middle Wairarapa Valley. Map base layer shows a digital terrain model in combination with surficial geology (Begg and Johnston, 2000; Lee and Begg, 2002). Circled numbers denote geographic features described in the text: 1) Tararua Ranges, 2) Waiohine River, 3) Mangatarere Stream, 4) Carterton subbasin, 5) Waingawa River, 6) Ruamahanga River, 7) Waingongoro Stream.

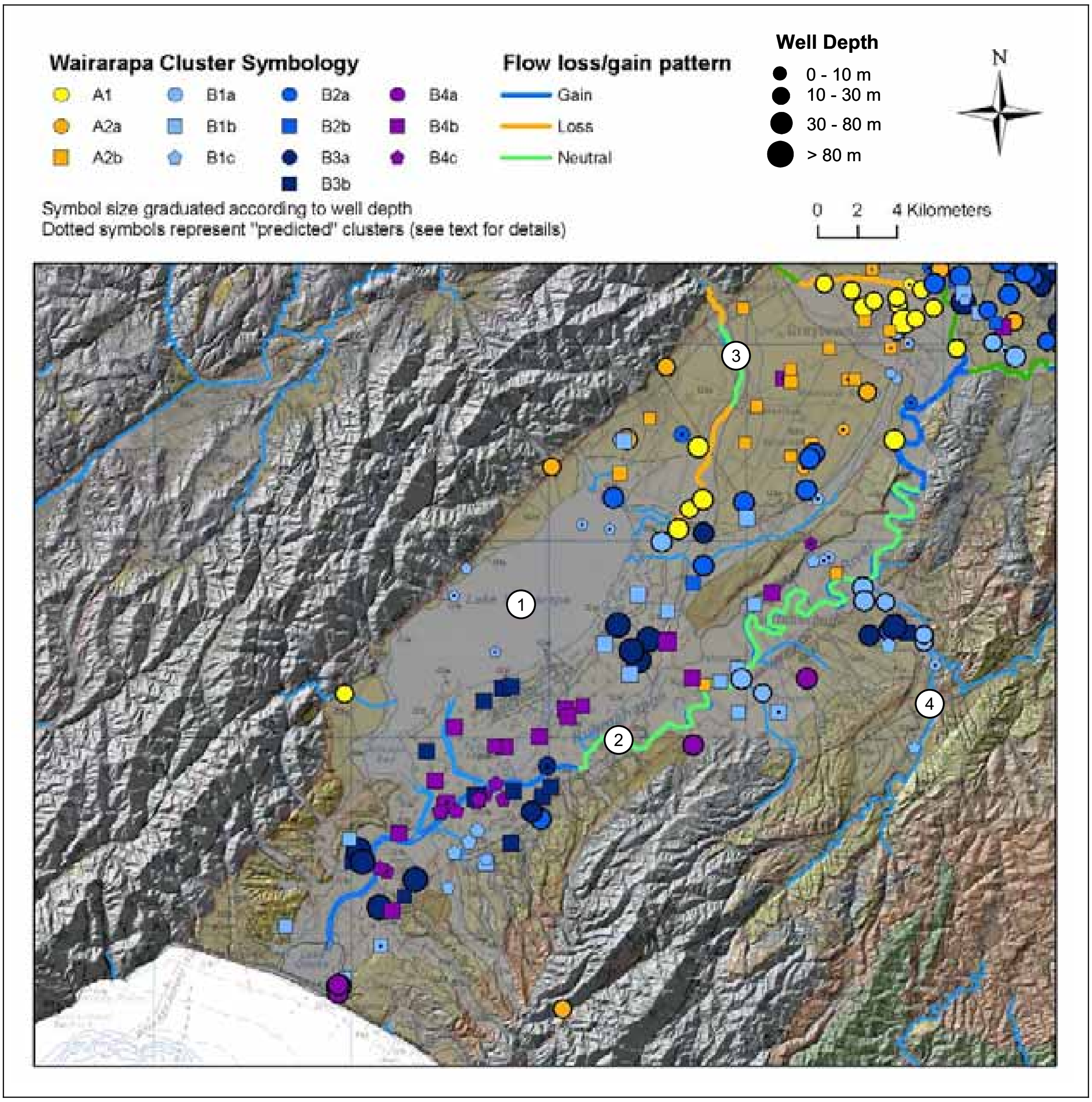

Figure 5. Cluster assignments, Lower Wairarapa Valley. Map base layer shows a digital terrain model in combination with surficial geology (Begg and Johnston, 2000; Lee and Begg, 2002). Circled numbers denote geographic features described in the text: 1) Lake Wairarapa, 2) Ruamahanga River, 3) Tauherenikau River, 4) Huangarua Stream.

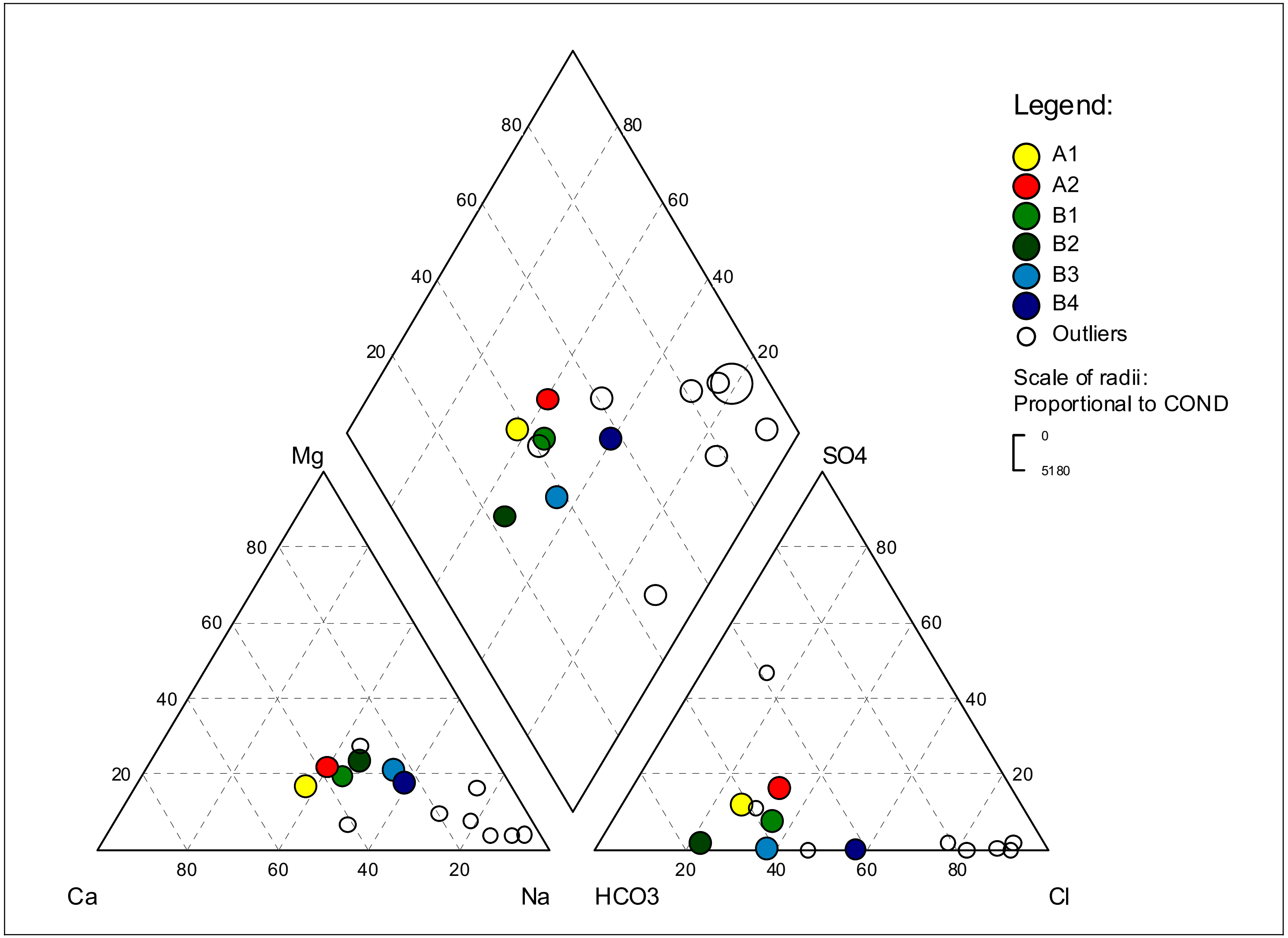

Figure 6. Piper diagram showing the variation of major ion ratios amongst the centroids of the six clusters defined by HCA at a separation threshold of ca. 500 (coloured symbols) and the eight outlier (residual) sites (unfilled symbols). The left and right triangular plots show the major cation and anion ratios respectively, and the centre diamond plot shows the projected position based on the two triangular plots. Symbol size in the central diamond is proportional to electric conductivity.

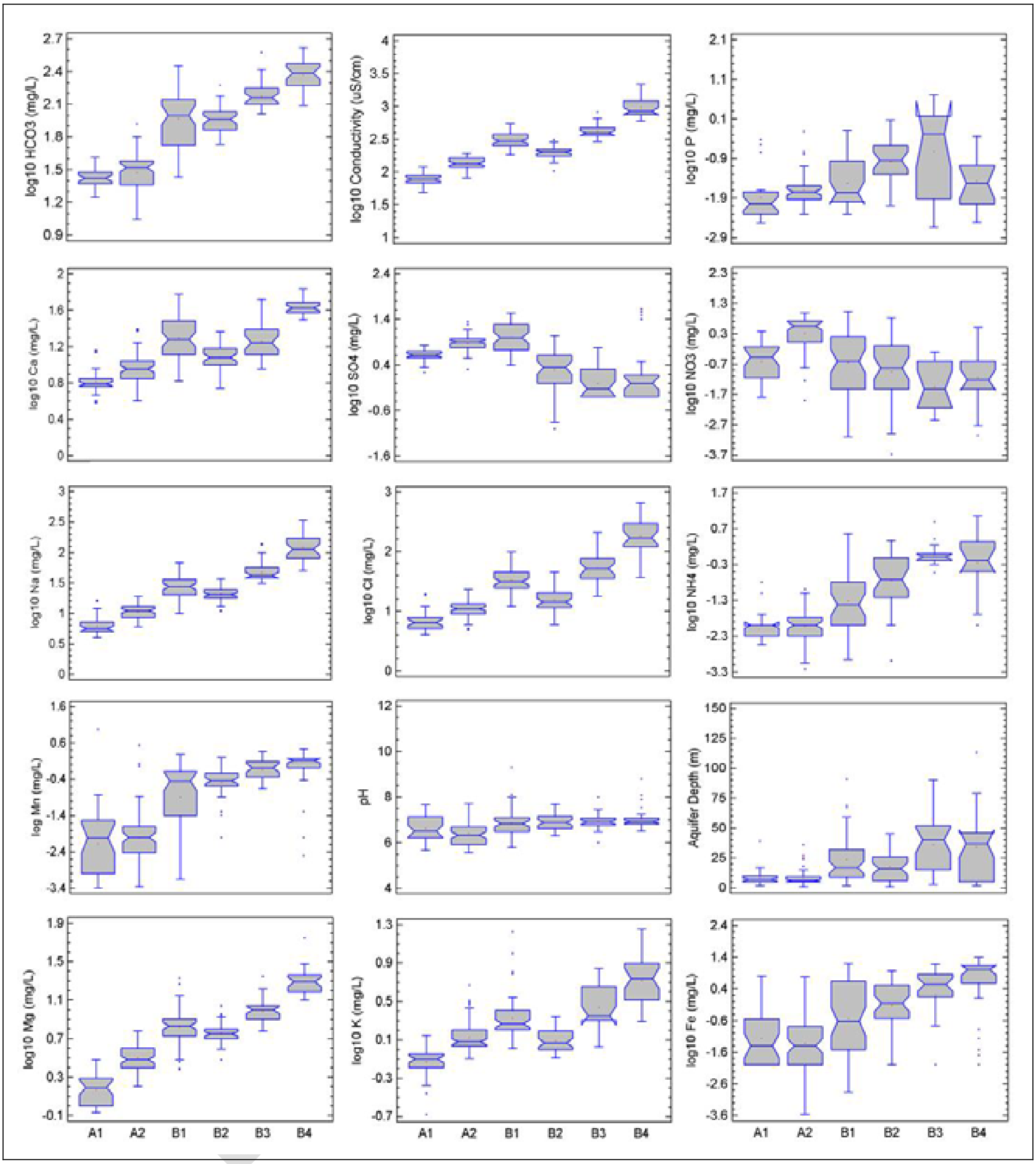

Figure 7. Box-whisker plots showing variation of selected parameters between six clusters defined by HCA. The rectangular "box" extends from the 25th to the 75th percentile, covering inter-quartile range, i.e. the centre half of each distribution. The horizontal line within the box shows the location of the median (50th percentile). The "whiskers" extend from the box to the minimum and maximum values in each category, except for outliers that are more than 1.5 times the interquartile range above or below the box (outliers are plotted as separate points above or below the whiskers).

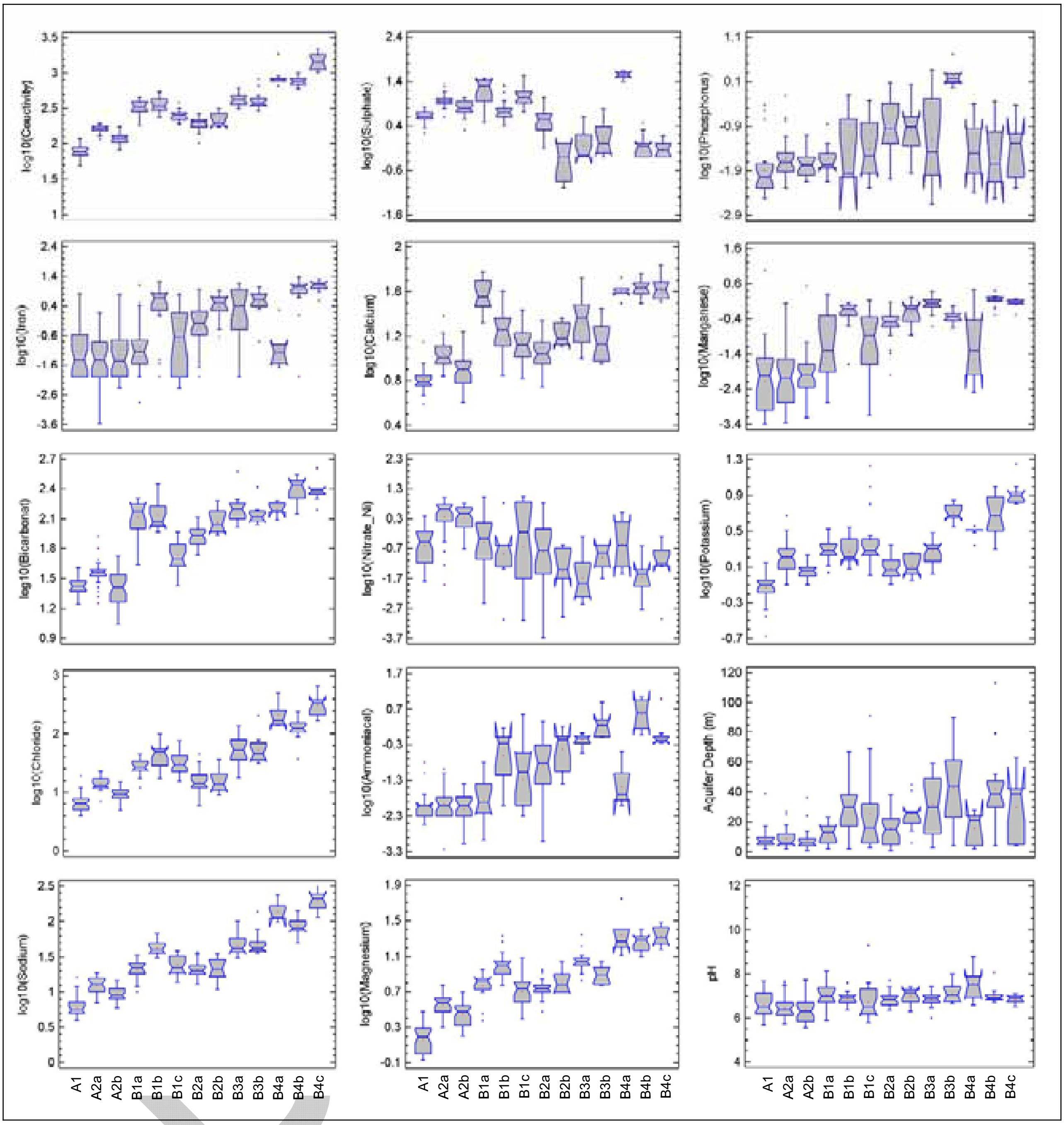

Figure 8. Box-whisker plots showing variation of selected parameters between thirteen subclusters defined by HCA. The rectangular "box" extends from the 25th to the 75th percentile, covering inter-quartile range, i.e. the centre half of each distribution. The horizontal line within the box shows the location of the median (50th percentile). The "whiskers" extend from the box to the minimum and maximum values in each category, except for outliers that are more than 1.5 times the interquartile range above or below the box (outliers are plotted as separate points above or below the whiskers).

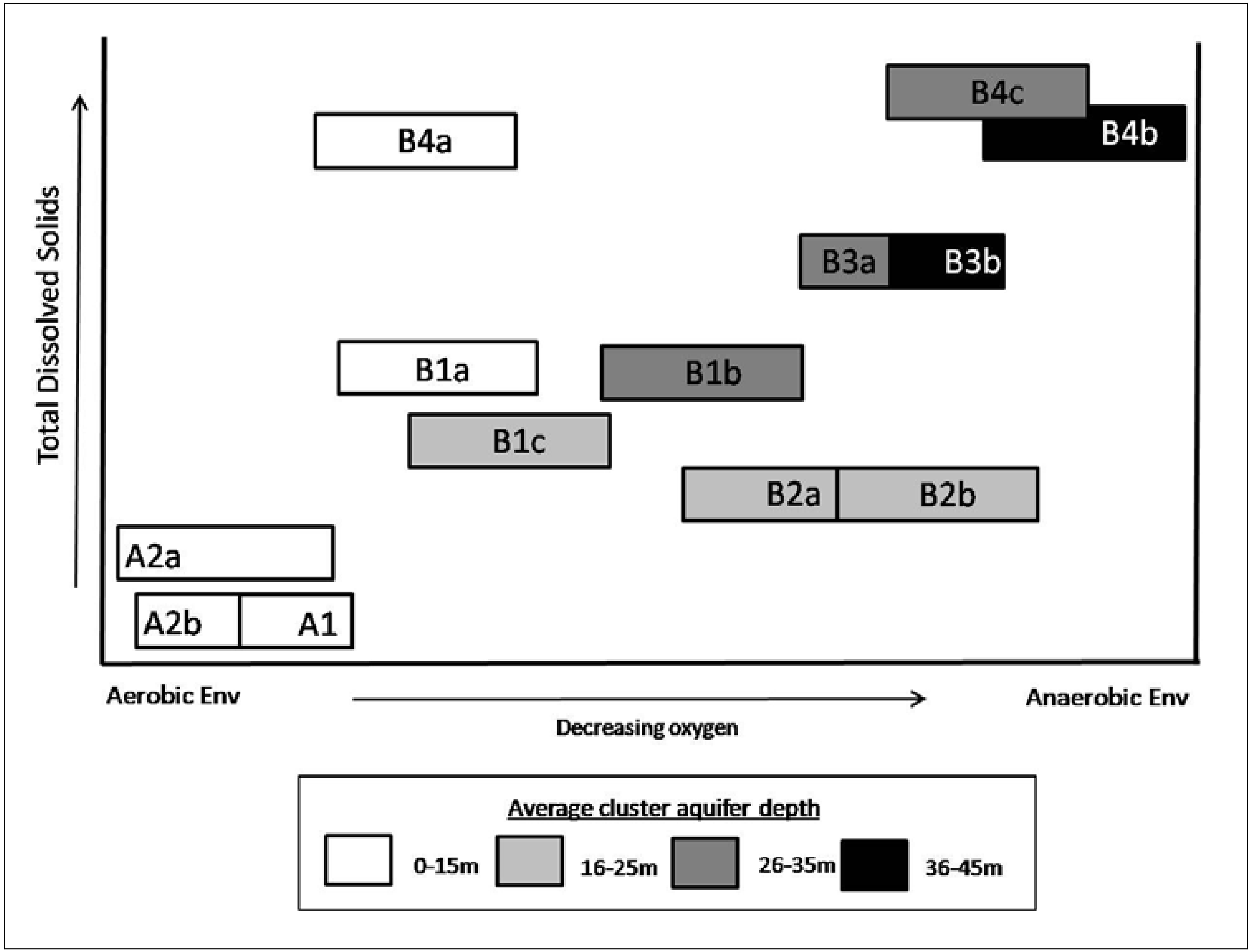

Figure 9. Simplified schematic representation of differences amongst the 13 subclusters (A1a-B4c) in relation to their total dissolved solids, aquifer depth and aerobic environment. Scale and axis is representative of increase only.

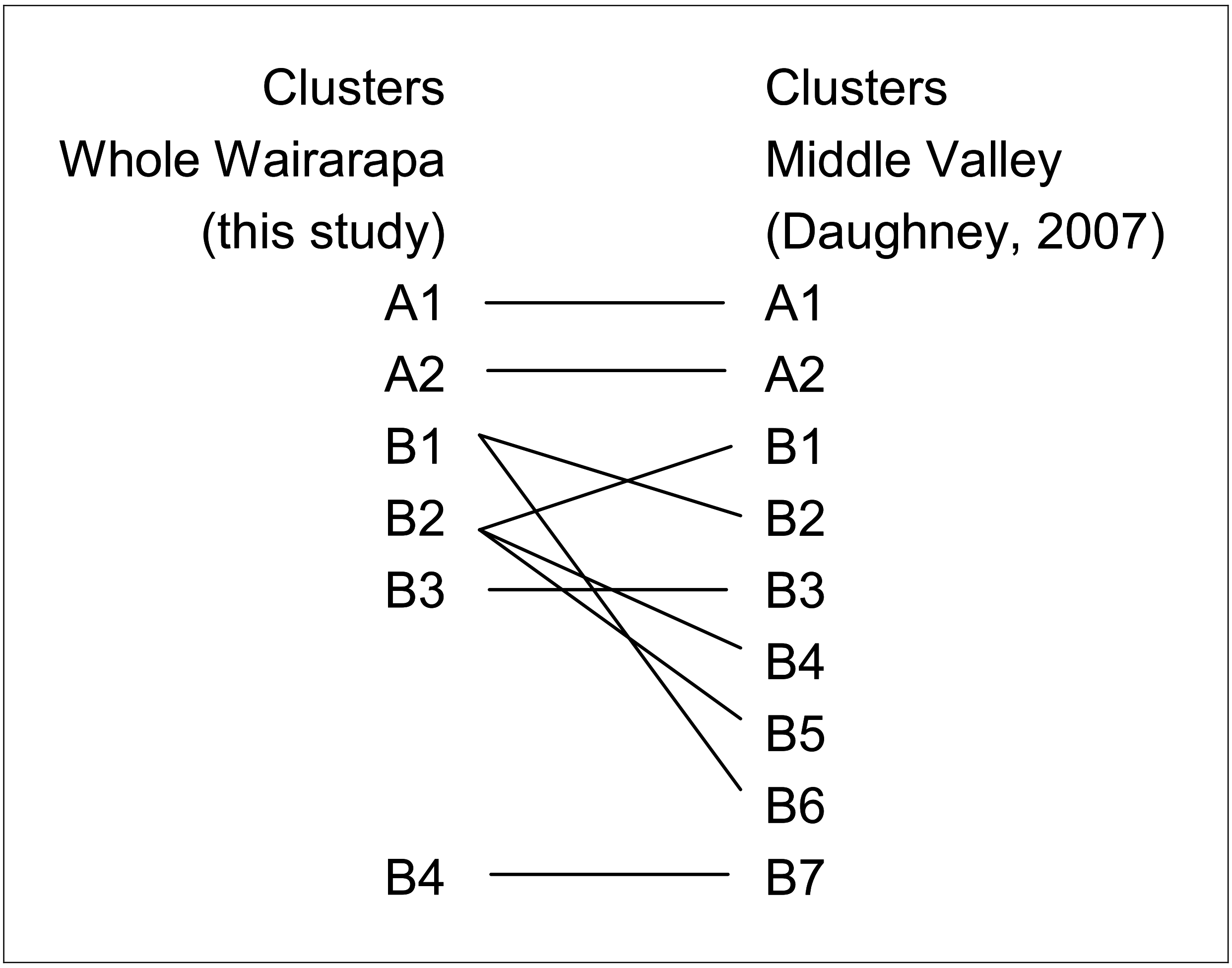

Figure 10. Correspondence of clusters defined for the Middle Wairarapa Valley (Daughney, 2007) with clusters defined for the whole Wairarapa Valley (this study).

Table 1. Median values (50th percentiles) in selected water quality parameters in the Wairarapa Valley compared to national and global datasets. Median parameter values for the Wairarapa Valley are calculated for all surface water (SW) and groundwater (GW) monitoring sites as a single group (ALL) or for subsets of monitoring sites representing the categories defined at three different separation thresholds using Hierarchical Cluster Analysis conducted with median electric conductivity (Cond) and median concentrations of the seven major ions (Ca, Mg, Na, K, HCO_3, Cl and SO_4). The national median values are derived from all SOE programmes operated by the 15 regional authorities (Ministry for the Environment, 2007); national median values derived from the three groundwater quality categories observed in the National Groundwater Monitoring Programme (NGMP) are taken from Daughney and Reeves (2005). The global median values for rivers and groundwaters are taken from Turekian (1977), Hem (1982) and Langmuir (1997). Calculated total dissolved solids (TDS) concentration is determined by summation of the concentrations of the major ions and SiO_2. Water type for each category is determined using AquaChem® software, based on the median concentrations of the seven major ions. ND indicates "not determined".

Category		Water Type	Number of Sites			Depth	Cond*	Ca*	Mg*	Na*	K*	HCO_3	Cl	SO_4	Fe	Mn	NH_4-N	NO_3-N	PO_4-P	SiO_2	Calc TDS
			Total	SW	GW	m	µS/cm	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
World		Average River Water	ND	ND	ND	ND	ND	15.0	4.1	6.3	2.3	50.0	7.8	3.7	0.05	0.01	ND	ND	ND	14	120.0
World		Average Groundwater	ND	ND	ND	ND	ND	50.0	7.0	30.0	3.0	200.0	20.0	30.0	0.70	0.03	ND	ND	ND	16	350.0
NZ	NGMP	Oxidised Unimpacted	34	0	34	21.9	110.0	11.7	2.5	6.7	1.2	51.3	4.5	4.6	0.02	0.00	0.01	2.97	0.01	26.9	99.0
NZ	NGMP	Oxidised Impacted	45	0	45	20.4	239.0	14.6	7.4	17.4	1.9	62.1	19.5	10.4	0.01	0.00	0.01	10.27	0.01	15.8	162.5
NZ	NGMP	Reduced (Evolved)	28	0	28	55.0	325.0	36.5	9.6	38.0	3.5	216.8	27.0	2.2	0.47	0.15	4.10	0.04	0.04	31.8	370.4
NZ		All Regional SOE Programmes	1068	0	1068	20.0	210.0	15.5	4.6	15.0	1.6	62.7	15.3	6.5	0.03	0.01	0.01	5.76	0.02	17.0	148.8
Wairarapa Valley (GWRC Data)	**ALL**	Ca-Na-Mg-HCO_3	268	22	246	16.0	219.2	12.8	4.8	20.7	1.7	62.6	22.9	4.6	0.24	0.13	0.02	0.32	0.02	20.8	151.6
Wairarapa Valley (GWRC Data)	**A**	Ca-Na-HCO_3-Cl	109	18	91	7.8	113.7	8.1	2.5	8.9	1.1	28.8	9.3	6.2	0.04	0.01	0.01	1.81	0.02	13.9	80.7
Wairarapa Valley (GWRC Data)	**B**	Na-Ca-Mg-HCO_3-Cl	159	4	155	28.0	358.6	19.6	8.4	37.8	2.3	121.0	40.7	2.8	1.79	0.52	0.29	0.05	0.05	29.5	264.9
Wairarapa Valley (GWRC Data)	**A1**	Ca-Na-HCO_3-Cl	34	8	26	7.0	77.1	6.5	1.5	6.1	0.7	26.6	6.5	4.1	0.03	0.01	0.01	0.32	0.01	11.0	63.3
Wairarapa Valley (GWRC Data)	**A2**	Na-Ca-Mg-HCO_3-Cl	75	10	65	8.2	135.5	9.0	3.1	10.7	1.3	29.8	11.0	7.5	0.04	0.01	0.01	3.62	0.02	14.8	91.0
Wairarapa Valley (GWRC Data)	**B1**	Na-Ca-HCO_3-Cl	54	4	50	16.7	300.9	19.8	6.5	27.7	2.1	93.5	33.3	10.1	0.23	0.35	0.02	0.25	0.02	23.3	217.1
Wairarapa Valley (GWRC Data)	**B2**	Na-Ca-Mg-HCO_3-Cl	44	0	44	18.7	198.0	12.0	5.7	20.9	1.2	90.7	15.3	2.0	0.86	0.35	0.19	0.04	0.11	34.5	184.0
Wairarapa Valley (GWRC Data)	**B3**	Na-Ca-HCO_3-Cl	30	0	30	44.0	421.2	18.0	9.6	46.9	2.8	149.3	52.2	1.0	3.44	0.82	0.81	0.01	0.52	27.7	313.1
Wairarapa Valley (GWRC Data)	**B4**	Na-Ca-Cl-HCO_3	31	0	31	40.0	968.1	42.3	19.7	121.8	5.2	233.0	181.9	1.4	10.00	1.31	0.64	0.05	0.03	38.1	655.5
Wairarapa Valley (GWRC Data)	**A2a**	Na-Ca-Mg-HCO_3-Cl	32	4	28	6.8	162.5	10.8	3.6	12.6	1.6	36.3	13.7	9.4	0.04	0.01	0.01	4.19	0.02	18.9	111.3
Wairarapa Valley (GWRC Data)	**A2b**	Na-Ca-Mg-HCO_3-Cl	43	6	37	8.6	118.4	7.8	2.8	9.4	1.1	25.8	9.3	6.4	0.04	0.01	0.01	2.90	0.02	13.6	79.3
Wairarapa Valley (GWRC Data)	**B1a**	Ca-Na-HCO_3-Cl	16	4	12	12.5	325.7	37.2	5.9	20.8	2.0	129.7	26.7	15.3	0.07	0.05	0.01	0.43	0.02	10.7	248.8
Wairarapa Valley (GWRC Data)	**B1b**	Na-Ca-Mg-HCO_3-Cl	17	0	17	29.6	354.1	17.3	9.9	42.8	1.9	137.3	43.8	5.5	4.70	0.76	0.53	0.17	0.01	48.9	313.6
Wairarapa Valley (GWRC Data)	**B1c**	Na-Ca-Cl-HCO_3	21	0	21	16.0	248.2	13.6	5.1	24.3	2.5	53.3	31.6	12.0	0.23	0.13	0.01	0.70	0.03	28.8	172.2
Wairarapa Valley (GWRC Data)	**B2a**	Na-Ca-Mg-HCO_3-Cl	34	0	34	17.3	193.0	11.0	5.5	20.8	1.2	84.6	15.5	3.1	0.66	0.33	0.15	0.07	0.11	34.0	177.0
Wairarapa Valley (GWRC Data)	**B2b**	Na-Ca-Mg-HCO_3	10	0	10	26.0	216.0	16.3	6.5	21.2	1.3	115.2	14.9	0.4	3.35	0.76	0.68	0.02	0.12	35.1	215.9
Wairarapa Valley (GWRC Data)	**B3a**	Na-Ca-Mg-HCO_3-Cl	18	0	18	43.0	427.6	21.3	11.1	45.8	1.9	158.0	52.2	0.9	2.57	1.07	0.74	0.00	0.03	25.4	321.0
Wairarapa Valley (GWRC Data)	**B3b**	Na-HCO_3-Cl	12	0	12	46.5	411.7	13.9	7.9	48.5	5.0	137.2	52.3	1.2	4.32	0.45	1.78	0.03	1.50	39.3	313.3
Wairarapa Valley (GWRC Data)	**B4a**	Na-Ca-Cl-HCO_3	5	0	5	24.0	911.1	40.2	22.2	136.2	3.0	156.3	214.6	34.4	0.07	0.05	0.02	0.25	0.03	23.6	631.1
Wairarapa Valley (GWRC Data)	**B4b**	Na-Ca-HCO_3-Cl	16	0	16	40.4	772.0	42.7	18.0	86.7	4.7	251.5	122.3	0.8	11.22	1.40	3.92	0.01	0.02	40.0	583.3
Wairarapa Valley (GWRC Data)	**B4c**	Na-Cl-HCO_3	10	0	10	40.8	1433.4	42.7	21.4	198.5	8.3	251.9	315.9	0.7	13.75	1.15	0.64	0.06	0.05	38.1	893.0

Note: Wairarapa medians for major cations pertain to "combined" fields based on reported values for both dissolved and total concentrations; medians for conductivity pertain to "combined" field based on reported values for both laboratory and field measurements (see Appendix 1).

Table 2. Summary of significant hydrochemical variations between clusters. 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.

	Cluster A1	Cluster A2	Cluster B1	Cluster B2	Cluster B3
Cluster A2	Compared to A1, A2 has slightly higher Na, K, Ca, Mg, HCO_3, Cl, SO_4, P, NO_3 and conductivity. There is no difference in Mn, Fe, NH_4 and depth. pH slightly lower				
Cluster B1	Compared to A1, B1 is deeper and has higher Na, K, Ca, Mg, HCO_3, Cl, NH_4, Mn, Fe, depth and cond. B1 is lower in NO_3, and there is no difference in pH.	Compared to A2, B1 is deeper and has higher Ca, HCO_3, Cl, Na, Mg, K, NH_4, Fe, Mn, pH and cond. There is no difference in SO_4, and P, and B1 has lower NO_3.			
Cluster B2	Compared to A1, B2 is deeper and has higher Na, Ca, Mg, HCO_3, Cl, P, K, Mn, Fe, NH_4, cond. and lower SO_4 and NO_3. There is no difference in pH.	Compared to A2, B2 is deeper and has higher Ca, HCO_3, Cl, P, Na, Fe, Mn, NH_4 , pH and cond. B2 has lower K, NO_3 and SO_4.	Compared to B1, B2 is shallower and has lower Ca, Na, Cl, cond, K, Mg, NO_3 and SO_4. There is no difference in pH and Mn, and B2 has higher NH_4 , Fe and P.		
Cluster B3	Compared to A1, B3 is much deeper and has higher Na, Ca, Mg, HCO_3, Mn, K, NH_4, Cl, Fe and cond. B3 has lower NO_3 and SO_4, and there is no difference in pH.	Compared to A2, B3 is deeper and has higher Na, Ca, Cl, HCO_3, Mg, K, P, Fe, Mn, NH_4 and cond. and lower SO_4 and NO_3. There is no difference in pH.	Compared to B1, B3 is deeper and has higher HCO_3, Na, Cl, Mg, K, P, NH_4, Mn, Fe and cond. B1 has lower NO_3 and SO_4. There is no difference in Ca and pH.	Compared to B2, B3 is deeper and has lower SO_4. B3 has higher Ca, Na, Cl, HCO_3, K, Mg, Fe, Mn, NH_4 and cond. There is little difference in NO_3, P and pH.	
Cluster B4	Compared to A1, B4 is much deeper and has higher Na, K, P, Ca, Mg, Cl, pH, Fe, Mn, NH_4, HCO_3 and cond. B4 has lower SO_4 and NO_3.	Compared to A2, B4 is much deeper and has higher Na, K, Ca, Mg, Cl, pH, Fe, Mn, NH_4 , HCO_3 and cond. B4 has lower SO_4 and NO_3, and there is no difference in P.	Compared to B1, B4 is deeper and has higher Na, K, Ca, Mg, Cl, Fe, Mn, NH_4, HCO_3 and cond. B4 has lower SO_4, and there is little or no difference in P, NO_3 and pH.	Compared to B2, B4 is shallower and has higher Na, Ca, Cl, HCO_3, Mg, K, P and cond. and lower P and SO_4 There is no difference in NO_3, Mn, pH and depth.	Compared to B3, B4 has higher Ca, Cl, Na, Mg, K, HCO_3 and cond. and lower SO_4 and P. There is no difference in NO_3, NH_4 , SO_4, pH, depth, Fe and Mn.

Table 3. Assignment of monitoring sites to clusters defined by HCA.

A1	A2a	A2b	B1a	B1b	B1c	B2a	B2b	B3a	B3b	B4a	B4b	B4c
Beef Creek Ruamahanga River at McLays Tauherenikau Waingawa River Waiohine River at Bicknells Waiohine River at Gorge Waiorongomai River S26/0034 S26/0317 S26/0457 S26/0547 S26/0846 S26/0911 S27/0070 S27/0198 S27/0299 S27/0330 T26/0003 T26/0011 T26/0259 S26/0051 S26/0060 S26/0252 S26/0326 S26/0399 S26/0401 S26/0403 S26/0520 S26/0540	Mangatarere River Parkvale Stream Parkvale tributary Tauanui River S26/0117 S26/0223 S26/0267 S26/0439 S26/0467 S26/0705 S26/0709 S26/0734 S26/0738 S26/0824 S27/0009 T26/0099 T26/0201 S26/0668 S26/0669 S27/0018 S27/0024 S27/0192 T26/0160 T26/0293 T26/0334 T26/0428 T26/0480 T26/0500 T26/0513	Ruamahanga River at Gladstone Bridge Ruamahanga River at Pukio Ruamahanga River at Te Ore Ore Waipoua River S26/0155 S26/0220 S26/0244 S26/0259 S26/0299 S26/0319 S26/0830 S27/0106 S27/0136 S27/0202 T26/0087 T26/0430 S26/0113 S26/0140 S26/0237 S26/0248 S26/0320 S26/0500 S26/0529 S26/0667 S26/0780 S27/0011 S27/0031 S27/0043 S27/0096	Huangarua River at Ponatahi Bridge Kopuaranga Taueru Whangaehu River S26/0395 S26/0756 S27/0396 S27/0574 S27/0681 T26/0538 S26/0659 S27/0249 S27/0273 S27/0420 S27/0481 S27/0541	S26/0614 S26/0642 S26/0744 S27/0614 R27/0004 R27/0006 S26/0550 S27/0012 S27/0261 S27/0326 S27/0340 S27/0351 S27/0465 S27/0466 S27/0473 S27/0502 S27/0503	S26/0660 S26/0662 S26/0708 S27/0008 S27/0344 S27/0547 S27/0571 S27/0588 S27/0609 S27/0615 T26/0332 T26/0489 T26/0490 T26/0492 S26/0779 S27/0163 S27/0188 S27/0258 S27/0603 S27/0618 S27/0619	S26/0106 S26/0229 S26/0545 S26/0582 S26/0591 S26/0624 S26/0629 S26/0649 S26/0666 S26/0721 S26/0736 S27/0099 S27/0263 S27/0271 S27/0293 S27/0604 T26/0092 T26/0204 T26/0437	S26/0568 S26/0632 S26/0753 S27/0283 T26/0413 S26/0236 S26/0271 S26/0653 T26/0416 T26/0424	S26/0573 S26/0740 S26/0743 S26/0758 S26/0762 S27/0268 S27/0585 S27/0594 S27/0717 S27/0282 S27/0304 S27/0419 S27/0446 S27/0449 S27/0450 S27/0596 S27/0597 S27/0606	S27/0435 S27/0602 S27/0640 S27/0425 S27/0428 S27/0440 S27/0441 S27/0463 S27/0581 S27/0600 S27/0601 S27/0620	R28/0012 S27/0522 R28/0001 R28/0015 S27/0478	S26/0768 S27/0427 S27/0433 S27/0495 S26/0622 S27/0376 S27/0426 S27/0429 S27/0439 S27/0443 S27/0447 S27/0461 S27/0464 S27/0489 S27/0593 S27/0595	S27/0607 S27/0621 S27/0438 S27/0579 S27/0583 S27/0599 S27/0605 S27/0622 S27/0623 S27/0624
34	32	43	16	17	21	19	10	18	12	5	16	10

Table 4. Predicted assignment of monitoring sites to clusters defined by HCA. Predicted cluster assignments are given for those sites with CBE outside the acceptable limits of -10% to +10%, and for which median values were not available for between one and three of the eight input variables required for HCA. The square of the Euclidean distance was calculated between each site's median parameter values and the centroid of each of the clusters defined using Ward's method. The predicted cluster for each site was determined on the basis of minimum site-to-centroid separation distance.

A1	A2a	A2b	B1a	B1b	B1c	B2a	B2b	B3a	B3b	B4a	B4b
S26/0185	S26/0086	S26/1066	T26/0237	S27/0518	Lake Wairarapa 1	S26/0164	S26/0945	S27/0442	S27/0580		S27/0133
S26/1072	S26/0092	S26/0032	T26/0482	R28/0017	Lake Wairarapa 2	S26/0449	S26/0471				S27/0591
S26/0016	S26/0101	S26/0071	T26/0488	S28/0003	Lake Wairarapa 3	S27/0059	S26/0664				S27/0592
S26/0045	S26/0355	S26/0166	T26/0499		Lake Wairarapa 4	T26/0242	S26/0672				
S26/0398	S26/0381	S26/0178	T26/0503		S26/0204	T26/0517	T26/0072				
S26/0730	S26/0386	S26/0179	T26/0508		S26/0978	T26/0525					
S27/0035	S26/0437	S26/0213	T26/0509		S26/0268	T26/0555					
T26/0400	S26/0803	S26/0254	T26/0541		S26/0277	T26/0232					
T26/0502	S26/0877	S26/0265	T26/0547		S26/0301	S26/0290					
S26/0028	S26/0977	S26/0378	T26/0254		S26/0480	S26/0239					
	S26/1034	S26/0387	T26/0493		S26/0661	S26/0663					
	S26/1035	S26/0432	T26/0498		S26/0726	S27/0006					
	S26/1069	S26/0481	T26/0505		S27/0167	S27/0196					
	T26/0227	S26/0552	T26/0542		S27/0184	T26/0057					
	S26/0122	S26/0563	S27/0250		S27/0248						
	S26/0243	S26/0646	S27/0545		S27/0345						
	S26/0288	S26/0693	T26/0071		S27/0362						
	S26/0354	S26/0732	T26/0530		S27/0374						
	S26/0637	S26/0781	T26/0531		T26/0622						
	S26/0644	S27/0185	T26/0540								
	S26/0651	S27/0206									
	S26/0658	T26/0064									
	S27/0107	T26/0238									
	S27/0108	T26/0408									
	S27/0110										
	T26/0028										
	T26/0165										
	T26/0172										
	T26/0212										
	T26/0412										
	T26/0426										
	T26/0429										
	S26/0168										
1	34	24	21	3	20	14	5	1	1	0	3

APPENDIX 1: PREPARATION OF DATA FOR APPLICATION OF MULTIVARIATE METHODS

The data array provided by GWRC consisted of analytical results for a total of 50 analytes in ca. 6000 water samples collected from 633 monitoring sites (31 surface water monitoring sites and 602 groundwater monitoring sites). Not all samples were analysed for every analyte. 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 50 parameters for all monitoring sites at which analytical results were available for the parameter of interest. 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 50 analyte $\times$ 633 site array. Note that no distinction is made in this report between the results for the sites that had been sampled only once (which might have high uncertainty) compared to the median values calculated at the 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 parameters 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, SO_4, Cl 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 ca. 5% of the monitoring 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.

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 50 analyte $\times$ 633 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 to ensure that the statistical tests are not biased by combined results for Mn, or by data from the few sites (e.g. in the Te Ore Ore sub-basin) 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 311 sites; for the remaining sites, CBE could not be calculated because median values for two or more major ions could not be determined due to lack of analytical data. The median and average CBE were 1.1% and 1.8%, respectively. Of all sites for which CBE could be calculated, 6 had CBE below -10% and 28 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 CBE less than -10% or more than +10% were excluded from further statistical analysis.

A1.4 References

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Helsel, D. R., Cohn, T. A. (1988). Estimation of descriptive statistics for multiply censored water quality data. Wat. Resources Res. 24: 1997-2004.

Güler, C. Thyne, G. D. McCray, J. E., Turner, A. K. (2002). Evaluation of graphical and multivariate statistical methods for classification of water chemistry data. Hydrogeol. J. 10:455-474.

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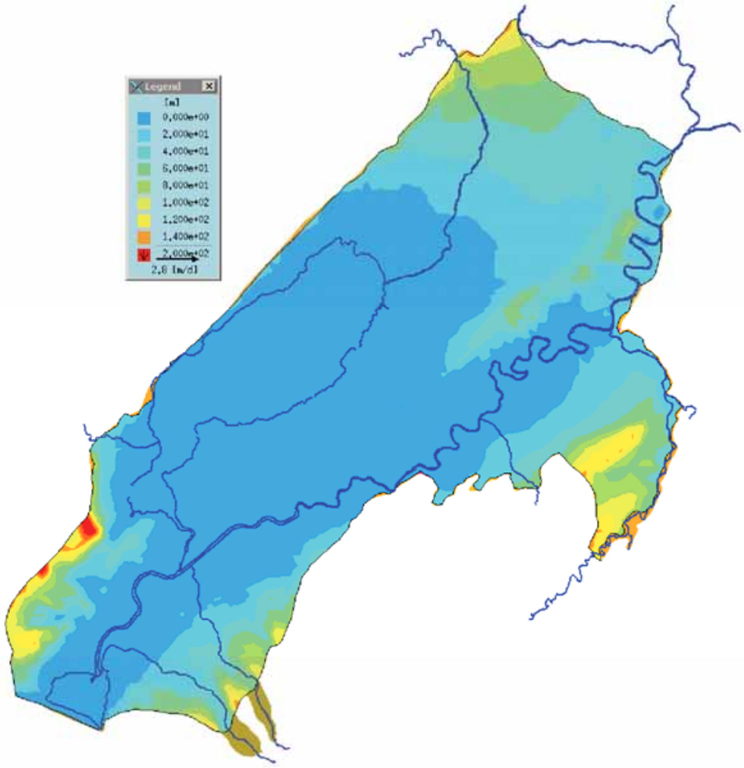
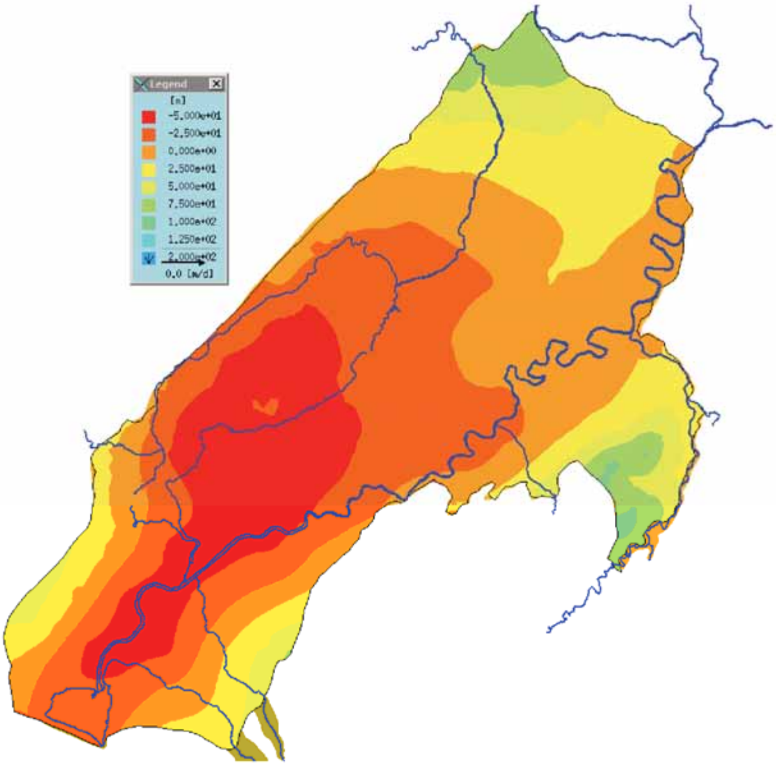
Appendix 5:

Model slice structure contours



Structure contours: SLICE 1



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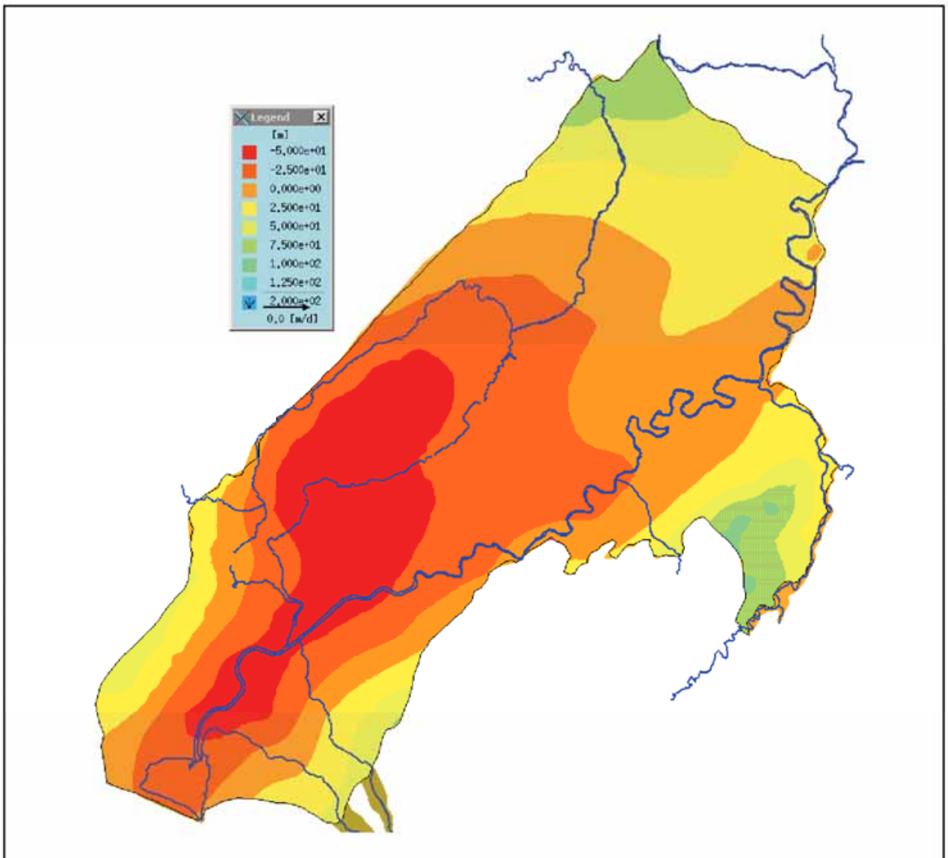

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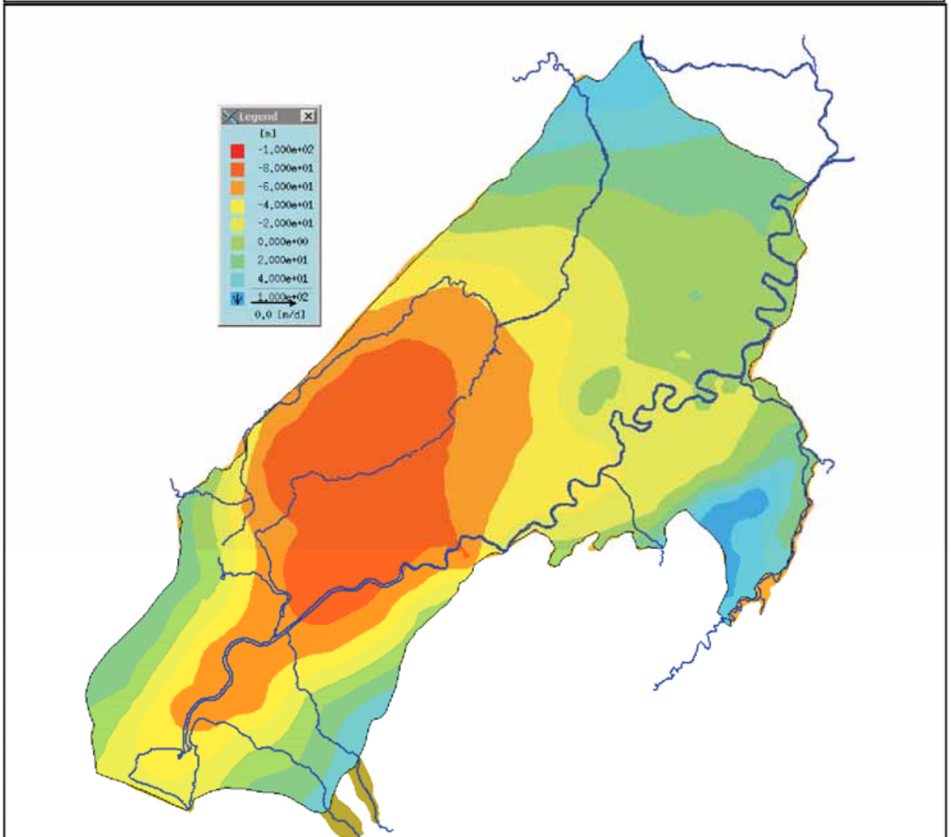

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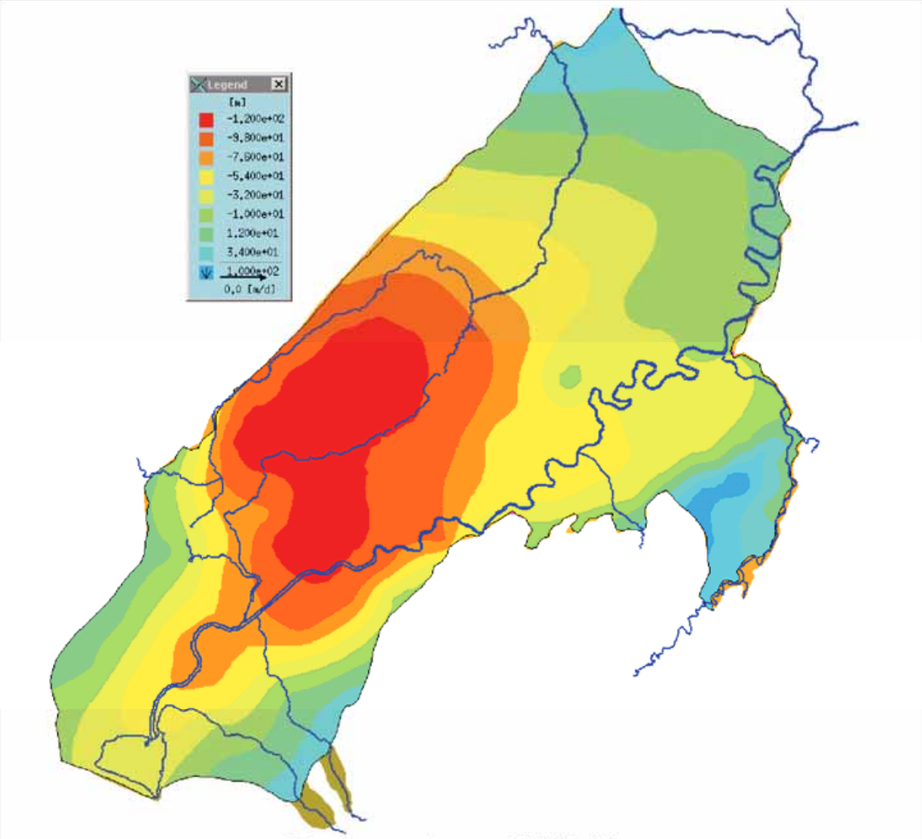

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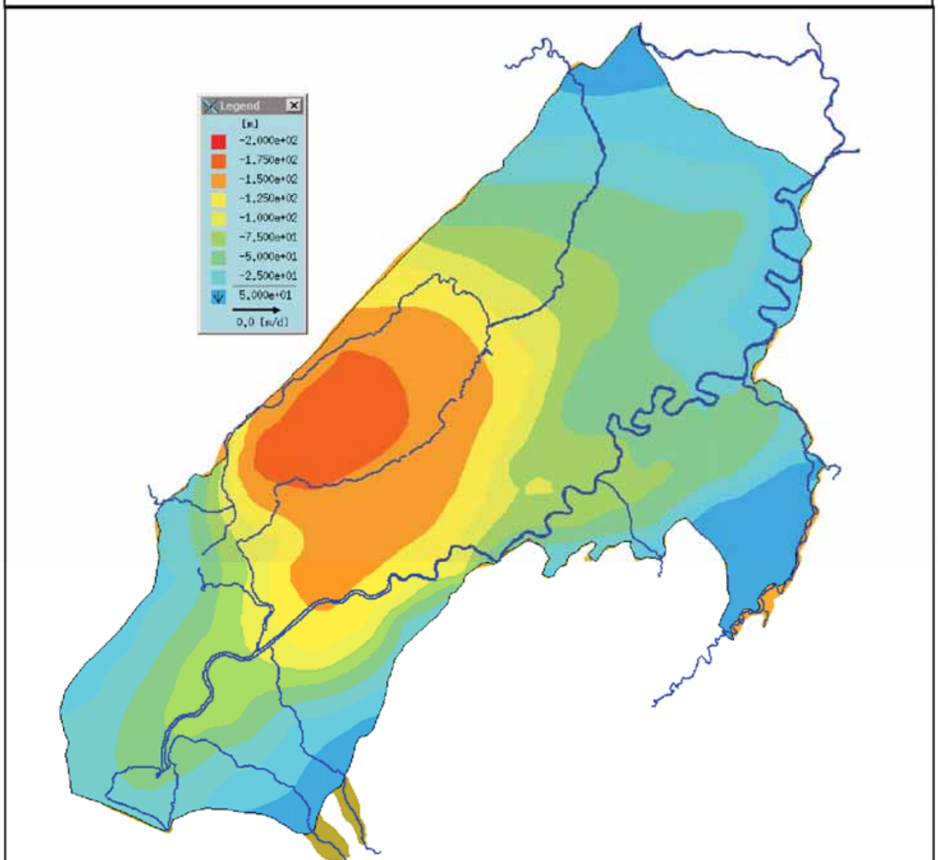


Structure contours: SLICE 18

Appendix 6:

MIKE11 surface water model for the Lower Valley catchment

A MIKE11 surface water model was developed for the Lower 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) 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 Lower Valley surface water model incorporates the Ruamahanga River downstream of the Waiohine River confluence to the coast at Lake Onoke and its major tributary, the Huangarua River. The Lower Valley catchment also contains the Tauherenikau River, which was also included in the Lower Valley surface water model.

Input flow data

Flow data were available for a number of recorder sites within the catchment and are archived in Greater Wellington's hydrological database (Hilltop) as detailed in Table A6.1. The flow data used covered the period June 1992 to October 2008 (the FEFLOW model calibration period). Although the Huangarua River at Hautotara site has been operational since 1968, it was primarily used for flood warning purposes and therefore has only been rated for medium to high stage heights. Due to bed degradation, this site has never been properly rated at low-flow. Stage height data for Lake Wairarapa and Lake Onoke were used for the end points of the Tauherenikau and Ruamahanga rivers respectively.

Table A6.1: Flow and stage data

Site	Site No.	Map reference
Ruamahanga at Top of LV model	Synthetic	
Ruamahanga at Waihenga Bridge	29202	S27:146-982
Huangarua River at Hautotara	29222	S27:173-871
Ruakokopatuna River at Iraia	29250	S28:084-782
Tauherenikau River at Gorge	29251	S26:081-127
Lake Wairarapa at Burlings (stage)	29209	S27:918-948
Lake Onoke at Lake Ferry (stage)	29237	R28:892-770

Ruamahanga River inflow to Lower Valley model domain

There is no flow gauge at the top of the Ruamahanga River where it enters the Lower Valley model domain and therefore a synthetic data set was developed for this location. The synthetic record was based on the flow measured at Waihenga Bridge minus the derived flow for Huangarua River at Hautotara, with a time step adjustment to account for the travel time. The stretch of the Ruamahanga River between the upstream boundary of the model and Waihenga bridge is neutral in terms of loss/gain to groundwater – the only major tributary being the Huangarua River.

Huangarua River flow at Hautotara

To compensate for the poor flow record for the Huangarua River at Hautotara, a synthetic record was developed using a relationship between Hautotara and the NIWA site 'Ruakokopatuna at Iraia' (a tributary of the Huangarua River). The relationship was developed by comparing the rated flow record at Iraia with low flow gaugings at Hautotara. As the Iraia site is much further upstream than the Hautotara site, a time lag adjustment was also applied. This relationship was used only for the less reliable low flow parts of the Hautotara record – higher stages at Hautotara have an acceptable rating for the purposes of this model (except as discussed below). For some intervals early in the model run, the original full range flow data for Huangarua River at Hautotara were found to be more suitable than the synthetic record. The relationship is as follows:

> *Huangarua River at Hautotara (m^3/s) = 4.0245 (Ruakokopatuna River at Iraia (m^3/s) + 0.1495*
>
> Note: In the current model version an error was made when the above relationship was entered into the Hilltop Virtual Measurement (the value 0.1495 was entered as 0.015 which means that the values for low flows used in the model run were around 0.135 m^3/s too low). Considering that the interaction between the surface water and groundwater models is based on stage levels rather than flow the overall effect of this error is considered minimal. However if further model runs are made this should be corrected.

The synthetic record for the site Huangarua River at Hautotara includes data from the following sources:

- For the large gap at the beginning of Hautotara record the above relationship was used for all flow ranges.

- For the period 3 August 1993 130000 to 5 May 2006 173000 the original rated data for Huangarua River at Hautotara were used as they were very similar to the derived flow using Ruakokopatuna River at Iraia.

- For the period 5 May 2006 173000 to 27 November 2007 140000 the derived low flow data were used where the original rated flow data at Huangarua River at Hautotara were below 1.875 m^3/s.

- For the period 27 November 2007 140000 to the end of record the derived low flow data were used where the original rated flow data at Huangarua River at Hautotara were below 1.48 m^3/s.

Stage data for Lake Onoke and Lake Wairarapa

The end points of the MIKE11 models are required to be either a continuous water level record or stage-discharge relationship. The Ruamahanga River discharges into Lake Onoke on the Wairarapa's south coast and the lake has a water level gauge at Lake Ferry. The Tauherenikau River discharges into Lake Wairarapa and this lake has a gauge at Burlings. These two water level sites were used as the end points for the Ruamahanga and Tauherenikau branches respectively. The stage level for both of these sites was converted from the Wairarapa Datum to the L&S datum to match the datum used for the cross sections and that used in the FEFLOW groundwater model.

The flow and stage data were collated in Hilltop and exported to a suitable format for MIKE11.

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. All flow records were averaged in this way; the stage records for Lake Onoke and Lake Wairarapa were kept as 1-hour interval records as the model stability was affected badly when they were converted to a 7-day average.

Cross section data

River cross sections are surveyed by Greater Wellington as part of its flood protection role. A total of 226 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 A6.2. 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 Hilltop.

Table A6.2: Cross section data

River	Survey date	Number of sections
Ruamahanga River	1999-2005	168
Huangarua River	2000	28
Tauherenikau River	2007	30

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 for the Lower Valley catchment consists of three branches (Ruamahanga, Huangarua and Tauherenikau) that replicate the drainage system. A total of 227 Hnode points were used in the model – corresponding to the 226 surveyed cross sections plus interpolated sections at river confluences and the FEFLOW model boundaries.

The frictional effect of the river channels on flows was represented by the Manning's n channel roughness coefficient using a value of 0.045 for all branches of the model. This is the same value as that used in the Middle Valley catchment model where it was found to be appropriate. No structures were incorporated into the model.

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 7:

Parameter zonation framework for the Lower Valley catchment model

Zone	Param	Location	Hydrostratigraphic unit	Layers
1	k x	Upper Tauherenikau fan	A: Alluvial fan gravels	1–10
2	k x	Mid-lower Tauherenikau fan	A: Alluvial fan gravels	1–7
3	k x	Tauherenikau Holocene	B: Q1 unconfined aquifer	1–3
4	k x	Upper Ruamahanga; Huangarua valley	B: Q1 unconfined aquifer	1–1 7
5	k x	Te Marie ridge/Onoke N. terraces	F: Flow barriers	1–17
6	k x	Recent Lake Wairarapa sediments	B: Q1 unconfined aquifer	1
7	k x	Mid Quaternary coastal S. terraces	F: Mid-Quaternary terraces	1–17
8	k x	Lake Basin /Onoke Holocene cover; side valley fans	B: Q1 unconfined aquifer	1
9	k x	Harris anticline core	F: Flow barriers	1–17
10	k x	Martinborough terraces	E: Martinborough terrace deposits	1–9
11	k x	Onoke/Narrows Holocene	B: Q1 unconfined aquifer	2
12	k x	Side-valley fans	B: Q1 unconfined aquifer	2
13	k x	Holocene lacustrine aquitard	D: Q1 Aquitard	2
14	k x	Lower Tauherenikau fan	B: alluvial fan gravels	6–7
15	k x	Q2 aquifer – Tauherenikau delta/ Kahutara area, and N. Lake basin	C: Q2 confined aquifer	6–7
16	k x	Q2 aquifer – N. Onoke area (zone 102 in S.)	C: Q2 confined aquifer	6–7
17	k x	Dry River	E: Martinborough terrace deposits	1–2
18	k x	Q3 aquitard Lake basin	D: Q3 and Q5 aquitards	8–10
19	k x	Ruamahanga valley – Tawaha	D: Q5 aquitard	12–14
20	k x	Q4 confined aquifer Tauherenikau zone	C: Q4 confined aquifer	11
21	k x	Q4 aquifer, Onoke N. zone	C: Q4 confined aquifer	11
22	k x	Martinborough Terrace, confined	E: Martinborough terraces deposits	10–12
23	k x	Huangarua Valley, deep	C: Q4 confined aquifer	11
24	k x	Martinborough and Dry River – deep aquitard	E: Martinborough terrace deposits	13–14
25	k x	Q6 aquifer Lake Basin – proximal	C: Q6 confined aquifer	15
26	k x	Q6 aquifer Lake Basin – intermediate	C: Q6 confined aquifer	15
27	k x	Q6 aquifer Lake Basin – distal	C: Q6 confined aquifer	15
28	k x	Q6 aquitard Onoke	D: Q6 aquitard	15
29	k x	Martinborough terraces – deep confined	E: Martinborough terrace deposits	15
30	k x	Martinborough Fault	F: Low k barrier	15–17
31	k x	Q7 aquitard Lake basin	D: Q7 aquitard	16–17
32	k x	Martinborough and Dry River – deep confined	E: Martinborough terrace deposits	16–17
33	k x	Huangarua valley	D: Q3 aquitard	9–10
34	k x	S. Lake basin	C: Q2 aquifer	6–7

Zone	Param	Location	Hydrostratigraphic unit	Layers
35	k x	S. Lake basin	C: Q4 aquifer	11
36	k z	Ruamahanga valley – Tawaha	D: Q1 transition aquitard	3–5
37	k z	Lake basin	D: Q3 aquitard	8–10
38	k z	Tauherenikau fan	D: Transition Q3 aquitard	8–10
39	k z	Ruamahanga valley – Tawaha	D: Transition Q3 aquitard	8–10
40	k z	Lake basin	D: Q5 aquitard	12–14
41	k z	Ruamahanga valley – Tawaha	D: Q5 aquitard	12–14
42	kz	Martinborough terraces – Dry River	E: Martinborough terrace deposits - aquitard	12–14
43	k z	Onoke side valleys	D: Q1 aquitard	3–5
44	k z	Lake basin	D: Q1 aquitard	3–5
45	k z	Tauherenikau fan	D: Q1 transition aquitard	3–5
46	Ss	Ruamahanga valley	B: Q1+ unconfined aquifer	1–5
47	Ss	Lake basin and Onoke	C + D	6–10
48	Ss	Tauherenikau fan, Ruamahanga valley and Martinborough	A, C, D	6–10
49	Ss	Lake basin and Onoke	C + D	11–17
50	Ss	Tauherenikau fan, Ruamahanga valley and Martinborough	A, C, D	11–17
51	Ss	Whole domain	All units	1–5
52	Sy	Lake basin – Onoke	D: Q1 aquitard	1–4
53	Sy	Whole domain	All units	5–17
54	It	Tauherenikau floodplain/Dock Ck	B: Q1+ unconfined aquifer	1–17
55	Ot	Tauherenikau floodplain/Dock Ck	B: Q1+ unconfined aquifer	1–17
56	It	Ruamahanga valley	B: Q1+ unconfined aquifer	1–17
57	Ot	Ruamahanga valley	B: Q1+ unconfined aquifer	1–17
58	It	Lake basin – Ruamahanga R.	B: Q1+ unconfined aquifer	1–17
59	Ot	Lake basin – Ruamahanga R.	B: Q1+ unconfined aquifer	1–17
60	It	Onoke side valleys	B: Q1+ unconfined aquifer	1–17
61	Ot	Onoke side valleys	B: Q1+ unconfined aquifer	1–17
62	It	Lake basin – Lake Wairarapa	B + D	1–17
63	Ot	Lake basin – Lake Wairarapa	B + D	1–17
65	k x	Martinborough terrace – Harris anticline edge	E: Martinborough terrace deposits	1–14
66	k z	Martinborough terraces	E: Martinborough terrace deposits	1–9
67	k z	Martinborough terraces – Harris anticline edge	E: Martinborough terrace deposits	1–15
68	k x	Dry River	D: Transition Q1 aquitard	3–5
69	k x	Ruamahanga valley – Tawaha	D: Transition Q1 aquitard	3–5
70	k x	Dry River	C: Q2 aquifer	6–7
71	k x	Dry River	D: Q3 aquitard	8–10
72	k x	Ruamahanga valley – Tawaha	D: Transition Q3 aquitard	8–10
73	k x	Dry River	C: Q4 aquifer	11
74	k x	Tauherenikau channel	B: Q1 unconfined aquifer	1–2

Zone	Param	Location	Hydrostratigraphic unit	Layers
75	Sy	Tauherenikau fan	A: Alluvial fan gravels	1–4
76	Sy	Ruamahanga valley and Huangarua valley	B: Q1 unconfined aquifer	1–4
77	Sy	Tauherenikau fan	A: Alluvial fan gravels	1–4
78	k x	Side river alluvium – Onoke	B: Q1 unconfined aquifer	1–11
79	k x	Ruamahanga valley – Pukio	D: Transition Q1 aquitard	3–5
80	k x	Ruamahanga valley – Tawaha	D: Transition Q3 aquitard	3–5
81	k x	Ruamahanga valley – Pukio	D: Transition Q5 aquitard	12–14
82	k z	Ruamahanga valley – Pukio	D: Transition Q1 aquitard	3–5
83	k z	Ruamahanga valley – Pukio	D: Transition Q3 aquitard	8–10
84	k z	Ruamahanga valley – Pukio	D: Transition Q5 aquitard	12–14
85	k z	Tauherenikau fan – Featherston	D: Q3 aquitard	8–10
86	k x	Ruamahanga valley – Tawaha	C: Q2 aquifer	6–7
87	k x	Ruamahanga valley – Tawaha	C: Q4 aquifer	11
88	k x	Onoke	C: Q2 aquifer/side fan	6–7
89	k x	Tauherenikau delta transition zone	B: Q1 unconfined aquifer	1-2
90	k x	Tauherenikau delta transition zone	B: Q1 unconfined aquifer	3
91	k x	Tauherenikau delta transition zone	B: Q1 unconfined aquifer	3
92	k x	Tauherenikau fan	A: Alluvial fan gravels	8–11
93	k x	Tauherenikau fan	A: Alluvial fan gravels	12–17
94	It	Dry River	B: Q1 unconfined aquifer	1–17
95	Ot	Dry River	B: Q1 unconfined aquifer	1–17
96	It	Tauherenikau delta	A: Alluvial fan gravels	12–17
97	Ot	Tauherenikau delta	A: Alluvial fan gravels	12-–17
98	k z	Dry River	D: Transition Q1 aquitard	3–5
99	k z	Dry River	D: Transition Q3 aquitard	8–10
100	It	Tauherenikau fan – Featherston	A: Alluvial fan gravels	1–17
101	Ot	Tauherenikau fan – Featherston	A: Alluvial fan gravels	1–17
102	k x	Onoke	C: Q2 aquifer	6–7
103	k x	Onoke (south)	C: Q4 aquifer	11
104	k x	Upper Dry River fan	B: Alluvial fan gravels	1–17

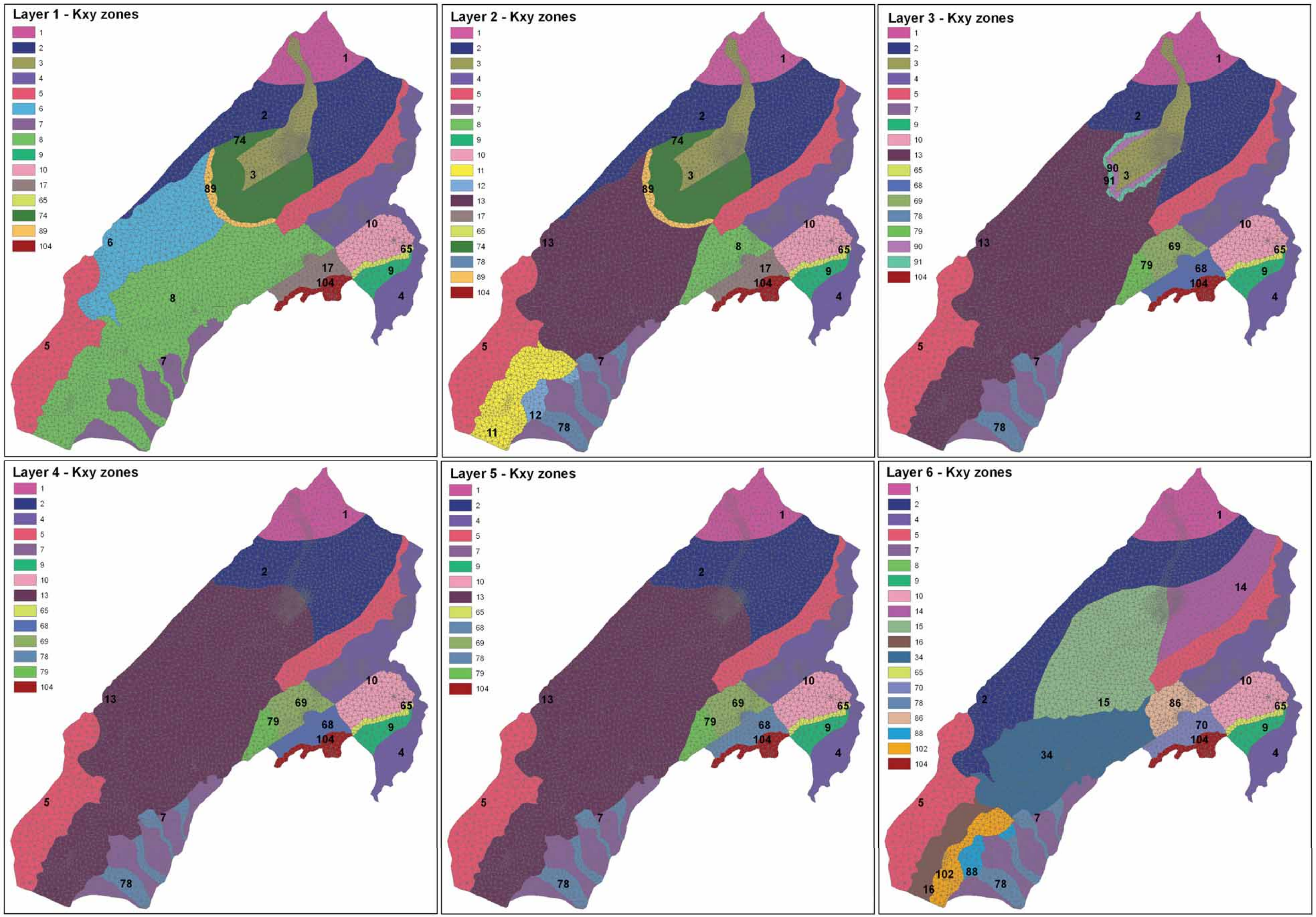


Figure A7.1: Kxy zones for model layers 1 to 6

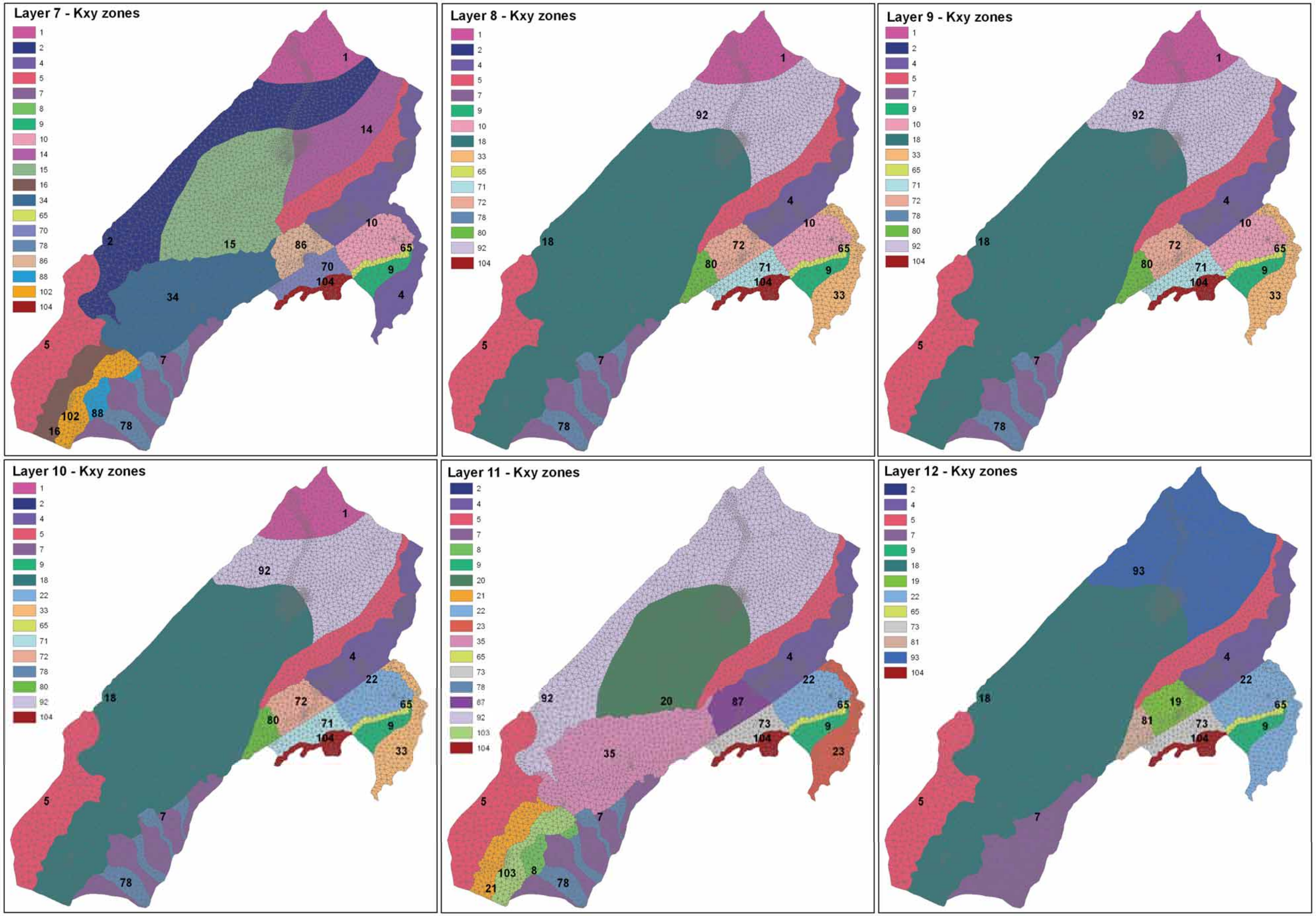


Figure A7.2: Kxy zones for model layers 7 to 12

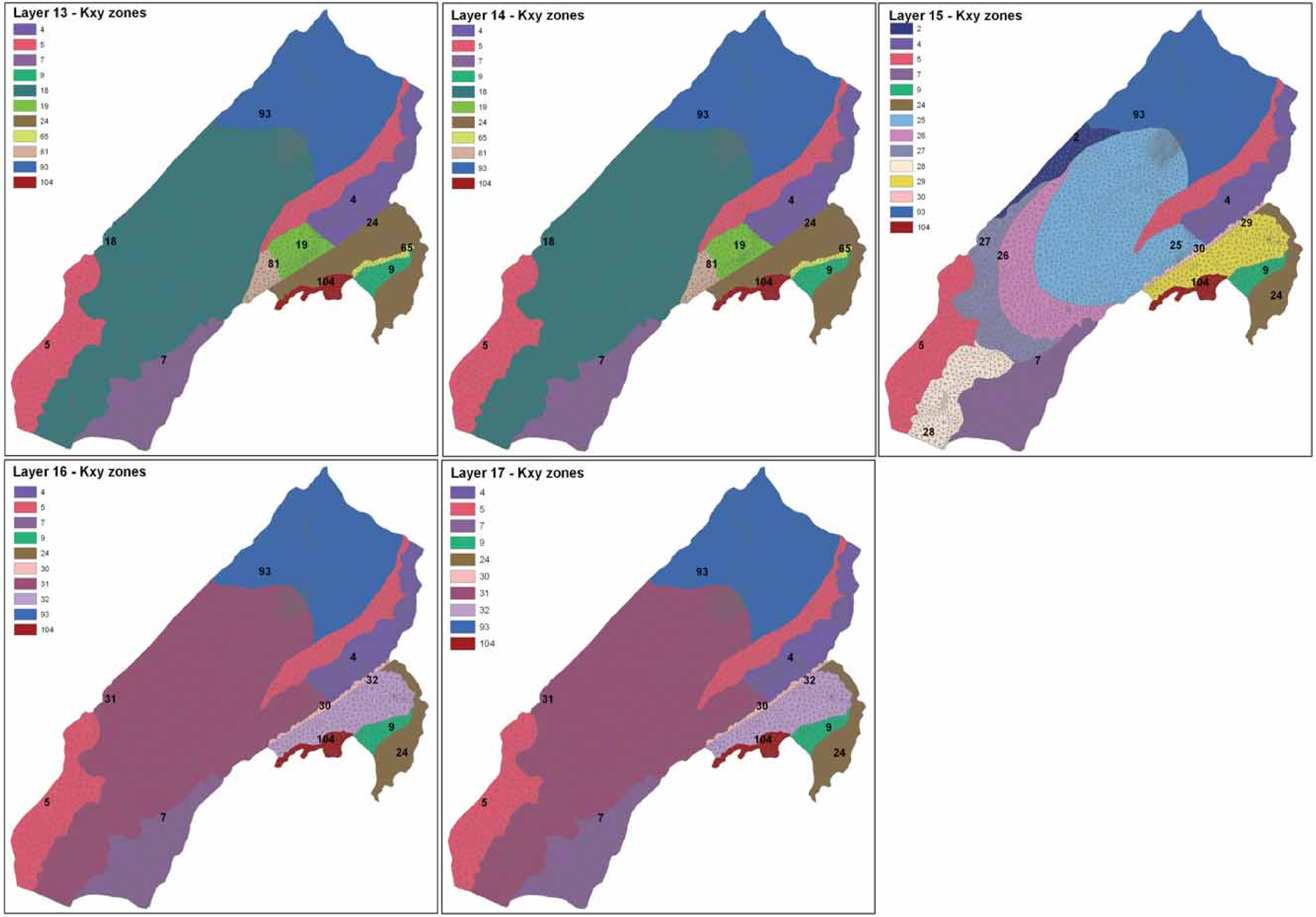


Figure A7.3: Kxy zones for model layers 13 to 17

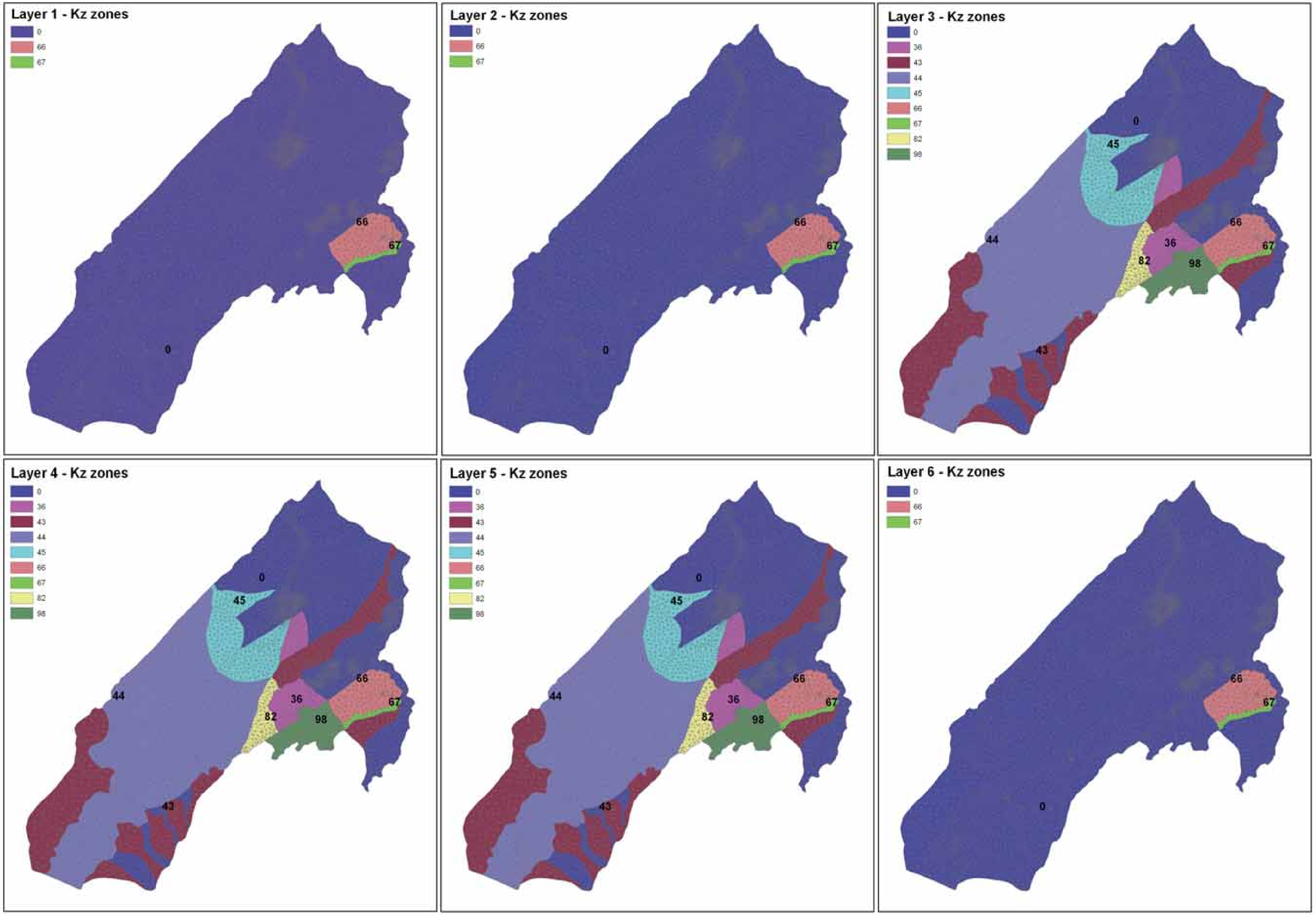


Figure A7.4: Kz zones for model layers 1 to 6

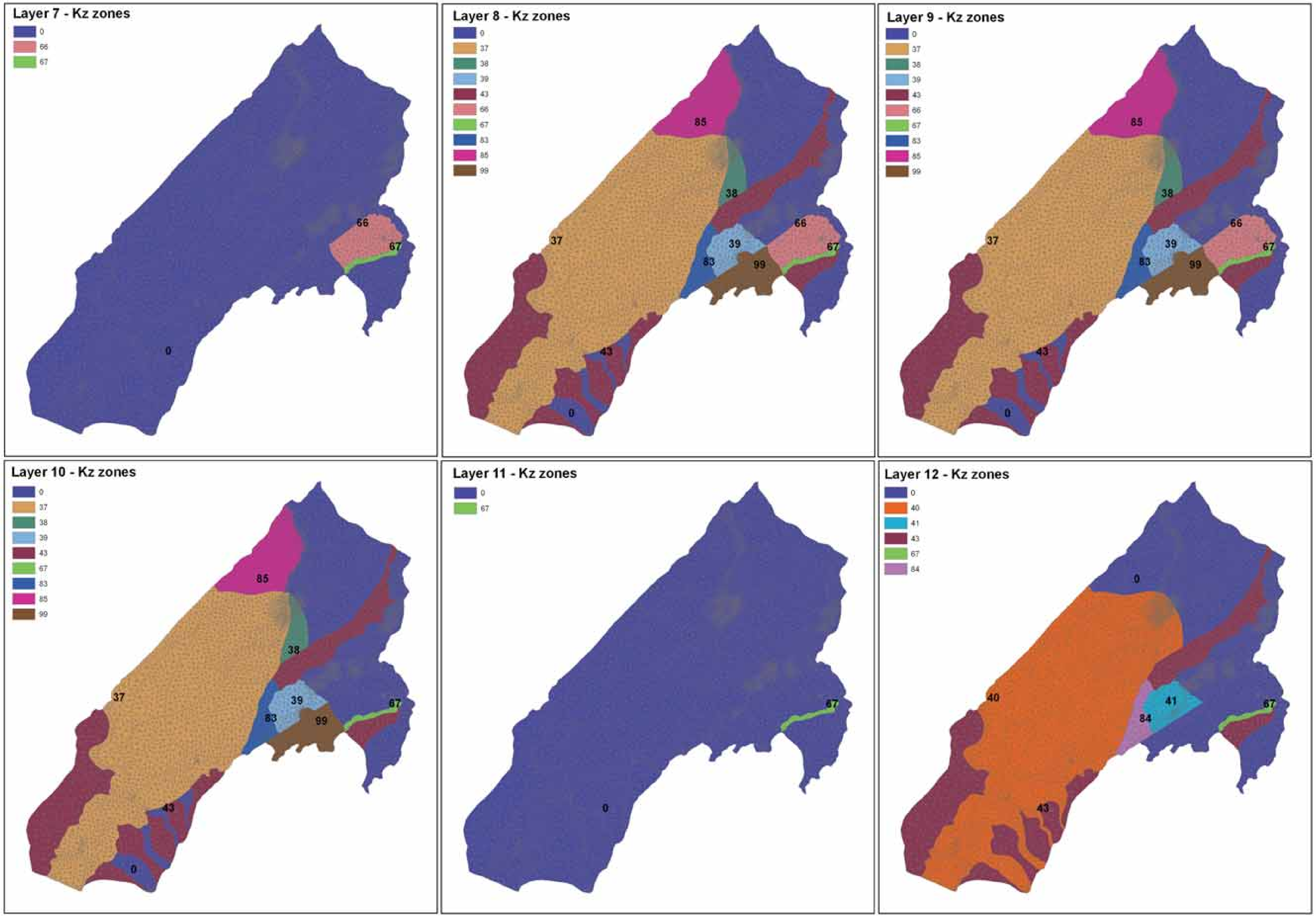


Figure A7.5: Kz zones for model layers 7 to 12

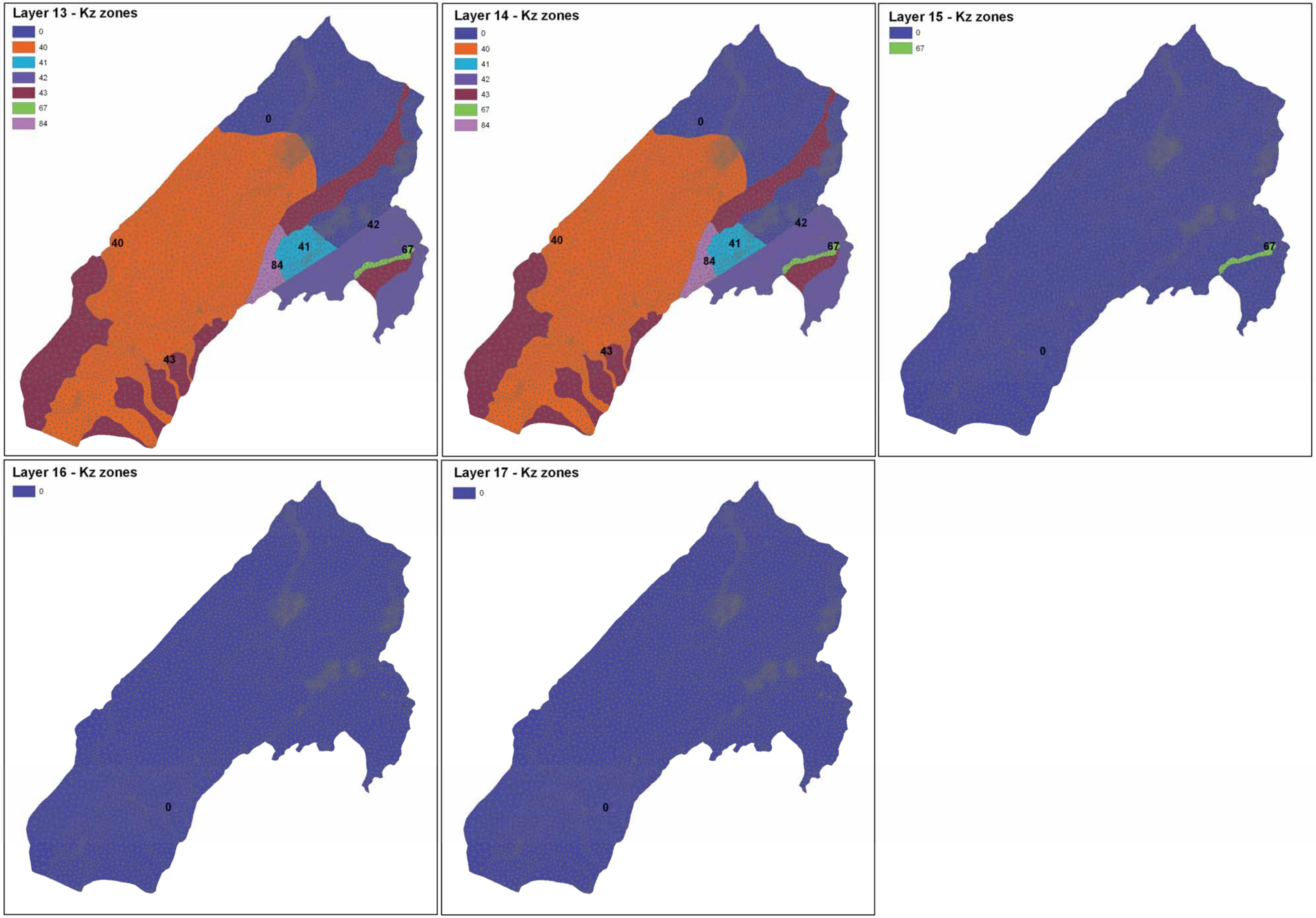


Figure A7.6: Kz zones for model layers 13 to 17

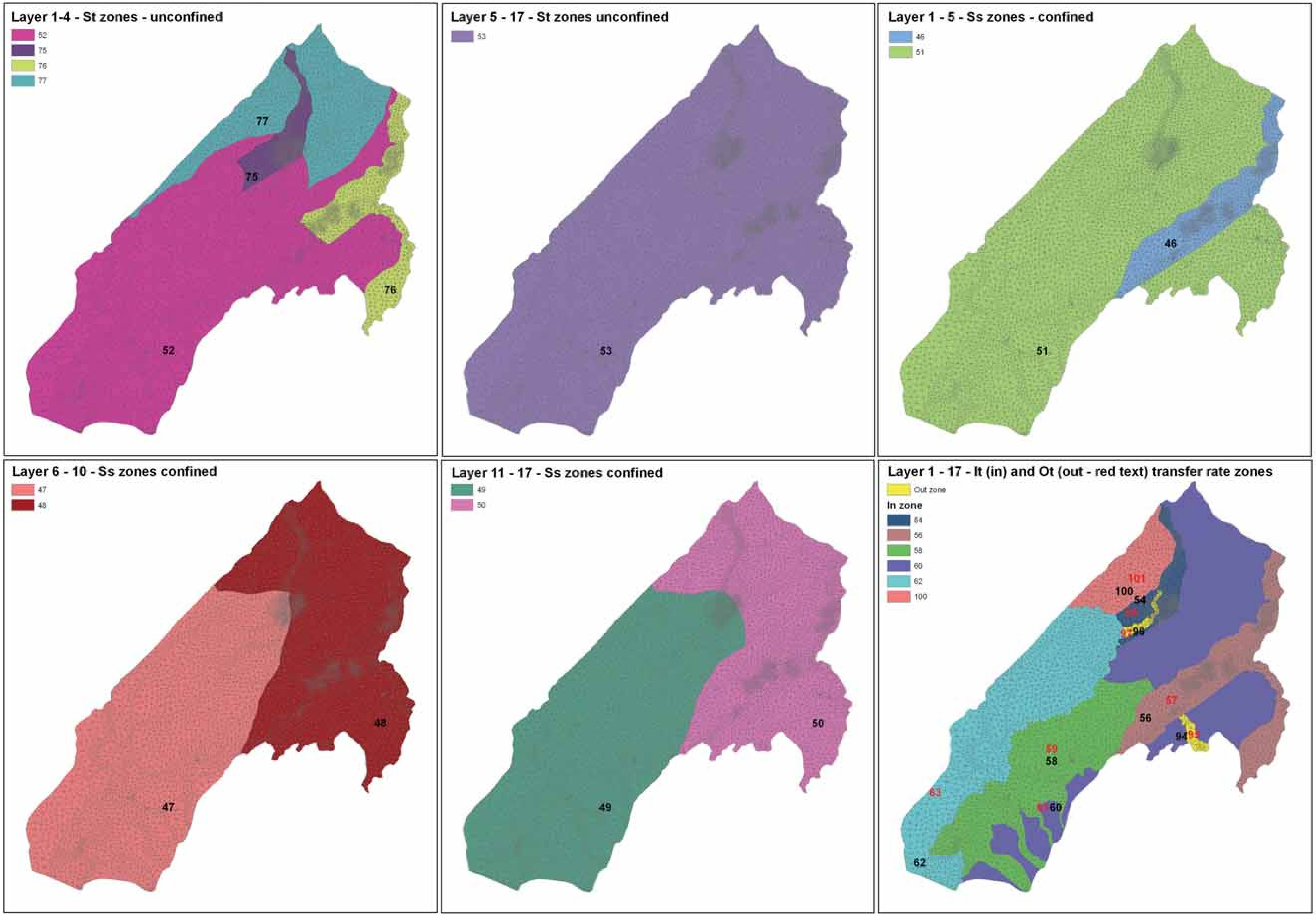


Figure A7.7: Ss, St, It and Ot zones for model layers 1 to 1

Appendix 8:

Groundwater flow model for the middle valley catchment of the Wairarapa Valley: A PEST interface to perform automated FEFLOW model calibration

APPENDIX B

GROUNDWATER FLOW MODEL FOR THE MIDDLE VALLEY CATCHMENT OF THE WAIRARAPA VALLEY

A PEST INTERFACE TO PERFORM AUTOMATED FEFLOW MODEL CALIBRATION

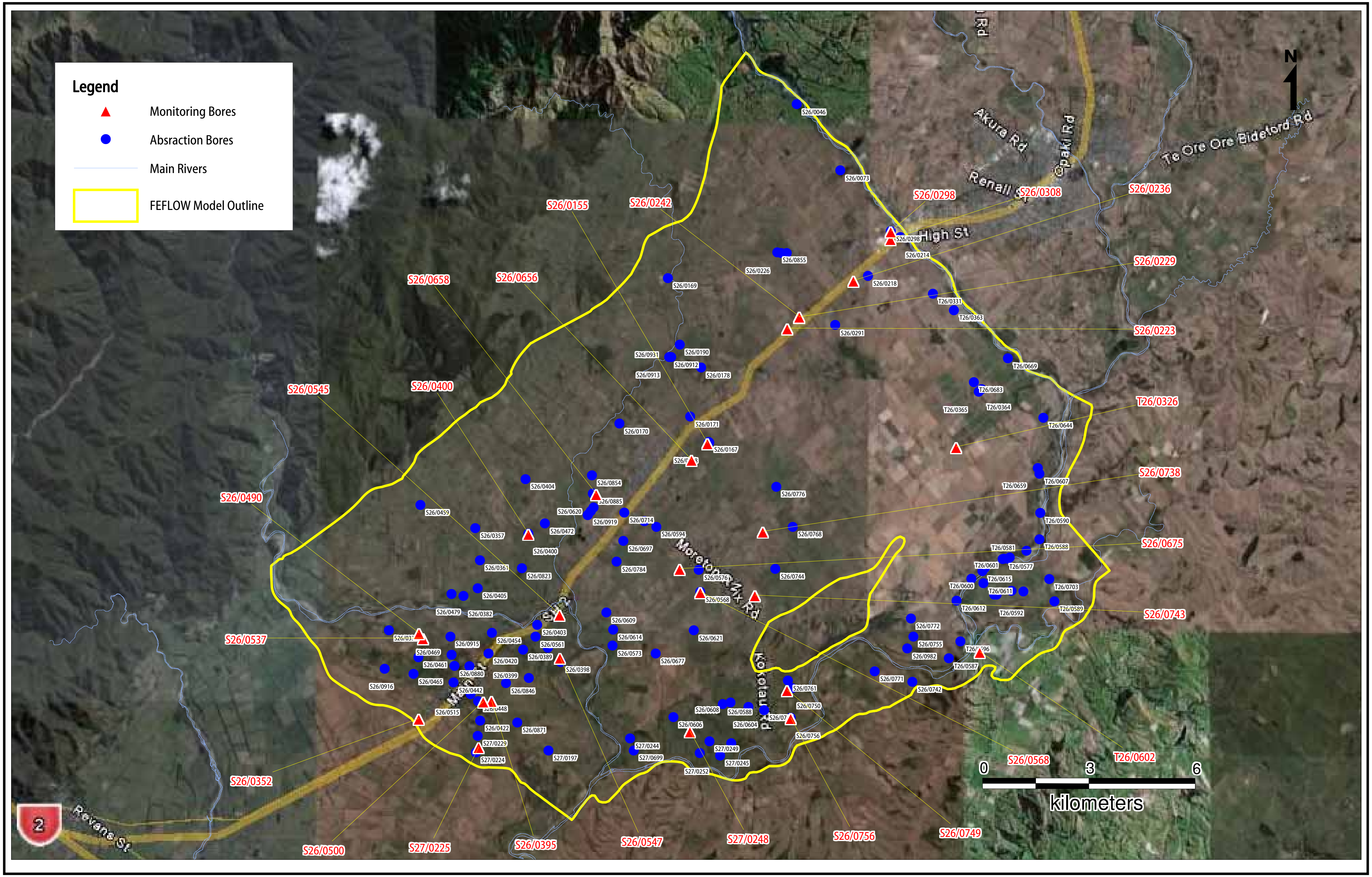
Introduction

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.



GW-09-08-REP-002 Rev A
May 2009

Figure 1
GWRC REGISTERED GROUNDWATER BORES

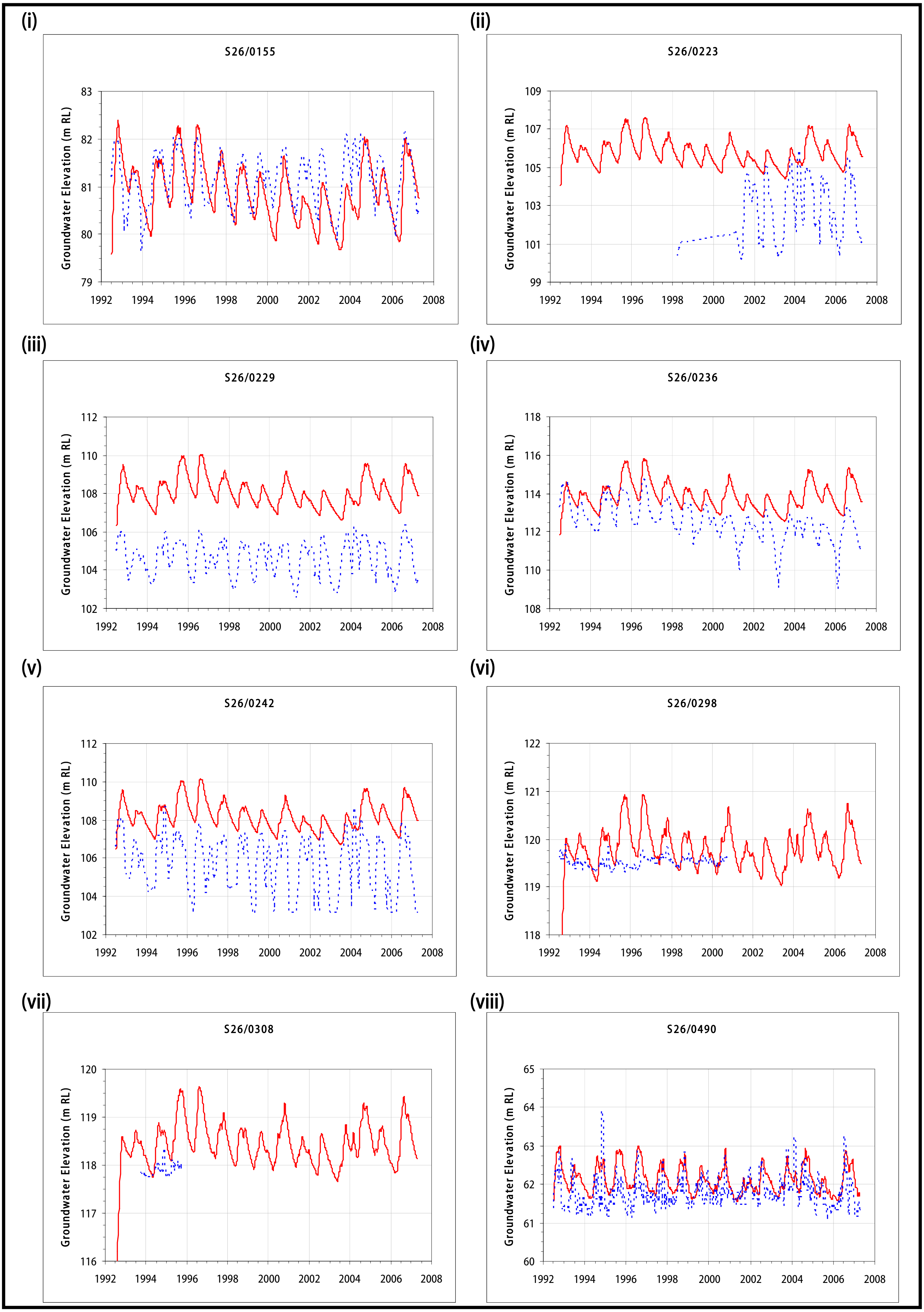


Figure 2
COMPARISON OF OBSERVED & SIMULATED HYDROGRAPHS (AFTER GWRC MANUAL CALIBRATION)

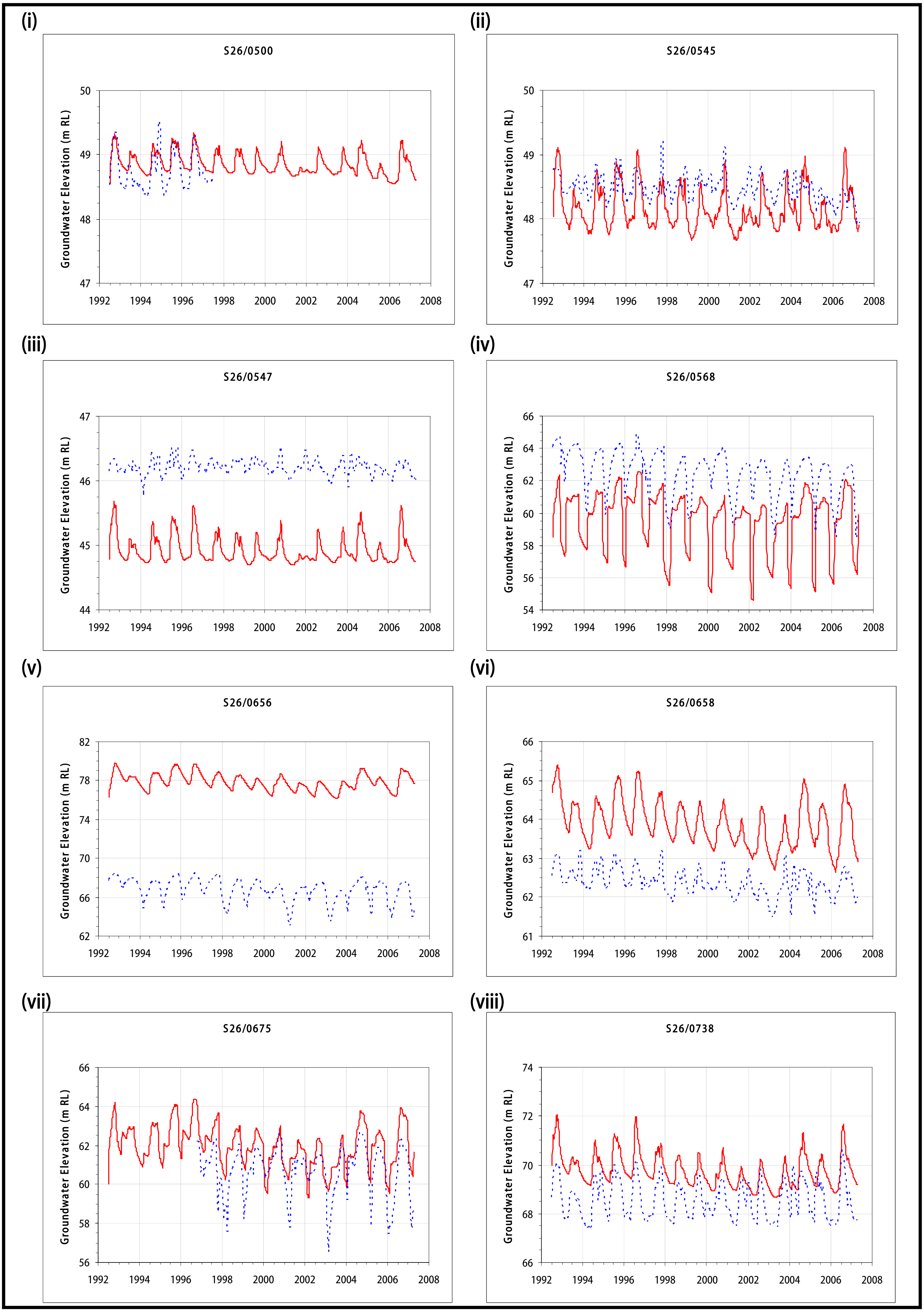


Figure 3
COMPARISON OF OBSERVED & SIMULATED HYDROGRAPHS (AFTER GWRC MANUAL CALIBRATION)

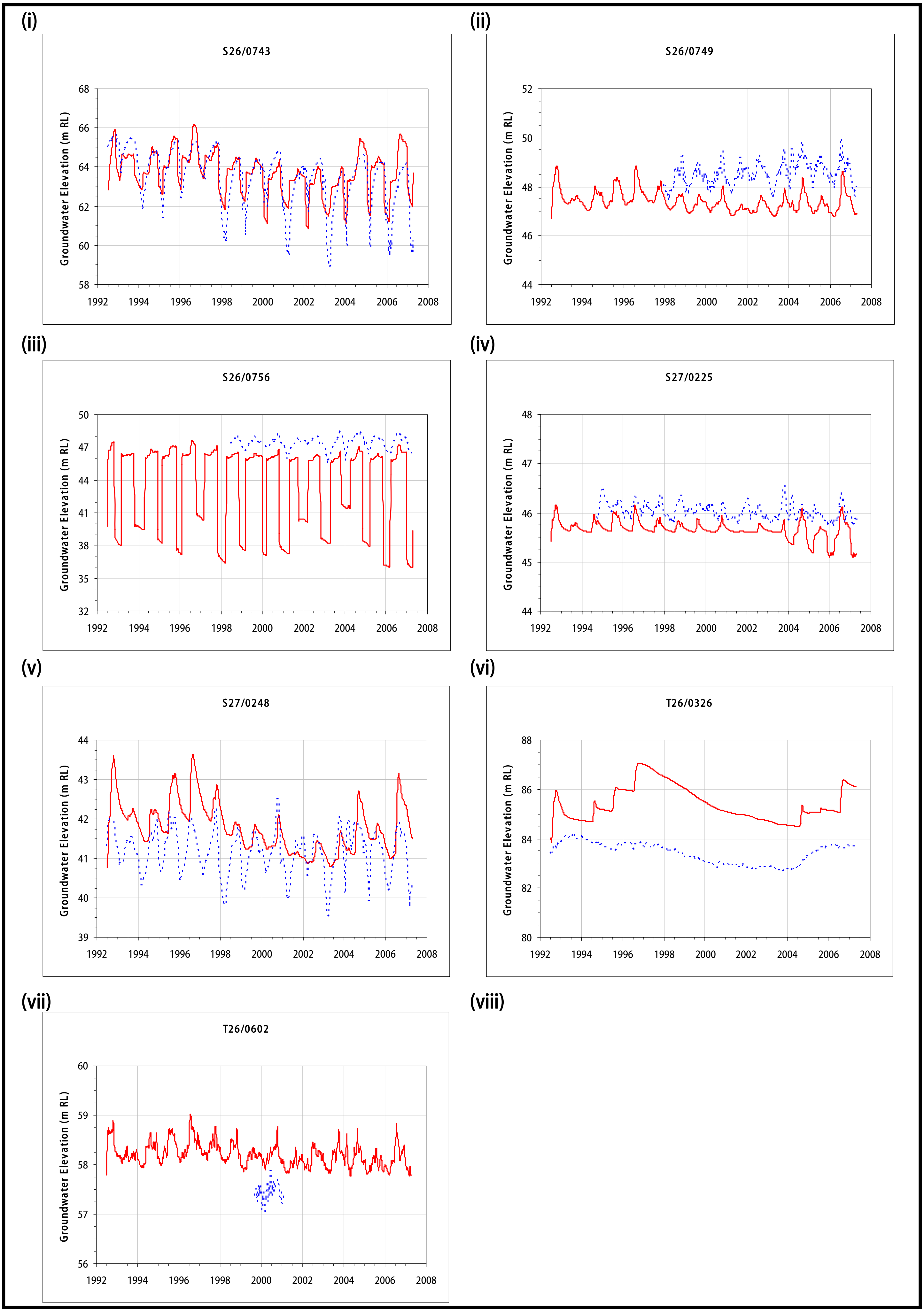


Figure 4
COMPARISON OF OBSERVED & SIMULATED HYDROGRAPHS (AFTER GWRC MANUAL CALIBRATION)

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	#

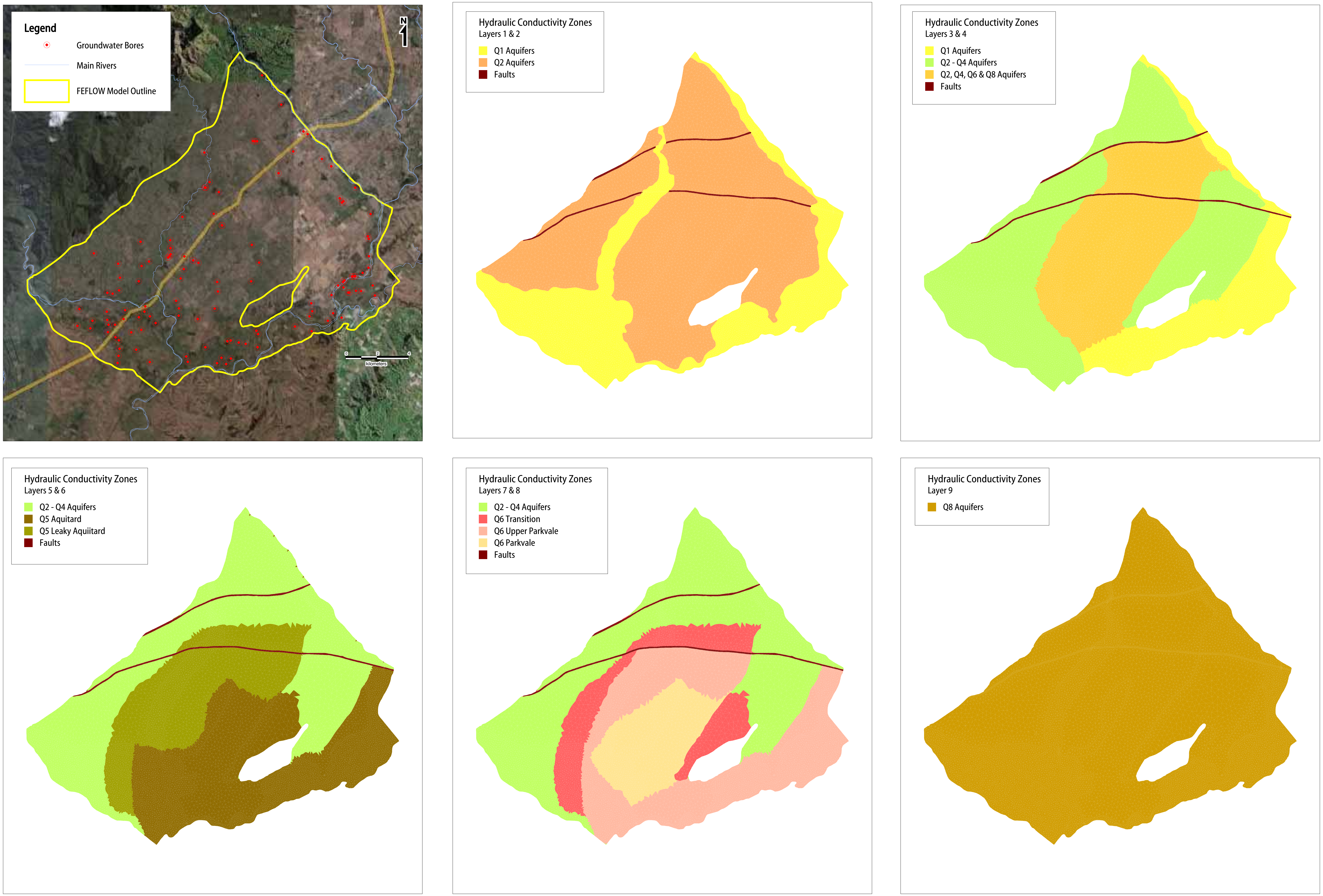


Figure 5
HYDRAULIC CONDUCTIVITY ZONATION

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).

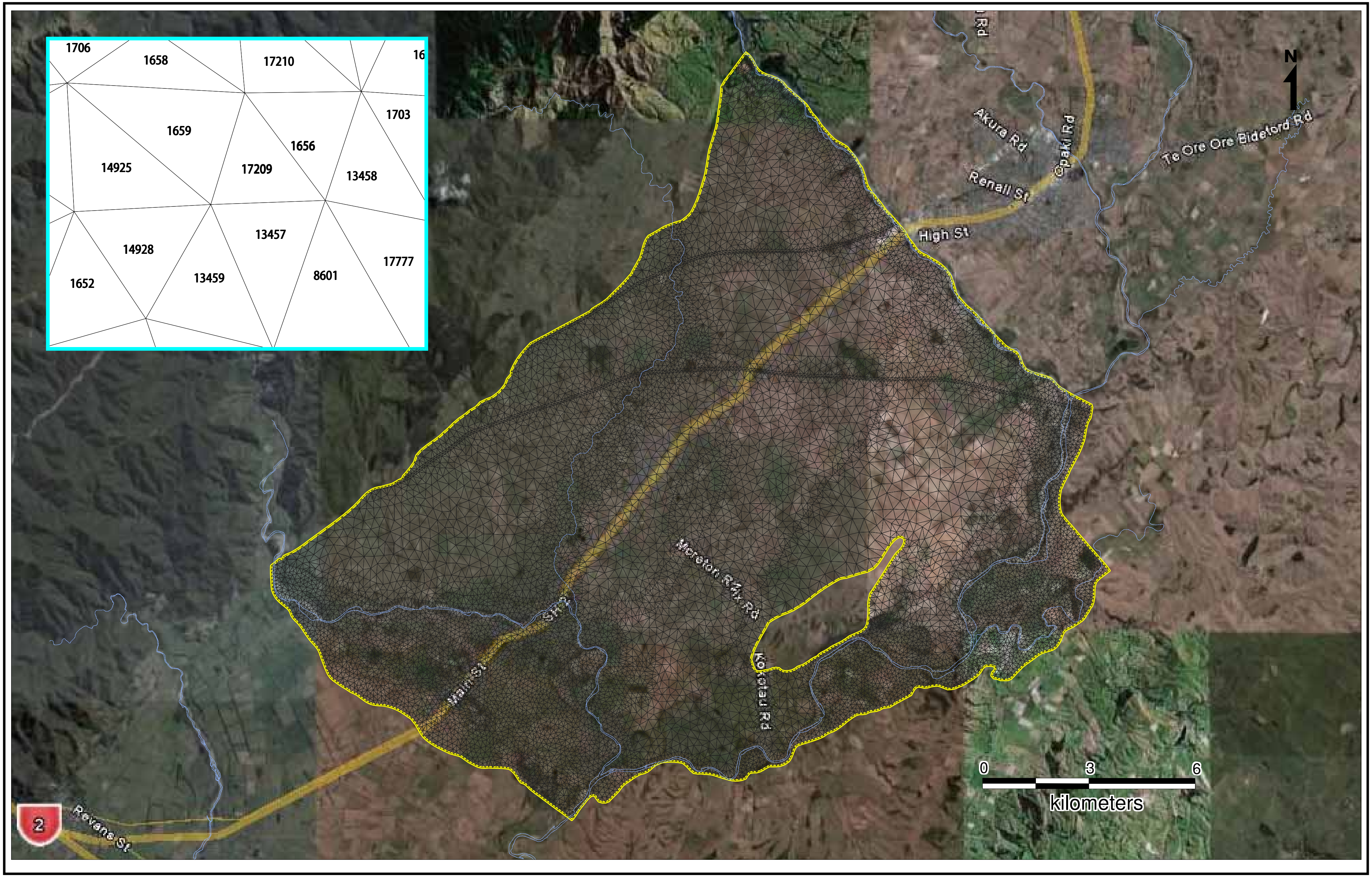


Figure 6
FEFLOW MODEL GRID AND ELEMENT NUMBERS IN LAYER 1

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.

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