Wairarapa Valley groundwater resource investigation

Upper Valley catchment hydrogeology and modelling

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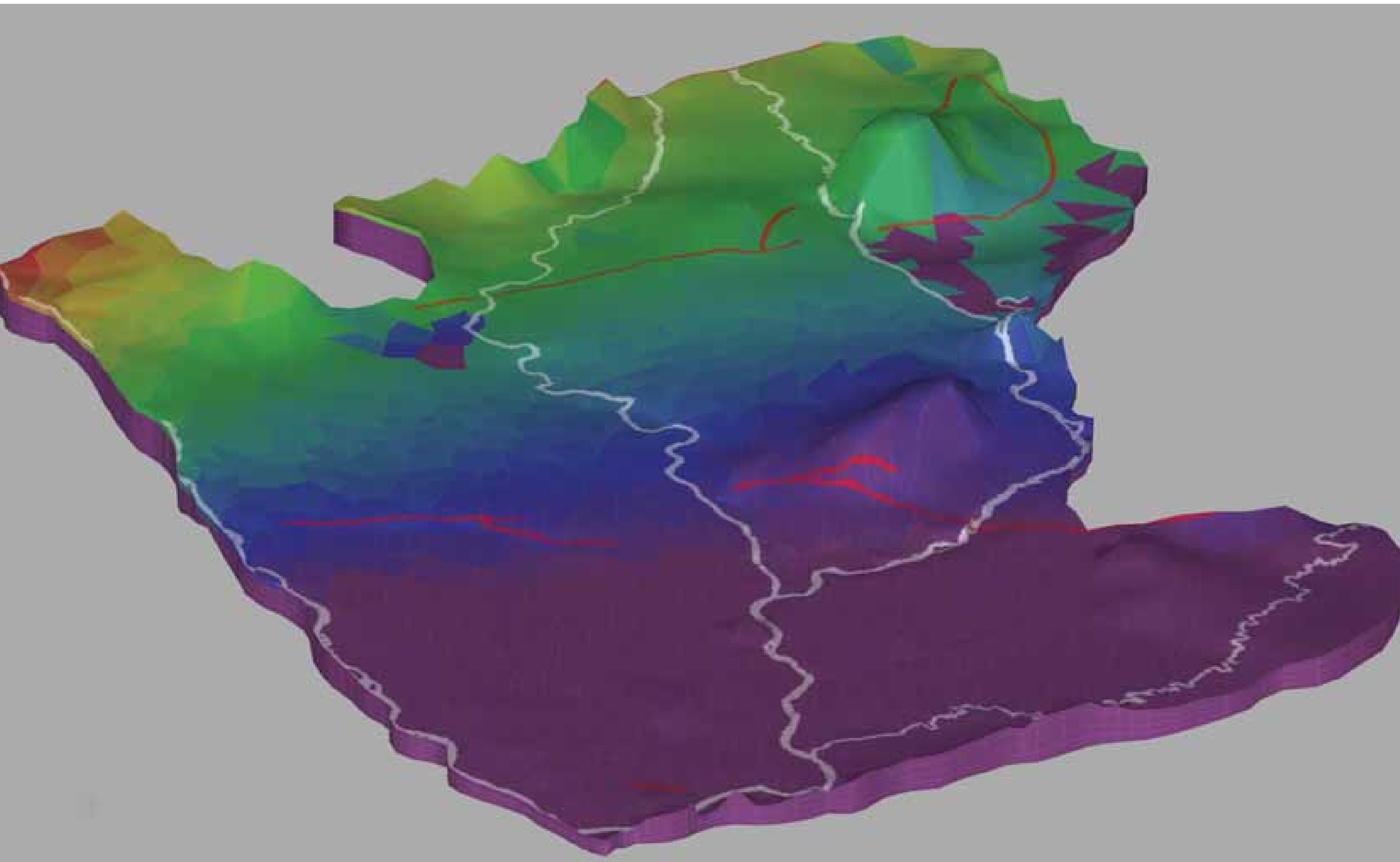

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Executive summary

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 aquifer sustainable yields and assist in a review of Greater Wellington's existing groundwater allocation policy for the Wairarapa Valley.

This report documents the results and outcomes of the Phase 2 hydrogeological and groundwater modelling investigation for one of three sub-regions of the Wairarapa Valley – the Upper Valley catchment. This catchment encompasses an area of 160 km^2 largely to the northeast of the Waingawa River and centred on the town of Masterton. The smaller Waipoua, Kopuaranga and Whangaehu tributaries of the Ruamahanga River also occur in the catchment along with numerous small streams and spring systems on the lowland fans and plains. Agriculture is the dominant landuse in the catchment, particularly sheep and beef farming. The Te Ore Ore plain is an intensively farmed area within the catchment where a significant amount of groundwater abstraction occurs for irrigation purposes.

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, river and spring flow gaugings, a water metering study, piezometric surveying and hydrochemical sampling.

Core research themes of the investigation were:

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

Formulation of a three-dimensional geological framework assisted in the characterisation of the Upper Valley groundwater environment. A heterogeneous succession of late Quaternary and Holocene unconsolidated sediments comprise the dynamic groundwater environment of the catchment. Variable degrees of sediment sorting, reworking, compaction and deformation by faulting and folding have resulted in a complex aquifer system. Major structural features, such as the Masterton and Mokonui faults, have dislocated and folded the sediment sequence and created the Te Ore Ore basin. Four broad hydrostratigraphic units were identified – the most important, in terms of groundwater resource potential, are recent (Holocene age) alluvium connected to major river systems, and older Tararua-sourced alluvium in the Te Ore Ore basin forming semi-confined aquifers.

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

Rainfall recharge was modelled using a soil moisture balance technique on a 500 m^2 grid incorporating detailed spatial climate modelling and soil property mapping. The modelling showed that about 30-40% of rainfall goes to recharging groundwater over the western and northern areas of the catchment, while less than 10% of rainfall reaches the water table over the drier eastern part. The average recharge, for the 16-year period ending in 2008, was 48 x 10^6 m^3/year, or 130,000 m^3/day. Temporal changes in the dynamics of the groundwater system are attributable to a combination of natural climatic variability and abstraction stresses. Inter-seasonal variability in recharge rate reflects temporal rainfall patterns driven by the El Nino Southern Oscillation (ENSO). Areas such as the Te Ore Ore basin also show clear evidence of abstraction-related seasonal declines in groundwater level.

Fluxes between shallow groundwater and surface water dominate the groundwater balance for the Upper Valley catchment. Natural groundwater discharges occur as river base flow, spring flow and diffuse seepage into wetlands. Some reaches of the main river channels recharge groundwater by losing part, or sometimes all, of their flow into underlying aquifers. Concurrent river gauging surveys show that the three principal river systems – the Ruamahanga, Waipoua and Waingawa rivers – 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 past 10 years primarily due to demand for seasonal pasture irrigation. At the time of initial groundwater model development in 2008, the total consented groundwater allocation was about 46,000 m^3/day and 8.25 x 10^6 m^3/year. About 85% of the total abstraction occurs on the Te Ore Ore plain and from bores near the Ruamahanga River upgradient of Lansdowne Hill. Annual meter readings show that water users do not normally exceed 50% of their annual allocation (10-30% being the norm). A metering study showed that resource consent holders tend to abstract about 60-70% of their consented daily rate. During the 2007/08 irrigation season the metered abstraction was about 27,000 m^3/day – 60% of the allocated daily volume. Historical groundwater abstraction rates for the catchment were modelled using soil moisture deficits to estimate demand periods in conjunction with available annual meter records.

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

Conceptually, the Upper Valley groundwater catchment is characterised as a ‘closed’ groundwater basin in which the dominant water balance components are rainfall recharge and fluxes between surface water and groundwater. Rainfall infiltration and river bed leakage are both important for recharge. The most important hydrogeological characteristic of the catchment is the strong interdependence of surface water and groundwater. Groundwater abstraction constitutes more than 10% of the catchment water balance during the summer months. The effects of abstraction on shallow, unconfined, dynamic aquifers are of particular significance since these aquifers are freely connected to the surface water environment (rivers, streams, springs and wetlands).

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

Calibration robustness was achieved for the principal aquifers – the shallow unconfined Holocene aquifer of the Waingawa, Waipoua and Ruamahanga floodplains, and the semi-confined aquifers in the Te Ore Ore basin.

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

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

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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 public water supply source 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 – particularly given that surface water resources are approaching full allocation in many areas.

Nearly half[1] of Wairarapa groundwater management zones, as defined in the Regional Freshwater Plan (RFP, 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 second 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

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[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 Lower Valley catchments respectively.

culminated with the production of a regional conceptual model and 'bulked' 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 Upper Valley. It comprises the following sections:

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

2.1 Physical setting and land use

The Upper Valley catchment (Figure 2.1) of the Wairarapa Valley is bounded by the Waingawa River to the south, the Tararua Range to the north, and the eastern hill country to the south and east. The town of Masterton is the only population centre in the catchment.

The catchment covers an area of about 160 km^2 and has a generally low relief (Figure 2.2) sloping gently from alluvial fan areas in the north-west to the south. Lansdowne Hill near Masterton is a local topographic feature.

The Ruamahanga River and its tributaries, the Waingawa and Waipoua rivers, are the principal surface water drainage systems in the Upper Valley catchment (Figure 2.2). Other tributaries of the Ruamahanga River in this area are the Kopuaranga and Whangaehu rivers, and numerous small streams and spring systems of the alluvial fans and plains. The Te Ore Ore plain, located between the Ruamahanga and Whangaehu rivers, is an intensively farmed lowland area.

Agriculture is the dominant land use in the catchment. Sheep is the dominant farm type (23% of the catchment area), followed by beef (18%), sheep and beef (15%) and dairy (13%) farming. A significant portion of the catchment is also urban (12%), which includes the town of Masterton. The distribution of land use in the Upper Valley catchment is shown in Figure 2.3.

2.2 Soils

The distribution of soils groups in the Upper Valley catchment is shown in Figure 2.4. There are three dominant soils groups in the catchment – Brown Soils, Recent Poorly Drained Soils, and Recent Well Drained Soils.

Brown Soils dominate the alluvial fan areas between the modern-day flood plains of the main drainage systems. These are mainly yellow-brown shallow silt loams on a gravel substrate which are well, to excessively, drained.

Recent Well Drained Soils occur on the recent alluvial floodplains of the Waingawa and Ruamahanga rivers. Extensive areas of this soil group also occur around Masterton, and a wide band occurs to the north-west of the town between the Waingawa and Waipoua rivers (Figure 2.4). This soil group comprises stony sands that are well, to excessively, drained.

Recent Poorly Drained Soils are silt loams which occur in low-lying water-logged areas such as the Te Ore Ore plain and around the Masterton springs (Figure 2.4).

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

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

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

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

*Does not include data for 2008.

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

Figure 2.7 shows six prominent inflection points over the past 40 years in 1974, 1982, 1992, 1997, 2003 and 2007. These trends are important when interpreting long-term groundwater level hydrographs (Section 7.1.4).

3. Surface water environment

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

3.1 Channel systems and flow characteristics

The Upper Valley catchment is traversed by the Ruamahanga River and its two major south-easterly flowing tributaries – the Waingawa and the Waipoua rivers. Other tributaries of the Ruamahanga River within the Upper Valley include the Whangaehu River, which emerges onto the Te Ore Ore plain from the eastern hills, and the Kopuaranga River sourced in the northern hill country (Figure 3.1). Figure 3.2 shows the longitudinal bed profiles of the main rivers and streams within the Upper Valley catchment (derived from the MIKE 11 surface water model, see Section 10.5.3).

Flows in the Ruamahanga, Waingawa and Waipoua rivers are measured at gauges located in the foothills, a short distance before each waterway emerges onto the plains (Figure 3.1). Flow in the Ruamahanga River is also measured where the river leaves the Upper Valley study catchment at Wardell's Bridge, a short distance upstream of the Waingawa River confluence. Gauges on the Kopuaranga and Whangaehu rivers are also shown on Figure 3.1. Flow statistics for the sites are shown in Table 3.1.

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

	Catchment area above flow site (km^2)	Mean flow (m^3/s)	Median flow (m^3/s)	Mean annual low flow (m^3/s)	Maximum recorded flood (m^3/s)
Ruamahanga River at Wardells (upstream of Waingawa River	637	23.8*	12.5*	2.7*	844
Waingawa River at Kaituna	79	10.2	5.1	1.2	426
Waipoua River at Mikimiki	80.3	6.0	3.7	0.31	355
Kopuaranga River at Palmers	100.3	2.6	1.2	0.28	60
Whangaehu River at Waihi	36.6	0.54	0.16	0.018	80

*Flow statistic likely to be affected by upstream abstraction of water.

3.1.1 Ruamahanga River

The Ruamahanga River is the principal drainage system for the Wairarapa Valley having a mean flow of about 24 m^3/s at the Wardells Bridge gauge site (Figure 3.1). The river originates in the north eastern Tararua Range near Mt

Dundas (1,500 m above mean sea level) and flows south through the Wairarapa Valley to Lake Onoke (which discharges directly into the sea). The river is about 162 km long with a catchment area of approximately 3,430 km^2. It has three major tributaries rising in the Tararua Range: the Waipoua, Waingawa and Waiohine rivers, and other main tributaries that join from the northern and eastern hill country (being the Kopuaranga, Whangaehu, Tauweru and Huangarua rivers).

The Ruamahanga River emerges onto the Wairarapa plains at Mt Bruce, about 21 km north of Masterton. In general, this upper reach of the river tends to have a wide, semi-braided form, although it narrows to a single-thread channel in places, particularly where it is confined by terrace bluffs. As the river flows past Masterton it has an incised single channel, with beaches on the inside of river bends. Immediately downstream of the Waingawa River confluence, the Ruamahanga River changes to a wide semi-braiding channel.

3.1.2 Waingawa River

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

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

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

3.1.3 Waipoua River

The Waipoua River is the first major western tributary of the Ruamahanga River in the Wairarapa Valley, with a catchment area of 149 km^2. A large part of the catchment is contained in the lower foothills of the Tararua Range; the river originates in the Blue Range within the eastern Tararua Range and emerges onto the Wairarapa plains about 18 km north of Masterton before flowing across the plains to join the Ruamahanga River at Masterton. In the reach upstream of Masterton there is significant gravel accumulation and during times of low flow the river often disappears below bed level. The mean flow of the Waipoua River is 6.0 m^3/s (Table 3.1).

The Waipoua River is a steep gravel-phase river with a relatively stable and narrow single thread channel, although in its upper reaches there are some short semi-braided sections. The channel has been artificially confined and modified, particularly in the reaches downstream of the Mikimiki Road bridge and through Masterton township where extensive river straightening has occurred. In places, the channel alignment is maintained by gravel extraction, with three grade control weirs installed near Masterton to stabilise the riverbed (Heslop et al. 1996).

3.1.4 Whangaehu River

The Whangaehu River catchment (144 km^2) is bounded by the Kopuaranga catchment to the west and the Tauweru catchment to the east. The river rises in the steep hill country of northern Wairarapa near Ihuraua, and flows for 61 km to join the Ruamahanga River on its true left bank at Homebush on the Te Ore Ore plain, 4.5 km south of Masterton. For much of its length, the Whangaehu River flows within a narrow, steep valley in a tightly meandering channel. As the valley widens, the river crosses the Te Ore Ore plain for 19 km in a perched channel that remains distorted and tightly meandering (Williams 1977). The mean flow of the Whangaehu River in its middle reaches is only 0.54 m^3/s and the mean annual low flow is 18 L/s (Table 3.1) – significantly less than the flow in the Waipoua and Waingawa rivers.

3.1.5 Kopuaranga River

The Kopuaranga River rises near Mt Bruce and flows for about 59 km to join the Ruamahanga River on its true left bank east of Opaki, 6.5 km northeast of Masterton. The Kopuaranga River has a catchment area of 164 km^2 draining the rolling to steep hill country of northern Wairarapa. The upper reaches of the Kopuaranga River are within a narrow valley, with a single-thread, tightly meandering and entrenched channel. In its lower reaches the river meanders across the poorly sorted gravel plains for 15 km to its confluence with the Ruamahanga River. The mean flow in the Kopuaranga River is 2.6 m^3/s (Table 3.1).

3.2 Springs

Numerous springs emerge in the low-lying areas of the Upper Valley catchment, in particular on the Te Ore Ore plain and in the Masterton area around the Masterton Fault. These areas were probably once extensive wetlands or swamps. They are now drained and a discreet network of springfed channels is all that remains.

3.2.1 Masterton springs

The Masterton springs comprise an extensive channel network occupying the area between the Masterton Fault, Ruamahanga River and Waingawa River (Figure 3.4). Many of the springs emerge around the Masterton Fault which appears to impede the flow of groundwater from the upstream alluvial fans and forcing it to the surface. The springs also seem to be associated with palaeochannels of the Waingawa River formed when it flowed though the

Masterton area. The channel structure shows clearly in the LIDAR image of Figure 3.3.

The Masterton springs comprise three main channel ‘arms’ – termed the Makoura, Kuripuni and Solway (Figure 3.5). In general flow in the springs tends to decrease with distance from the Waipoua River. The spring flows have been characterised using a series of summer gauging surveys carried out in the late 1970s and in 1981. Channel flow is sustained by groundwater discharge during dry periods but also via a surface water runoff component.

The Solway arm contains stagnant water during summer and it is likely that it never flows above 10 L/s, except perhaps following significant rainfall. The stream is weed-infested and quite degraded. The Fleet Street arm is of similar quality with negligible flow occurring during summer. Winter flows are up to 80 L/s at South Road with a 40 L/s gain from the spring head. The lower Fleet Street-Solway system gains 50-55 L/s to Manaia Road in the summer and about 480 L/s during winter.

The Kuripuni system follows the Masterton Fault scarp at its headwaters and receives 40-50 L/s from the fault during summer and about 150 L/s during winter. The 1981 gaugings show that there is negligible gain downstream of Dixon Street.

The Makoura system receives flow from several point sources at its headwaters, and there is very little gain in flow below Chapel Street. The whole Makoura catchment can be measured at Colombo Road and is expected to be 60-70 L/s in summer and about 250 L/s in winter.

Totalling the measured flows from each of the spring channels it appears that the summer discharges from the Masterton springs is in the order of 150-200 L/s. Winter flow characteristics are difficult to ascertain due to the lack of gauging data and the influence of surface water runoff to the spring channels.

3.2.2 Poterau springs

The Poterau Stream flows across the Te Ore Ore plain (Figure 3.5) and is spring-fed from an underlying gravel aquifer. The stream is located along a geological boundary between silt-rich alluvium sourced from the Whangaehu catchment and more gravel-rich alluvium associated with the Ruamahanga River. Flows are highly seasonal with negligible flow occurring during the summer months. There has been a noticeable decrease in summer flows in recent years which may be due to increased groundwater abstraction for irrigation.

Flow in the Poterau Stream at the Whangaehu River confluence was gauged in March 2008 (17 L/s) and again in August 2008 (405 L/s). The Poterau seepage face during summer appears to be 400 to 550 m downstream of Morris Road. During winter the majority of flow gain occurs below Morris Road, with less than about 50 L/s inflow occurring above this point. The seepage face during winter is expected to be 250 to 300 m upstream of Watsons Road (see Figure 3.5 for locations).

3.2.3 Other minor springs

There are two minor spring systems north of Masterton emanating on the alluvial fan system between the Waipoua and Ruamahanga rivers. These are the Golf Course Spring and the Waipipi Stream (Figure 3.4).

The Waipipi Stream originates north of the Mokonui Fault and runs parallel to the Ruamahanga River for about 6 km remaining on the northern side of Lansdowne Hill. It joins the Ruamahanga River where the Masterton Fault crosses. The few gauging results available for this stream suggest a flow of about 20-30 L/s during the summer months with most of the gain occurring above the Mokonui Fault.

The Golf Course Spring emanates on the fan north of Lansdowne Hill and flows southwards to the Waipoua River at Masterton. There are no flow gaugings available but the spring is thought to flow at 20-50 L/s and is utilised by the Mahunga Golf Course for irrigation.

There are also minor spring-fed streams on Lansdowne Hill which flow down to the Masterton area and join the Waipoua River. One of these is the Opaki Stream which had a gauged flow of only about 10 L/s in April 2002.

3.3 Water races

The Wairarapa Valley has an extensive network of gravity-fed water races that divert water from the main rivers into a system of unlined channels. The water is used principally for stock water supply and limited irrigation[3]. Water races were constructed in the first half of the 20th century by the local authority (now Masterton District Council) and are still administered by them under resource consents issued from Greater Wellington. The races distribute water across catchment boundaries and probably contribute to some groundwater recharge in more permeable fan areas, and receive spring discharges in low-lying areas.

The water race network in the Upper Valley catchment comprises a complex channel system often connected to existing natural waterways, agricultural drainage systems and springs. Figure 3.4 shows the two main channel systems in the Upper Valley catchment – the Opaki and Te Ore Ore water races.

There was previously another water race system – the Upper Plains Water Race – which diverted water from the Waingawa River and fed a network of channels north of Masterton. The race discharged into the Waipoua River and into the Masterton spring channel system. The present day flow in the remnant channels is very small and is probably spring-fed.

3.3.1 Opaki Water Race

The Opaki Water Race diverts water from the Ruamahanga River where the Mokonui Fault crosses, about 3.5 km upstream of the Kopuaranga River confluence (Figure 3.4). Water Permit WAR010204 authorises Masterton

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[3] Some areas in the Wairarapa Valley use weirs to increase water race water levels during summer for passive irrigation of 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.

District Council to divert water from the river at a maximum rate of 250 L/s. The Opaki Water Race network extends westwards from the river over the fan area north of Lansdowne Hill and any water remaining in the race discharges into the Waipoua River at several points.

3.3.2 Te Ore Ore Water Race

The Te Ore Ore Water Race diverts water from the Ruamahanga River immediately west of Lansdowne Hill before the river enters the Te Ore Ore plain (Figure 3.4). This intricate race network extends across the eastern part of the plain and links to the Whangaehu River at several locations. A water permit (WAR010203) authorises the diversion of water into the race from the Ruamahanga River at a rate of 250 L/s.

4. Previous studies

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 5.4×10^8 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 Upper Valley catchment – these are listed in Table 4.1 along with their individual previously defined safe yield estimates and current status of water allocation.

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

Groundwater zone	Zone area (km^2)	RFP safe yield (m^3/year x 10^6)	% safe yield allocated[1]	Resource potential
Te Ore Ore	27.9			Good
Aquifer 1		4.6	38	
Aquifer 2		3.0	100	
Masterton (combined)	21.5	5.5	10	Poor–moderate
Upper Plain	35.1	17.0	20.1	Poor (good around rivers)
Opaki	22.2	2.3	3	Poor
Upper Opaki	21.6			Poor (moderate around rivers)
Rathkeale	12.9	3.0	80	Moderate–good
Fernridge	5.4	n/a	n/a	Poor

[1] Percentage safe yield allocated as at 16 February 2009.

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.

The heavily used Te Ore Ore groundwater zone has been described in a separate resource report prepared by Professional Groundwater and Environmental Services Limited (Butcher 1997). A subsequent resource report by the same author has also been prepared for the Rathkeale groundwater zone (Butcher 2004). The reports are summarised below.

4.2.1 Te Ore Ore groundwater zone

A localised Quaternary age depositional basin lies beneath the Te Ore Ore plain to the east of Masterton covering an area of about 2,400 ha. The plains are used intensively for dairy farming and a large number of irrigation bores have been constructed in recent years. Butcher (1997) identified a shallow highly heterogeneous unconfined (or locally confined) aquifer between about 5 and 15 m depth. Beneath this a semi-confined aquifer between about 20-30 m depth was recognised. At the western boundary of the plains, semi-confined or confined aquifers were also described at 40-50 m depth (T3) and at a deeper level (T4). The sedimentary sequence was noted to be highly stratified with groundwater flowing in relatively thin gravel layers.

Groundwater quality in the Te Ore Ore basin was described by Butcher (1997) as being reasonably good, but spatially variable and deteriorating to the east as iron and hardness become elevated. High nitrate concentrations were described in aquifers T1 and T2 in the central parts of the plains.

The recharge source to the T2 and deeper aquifers was regarded to be from rainfall infiltration with the T1 shallow aquifer being recharged through a combination of rainfall and river recharge (Ruamahanga River).

Discharge from the Te Ore Ore basin was described to occur primarily via spring discharge to the Poterau Stream and possibly by discharge back to the Ruamahanga River. Poterau Stream flows were noted to have reduced significantly since the 1970s coincident with the decline in minimum T2 aquifer levels – both attributed to groundwater abstraction and degradation of the Ruamahanga River bed.

Yield estimates of the groundwater zone were based upon aquifer recharge estimates with the caveat that these may need to be reduced to prevent excessive depletion effects in the spring flow to the Poterau Stream.

4.2.2 Rathkeale Groundwater Zone

Butcher (2004) describes the Rathkeale Groundwater Zone as the area of thin permeable Holocene alluvium associated with the Ruamahanga River upstream of the Te Ore Ore plain. Increasing groundwater use in this zone since the mid-1990s appears to have resulted in a seasonal decline in levels of about 0.2-0.3 m. The aquifer was postulated to be recharged both from rainfall infiltration and river leakage. Water quality was found to be relatively good, but moderately aggressive (low pH). A tentative ‘safe yield’ was recommended although, to avoid adverse effects on connected surface waters it was considered that a lower quantity might be ‘safer’.

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

- Stratigraphic drilling and monitoring bore construction
- Water meter readings of selected groundwater takes
- Groundwater sampling and analysis
- Low flow river concurrent gaugings
- Springs surveys
- Piezometric surveys.

5.1 Stratigraphic drilling and monitoring bore construction

Drilling for the Phase 2 investigation was carried out from April to July 2008 to augment existing hydrogeological knowledge. One site was selected in the Upper Valley catchment adjacent to the Poterau Stream on the Te Ore Ore plain (T26/0814 GWRC/Lucas; 2736442 6022306). The bore was drilled on 29 April 2008 to a depth of 10.3 m and screened between 7 and 10 m with a slotted pvc pipe.

5.2 Water meter study

Historical groundwater abstraction data are very limited within the Upper Valley catchment with most available records being restricted to annual quantities abstracted by larger users. To provide information on intra-seasonal abstraction patterns all consented and metered takes greater than 10 L/s across the Wairarapa Valley were read on a fortnightly basis (Figure 5.1) during the 2007/08 irrigation season. In total, the meter study involved 122 bores, 14 of which were located in the Upper Valley catchment. Abstraction from some bores could not be monitored because of malfunctioning meters. 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 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, 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 Upper Valley catchment. Concurrent gauging runs carried out on the Ruamahanga, Waingawa and Waipoua rivers are listed in Table 5.1.

Table 5.1: Concurrent gauging runs carried out in the Upper Valley catchment during 2006–2008 (data are plotted in Figure 7.21)

River	Dates of concurrent gauging
Ruamahanga	22/02/2006*, 16/03/2006, 21/02/2007
Waingawa	21/02/2006, 22/02/2007, 20/02/2008
Waipoua	21/02/2006, 21/02/2007, 28/08/2008

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

5.5 Springs survey

Numerous springs are located within the Upper 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 Masterton spring system and the Poterau Stream.

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 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 Upper Valley catchment groundwater model. The work involved a spring bed level survey and river water level (summer low flow and winter stable flow) survey (Figure 5.2). Differential GPS surveying was also undertaken to provide accurate elevation data for the new groundwater level monitoring bores.

6. Geology and hydrostratigraphy

6.1 Regional geological setting

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

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

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

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

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

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

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

Relative age	Material	Name	Depositional environment	Map symbol[1]	Absolute age (ka)
Holocene	Mud & silt		Estuarine, lacustrine	Q1m Q1s	0-7
Holocene	Gravel & sand		Alluvial	Q1a	0-10
late Quaternary Late Otiran	Gravel & sand	Waiohine *[Equivalent to Waiwhetu Gravel in L. Hutt Basin]*	Alluvial	Q2a	10-25
late Quaternary middle Otiran	Gravel & sand	Ramsley	Alluvial	Q3a	50-25
late Quaternary Early Otiran	Gravel & sand	Waipoua	Alluvial	Q4a	70-50
late Quaternary Kaihinu Interglacial	Mud, silt, sand & minor gravel	Francis Line	Swamp, lacustrine	Q5m	125-70
late Quaternary Kaihinu Interglacial	Sand, some gravel	Eparaima	Marginal marine	Q5b	125-70
middle Quaternary Waimea Glacial	Gravel & sand	*[Equivalent to Moera Gravel in L. Hutt Basin]*	Alluvial	Q6a – Q8	186-125
middle Quaternary	Gravel, sand, silt, loess, tephra	Ahiaruhe	Alluvial, swamp	mQa	>500-186
early Quaternary	Gravel, sand, silt, loess, tephra	Te Muna	Alluvial, swamp	eQa	c. 1000-500

[1] GNS QMap (1:250 000) of Wellington and Wairarapa areas.

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

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

The units shown in Table 6.1 were mapped out on the valley floor (Figure 6.1), relying upon stratigraphic principles to help constrain their three-dimensional distributions. The ages of terrace surfaces were estimated by examining the coverbed sequences (loess, paleosol and tephra horizons). Degradational gravel surfaces of low elevation that are not overlain by loess units are considered to be Holocene in age (Q1a). Aggradational gravels a level higher, with cobbles sitting at the surface, and a straw-coloured loess are late last glacial (14,000-18,000 yrs) in age (Q2a). Higher gravels with a coverbed sequence of a single loess unit (Ohakea loess) and tephra (Kawakawa Tephra) are Ratan (Q3a) in age. Gravels at yet higher elevation which are overlain by a red loess (Rata loess) as well as the Ohakea loess are Porewan in age (Q4a). Weathered gravels at even higher elevations again have a cover of three loesses. Loess and coverbed stratigraphy is not as well developed or is poorly preserved in the Ruamahanga River valley north of Masterton, possibly due to wind stripping.

6.2 Upper Valley geology

The sub-regional characterisation of the complex Upper Valley catchment geology was undertaken as a basis for understanding and interpreting the hydrogeological functioning of the area (Figure 6.2).

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

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

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

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

- The regional active Wairarapa Fault bounding the western side of the catchment against the Tararua hills.

- Major splay faults of the Wairarapa Fault – the active Masterton and Mokonui faults are responsible for major displacement and deformation of the Quaternary and Holocene aquifer sequences and for the creation of sub-basins between the faults.

- Te Ore Ore basin – a discrete, relatively deep structurally-controlled basin beneath the Te Ore Ore plain on the southern side of the Masterton Fault. The basin is filled largely with alluvium and glacial outwash material derived from the Tararua Range from the Ruamahanga and Waipoua river systems, with input of finer-grained sediment from the eastern hills by the Whangaehu River.

- Lansdowne and Tirohanga hills (see Figure 2.2 for locations) representing folded outliers of older Quaternary and Tertiary sediments associated with major faults.

- The Waingawa fan system which has spread relatively recent alluvium across to the Waipoua River and through the Masterton area.

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

Three major cross-valley active faults branch eastwards from the Wairarapa Fault in the upper valley area and ‘compartmentalise’ the regional groundwater system in some areas. These are the active Mokonui, Masterton and Carterton faults. Each cuts across the rivers (and their terrace gravels) flowing into the northern end of the valley. The faults locally form flow barriers, principally as a result of tilting and deformation, as shown by the common emergence of springs along the fault traces and uplifted areas of folded older deposits (e.g. Lansdowne Hill).

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

A similar structural arrangement occurs at the north-eastern end of the **Masterton Fault**. This fault splays from the Wairarapa Fault near the southern end of the Fensham Reserve. It then traverses the Waiohine surface, crossing the Waingawa River and runs through Masterton. The fault raises Miocene-Pliocene mudstone to the surface at Lansdowne and in the Ruamahanga River and may curve northwards up the Ruamahanga River. Terrace gravels on the north-western side of the fault at Lansdowne are back-tilted to the northwest. The Ruamahanga and Waingawa rivers (and their terraces) are likely to be affected by the fault and impedance of groundwater movement probably occurs north of Masterton as indicated by spring emergence along the fault. The LIDAR image (shown in Figure 3.3) clearly shows the trace of the Masterton Fault.

6.3 Hydrostratigraphy of the Upper Valley catchment

The geologic framework as described above provides a basis for the characterisation of the groundwater environment and the identification of the hydrostratigraphic sequence. The late Quaternary unconsolidated sedimentary sequence (Table 6.1) comprises a large spectrum of sediment types which have been subjected to various degrees of sediment sorting, reworking, compaction and deformation by faulting and folding. The system is therefore highly heterogeneous in which laterally continuous litho-units rarely occur. All units are saturated below the water table and the coarser grained sand and gravel dominated units have enhanced transmissivities. These are the result of better sorting within these sediments. These constitute a complex series of aquiferous units within an overall leaky aquifer system.

A suite of distinctive hydrostratigraphic units has been identified from the available geological data and bore yield information. Four broad units (A-D) are listed in Table 6.2 together with their spatial distributions and general hydrogeological properties.

Table 6.2: Principal hydrostratigraphic units (HSU) of the Upper Valley catchment – summary of properties and occurrence

HSU ID	Unit	General hydrogeological properties	Occurrence
A	Alluvial fan gravels – Tararua-sourced (Q2 +)	Poor-moderate aquifers, generally low hydraulic conductivity, poorly sorted gravels with silts/clay and organic lenses. Improved sorting distally where higher bore yields are. Poor bore yields generally at depth in the upper fan areas.	Widespread
B	Q1 Holocene alluvium (Tararua-sourced)	Unconfined aquifer, generally high hydraulic conductivity, reworked gravels, strong connection with rivers.	Widespread, associated with main drainage systems
C	Q2+ Tararua-sourced basin fill alluvium	Heterogeneous mixture of predominantly Tararua-sourced alluvium, some persistent water-bearing horizons, low-permeability silt/clay lenses of limited lateral extent. Recognised as a single unit. Aquifers: medium-high hydraulic conductivity, gravel rich, discreet, thin (semi) confined units	Te Ore Ore basin
D	Q2+ Eastern hill sourced basin fill alluvium	Heterogeneous mixture of predominantly eastern hill -sourced alluvium, generally rich in fines but with occasional gravel horizons (possibly Tararua-sourced). Recognised as a single unit. Lower bulk hydraulic conductivity than Q2-8 Tararua basin fill.	Te Ore Ore basin

6.3.1 Unit A: Tararua-sourced alluvial fan gravels (Q2+)

The Waingawa, Waipoua, Ruamahanga and Kopuaranga rivers are associated with extensive aggradational fluvio-glacial fan systems. This unit is the most prevalent in the Upper Valley catchment occurring extensively above the Masterton Fault, but also present below it between the Waingawa and Ruamahanga rivers.

The fan deposits are poorly sorted matrix-rich gravels, silts and sands deposited mainly during cold (glacial) periods. They generally possess a low hydraulic conductivity therefore tend to be poor aquifers. The fans are mapped at the surface as Q2 age, but increase in age with depth where they probably transition into mQa and eQa age deposits. The sequence is very heterogeneous, behaving essentially as a single hydraulic unit; there are no laterally continuous lithological units.

As a consequence of its inherent properties, the fan sequence does not produce high bore yields and is utilised only for minor supply sources. Localised sediment reworking occasionally allows bores to produce higher yields

The fan sequence is traversed by the Masterton and Mokonui faults which have created a series of shallow sub-basins between the faults. The aquifer sequence has been uplifted on the upgradient side of the faults. This configuration causes groundwater to discharge in the vicinity of the faults.

6.3.2 Unit B: Q1 Holocene alluvium

Shallow re-worked gravels of Q1 age occur along the modern day channels and floodplains of all the major river systems in the Upper Valley catchment. The gravels lie on top of older less permeable fan sequences.

This hydrostratigraphic unit is generally less than 10 m thick and tends to be a high-yielding aquifer which is hydraulically connected to surface water. The shallow Q1 aquifer is extensively utilised particularly along the Waingawa and Ruamahanga rivers.

6.3.3 Unit C: Q2+ Tararua-sourced basin –fill alluvium

This unit is restricted to the northern and western side of the Te Ore Ore basin. These sediments tend to be better sorted (though of similar age) than Unit A and comprise Tararua-sourced alluvium to a depth of up to 70-80 m. Laterally continuous more permeable gravel-rich horizons are recognisable with intermittent horizons dominated by fine material. However, the sequence is relatively heterogeneous and lacks a strong stratification with a distinct aquifer-aquitard sequence (recognised in other parts of the Wairarapa Valley, e.g., Parkvale basin in the Middle Valley catchment and the much larger Lake basin in the Lower Valley catchment).

6.3.4 Unit D: Q2+ eastern hill-sourced basin fill alluvium

This unit is restricted to the southern side of the Te Ore Ore basin and was deposited at the same time as Unit C – the two alluvium units being sourced from geologically distinct catchments. Unit D is sourced from an eastern hill

Tertiary mudstone catchment and therefore tends to be richer in fines with occasional gravels (possibly Tararua-sourced).

6.4 Cross sections and three-dimensional geological model

Data from bore logs have been used to construct geological cross sections to develop a three-dimensional model as a basis for the conceptualisation of the Upper Valley groundwater environment. Figure 6.3 shows the locations of six cross sections and the locations of bores with reliable geological data upon which the sections have been based. Figures 6.4 to 6.9 contain cross sections 1 to 6 respectively.

The cross sections show the interpreted hydrostratigraphy and the way that the sequences have been affected by the major structures. Interpretation of the catchment geology and the cross sections has involved John Begg of GNS Science who was responsible for the recent 1:250,000 scale geological maps for the Wairarapa Valley. However, it should be appreciated that the geological environment is very complex and difficult to interpret unequivocally. In many of the cross 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 history, feasible unit thickness and depths, 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 contour maps are provided in Appendix 1).

The salient features and interpretation of the sections relevant to the hydrogeological environment are summarised in the following sections:

6.4.1 NW-SE sections 1, 2 and 3 (Major faults and Te Ore Ore basin)

The dominating features of the cross valley sections are the Mokonui and Masterton faults, and the Te Ore Ore basin structures. Vertical displacement and deformation along the Masterton and Mokonui faults is expressed at the ground surface by features such as Lansdowne Hill (Figure 2.2) which represents a fold associated with movement along the Masterton Fault. The hill contains older mQa sediments in the core of the fold (the morphology of this structure is shown particularly well by the LIDAR image in Figure 3.3).

Uplift and back-tilting of the alluvial fan gravels (Unit A) behind the faults is characteristic of these structures resulting in the creation of a series of shallow ‘basins’ between the faults. The aquifer sequences markedly thin towards the faults causing groundwater discharge along the fault lines and on downgradient scarps. The prolific spring discharges along the Masterton Fault are testament to this process.

The depth of the active groundwater system behind the Masterton and Mokonui faults has been estimated on the basis of bore depths and scant bore log information. It seems that the aquifer sequence does not exceed 40-50 m in these areas.

The Te Ore Ore basin is clearly shown on the cross sections as a syncline structure aligned with the Whangaehu Valley. It contains late Quaternary sandy and silty gravels (Unit C) with silt/clay horizons becoming more dominant to the east (Unit D). The basin is bounded to the north by Tertiary hill country and to the west by the Masterton Fault and the toe of the alluvial fans formed by the Waingawa and Waipoua rivers. The Ruamahanga River is roughly coincident with the latter boundary. Geophysical surveying (Butcher 1997) indicates that the basin has a very steep south-eastern side and is at least 100 m deep (to the top of underlying Tertiary mudstone and limestone). The basin is a locally important groundwater resource for irrigation supply and is exploited by numerous bores of between just a few metres to over 50 m depth.

The cross sections (particularly section 1, Figure 6.4) show a prevalence of bore screens in a 20-30 m depth range in the central part of the basin, but shallowing to 10-20 m on the western side. Few bores are screened deeper than about 40 m. The sections also indicate an increased proportion of fine-grained sediment on the eastern side of the basin which is attributed to an eastern hill sediment source (Tertiary mudstone dominated) from the Whangaehu River catchment. In effect, it appears that the central part of the Te Ore Ore basin represents a mergence zone of Tararua-sourced alluvium deposited by the Ruamahanga River and eastern hill-sourced alluvium deposited by the Whangaehu River. The boundary is a broad zone which has probably migrated across the basin over time. It is also clear from bore log data that although the sediment sequence is stratified, there are no laterally persistent layers or aquitards. The basin fill is therefore regarded to be a single heterogeneous hydrostratigraphic unit with aquifer conditions ranging from unconfined near the surface (particularly in south and west), through to leaky-confined at depth. This concept is supported by groundwater level and hydrochemistry data (Sections 7 and 8 respectively).

6.4.2 NW-SE sections 4 and 5 (Major faults and Waingawa fan)

The sloping northwest to southeast topography depicted in cross sections 4 and 5 (Figures 6.7 and 6.8) represents the Waingawa fan. Beneath the aggradational fan surface, the sections show the same structural characteristics as the other NW-SE oriented sections – the deformation associated with the Masterton and Mokonui faults. The sections also show a series of interpreted shallow sub-basins between the faults, with the aquifer sequence being uplifted to within 10 m or so of the land surface on the faults. Below the Masterton Fault, cross section 5 shows the diminishing influence of the Te Ore Ore basin structure which is estimated to be less than 50 m in depth on this section line. Cross section 5 in particular illustrates the paucity of deep bores with reliable stratigraphic information. The process of defining the base of the groundwater system is described above (Section 6.4) using isopach and contour maps in conjunction with the cross sections. Appendix 1 contains a contour map for the interpreted base of the groundwater basin (the mQa surface).

6.4.3 SW-NE section 6 (Te Ore Ore basin and Waingawa Fan)

Cross section 6 (Figure 6.9) shows the southwest-northeast morphology of the Te Ore Ore basin and how it merges with the Waingawa fan system. The basin rises onto the fan conceptually although lithologically there is little distinction between the Ruamahanga-derived alluvium and the Waingawa-derived alluvium. Within the Te Ore Ore basin, there is a distinction between the more silt and clay dominated alluvium associated with the eastern hill catchments, and the more gravel and sand-rich Tararua alluvium. Highly permeable shallow aquifers within the latter are shown by the dominance of bores with shallow screens (<10 m). In contrast, bores in the eastern hills alluvium are contently about 30 m depth which could represent a horizon of Tararua alluvium that spread extensively over the plains.

7. Hydrogeology

7.1 Temporal and spatial groundwater level patterns

7.1.1 Upper Valley groundwater level monitoring network

Greater Wellington operates a network of 16 automatic and manual groundwater level monitoring sites in the Upper Valley catchment. The locations of the monitoring sites are shown in Figure 7.1. Table 7.1 provides the details for each monitoring bore. An additional monitoring bore was constructed as part of the project field programme (refer to Section 5).

Table 7.1: Upper Valley groundwater level monitoring sites monitored by Greater Wellington

Monitoring well no.	Monitoring record	Depth (m)	Manual (M) or Auto (A)	Dedicated monitoring (D), Pumping Domestic (PD) or Pumping Irrigation (PI)	Screen type	Depth to WL (m)	7-day mean observed data mRL	
							Min	Max
S26/0033	30/9/1983 to current	12	A	D	Open hole	-5.53	138.55	141.13
S26/0031	17/1/1983 to 20/12/2000	5	M	PD	Open hole	-4.9	131.6	134.1
S26/0032	5/10/1979 to 22/7/1997	6(Dug)	M	PD	Concrete liner	-5.20	134.98	136.56
S26/0030	17/1/1983 to current	38	M	D	Stainless steel	-7.85	129.28	131.93
T26/0003	2/3/1997 to current	6		PD	Open hole	-1.50	173.60	175.2
T26/0170	24/11/1986 to 13/8/2002	15		PD	?	-5.40	144.08	146.59
T26/0239	26/8/1997 to current	6(Dug)		PD	No screen	-3.19	138.46	140.90
T26/0208	12/1/1984 to current	17		D	Open hole	-6.13	127.41	131.58
T26/0429	10/2/1986 to current	10	M	D	No screen	-4.40	114.45	116.67
T26/0535	2/10/1997 to 4/9/2000	6	A	D	?	-3.82	93.94	96.14
T26/0494	28/11/1981 to current	23	A	D	No screen	-8.76	90.31	99.23
T26/0501	16/7/1983 to current	5	A	D	?	-3.90	96.26	99.64
T26/0243	3/10/1988 to current	47	M	D	Stainless steel	-9.16	94.07	98.89
T26/0232	19/9/1983 to current	31	M	PI	Stainless steel	-6.67	96.18	99.30
T26/0814	6/8/2008 to current	10	A	D	Stainless steel	-2.61	91.82	92.84
T26/0366	24/6/2002 to current	5	M	PI	No screen	-1.8	95.94	97.26

7.1.2 Regional groundwater flow pattern

Concurrent groundwater level measurements taken over the past two decades from a large number of monitoring bores enables a spatial characterisation of regional groundwater flows in the Upper Valley catchment. Figures 7.2 and 7.3 show the piezometric surfaces for March 2007 and September 2008 respectively.

The general regional flow pattern within the catchment reflects the regional topography. Groundwater flows south-easterly off the fan deposits towards the Te Ore Ore plain and lower reaches of the Ruamahanga River.

The Waipoua and Waingawa rivers locally exert a strong control on the flow pattern, each in a markedly different way. The shape of the contours indicates that the Waipoua River predominantly receives inflow from groundwater above the Masterton Fault (it is a ‘gaining’ river), whereas the Waingawa River seems to discharge flow to groundwater (it is a ‘losing’ river) for much of its length. Flows are deflected around the low-permeability Lansdowne and Tirohanga hills (see Figure 2.2 for locations).

The groundwater flow gradients on the fans above the Te Ore Ore plain are consistently about 0.008. Levels drop from over 150 m amsl at the top of the fans to about 95 m amsl in Te Ore Ore basin.

Beneath the Te Ore Ore plain the flow gradient abruptly flattens to 0.0005 and the groundwater flow converges towards the Ruamahanga River and spring-fed streams such as the Poterau Stream.

7.1.3 Vertical flow gradients

There are two clusters of monitoring bores in the Upper Valley catchment where the vertical head characteristics can be studied. Figures 7.4A and 7.4B show hydrographs for the Te Ore Ore basin and the Waingawa fan above the Masterton Fault respectively. Both areas show downwards head gradients suggesting they are located in recharge zones to the deeper groundwater environment.

Figure 7.4A shows three hydrographs relating to different aquifer depths on the northern edge of the Te Ore Ore basin for the one year period September 2007 to September 2008. Interpretation of these plots together must take into account the downgradient position of shallow monitoring bore T26/0501 (5 m). This, when normalised to the same location as the other bores, has a head about 2 m higher (see Figure 7.3 for bore locations and piezometric contours upon which the adjustment has been estimated). When this adjustment is taken into consideration there is a clear downwards head gradient in this area of the Te Ore Ore basin in the order of 4 m over a depth of about 40 m (a vertical gradient of 0.1). The vertical gradient may be accentuated during summer by groundwater abstractions from the deeper aquifers.

Figure 7.4B shows hydrographs for monitoring bores S26/0033 (12 m deep) and S26/0030 (38 m deep), located close to the Waingawa River north of the Masterton Fault (see Figure 7.1 for locations). Because bore S26/0030 lies about 1 km downgradient of S26/0033 it should be 'normalised' by about 6 m (using Figures 7.2 and 7.3). Comparison of the normalised plots shows a strong downwards hydraulic gradient of about 4 m over a vertical distance of about 25 m (a gradient of 0.15).

7.1.4 Temporal groundwater level characteristics

(a) Te Ore Ore basin

Figure 7.5 displays hydrographs for monitoring bores in the Te Ore Ore basin. There are three established automatic level recorders in the basin: T26/0501 ('Oliver – shallow', 5.1 m deep), T26/0494 ('Oliver – deep', 23 m deep) and T26/0535 ('Percy', 5.8 m deep). These can be used to provide information on the groundwater level and recharge dynamics of the basin's aquifers. There are also two other manually-monitored bores, T26/0243 ('MDC' 47.5 m), and T26/0232 ('WCB', 30.6 m) in the basin. The locations of these monitoring bores are shown in Figure 7.1.

Water levels in the shallow (unconfined) aquifer are characterised by monitoring bores T26/0501, T26/0535 and the newly constructed T26/0814 ('Lucas', 10.3 m). Figure 7.5 shows that the levels in the shallow aquifer fluctuate by 2-3 m annually with the longest record (T26/0501) showing a slight long-term recession which may be attributable to bed level changes in the nearby Ruamahanga River.

Figure 7.6 displays detailed average daily water level data for bore T26/0501 over winter 2007 (June-Dec) and summer 2008 (Jan-June). Average daily flow measured in the Ruamahanga River (measured at the Wardells Bridge gauging site) and daily rainfall measured at Te Ore Ore are also shown on the plots. The data show that the shallow aquifer in this area (about 500 m from the river) exhibits a correlation river stage and flow conditions but has little relationship with rainfall. Water levels in the monitoring bore respond rapidly to increases in river flow (time lag = c. 1 day), suggesting it is a very dynamic shallow aquifer system connected to the surface water environment. The predominant recharge mechanism to this aquifer appears to be river bed leakage.

Data relating to the water level characteristics of deeper aquifer levels in the Te Ore Ore basin are provided by monitoring bores T26/0494, T26/0232 and T26/0243. Figure 7.5 shows the deeper aquifer levels have a similar seasonal fluctuation to the shallow aquifer of about 2-3 m. From early 2002, accentuated seasonal level minima are evident in all three deeper monitoring bores, but particularly in bore T26/0494 on the central Te Ore Ore plain where seasonal level drops of 7-8 m have been recorded since about 2004. This is related to rapidly increasing attraction for irrigation abstraction on the Te Ore Ore plain over the past 10 years (see Section 7.4).

Figure 7.7 shows the winter 2007 and summer 2008 water level plots for monitoring bore T26/0494 in the centre of the Te Ore Ore plain mid-way between the Ruamahanga and Whangaehu rivers. Figure 7.7 shows the Ruamahanga River flow record (measured at Wardells Bridge) and Figure 7.8 shows the Whangaehu River flow record (measured at the 'Waihi' gauge). Rainfall at Te Ore Ore is also shown on Figure 7.7. Any relationship between river flow, rainfall and groundwater level during the summer is heavily masked by irrigation pumping in this area. The prominent rebound in groundwater level at the start of April 2008 represents the cessation of seasonal pumping which appears to have depressed groundwater levels by 4-5 m by the end of the summer (compared to November 2007 levels). During this time flows in the nearby Poterau Stream virtually cease. There does appear to be a weak correlation between groundwater level and river conditions in the winter record; this is probably due to the influence of the Ruamahanga River which is expected to exert a widespread control on the Te Ore Ore basin aquifers. There is no recognisable correlation between groundwater level and rainfall in this area.

(b) Waingawa fan between Waingawa and Waipoua/ Ruamahanga rivers

There are six monitoring bores in this area (Figure 7.1), five relatively close to the Waingawa River, and one in the Masterton area. Only one of the bores is deep (S26/0030, 38 m), with the remaining bores being shallower than 12 m. Figure 7.9A and 7.9B shows the full groundwater monitoring records for all six bores. All the bores show a seasonal water level fluctuation in the order of 1 m and levels also appear to be controlled by the Waingawa River. Bore S26/0033 (12 m deep) shows a long-term level decline which is probably attributable to changes in the bed elevation of the Waingawa River located about 500 m away. The trend does not seem to be associated with long-term rainfall recharge trends (as shown by the cusum plot on Figure 7.9A for monthly average rainfall at the Bagshot rainfall site; see Section 2.3).

Figure 7.10 displays average daily water level data for bore S26/0033 during winter 2007 (Jun-Dec) and summer 2008 (Jan-Jun). Average daily flow measured in the Waingawa River (at Kaituna) and calculated weekly rainfall recharge (from a soil moisture balance model described in Section 7.2.2) are also shown. It is evident that the shallow aquifer at this site is intimately associated with the river and fluctuations in river flow are mirrored by fluctuations in groundwater levels. Any influence of rainfall recharge is dominated by the river signature at this site. The remaining monitoring bores in this area (all of which are manually read) behave in a similar manner to bore S26/0033 (as shown in Figure 7.9A) given their locations in the same hydrostratigraphic unit (Q2 fan gravels).

(c) Upper Waipoua and Ruamahanga fans

There are four shallow (<18 m) monitoring bores in this area, three are manually read (T26/0003, T26/0170 and T26/0208) and one has an automatic recorder (T26/0239). Bore T26/0208 (17 m deep) lies in the centre of the Waipoua fan on the Q2 last glacial surface and exhibits a strong seasonal variation of 2-4 m which is probably related to rainfall infiltration. The remaining bores lie close to either the Waipoua or Ruamahanga rivers and exhibit a somewhat attenuated correlation with river flow as demonstrated by the data presented in Figure 7.11 for bore T26/0239 (6 m deep). The winter and summer hydrographs show a muted response to Ruamahanga River flow which could indicate a poor degree of connection between the shallow aquifer and the river, or it could be an artefact of the design and construction of the monitoring site which was dug rather than drilled and therefore has a larger diameter than usual (the large diameter may mute fluctuations in groundwater level). Rainfall recharge (calculated using the soil moisture balance model) does not appear to have a significant influence on aquifer levels, or is masked by the river signature.

7.2 Rainfall recharge

7.2.1 Occurrence and spatial variability

Rainfall infiltration is an important groundwater recharge source in the Upper Valley catchment in addition to river bed leakage. The main influence on the spatial variability of recharge is the steep rainfall gradient across the valley from the Tararua Range to the eastern hills, as shown by the annual average rainfall map (Figure 7.12). The highest annual rainfall of 1,200-1,300 mm occurs close to the range, reducing to 600-700 mm on the eastern side of the valley in the Te Ore Ore area. Because of the high rainfall gradient, rainfall recharge is expected to demonstrate large spatial variability across the catchment.

Soil type, unsaturated zone thickness and the nature of the unsaturated zone also control the spatial patterns and levels of rainfall recharge. Well-drained soils with a low field capacity will generally be more conducive to rainfall infiltration. The soils map (Figure 2.4) shows the distribution of broad soil categories with brown soils that are well-drained dominating the fan surfaces where rainfall infiltration will be expected to be the dominant recharge mechanism. Figure 7.13 shows that field capacity varies considerably across the catchment since the soil groups comprise a number of different sub-groups (see Appendix 2). The variation in soil moisture holding capacity also has a significant control on the infiltration of rainfall to the water table.

Depth to water table with reference to the nature of the unsaturated zone is also a good indicator of rainfall recharge potential. Figure 7.14 contains a contour map which depicts the depth to groundwater level (water table) in the Upper Valley catchment. This information, in conjunction with knowledge of the nature of the unsaturated zone in terms of its water transmitting capacity, has been used to make an assessment of where rainfall recharge processes are important and to delineate groundwater discharge area. Areas where the water table lies at depth (Figure 7.14) and the unsaturated zone has a reasonable to good hydraulic conductivity are more likely to receive rainfall recharge. These areas are:

- The fan areas between the main river north of the Masterton Fault;
- Lansdowne and Tirohanga hills; and
- The eastern side of the Te Ore Ore basin.

Areas where the water table is very shallow, or at the ground surface, occur over the Te Ore Ore plain and Masterton areas indicating groundwater discharge processes. Figure 7.4 also shows very shallow depths to water table along the main rivers (note Figure 7.4 may not be accurate in the northern area outside the LIDAR coverage area).

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 Upper 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 evapotranspiration 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 patterns

Figure 7.15 shows the modelled annual average recharge for the Upper Valley catchment using the distributed soil moisture balance model. The recharge pattern is strongly influenced by the rainfall gradient and soil properties (Figure 7.12 and 7.13). The highest recharge of 800-900 mm occurs in small areas along the northern edge over the upper fan areas on the most permeable soils close to the Waingawa and Ruamahanga rivers (see Figure 2.4). The upper fan areas remote from the rivers experience an average of 400-600 mm of recharge a year, whilst around Masterton and on the Te Ore Ore plain, the average annual recharge is 100-300 mm.

Figure 7.16 (derived from Figures 7.12 and 7.15) shows recharge as a percentage of average annual rainfall. Over the upper fan areas (north of Masterton), about 30-40% of rainfall infiltrates to become groundwater recharge. Where more permeable soils occur, such as along the recent gravel floodplains of the Ruamahanga and Waingawa rivers, recharge can reach 60-70% of rainfall. Over the drier central and southern area, less than 25% of rainfall becomes recharge due to higher proportional losses to evapotranspiration.

Figures 7.17 and 7.18 are representative outputs from the distributed recharge model for late June 2006 and June 2007 respectively. These two periods represent particularly wet and dry winters respectively. Figure 7.17 shows modelled recharge during a particularly wet winter which resulted in widespread recharge across the catchment of about 10-15 mm/day, with increased amounts along the Ruamahanga and Waingawa rivers of about 18-20 mm. Very low recharge is modelled on areas such as Lansdowne Hill where low-permeability soils occur. During the subsequent, much drier 2007 winter (Figure 7.18) the area experienced a different pattern with virtually no recharge over most of the fan area and the Te Ore Ore plain and less than

5 mm/day in the northern areas where more permeable soils occur (Figure 7.18).

7.2.4 Simulated recharge trends 1992–2008

Recharge trends for the modelled period (1992–2008) can be characterised using the recharge model outputs. Figures 7.19A and 7.19B show the calculated daily recharge (as a weekly mean) and annual total recharge for the entire Upper Valley catchment for the period 1992 to 2008 respectively. The average annual recharge for the 16 year period is 48 x 10^6 m^3 and the average daily recharge is 130,000 m^3.

The large inter-seasonal recharge variability reflects the long-term rainfall trend with very dry years occurring in 1993, 2001 and 2007. Particularly wet years – when total catchment recharge exceeded the annual average 48x10^6 m^3/year – occurred in 1992, 1995, 1996, 2000, 2004, 2006 and 2008.

To provide an appreciation of the spatial variability of recharge across the catchment, Figure 7.20 shows the annual recharge over the past 16 years for three 500 m^2 recharge cells. The soil properties for the cells are listed in Table 7.2.

Table 7.2: Soil properties for representative cells in the distributed recharge model

Cell ID	Location	FC (mm)	Wilt (mm)	SCS	Fract
51344	North Ruamahanga fan	110	40	81	0.7
51877	Masterton–Waingawa fan	330	120	87	0.7
52924	East Te Ore Ore	65	25	61	0.7

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

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

Cell 51344 in the upper Ruamahanga fan lies in a higher rainfall zone and has a relatively free-draining soil with low field capacity. These conditions are reflected by the significantly higher recharge amounts compared with the other two cells. By contrast, cell 51877 has lower rainfall but a significantly more retentive soil which has resulted in the simulation of a lower annual recharge than the low-rainfall Te Ore Ore site (cell 52924).

The long-term variability in rainfall recharge does not tend to produce noticeable effects on groundwater levels in areas where shallow aquifers are connected to the surface water environment. Fluxes between surface water and groundwater tend to mute any long-term rainfall recharge trends in such areas.

7.2.5 Recharge model verification

The accuracy of the Rushton et al. (2006) soil moisture balance model was verified by comparing the calculated recharge with lysimeter data from the Canterbury plains (data provided by Environment Canterbury). The SOILMOD and the Soil Water Balance Model outlined in White et al. (2003) were also tested for comparison. Details of the verification process and results are provided in Appendix 2.

The verification exercise showed that the Rushton model provides the most accurate estimation of weekly rainfall recharge of all the three soil moisture balance models 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.

7.3 Groundwater–surface water interaction

7.3.1 Background

Large components of the groundwater balance for the Upper Valley catchment are associated with fluxes between shallow groundwater and surface water. Hydrographs for shallow bores in the vicinity of rivers exemplify the connection between these environments (see section 7.1.4). Natural groundwater discharges occur as river base flow, spring flow and diffuse seepage into wetlands and lakes. The major fault systems, particularly the Masterton Fault, also appear to play an important role in impeding the flow of groundwater and forcing discharge to springs and into rivers close to their surface expressions.

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

The degree of the interaction between groundwater and surface water is dependent upon the head gradient between the aquifer and the river and upon the degree of connectivity between both water bodies. The connectivity is a function of the permeability of the stream/river bed and aquifer, as well as the size and geometry of the contact area. Geological structure resulting in the impedance of groundwater flow (either through deformation of the aquifer sequence or the creation of flow barriers) also exerts a strong control on vertical flow gradients in the aquifer. It is important to recognise that the flow gradients between a river or stream and the adjacent aquifer can vary seasonally, or even reverse. For example, a losing river in summer may become a gaining river in winter due to seasonal changes in groundwater level.

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

7.3.2 Connected surface water environments

The three principal river channel systems in the Upper Valley catchment – the Ruamahanga, Waipoua and Waingawa rivers – exhibit complex patterns of flow gain and loss down their profiles. The Whangaehu and Kopuaranga rivers may also interact with groundwater although very little gauging information is available with which to characterise these systems.

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

Figure 7.21 summarises the available concurrent gauging data for the Waingawa, Waipoua and Ruamahanga rivers in the Upper Valley catchment. The locations of the gauging sites are shown in Figure 7.22. The plots take into account inflows (from tributaries and other discharges) and outflows (from major takes such as water races and diversions) which were measured during each survey. The information present therefore represents flow losses or gains with respect to the groundwater environment.

Figure 7.22 summarises the gauging information in the form of a map showing general patterns of losses and gains for the summer period. It should be appreciated that the patterns may change significantly during winter months. The patterns shown in Figure 7.22 are clearly closely associated with the intersections of major faults with the river channels. It is also apparent that each river has a slightly different relationship to the fault structures.

The characteristics of the three rivers are described separately below.

(a) Waingawa River

Three concurrent gauging runs made during February 2006, 2007 and 2008 (Figure 7.21A) indicate that the Waingawa River characteristically loses flow to groundwater over much of its length. However, the gaugings indicate that the river switches between gaining and losing upstream of the old intake weir (see Figure 7.22 for location).

The 2006 concurrent data indicate a total flow loss in the order of 800 L/s between the Wairarapa Fault and the Waingawa River's confluence with the Ruamahanga River. However, the 2007 gauging indicates a smaller loss of about 500 L/s, whilst the 2008 data indicates a relatively small change in flow.

It seems apparent that this river loses flow to groundwater consistently but the rate of loss is highly dependent upon river stage and groundwater level conditions. It must also be borne in mind that the Waingawa River is difficult to gauge accurately due to its wide, unstable gravel bed – gauging errors could well exceed 10%.

The Mokonui and Masterton faults do not appear to affect flow, although the 2007 and 2008 data indicate that the Waingawa River seems to gain slightly upstream of the Wairarapa Fault.

(b) Waipoua River

The significantly smaller Waipoua River system has a less complicated interaction with groundwater than that of the Ruamahanga River. Figure 7.21B shows a gradual flow loss to groundwater between the Wairarapa Fault and just upstream of the Masterton Fault where, in some years, the river can be dry. The magnitude of loss over this reach is about 150-300 L/s.

There is a distinct gain in flow from groundwater in the order of 100-200 L/s upstream of the Masterton Fault, followed by a flow loss in the reach down to the Ruamahanga River confluence of about the same magnitude. This gain-loss pattern across the Masterton Fault mirrors the effect the Mokonui Fault has on the Ruamahanga River. It is also consistent with the conceptual hydrogeological model of aquifer thinning upstream of the fault. Such thinning forces groundwater discharge and the rapid thickening of the younger sediment sequence on the downgradient side of the fault resulting in flow losses to the aquifer.

(c) Ruamahanga River

Figure 7.21C contains the results of three concurrent gauging surveys on the Ruamahanga River in February 2006, March 2006 and February 2007. The data show a complex and consistent pattern of flow losses and gains around the major fault systems. Flows are fairly constant above the Mokonui Fault, with a possible small gain before the fault of 3-400 L/s (March 2006). All three gauging runs indicate that there is a large loss of flow to groundwater (in the order of 1,000 L/s) immediately downstream of the fault. The flow pattern is consistent with the conceptual hydrogeological model which proposes a large uplift on the upstream side of the fault forcing groundwater discharge, and sudden thickening of the aquifer sequence on the downstream side creating conducive recharge conditions.

From the Mokonui Fault there is a gradual increase in flow due to groundwater discharge. In February 2006 the gain between the Mokonui Fault and the Waingawa River confluence was measured at about 1,200 L/s. The other gaugings show a similar magnitude of gain. The Masterton Fault does not seem to impact the gaining pattern.

7.4 Groundwater abstraction

7.4.1 Abstraction trends and allocation status in 2008

Groundwater abstraction in the Upper Valley catchment has increased significantly over the past 20 years, and more than doubled over the past 10 years. Much of this growth is driven primarily by the dairy industry for seasonal pasture irrigation (generally November to April), mostly on the Te Ore Ore plain.

Figure 7.23 shows the trend in groundwater allocation in the Upper Valley catchment over the past 16 years (1992-2008). Based on 2008 data there are 66 consented groundwater takes in the Upper Valley totalling 45,693 m^3/day and 8.25 x 10^6 m^3/year. In 1992 allocation was about 12,000 m^3/day and gradually rose to about 25,000 m^3/day by 2003. Then in 2003 there was a large jump in allocated volume from about 25,000 to 35,000 m^3/day, rising to almost 46,000 m^3/day in 2008.

To assist in the spatial analysis of abstraction the locations of consented groundwater abstractions are shown in Figure 7.24. Consented pumping volumes are summarised in Table 7.3, grouped into five abstraction sub-regions.

Table 7.3: Groundwater allocation in the Upper Valley catchment based on 2008 records

Area	Location	No. consented groundwater takes	Consented volume (m^3/day)	Consented volume (m^3/year)
1	Waingawa fan above Masterton Fault	9	1,423	339,566
2	Waingawa fan below Masterton Fault	6	1,539	285,513
3	Te Ore Ore plain	35	29,544	4,821,875
4	Waipoua fan	7	3,065	645,586
5	Upper Ruamahanga valley above Masterton Fault ('Rathkeale')	9	10,122	2,152,880
	Total	*66*	*45,693*	*8,245,420*

Table 7.3 shows that about 85% of the total abstraction occurs on the Te Ore Ore plain (Area 3) and from a small cluster of high-yielding bores near the Ruamahanga River upstream of Lansdowne Hill (the 'Rathkeale' area, Area 5). Abstraction on the Te Ore Ore plain accounts for about 65% of the total annual allocation for the catchment.

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 7.25 provides a broad evaluation for the whole of the Wairarapa Valley regarding the proportion of the consented annual abstraction volume which was used over the period 2002/03 to 2008. Reliable annual meter readings were compared against the maximum authorised take; the resulting plot illustrates that very few groundwater takes exceed 50% of their annual allocation and that most water users take 10-30% of their allocation.

Figure 7.26 shows a cumulative frequency plot for the same data. Seventy-five per cent of meter readings show that the annual use was 35% or less of the consented volume, with only 10% of readings showing an actual annual use greater than 50% of the allocated volume.

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

The metering exercise demonstrated that resource consent holders tend to abstract groundwater at a rate of up to about 60-70% of the consented daily rate when necessary. However, on an annual basis the usage is considerably less than the allocated annual volumes. Therefore, it is clear that the methodology used to calculate annual allocations needs to be reviewed.

7.4.3 Abstraction modelling

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

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

A methodology based upon the utilisation of soil moisture balance modelling and annual metering data (where available) was developed to model historic groundwater abstractions on a weekly basis for the period 1992 to 2008 (the numerical model calibration period). A variable soil moisture deficit linked ‘adjustment factor’ was also applied to consented daily maximum volumes to account for the observed disparity between maximum consented and actual abstraction quantities.

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

2007/08 were used to help identify the trigger level. Appendix 2 contains the detailed methodology developed for this study of abstraction simulation.

Alongside the consented daily volumes, Figure 7.23 also shows the results of the modelling as a combined daily volumetric basis for the entire Upper Valley catchment. Abstraction modelling indicates that the actual daily quantity of water used is 50-60% of the total daily allocated volume. For instance, in the 2007/08 irrigation season, the estimated total quantity of groundwater used in the Upper Valley catchment was calculated to be 27,000 m^3/day – about 60% of the allocated daily volume.

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 Upper Valley catchment was estimated from the location of known bores, associated land use (using the 'Agribase' database) and the assumed abstraction rates in Table 7.4.

Table 7.4: Assumed daily water demand in relation to land use applied in the estimation of groundwater taken in the Upper Valley catchment as a permitted activity

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

The distribution of permitted groundwater takes is shown in Figure 7.27 plotted against consented takes. A total of 595 permitted takes abstract an estimated volume of 2,400 m^3/day, or approximately 5% of consented groundwater abstraction volume.

Cumulatively, the volume of permitted groundwater takes is not significant in relation to consented takes, although there may be localised effects from dense clusters of permitted takes within lower permeability sediments (Figure 7.27). Permitted groundwater takes were not considered in the abstraction model.

7.5 Aquifer hydraulic properties

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

Figure 7.28 is a map of the spatial distribution of the observed transmissivity data. The map shows a pattern that reflects the distribution of the principal hydrostratigraphic units. Particularly apparent are the high transmissivities within the Te Ore Ore basin and close to the major river courses within shallow Q1 (Holocene) alluvium. The main Waingawa, Waipoua and Ruamahanga fan areas (Q2 and older) have consistently low hydraulic conductivity characteristics.

Table 7.5 contains a summary of the Type 1 aquifer test data – spatially differentiated into the groundwater areas described in Section 7.1.

Table 7.5: Analysis of transmissivity and storage values derived from 'Type 1' pumping tests for the Upper Valley catchment

Hydrostratigraphic unit	No of Type tests	Mean T	Geomean T	Std Dev T	Mean S	Geomean S	Mean St
1 – Waingawa Fan alluvium	10	920	600	740	-	-	0.05-0.1
1 – Upper Waipoua and Ruamahanga fans	9	421	145	960	-	-	nd
1 – Kopuaranga Fan	3**	100	50	130	nd	nd	nd
2 - Q1 Alluvium	19	2,020	1,400	1,400	0.07	0.04	0.07
3 - Te Ore Ore basin - West	15	3,800* 1,300	3,200* 1,100	2,000* 700	- 6 E-4	- 3 E-4	nd -
4 – Te Ore Ore basin - East	5	1,100	930	600	6 E-4	5 E-4	

* unconfined aquifer, ** Type 2 tests only available, Transmissivity in m^2/day, nd – no data

The geometric mean, unlike the arithmetic mean, tends to dampen the effects of data-sets with a high standard deviation which would tend to skew the arithmetic mean. Although the geometric mean values in Table 7.5 are regarded to be representative of the test data, they are not necessarily representative of the 'bulk' material properties for the hydrostratigraphic units. This is because most of the tests are performed on successful, higher-yielding bores for resource consenting purposes resulting in an inherent bias in the data-set towards areas and horizons more favourable for groundwater development.

Highest transmissivities occur in the Te Ore Ore basin shallow unconfined aquifers (probably Q1 age) on the western side of the valley and around the Ruamahanga River. The geometric mean transmissivity for these deposits is about 3,200m^2/day (equivalent to a hydraulic conductivity of around 200-300 m/day if an aquifer thickness of 5-10 m is assumed). Q1 age alluvium outside the Te Ore Ore plain has a similar transmissivity of around 1,400-2,000 m^2/day and a specific yield of about 4%.

Deeper semi-confined or confined aquifers in the Te Ore Ore basin (west and east) exhibit a lower transmissivity than the shallow aquifer of about 1,000 m^2/day, and a confined storage coefficient of 5×10^{-4}.

There is a distinction between the transmissivity of the Waingawa fan and the upper Waipoua/Ruamahanga fans. The Waingawa fan has an average transmissivity representative of shallow aquifers (<15 m deep) of about 600 m^2/day and a specific yield of 5–10%. In contrast, the Waipoua and Ruamahanga fans exhibit a significantly lower transmissivity of about 150 m^2/day. This pattern can be explained by the relatively recent migration of the Waingawa River across the fan towards the Waipoua River and southwards through the Masterton springs area (shown clearly in the LIDAR image in Figure 3.3). This migration has probably resulted in the reworking of fan gravels over a wider area.

Table 7.6 provides representative hydraulic properties of the hydro-stratigraphic units based upon a synthesis of groundwater pump test data.

Table 7.6: Representative transmissivity, hydraulic conductivity and storage properties for Upper Valley catchment hydrostratigraphic units

Unit	Representative transmissivity (m^2/day)	Representative hydraulic conductivity (m/d)	Storage (S or St)
Alluvial fan gravels – Tararua-sourced (Q2 +)	Waingawa fan: 600 Waipoua/Ruamahanga fan: 150 Kopuaranga fan: 50	60-100 15-20 5-10	St: 5-10% St: 3-5% St: 3-5%
Q1 Holocene alluvium (Tararua-sourced) unconfined aquifers	Te Ore Ore basin: 2,000 Main rivers: 1,500 – 2,000	200-300 150-200	St: 0.1 St: 7-10%
Q2+ Tararua-sourced basin fill alluvium	Te Ore Ore basin: 1,200	100-150	S: 5 E-4
Q2+ Eastern hill-sourced basin fill alluvium	Te Ore Ore basin: 1,000	100	S: 5 E-4

8. Hydrochemistry

8.1 Introduction

Water chemistry data for the Upper 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 Upper Valley catchment. It also summarises the results of groundwater age dating and isotope testing. The analysis builds on previous work presented by Morgenstern (2005) as part of Phase 1 of the Wairarapa Valley groundwater resource investigation (documented by Jones and Gyopari (2006)).

8.2 Multivariate statistical analysis

Using both groundwater and surface water chemistry data, multivariate statistical analysis 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[4]), 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 Upper 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 bores 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.

Most of the surface water sites, as well as 40% of groundwater sites, fall within Category A. These are oxygen-rich dilute waters with Ca and HCO_3 as the dominant cations typical of river waters and groundwaters recharged recently from rivers or rainfall in areas of low intensity land use. 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.

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[4] 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.

About 60% of the groundwater bores fall into Category B chemistry which is dominated by Na and HCO_3. This is a more evolved (or reduced) water in which the concentrations of most ions are considerably higher than for Category A. The chemistry of Category B waters therefore suggests 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 the concentrations of 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 and are probably influenced by the different catchment geology (Miocene-Pliocene marine deposits) compared to 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 bores of shallow to moderate depth (Q4-Q6?). Cluster B3 waters tend to have higher concentrations of most major ions and lower concentrations of SO_4 compared to B1 and B2 waters. B3 groundwaters are therefore slightly older and more chemically evolved than B1 and B2 sites and are characteristic of relatively deep bores. Cluster B4 sites have the highest conductivity and concentrations of major ions indicating 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 only occur in the Lower Valley catchment lake basin at depth.

8.3 Results of HCA analysis

Figure 8.1 shows the results of the Upper Valley groundwaters HCA analysis. The following observations can be made from the analysis:

- Rivers that drain the Tararua Range on the western side of the valley (e.g. Waingawa River, Waipoua River upstream of Masterton and Ruamahanga River upstream of the Kopuaranga River 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 Range are assigned to Cluster Al. The implication is that the rocks of the Tararua Range 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 and Kopuaranga rivers) 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 "Tararua-like" hydrochemistry (Cluster Al) is found in shallow wells in Q1 gravels near the losing reaches of rivers that drain the Tararua Range, such as the Waingawa, Waipoua and Ruamahanga rivers. 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 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 inter-mixed group of Al-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 River is Tararua-sourced and assigned to Cluster Al), 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 bores 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 Al- 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 catchment, 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 basin is chemically similar to the rivers that drain the eastern hills (Cluster B1). This may indicate that groundwater in the Te Ore Ore 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 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 basin.

8.4 Groundwater residence time

Groundwater residence times and flow pathways in the Upper Valley catchment were examined using tritium, CFC, SF6 and C14 analysis. A detailed description of this work is discussed in Morgenstern (2006) but, since this study, supplementary data have contributed to a revised compilation of mean residence times as shown in Figure 8.2.

8.4.1 Waingawa and Waipoua fans

Four sites were sampled for age-determination on the Waingawa fan north of the Masterton Fault. Shallow bores indicate a groundwater age of about one year, and one deeper bore (47 m) provided an age of 40 years (Figure 8.2). This is consistent with the HCA analysis for this area which suggested an inter-mixed river-rainfall recharge characteristic for this area (A1 and A2), with oxygen-poor older waters at depth (B2).

8.4.2 Te Ore Ore basin

Age dates for the Te Ore Ore basin fall in the 30-40 year range for all bore depths (15-54 m), apart from one shallow bore which provides a date of just 2 years – possibly due to a connection to the Poterau Stream. The predominant age is consistent with the more evolved B1 HCA classification for groundwaters in the basin. That there is no age stratification in the basin is consistent with the hydrogeological assessment which shows that the fill sequence is a single leaky aquifer system.

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.*

The conceptual hydrogeological model was tailored to ensure it can adequately address the key issues faced in the management of the groundwater resources in the Upper Valley catchment. Specifically these are:

- The impacts of groundwater abstraction on the surface water environment;
- Excessive aquifer drawdowns in the Te Ore Ore basin; and
- Declining shallow groundwater levels and impacts on aquifer discharge fluxes (to springs and wetlands) in the Te Ore Ore and Masterton areas.

Figures 6.4 to 6.9 are a series of cross sections which describe the conceptual model developed for the Upper Valley catchment. The various boundaries, physical geological framework, hydrological features and water balance components are discussed separately below.

9.2 Groundwater system boundaries

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

North-western: this boundary coincides with the Wairarapa Fault and represents the emplacement of a younger Quaternary fan sequence against very low permeability greywacke bedrock along a vertical plane.

North-eastern and south-eastern: this boundary coincides with the geological boundary between younger Quaternary age alluvium and the eastern hill country of predominantly Tertiary age mudstones and limestones (and in places clay-bound gravels of Tertiary or early Quaternary age). This no-flow boundary dips westwards and southwards into the groundwater basin.

South-western boundary: the Waingawa River forms a hydraulic boundary between the Upper Valley model and the Middle Valley model (Gyopari and McAlister 2010b). It is assumed that no regional flow crosses this boundary. The flow losses and gains from this river to each model domain are apportioned automatically by the respective models.

Internal physical boundaries: There are several major geological structures within the Upper Valley catchment which disrupt or impede the flow of groundwater. The following features form internal, low permeability flow barriers:

- Masterton Fault
- Mokonui Fault
- Lansdowne Hill fold structure (on Masterton Fault)
- Tirohanga fold structure (on Mokonui Fault)

9.3 Geological framework

On a sub-regional basis, the geological framework for the Upper Valley catchment is summarised below with reference to the principal hydrostratigraphic units listed in Table 6.2.

9.3.1 Waingawa fan system

The Waingawa fan is the extensive aggradational fluvio-glacial outwash surface between the Waingawa, Wapoua and Ruamahanga rivers. The fan is traversed by the Masterton and Mokonui faults which have created a series of shallow sub-basins between the faults. The fan sequences have been uplifted on the upgradient side of the faults causing groundwater to discharge in the vicinity of the Masterton Fault in particular. Shallow fan deposits to the north of the Masterton Fault appear to be the product of the Waingawa River migrating eastwards to the Waipoua River, and southwards through the Masterton springs area, relatively recently. As a consequence, the shallow deposits are regarded to exhibit a higher hydraulic conductivity than deeper deposits due to sediment reworking during river migration.

Shallow reworked gravels of Q1 age occur along the modern day channels and floodplains of all the major river systems. The gravels lie on top of an older, less permeable fan sequence, are generally less than 10 m thick. These gravels constitute high-yielding aquifers which are hydraulically connected to surface water. The shallow Q1 aquifer is extensively utilised along the Waingawa River for abstraction.

9.3.2 Te Ore Ore basin

The Te Ore Ore basin is a synclinal structure containing late Quaternary sandy and silty gravels to at least 100 m depth. It is bounded to the north by the Tertiary hill country and to the west by the Masterton Fault, and merges with the toe of the alluvial fans formed by the Waingawa and Waipoua rivers.

The sediment sequence is stratified; there are no laterally persistent layers or aquitards. The basin fill is regarded to be a single heterogeneous hydrostratigraphic unit with aquifer conditions ranging from unconfined near the surface (particularly in the south and west) through to leaky-confined at depth.

The central part of the Te Ore Ore basin represents a mergence zone of Tararua-sourced gravel-rich alluvium deposited by the Ruamahanga River, and eastern hill-sourced silt-rich alluvium deposited by the Whangaehu River.

Groundwater recharge occurs from rainfall and river bed losses where the Ruamahanga River enters the basin. Discharge occurs via the spring-fed Poterau Stream and the Ruamahanga River, as well as a well developed agricultural drainage system.

The Te Ore Ore basin is a locally important groundwater resource for irrigation supply and is exploited by numerous bores at depths ranging from just a few metres to over 50 m. High yielding abstraction bores in the basin tend to tap the high transmissivity shallow unconfined aquifer, particularly in the central and western part of the plains, or deeper permeable horizons at about 30 m deep.

Intensive irrigation abstraction has been directly linked to increased seasonal reductions in the water table and associated spring flow reductions in the Poterau Stream.

Shallow reworked gravels of Q1 age occur along the modern day channel of the Ruamahanga River and are spread across the Te Ore Ore plain. The deposits are generally less than 10 m thick and constitute high-yielding gravel-rich aquifers that are hydraulically connected to surface water.

9.3.3 Upper Waipoua and Ruamahanga fans and Kopuaranga valley

These upper fan systems are regarded as having low hydraulic conductivity; they are poorly sorted fan deposits (Q2+) which have not been reworked. As a consequence, they do not produce high bore yields and are utilised only as minor water supply sources.

The fans are traversed by the Mokonui and Masterton faults along which there has been considerable displacement and deformation on the Quaternary sediments. Lansdowne Hill represents uplift and folding associated with movement along the fault.

Shallow reworked gravels of Q1 age occur along the modern day channels and floodplains of the major river systems (Ruamahanga and Waipoua). The deposits are generally less than 10 m thick and constitute high-yielding aquifers which are hydraulically connected to surface water. Extensive abstraction from these deposits occurs along the Ruamahanga upstream of Lansdowne Hill where there are some particularly large abstractions.

9.3.4 Internal flow barriers

Two major fault structures displace and deform the geological sequence in the Upper Valley catchment. These are the Masterton and Mokonui faults which are regarded to have a major influence of groundwater flow. The geological cross sections in Figures 6.4 to 6.9 illustrate their role in impeding regional flow, resulting in spring discharges or river flow gains in their vicinity. Associated with the two faults are large fold structures at Lansdowne Hill and Tirohanga Hills which also form barriers to regional groundwater flow.

9.4 Hydrological framework and water balance estimation

The conceptual model for the Upper 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 regional 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
	Spring flow
	Abstraction from bores (or, more strictly, supply to bores)
	Throughflow to Middle Valley catchment*

* 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 valuable check on the numerical model flow balance predictions. Table 9.1 summarises the estimated water balance for the Upper Valley groundwater catchment.

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

	In (m^3/day)	Out (m^3/day)
Rainfall recharge	130,000	
River flow loss/groundwater recharge	100,000	
River flow gain/groundwater discharge		200,000
Springs and diffuse evapo-transpiration		20,000
Abstraction		10,000*
Total	*230,000*	*230,000*

* Seasonal irrigation quantities are about 30,000 m^3/day.

The sources of the various balance quantities are as follows:

- *Rainfall recharge*: soil moisture balance model (annual average)
- *River inflow and outflow*: values based on concurrent gaugings (average fluxes)
- *Springs/evapo-transpiration (ET)*: gauging data estimate
- *Abstraction*: estimate at 25% of total consented rate (annual average).

Although Table 9.1 shows that abstraction is a relatively small proportion of the overall water balance, some areas show a probable abstraction-related stress (such as the Te Ore Ore basin). However, reference to Table 7.3 shows that abstraction is not distributed evenly across the catchment and that about 85% of the total amount of water pumped comes from the Te Ore Ore basin.

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 Upper 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 Upper Valley groundwater system based upon a synthesis of available geological and hydrogeological information.
- Build a numerical groundwater flow model for the Upper 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 Upper Valley groundwater resource and explore effective management options.

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

10.2 Model code selection

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

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

- Ability to represent complex and irregular geology and complex aquifer conditions.
- Capability to coarsely discretise the mesh/grid in areas where there is little data and low groundwater use (i.e. alluvial fans), but refine the numerical mesh around important features such as rivers.
- Ability to accurately simulate the interaction between groundwater and surface water and facilitate the coupling of a surface water model (MIKE 11) with the groundwater model.

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

The specific advantages of the FEFLOW application include:

- Flexibility of the mesh design enabling a refinement in areas of interest and therefore a more precise simulation of physical features (pumping bores, rivers, etc.).
- Ability to shape the triangular mesh to complex boundary conditions and along specific features.
- Ability of the elements to conform to the pronounced vertical variation of aquifer / aquitard layers.
- Stable water table simulation that facilitates more accurate simulation of the shallow subsurface (FEFLOW avoids the wetting-drying cycling typical of finite difference models such as MODFLOW that can cause solution convergence and stability problems).
- The possibility to couple FEFLOW with MIKE 11 to simulate the dynamic flow exchange between surface water and groundwater, as a result of the recent development of the IFM Tool (FEFLOW Open Inter-Face Module)

10.3 Model complexity

The MDBC (Middlemis 2001) and Ministry for the Environment (2002) 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, bulked 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 aquifers exist and where complex groundwater-surface water interactions are taking place.

The Phase 2 model for the Upper Valley catchment is therefore a complex multi-layer simulation consistent with the purpose and objectives of the Wairarapa Valley groundwater investigation. A sufficiently detailed conceptual understanding of the Upper Valley catchment has been developed (Sections 6 and 7) and a large volume of data exists to support model development and calibration.

10.4 Groundwater model development

10.4.1 Model domain

The location and extent of the model domain (Figure 10.1) covers an area of about 160 km^2 and encompasses the late Quaternary and Holocene alluvial sediments of the Upper Valley catchment.

The length of the model domain is about 14 km extending from the Wairarapa Fault to the southern edge of the Te Ore Ore plain. The width is approximately 10 km, extending from the base of the eastern hills in the north-east to the Waingawa River.

The Upper Valley groundwater catchment incorporates the alluvial fans of the Waingawa, Waipoua and Ruamahanga rivers, and also the Te Ore Ore plain.

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 hydrogeologically distinct areas defined by physical aquifer boundaries (such as geological boundaries). Figure 10.2 shows the super-element mesh created for the model domain comprising 33 super elements. 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 along and on these features.

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 can incorporate line and point add-ins. The number of elements within 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 resulting finite element model consists of 22,156 elements, 14,540 nodes and 4 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's configuration settings.

Table 10.1: Upper Valley catchment groundwater model configuration

Type of model	**3-D saturated flow**
Type of aquifer	Unconfined top layer with phreatic surface
Model layers	4 layers (5 slices)
Type of simulation	Steady state and transient flow
Type of elements	6-node, triangular prisms
Number of elements	22,156
Number of nodes	14,540
Equation solver	Iterative
Time stepping	AB/TR predictor-corrector

10.4.4 Model layers and ground elevation model

The model has four layers (five 'slices') to represent the stratified nature of the aquifer system and to adequately simulate vertical head gradients (Table 10.2). In this respect the layers are not intended to specifically represent hydrogeological units, but rather to allow the simulation of a leaky, layered aquifer system. However, the uppermost layer (1) does coincide with the approximate thickness of the unconfined Holocene gravels and has a constant thickness of 7 m across the model. The constant thickness of this layer is also necessary to simulate the river and spring boundaries (transfer conditions) on the vertical plane.

Appendix 1 contains the structure contours for each slice and Figures 10.4 to 10.6 provide further information on the model layer structure. Each layer surface ('slice') was based upon elevation data obtained from the cross sections presented in Figures 6.6 to 6.9 which were then modelled (contoured) externally using ArcMap prior to being imported into FEFLOW as a grid file. The process of developing the slice surfaces was therefore 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.

Table 10.2: Upper Valley catchment model layer configuration

Layer	Unit	Slice
	Ground surface	▼ SLICE 1
Layer 1	Unconfined layer Constant 7m thick	▼ SLICE 2
Layer 2	Te Ore Ore confined aquifer base / Holocene Q1 gravel base	▼ SLICE 3
Layer 3	Non-specific layer	▼ SLICE 4
Layer 4	Non-specific layer	▼ SLICE 5

Slice 1 represents the ground surface and was modelled using a combination of high accuracy LIDAR data which covers the main part of the model area, including the Te Ore Ore plain (see Figure 3.3) and the 20 m contour topographic map. Where the topographic 20 m contour data were used, the error in ground surface definition is estimated to be up to +/-5 m. Table 10.3 shows a verification of the groundwater elevation model by comparing the model elevations with surveyed elevation at selected monitoring bores (see Figure 7.2 for bore locations).

Table 10.3: Ground elevation verification using selected surveyed monitoring bore locations

Bore ID	Location	Elevation source (LIDAR or topo map)	Assigned elevation (m amsl)	Surveyed ground level (m amsl)	Difference (m)
T26/0003	North of Mokonui Fault	topo	177.02	175.7	1.32
T26/0170	North fan	topo	152.7	150.0	2.7
T26/0239	North fan	LIDAR	141.73	142.0	0.27
T26/0208	North fan	LIDAR	135.33	135.4	0.07
T26/0494	Te Ore Ore	LIDAR	103.63	104.43	0.8
T26/0814	Te Ore Ore	LIDAR	93.45	93.82	0.37
T26/0429	Waingawa fan	LIDAR	119.33	119.6	0.27
S26/0032	Waingawa fan	LIDAR	140.00	140.65	0.65

The greatest errors in elevation occur in the northern area outside the LIDAR coverage, with the maximum error being 2.7 m. Generally, Table 10.3 shows that the ground elevation model is highly accurate where there is LIDAR coverage, and acceptable in areas where the 20 m topographic map has been relied upon.

Layer 2 is designed to represent the stratified nature of the fan deposits over much of the model, except in the Te Ore Ore basin where the base of this layer (Slice 3) coincides with the approximate base of the productive confined aquifer system at about 30-35 m depth.

The base of Layer 2 (Slice 3) was placed at the mid-point between the base of Layer 1 (Slice 2) and model base – it therefore has a variable thickness proportional to the total saturated aquifer thickness (i.e. thicker in the basin areas and very thin over the fault structures). The base of Layer 2 also corresponds to the base of the confined aquifer in the Te Ore Ore basin as well as the base of Holocene gravels along the major river courses.

Slice 4 (base of Layer 3) was set at the mid-point between Slice 3 and Slice 5 (model base). The function of this slice is to simulate the vertical head gradients within the layered aquifer sequences which do not correspond to any specific hydrogeological unit.

The base of the model (Slice 5) coincides with the interpreted lower boundary of the Q8 alluvial sediments which is considered to represent the base of the groundwater flow system. The influence of displacement on the Masterton and Mokonui faults is clearly visible, as is the Te Ore Ore basin.

Figure 10.5 shows the total thickness of the groundwater system by subtracting the groundwater surface from the model base elevation. Appendix 1 shows elevation contours for each of the model layers.

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, since the steady state generated head distribution is not consistent with the commencing boundary stresses of the transient model, alternative initial head conditions were 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 matches the starting heads at the beginning of the simulation (both winter conditions).

10.5 Boundary conditions

10.5.1 External model boundaries

The model boundaries coincide with the catchment boundaries which were defined during the conceptual model development (see Section 9.2) and are shown in Figures 10.1 and 10.2. All external model boundaries are of ‘no-flow’ type except the south-western boundary which follows the Waingawa River (Cauchy/3rd kind).

10.5.2 Rivers and spring-fed streams

Transfer (Cauchy/3rd kind) boundary conditions were assigned along the full lengths of the Ruamahanga, Waipoua, Waingawa, Whangaehu and Kopuaranga rivers to simulate the interaction between the rivers and the aquifer system. Spring-fed streams, such as the Poterau and Masterton spring systems, were also simulated using the transfer boundary type.

The locations of transfer boundary nodes for main river and stream channels are shown in Figure 10.7. The ‘transfer’ type of boundary condition describes a time-varying reference hydraulic head (river stage) which has an imperfect hydraulic contact with the groundwater system. The boundary type allows inflow and outflow of water at a rate proportional to the hydraulic head difference between groundwater and surface water. River stage and a proportionality constant (the ‘transfer rate’) need to be assigned to each boundary node.

Transfer boundary conditions also require the definition of an area across which flux is calculated. In a regional 3-dimensional 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’s width. The exchange area in an unconfined aquifer will naturally vary depending upon the saturated thickness of the layer unless use of the full layer thickness is specified.

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 IFM-MIKE11 interface module developed by WASY (2009). However, it proved problematic to fully couple the surface water and groundwater models due to numerical instability problems with MIKE11 and exceedingly long model run times. Consequently, the MIKE11 transient stage data, modelled at each Hnode, were transferred manually to the FEFLOW model river boundary nodes.

The MIKE11 surface water model incorporates the Waingawa, Waipoua and Ruamahanga rivers. Appendix 5 contains a full description of the MIKE11 model.

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

Regular river cross section surveying is carried out by Greater Wellington as part of its flood protection role. A total of 190 river cross sections with corresponding level data and location co-ordinates were incorporated into the MIKE11 model. Channel cross section surveys are available at approximately

100 m intervals down each of the rivers. Figure 3.2 contains the bed profiles for each of the rivers as modelled by MIKE11.

The river stage heights for the Waingawa River were modelled using an upstream gauging site at Kaituna located just outside the model domain. For the Ruamahanga River, the Wardells Bridge flow monitoring site (downstream of the Waingawa River confluence) was used.

Deriving stage data for the Waipoua River at Mikimiki (edge of model area) proved more problematic because there was only about one year of reliable monitoring data for this site. Therefore, a correlation between the flows in this river and the Waingawa River and Mangatarere Stream was used to develop a synthetic record for this site prior to 2007.

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 Hnode 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 Hnode sites. This procedure enabled 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 Assignment of stage heights for minor streams

The Waihi gauge was used to assign the stage height for the Whangaehu River, although this river was not modelled with MIKE11. Stage data relating to the gauging site were linearly extrapolated to downstream or upstream nodes using bed survey data for 2002 and 2004 (Greater Wellington).

For the Poterau Stream and Masterton spring system, elevations for the transfer boundary nodes were derived using high-accuracy LIDAR data. Constraints were set on these boundaries to only allow water out of the model (to avoid them becoming recharge sources if the modelled water table dropped below the set stage/stream base heights).

10.5.6 Cauchy boundary transfer rates

Transfer boundaries need to have an associated ‘transfer rate’ to control the leakage rate between the river and aquifer. Large values for 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: Transfer rates for 3rd kind (Transfer/Cauchy) boundary conditions

River/stream	Transfer rate (1/d)
Ruamahanga River	2
Waipoua River	3
Waingawa River	5
Whangaehu River	0.005
Kopuaranga River	0.005
Masterton spring system	10
Poterau Stream	1

10.5.7 Recharge grid

Recharge was modelled externally on a 500 m^2 grid using the methodology described in Appendix 2 (summary information on the recharge model is provided in Section 7.3). Recharge was calculated on a daily time step for the 16-year calibration period and 7-day averages were supplied to the FEFLOW simulation. The one-day time step was used because significant errors can occur when running soil moisture balance models at larger time-steps.

The gridded recharge data were imported into FEFLOW by overlaying the 500 m^2 square grid as an ArcGIS polygon shape file and then tying each of the grid polygons/cells (727 in total) via its 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 727 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 specific to each consented take.

10.6 Hydraulic property zonation framework

Development of the hydraulic property zonation framework for the Upper 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 10.8 to 10.11 show the hydraulic conductivity and storage zones assigned to each of the model layers. Model layers 1 and 2 represent discrete hydrostratigraphical units, or distinct changes within the same unit. Each of these two layers consequently has a unique set of parameter zones. By contrast, layers 3 and 4 broadly represent the deeper heterogeneous fluviatile sequence – the boundary between the layers enables the general stratification of the system to be simulated facilitating the control of vertical flow in the aquifer sequence. The bottom two layers therefore share parameter zones and a more complex parameter zonation framework has been used in the upper two layers due to better characterisation from available data in comparison to the deeper system.

Section 10.4.4 provides further detail on the model layer design.

10.6.1 Horizontal hydraulic conductivity (Kx,y) zones

(a) Layer 1

Figure 10.8 shows the horizontal hydraulic conductivity parameter zonation for the four model layers. Within layer 1, the alluvial fan gravels north of the Masterton Fault (Unit A, Table 6.2) are divided into four zones (Kx 1, 2, 4, 8) to facilitate changes in the nature of the fan sediments from lower permeability fan deposits adjacent to the foothills, to more reworked and better sorted deposits downgradient. Immediately north of the fault, the fan gravels are more permeable as a result of sediment reworking along the former course of the Waingawa River (see Section 9.3.1).

The Mokonui and Masterton faults are represented by thin hydraulic conductivity bands about 500 m wide (Kx101 and Kx99 respectively) extending through all layers to enable simulation of the observed groundwater flow impedance across them.

Recognising that sediment sorting increases distally, and coupled with the probable influence of major fault structures on the depositional environment, the Waingawa alluvial fan (Unit A) below the Masterton Fault is represented by a separate zone (Kx12).

Three zones are used for the Te Ore Ore basin (Kx 9, 10, 11) acknowledging the spatial changes in the character of basin fill sediments from Tararua-sourced gravel-rich alluvium in the west, to silt-rich alluvium sourced from the eastern hill country.

The Q1 alluvium (Unit B) associated with the main river systems is represented by three zones to reflect changes in the bed characteristics between fluvial systems. These zones are Kx3 (Waingawa), Kx5 (Waipoua) and Kx6 (Ruamahanga).

The low permeability folded blocks of older Quaternary and Tertiary sediments along the major faults – Lansdowne and Tirohanga hills – are represented by a single zone (Kx7) extending through all model layers.

(b) Layer 2

Layer 2 has an identical zonation framework to layer 1 although hydraulic conductivity values for most of the zones are not tied to layer 1. This recognises the potentially changing nature of the alluvial sediments with depth, particularly in areas such as the Te Ore Ore basin. Zones Kx1, Kx4, Kx7, Kx99 and Kx100 are common to layers 1 and 2 over the upper fan areas.

(c) Layers 3 and 4

The zonal framework for horizontal hydraulic conductivity in layers 3 and 4 is identical except in the Te Ore Ore basin. A much simpler zonation framework for these layers reflects both the relative lack of data at depth in the fans and also the perceived bulk uniformity of the poorly sorted, low-yielding fan sediments. There are two zones north of the Masterton Fault (Kx15 and Kx16), as well as the up-folded areas of zone Kx7 (common to all layers).

South of the Masterton Fault the Te Ore Ore basin has four central zones (Kx25, 28, 31 and 36) in layer 3 reflected by four corresponding zones in layer 4 (Kx26, 29, 32 and 100). The zonation framework in deep Te Ore Ore provides the ability to simulate spatially varying aquifer properties and the observed layering of the system.

10.6.2 Vertical hydraulic conductivity (Kz) zones

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

10.6.3 Specific yield (St) zones

Specific yield (unconfined storage) parameter zones are only assigned to layers 1 and 2 since the water table will not drop into deeper layers. Figure 10.10 shows the unconfined storage (St) parameter zones for layers 1 and 2. There are four zones corresponding to: the upper fan gravels (Unit A, St79), Q1 Holocene alluvium (Unit B, St82), Te Ore Ore basin fill alluvium (Unit C, St84) and Waingawa fan gravels spanning the Masterton Fault (St88). In layer 2, the Te Ore Ore basin fill has been assigned a separate zone to allow for changing storage properties with depth in the basin.

10.6.4 Specific storage (Ss) zones

There are two specific storage (confined storage) parameter zones (Ss78 and Ss97) which are present in all model layers. The zonation framework differentiates between the fan gravels and the Te Ore Ore basin (Figure 10.10).

11. Model calibration

11.1 Calibration process

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

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

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

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

Following completion of a manually calibrated model, 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. Lastly, a verification run was performed over a 16-year period (1992–2008).

11.2 Addressing non-uniqueness

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

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

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

b) Calibrate to a range of hydrogeological conditions (wide range of climate and induced stresses such as abstraction).

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

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

With reference to requirement a), pumping test data were used to guide hydraulic conductivity (Table 7.6) for the main aquifer units where available. However, the biased nature of these data towards more productive aquifer zones (rather than regionally representative bulk material values) is recognised.

To address requirement b), the transient model calibration and verification period covered a 16-year period over which both climate stresses and abstraction stresses experience large variation. This is discussed further in Section 11.5 whilst Figure 7.19 illustrates the calculated range in recharge patterns over the 16-year transient model calibration period.

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

11.3 Calibration evaluation criteria

Model calibration was evaluated in both quantitative and qualitative terms by comparing the simulation results and 'real-world' field observations. 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 7.4) and gauged spring flows were used to constrain the calibration.

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

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

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

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

To ensure that the transient model calibration period from 1 July 1992 to 1 May 2008 is not biased towards a particular climatic period (such as an unusually wet or dry interval), 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 Valley. 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 manual steady-state calibration

It is customary practice to use a steady-state model to test the conceptual model, ensure that the parameter zonation framework is appropriate, and check that the model predicts a water balance which is consistent with the estimated fluxes discussed in Section 7. The steady state process also has the purpose of checking model set-up and identifying 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. Equilibrium conditions rarely occur in Wairarapa Valley groundwater systems which are dominated by volatile river-aquifer flow dynamics 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 time is controlled by the availability of detailed concurrent groundwater head survey data which coincides with relatively stable aquifer conditions. Regional groundwater level surveys were available for April 2007 and September 2008. The latter was used for the steady state calibration to represent stable late winter groundwater conditions (Figure 7.3 shows the measurement sites and contoured groundwater levels associated with this survey).

The steady state model was set up using recharge calculated for the week of 3 September 2008 (134,000 m^3/day), which represents a rate approximating the daily average recharge for 2007/08 using the soil moisture balance recharge model (see Section 7.2). Initial hydraulic conductivity values used were derived from the ranges presented in Table 7.6 but these values were later refined during the steady state and subsequent transient calibration.

Steady state calibration was achieved by manually calibrating the model to head targets measured in 40 bores for all aquifer depths in the Upper Valley catchment. The results of the steady state calibration run are shown in Figure 11.3 and the calibration statistics are summarised in Table 11.3. The overall residual mean of the calibration is encouragingly low at 1.77 m. The highest residual of -10.01 m is for a very shallow bore (T26/0165) on the edge of Lansdowne Hill which is thought to intercept much older formations on the fold structure.

The scatter plot comparing computed versus measured groundwater heads in Figure 11.3 shows that there is no model spatial bias (i.e. there is no spatial pattern in either the under or over-prediction of groundwater levels).

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

Statistical performance measure	Calibration statistic	Unit
Absolute residual mean	-0.46	m
Min residual	-10.01	m
Max residual	5.16	m
Sum of residuals	70.7	m
Residual standard deviation	2.06	m
Observed range in head	83.1	m
Mean sum of residuals	1.77	m
Scaled mean sum of residuals	0.05	%
Sum of residual squares	290.3	m^2
Root mean square (RMS error)	2.69	m
Scaled RMS	3.24	%

The root mean square statistic (RMS) is an absolute measure of the calibration that is problem-specific (its value is affected by the measured values). It is a good indicator of error, along with the scaled RMS. The scaled RMS of 3.2% indicates that the ratio of error to the total head differential is small and is indicative of a good match between measured and observed groundwater levels, flow gradients and spatial flow patterns.

Figure 11.4 shows the steady state modelled head distribution over the model domain, contoured using the same data points and contouring algorithm as the measured September 2008 heads. Comparison to computed and measured contour sets shows a close agreement.

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

11.5.1 Steady state mass balance

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

Total inflow is about 231 million litres per day (ML/d) – 97.5M L/d from river recharge and 133.5 ML/d from rainfall recharge. Outflow from the groundwater system is dominated by discharge back into the rivers (180 ML/d) and discharge to springs (49.4 ML/d).

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

Flow component	**Inflows (m^3/day)**	**Outflows (m^3/day)**
Rivers	97,500	180,000
Springs:		
Poterau		12,700
Masterton		36,700
Abstraction		1,500
Rainfall recharge	133,500	
Total	*231,000*	*230,900*

Comparison of the steady state model output and the estimated water balance for the catchment presented in Table 9.1 shows that the simulated flows are in general agreement with the estimated flow budget.

In terms of the Poterau Spring flow, Section 3.2.2 described a winter flow of about 400 L/s and a negligible summer flow. This suggests that the annual average flow is probably about 200 L/s (c. 17,000 m^3/day) which is close to the predicted average flow for this spring. The predicted summer total flow for the Masterton springs is 150-200 L/s (13,000-17,000 m^3/day; Section 7.3.1) and therefore the modelled annual average of about double this is also of the correct magnitude for this spring system.

The head and water balance predictions of the steady state calibration are encouraging as they provide confidence in the conceptualisation of the groundwater system and the ability of the model to predict heads and fluxes which are consistent with observed information.

11.6 Transient model calibration

11.6.1 Transient simulation set-up

The transient flow calibration was set up for a 16-year period between 1 July 1992 and 30 September 2008 and simulates the transient groundwater system behaviour at a weekly time step. Choice of a seven-day stress period is consistent with the temporal responses of the groundwater system to stresses and monitoring data availability. The transient model has 848 seven-day stress periods and a run interval of 5,936 days. The head output from the steady state model was used as a starting condition for the initial transient run.

11.6.2 Automated calibration (PEST)

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

Because FEFLOW (version 5.4) does not support the most recent version of PEST, scripts facilitating the exchange of data between the FEFLOW input and output files (*.fem and *.dar) and PEST were written. Appendix 6 contains a description of the PEST interface developed for FEFLOW.

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

A total of 30 zones were fixed, including river boundary transfer rate zones. Thirty-one parameter zones were also tied to parent parameters where appropriate.

A total of 40 ‘unknown’ hydraulic conductivity (horizontal and vertical) and unconfined and confined storage parameters were estimated by PEST. The unknown parameters were allowed to vary between prescribed upper and lower bounds within each zone whilst the objective function was minimised. The bounds were prescribed on the basis of groundwater pump test data and plausible ranges for the type of material contained within the zone.

Table 11.5 lists the unknown, tied and fixed parameter zones. All PEST-estimated unknown parameters were log-transformed.

Recharge was not estimated using PEST due to the complexity of the distributed model which has several hundred recharge zones. Confidence in the recharge inputs was gained through an independent verification process documented in Appendix 2. Therefore recharge was not treated as a variable parameter in the calibration process.

Table 11.5: Transient calibration parameter zone designation (Kx – horizontal hydraulic conductivity, Kz – vertical hydraulic conductivity, St – specific yield, Ss – specific storage, it – transfer rate in, ot – transfer rate out). Kx and Kz values are in m/day.

Unknown parameter	Lower bound	Upper bound	Tied parameter	'Parent' parameter	Fixed parameter	Value
Kx02	50	180	Kx03	Tied Kx02	Kx01	70
Kx04	3	10	Kx10	Tied Kx09	Kx05	150
Kx06	90	120	Kx14	Tied Kx11	Kx07	8.64
Kx08	10	60	Kx15	Tied Kx16	Kx13	1.2
Kx09	90	110	Kx18	Tied Kx22	Kx17	5.3
Kx11	60	80	Kx25	Tied Kx36	Kx21	1.2
Kx12	80	110	Kx26	Tied Kx100	Kz38	0.5
Kx16	5	60	Kx29	Tied Kx100	Kz45	1.73
Kx19	50	150	Kx31	Tied Kx28	Kz51	0.023
Kx20	60	110	Kx32	Tied Kx100	Kz58	0.008
Kx22	30	50	Kx33	Tied Kx30	Kz65	0.08
Kx23	60	100	Kx34	Tied Kx28	Kz66	0.1
Kx24	60	110	Kx35	Tied Kx100	St79	0.075
Kx27	50	80	Kx37	Tied Kx36	it80	0.005
Kx28	8	30	Kz41	Tied Kz40	ot81	0.005
Kx30	30	70	Kz42	Tied Kz46	it85	10
Kx36	40	80	Kz48	Tied Kz47	it86	10
Kz40	0.1	2	Kz52	Tied Kz49	it87	5
Kz43	0.1	1	Kz53	Tied Kz54	it88	3
Kz44	1.00E-02	0.2	Kz55	Tied Kz59	it89	3
Kz46	5.00E-02	0.8	Kz61	Tied Kz62	it90	2
Kz47	1.00E-02	0.2	Kz63	Tied Kz62	ot91	10
Kz49	1.00E-02	0.2	Kz64	Tied Kz62	ot92	10
Kz50	5.00E-02	0.8	Kz68	Tied Kz76	ot93	5
Kz54	0.2	5	Kz69	Tied Kz102	ot94	3
Kz56	1.00E-02	0.2	Kz71	Tied Kz102	ot95	3
Kz57	1.00E-03	5.00E-02	Kz72	Tied Kz70	ot96	2
Kz59	1.00E-02	0.2	Kz73	Tied Kx102	St98	0.0000018
Kz60	1.00E-02	0.2	Kz74	Tied Kz70	Kx99	5
Kz62	1.00E-03	1.00E-02	Kz75	Tied Kz102	Kx101	0.2
Kz67	5.00E-02	5	Kz77	Tied Kz76		
Kz70	1.00E-04	5.00E-03				
Kz76	1.00E-04	8.00E-03				
Ss78	5.00E-06	3.00E-04				
St82	2.00E-02	0.15				
St83	2.00E-02	0.15				
St84	1.00E-02	0.1				
Ss97	1.00E-06	1.00E-04				
Kx100	20	90				
Kz102	5.00E-05	8.00E-03				

11.6.3 Calibration targets and weighting

Figure 11.5 shows the locations of 21 monitoring bores (also listed in Table 11.6). The bores are distributed across the Upper Valley catchment and measure groundwater levels at various depths ranging from less than 10 m to greater than 30 m.

Table 11.6: Transient calibration groundwater level targets and weightings (refer to Figure 11.5 for locations)

Monitoring bore	Depth (m)	Continuous or Manual / Dedicated or Pumping	Calibration weighting*	7-day mean observed data mRL		Range of fluctuations (m)	Number of observed data
				Min	Max		
S26/0033	12	/ D	1.00	138.55	141.13	2.57	598
S26/0032	6	/ P (Dug)	0.75	134.98	136.56	1.59	265
S26/0030	38	/ D	0.75	129.28	131.93	2.65	847
T26/0003	6	/ P	0.75	173.60	175.2	1.6	598
T26/0170	15	/ P	0.75	144.08	146.59	2.52	529
T26/0239	6	/ P (Dug)	1.00	138.46	140.90	2.44	576
T26/0208	17	/ D	1.00	127.41	131.58	4.17	848
T26/0429	10	/ D	0.75	114.45	116.67	2.22	848
T26/0535	6	/ D	1.00	93.94	96.14	2.20	150
T26/0494	23	/ D	1.00	90.31	99.23	8.92	848
T26/0501	5	/ D	1.00	96.26	99.64	3.39	848
T26/0243	47	/ D	0.75	94.07	98.89	4.82	848
T26/0232	31	/ P	0.75	96.18	99.30	3.11	848
T26/0366	5	/ P	0.75	95.94	97.26	1.32	182
T26/0841	5?	M / D	0.75	81.85	82.88	1.03	247
T26/0849	5?	M / D	0.75	84.81	85.22	0.41	173
T26/0845	5?	M / D	0.75	85.99	87.32	1.33	231
T26/0800	5	M / D	0.75	89.53	89.86	0.33	24
T26/0848	5?	M / D	0.75	88.29	90.02	1.73	173
T26/0843	5?	M / D	0.75	89.57	90.89	1.32	231
T26/0853	5?	M / D	0.75	89.26	89.98	0.72	24

* Calibration weighting: 1 = reliable, 0.75 = reasonable

The data were processed to provide a representative value every seven days resulting in 10,205 head observations for the 21 monitoring bores. 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).

Concurrent river flow gaugings (see Section 7.3) also provided important information on the quantities of water moving between surface water and groundwater for specific reaches of river. Spring flow gaugings additionally provided data on the magnitude of groundwater discharge to the various spring systems in the Upper Valley catchment.

Concurrent river flow data and the spring gauging data were explicitly used as calibration targets for the transient model. These are documented in Sections 3.2 and 7.3. However, the flux targets could not be incorporated into the PEST optimisation process due to the restrictions inherent in the FEFLOW model output file format. To circumvent this restriction, parameters which were recognised as sensitive to surface water interactions (e.g. hydraulic conductivity in the vicinity of rivers and springs and transfer rates) were manually constrained during the PEST calibration to ensure that the final calibration was consistent with the water balance targets.

11.6.4 Objective function formulation

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

11.6.5 Transient calibration results

Table 11.7 provides the PEST optimisation results. The overall objective function (phi) reduced from 7,563 m^2 to 4,746 m^2 (i.e. 37% reduction); the contribution from each of the monitoring bores is also listed. Table 11.8 provides a summary of quantitative measures for the calibration quality following the automated PEST calibration procedure.

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

Table 11.7 shows that Area 3 has the highest contribution to the total model phi (1,749 m^2). This is primarily because the area has the greatest number of observations (and residuals) in comparison to the other areas. In this area some individual bores also have a high phi (i.e. T26/0535 and T26/0501) which is discussed in further detail below. The Waipoua fan (Area 4) also has a relatively high contribution to the total phi when compared to Area 1 which has the same number of residuals.

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

Objective function ----->	
Sum of squared weighted residuals (i.e. phi)	4,746
AREA 1 (Waingawa Fan N. Masterton F)	
Contribution to phi from observation group "s26_0033"	169
Contribution to phi from observation group "s26_0032"	65
Contribution to phi from observation group "s26_0030"	514
Total contribution Area 1 (1963 residuals)	*(748)*
AREA 2 (Waingawa Fan S. Masterton F.)	
Contribution to phi from observation group "t26_0429"	75
Contribution to phi from observation group "t26_0366"	64
Contribution to phi from observation group "t26_0853"	53
Contribution to phi from observation group "t26_0845"	76
Contribution to phi from observation group "t26_0849"	25
Contribution to phi from observation group "t26_0841"	248
Contribution to phi from observation group "t26_0800"	18
Contribution to phi from observation group "t26_0848"	70
Contribution to phi from observation group "t26_0843"	149
Total contribution Area 2 (2142 residuals)	*(778)*
AREA 3 (Te Ore Ore basin)	
Contribution to phi from observation group "t26_0232"	65
Contribution to phi from observation group "t26_0243"	82
Contribution to phi from observation group "t26_0501"	532
Contribution to phi from observation group "t26_0494"	733
Contribution to phi from observation group "t26_0535"	337
Total contribution Area 3 (3546 residuals)	*(1,749)*
AREA 4 (Waipoua Fan)	
Contribution to phi from observation group "t26_0208"	516
Contribution to phi from observation group "t26_0239"	329
Contribution to phi from observation group "t26_0170"	258
Total contribution Area 4 (1955 residuals)	*(1,103)*
AREA 5 (Upper Waipoua/Ruam/Kop fans)	
Contribution to phi from observation group "t26_0003"	368
Total contribution Area 5 (599 residuals)	*(368)*
Correlation Coefficient ----->	
Correlation coefficient, R	0.9997
Analysis of residuals ----->	
All residuals:-	
Number of residuals with non-zero weight	10,205
Mean value of non-zero weighted residuals	-0.1661
Maximum weighted residual	
[observation "o5367" t26_0243]	2.113
Minimum weighted residual	
[observation "o7887" t26_0494]	-4.486
Standard variance of weighted residuals	0.4669
Standard error of weighted residuals	0.6833

The errors and scaled errors presented in Table 11.8 provide further detail on the calibration performance in relation to simulated heads for individual monitoring bores. The scaled errors are particularly relevant since they take into account the range in measured values. Both SMSR and SRMS are expressed as a percentage and should be relatively low if the error to total head differential is small and hence errors will be a small part of the overall model response.

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

Monitoring bore	Error (m)					Scaled error (%)	
	No. of residuals	Minimum	Maximum	Absolute mean	Root mean square (RMS)	Scaled mean sum of residuals (SMSR) %	Scaled RMS (SRMS) %
AREA 1							
S26/0033	849	0.212	1.42	-1.22	0.45	14.49	17.51
S26/0032	265	-0.38	0.26	-1.15	0.50	24.24	31.45
S26/0030	849	-0.72	0.09	-1.18	0.78	27.13	29.43
AREA 2							
T26/0429	849	0.21	1.38	-0.43	0.30	11.39	13.51
T26/0366	183	0.56	1.00	0.26	0.59	42.41	44.70
T26/0853	25	-1.44	-1.19	-1.76	1.45	200.50	201.39
T26/0845	232	-0.54	0.074	-1.10	0.57	40.53	42.86
T26/0849	174	-0.31	0.00027	-0.92	0.37	76.11	90.24
T26/0841	248	-0.99	-0.51	-1.35	1.00	96.08	97.09
T26/0800	25	-0.78	-0.37	-1.28	0.85	237.58	257.58
T26/0848	174	-0.60	0.43	-1.12	0.63	35.15	36.42
T26/0843	232	-0.78	-0.13	-1.26	0.80	59.08	60.61
AREA 3							
T26/0232	849	0.18	1.25	-0.48	0.27	7.39	8.68
T26/0243	849	-0.085	2.11	-1.153	0.31	4.75	6.43
T26/0501	849	-0.72	0.75	-1.79	0.79	21.68	23.30
T26/0494	849	-0.16	1.77	-4.49	0.93	8.05	10.43
T26/0535	150	-1.46	-0.52	-2.83	1.50	66.50	68.18
AREAS 4 & 5							
T26/0208	849	-0.39	1.08	-2.67	0.78	13.76	18.71
T26/0239	577	0.55	1.86	-0.87	0.75	26.04	30.74
T26/0170	529	-0.12	1.10	-1.79	0.70	21.75	27.78
T26/0003	599	0.48	1.60	-1.42	0.78	41.26	48.75

For a regional-scale groundwater model which has a high degree of geological complexity and in which aquifers are recognised to be heterogeneous, scaled errors of up to about 25% are considered satisfactory. This magnitude of error equates to a calibration fit of a metre or so. The majority of monitoring bores have errors within this range except for several in Area 2 where some very high scaled errors in excess of 200% occur. These high errors are associated with monitoring bores with very limited observation data (i.e. a small number of residuals) such as T26/0853 and T26/0800 and are therefore not considered to be of particular concern in the evaluation of the model calibration. Table 11.7 shows that these bores only provide a very small contribution to the overall model objective function. Other bores showing relatively high errors are discussed in detail below.

Figures 11.6 to 11.9 show the simulated and observed groundwater levels for the 16-year calibration period for the head calibration target sites. The model-to-measurement calibration is discussed for each area below.

(a) Area 1 (Waingawa Fan north of Masterton Fault)

Figure 11.6 shows the head calibration plots for the three observation bores in Area 1. Since the head targets are clustered to the west (Figure 11.5), evaluation of the calibration for this area using the available data is restricted. The collective phi for this area is 1,749 m^2, almost half of which is dominated by bore S26/0030 – the deepest bore in the fan sequence (38 m). The scaled error for this bore is also slightly high at 27-30% but is within an acceptable range for the other two bores (Table 11.8). There is limited knowledge of the deeper fan sequence which is likely to be highly heterogeneous and randomly sorted. The calibration at depth is therefore regarded to be acceptable, particularly given that there is only one calibration target. Simulated levels in the shallow fan sequence are good and indicate that the model would be capable of representing the interaction of the Waingawa River with the aquifer reasonably well.

(b) Area 2 (Waingawa Fan south of Masterton Fault)

Figure 11.7 shows the head calibration plots for the nine observation bores in Area 2. The head targets are reasonably well distributed across the area and the collective phi for the nine bores is 778 m^2. Despite this, the scaled errors (Table 11.8) for most bores in this group are very high which can be attributed to the very brief monitoring record available for many of the head calibration targets.

Close fits between modelled and observed heads are evident close to the Waingawa River (bore T26/0429) and within the Masterton springs (bore T26/0366). The head magnitudes and seasonal variation appear accurate and therefore simulation of groundwater discharge from the spring system is likely to be reliable. The remaining seven observation bores are concentrated near to the Ruamahanga River and all exhibit close general agreement with observed head data.

(c) Area 3 (Te Ore Ore basin)

There is good spatial representation of observation bores in the Te Ore Ore basin (Area 3). Together they contribute 37% to the total objective function due to a proportionately large number of observations in this area. Model-to-measurement head comparisons are shown in Figure 11.8 for this group of observation bores.

The particularly high phi for bore T26/0494 (733 m^2) is related to nearby irrigation abstraction which has, over the past five to six years, had a pronounced seasonal impact on local groundwater level monitoring. However, Table 11.8 shows that the scaled error for this bore is only 8-10.5% because of the high range in the observation data (nearly 9 m due to pumping). It is difficult for the model to accurately replicate such drawdowns because the thin productive (reworked) gravel aquifers which are exploited by high-volume irrigators are not (and can not be) explicitly represented. The high degree of heterogeneity in the sediments means that the model necessarily 'averages' the sequence using bulk representative material properties. Accurately replicating pumping-drawdown at deeper confined levels in the groundwater system can not therefore be expected.

Shallow bore T26/0535 (5.8 m deep) near the Poterau Stream, although having a fairly low contribution to phi because of the short monitoring record, has the highest scaled error (66-68%) for this group (Table 11.8). The relatively high discrepancy between the higher modelled level and observed level at this site (of nearly 2 m) is probably related to the influence of nearby drainage channels which affect shallow groundwater levels.

The remaining four observation target sites in Te Ore Ore show a good agreement between modelled and simulated heads and low scaled errors indicating an accurate reproduction of seasonal and long-term head patterns. The vertical head gradients in the basin are also accurately simulated.

(d) Area 4 and Area 5 (Waipoua and Upper fans)

There are three observation bores in Area 4 which contribute about 23% to the model phi attributable to the fact that about 20% of the total model residuals are assigned to this area. The scaled errors for each of the bores (Table 11.8) are all acceptable and Figure 11.9 visually shows a good general agreement between modelled and observed heads in this area.

The one observation bore in Area 5 (T26/0003) has a large scaled error (40-50%) indicative of a poor model-to-measurement fit. There is a poor level of hydrogeological knowledge in this area which is remote from the area of prime interest (i.e. the productive aquifers to the south of the Masterton Fault). It is unlikely that the calibration could be improved in Area 5 without additional observation data.

11.6.6 Water balance outputs and calibration

(a) Global water balance

The simulated water balance outputs for the model are provided in Figure 11.10. The first two plots (A and B) depict modelled recharge on a daily and annual basis. Rainfall recharge is highly seasonal, averaging 130,000 m^3/day over the 16-year calibration period. The annual average recharge for this period is 48 x 10^6 m^3.

Large inter-seasonal variability in annual recharge volume is evident in Figure 11.10B. Extremely dry periods occurred in 1993, 2001 and 2007, interspersed with unusually wet years of higher than average recharge.

Figure 11.10C shows modelled total groundwater abstraction for the Upper Valley catchment. The steep ramping up of abstraction from 2001/02 is particularly evident. The peak abstraction rate during the 2007/08 irrigation season is about 27,000 m^3/day (27 ML/d).

The simulated interaction between groundwater and the surface water environment is shown in Figure 11.10D. The fluxes between river and aquifer are shown as either as an input to groundwater (river recharge = positive flux) or as a discharge from groundwater to rivers and springs (discharge = negative flux). The discharge component dominates the fluxes as shown by the net loss to surface water plot. The additional water is sourced from rainfall recharge which must discharge to surface water or go into storage.

Figure 11.10 therefore illustrates the water balance dynamics on a bulk catchment-wide scale. On an annual average basis, roughly equal quantities of recharge occur from rainfall infiltration and river bed losses. However, at any particular time the balances are very different as shown in Table 11.9 which lists the modelled global water balances for two stress periods in 2008 – summer (30 January) and winter (2 July). During the late summer groundwater discharge to rivers and springs dominates the balance providing an important base flow to rivers. Recharge to the aquifer from rivers in other parts of the catchment is also higher during summer due to lower groundwater levels and increased vertical flow gradients around river channels.

The winter 2008 balance in Table 11.9 shows rainfall recharge to be the dominant input to the groundwater system – over four times higher than river recharge. About half the combined river and rainfall input is discharged back into surface water, with the remaining portion entering aquifer storage (with an accompanying rise in level).

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

	Flux in (m^3/day)	Flux out (m^3/day)
30 January 2008 – summer		
Rainfall recharge	0	
River recharge	119,200	
Abstraction		26,400
River/spring discharge		181,400
Change in storage	88,600	
Total	*207,800*	*207,800*
2 July 2008 – winter		
Rainfall recharge	407.400	
River recharge	87,300	
Abstraction		1,400
River/spring discharge		266,500
Change in storage		226,800
Total	*494,700*	*494,700*

(b) Water balance calibration

The automated PEST calibration process was periodically interrupted and manually checked against water balance observations. The patterns of river flow losses and gains discussed in Section 7.3 as well as quantitative observations of river/spring losses and gains (Figure 7.22) were used as calibration targets. Parameters such as transfer rate and adjacent hydraulic conductivity parameters were adjusted or constrained where necessary so that the calibration maintained consistency with not only groundwater head observations, but also with available water balance observations (Note: the FEFLOW (version 5.4) output file format will not allow PEST to directly access water balance information and thereby introduce water balance targets in the automated calibration process).

Figure 11.11 shows the pattern of flow gains and losses at the model transfer boundary nodes on the main river and spring systems during the summer of 2008 (13 March 2008, model day 5,740). Comparison with Figure 7.22 in Section 7.4 shows that the simulated pattern of gains and losses along the main river courses, particularly around the main fault structures, is consistent with the observed pattern.

From a quantitative perspective, the calibration has relied on measured flow losses and gains for specific river reaches (or transfer node ‘Groups’) and spring discharges as shown in Figure 11.12 The observed fluxes represent intermittent measurements and by no means provide a complete characterisation of the interaction between groundwater and surface water. However, they do provide a general guide for the magnitude and nature of the fluxes. Figures 11.13 to 11.17 show transient water balance outputs for each of the transfer node groups with reference to target fluxes.

Waingawa River

The Waingawa River represents the western model boundary and interaction between groundwater and the river occurs both to the east and west of the river. Only the easterly portion of the flux is represented in the Upper Valley model, although most of the movement out of the river to groundwater probably occurs to the east. This is particularly so above the Masterton Fault since the river historically flowed eastwards through the Masterton area. A network of permeable gravel-filled channels will assist in preferentially diverting bed losses in this direction.

The Waingawa River generally loses flow along its entire length from the Wairarapa Fault to the Ruamahanga confluence during the summer (Figure 7.21). Figure 11.13 displays the simulated aquifer-surface water fluxes along three reaches.

The highest reach (Group 12: Wairarapa Fault to Mokonui Fault) has a simulated summer loss to groundwater of between 300 and 500 L/s. The gauged summer loss (Figure 7.21) is also within this range. The next downstream reach (Group 13) has a measured neutral gain/loss pattern and corresponding simulated neutral flux in the summer.

A generally losing reach occurs between the Masterton Fault and the Ruamahanga River confluence (Group 14). The simulated loss/gain for Group 14 ranges from a flow gain of up to about 200 L/s in winter (a negative flux value on the plots represents loss from groundwater to surface water) to a river flow loss of up to about 200-300 L/s in summer. The gauged summer flux for the Group 14 reach ranges from a gain of 200 L/s to a loss of up to 500 L/s (Figure 7.21) – more than the simulated quantity because a portion of the flow loss will occur towards the west of the channel.

Waipoua River

Five transfer node groups represent the Waipoua River between the Wairarapa Fault and the Ruamahanga River confluence (Figure 11.14). The Waipoua River exhibits a complex pattern of losses and gains associated with the Mokonui and Masterton faults which restrict the flow of groundwater and force discharge in river reaches up-gradient of the faults. The simulated flux pattern is consistent with the observed pattern as shown in Figure 11.11.

Figure 11.14 shows the model output for the five groups (groups 1 – 5). The simulated fluxes are consistent with observed targets (refer to Figure 7.21) as summarised in Table 11.10.

Table 11.10: Simulated groundwater-surface water fluxes for the Waipoua River (summer)

Node group	Observation group location	Measured flux from/to river (L/s)	Simulated flux from/to river (L/s)
1	Wairarapa Fault to mid point between Wairarapa and Mokonui faults	Loss 150-200	Loss 200-300
2	Group 1 to Mokonui Fault	Neutral/gain?	Gain 100
3	Group 2 to mid point between Mokonui and Masterton faults	Neutral	Neutral loss/gain <50
4	Group 3 to Masterton Fault	Gain 200-250	Gain 200-250
5	Group 4 to Ruamahanga confluence	Loss 50-100	Neutral-loss 50

Ruamahanga River

The Ruamahanga River is represented by six transfer node groups (groups 6-11) in Figure 11.15. Gauged losses and gains in this river are subject to relatively large errors due to the higher flow volumes in this river. The simulated aquifer-river flux patterns and order-of magnitude quantities are consistent with the observed information (Figure 7.21).

Minor rivers

Figure 11.16 shows the modelled aquifer-river fluxes for the Kopuaranga and Whangaehu rivers. There are no reliable observation data for these rivers but the model provides an indication of how these systems interact with groundwater. The Whangaehu River is known to exhibit a restricted interaction with the shallow Te Ore Ore aquifer and the model suggests that it loses flow in the order of up to 100 L/s to groundwater, dropping to zero loss seasonally (Groups 16 and 17). The Kopuaranga River (Group 21) seems to gain flow from groundwater at a rate of 100-200 L/s.

Springs

Figure 11.17 shows the simulated groundwater discharges to principal spring systems. The Poterau Stream (Group 15) shows a declining summer flow from about 100 L/s to about 50 L/s at the end of the calibration run (summer 2007/08). The decline mirrors the increasing abstraction trend and does not appear to be related to rainfall recharge trends (Figure 11.10). Winter base flow in this system frequently exceeds 250-300 L/s and can peak at over 600 L/s (surface water runoff will also contribute to the flow in the stream during the winter).

Transfer node groups 18-21 show the modelled discharges to the Masterton spring system (divided into a three main ‘arms’ – Makoura, Kuripuni and Solway). The simulated flows in all parts of the system are consistent with observed gauging data.

In general, review of the model water balance outputs for the calibration period shows that the flow dynamics between the aquifer and the surface water environment (rivers and springs) are consistent with observed flux patterns and measured quantities.

11.6.7 Calibrated parameter values

Tables 11.11 and 11.12 list the optimised values for unknown and tied model parameters respectively. Table 11.11 shows the lower and upper bounds placed on each of the unknown parameters to ensure that PEST maintains consistency with plausible ranges derived from groundwater pump tests and acceptable ranges for the material types.

Table 11.11: Calibrated parameters for the Upper Valley catchment transient groundwater flow model (Kx – horizontal hydraulic conductivity, Kz – vertical hydraulic conductivity, St – specific yield, Ss – specific storage). Kx and Kz values are in m/day.

Parameters	Lower bound	Upper bound	Calibrated value	95% confidence limits		Hydrostrat. unit(s), area and age
				Lower	Upper	
Kx02	50	180	180	169.3	191.4	(1) Waingawa fan Q2
Kx04	3	10	3	2.6	3.5	(4, 5) Upper Waipoua and Ruam fans Q2+
Kx06	90	120	116.7	102.7	132.6	(2,3,4,5) Q1 channel gravels
Kx08	10	60	60	56.1	64.1	(4) Waipoua fan north Lansdowne Q2+
Kx09	90	110	110	95.8	126.3	(3) Te Ore Ore east Q2-4
Kx11	60	80	80	71.0	90.1	(3) Te Ore Ore west Q1
Kx12	80	110	80	59.7	107.3	(2) Waingawa fan Q2
Kx16	5	60	20.3	19.8	20.8	(1) Fan north Masterton Fault Q2+
Kx19	50	150	150	143.9	156.4	(4) Waipoua Q1 gravels
Kx20	60	110	60	53.4	67.4	(2,3,4,5) Q1-2 channel gravels
Kx22	30	50	50	45.4	55.0	(1) Fan north Masterton Fault Q2+
Kx23	60	100	60	49.9	72.1	(2) Waingawa fan Q2+
Kx24	60	110	110	102.1	118.5	(3) Te Ore Ore west Q2+
Kx27	50	80	80	68.0	94.2	(3) Te Ore Ore transition Q2+
Kx28	8	30	19.4	13.2	28.4	(3) Te Ore Ore transition Q4+
Kx30	30	70	70	66.7	73.4	(3) Te Ore Ore east Q2-4
Kx36	40	80	78.1	75.2	81.1	(3, 2) Te Ore Ore west + Waingawa fan Q4+
Kz40	0.1	2	0.44	0.38	0.49	(1) Fan north Masterton Fault Q2+

Table 11.11 *cont.:* Calibrated parameters for the Upper Valley catchment transient groundwater flow model

Parameters	Lower bound	Upper bound	Calibrated value	95% confidence limits		Hydrostrat. unit(s), area and age
				Lower	Upper	
Kx36	40	80	78.1	75.2	81.1	(3, 2) Te Ore Ore west + Waingawa fan Q4+
Kz40	0.1	2	0.44	0.38	0.49	(1) Fan north Masterton Fault Q2+
Kz43	0.1	1	1	0.62	1.61	(4) Waipoua Q1
Kz44	1.00E-02	0.2	0.07	0.06	0.09	(2,3,4,5) Q1-2 channel gravels
Kz46	5.00E-02	0.8	0.05	0.043	0.059	(4, 5) Upper Waipoua and Ruam fans Q2+
Kz47	1.00E-02	0.2	0.01	0.007	0.014	(3) Te Ore Ore west Q1-2
Kz49	1.00E-02	0.2	0.06	0.04	0.09	(3) Te Ore Ore east Q1-2
Kz50	5.00E-02	0.8	0.8	0.56	1.14	(2) Waingawa fan Q2
Kz54	0.2	5	0.2	0.18	0.22	(4, 5) Upper Waipoua and Ruam fans Q2+
Kz56	1.00E-02	0.2	0.2	0.18	0.20	(4) Waipoua R. Q1
Kz57	1.00E-03	5.0E-02	0.0024	0.0014	0.0043	(2,3,4,5) Q1-2 channel gravels
Kz59	1.00E-02	0.2	0.033	0.0299	0.0368	(1) Waingawa fan Q2+
Kz60	1.00E-02	0.2	0.2	0.0695	0.5751	(2) Waingawa fan Q2+
Kz62	1.00E-03	1.0E-02	0.0057	0.0052	0.0063	(3) Te Ore Ore basin Q2+
Kz67	5.00E-02	5	0.05	0.0461	0.0542	(1) Fan N. Masterton fault Q4+
Kz70	1.00E-04	5.0E-03	0.0028	0.0011	0.0073	(3) Te Ore Ore east Q4+
Kz76	1.00E-04	8.0E-03	0.0001	0.00003	0.0003	(2,3) Te Ore Ore + Ruamahanga Q6+
Ss78	5.00E-06	3.0E-04	0.00013	0.00012	0.00014	(1, 3, 4, 5) Fan deposits Q2+
St82	2.00E-02	0.15	0.15	0.1327	0.1695	(1,2,3,4,5) Q1-2 channel gravels
St83	2.00E-02	0.15	0.15	0.1398	0.1610	(1,2) Waingawa fan Q2+
St84	1.00E-02	0.1	0.01	0.0089	0.0112	(3) Te Ore Ore basin, Q1
Ss97	1.00E-06	1.0E-04	0.0000023	0.000001	0.000004	(3) Te Ore Ore basin, Q4+1
Kx100	20	90	20	17.20	23.25	(2,3) Te Ore Ore + Ruamahanga Q6+
Kz102	5.00E-05	8.0E-03	0.00026	0.0001	0.0007	(2,3) Te Ore Ore + Ruamahanga Q6+

Table 11.12: Tied parameters and calibrated values for the Upper Valley transient groundwater flow model (Kx – horizontal hydraulic conductivity)

Parameters	Tied	Calibrated value
Kx03	Tied Kx02	270
Kx10	Tied Kx09	98.2
Kx14	Tied Kx11	80
Kx15	Tied Kx16	4.1
Kx18	Tied Kx22	50
Kx25	Tied Kx36	44.6
Kx26	Tied Kx100	10
Kx29	Tied Kx100	5
Kx31	Tied Kx28	15.1
Kx32	Tied Kx100	3.9
Kx33	Tied Kx30	35
Kx34	Tied Kx28	5.6
Kx35	Tied Kx100	1.25
Kx37	Tied Kx36	55.8
Kz41	Tied Kz40	0.27
Kz42	Tied Kz46	0.05
Kz48	Tied Kz47	0.01
Kz52	Tied Kz49	0.046
Kz53	Tied Kz54	0.2
Kz55	Tied Kz59	0.2
Kz61	Tied Kz62	0.009
Kz63	Tied Kz62	0.001
Kz64	Tied Kz62	0.0014
Kz68	Tied Kz76	0.00036
Kz69	Tied Kz102	0.00027
Kz71	Tied Kz102	0.00027
Kz72	Tied Kz70	0.0009
Kz73	Tied Kx102	0.00026
Kz74	Tied Kz70	0.0009
Kz75	Tied Kz102	0.00028
Kz77	Tied Kz76	0.0001

Table 11.11 also lists the 95% confidence intervals for the estimated parameters and the parameters tied to them, independent of the parameter bounds. 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 are estimated by PEST.

Figure 11.18 compares the measured ranges for hydraulic conductivity (black crossed lines) for various areas and hydrostratigraphic units (Table 7.5) with the calibrated values (represented as coloured squares). It can be seen that the automatic PEST calibration process has predicted values for hydraulic conductivity close to the observed ranges. Such consistency reduces the level of uncertainty and non-uniqueness associated with the model (Section 11.2).

11.6.8 Parameter sensitivity

Parameter sensitivities are listed in Table 11.13. PEST calculates the composite sensitivities following the calculation of the Jacobian matrix for each iteration. The relative sensitivity (obtained by multiplying the composite value by the magnitude of the value of the parameter) assists in comparing the effects of different parameters of different magnitude on the calibration process.

The relative sensitivities have been plotted in Figure 11.19 to help identify those parameters which most affect the calibration and to identify any parameters which may degrade the performance of the parameter estimation process (i.e. very insensitive parameters due to high degrees of correlation and/or an absence of observation data within some parameter zones).

In terms of insensitive parameters, Figure 11.19 shows that many of the Kz (vertical hydraulic conductivity) zones such as Kz40 to Kz50, Kz57 and Kz60 have low sensitivities. This is probably because there are sparse observation sites located in the different model layers from which this parameter can be accurately estimated outside the Te Ore Ore basin. The fixing or assigning of relatively narrow bounds to insensitive parameters during the estimation process (Table 11.11) has helped to reduce their effects on the calibration process. There is only one horizontal hydraulic conductivity zone which exhibits a low sensitivity – Kx04 – which covers the upper, northern fan areas. Again, there is a lack of monitoring data in this area (there is only one monitoring bore) and a tight bound was consequently used to constrain this parameter.

Table 11.14 lists the parameters which are highly sensitive (Figure 11.19) and which the model has therefore estimated with a higher degree of certainty. The most sensitive parameters are horizontal hydraulic conductivity and specific yield in the Te Ore Ore basin in layers 1 and 2. This is probably because of the larger number of observation bores in this basin at different depths. Other highly sensitive parameters include specific storage (Ss78) of the fan deposits in all areas and hydraulic conductivity in the deeper Te Ore Ore basin aquifers (Kx36) and deeper fan deposits north of the Masterton Fault (Kx16). The sensitive parameters generally occur in the southern and central part of the model where there is a good spread of observation data.

Table 11.13: Parameter composite and relative sensitivity for the Upper Valley catchment transient groundwater flow model (Kx – horizontal hydraulic conductivity, Kz – vertical hydraulic conductivity, St – specific yield, Ss – specific storage). Kx and Kz values are in m/day.

Parameter	Hydrostrat. unit(s), area and age	Composite sensitivity	Relative sensitivity
Kx02	(1) Waingawa fan Q2	7.33E-03	1.65E-02
Kx04	(4, 5) Upper Waipoua and Ruamahanga fans Q2+	2.39E-03	1.14E-03
Kx06	(2,3,4,5) Q1 channel gravels	2.79E-03	5.77E-03
Kx08	(4) Waipoua fan north of Lansdowne Q2+	7.06E-03	1.26E-02
Kx09	(3) Te Ore Ore east Q2-4	3.46E-03	7.06E-03
Kx11	(3) Te Ore Ore west Q1	1.65E-02	3.15E-02
Kx12	(2) Waingawa fan Q2	2.56E-03	4.87E-03
Kx16	(1) Fan north of Masterton Fault Q2+	2.01E-02	2.63E-02
Kx19	(4) Waipoua Q1 gravels	1.36E-02	2.95E-02
Kx20	(2,3,4,5) Q1-2 channel gravels	3.58E-03	6.36E-03
Kx22	(1) Fan north Masterton Fault Q2+	9.91E-03	1.68E-02
Kx23	(2) Waingawa fan Q2+	4.25E-03	7.55E-03
Kx24	(3) Te Ore Ore west Q2+	1.07E-02	1.07E-02
Kx27	(3) Te Ore Ore transition Q2+	4.54E-03	8.64E-03
Kx28		1.99E-03	2.56E-03
Kx30	(3) Te Ore Ore east Q2-4	1.95E-02	3.59E-02
Kx36	(3, 2) Te Ore Ore west + Waingawa fan Q4+	1.46E-02	2.76E-02
Kz40	(1) Fan north of Masterton Fault Q2+	5.24E-03	1.89E-03
Kz43	(4) Waipoua Q1	5.39E-03	5.39E-03
Kz44	(2,3,4,5) Q1-2 channel gravels	2.18E-03	2.46E-03
Kz46	(4, 5) Upper Waipoua and Ruamahanga fans Q2+	3.24E-03	4.21E-03
Kz47	(3) Te Ore Ore west Q1-2	1.63E-03	3.26E-03
Kz49	(3) Te Ore Ore east Q1-2	1.88E-03	2.33E-03
Kz50	(2) Waingawa fan Q2	1.60E-03	1.55E-04
Kz54	(4, 5) Upper Waipoua and Ruamahanga fans Q2+	1.71E-02	1.19E-02
Kz56	(4) Waipoua R. Q1	2.15E-02	1.54E-02
Kz57	(2,3,4,5) Q1-2 channel gravels	9.69E-04	2.53E-03
Kz59	(1) Waingawa fan Q2+	9.53E-03	1.41E-02
Kz60	(2) Waingawa fan Q2+	1.15E-03	8.02E-04
Kz62	(3) Te Ore Ore basin Q2+	8.92E-03	2.00E-02
Kz67	(1) Fan north of Masterton Fault Q4+	2.18E-02	2.84E-02
Kz70	(3) Te Ore Ore east Q4+	5.30E-03	1.36E-02
Kz76	(2,3) Te Ore Ore + Ruamahanga Q6+	1.06E-03	4.22E-03
Ss78	(1, 3, 4, 5) Fan deposits Q2+	7.59E-03	2.95E-02
St82	(1,2,3,4,5) Q1-2 channel gravels	2.88E-03	2.37E-03
St83	(1,2) Waingawa fan Q2+	8.58E-03	7.07E-03
St84	(3) Te Ore Ore basin, Q1	2.07E-02	4.14E-02
Ss97	(3) Te Ore Ore basin, Q4+1	1.66E-03	9.39E-03
Kx100	(2,3) Te Ore Ore + Ruamahanga Q6+	6.31E-03	8.21E-03
Kz102	(2,3) Te Ore Ore + Ruamahanga Q6+	5.27E-03	1.89E-02

Table 11.14: Summary of sensitive parameters for the Upper Valley catchment transient groundwater flow model (Kx – horizontal hydraulic conductivity, Kz – vertical hydraulic conductivity, St – specific yield, Ss – specific storage). Kx and Kz values are in m/day.

Parent parameter and tied parameters (brackets)	Relative sensitivity	Area	Model layer
St84	4.14E-02	(3) Te Ore Ore basin	1
Kx30 (Kx33)	3.59E-02	(3) Te Ore Ore east	2
Kx11 (Kx14)	3.15E-02	(3) Te Ore Ore east	1
Ss78	2.95E-02	(1, 3, 4, 5) Fan deposits	3-4
Kx19	2.95E-02	(4) Waipoua Q1 gravels	2
Kz67	2.84E-02	(1) Fan north of Masterton Fault	3-4
Kx36 (Kx25/37)	2.76E-02	(3, 1) Te Ore Ore west + Waingawa fan	3-4
Kx16 (Kx15)	2.63E-02	(1) Fan north of Masterton Fault	2-4
Kz62 (Kz61/63/64)	2.00E-02	(3) Te Ore Ore basin	2
Kz102 (Kz69/71/73/75)	1.89E-02	(3, 2) Te Ore Ore + Ruamahanga	4
Kx22 (Kx18)	1.68E-02	(1) Fan north of Masterton Fault	2
Kx02 (Kx03)	1.65E-02	(1,2) Waingawa fan and Waingawa Q1	1
Kz56	1.54E-02	(4) Waipoua R. Q1	2
Kz59 (Kz55)	1.41E-02	(1,2) Waingawa fan + Waingawa Q1	2
Kz70 (Kz72/74)	1.36E-02	(3) Te Ore Ore east	3
Kx08	1.26E-02	(4) Waipoua fan north Lansdowne	2
Kz54 (Kz53)	1.19E-02	(4, 5) Upper Waipoua and Ruamahanga fans	2

11.7 Summary

The Upper Valley catchment transient-flow groundwater model was calibrated for the period 1992–2008 to observed groundwater levels and to mass balance measurements. The calibration was evaluated in both qualitative and quantitative terms by comparing the simulation results with field measurements. Simulated mass balances and groundwater heads exhibit a good overall visual and statistical fit to observed data.

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

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

The importance of incorporating surface water–aquifer fluxes in the calibration process is stressed. Since the Upper Valley catchment groundwater system is essentially ‘closed’, the modelled output fluxes from the system are correlated to the inputs, particularly rainfall recharge. Calibration of the model to observed surface water outputs therefore provides a validation of the simulated spatial and temporal recharge dynamics (Appendix 2).

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 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, greater confidence can be placed in the calibration robustness in the southern part of the model area, below the Masterton Fault, incorporating the Te Ore Ore basin. Reduced confidence in the calibration in the northern, upper fan areas largely reflects a paucity of observation data. The resource potential in this area is, however, poor and the calibration uncertainty should not impact on the predictive ability of the model in the southern area.

11.8 Model limitations

There are a number of limitations and assumptions associated with the Upper 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 Waipoua 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 many of the spring systems for model calibration. This is mainly due to the fact that springs have a number of channels distributed over a wide area. Many groundwater discharges also probably lose a significant amount of water to evapo-transpiration around wetland areas. Where there is no LIDAR coverage (in the northern upper catchment area), spring and stream bed levels were estimated using the 20 m topographic map. In this respect, the upper surface of the model was assigned using the 20 m topographic data which may have an error of +/-5 m. It is therefore not feasible to allow the model to remove water when simulated heads reach the ground surface. However, this was addressed by assigning discrete spring and drain channels using transfer nodes.

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

- *Permitted abstractions*: there are a large number of permitted takes (generally less than 20 m^3/day) in the Upper 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.

Despite the above limitations and assumptions, the calibration outputs provide confidence that the transient numerical FEFLOW model provides a good representation of the Upper 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 'Upper Valley catchment' of the Wairarapa Valley. Filled with late Quaternary alluvium and glacial outwash deposits to depths in excess of 50 m, the basin hosts a highly heterogeneous groundwater system containing multiple discontinuous water-bearing strata. Major faulting and folding, both historical and contemporary, add considerable complexity to the hydrogeological functioning of the basin. Despite these complexities, the groundwater system appears to behave as a hydraulic continuum on a regional scale.

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

The Upper 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. Both rainfall infiltration and river bed leakage are important recharge sources. Groundwater abstractions constitute more than 10% of the catchment water balance during the summer months and may significantly impact aquifer discharge processes.

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

Groundwater abstraction has increased steeply 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 27,000 m^3/day, whilst the total maximum allocation was about 46,000 m^3/day.

Temporal changes in the dynamics of the groundwater system are attributable to a combination of natural climatic variability and rapidly developing abstraction stresses. Areas such as the Te Ore Ore basin show clear evidence of abstraction-related seasonal declines in groundwater level. In some areas the abstractions impact on base flow to surface water systems, or directly deplete flows in rivers such as the Ruamahanga.

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

Calibration robustness was achieved for the principal aquifers – the Q1 shallow unconfined aquifer of the Waingawa, Waipoua and Ruamahanga floodplains and the semi-confined aquifers in the Te Ore Ore basin.

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

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

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Figures

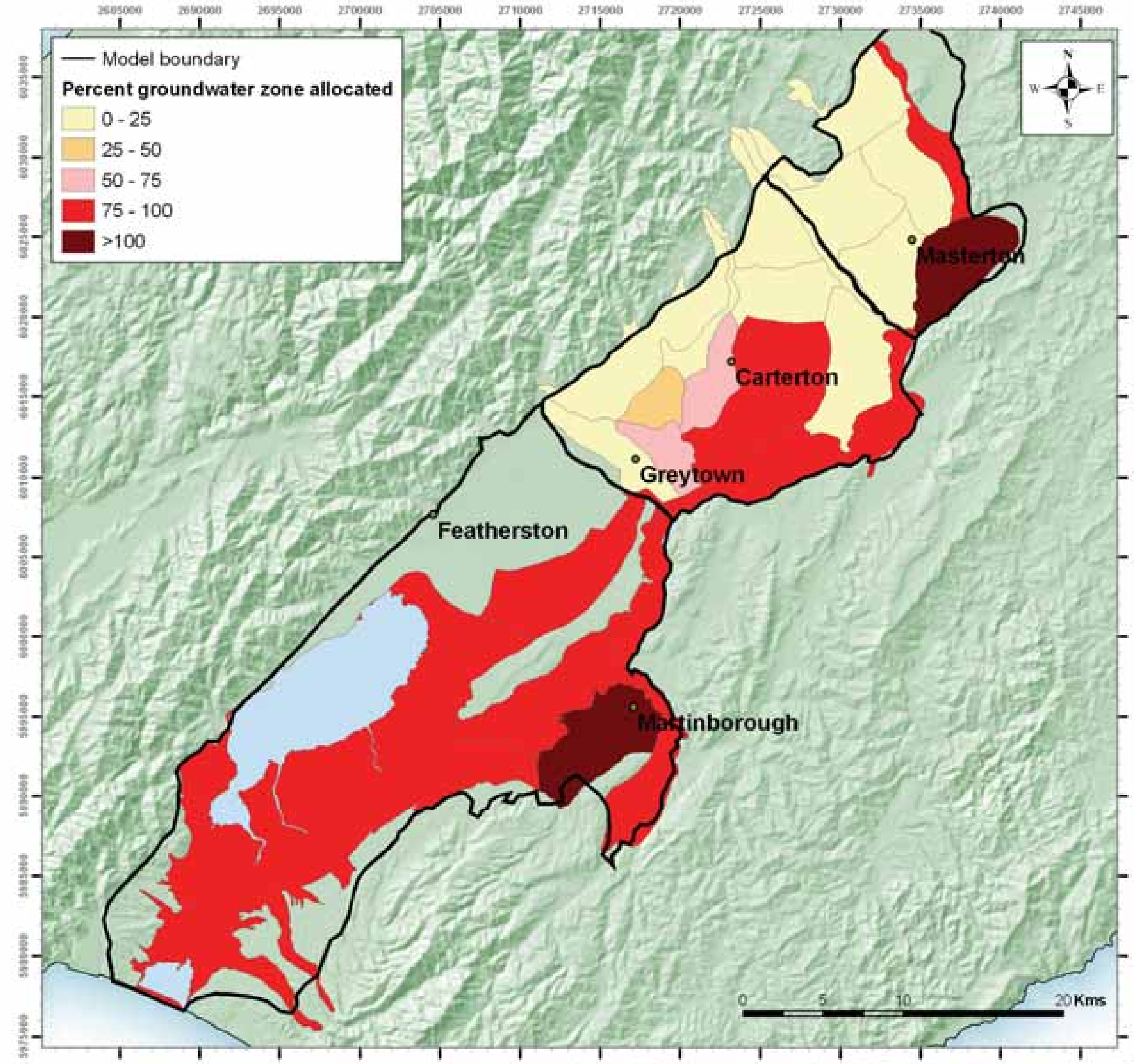

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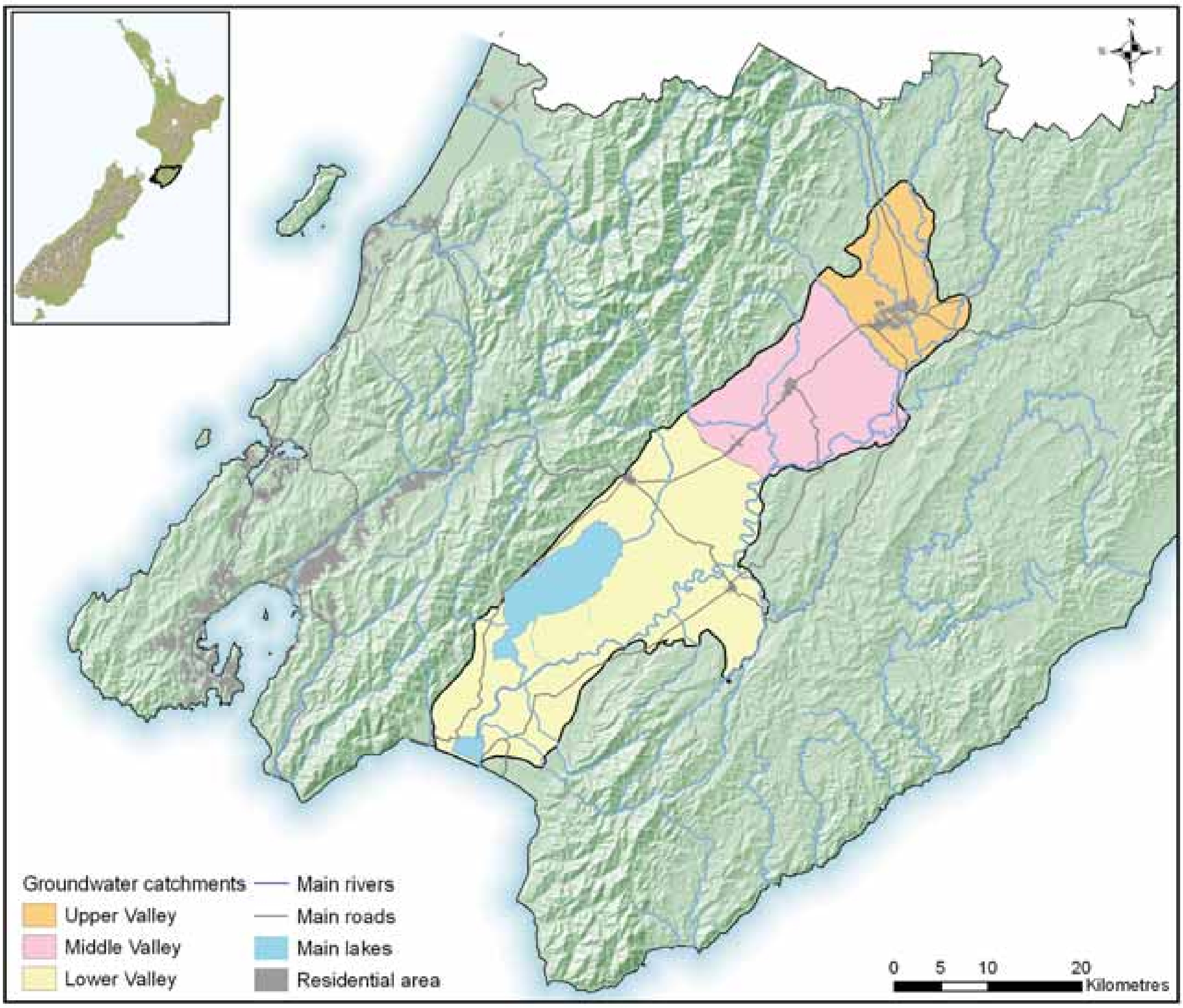
Figure 1.1: Allocation (%) of Wairarapa Valley groundwater zones as at June 2008



(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

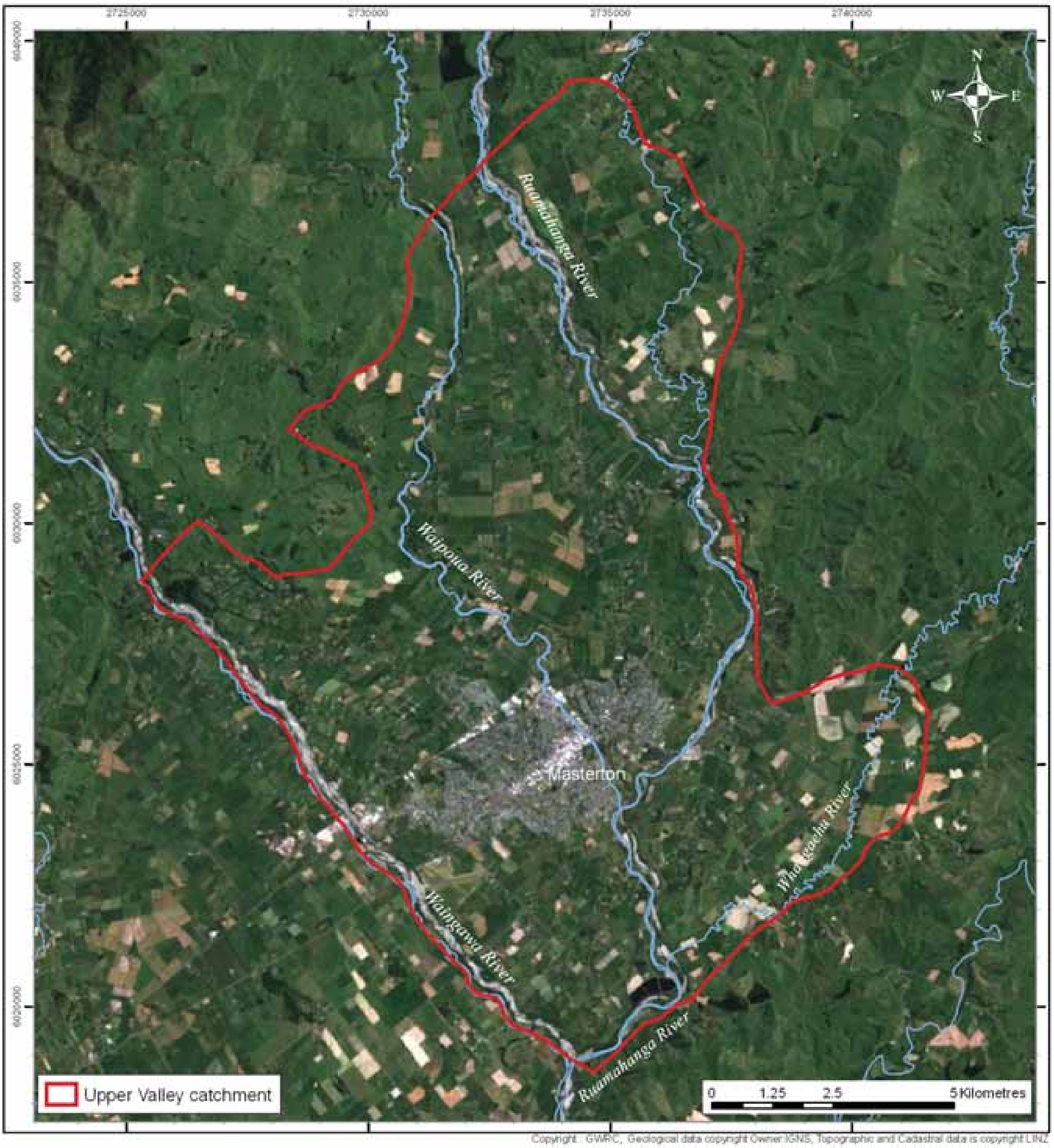


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Figure 2.1: Upper Valley catchment study area. Background image is Landsat 7 EMT 2003.

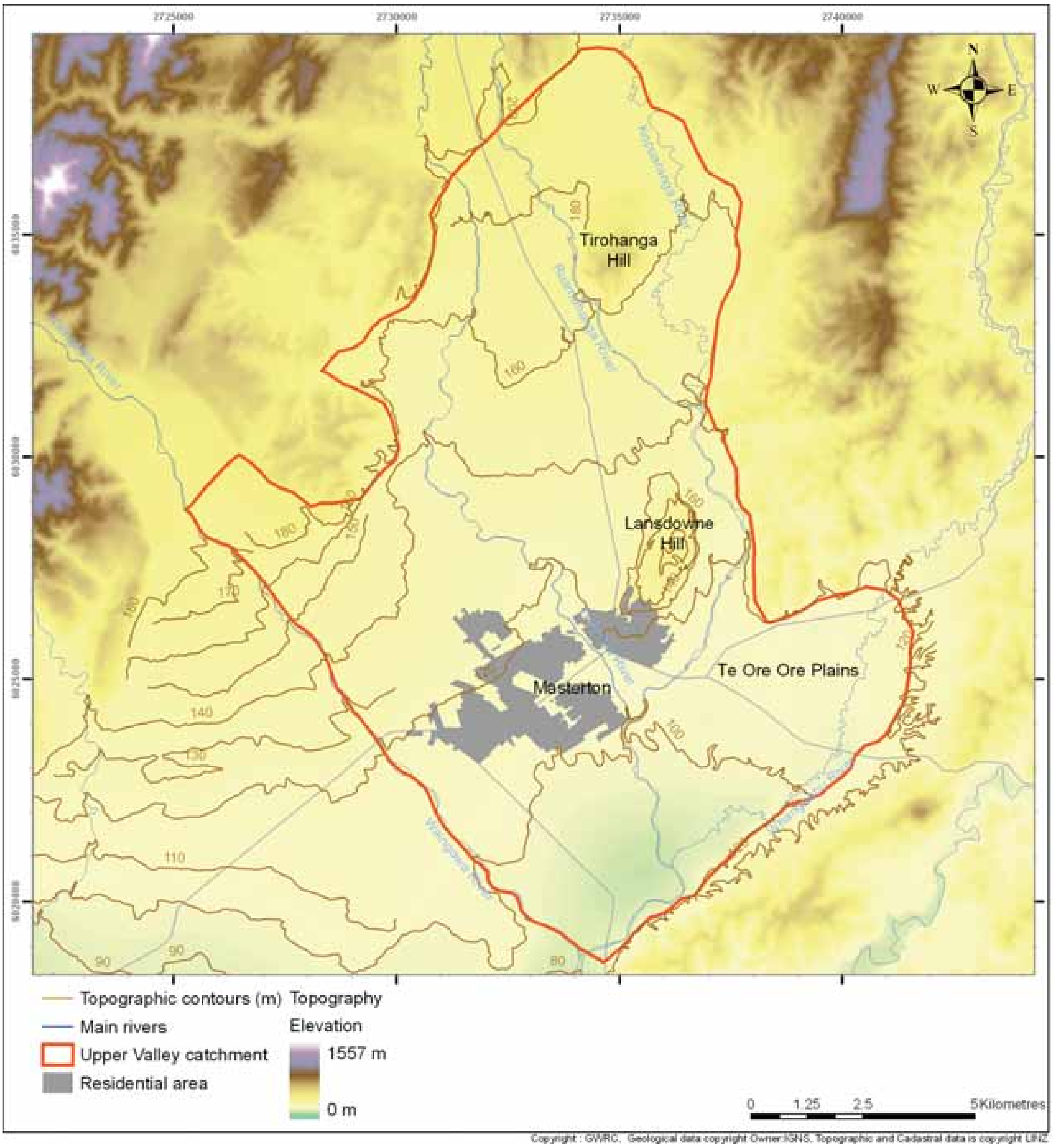

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Figure 2.2: Upper Valley catchment – topographic contour map

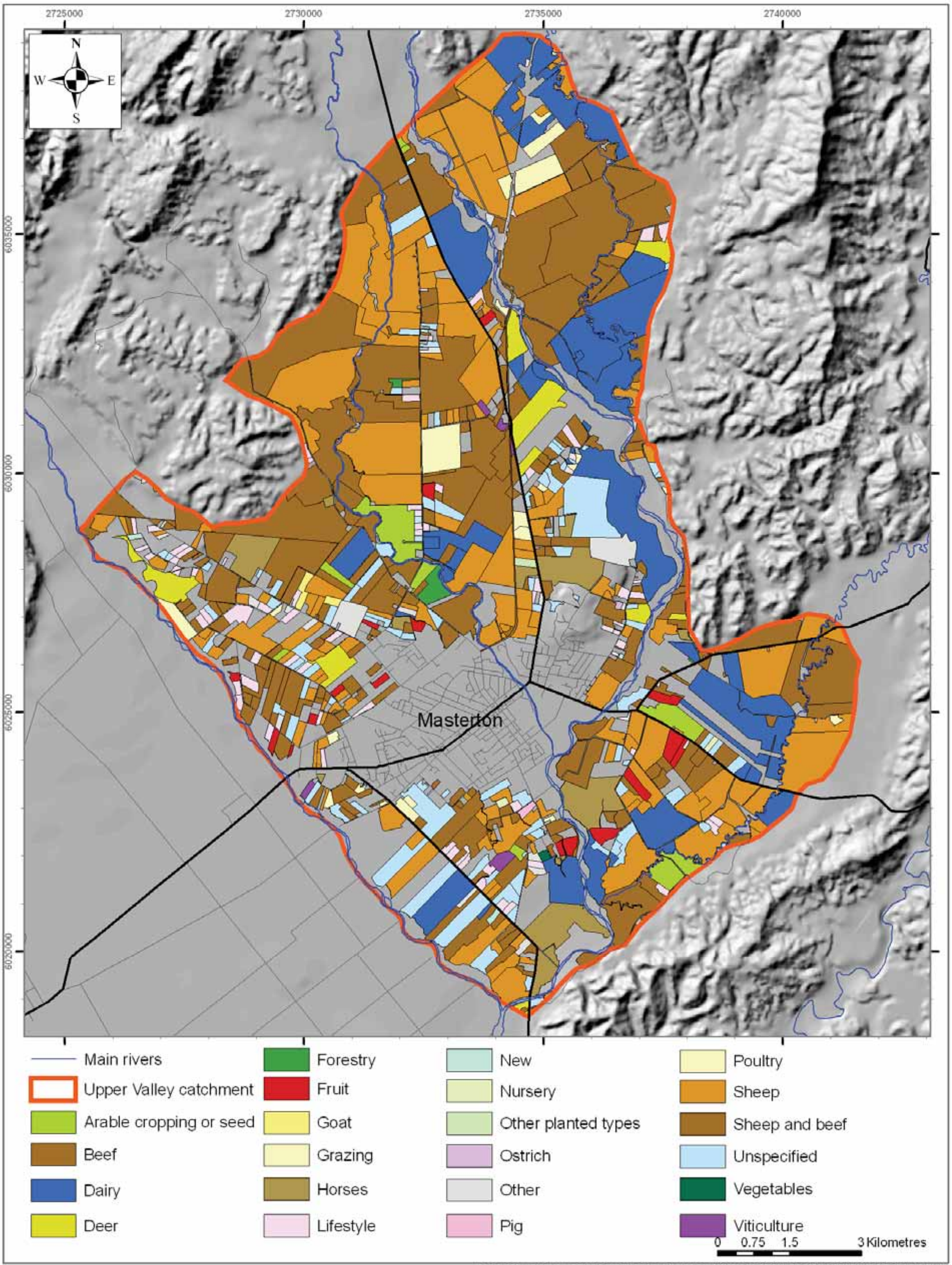

Figure 2.3: Landuse map, derived from Agribase (2001 version). Note the dominant sheep, beef and dairy landuse within the catchment.

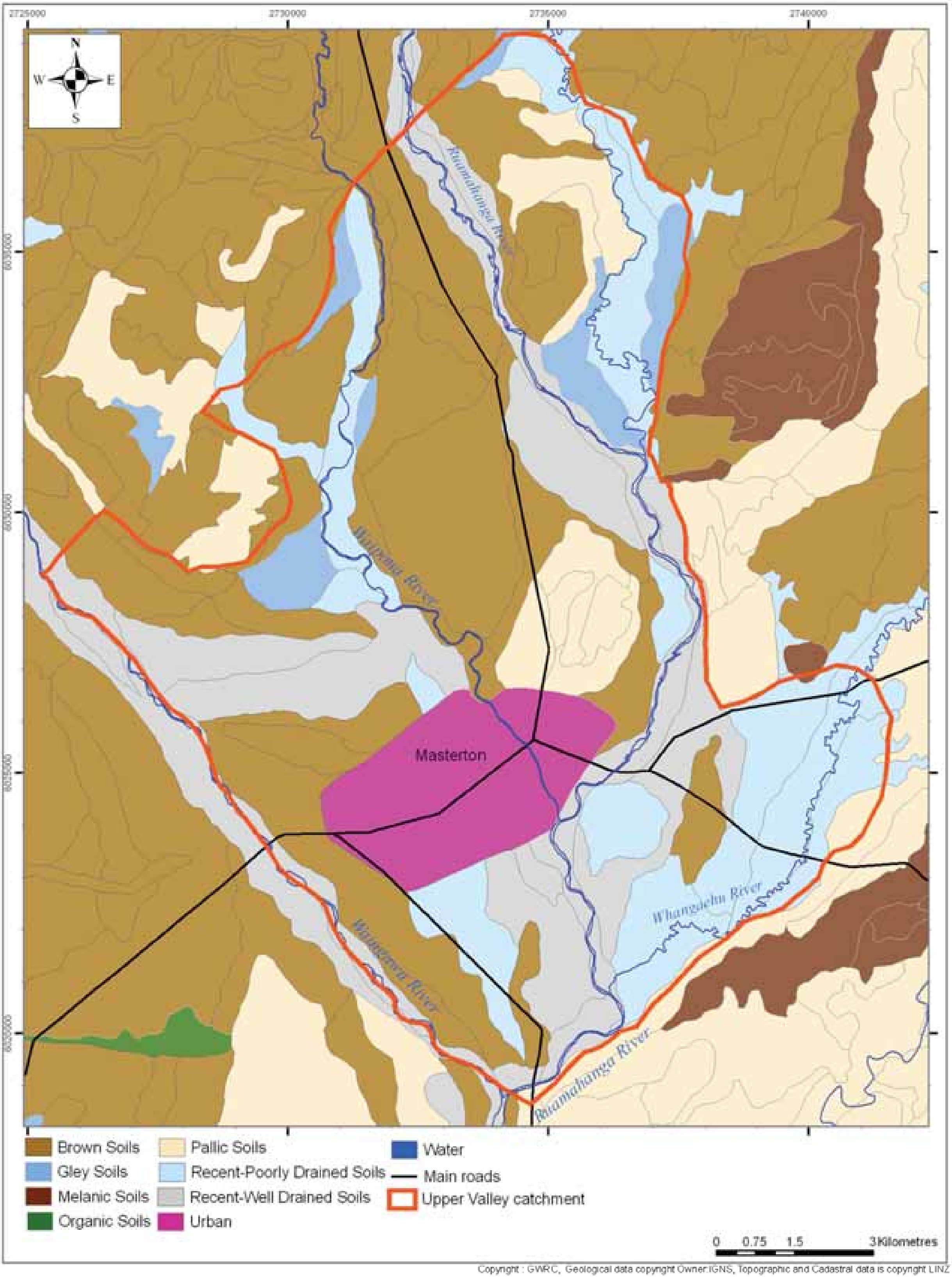

Figure 2.4: Soils of the Upper Valley catchment (Source: NZLRI)

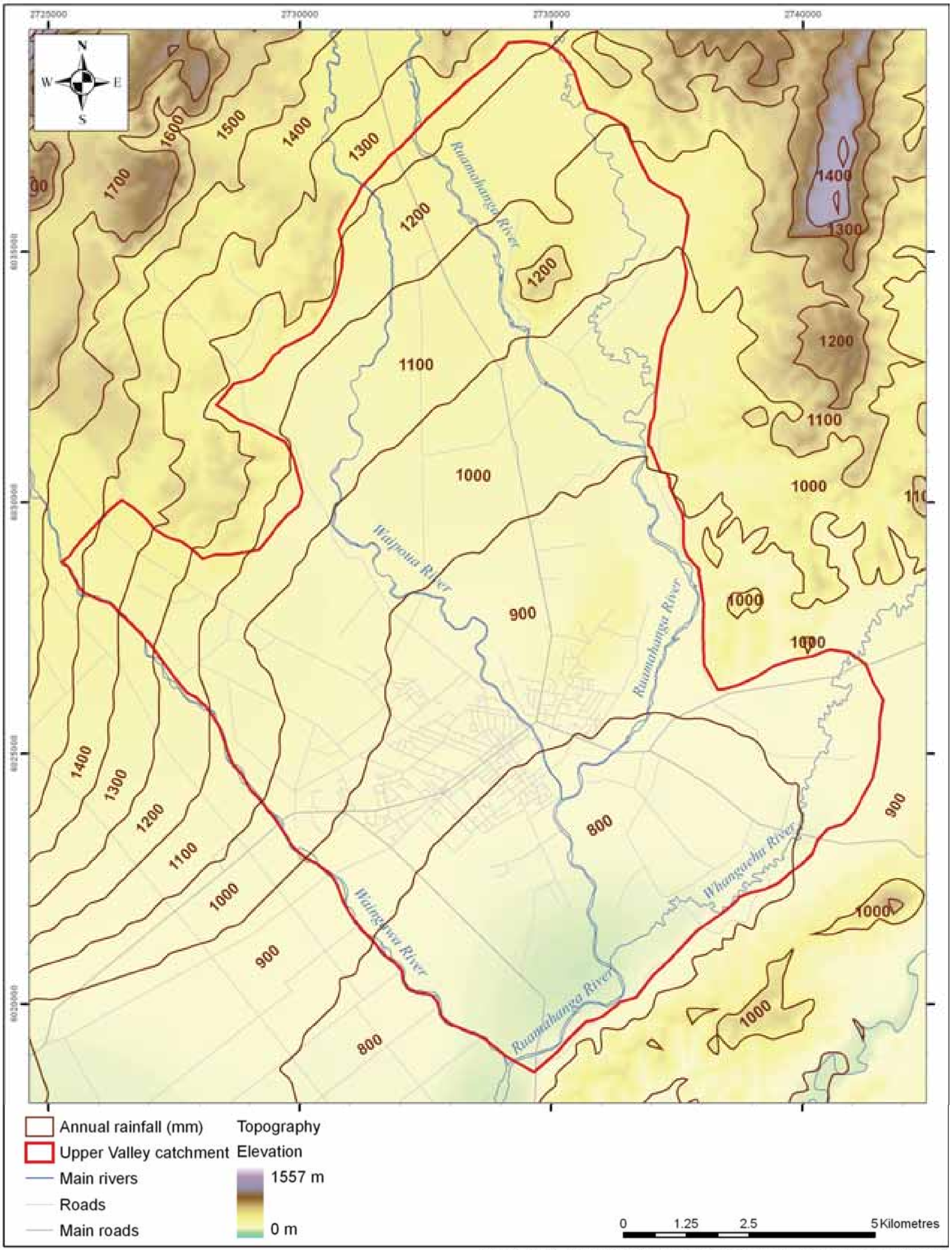

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Figure 2.5: Annual average rainfall isohyet map for the Upper Valley catchment (Source: LENZ)

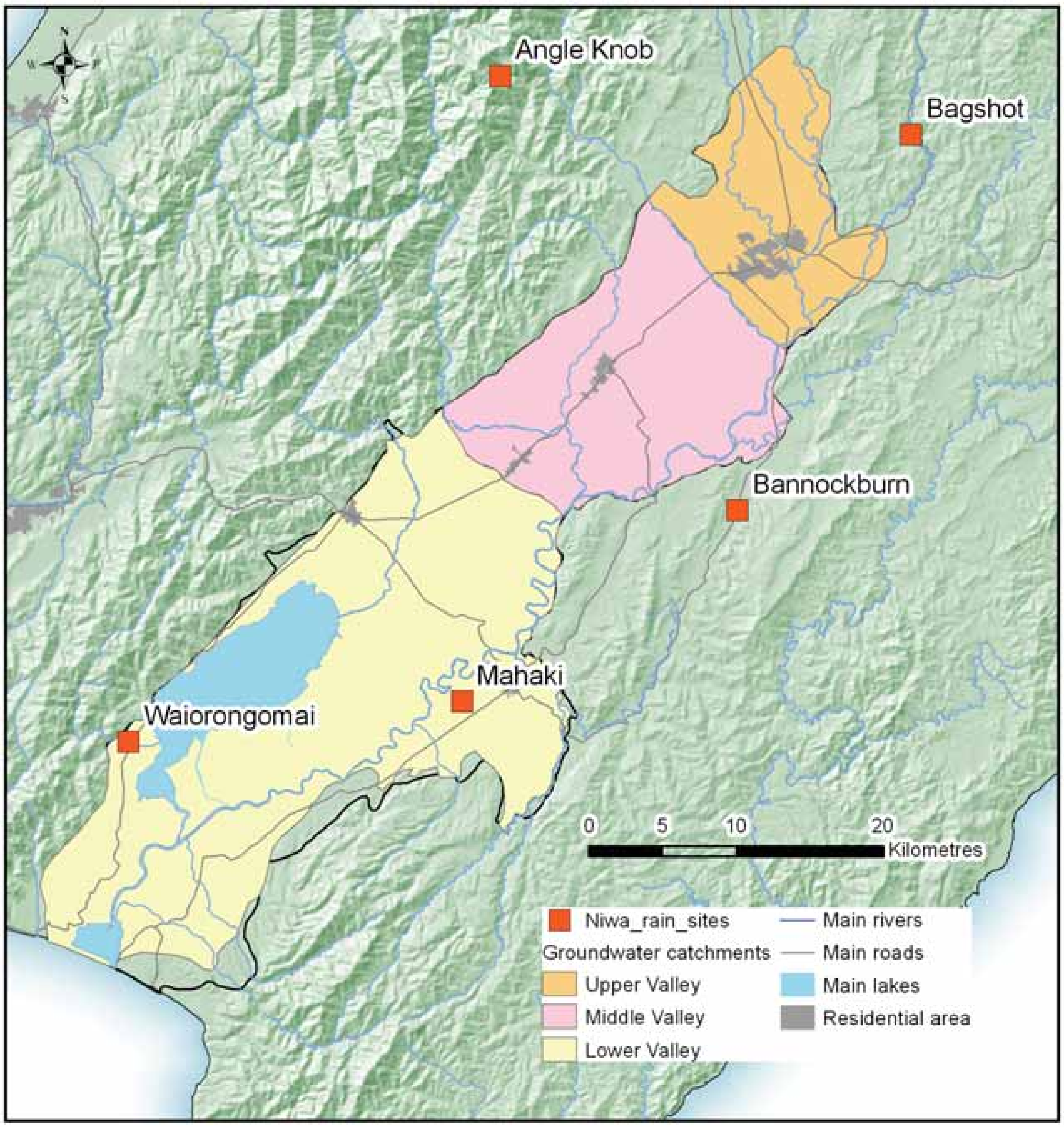

Figure 2.6: Long-term NIWA rainfall monitoring sites in the Wairarapa Valley and surrounding area

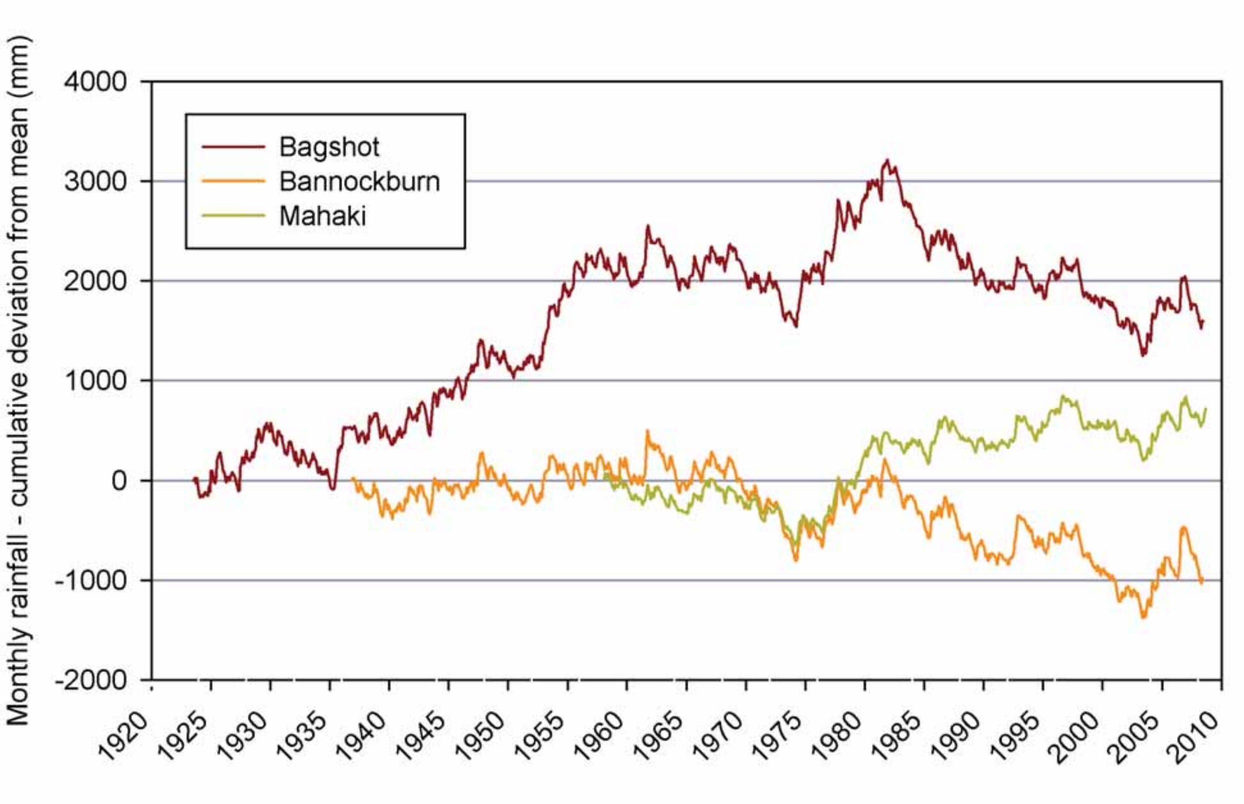

Figure 2.7: Cumulative deviation from the monthly mean rainfall plot (cusum) for long-term rainfall monitoring sites

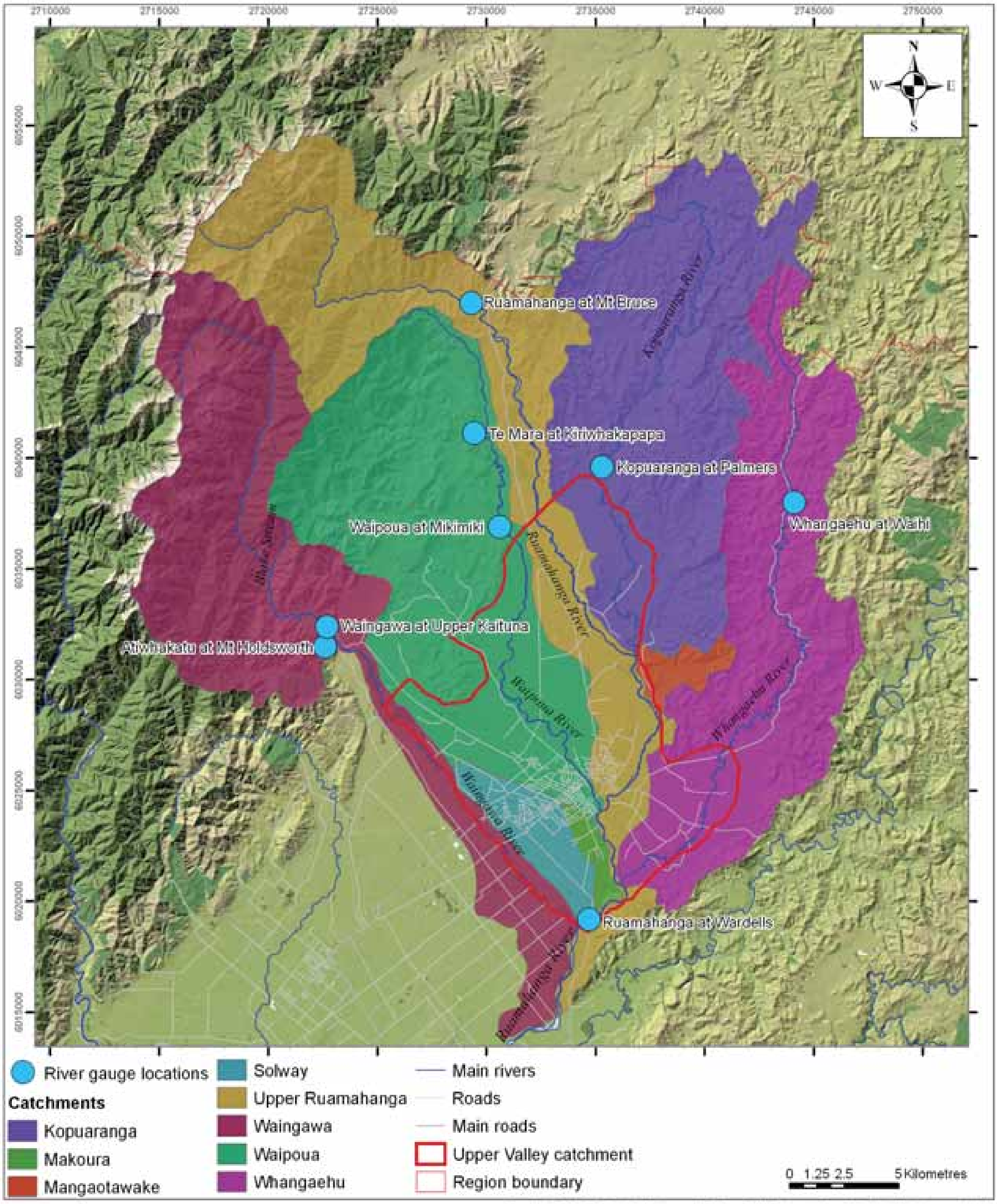

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Figure 3.1: Surface water gauge locations and catchments boundaries. Also shown is the Upper Valley catchment study area boundary.

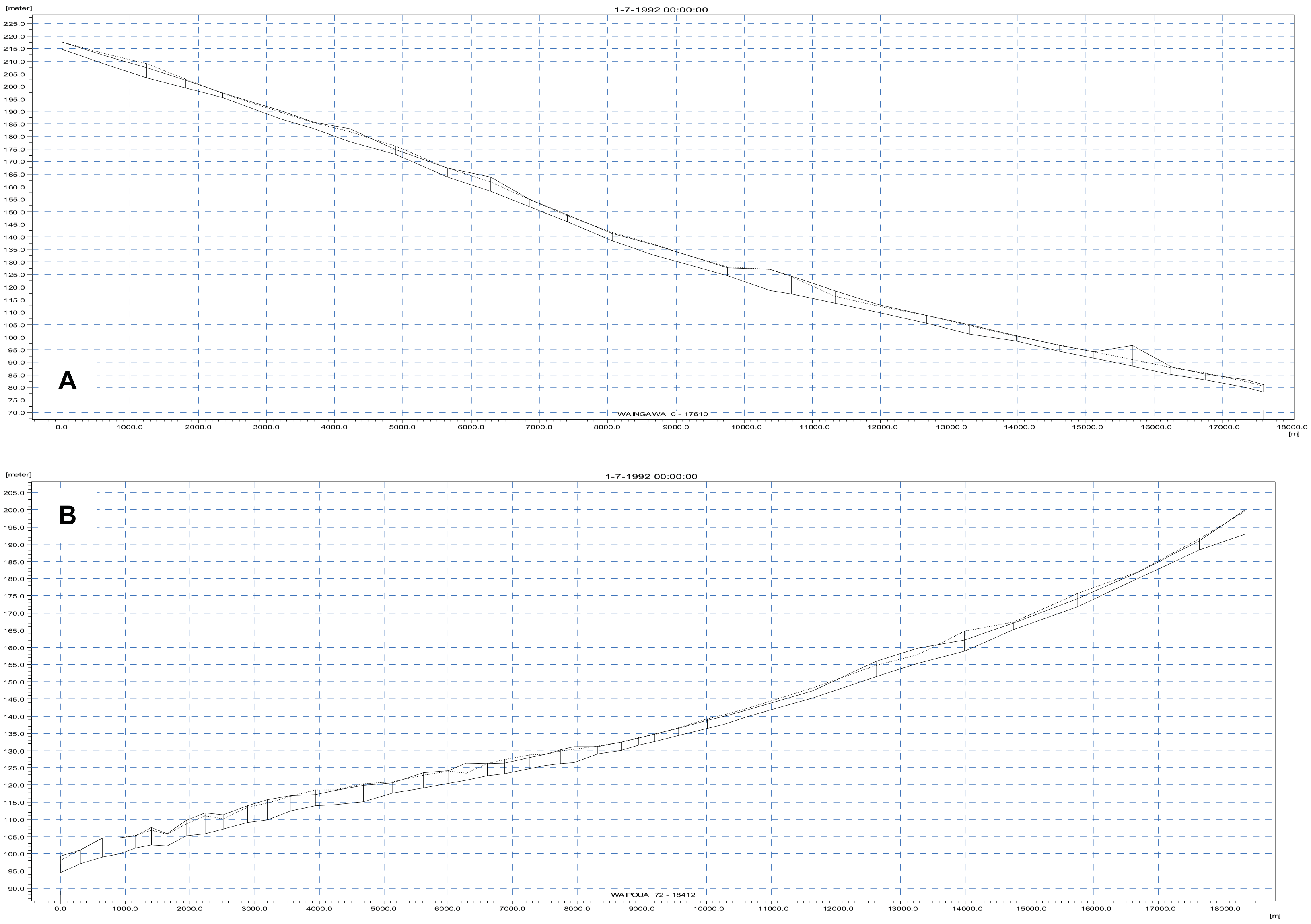

Figure 3.2: Longitudinal bed profiles for the Waingawa (A), Waipoua (B) and Ruamahanga (C) rivers in the Upper Valley catchment

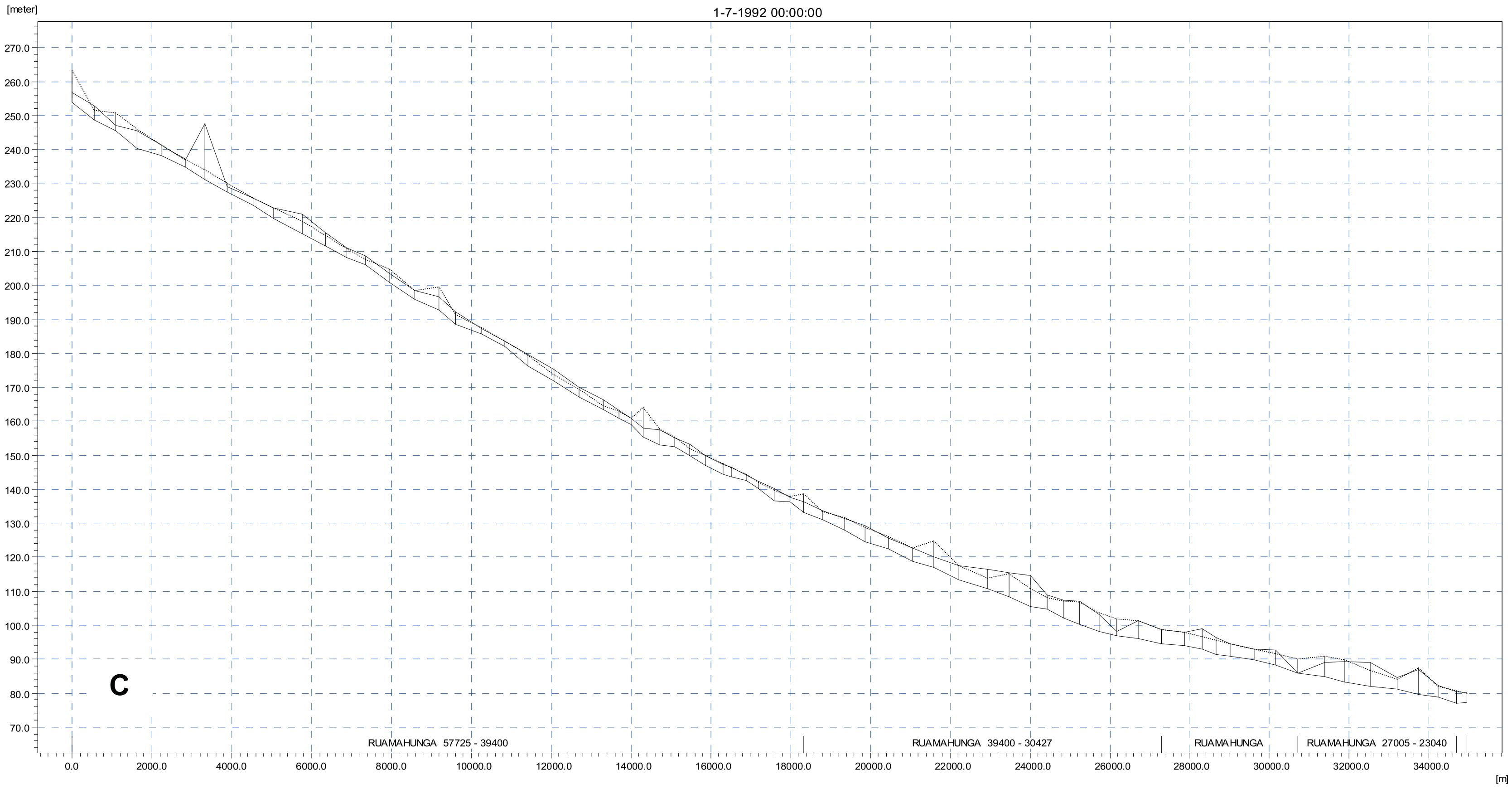

Figure 3.2 *cont.*: Longitudinal bed profiles for the Waingawa (A), Waipoua (B) and Ruamahanga (C) rivers in the Upper Valley catchment

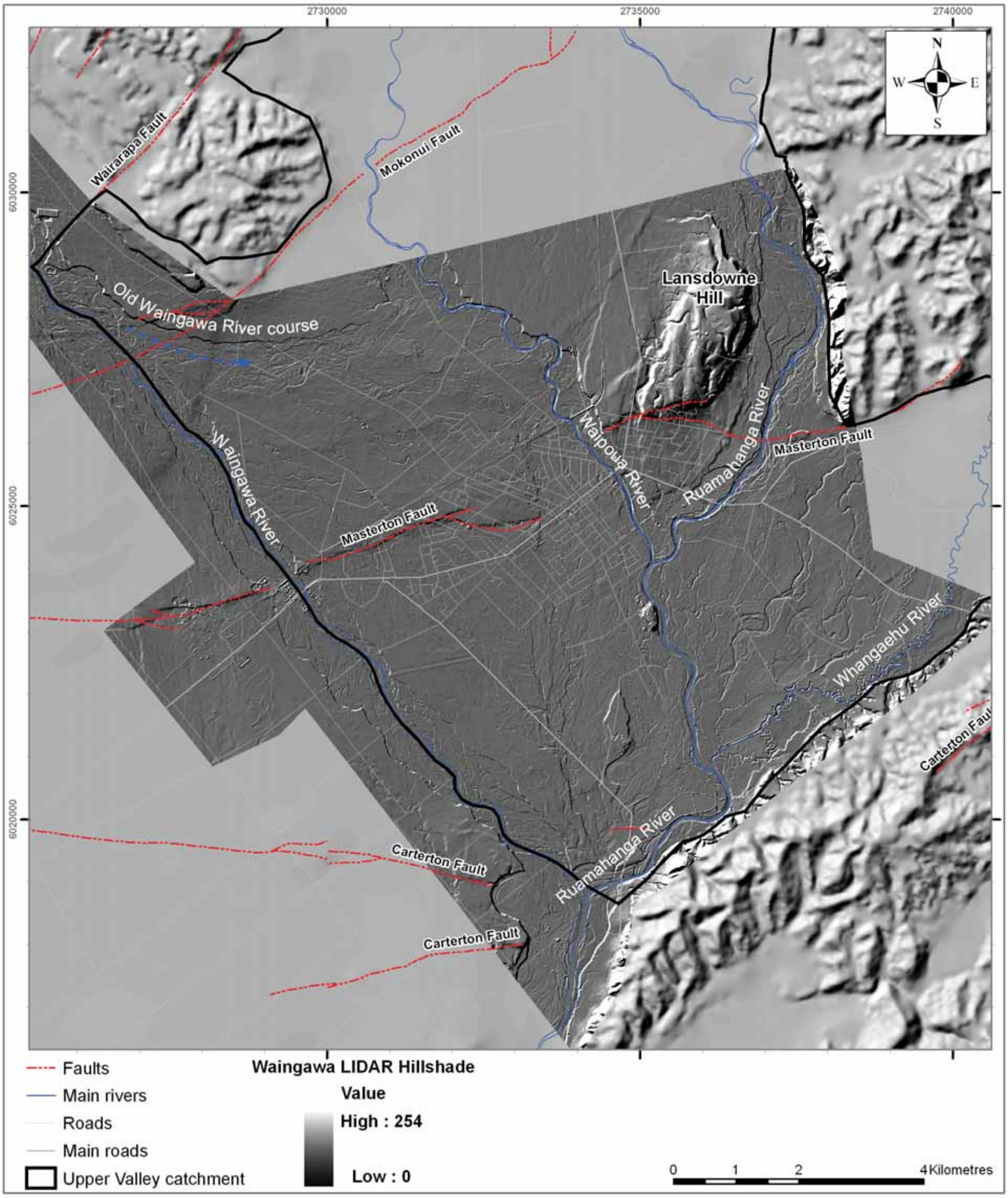

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Figure 3.3: Hillshade image processed from LIDAR for part of the Upper Valley catchment. The background image is Hillshade produced from historic topographic map data. The detailed hillshade image is particularly good in showing structures such as the Masterton Fault.

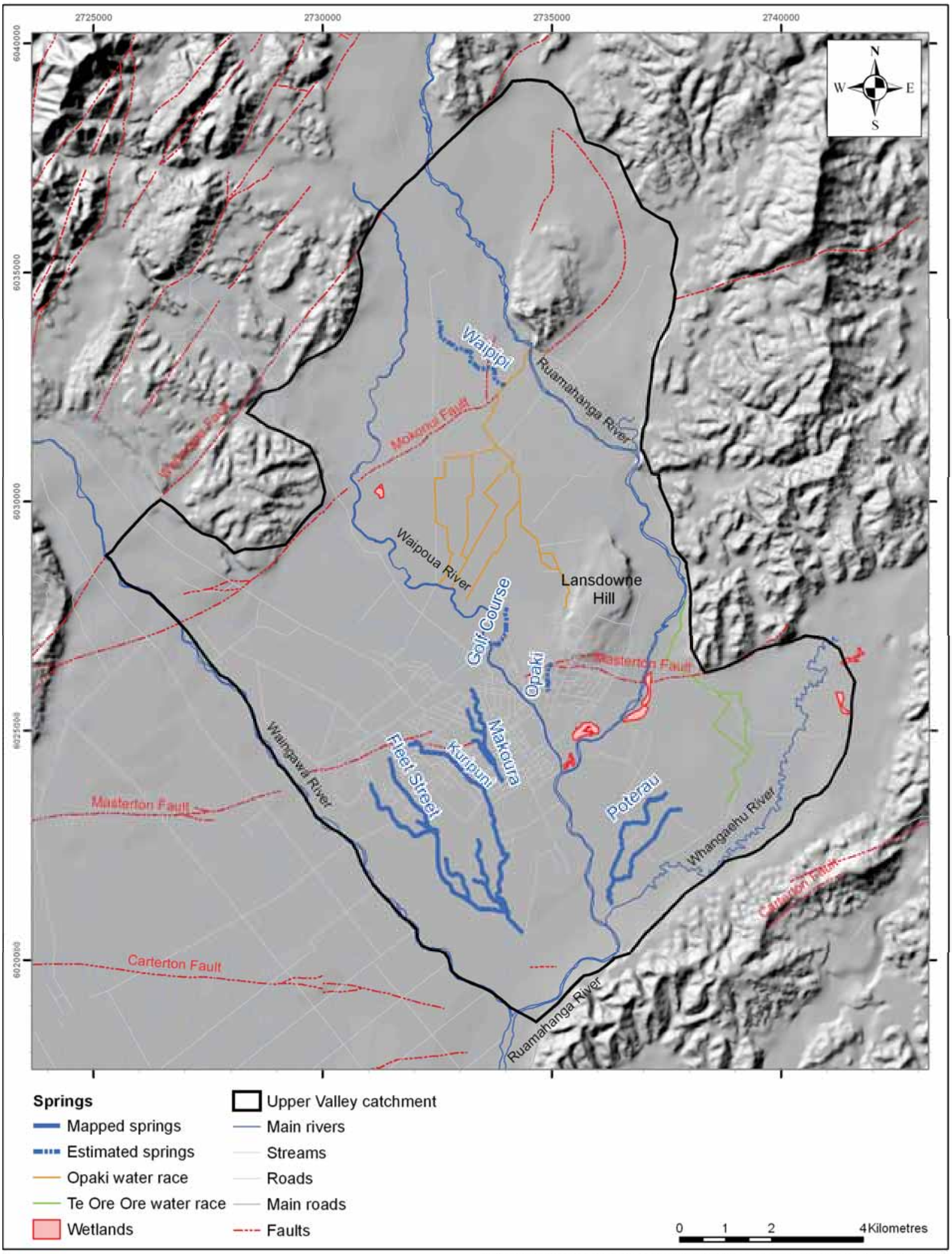

Figure 3.4: Main spring systems and water races within the Upper Valley catchment

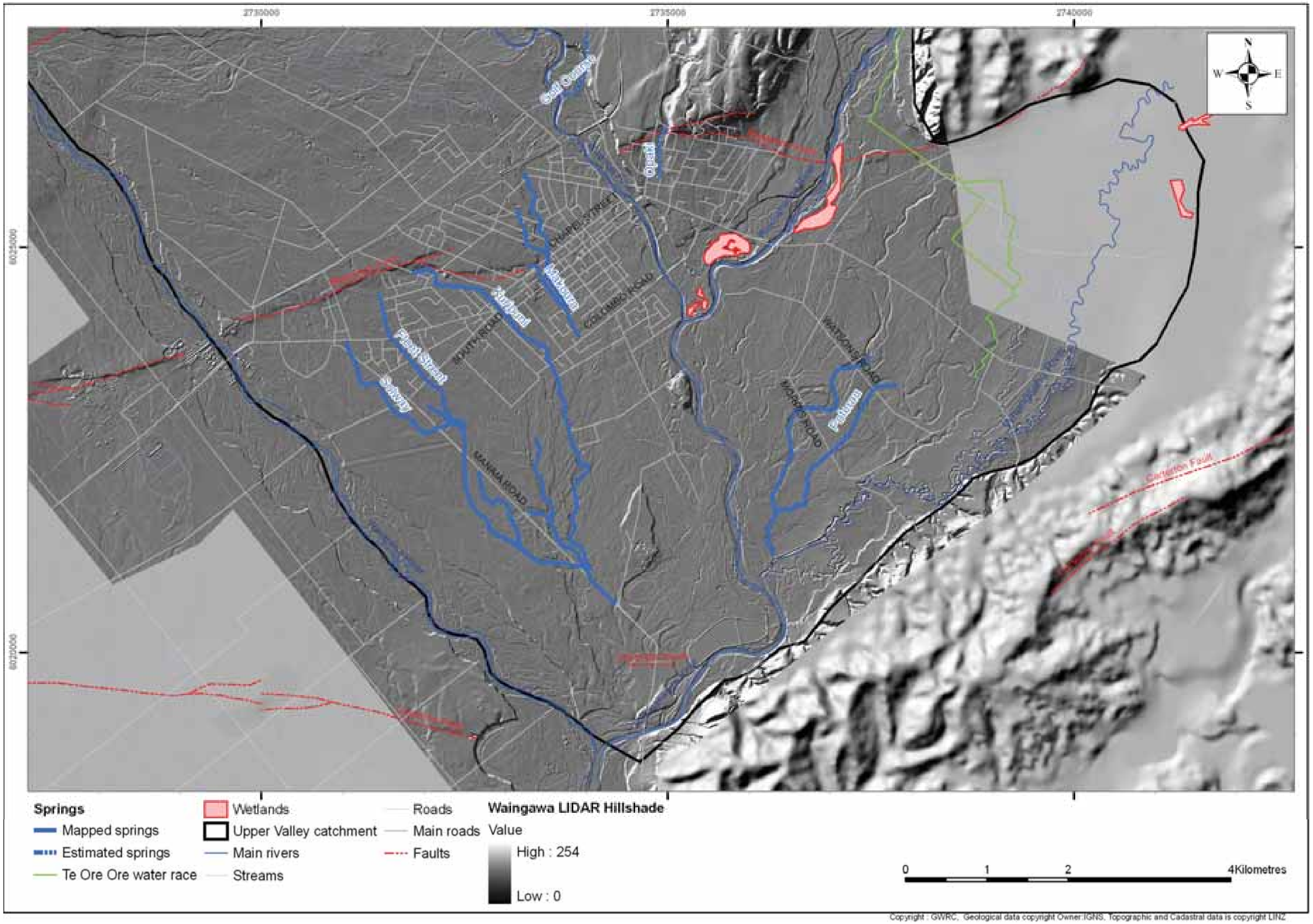

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Figure 3.5: Enlarged spring map for Poterau and Masterton springs, Upper Valley catchment

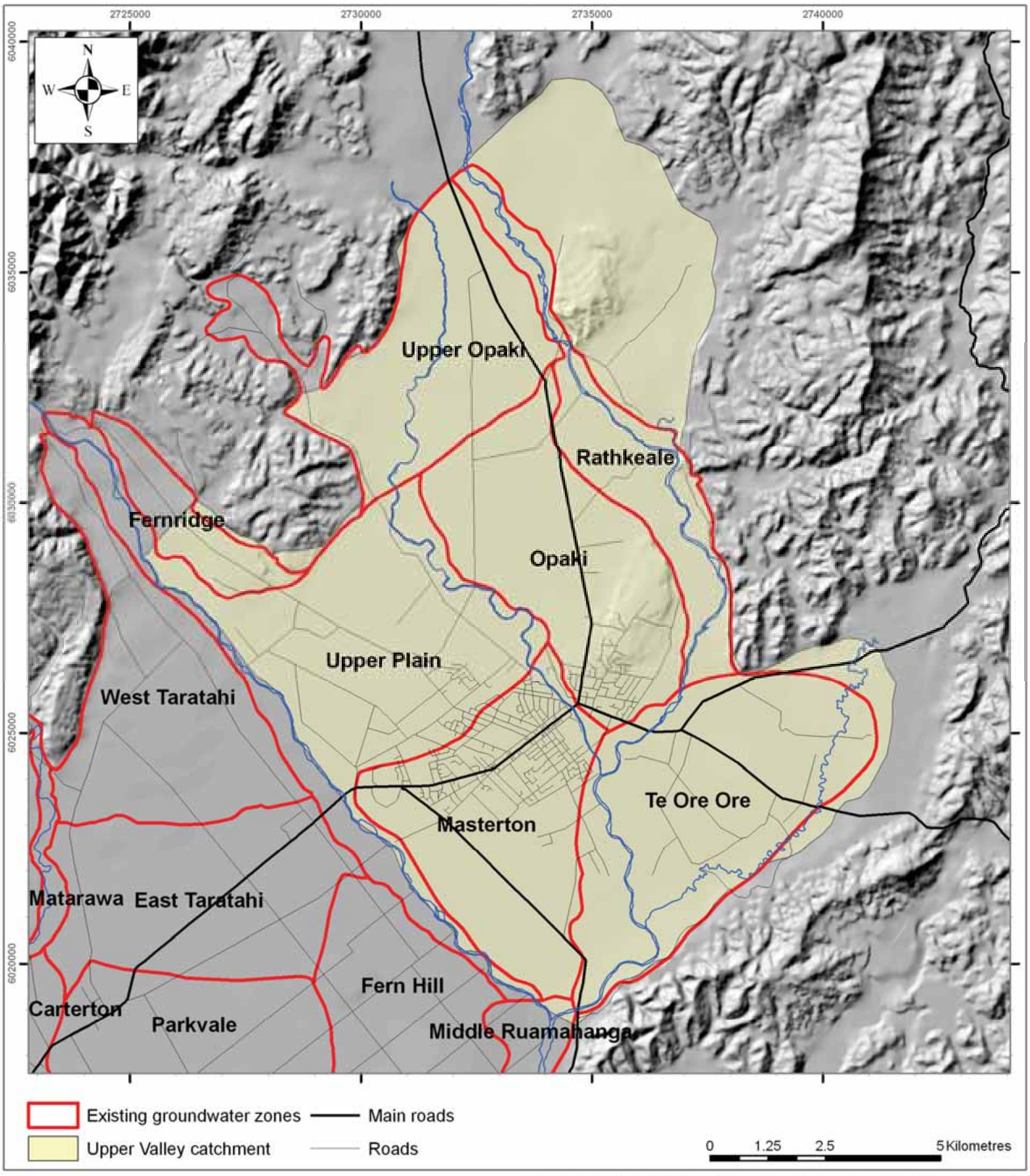

Figure 4.1: Existing groundwater zones in the Upper Valley catchment as identified in the Regional Freshwater Plan (WRC 1999). Note that some groundwater zones are partially located within the Upper Valley catchment.

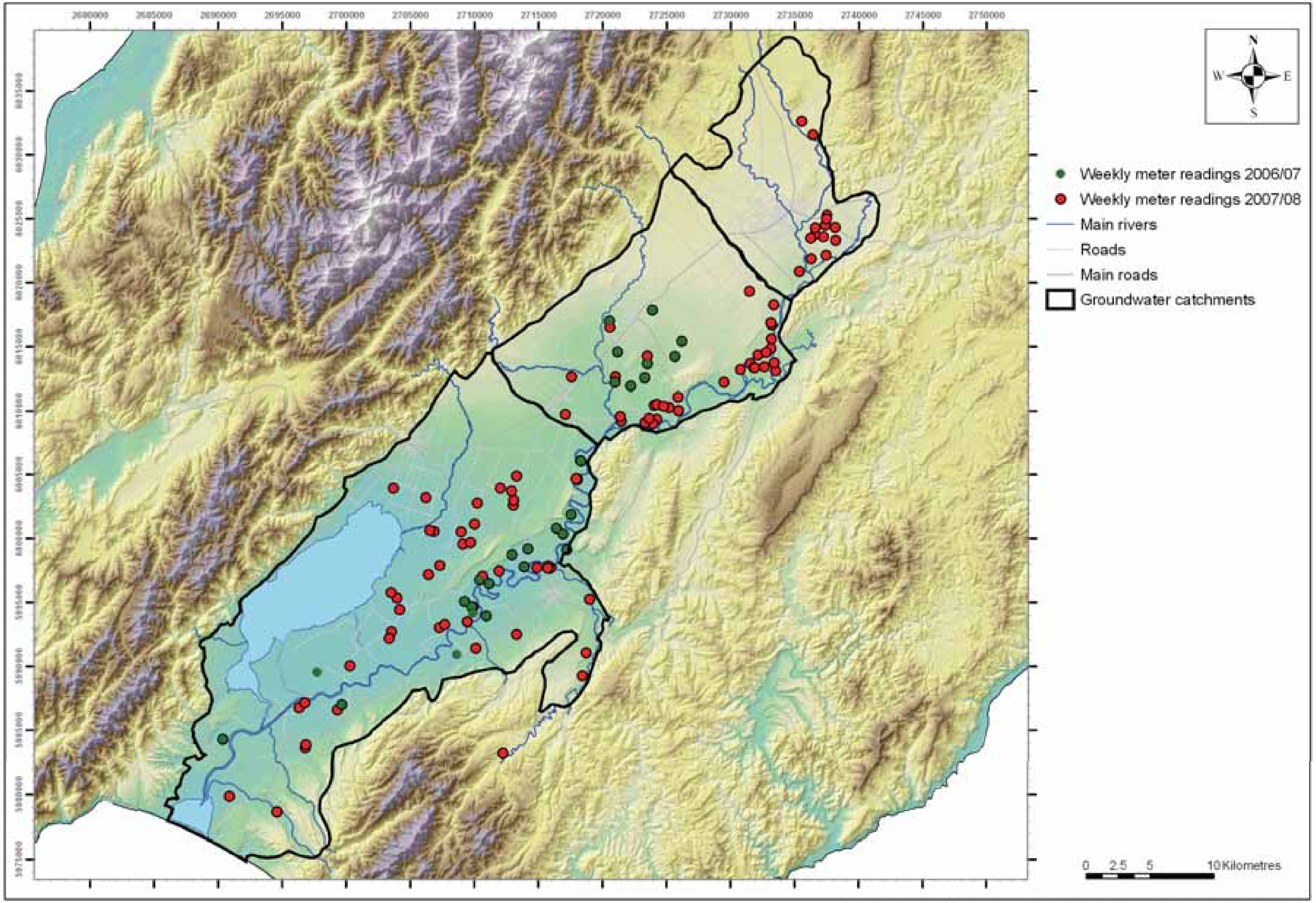

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Figure 5.1: Locations of water meters read during 2006/07 and 2007/08 on the Wairarapa plains

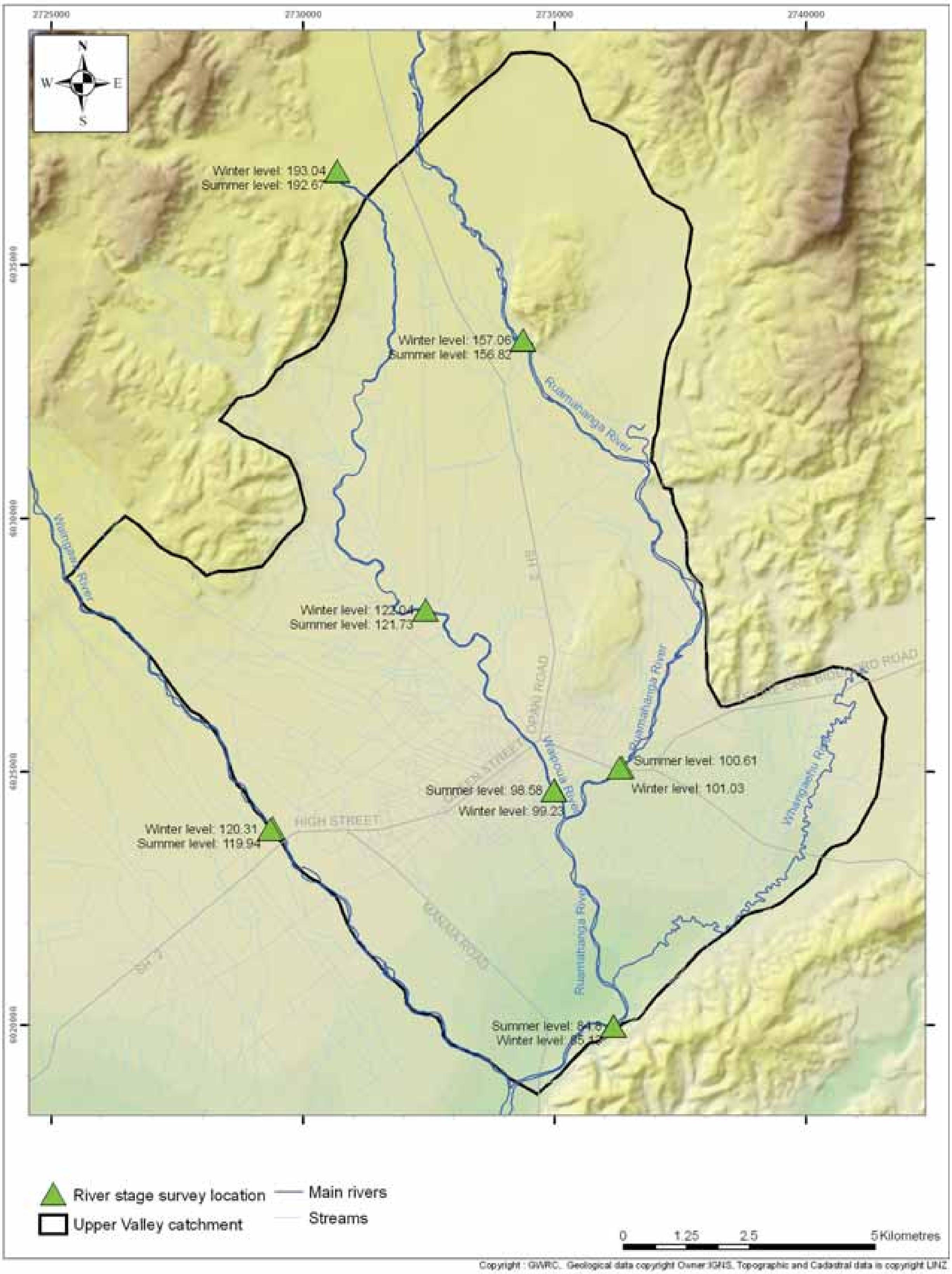

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Figure 5.2: GPS survey locations and summer and winter river levels in the Upper Valley catchment

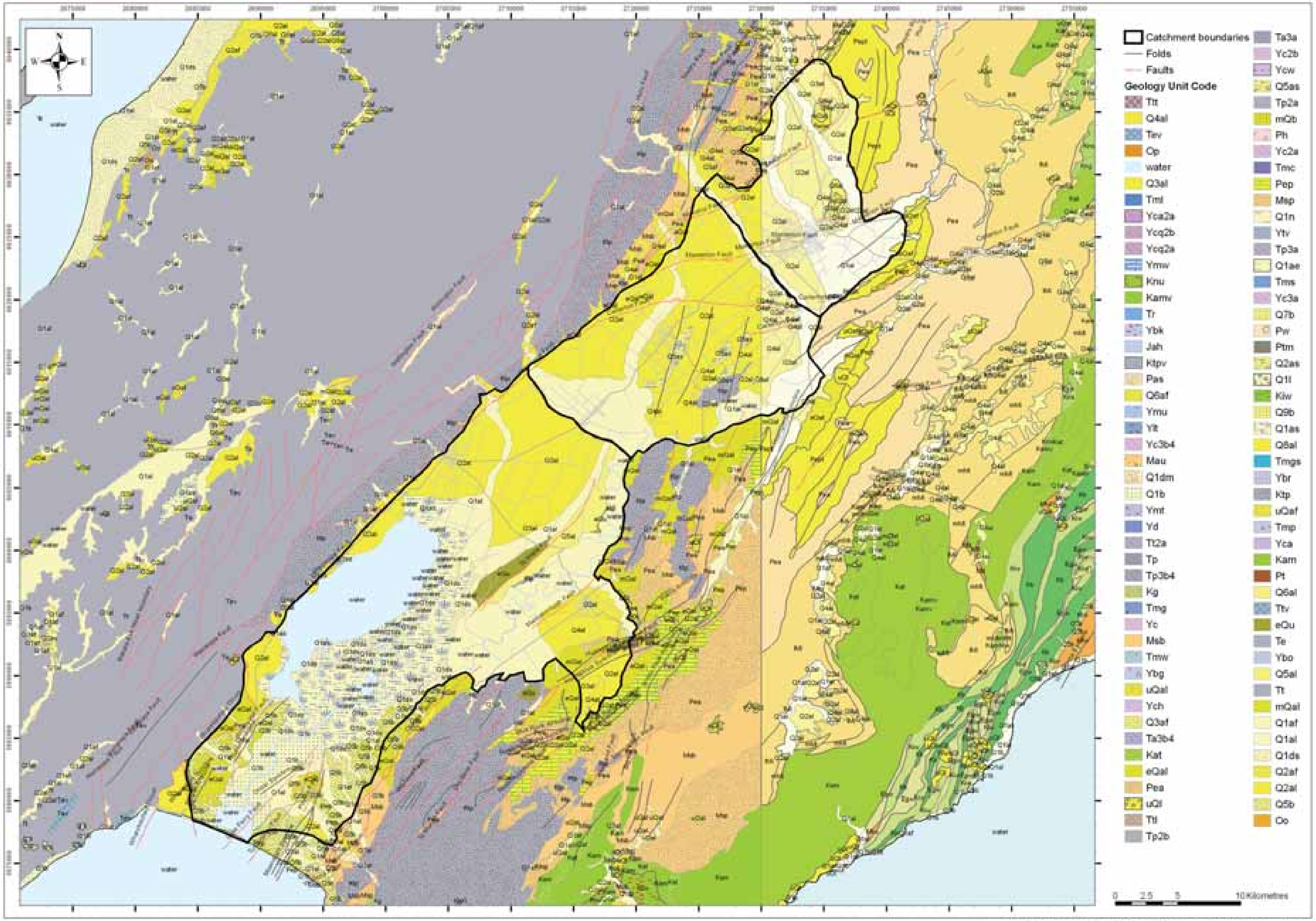

Figure 6.1: Geological map of the Wairarapa Valley showing the outlines of the three groundwater investigation sub-catchments (Source: GNS 2002)

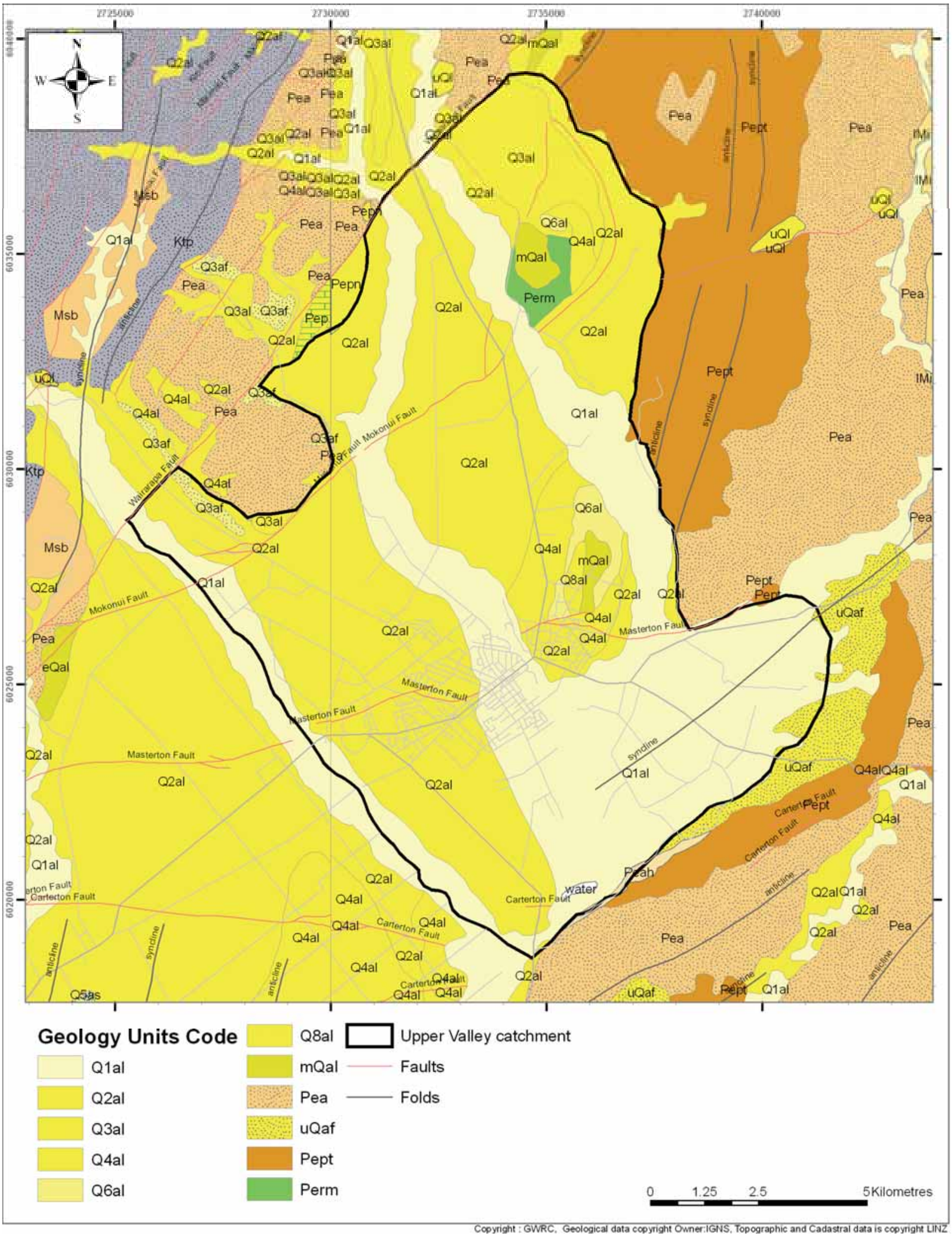

Figure 6.2: Detailed geology of the Upper Valley catchment (Source: GNS 2002)

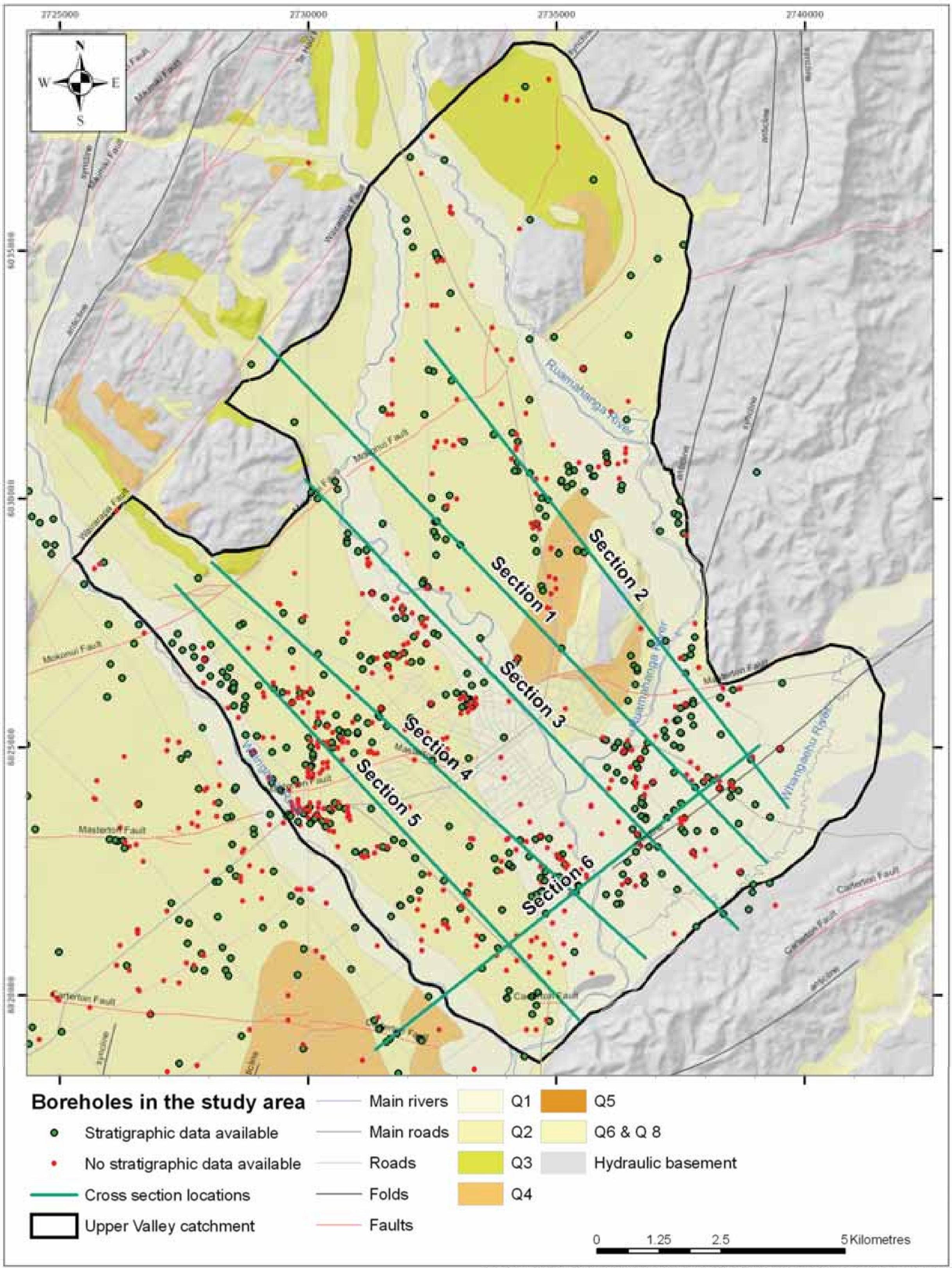

Figure 6.3: Locations of geological cross sections and known bores against a simplified geological map of the Upper Valley catchment

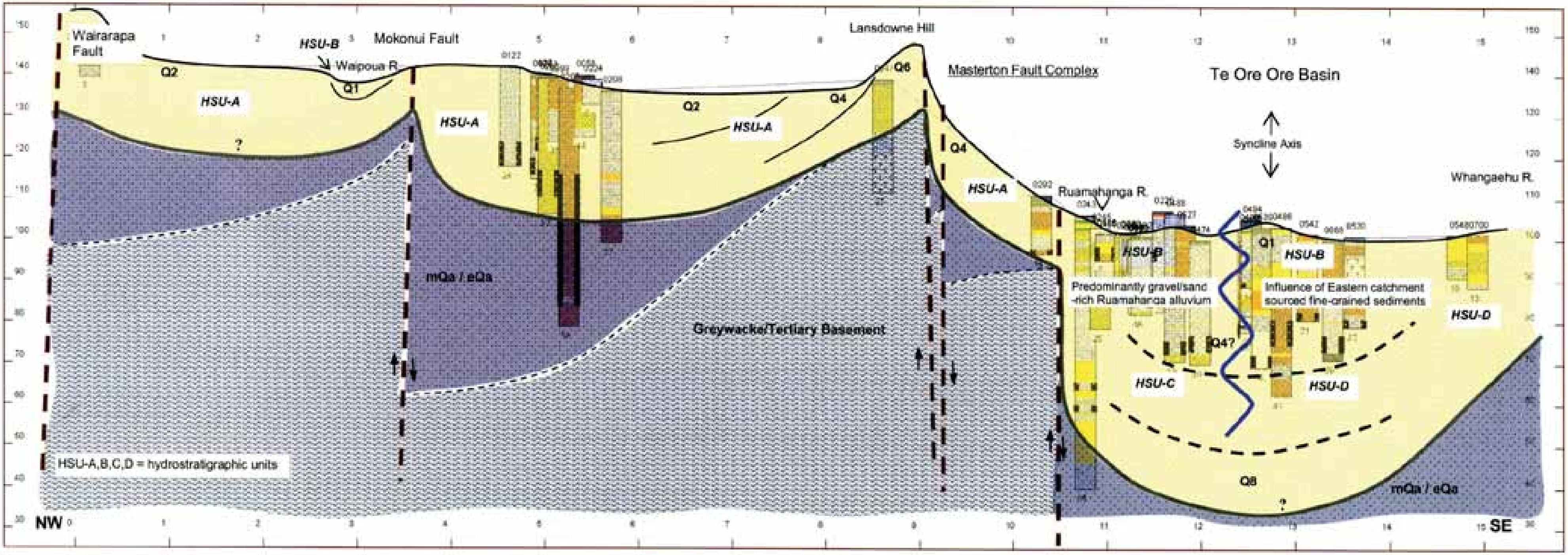

Figure 6.4: Upper Valley catchment – hydrogeological cross section 1

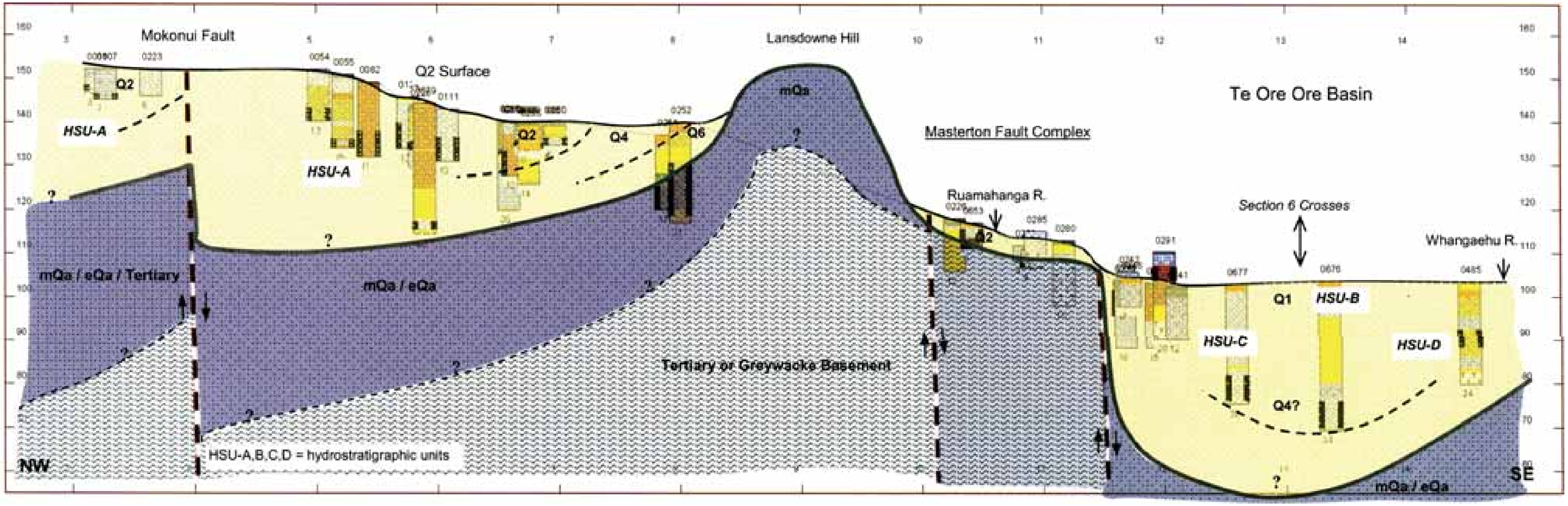

Figure 6.5: Upper Valley catchment – hydrogeological cross section 2

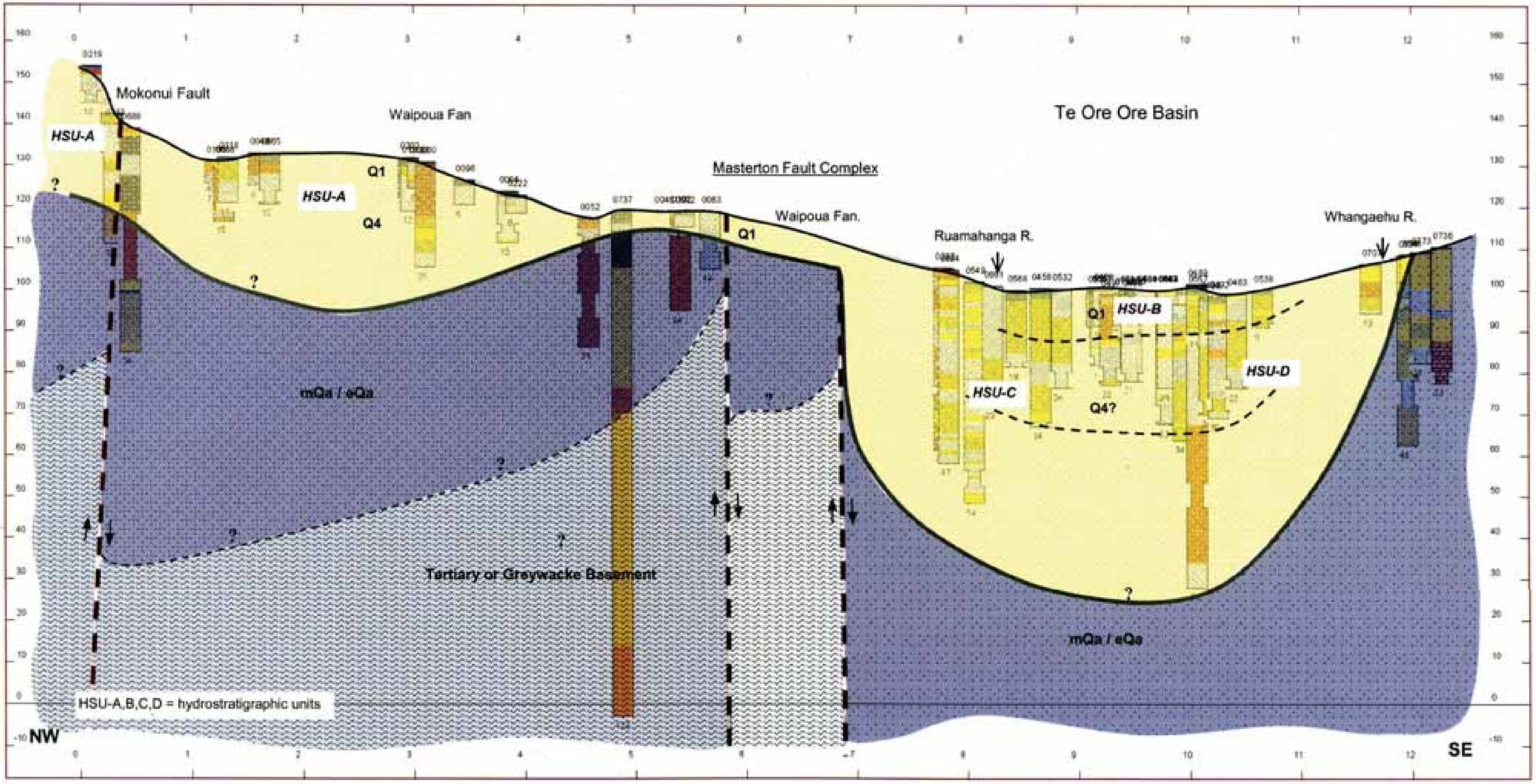

Figure 6.6: Upper Valley catchment – hydrogeological cross section 3

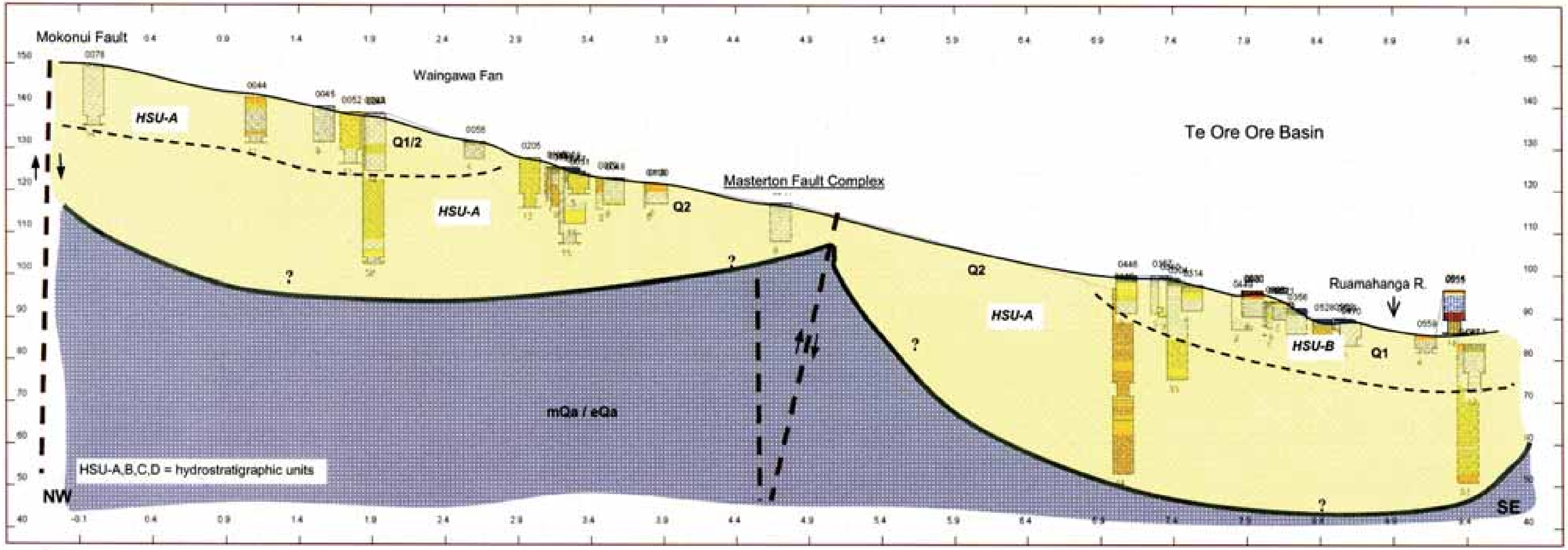

Figure 6.7: Upper Valley catchment – hydrogeological cross section 4

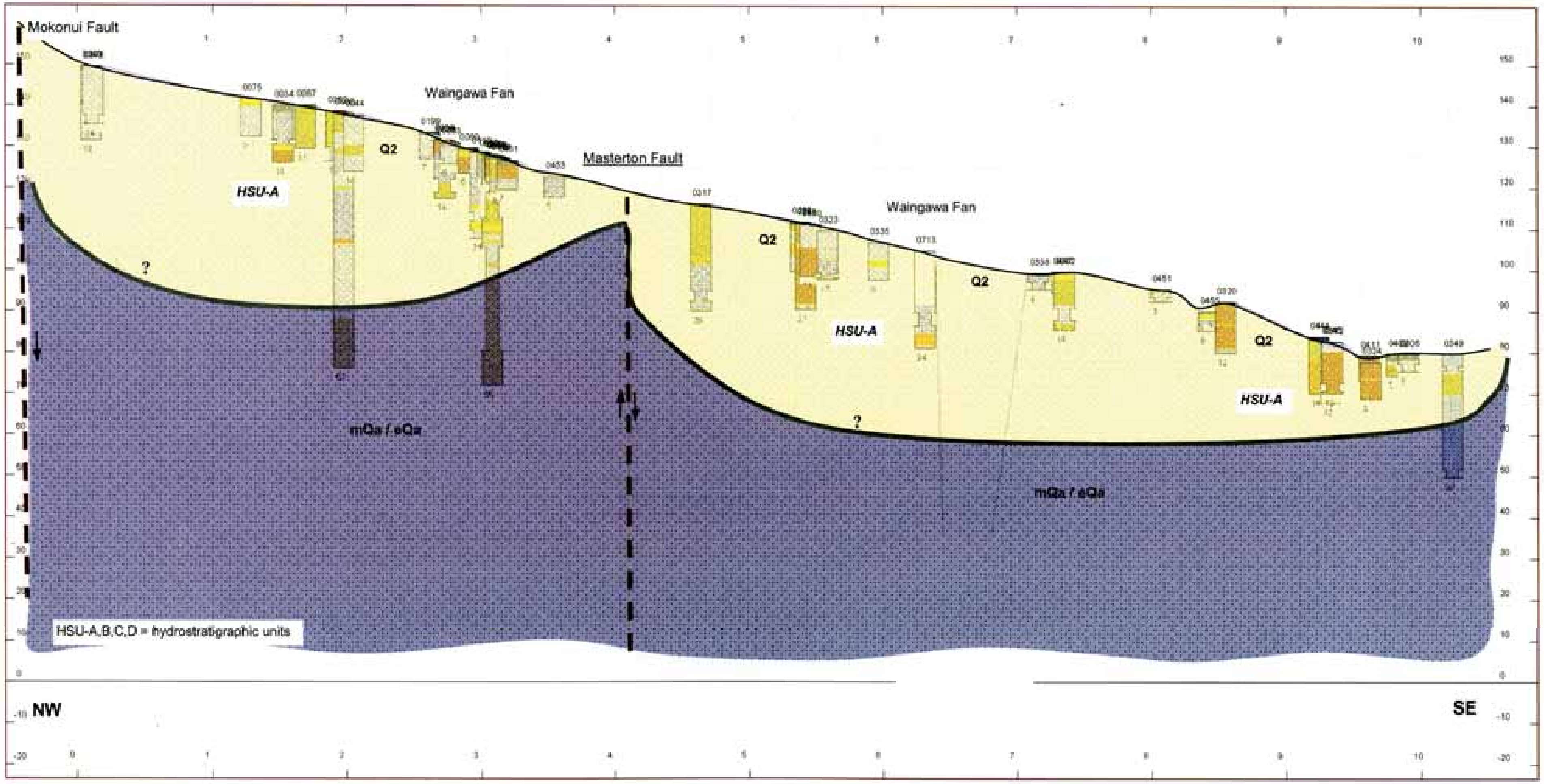

Figure 6.8: Upper Valley catchment – hydrogeological cross section 5

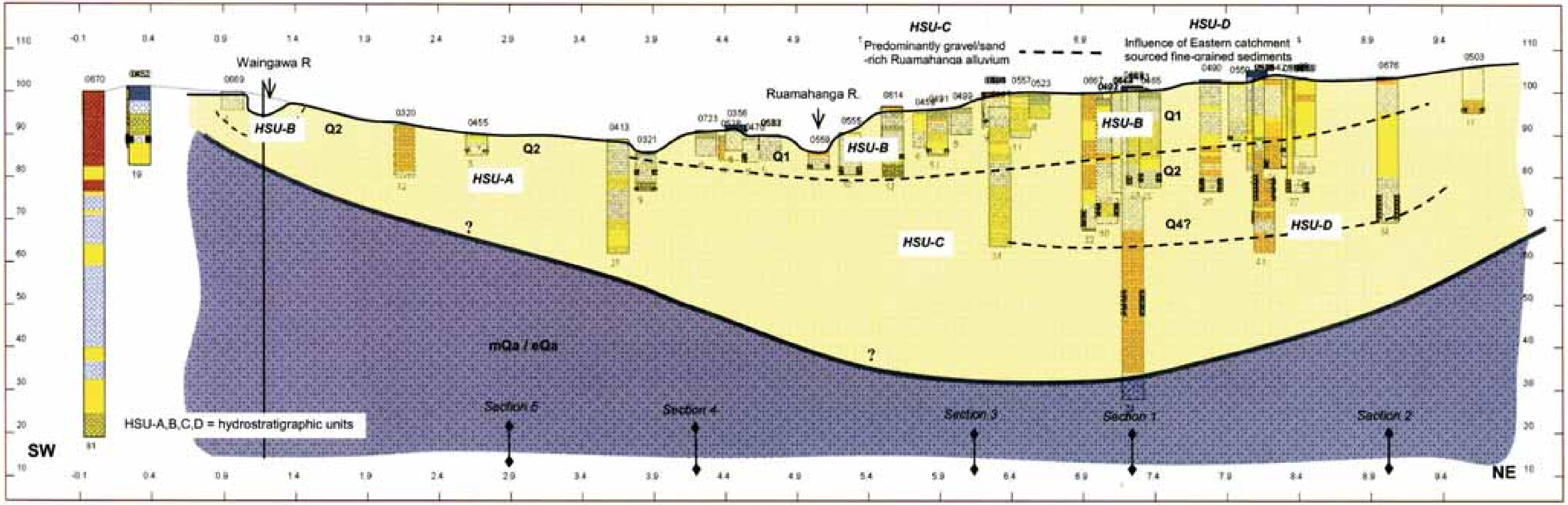

Figure 6.9: Upper Valley catchment – hydrogeological cross section 6

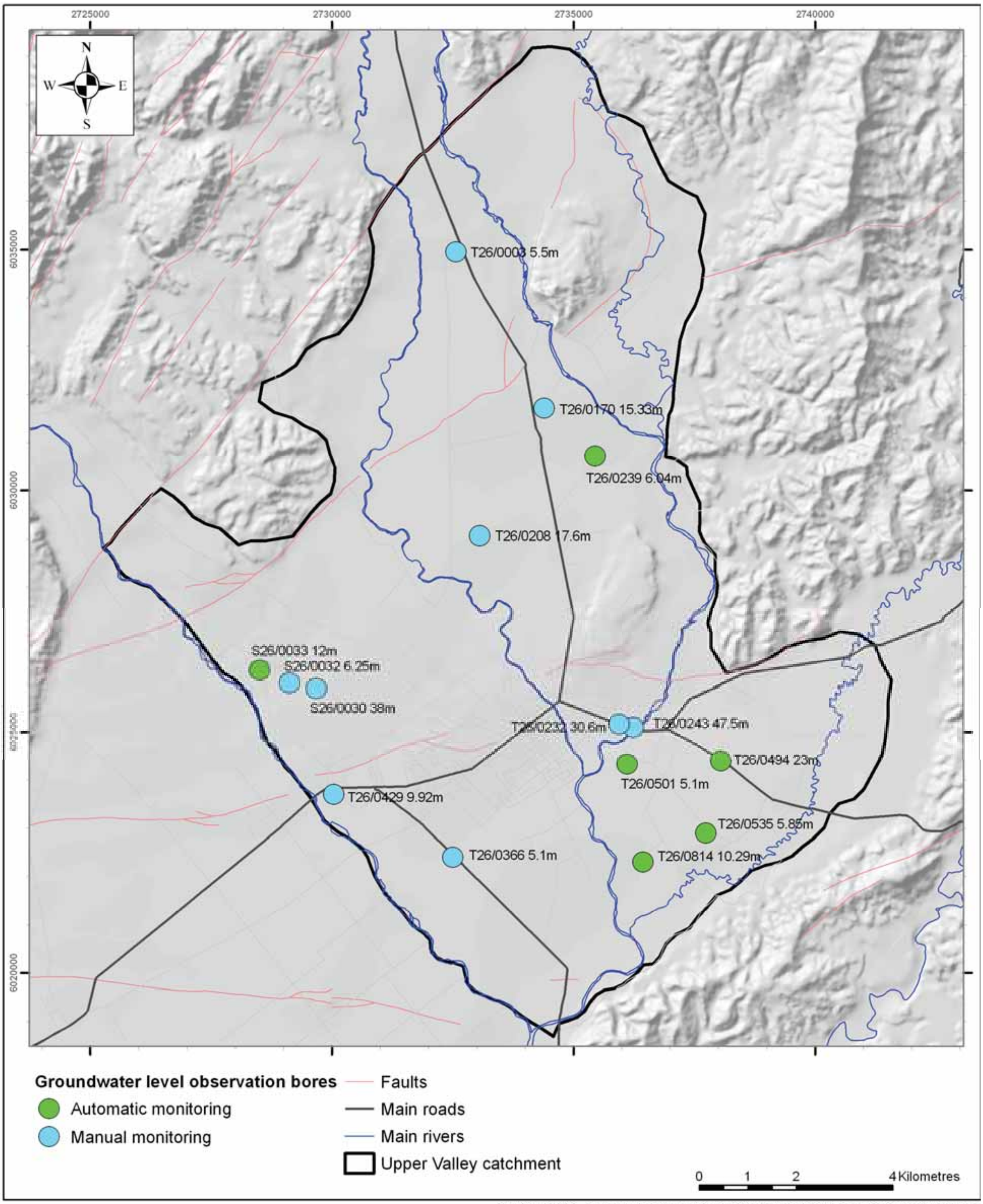

Figure 7.1: Groundwater level monitoring bores in the Upper Valley catchment

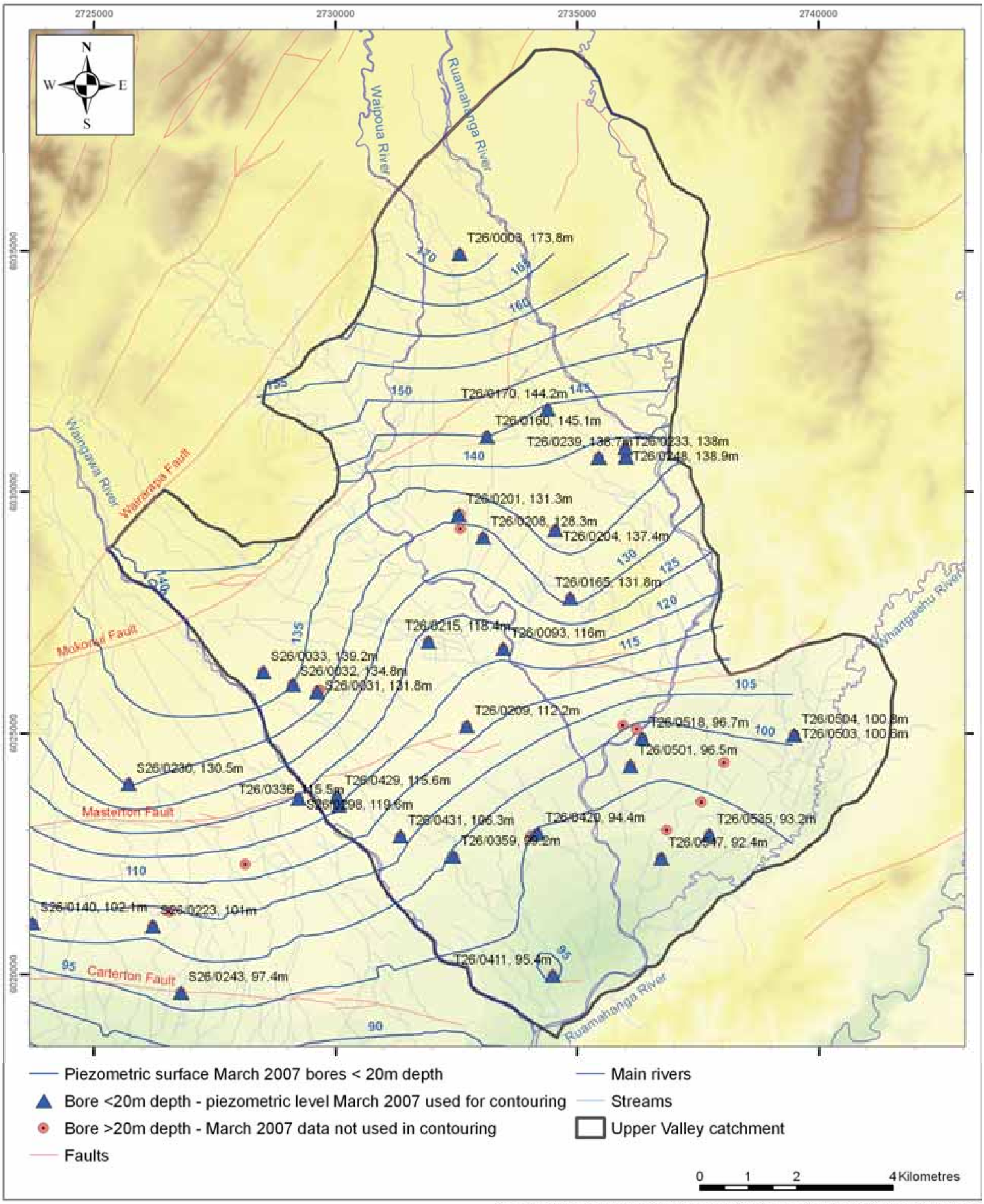

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Figure 7.2: Piezometric contours (March 2007) for the Upper Valley catchment. The contour map is based on piezometric data from bores <20 m deep. Point data used to develop the contours are also shown.

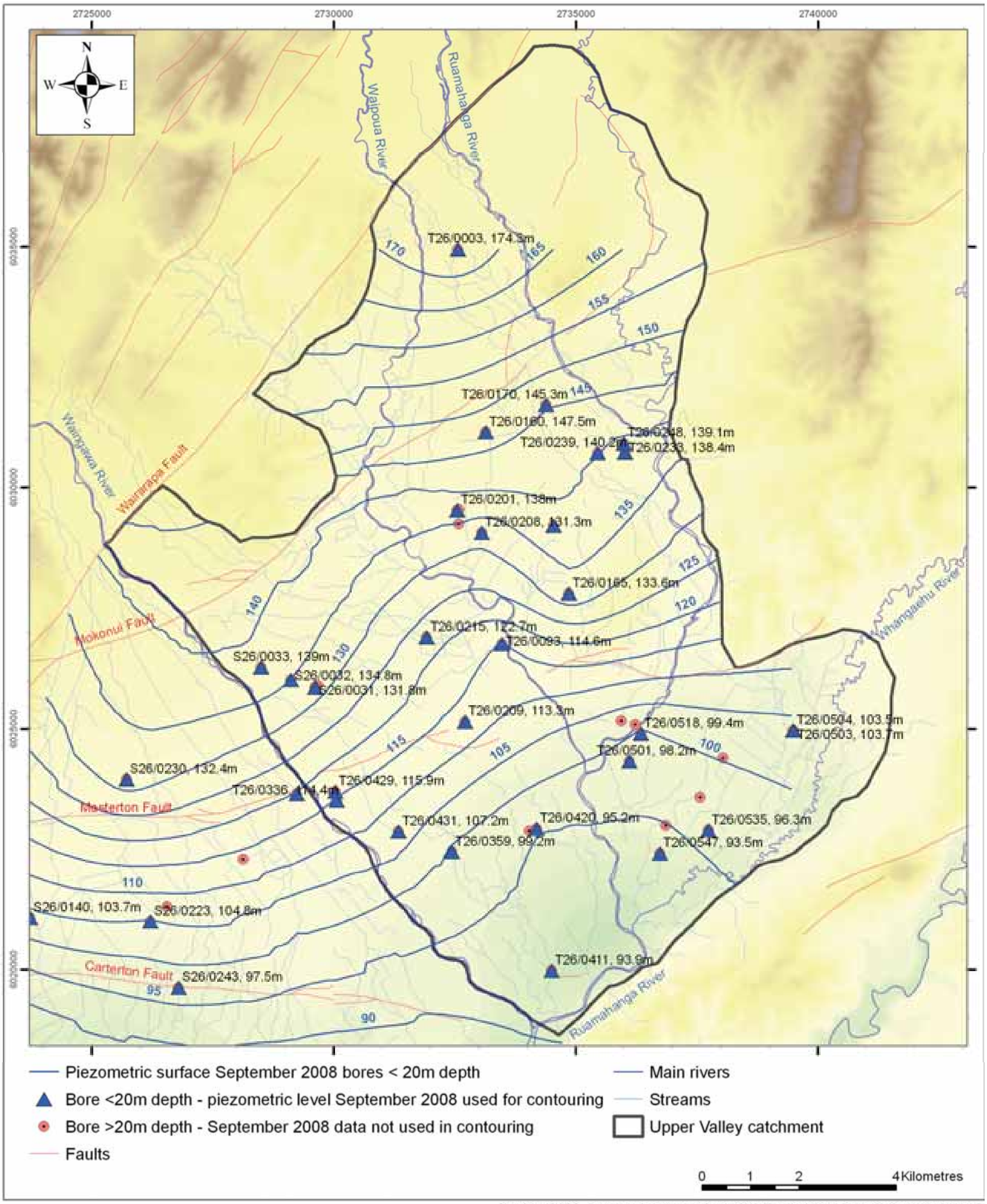

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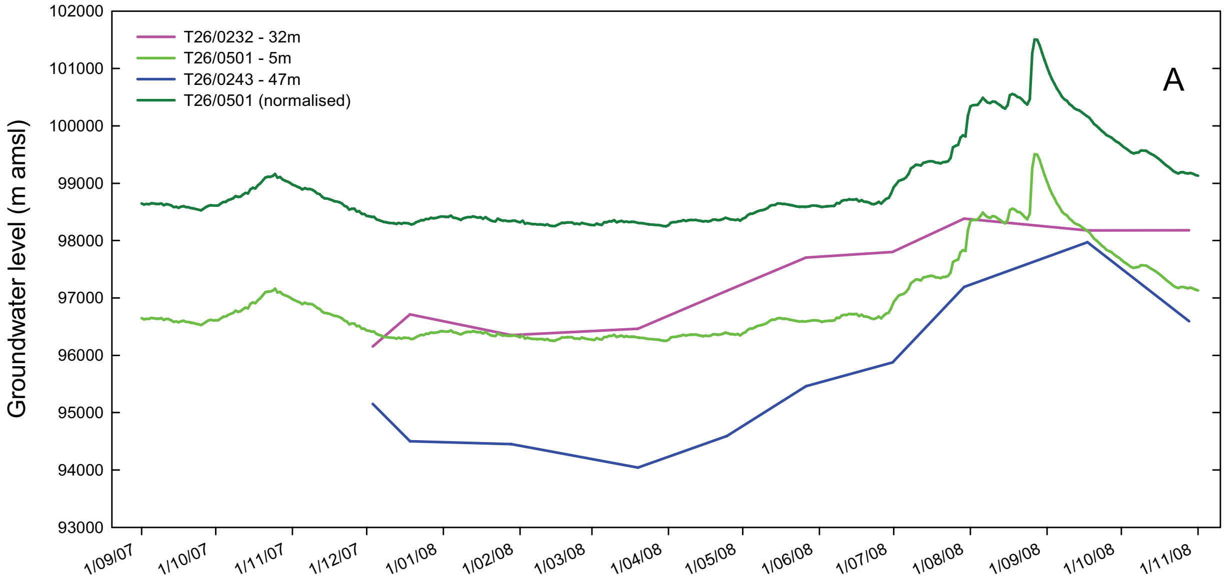
Figure 7.3: Piezometric contours (September 2008) for the Upper Valley catchment. The contour map is based on piezometric data from bores <20 m deep. Point data used to develop the contours are also shown.



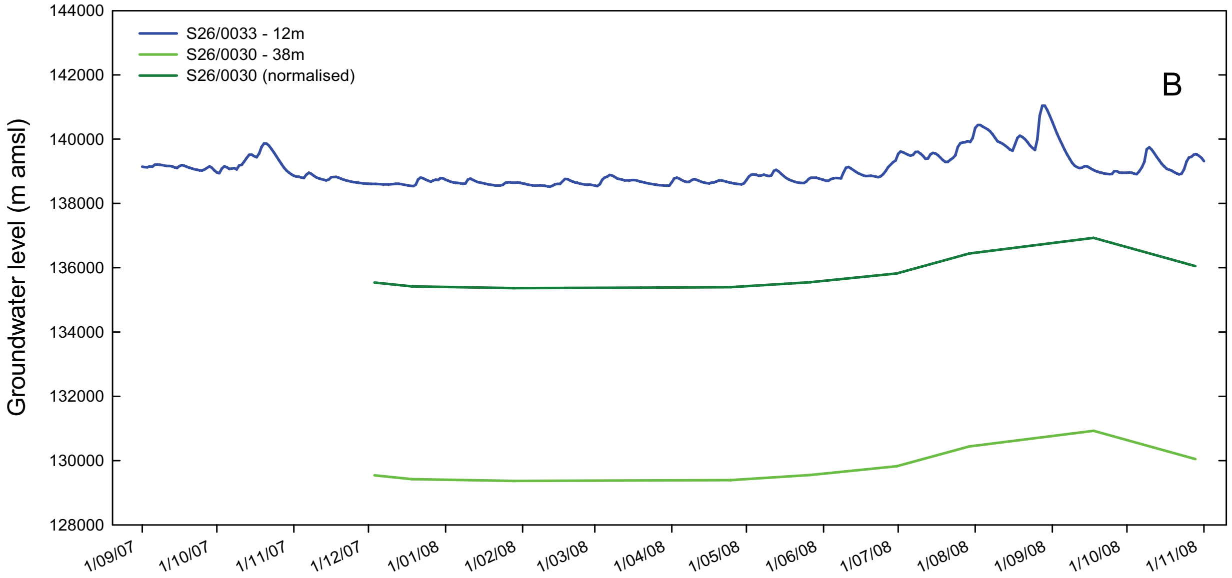


Figure 7.4: Demonstration of vertical hydraulic gradients in the Te Ore Ore basin (A) and Waingawa fan (B) – Upper Valley catchment

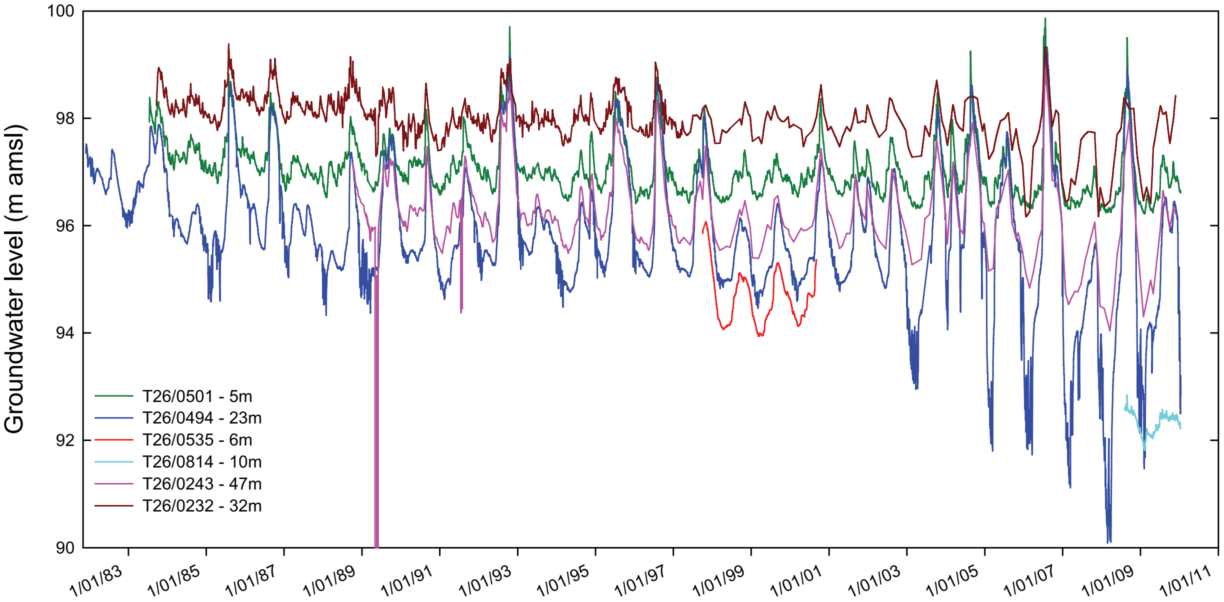


Figure 7.5: Te Ore Ore basin groundwater level hydrographs, Upper Valley catchment

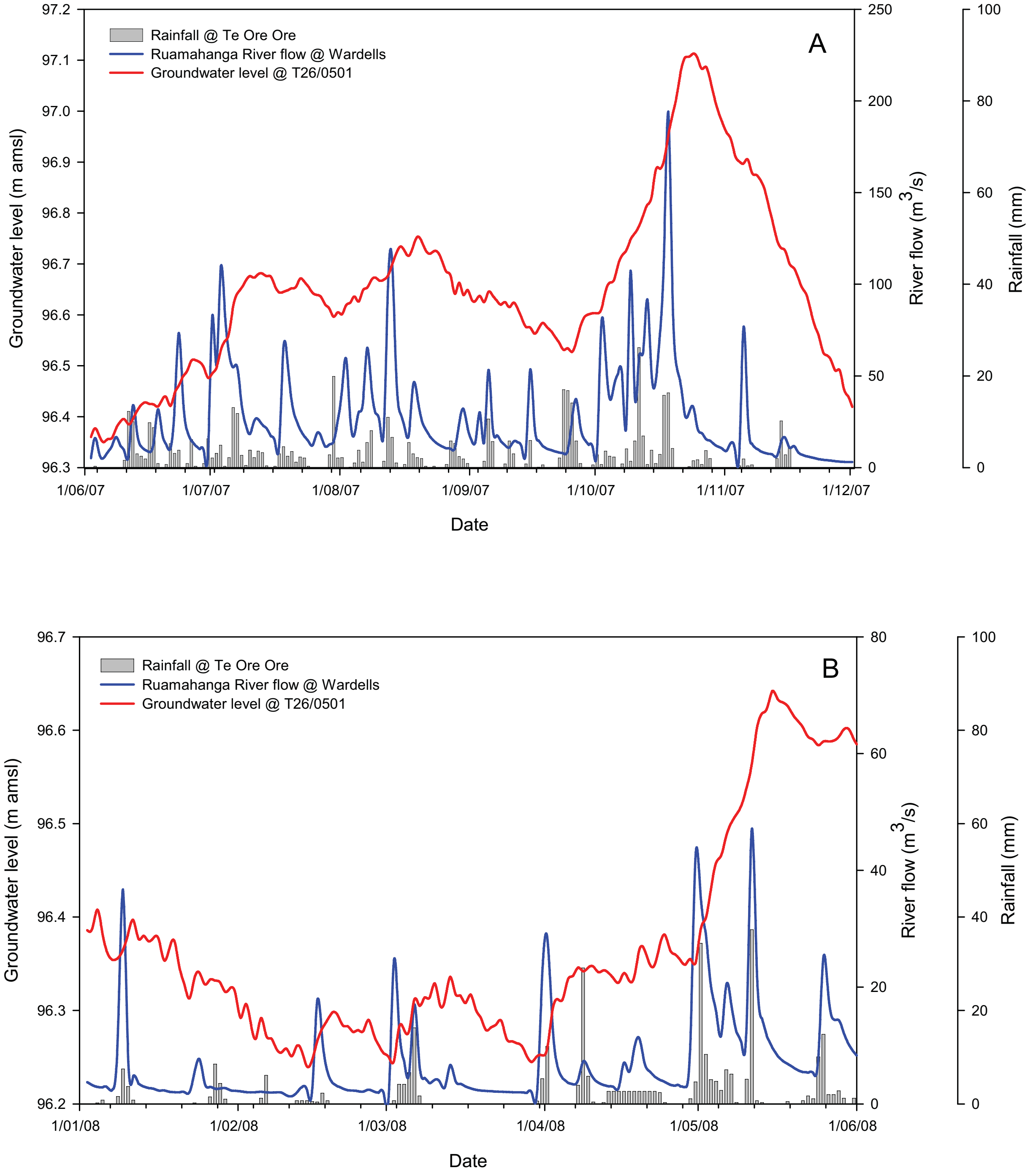


Figure 7.6: Automatic monitoring hydrographs for bore T26/0501 (with Ruamahanga River flow and rainfall); A – winter 2007, B – summer 2008

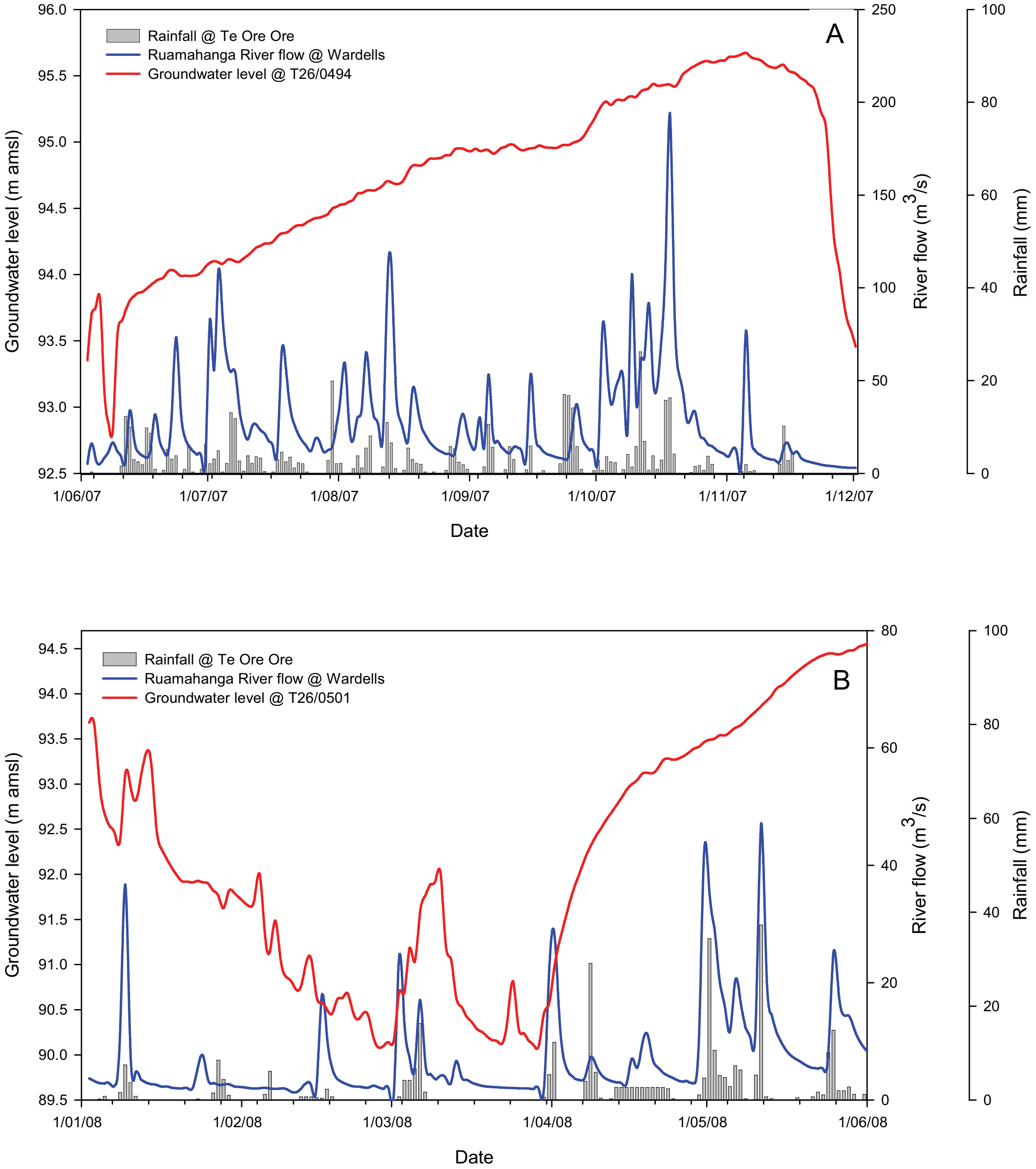


Figure 7.7: Automatic monitoring hydrographs for bore T26/0494 (with Ruamahanga River flow and rainfall); A – winter 2007, B – summer 2008

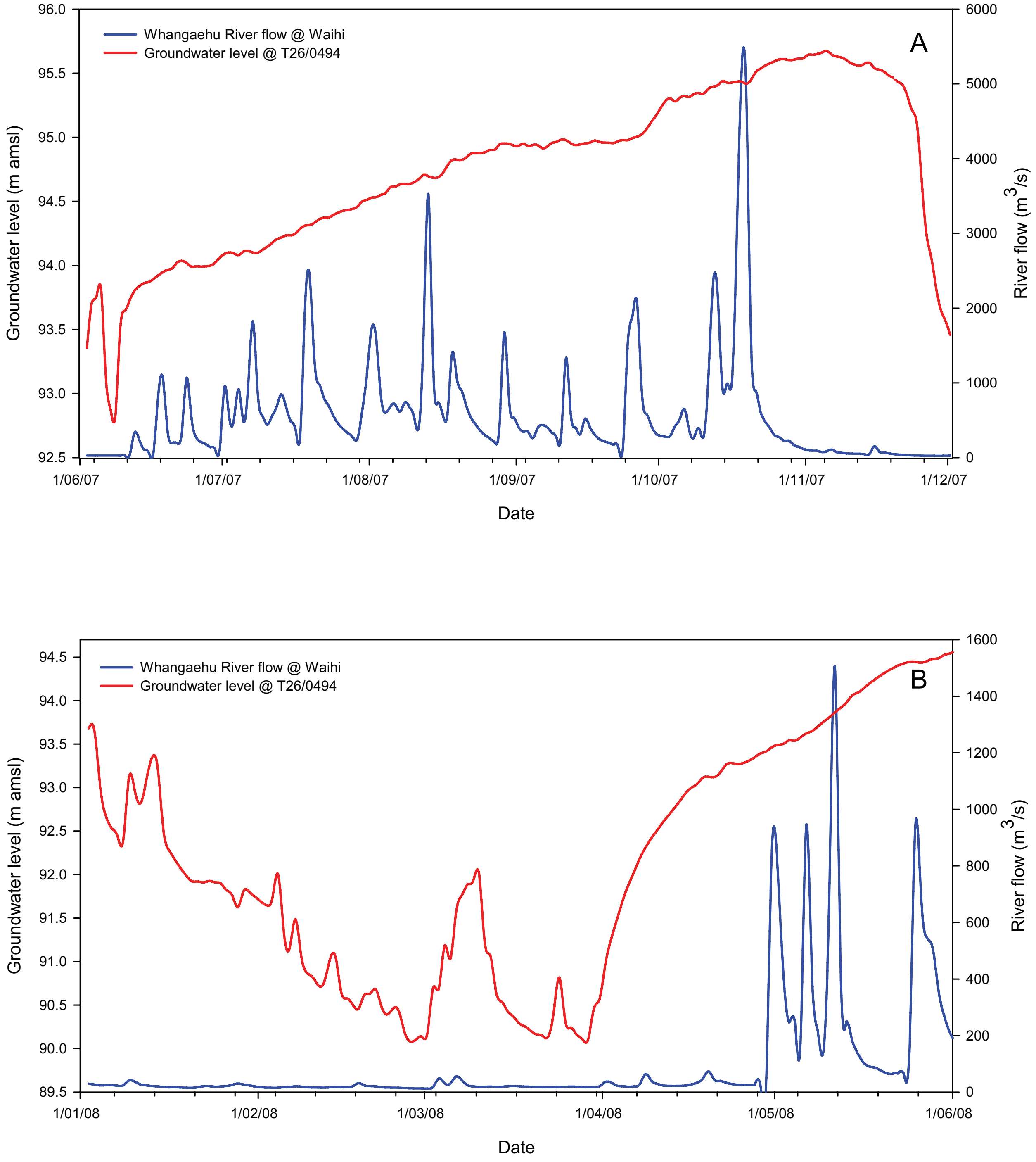
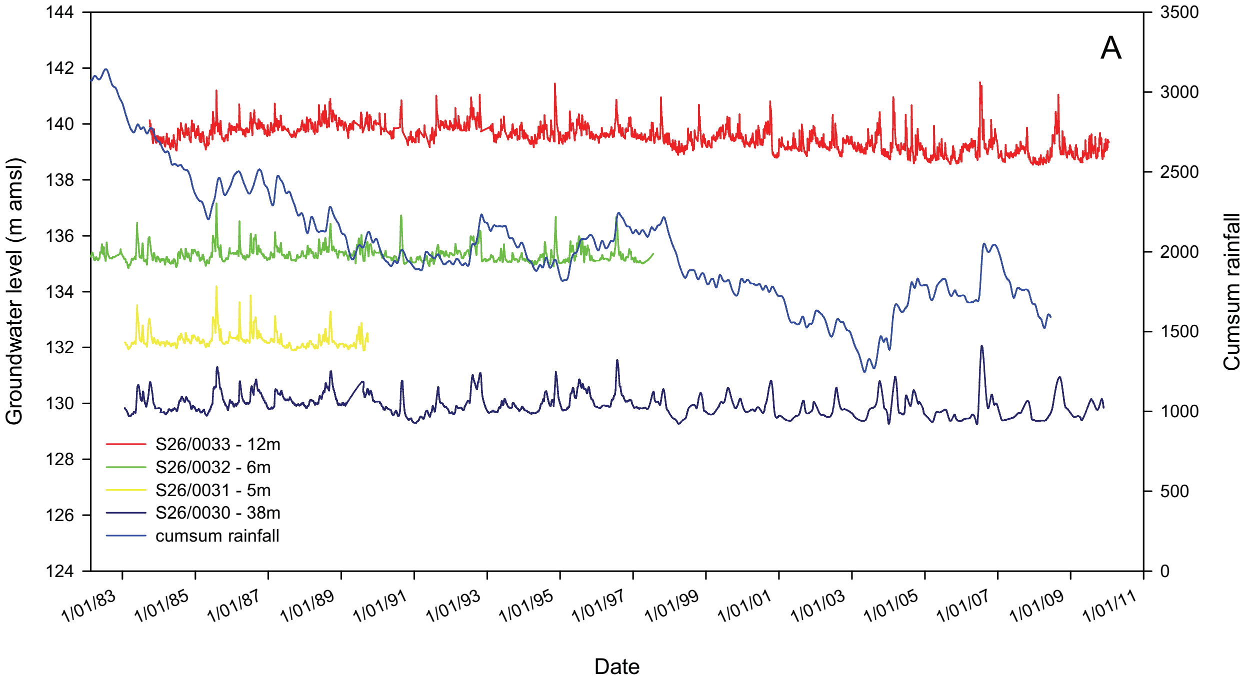


Figure 7.8: Automatic monitoring hydrographs for bore T26/0494 (with Whangaehu flow); A – winter 2007, B – summer 2008



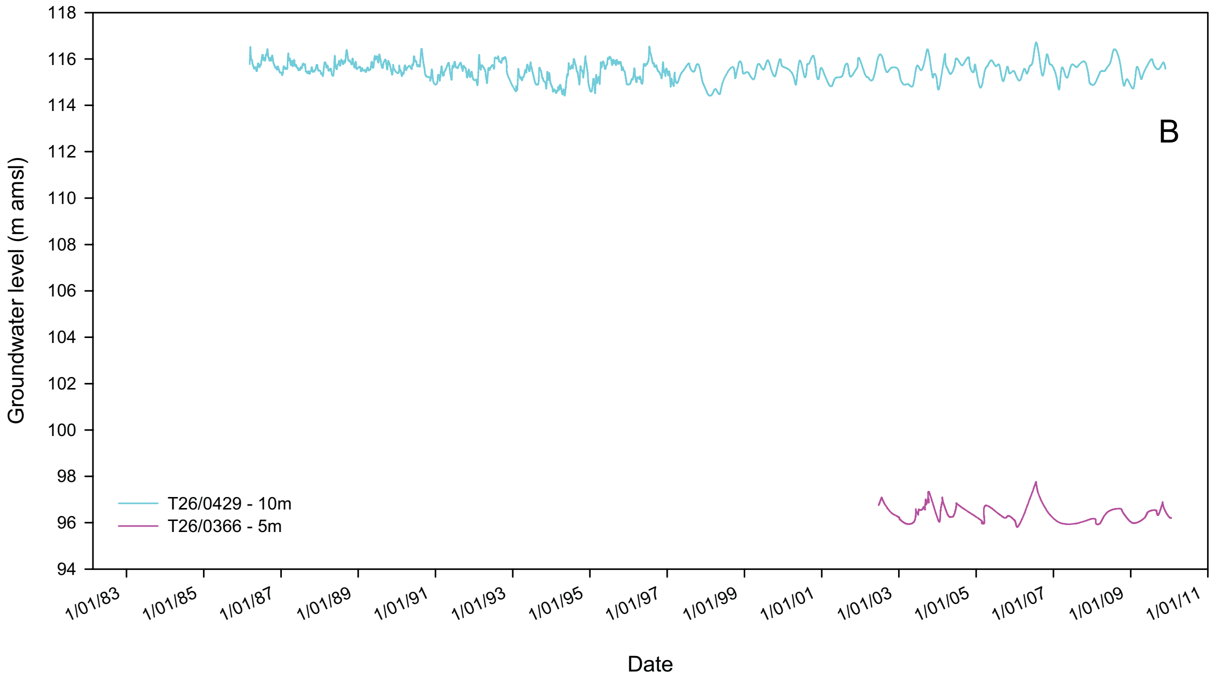
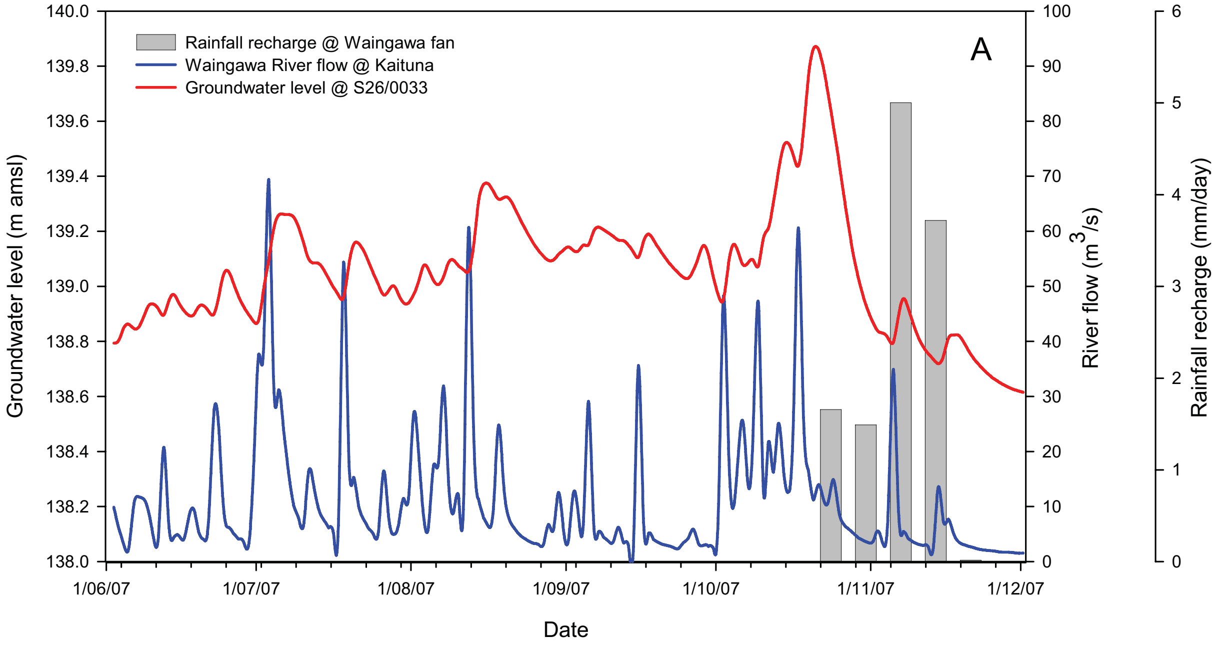


Figure 7.9: Groundwater level hydrographs for bores in the Waingawa fan above the Masterton Fault (A) and for bores below the fault (B)



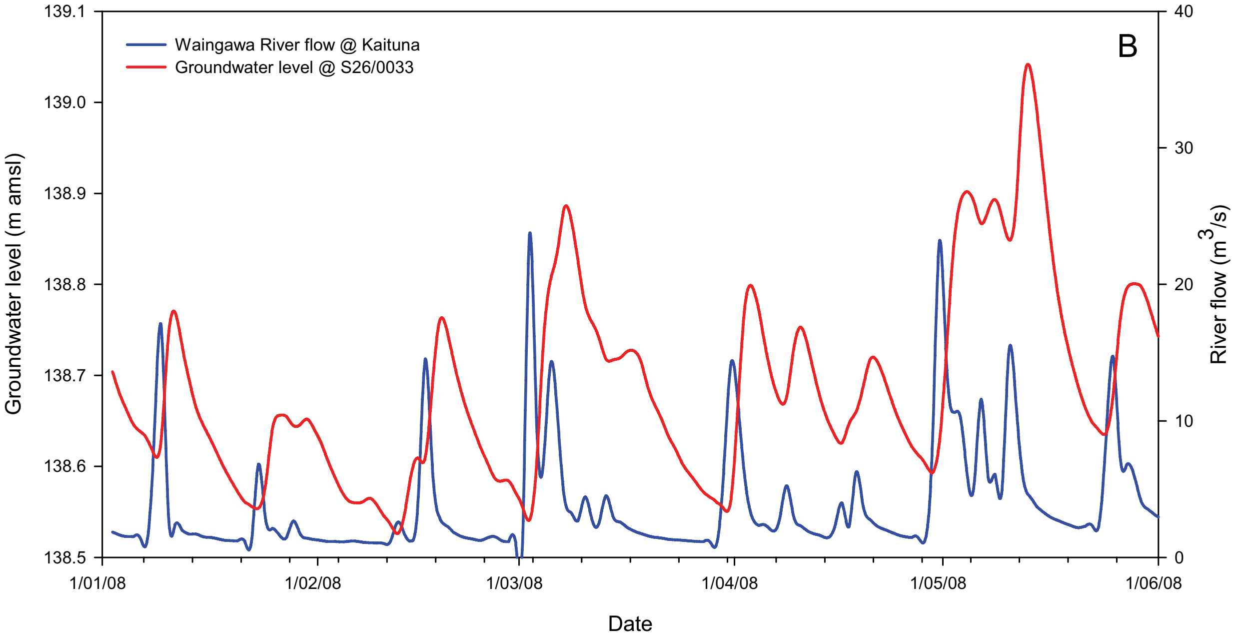
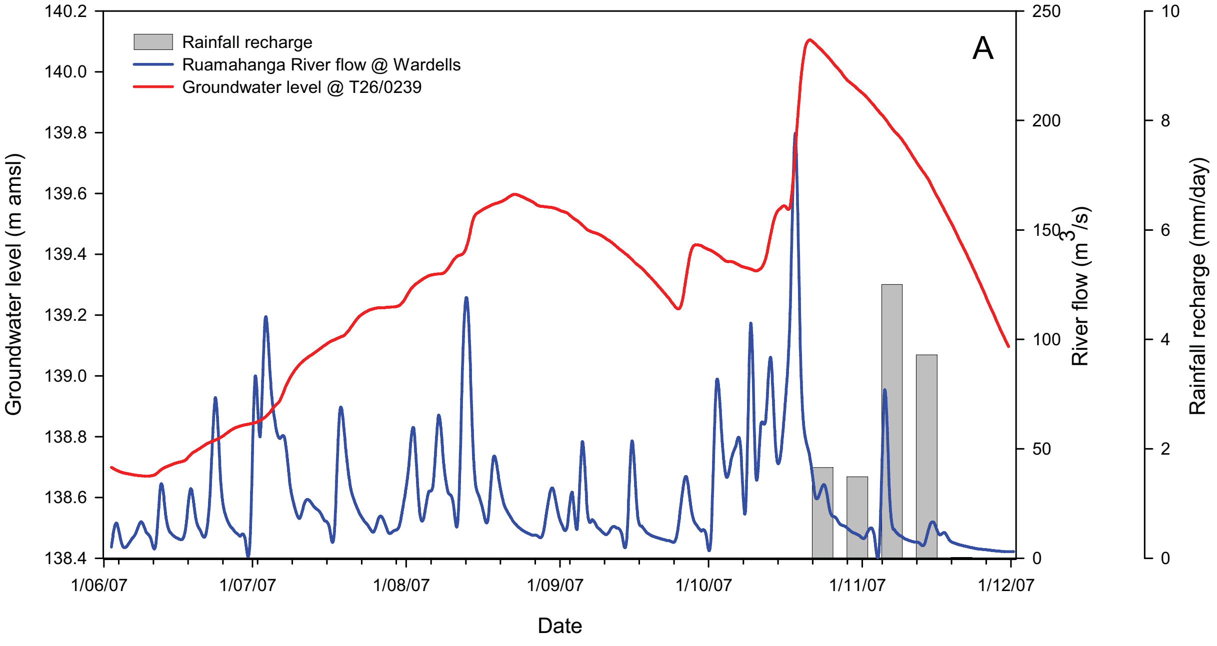


Figure 7.10: Automatic monitoring hydrographs for bore S26/0033 (with Waingawa River flow); A – winter 2007, B – summer 2008



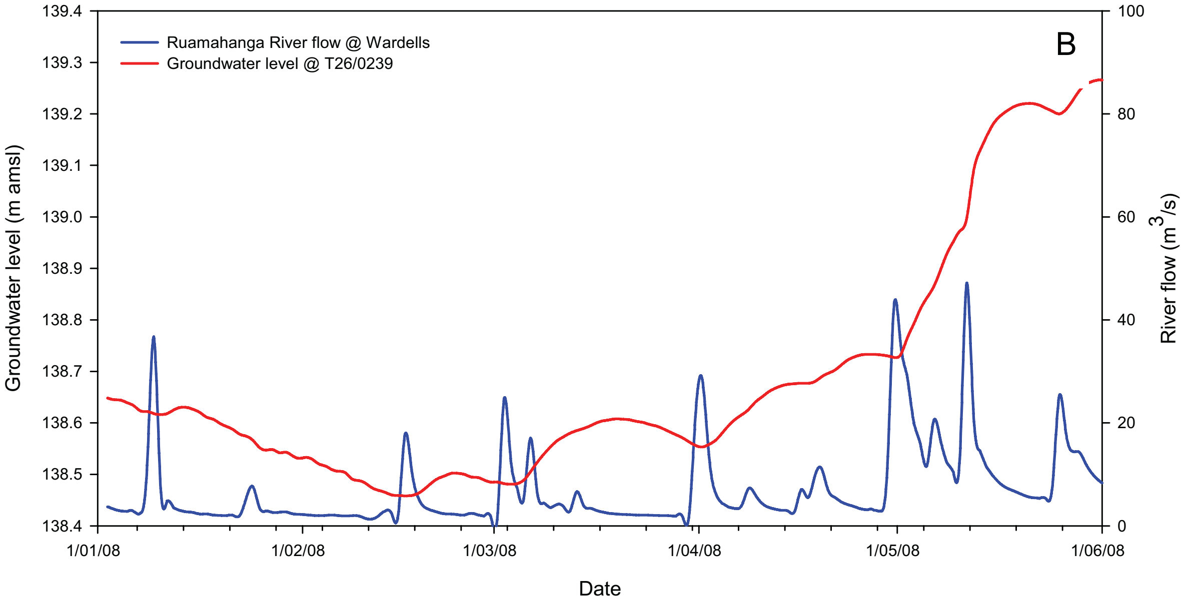


Figure 7.11: Automatic monitoring hydrographs for bore T26/0239 (with Ruamahanga River flow); A – winter 2007, B – summer 2008

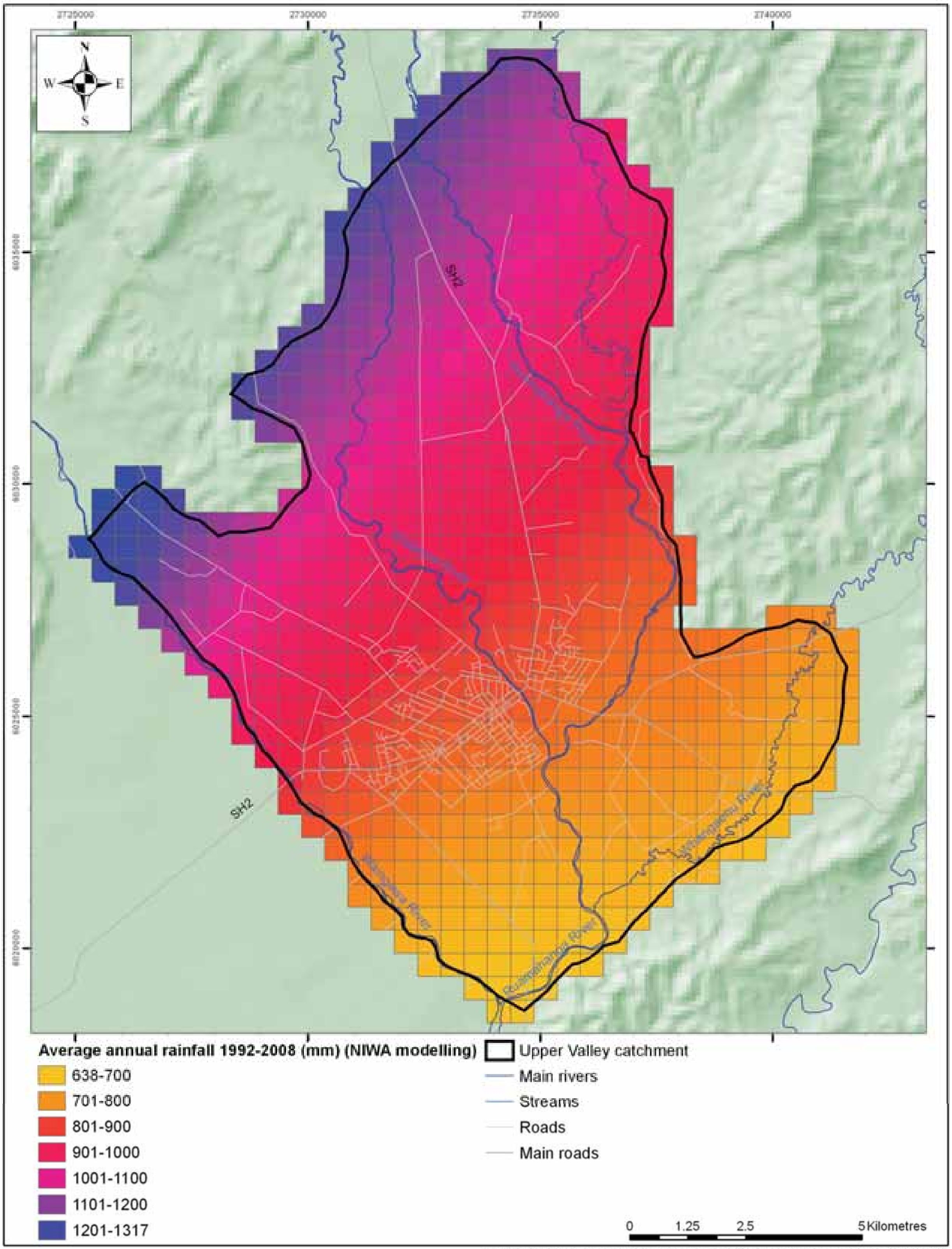


Figure 7.12: Average annual rainfall (1992-2008) for the Upper Valley catchment from NIWA modelling for 500 m^2 grid cell centre. Note the well defined rainfall gradient from NW to SE.

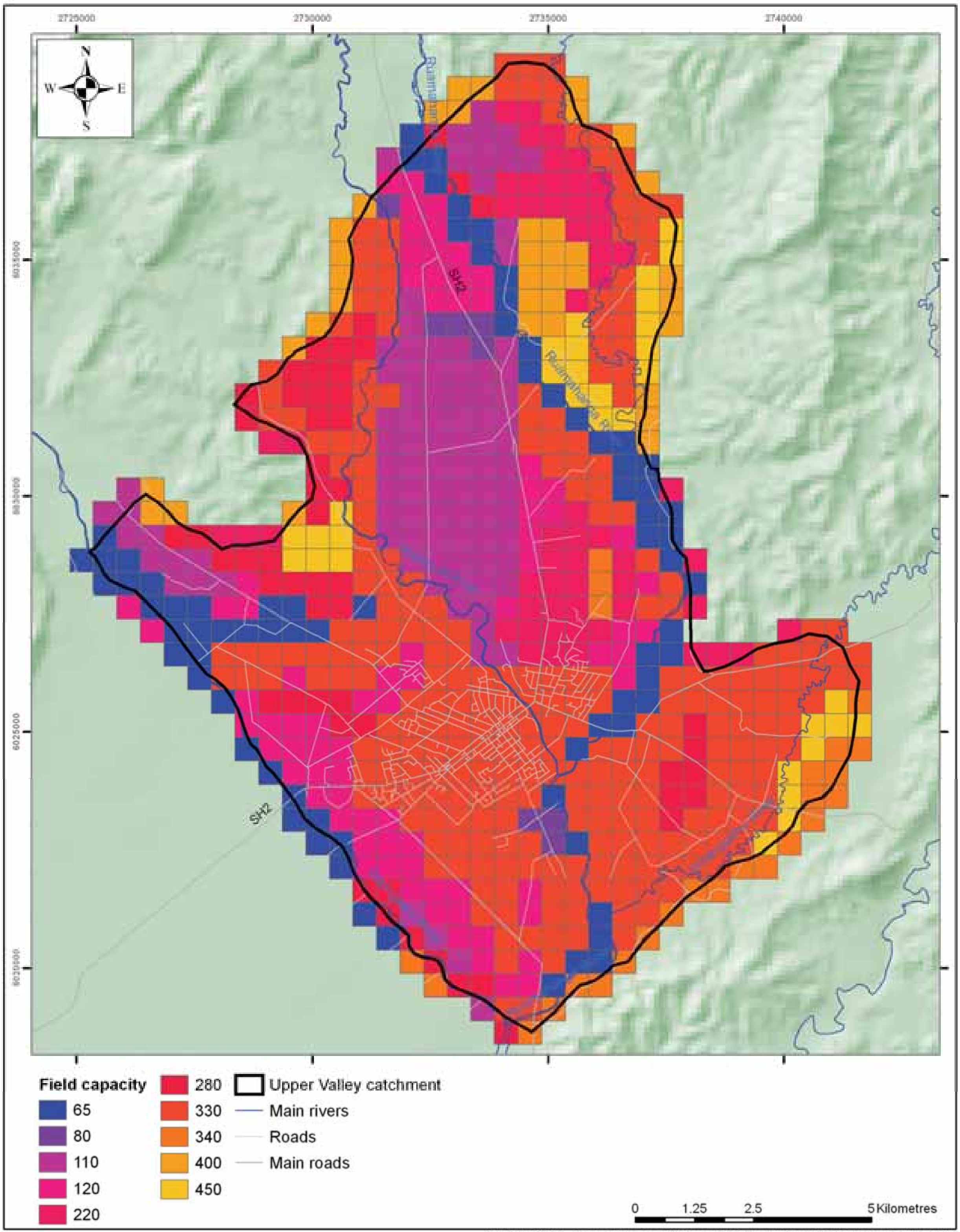


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Figure 7.13: Soil field capacity (mm) for the Upper Valley catchment demonstrating variation in soil drainage properties. A lower field capacity value indicates a better drained soil.

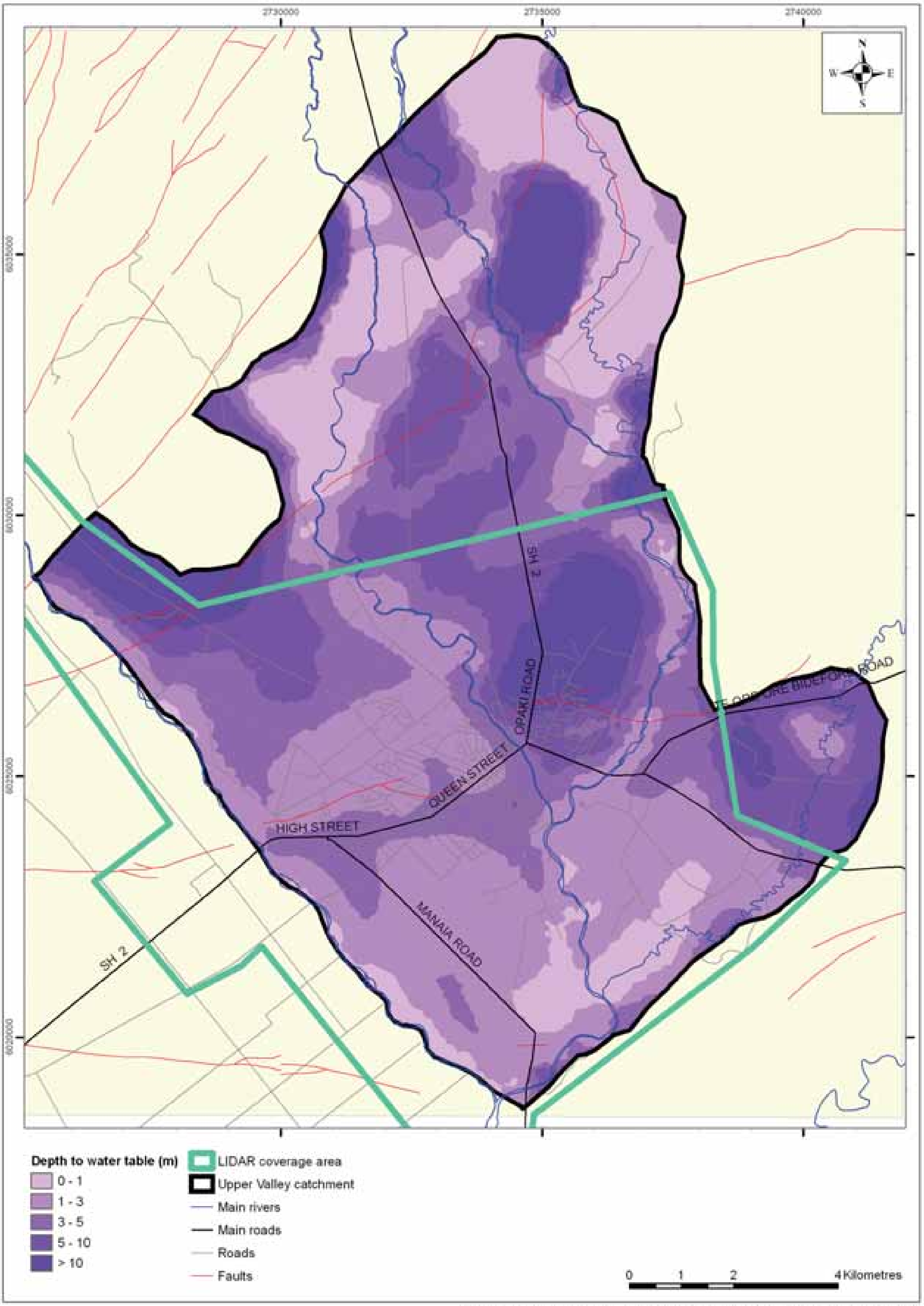

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Figure 7.14: Depth to water table contours, Upper Valley catchment

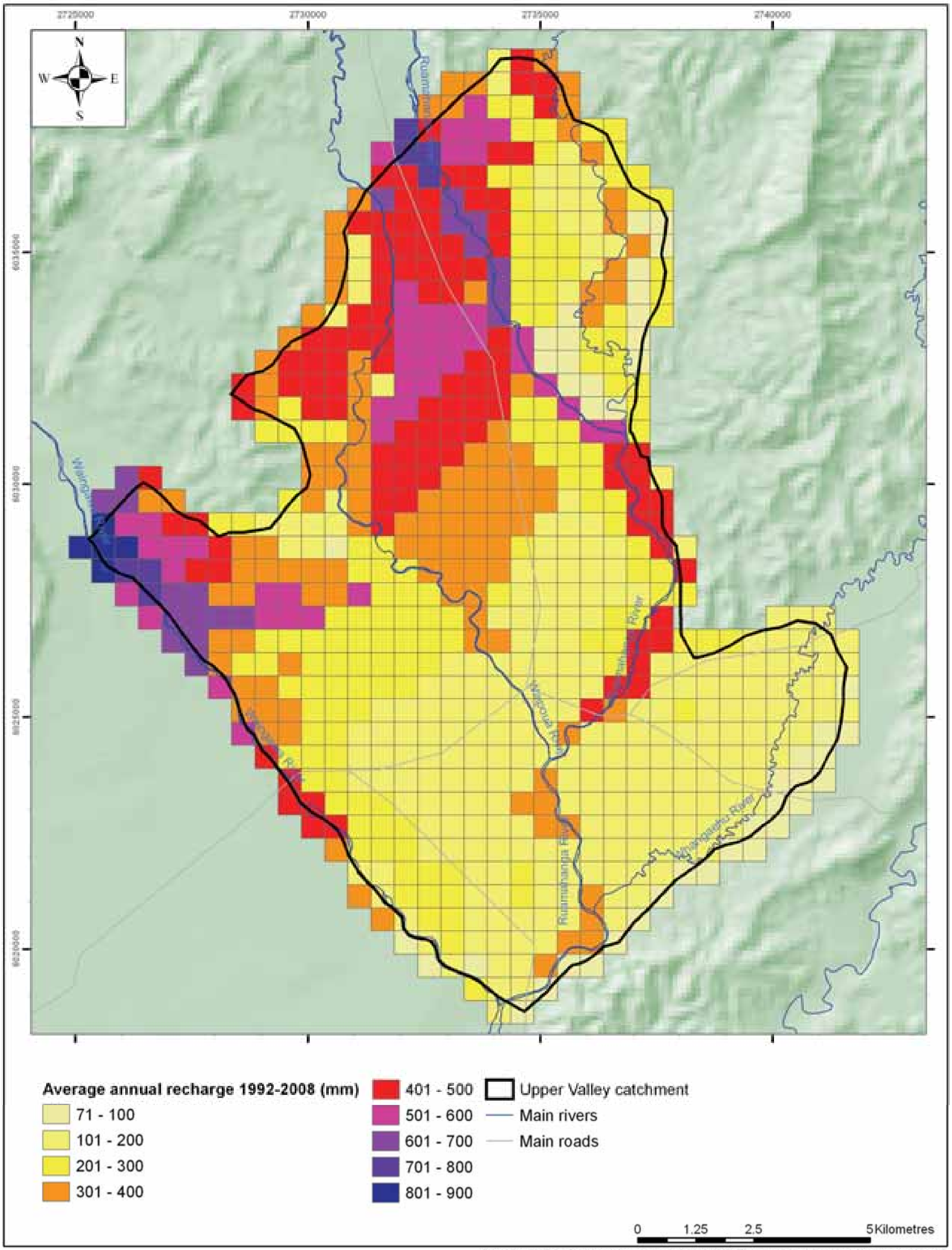

Figure 7.15: Average annual recharge for the Upper Valley catchment over the model period (1992-2008)

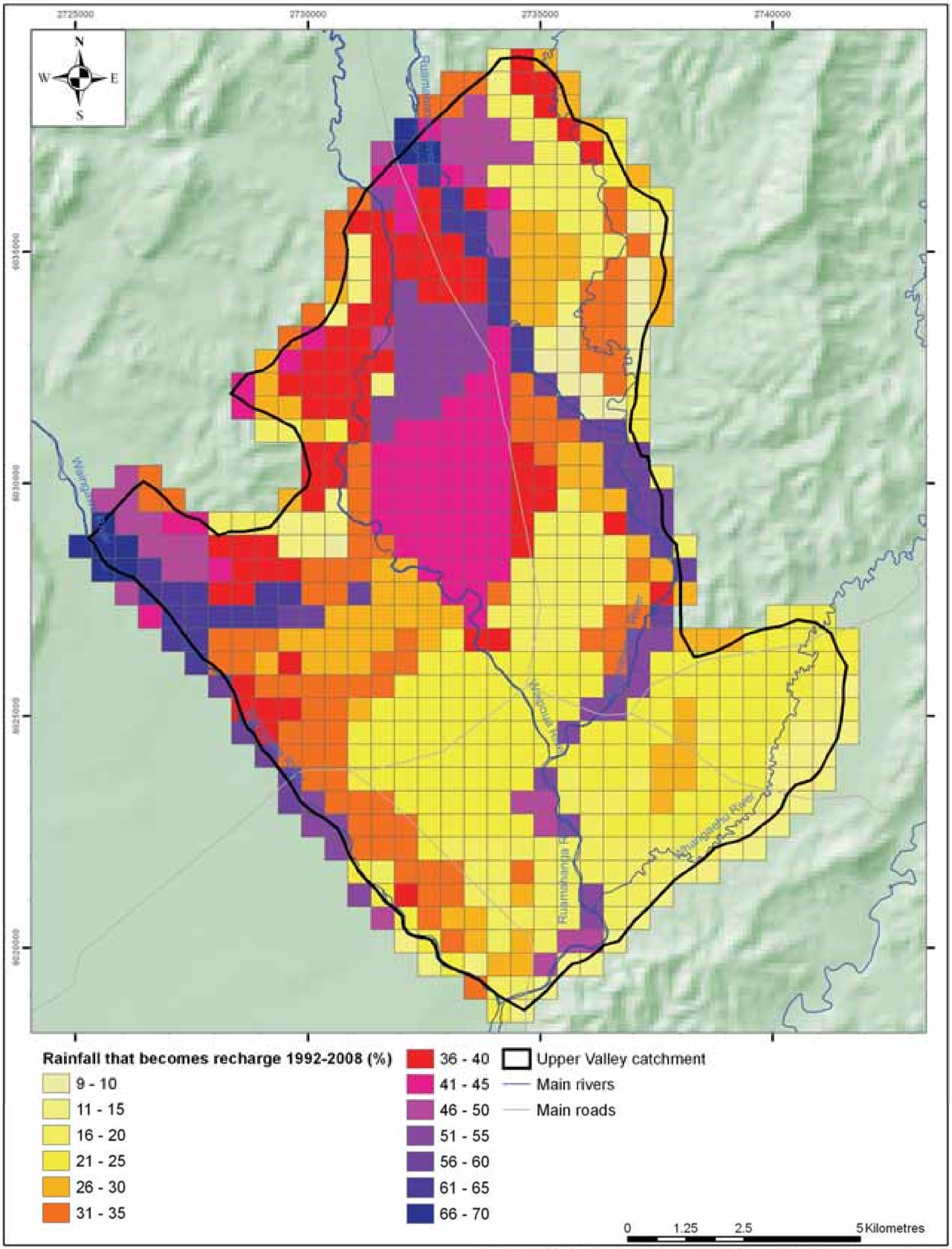

Figure 7.16: Modelled average percentage of rainfall that becomes recharge (free drainage from the soil profile) for the Upper Valley catchment

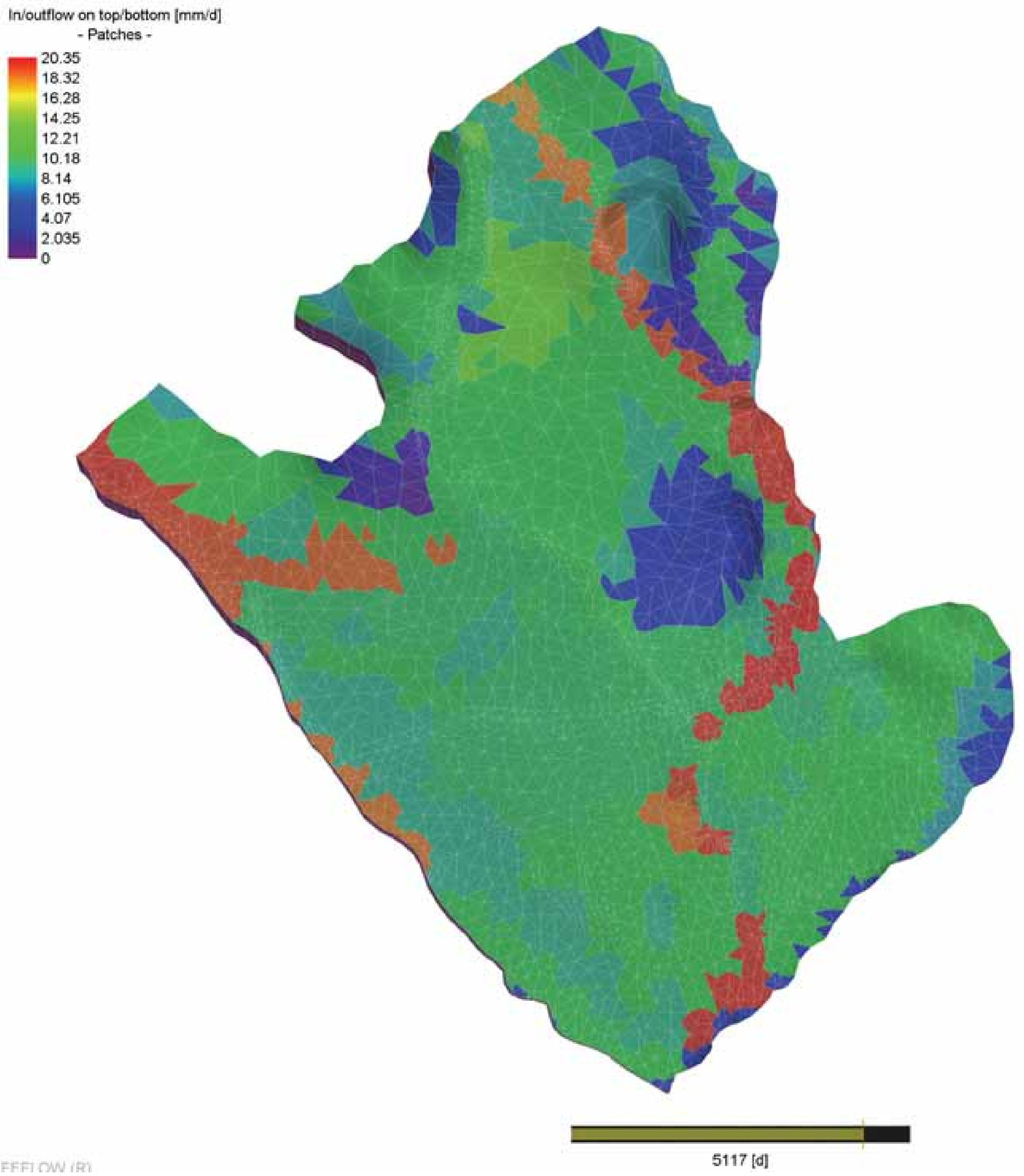

Figure 7.17: Modelled average rainfall recharge distribution over the Upper Valley catchment for the week commencing 28 June 2006 (wet year)

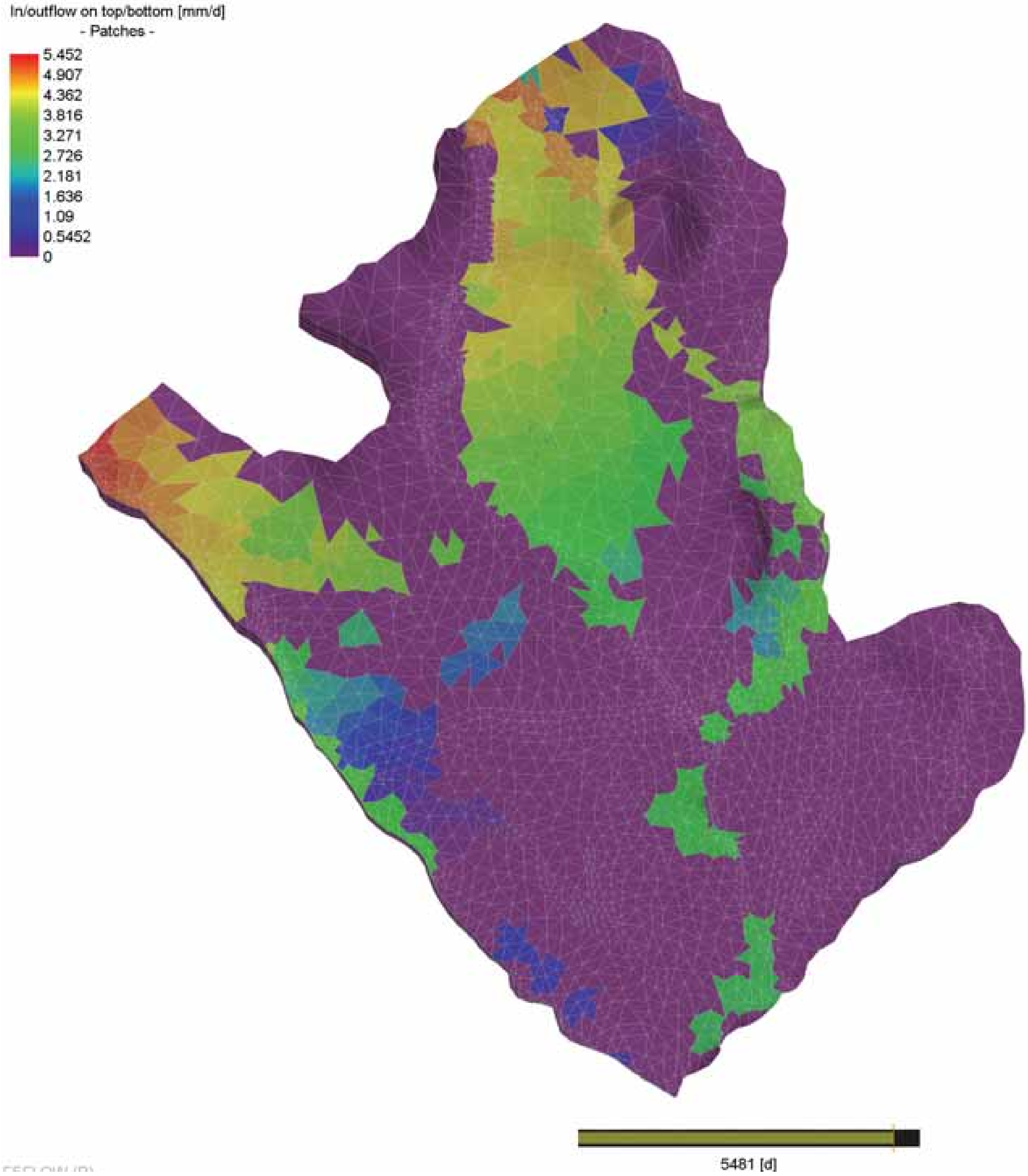

Figure 7.18: Modelled average rainfall recharge distribution over the Upper Valley catchment for the week commencing 27 June 2007 (dry year). Note the purple colour indicates zero recharge.

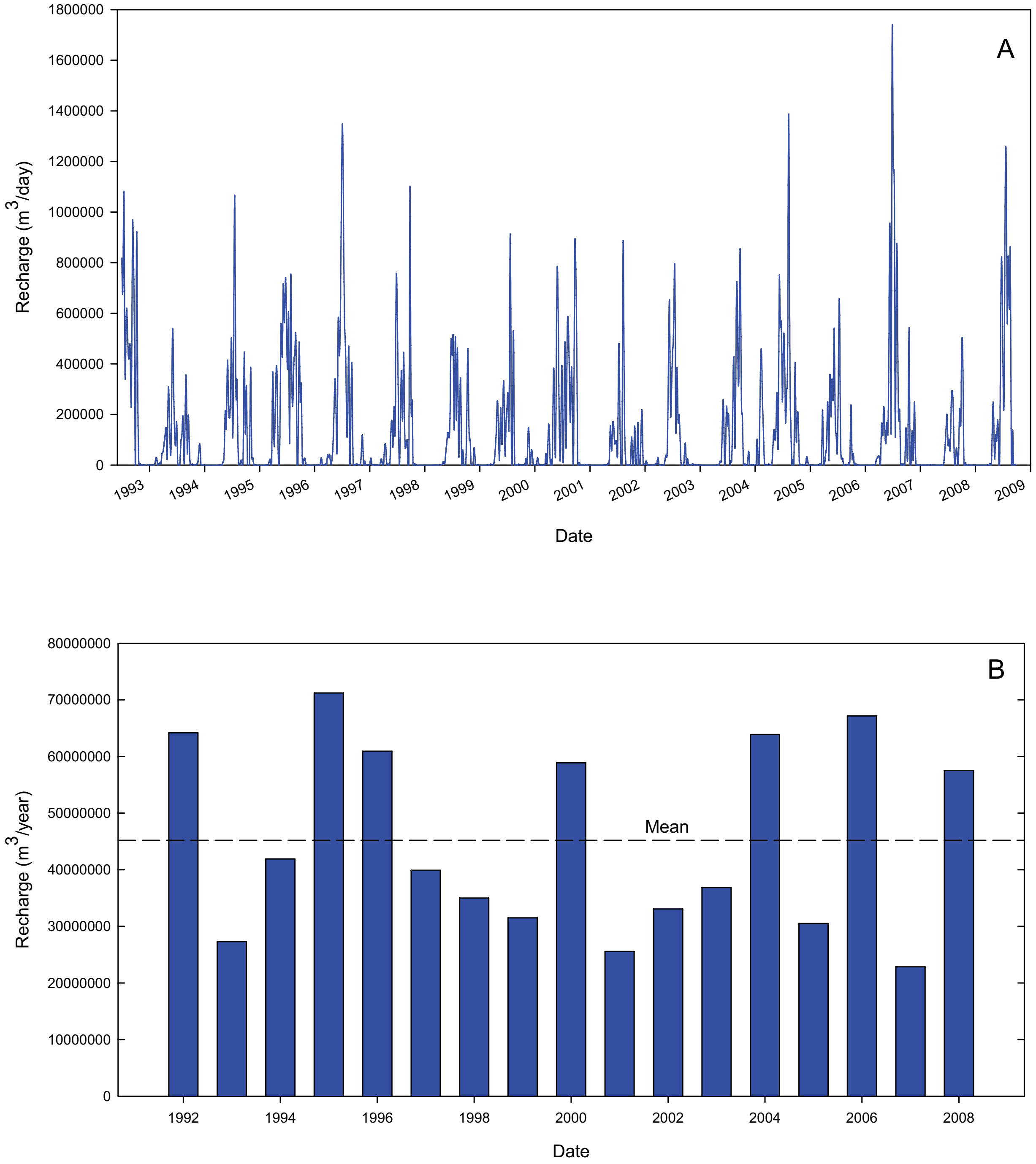

Figure 7.19: Simulated daily recharge (A) and simulated annual recharge (B) for the Upper Valley cathcment

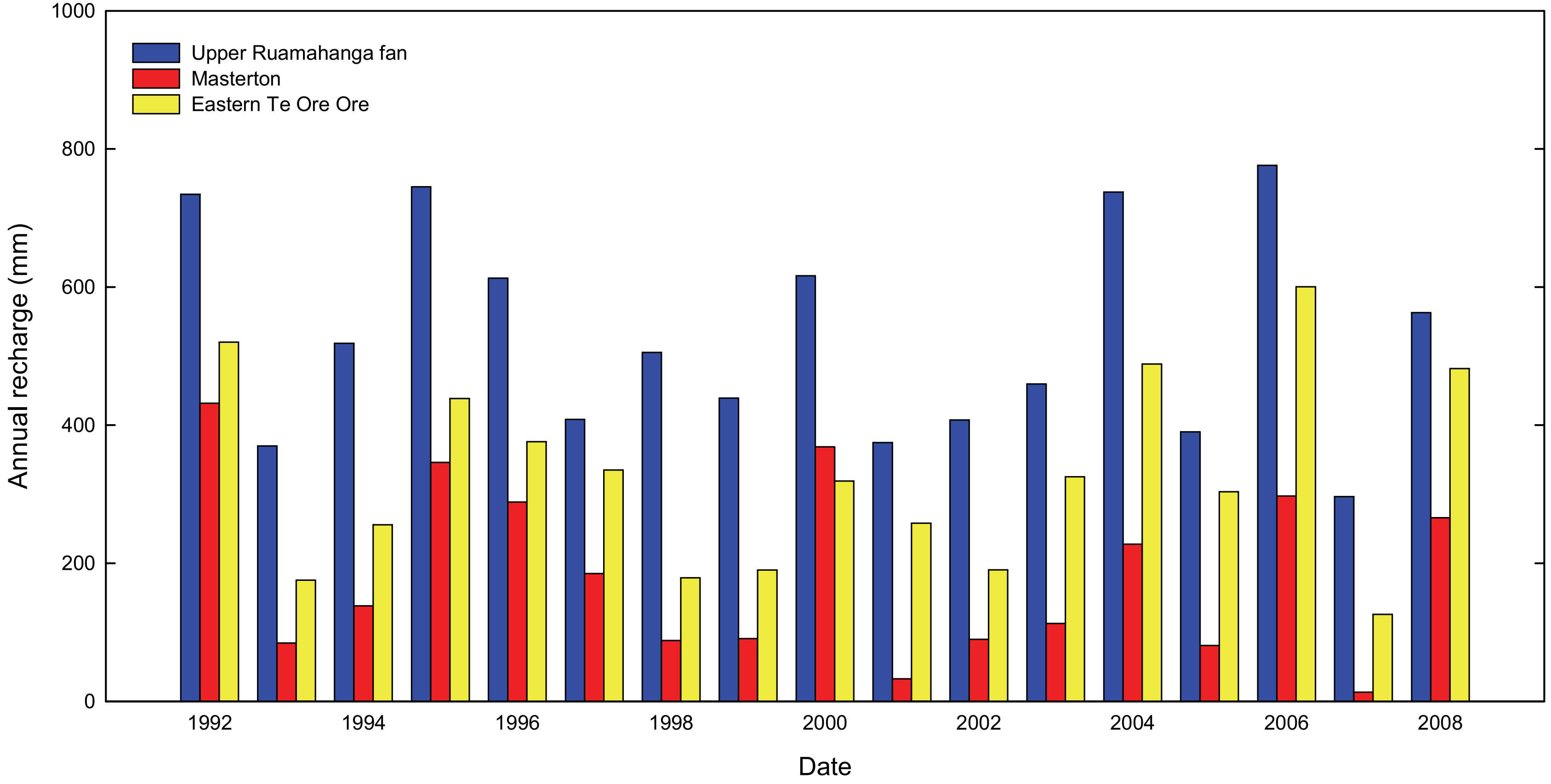

Figure 7.20: Modelled recharge for three 500 m² cells across the Upper Valley catchment for the period 1992-2008

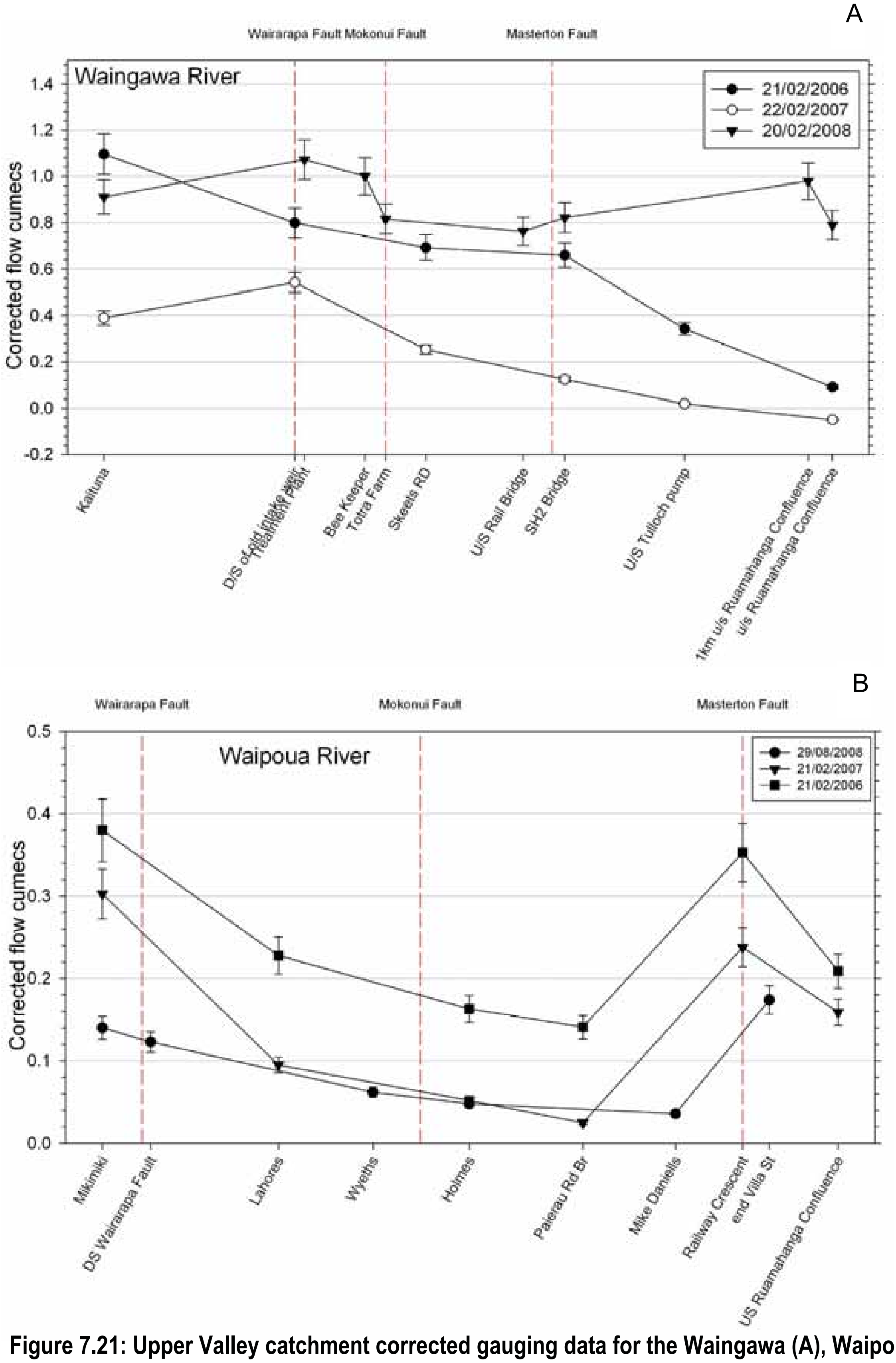

Figure 7.21: Upper Valley catchment corrected gauging data for the Waingawa (A), Waipoua (B) and Ruamahanga (C) rivers. Concurrent gauging data have been corrected to show gain and loss from groundwater only (surface inflow and outflows have been removed).

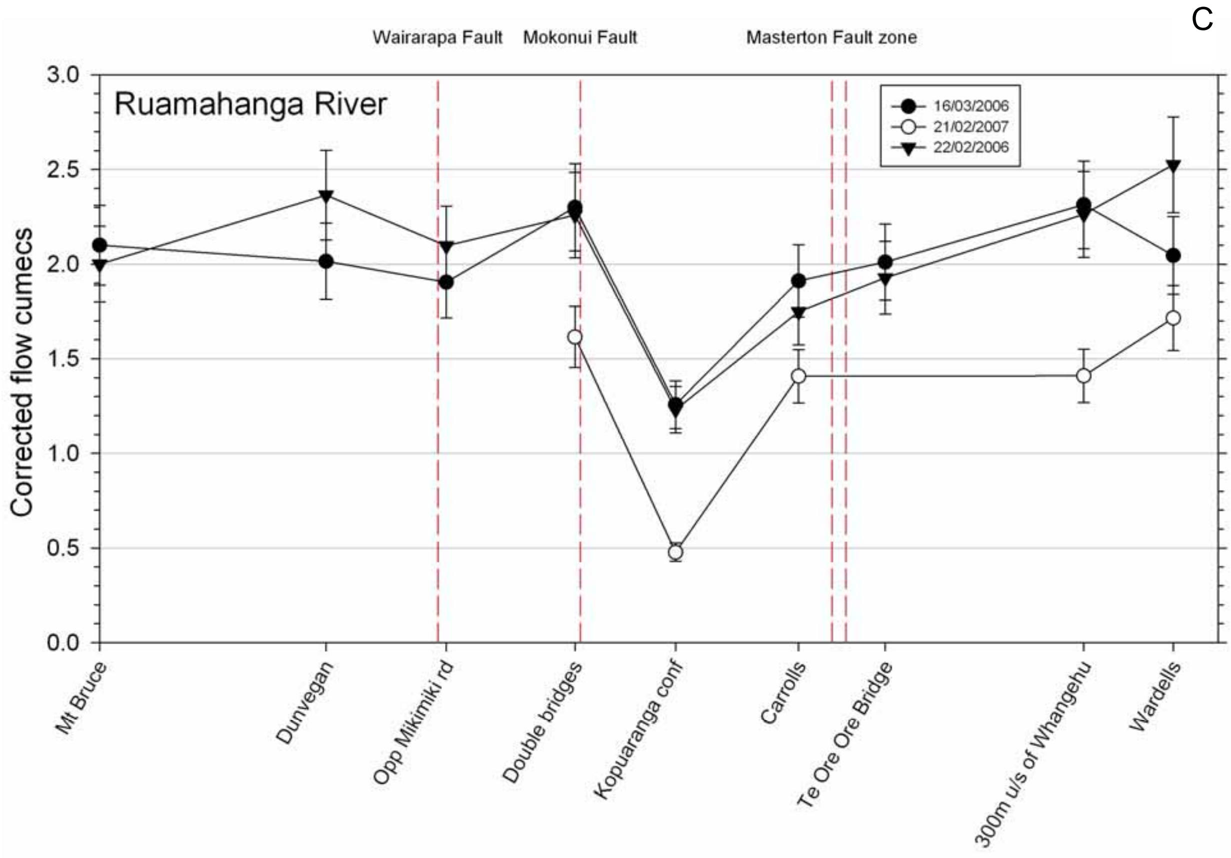

Figure 7.21 (continued): Upper Valley catchment corrected gauging data for the Waingawa (A), Waipoua (B) and Ruamahanga (C) rivers. Concurrent gauging data have been corrected to show gain and loss from groundwater only (surface inflow and outflows have been removed).

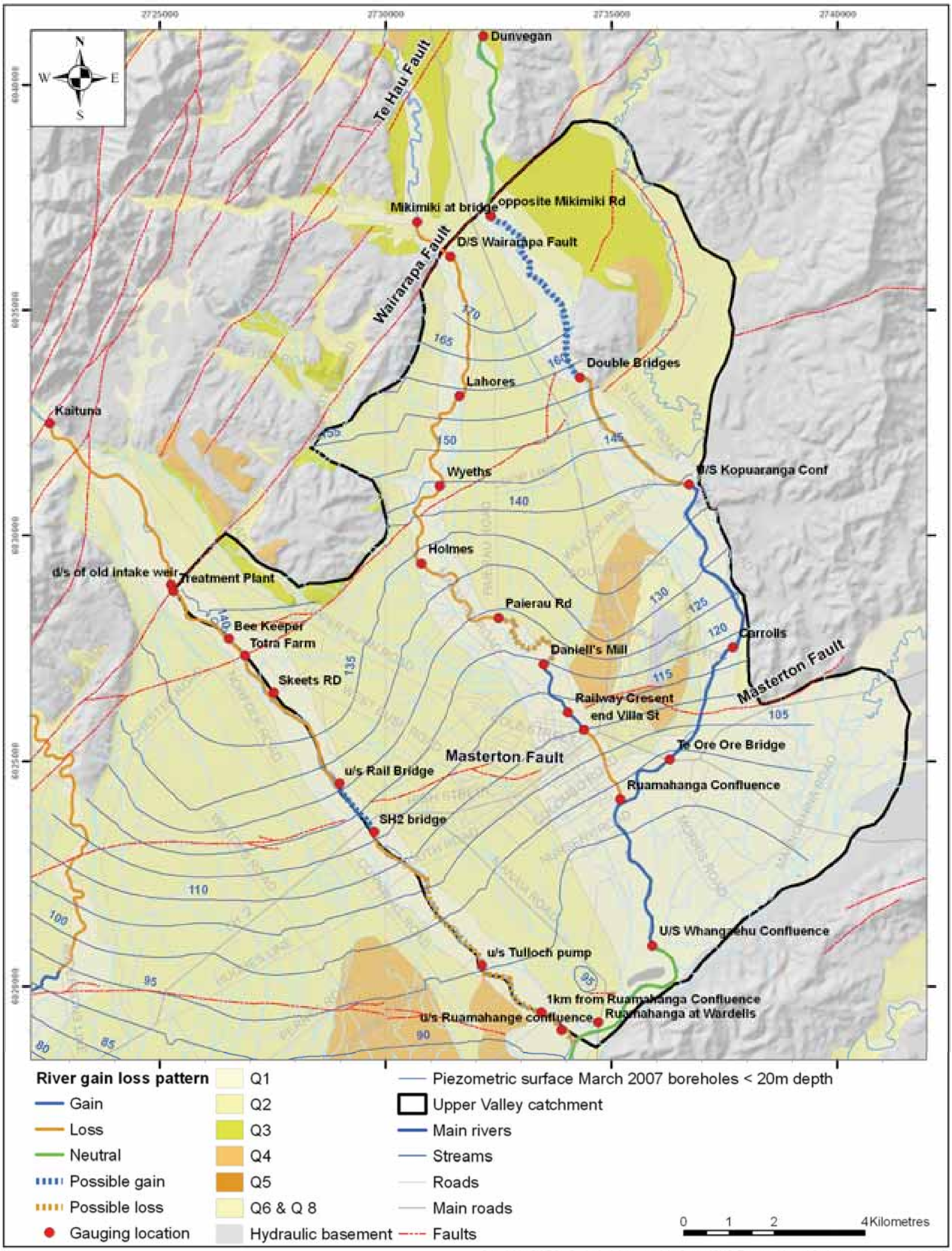

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Figure 7.22: Summary of concurrent gauging data showing recognised river gain-loss patterns for the Upper Valley catchment

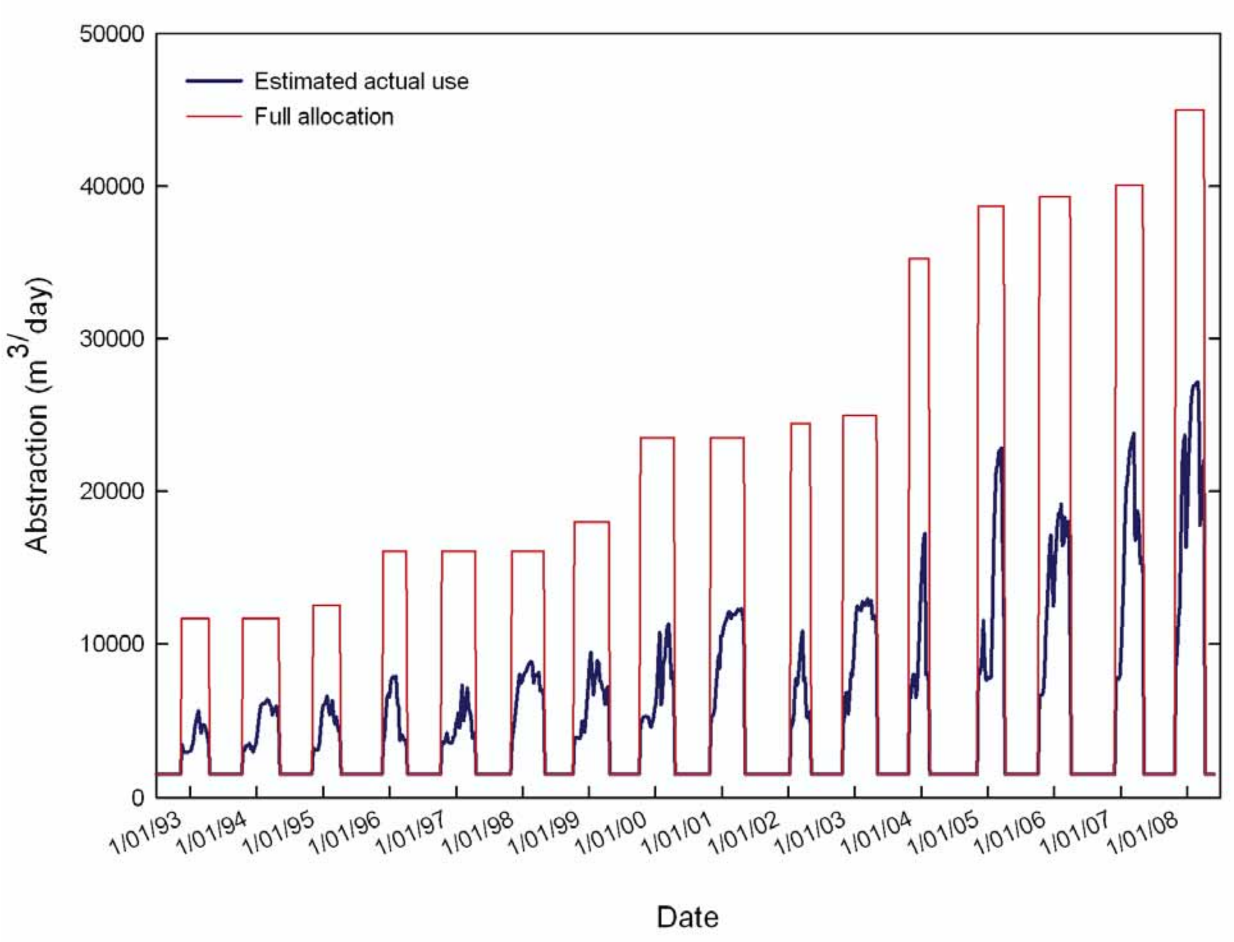

Figure 7.23: Total groundwater allocation for the Upper Valley catchment and estimated actual abstraction for the period 1992–2008

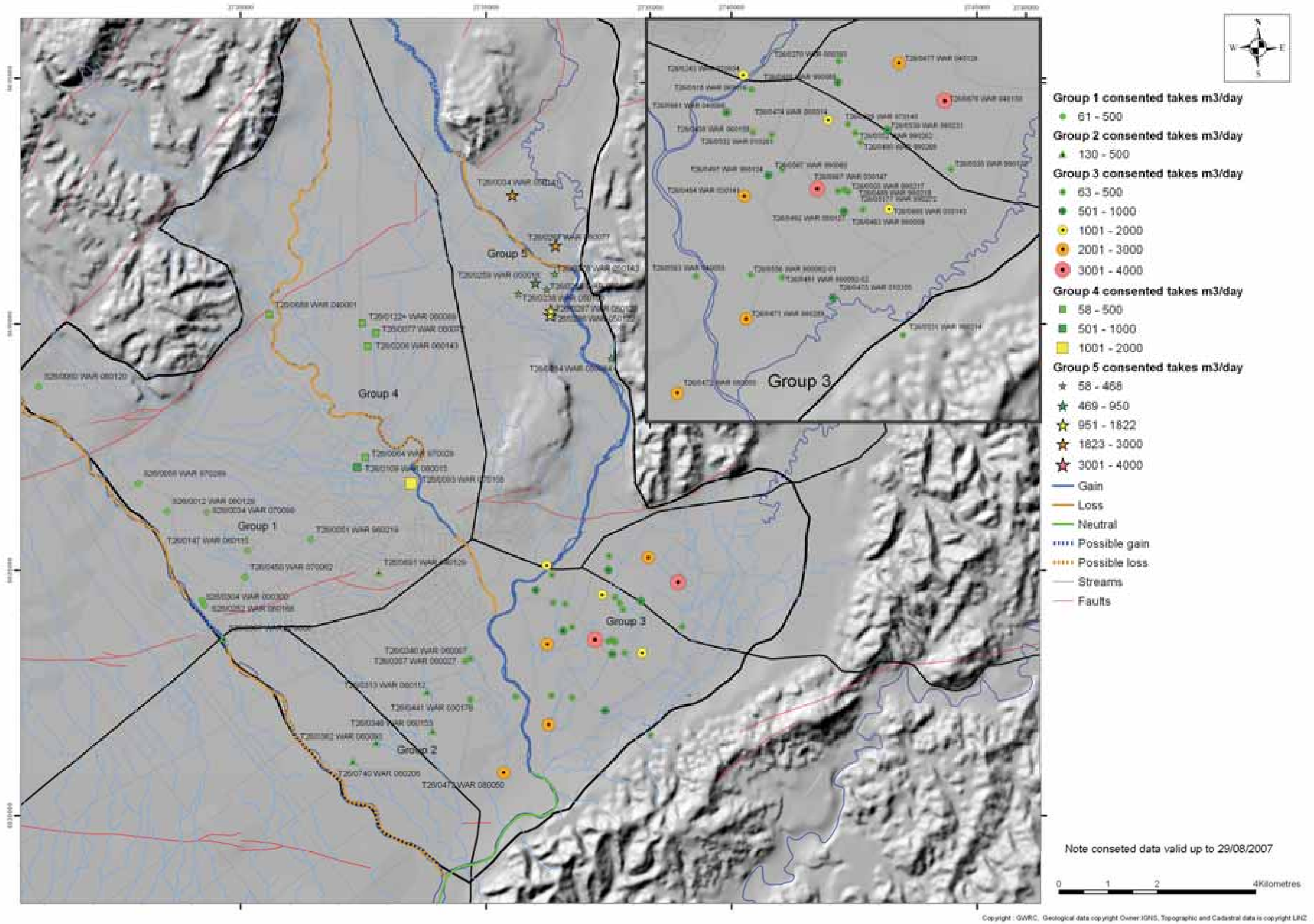

Figure 7.24: Consented groundwater abstractions within the Upper Valley catchment in m^3/day. Bore and consent numbers are shown. A total of 66 consented takes are shown on this figure.

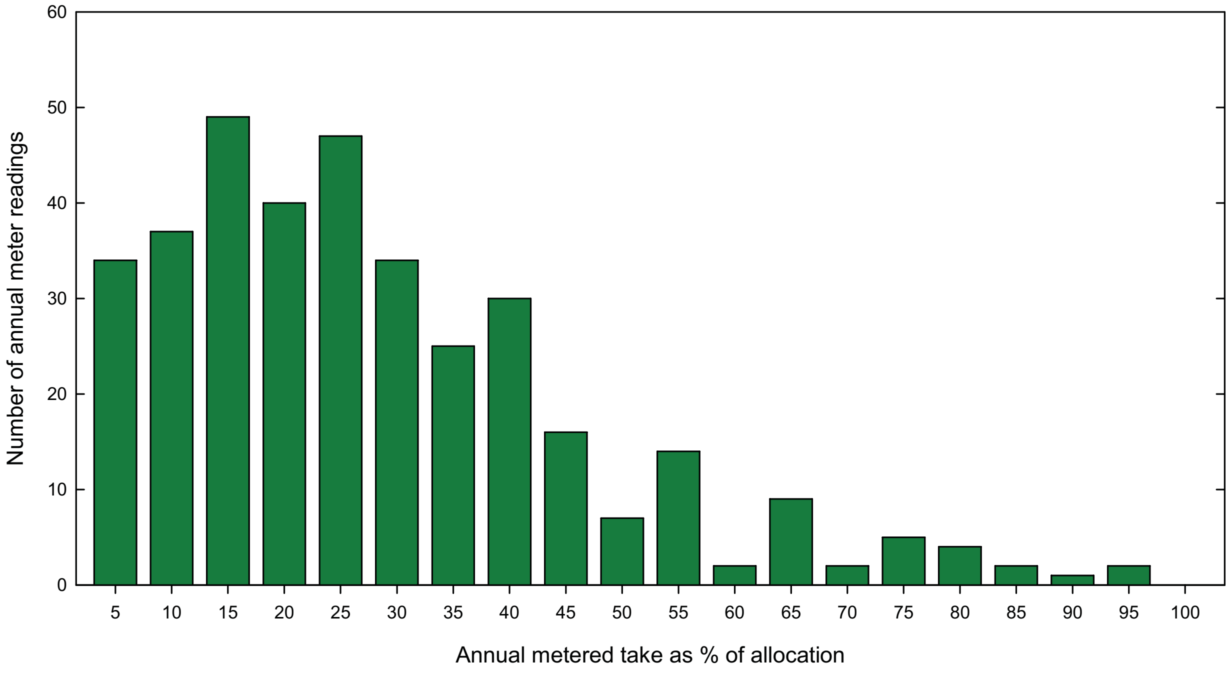

Figure 7.25: Annual water meter data plotted as a percentage of consented allocation for the Upper Valley catchment

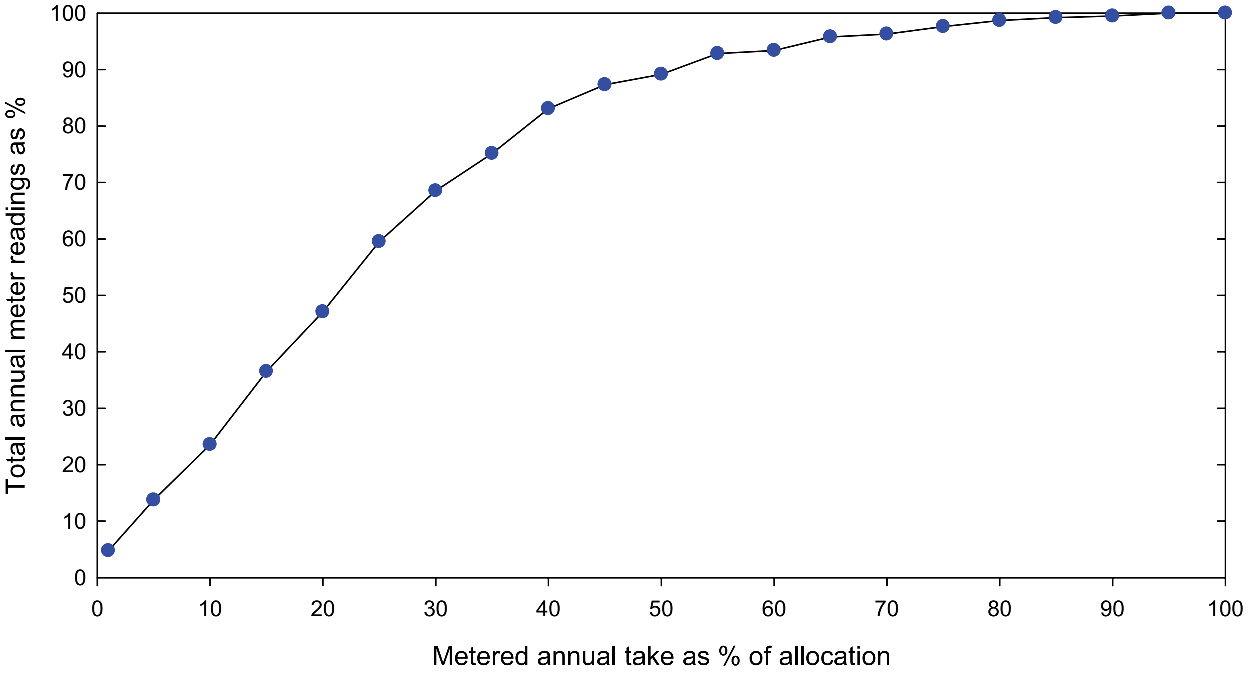

Figure 7.26: Cumulative-frequency plot for percentage of allocation used (based on annual water meter readings) for the Upper Valley catchment

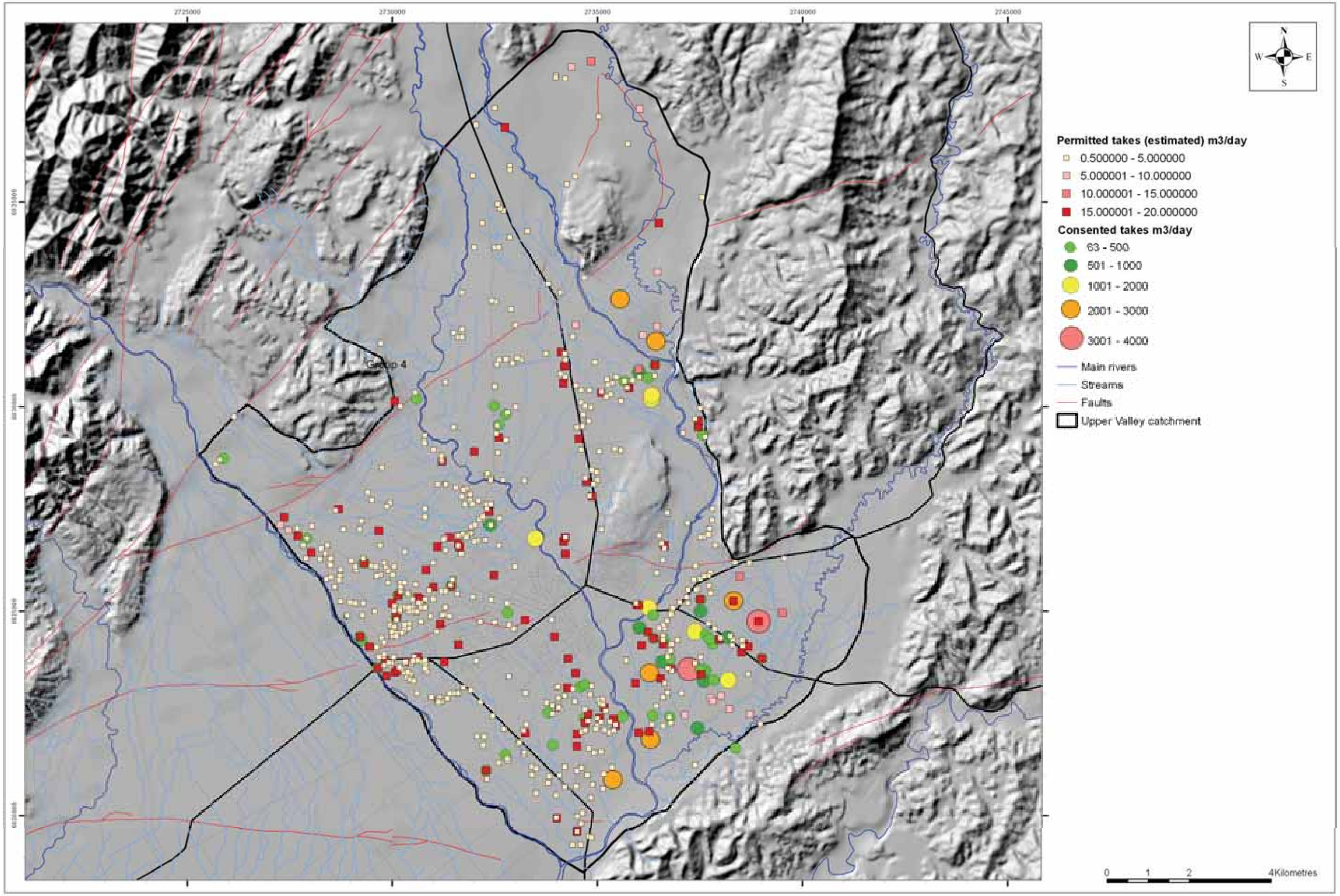

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Figure 7.27: Estimated non-consented (permitted) groundwater takes in the Upper Valley catchment

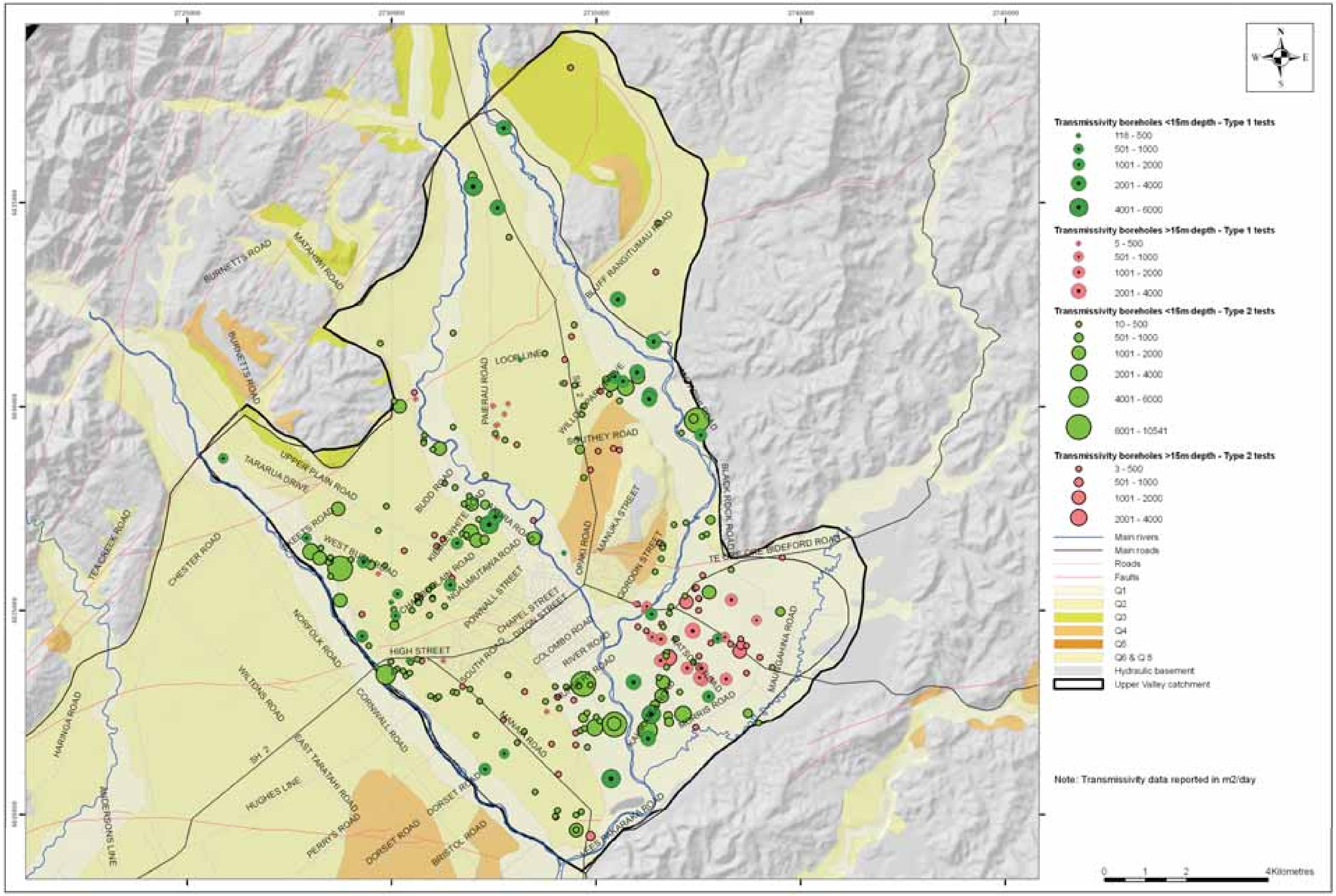

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Figure 7.28: Calculated transmissivity data derived from pumping test data for the Upper Valley cathment. Type 1 tests refer to pumping test results and Type 2 tests refer to basic yield tests.

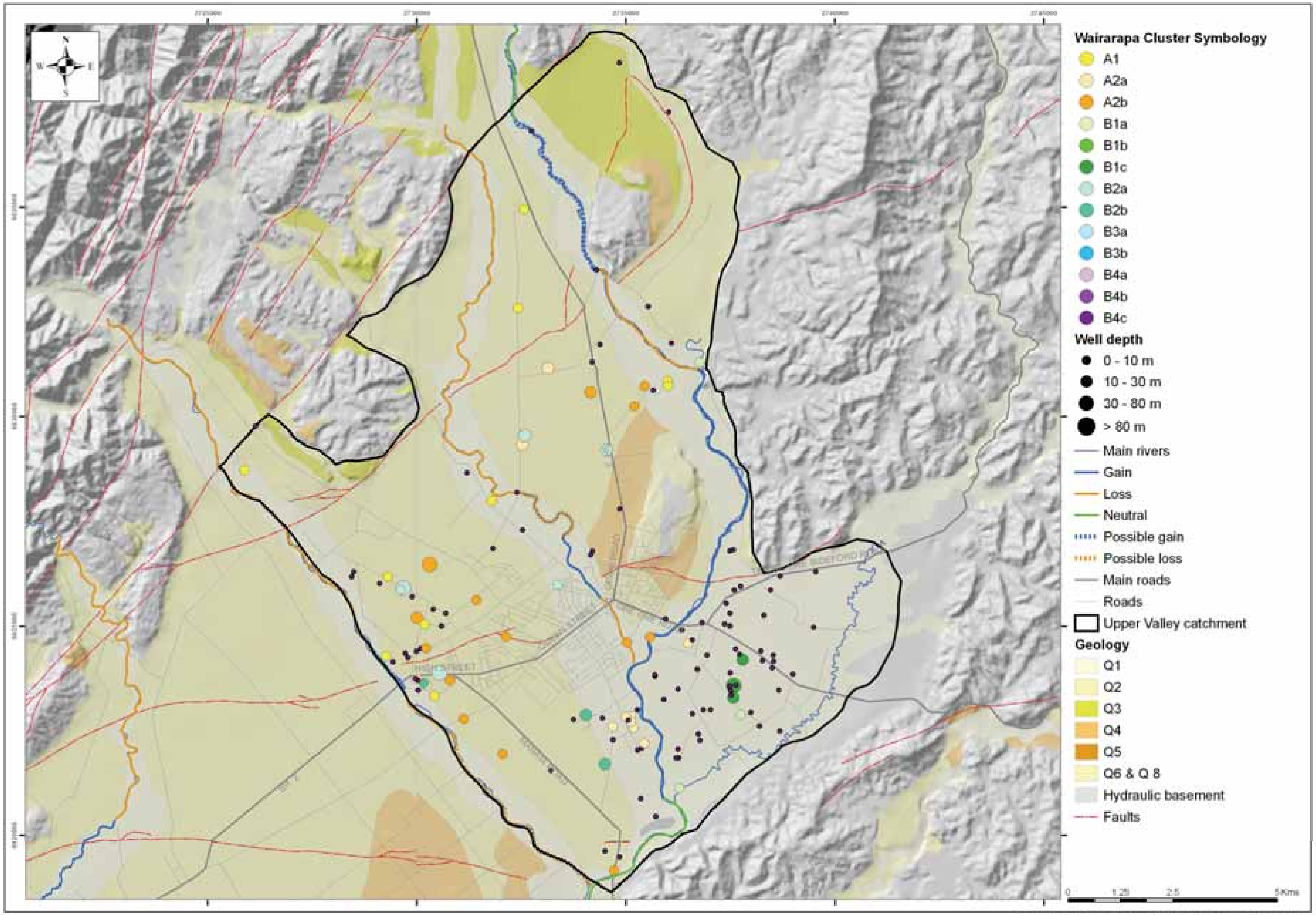

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Figure 8.1: Hydrochemistry cluster analysis, Upper valley catchment (derived from Daughney et al. 2009)

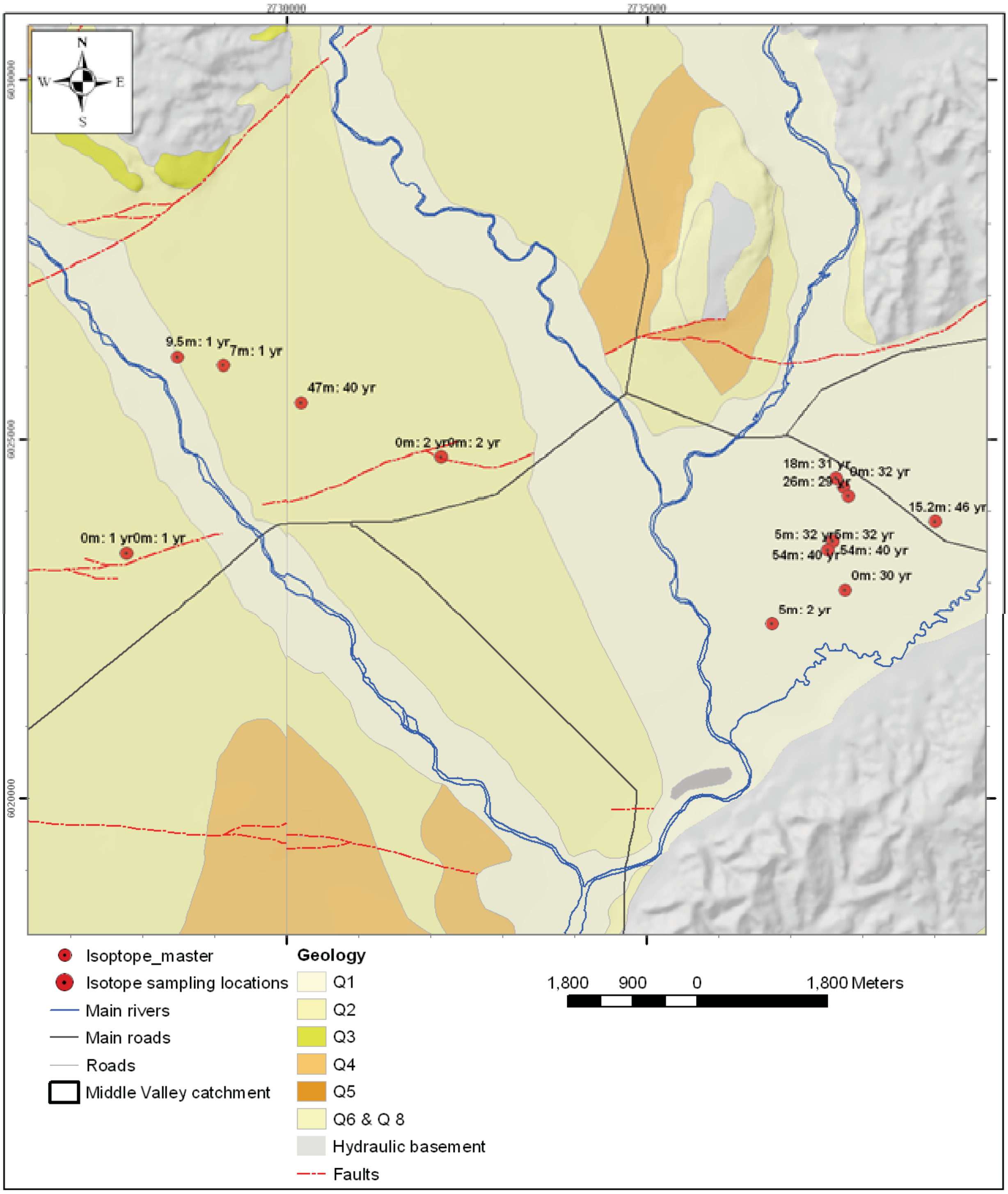

Figure 8.2: Groundwater residence time analysis using CFC, SF6 and C14 methods, Upper Valley catchment (wells depth in metres and age in years are shown next to sampling locations)

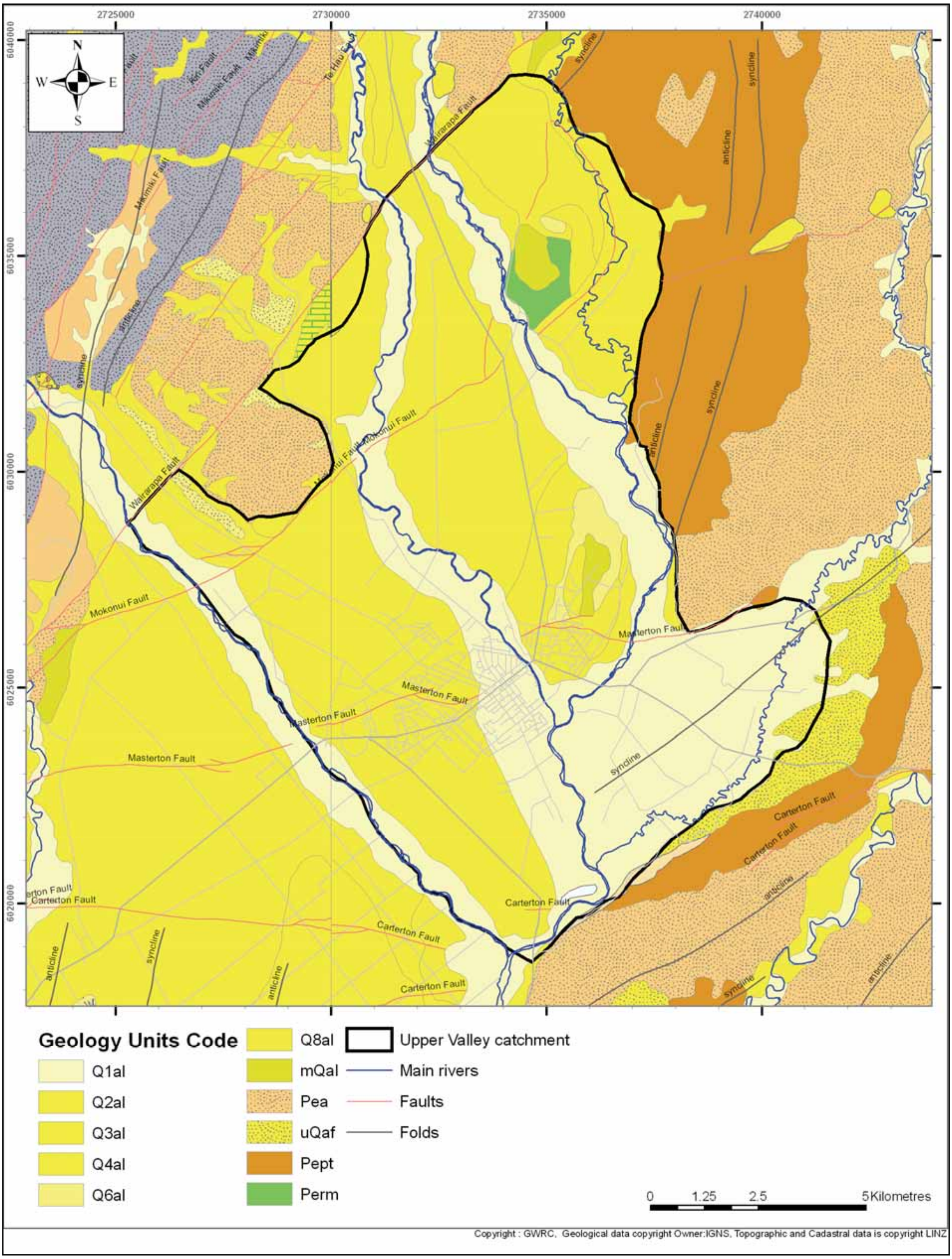

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Figure 9.1: The Upper Valley catchment showing the groundwater model domain boundaries

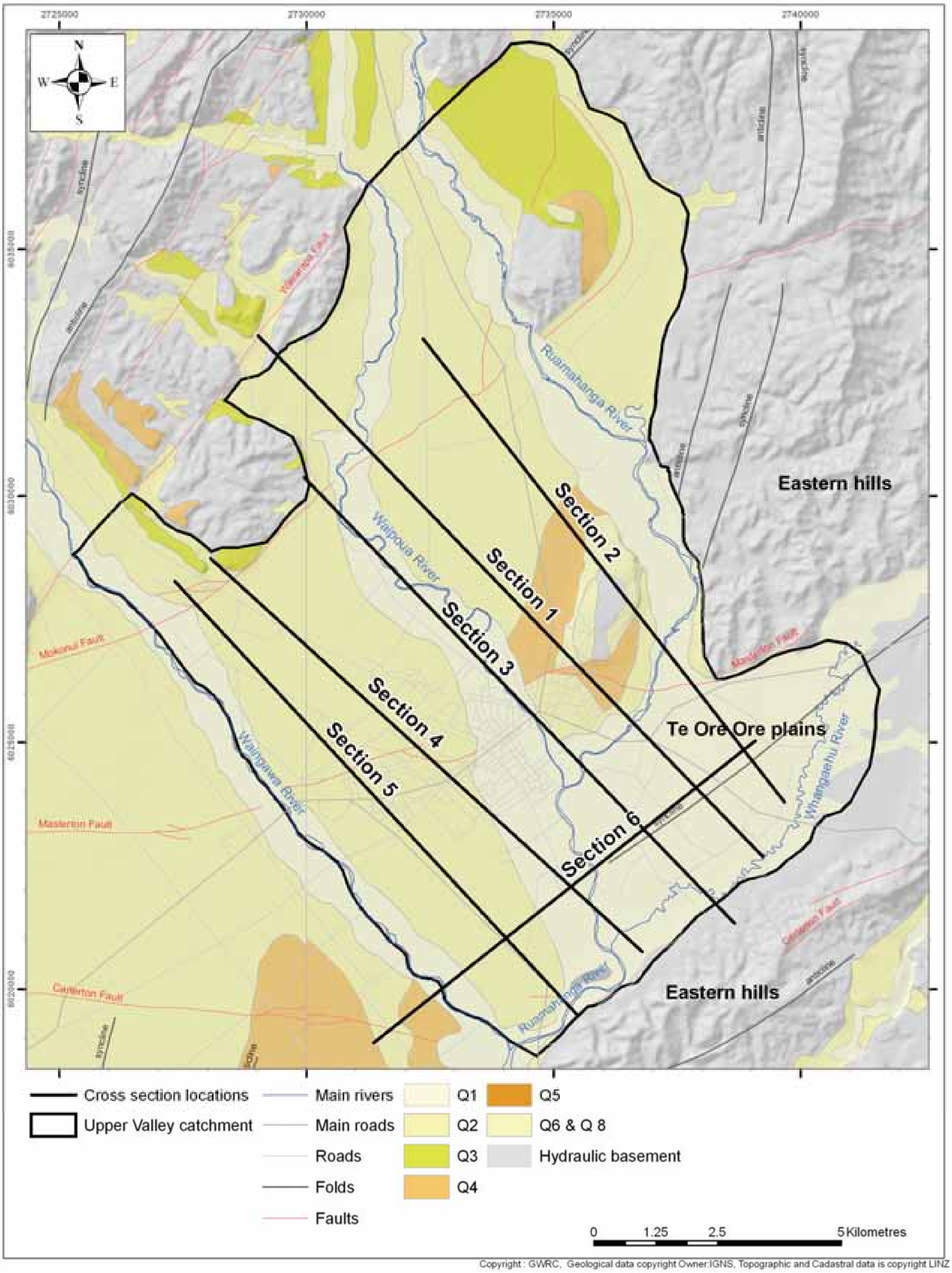

Figure 10.1: Upper Valley catchment groundwater model domain showing the locations of cross sections presented in Figure 10.6

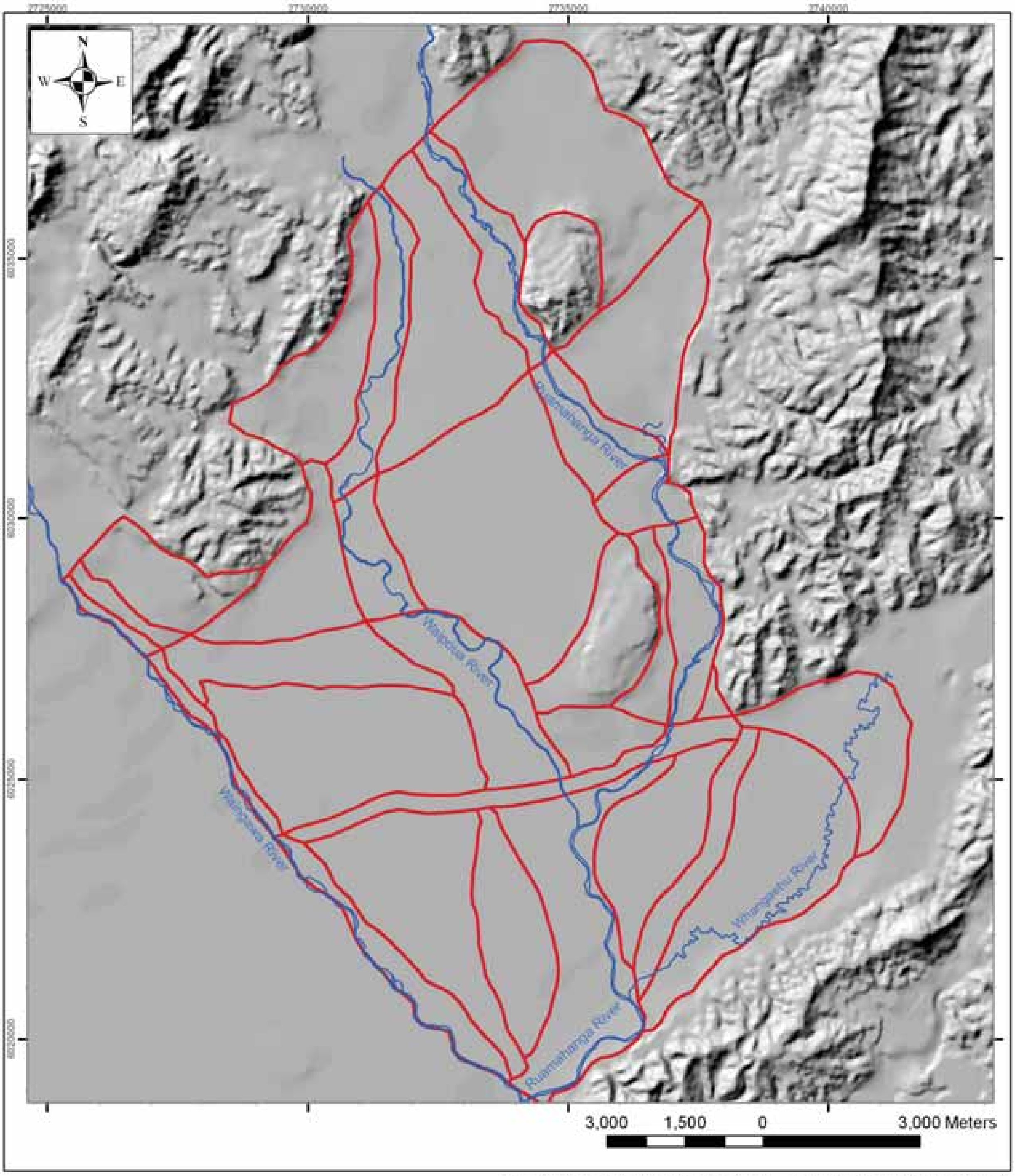

Figure 10.2: Upper Valley catchment groundwater model FEFLOW super element mesh

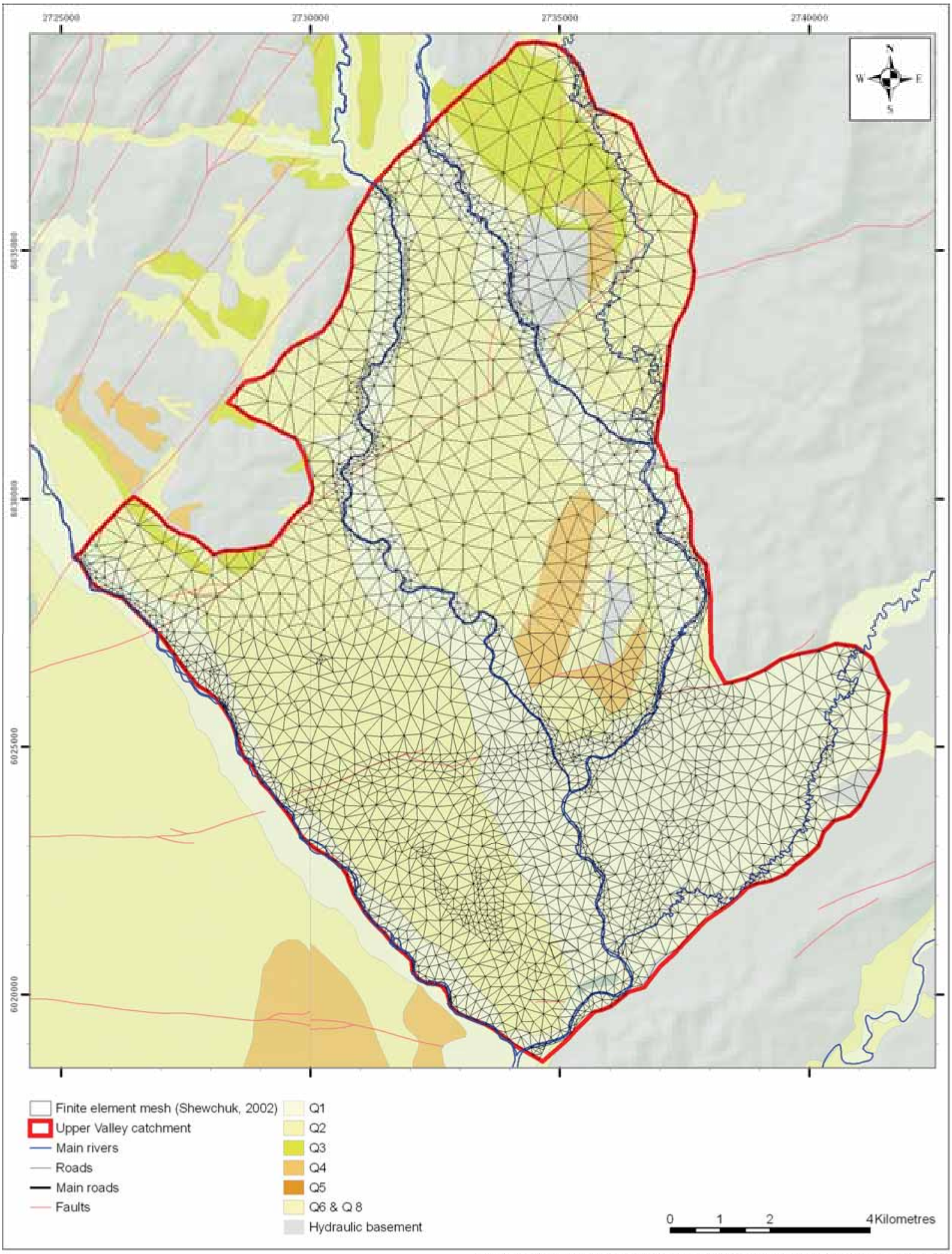

Figure 10.3: Upper Valley groundwater model finite element mesh generated using "Triangle" (Shewchuk 2002)

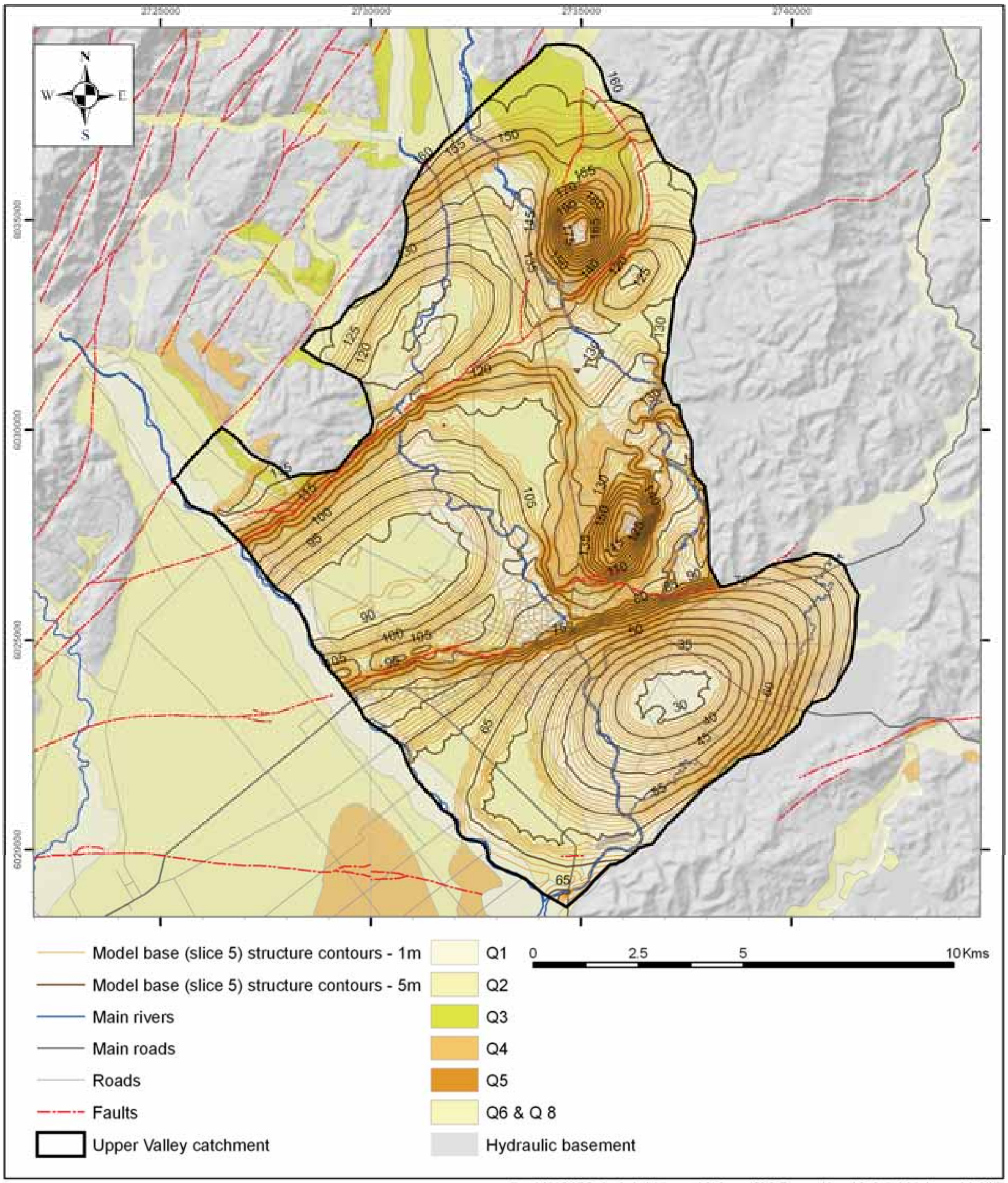

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Figure 10.4: Model base (slice 5) structure contours, Upper Valley catchment

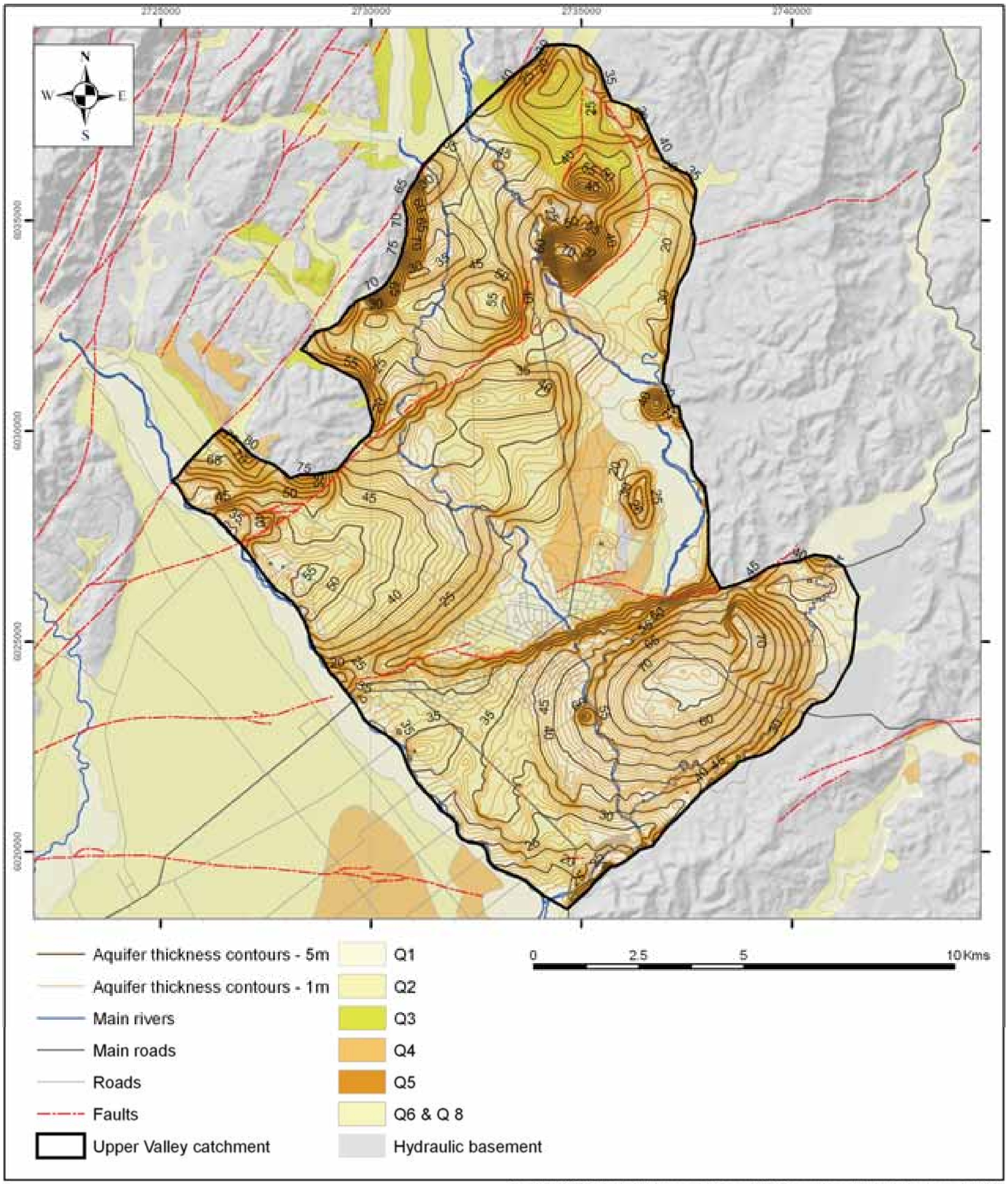


Figure 10.5: Aquifer thickness contours, Upper Valley catchment

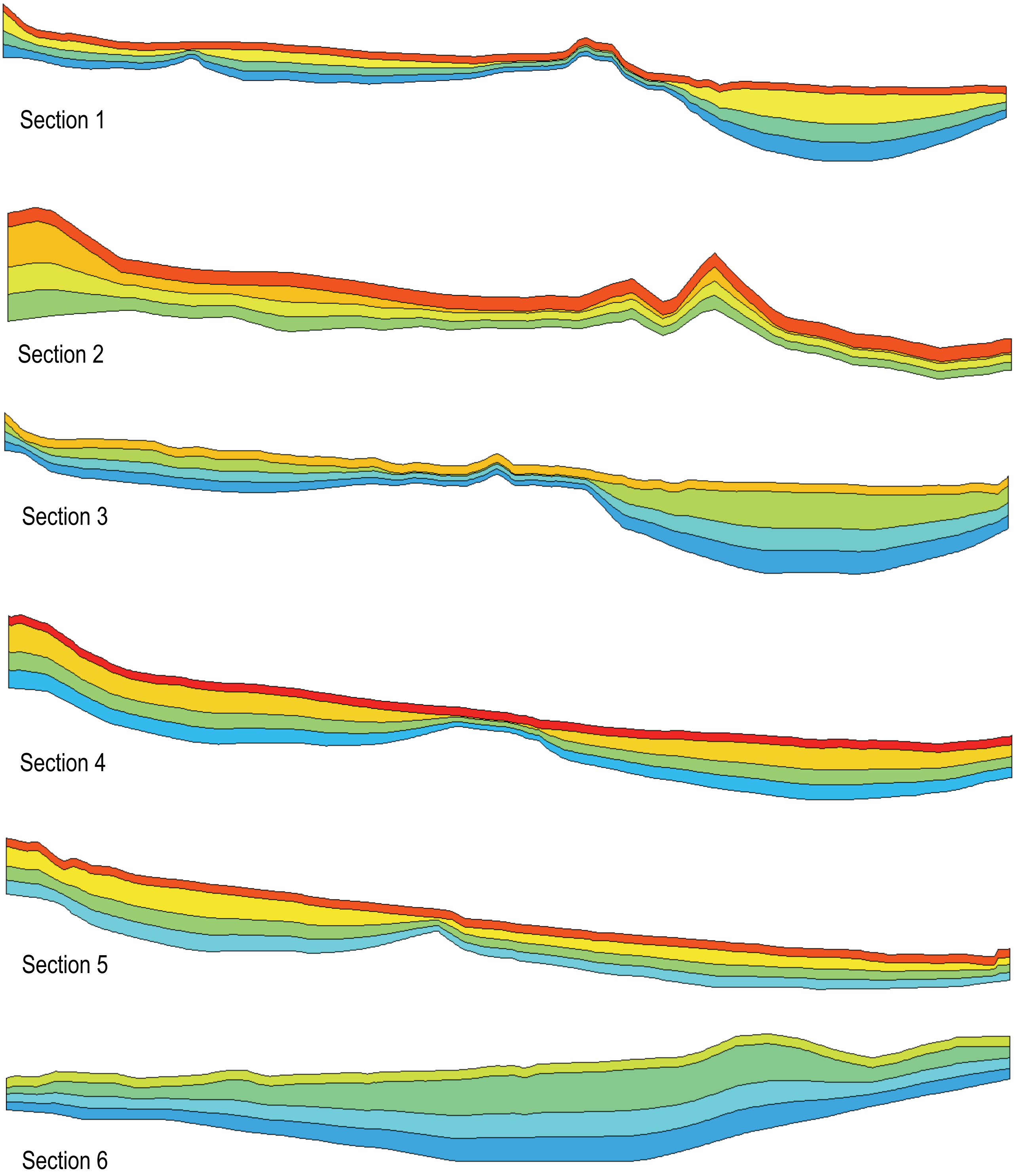


Figure 10.6: Cross sections through the FEFLOW groundwater model to illustrate model geometry and layer configuration (all sections have same vertical and horizontal scales). Section line locations are shown on Figure 10.1.

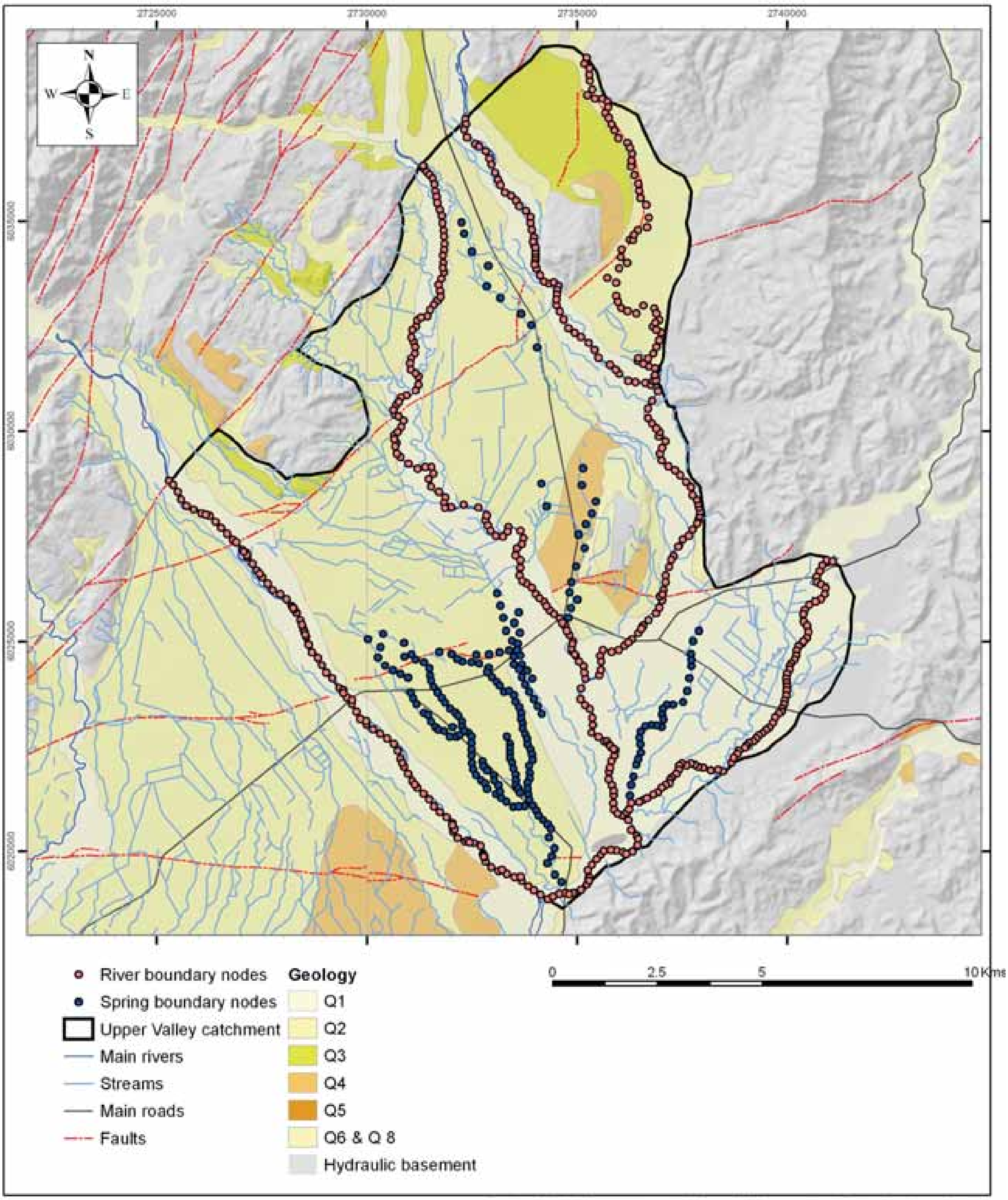


Figure 10.7: River and spring transfer nodes for the Upper Valley catchment groundwater model

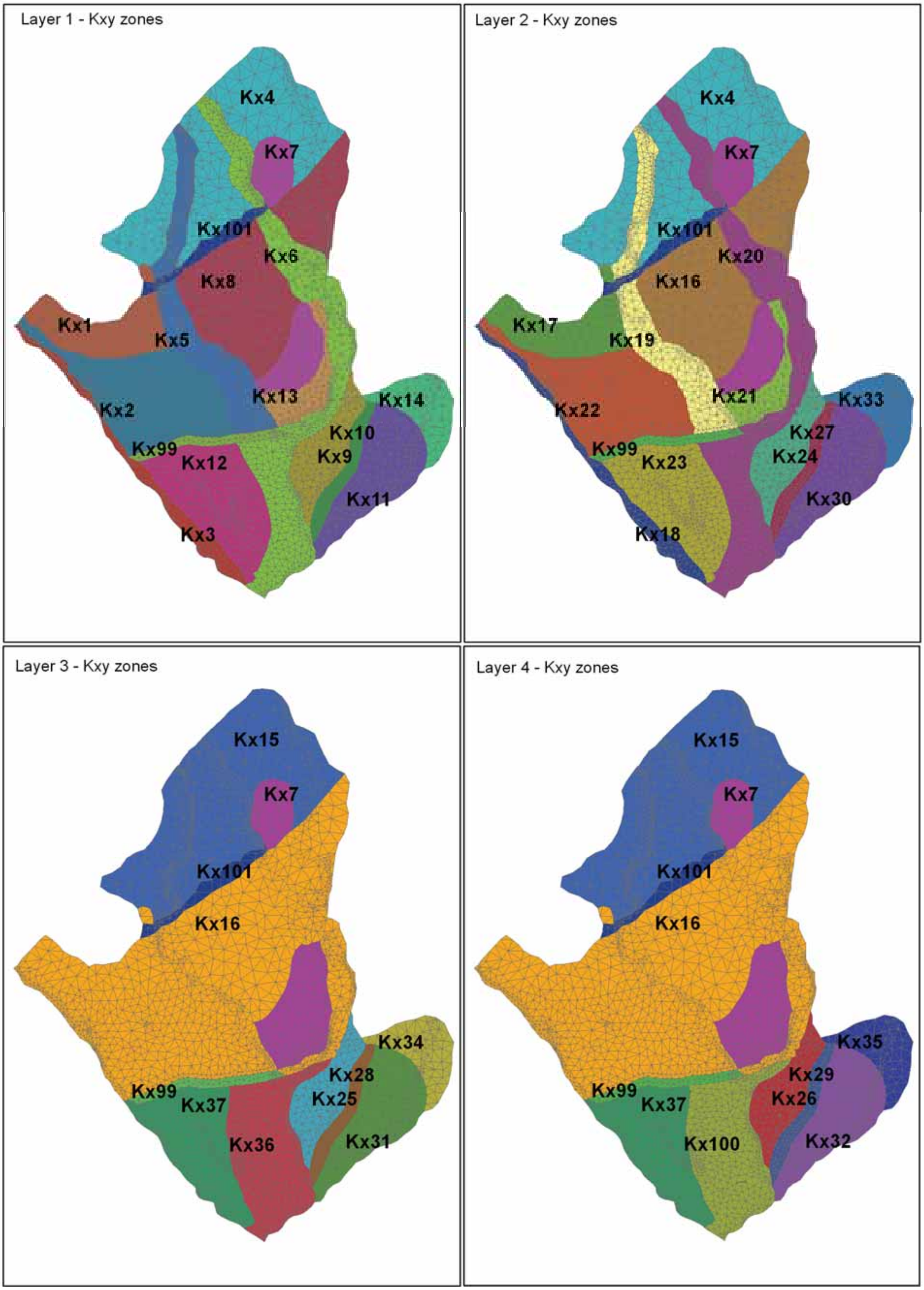


Figure 10.8: Horizontal hydraulic conductivity (Kx) zonation for the Upper Valley groundwater model

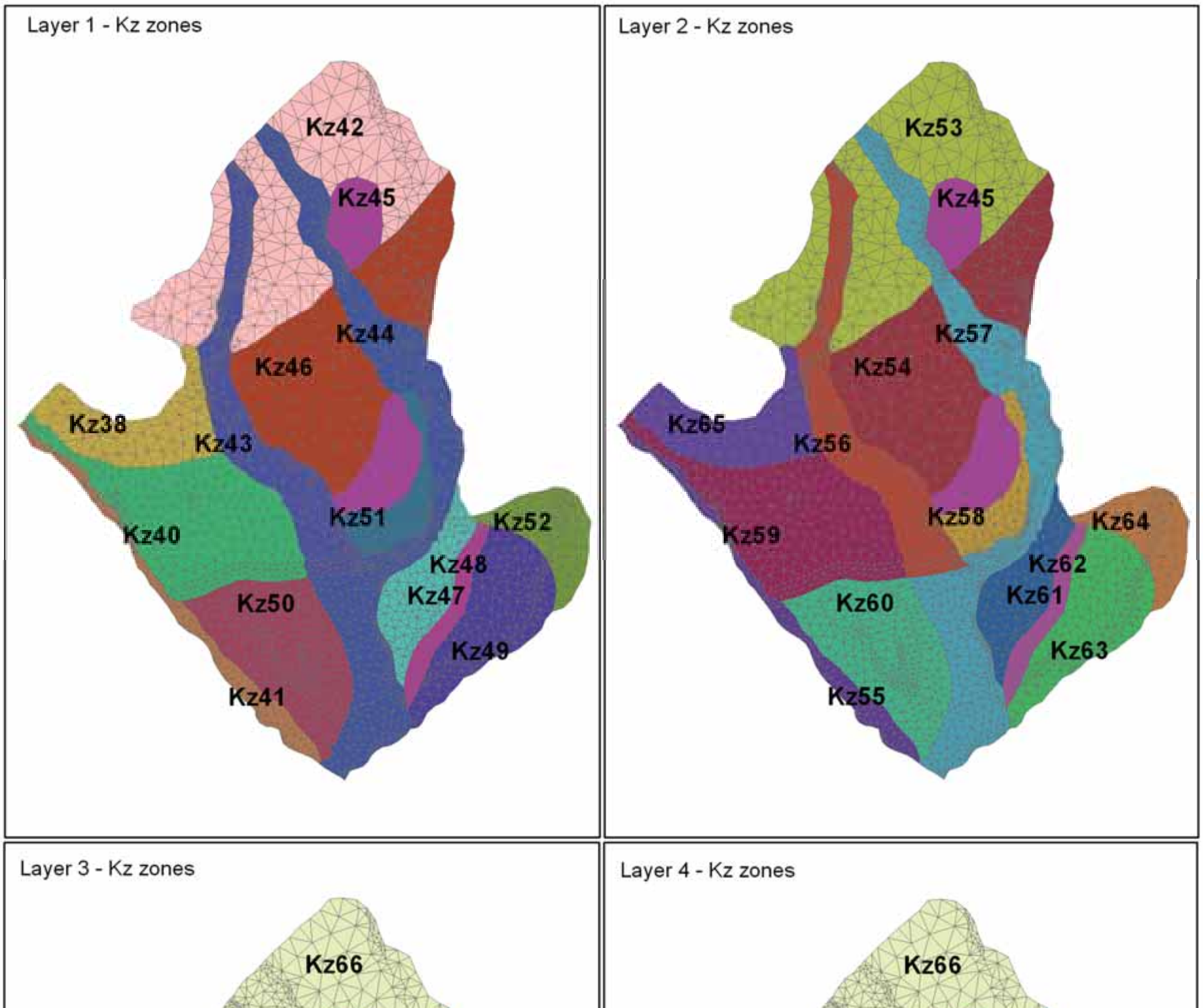


Figure 10.9: Vertical hydraulic conductivity (Kx) zonation for the Upper Valley groundwater model

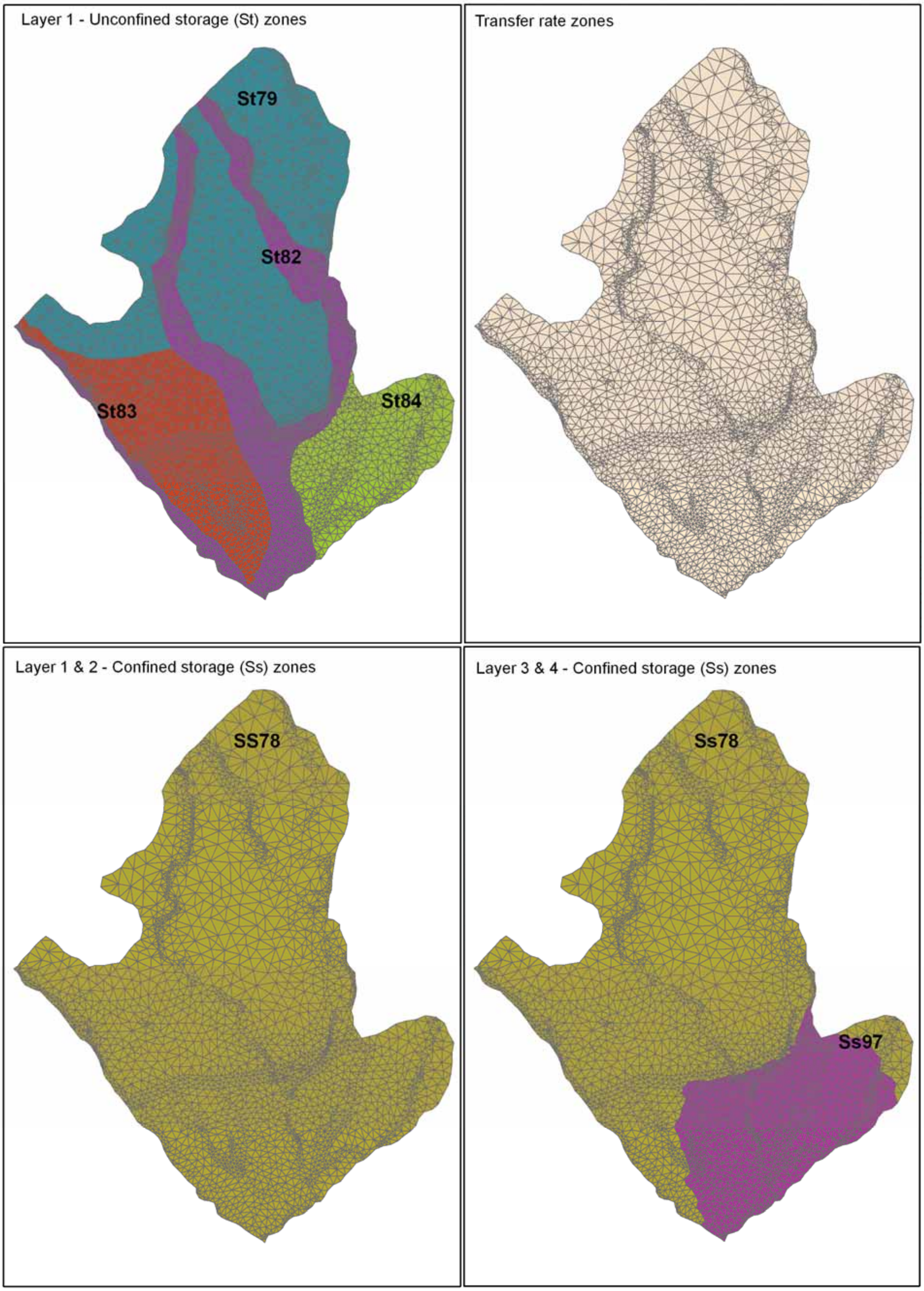


Figure 10.10: Unconfined storage (St) and confined storage (Ss) zonation for the Upper Valley groundwater model

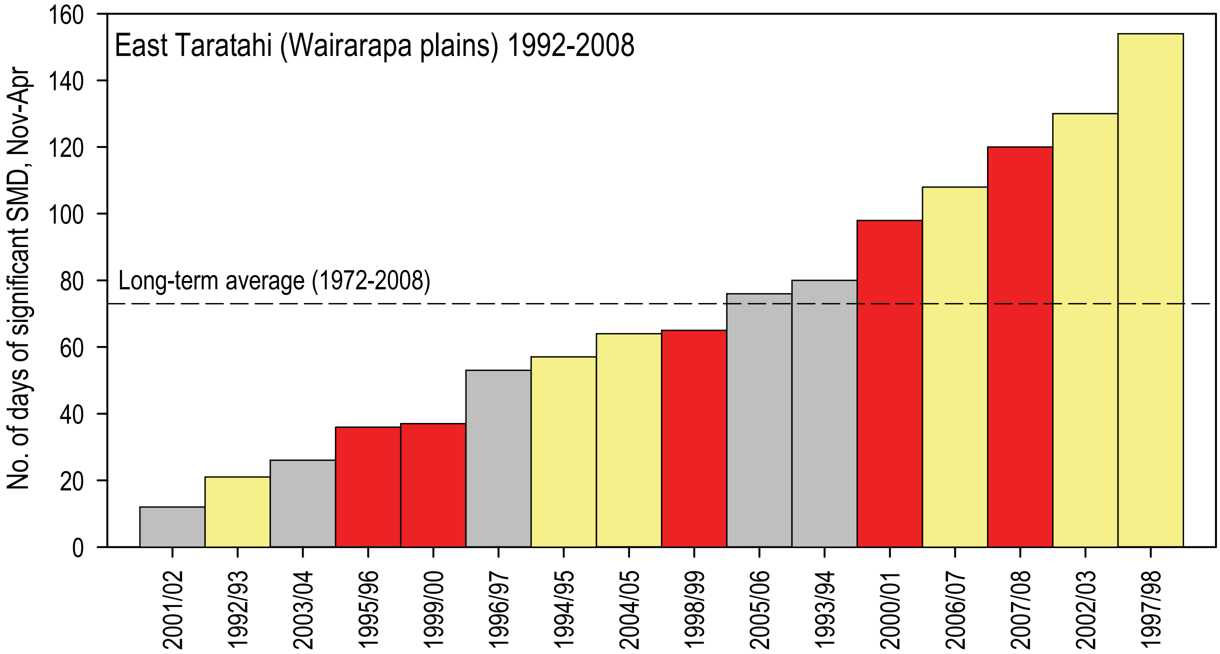


Figure 11.1: Number of days per growing season (November to April) with significant soil moisture deficit (greater than 110 mm) at East Taratahi near Masterton during the groundwater model calibration period (1992-2008). Yellow bars indicate El Nino, red indicate La Nina, and grey indicate neutral years.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

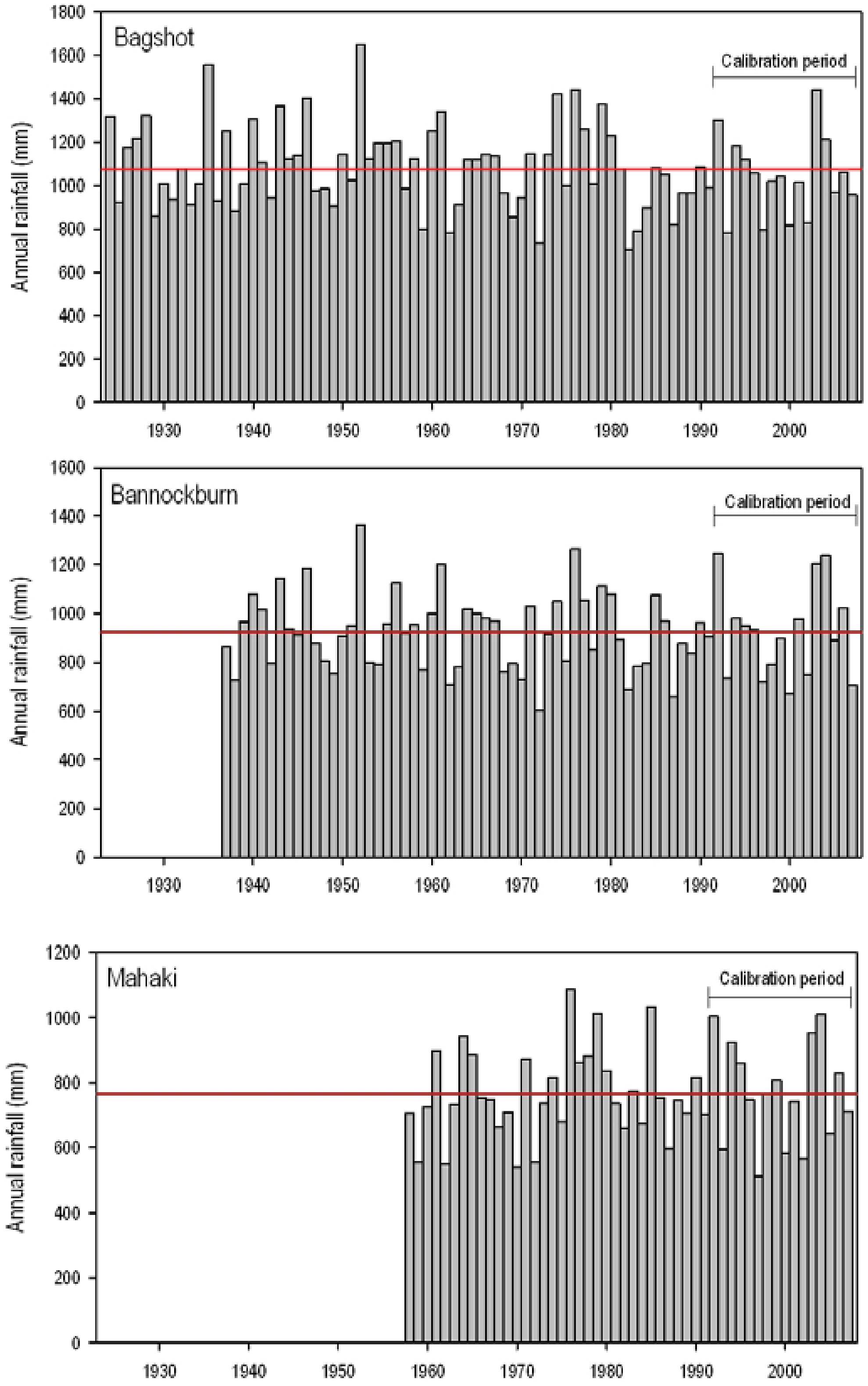
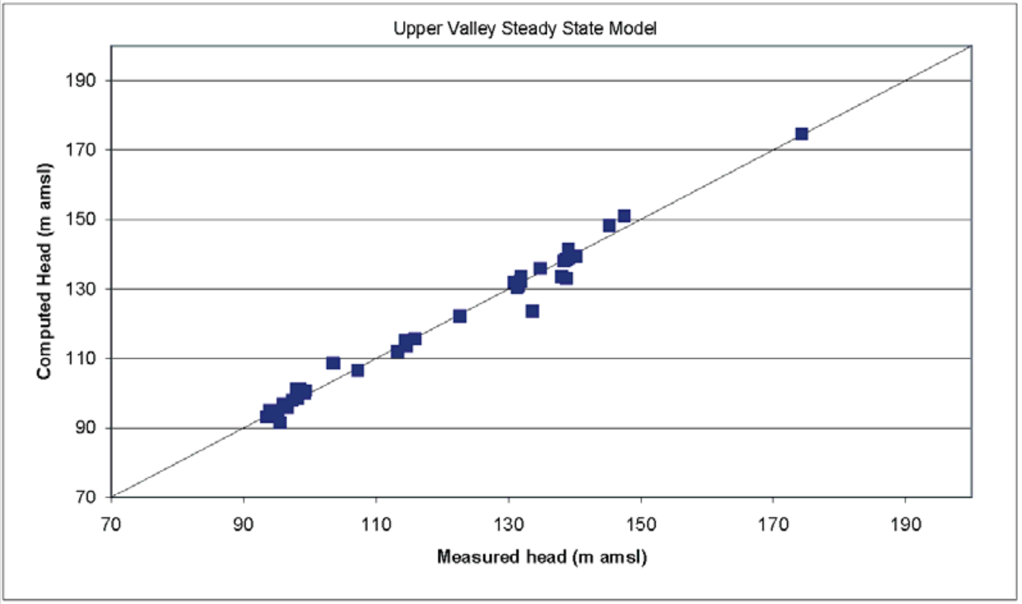


Figure 11.2: Annual rainfall at three long-term monitoring sites in the Wairarapa. The red line indicates the long-term mean at each site. Note the annual rainfalls shown are for a July to June year.

Well No	Depth m	Measured Head m	Computed Head m	Residual m	Abs residual m	Squared residual m2
T26/0165	74	133.61	123.59	-10.01	10.01	100.28
T26/0204	7	138.76	133.12	-5.64	5.64	31.81
T26/0504	6	103.46	108.62	5.16	5.16	26.67
T26/0503	9	103.69	108.61	4.93	4.93	24.29
T26/0201	44	138.00	133.54	-4.46	4.46	19.85
T26/0814	6	95.53	91.59	-3.93	3.93	15.48
T26/0160	9	147.50	151.07	3.57	3.57	12.73
T26/0243	13	97.97	101.31	3.34	3.34	11.14
T26/0170	11	145.26	148.40	3.14	3.14	9.85
T26/0494	5	98.48	101.26	2.78	2.78	7.74
T26/0232	10	98.15	100.67	2.52	2.52	6.36
S26/0033	47	139.05	141.50	2.45	2.45	5.99
T26/0206	14	131.92	133.72	1.80	1.80	3.25
T26/0518	3	99.38	100.89	1.51	1.51	2.29
T26/0209	33	113.27	112.04	-1.23	1.23	1.52
T26/0416	5	93.91	95.14	1.22	1.22	1.50
S26/0032	29	134.83	135.99	1.16	1.16	1.35
S26/0030	9	130.93	131.95	1.02	1.02	1.04
T26/0093	5	114.56	113.55	-1.00	1.00	1.01
T26/0208	4	131.31	130.32	-0.99	0.99	0.97
T26/0538	5	96.00	96.91	0.91	0.91	0.82
T26/0336	5	114.42	115.19	0.78	0.78	0.60
T26/0359	58	99.22	99.94	0.72	0.72	0.51
T26/0366	4	96.59	95.91	-0.68	0.68	0.47
T26/0489	6	97.38	98.06	0.68	0.68	0.46
T26/0239	16	140.18	139.51	-0.66	0.66	0.44
T26/0501	9	98.16	98.78	0.62	0.62	0.39
T26/0535	37	96.29	96.90	0.61	0.61	0.37
T26/0431	6	107.23	106.72	-0.51	0.51	0.26
T26/0003	6	174.29	174.73	0.44	0.44	0.19
T26/0207	11	131.51	131.10	-0.41	0.41	0.17
T26/0215	5	122.70	122.33	-0.37	0.37	0.13
T26/0233	9	138.42	138.08	-0.33	0.33	0.11
S26/0031	62	131.85	132.17	0.32	0.32	0.10
T26/0411	15	93.51	93.21	-0.29	0.29	0.09
T26/0429	6	115.91	115.71	-0.21	0.21	0.04
T26/0248	23	139.15	139.02	-0.12	0.12	0.02
T26/0420	5	95.18	95.10	-0.08	0.08	0.01
T26/0259	44	138.71	138.64	-0.07	0.07	0.01
T26/0487	18	94.48	94.47	-0.01	0.01	0.00



Calibration Statistics

Absolute residual mean	0.02 m
Min residual	-10.01 m
Max residual	5.16 m
Sum of residuals	70.71 m
Residual Standard deviation	*2.06 m*
Observed range in head	83.10 m
Mean sum of residuals	1.77 m
Scaled mean sum of residuals	0.05 %
Sum of residual squares	290.32 m2
Root mean square (RMS error)	2.69 m
Scaled RMS	3.24 %

Figure 11.3: Upper Valley catchment steady state model calibration – model-to-measurement fit

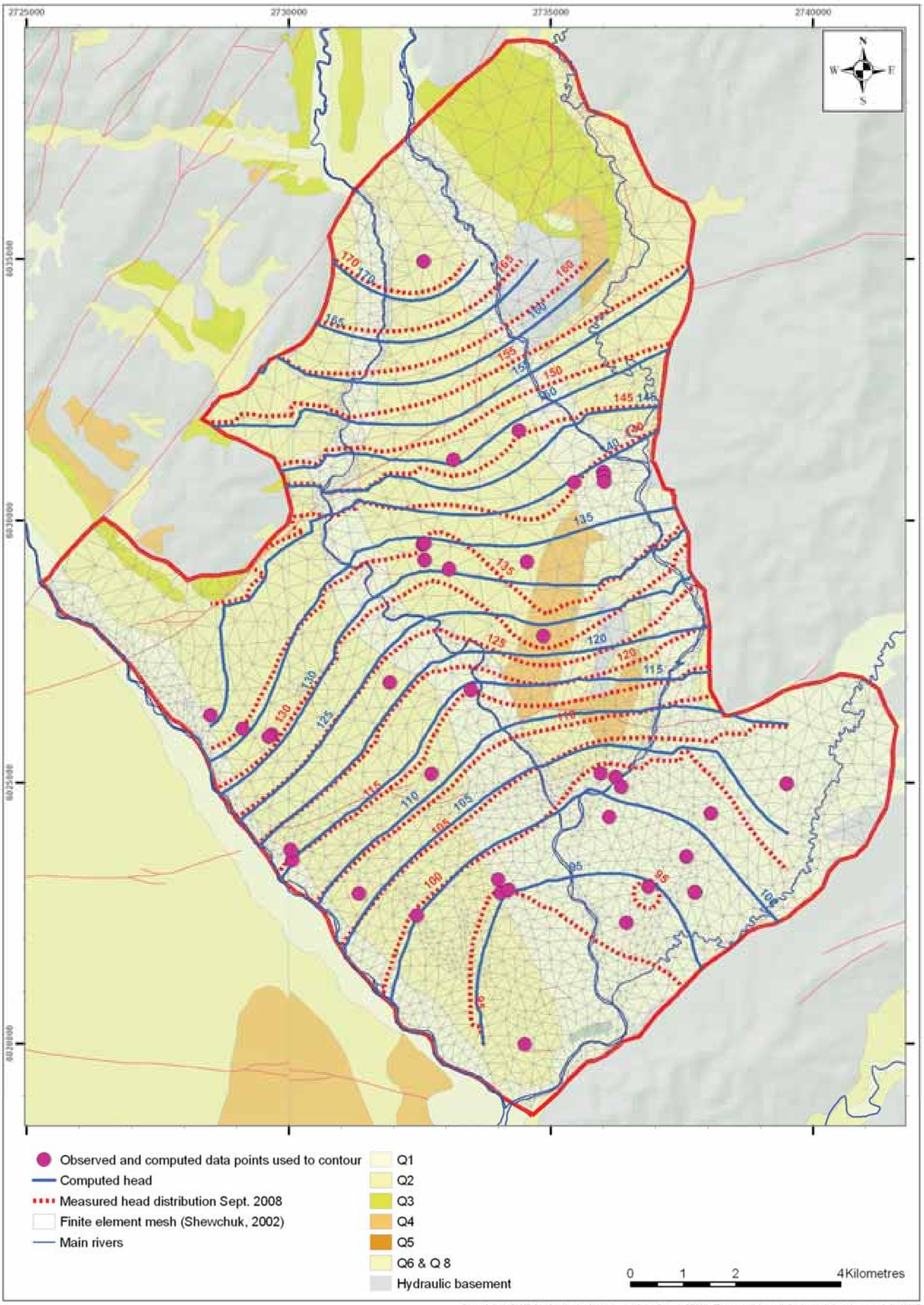


Figure 11.4: Upper Valley catchment steady state modelled and observed head. Both data-sets have been contoured using the same technique and data points to visually demonstrate model fit.

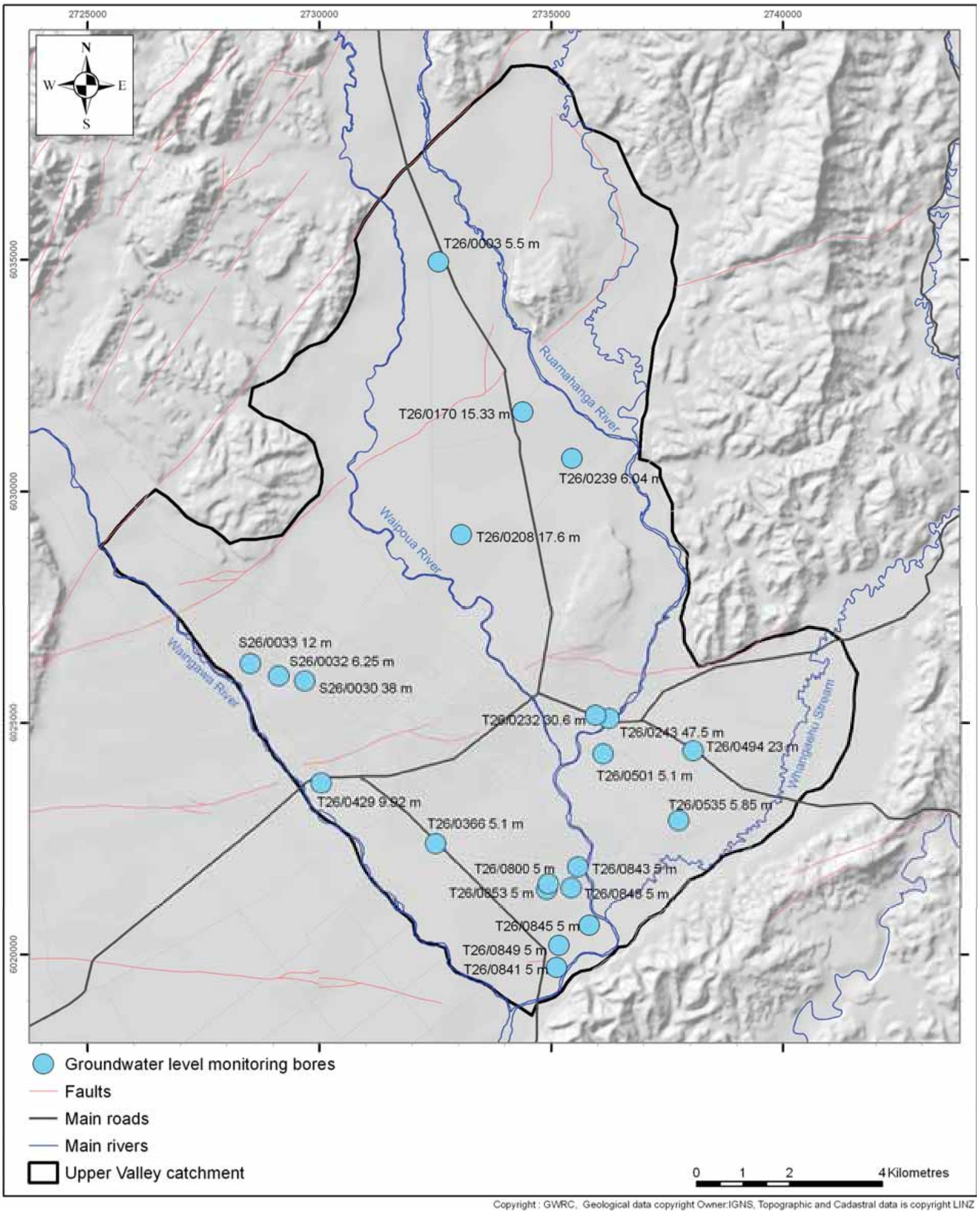


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Figure 11.5: Locations of the 21 groundwater bores used in calibration of the transient groundwater model for the Upper Valley catchment

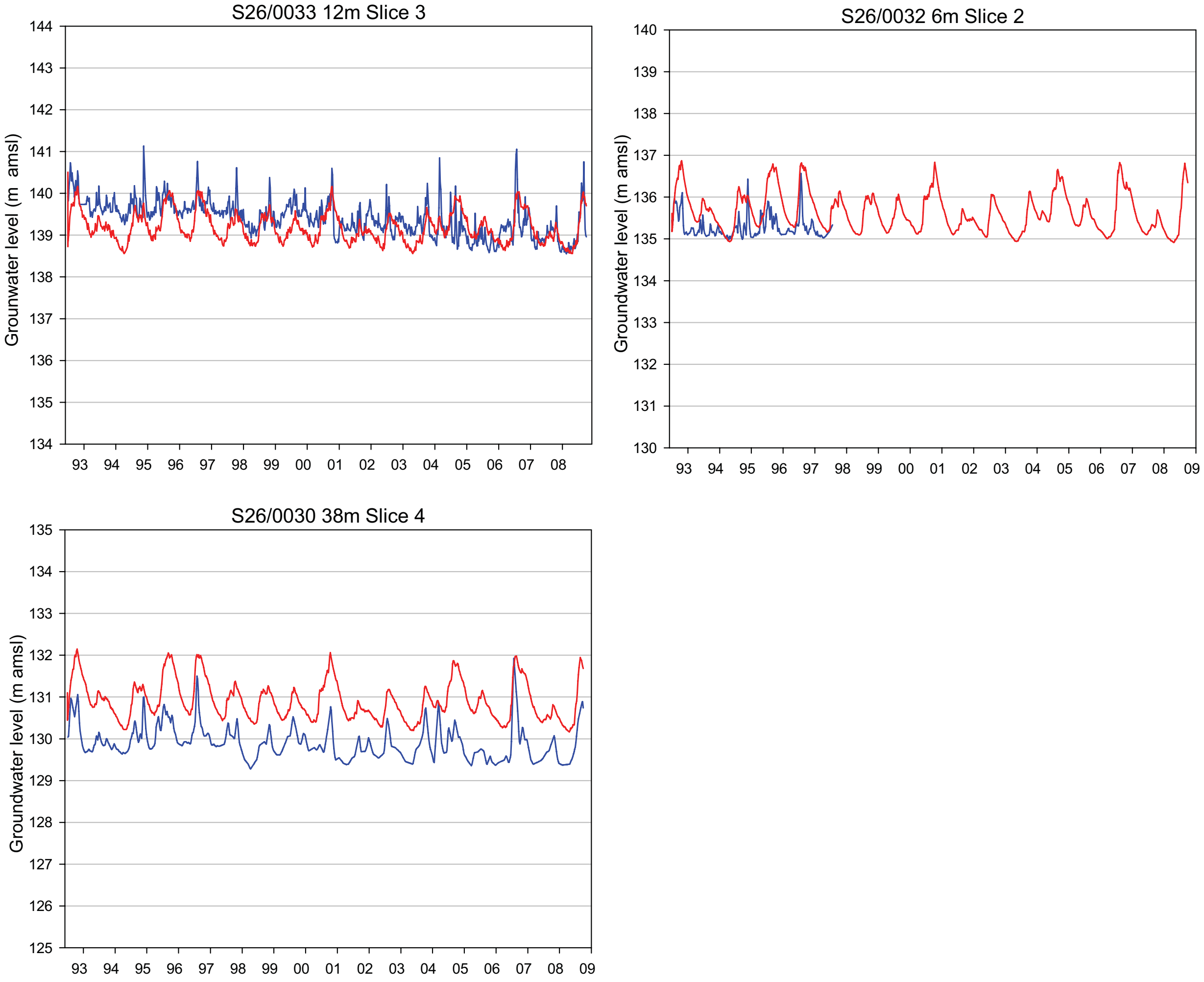

Figure 11.6: Groundwater head calibration plots for Area 1. The red line denotes the observed 7-day mean and the blue line denotes the calculated (simulated) values.

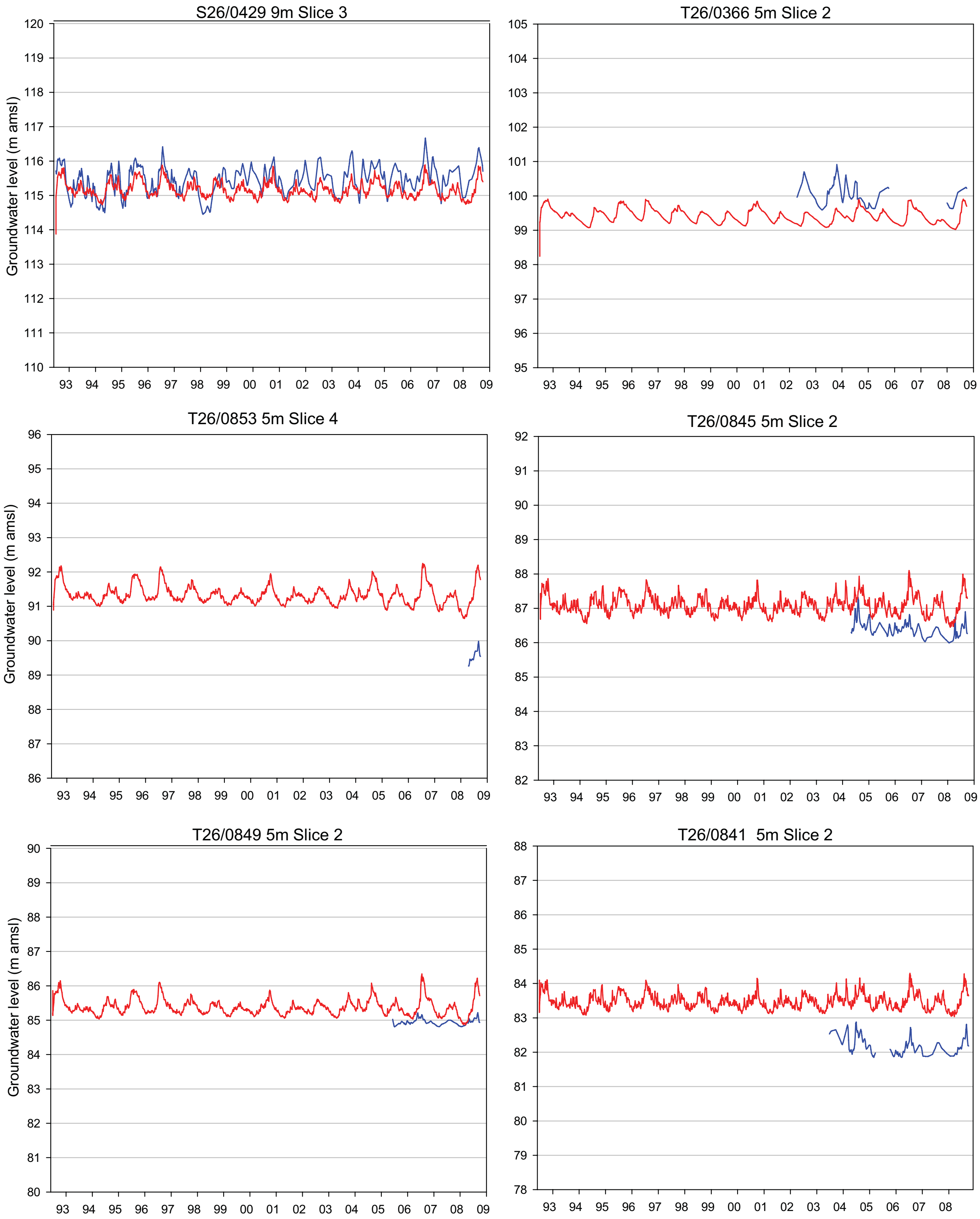

Figure 11.7: Groundwater head calibration plots for Area 2. The red line denotes the observed 7-day mean and the blue line denotes the calculated (simulated) values.

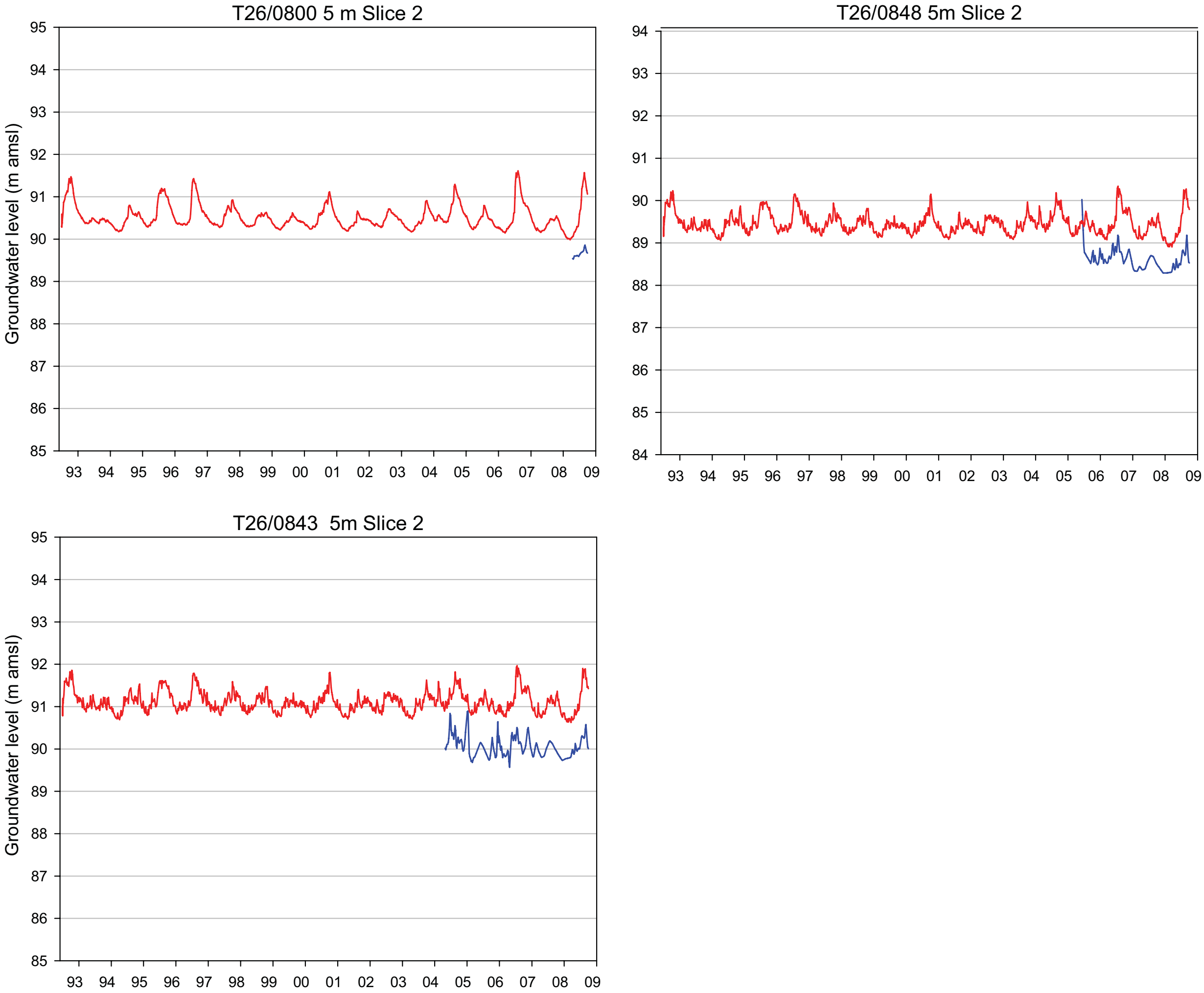

Figure 11.7 *cont.*: Groundwater head calibration plots for Area 2. The red line denotes the observed 7-day mean and the blue line denotes the calculated (simulated) values.

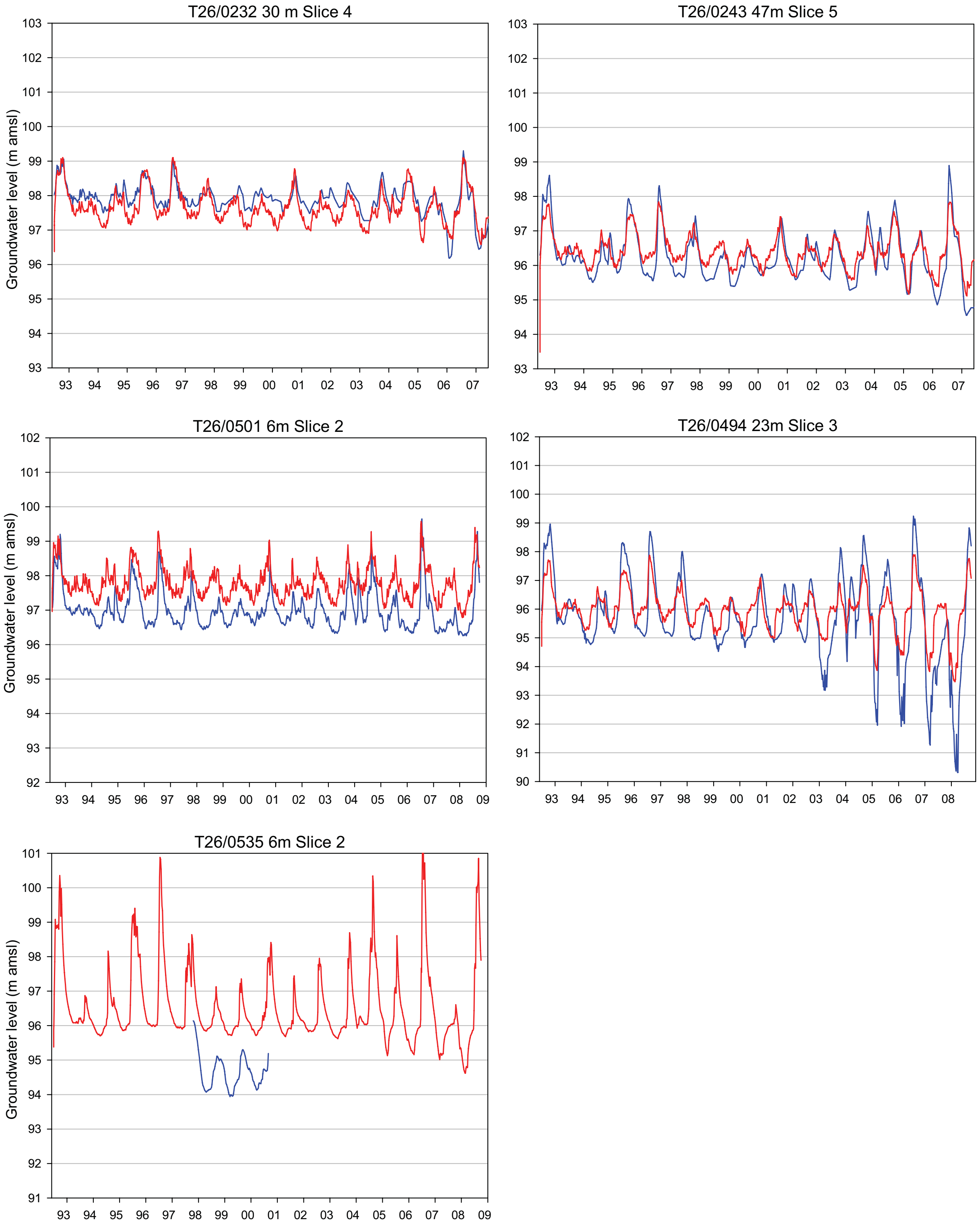

Figure 11.8: Groundwater head calibration plots for Area 3. The red line denotes the observed 7-day mean and the blue line denotes the calculated (simulated) values.

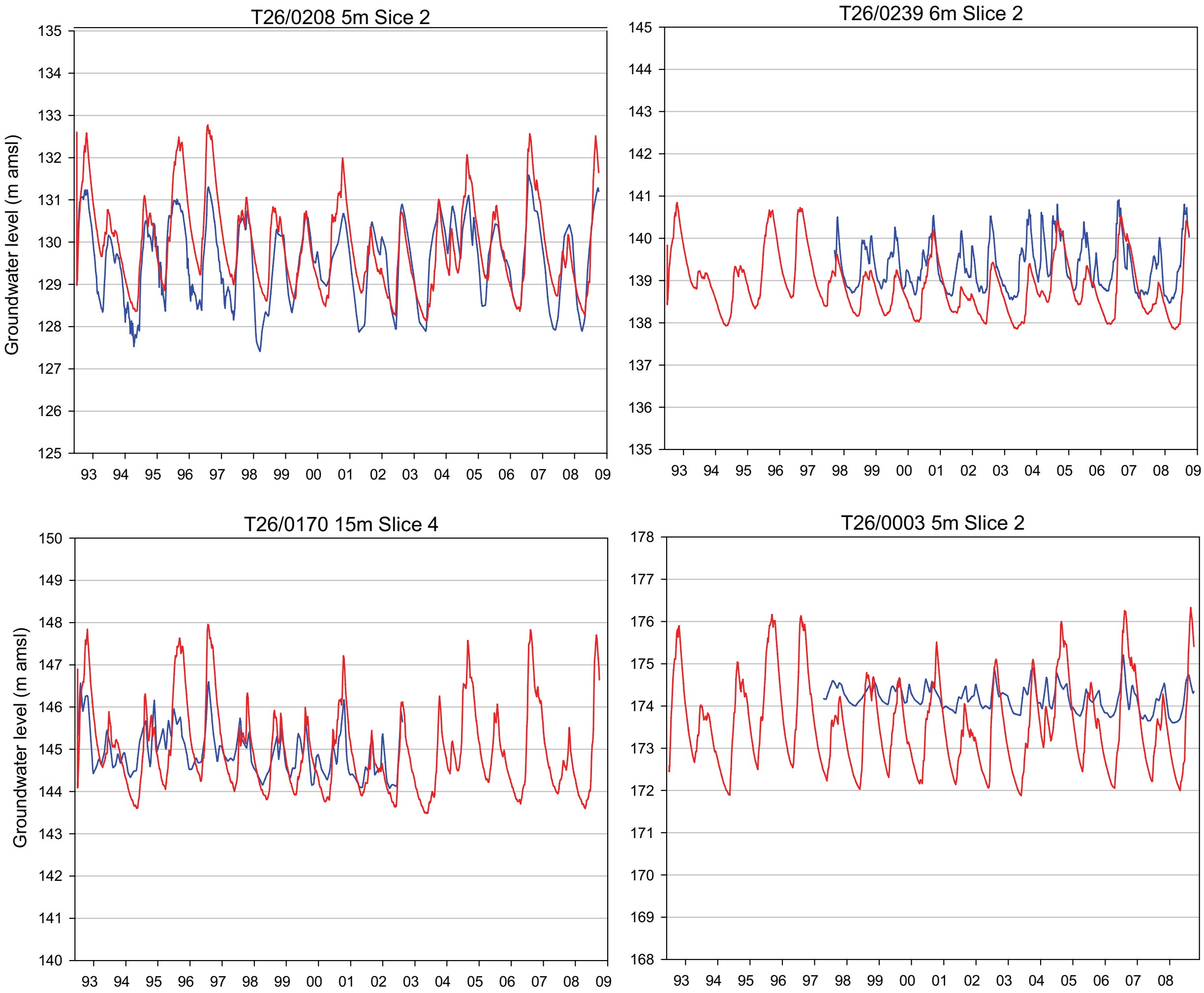

Figure 11.9: Groundwater head calibration plots for Areas 4 and 5. The red line denotes the observed 7-day mean and the blue line denotes the calculated (simulated) values.

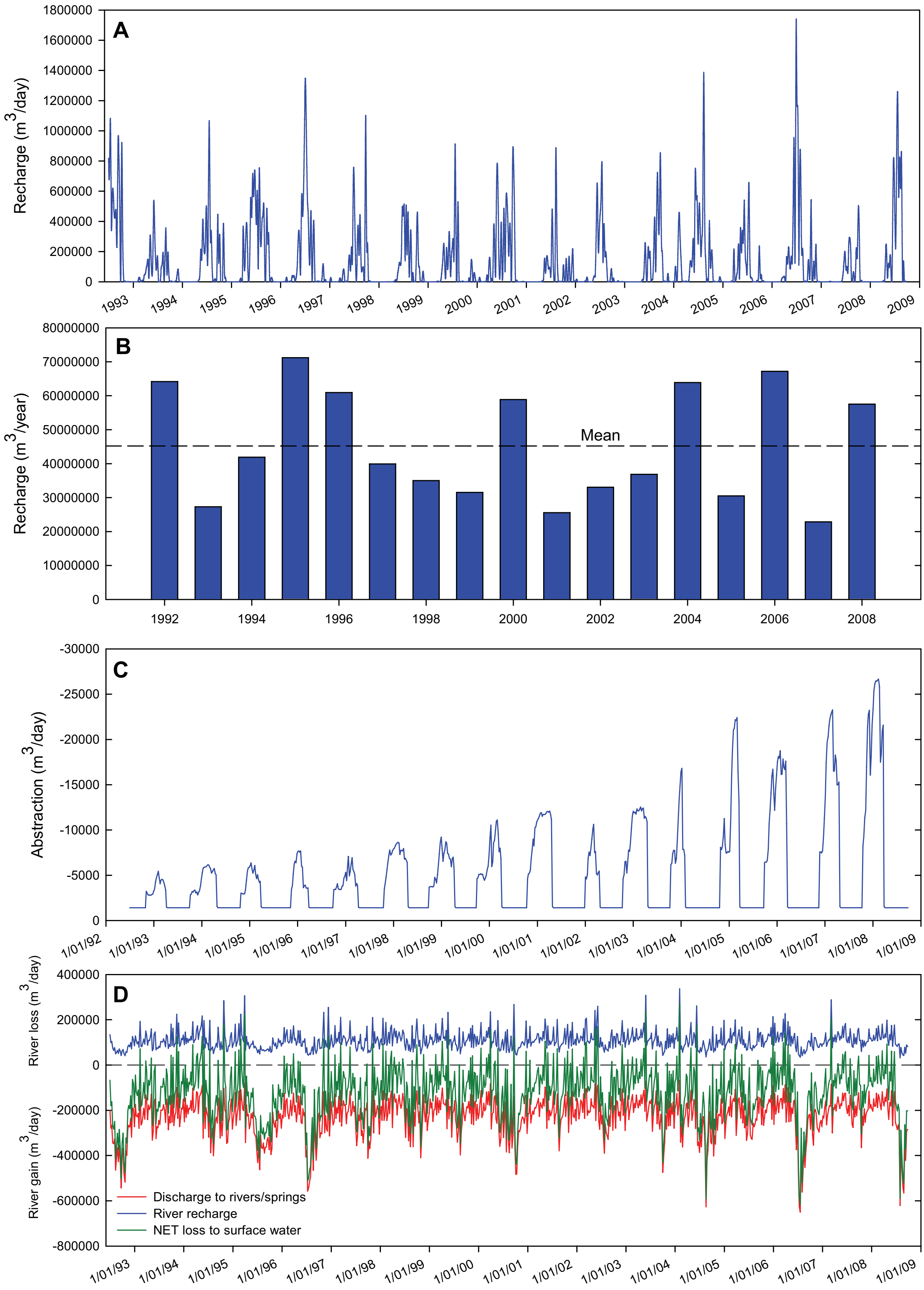

Figure 11.10: Upper Valley catchment transient groundwater model calibration simulated global water balances – A: Daily recharge, B: Annual recharge, C: Modelled daily abstraction, and D: Simulated net fluxes between groundwater and surface water

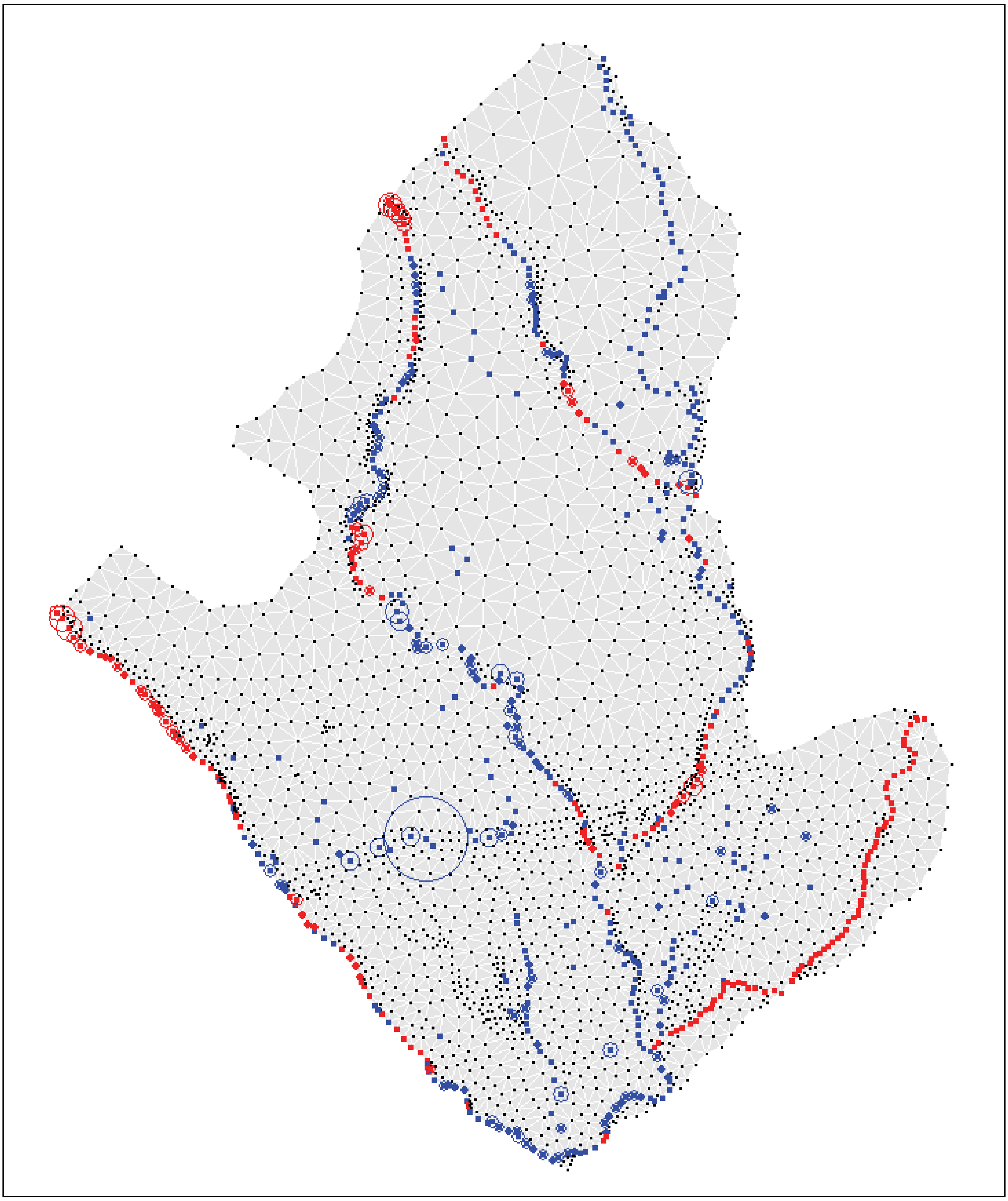

Figure 11.11: Simulated transfer node flux pattern in summer 2008 (blue symbols = flux out of model to surface water; red symbols = flux into model from surface water)

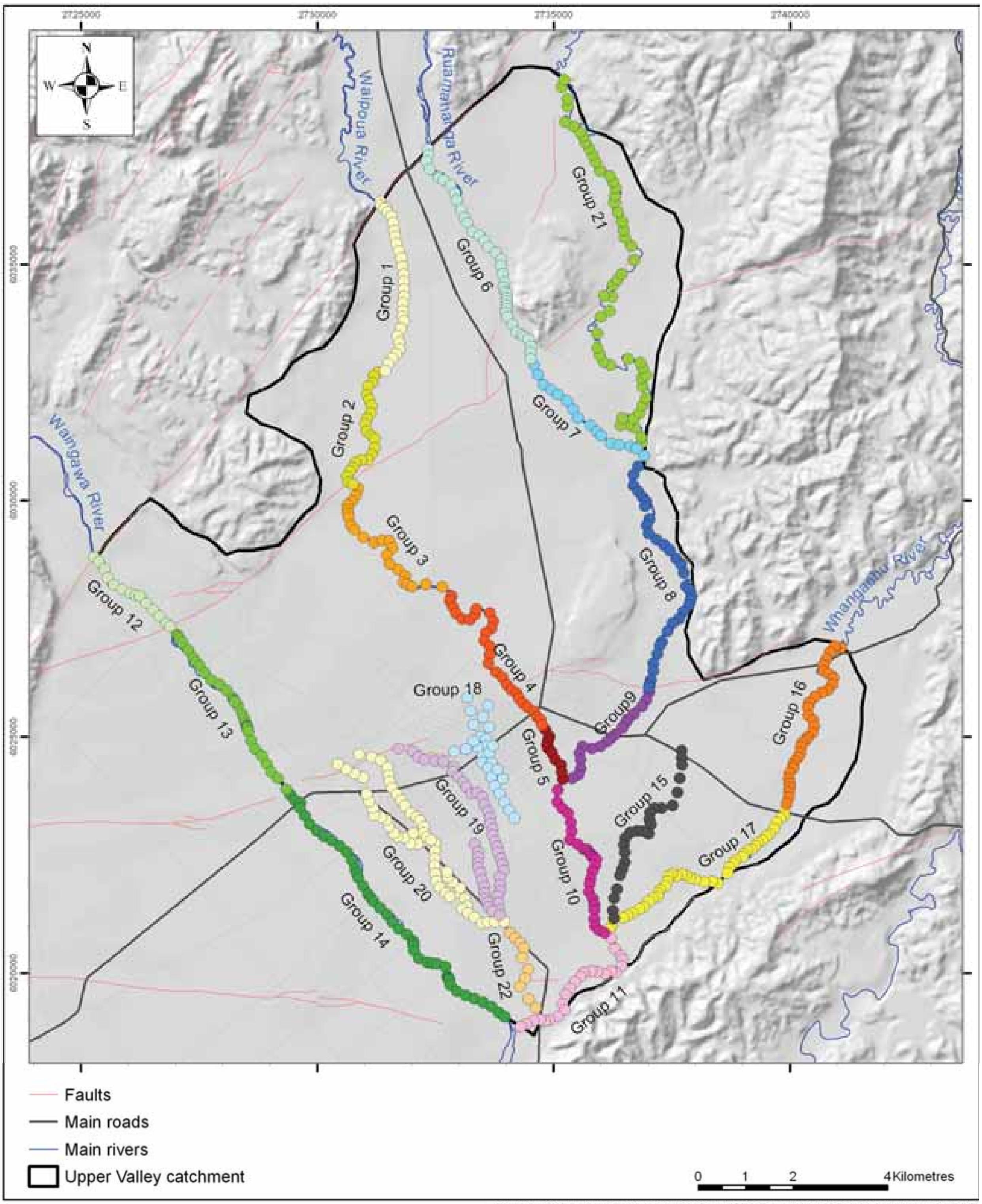

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Figure 11.12: Water balance observation groups used in the FEFLOW groundwater model for the Upper Valley catchment

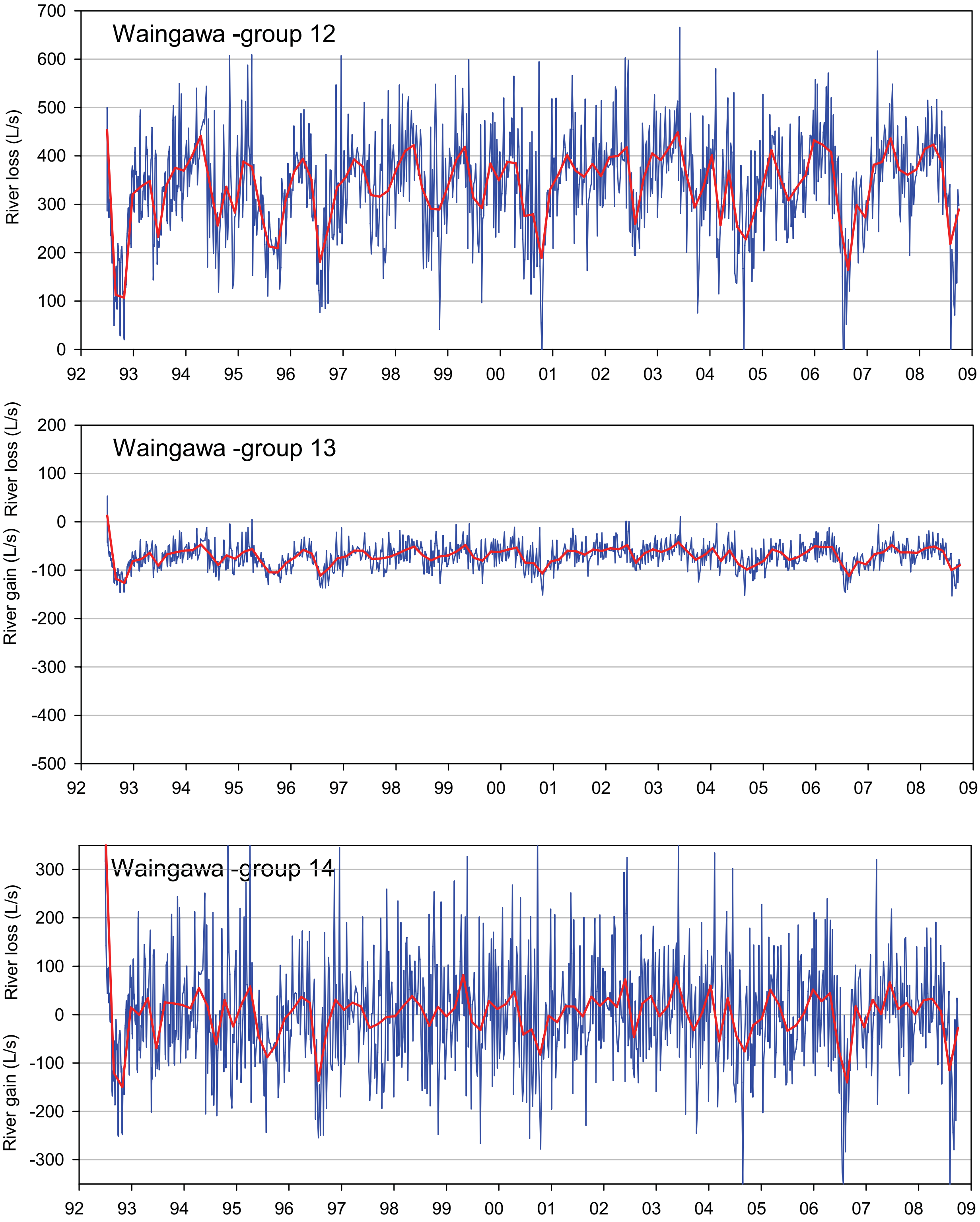


Figure 11.13: Simulated water balance plots – Waingawa River

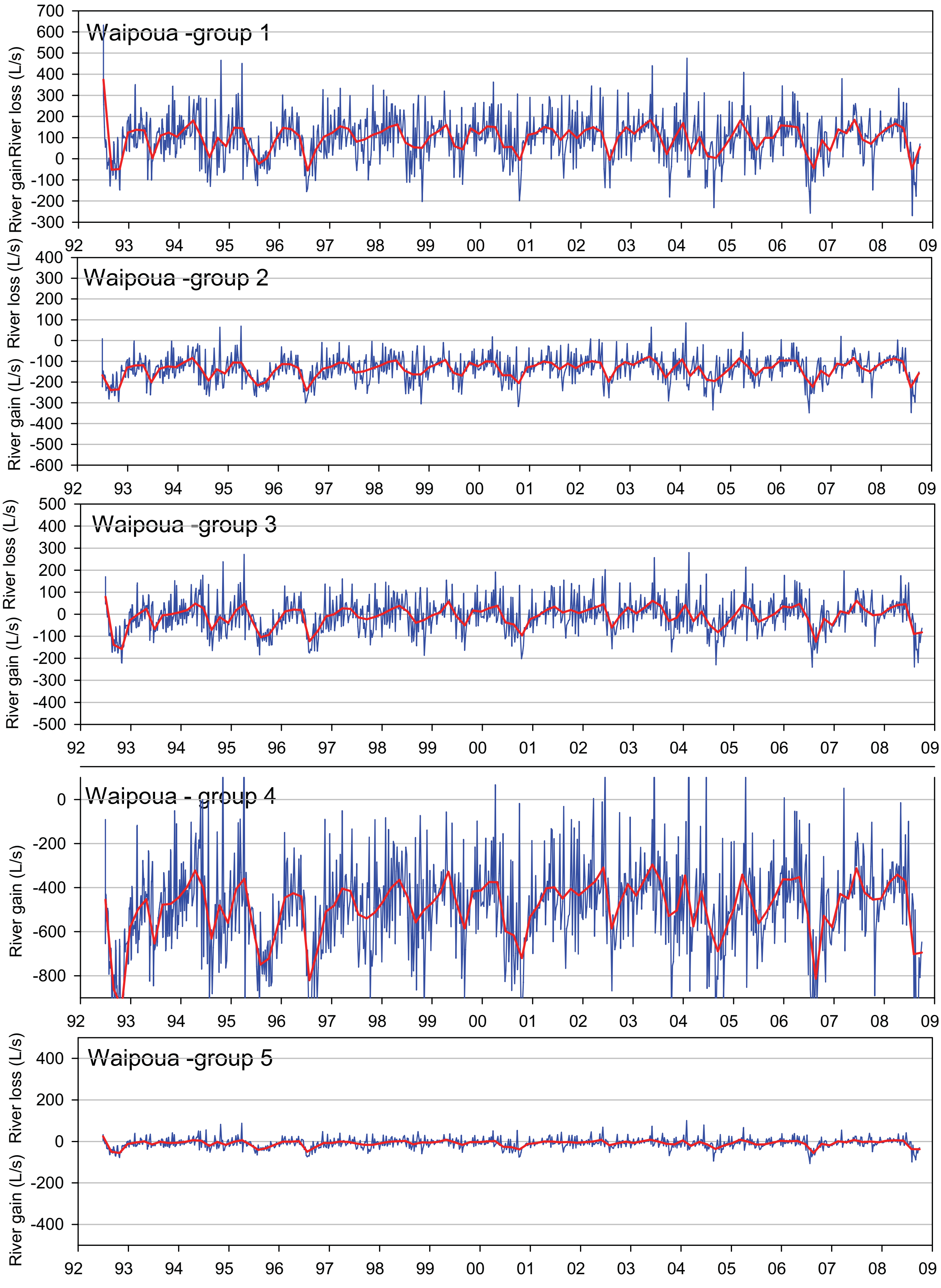


Figure 11.14: Simulated water balance plots – Waipoua River

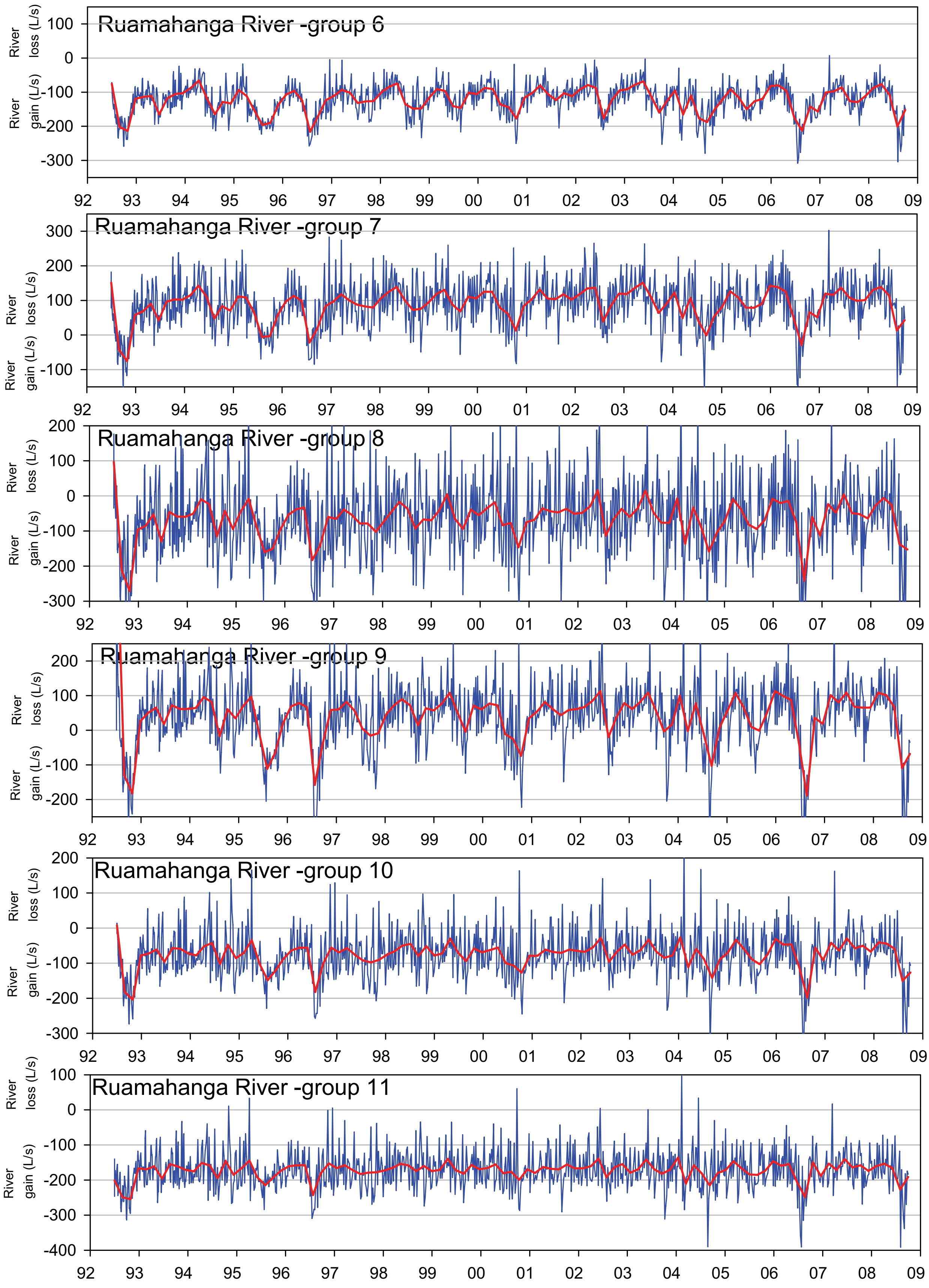


Figure 11.15: Simulated water balance plots – Ruamahanga River

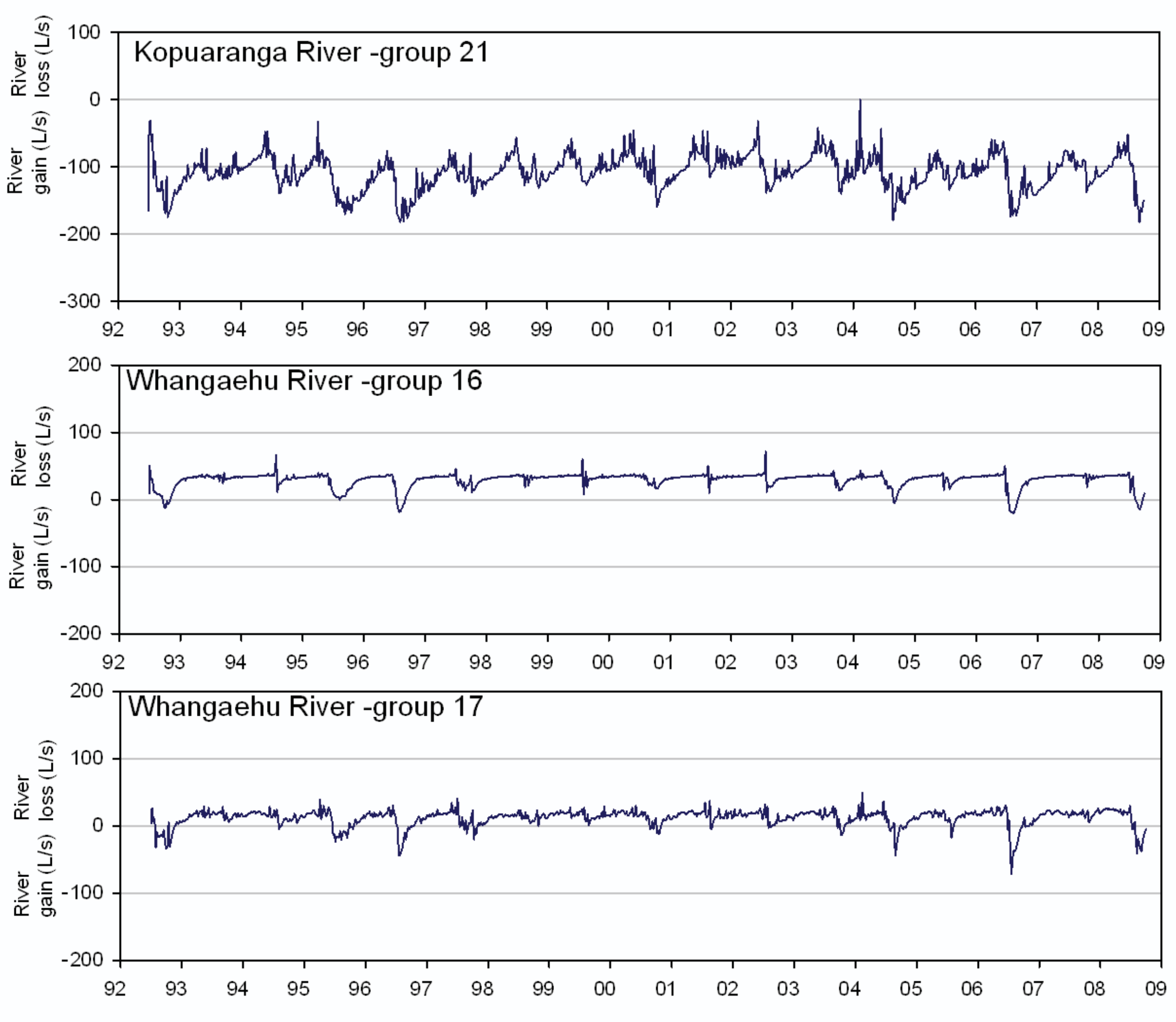


Figure 11.16: Simulated water balance plots – Kopuaranga and Whangaehu rivers

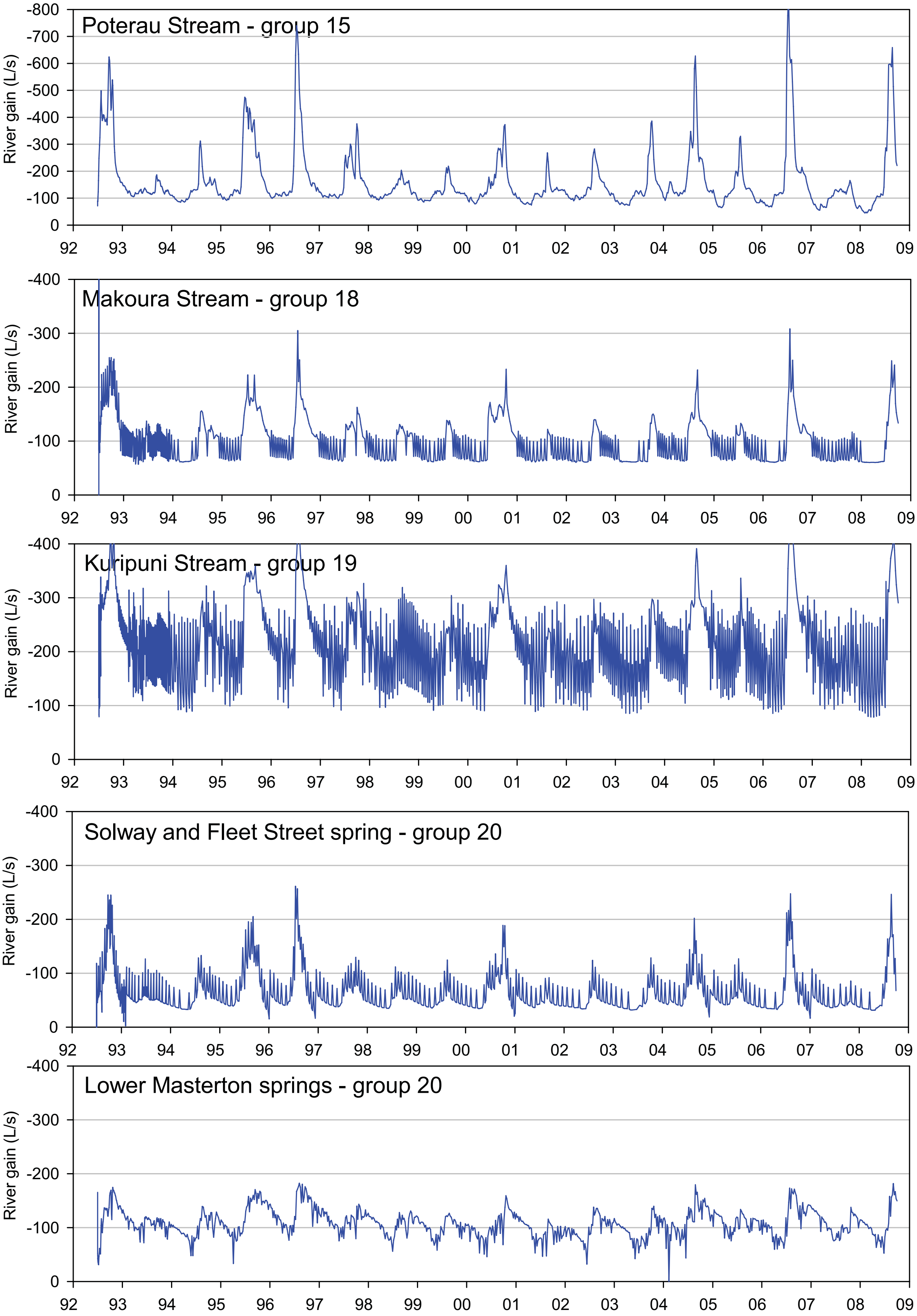


Figure 11.17: Simulated water balance plots – Poterau and Masterton springs

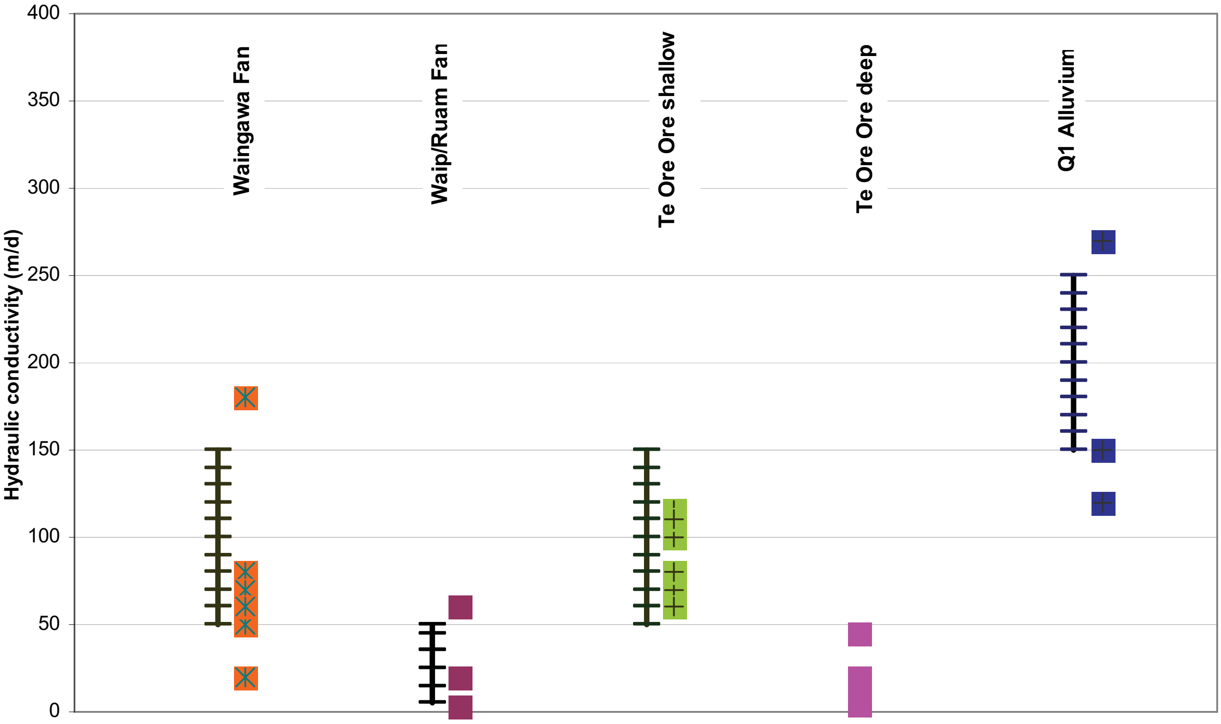


Figure 11.18: Comparison of observed and modelled hydraulic conductivity ranges. The vertical black crossed lines denote the measured range and the coloured squares represent calibrated model values.

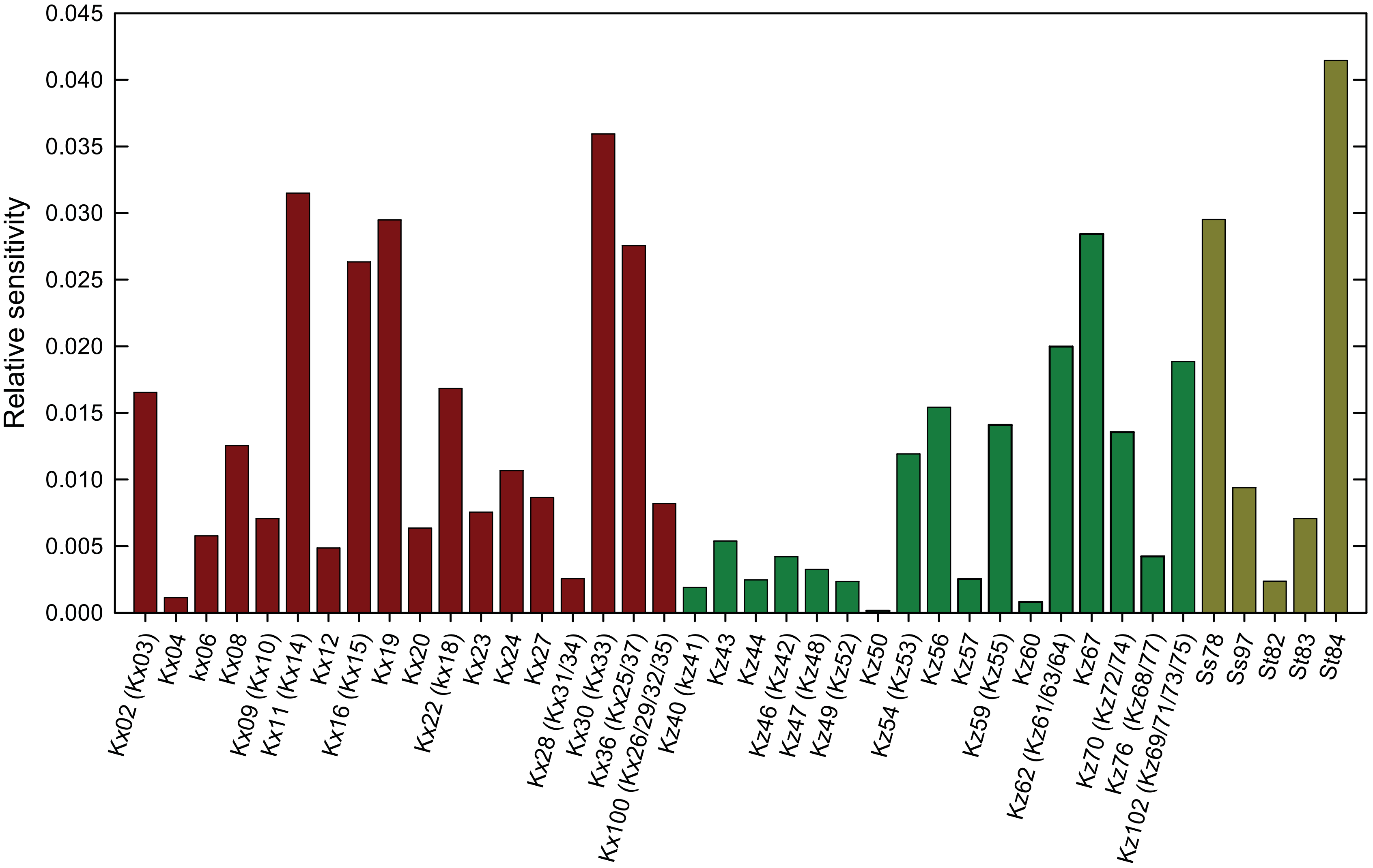
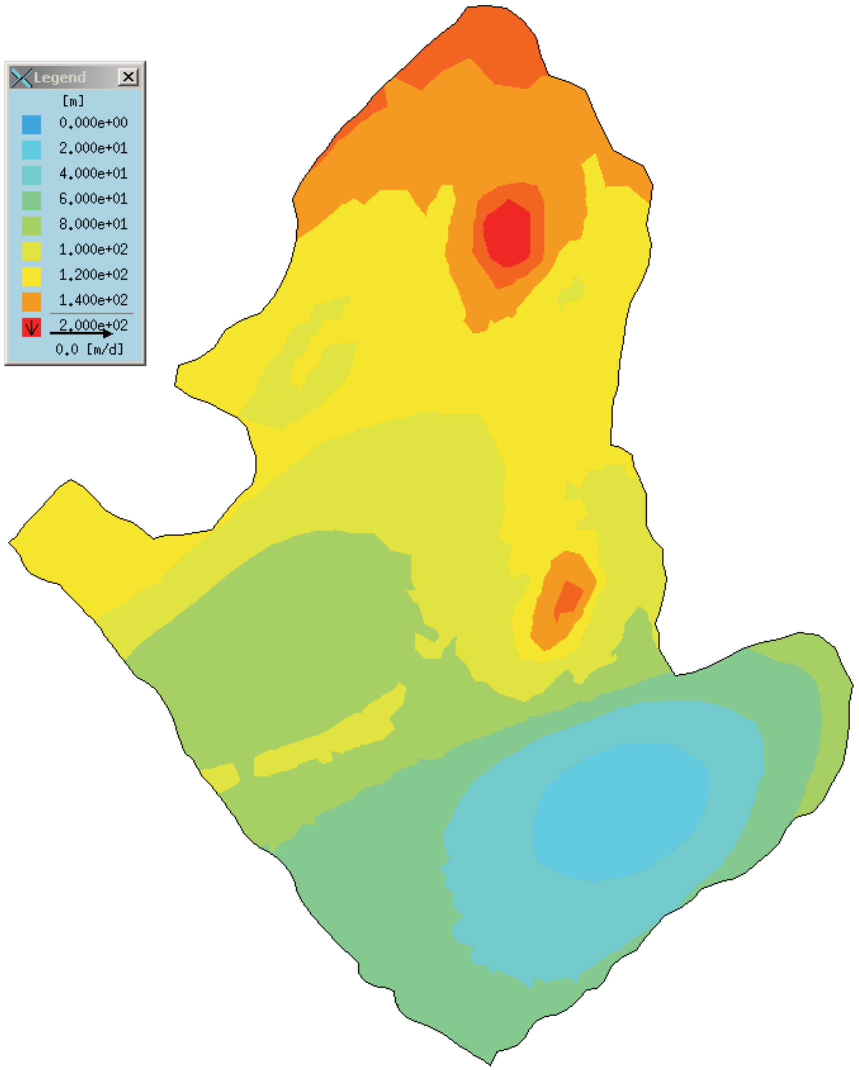


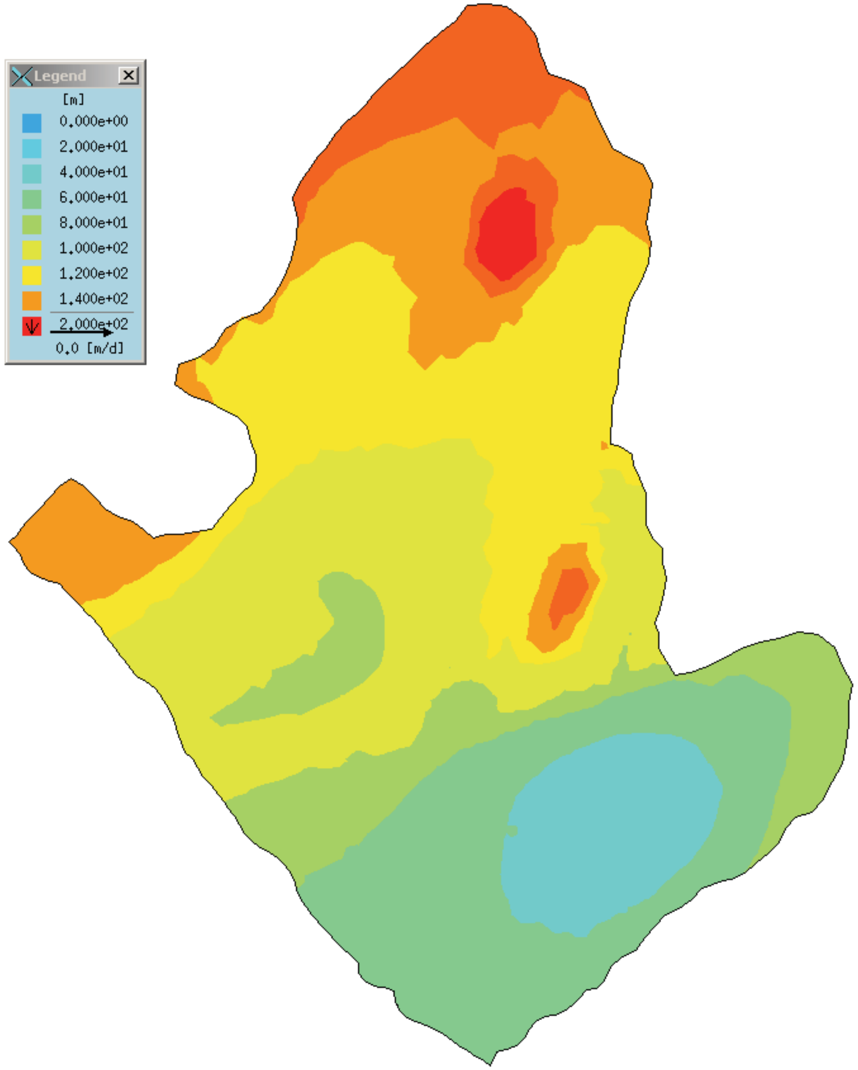
Figure 11.19: Parameter sensitivity calculated by PEST for the Upper Valley catchment groundwater model

Appendix 1:

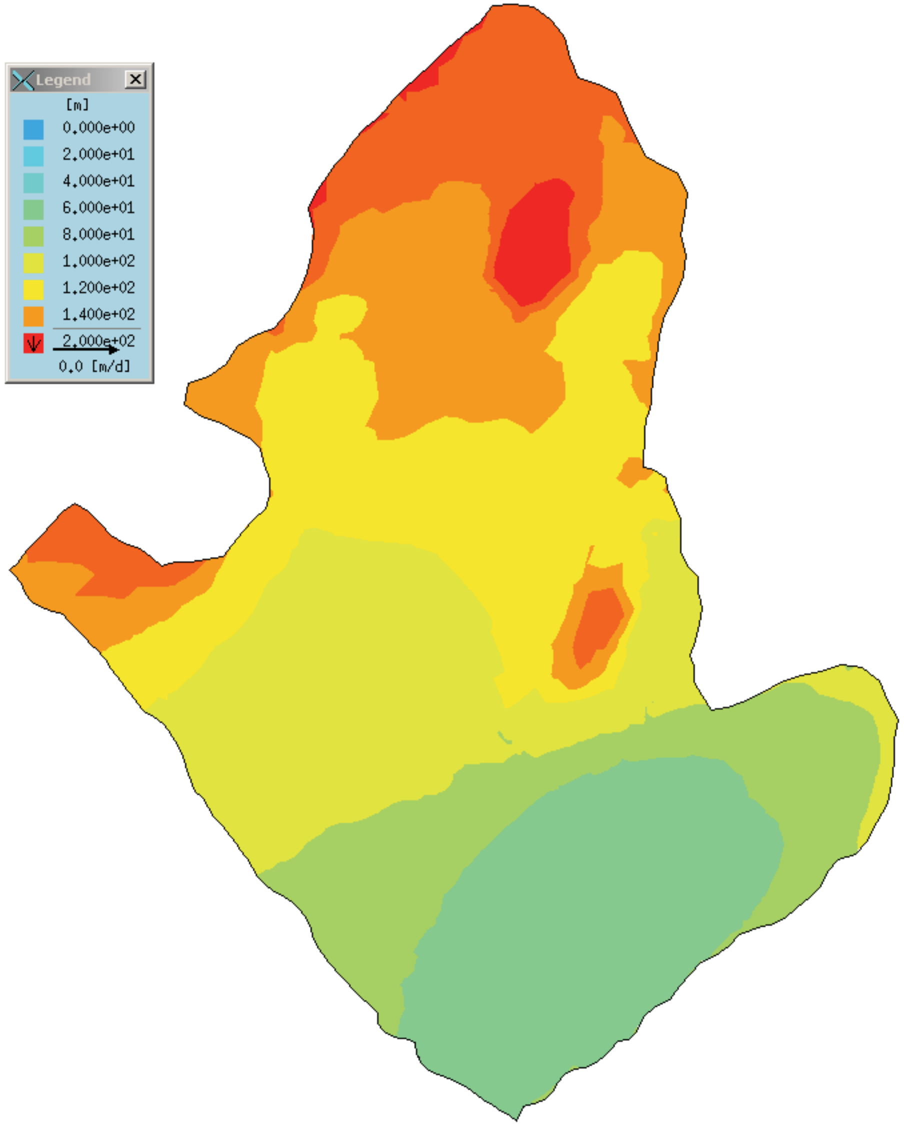
Model slice structure contours



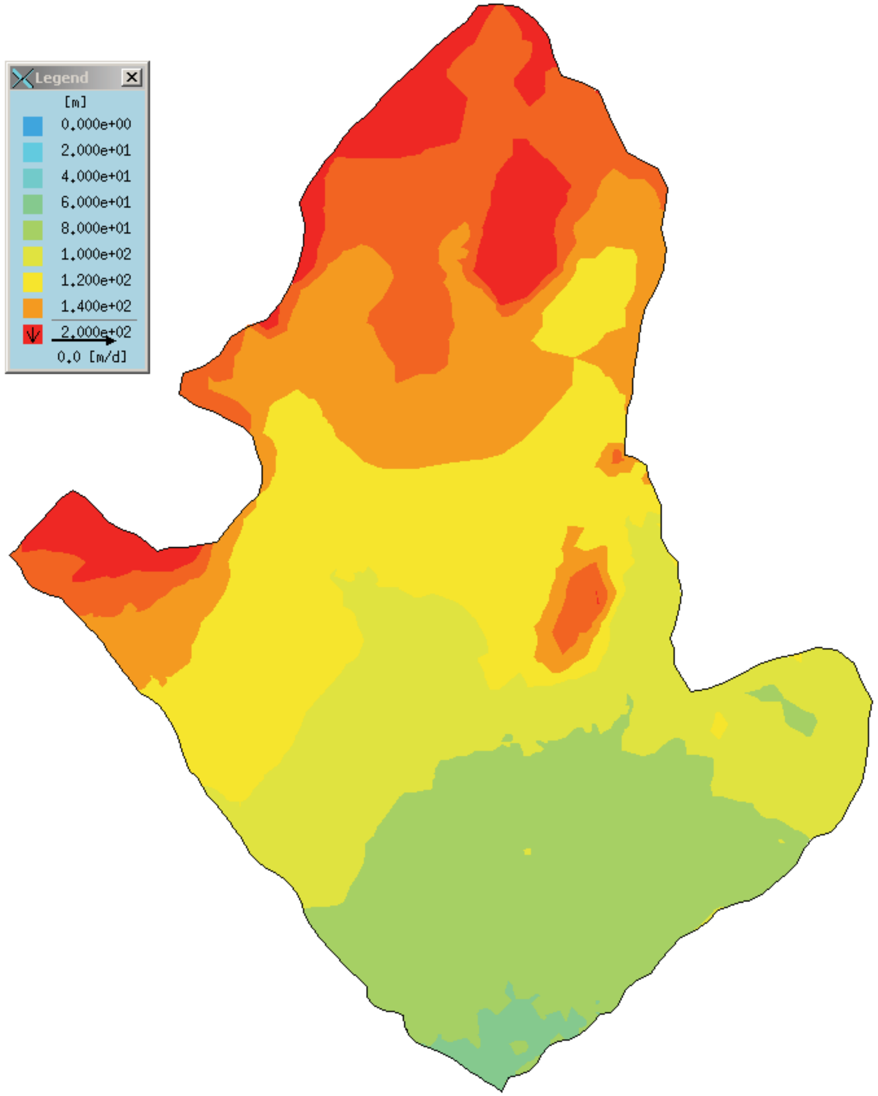
Slice 5 (Model base)



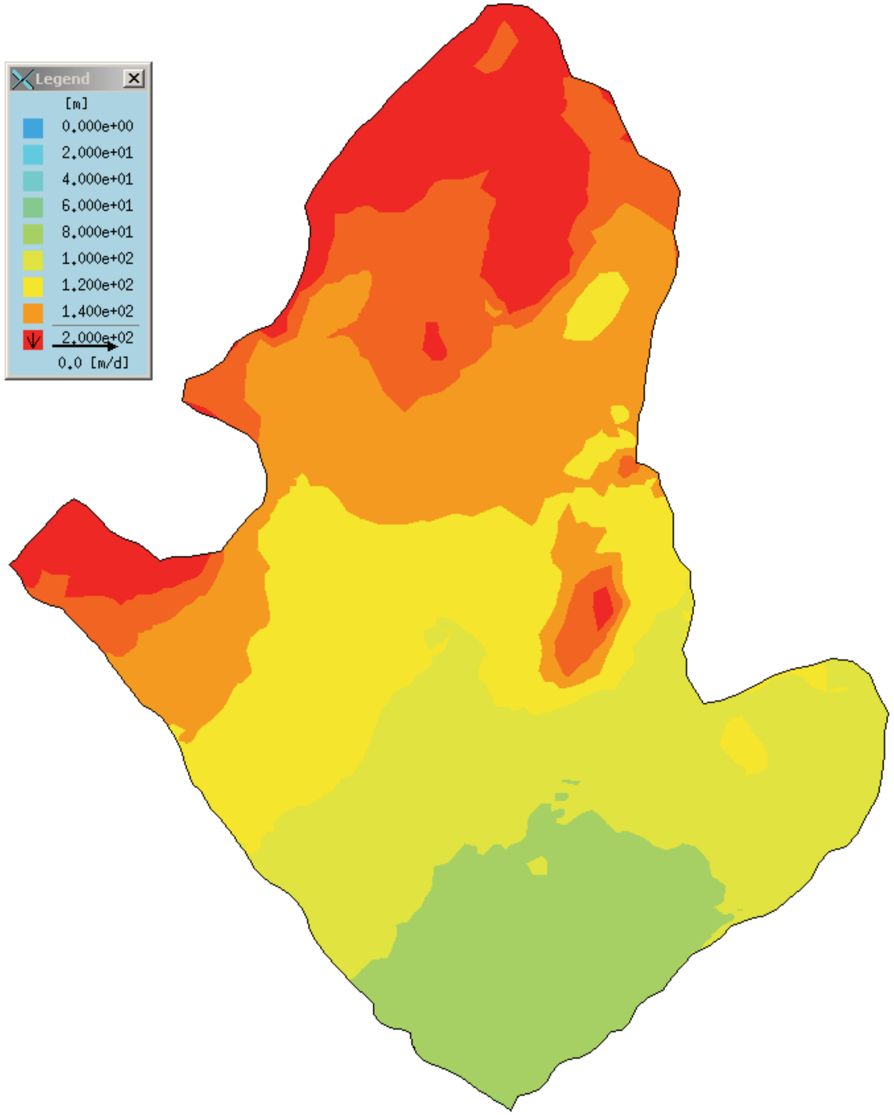
Slice 4



Slice 3



Slice 2



Slice 1 (Ground elevation)

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 Upper 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.

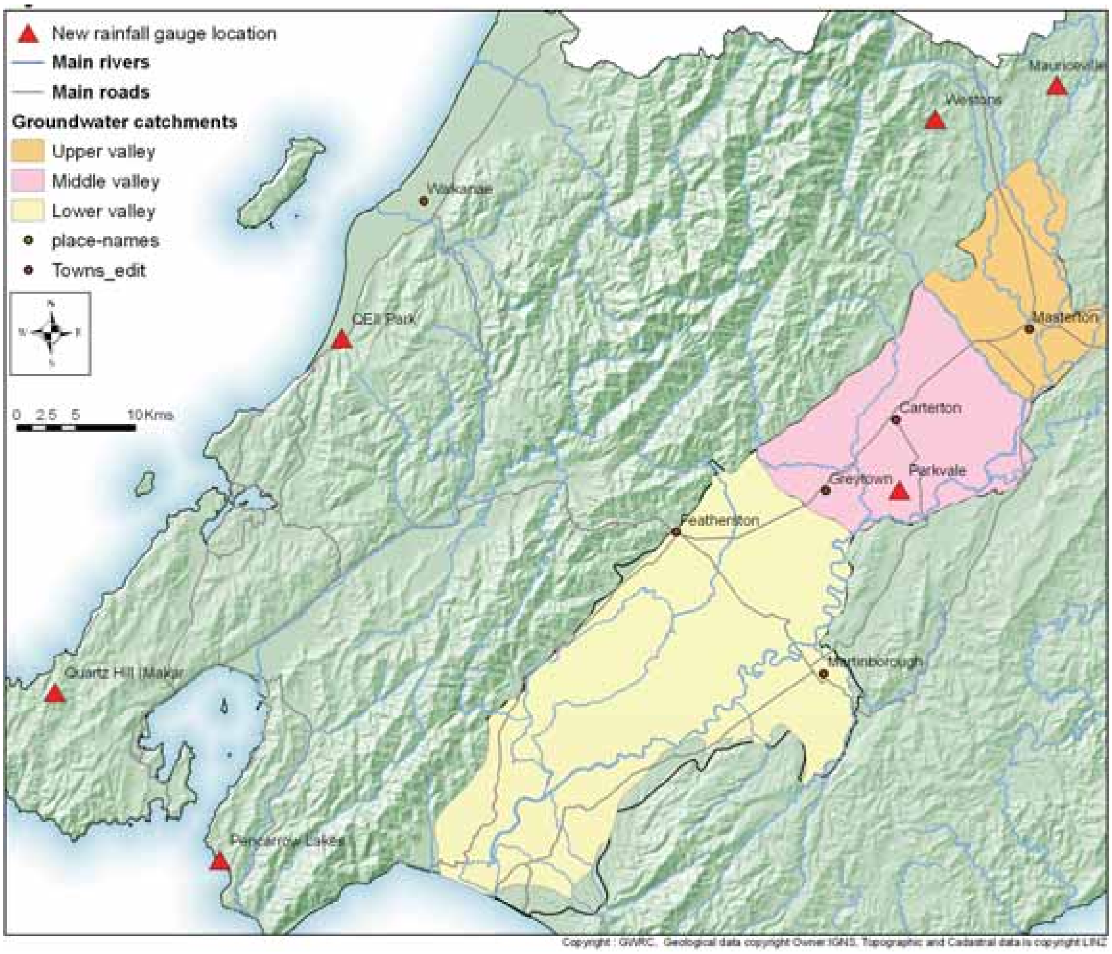


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Figure A2.1: Location of "new" rainfall stations used to verify the NIWA model

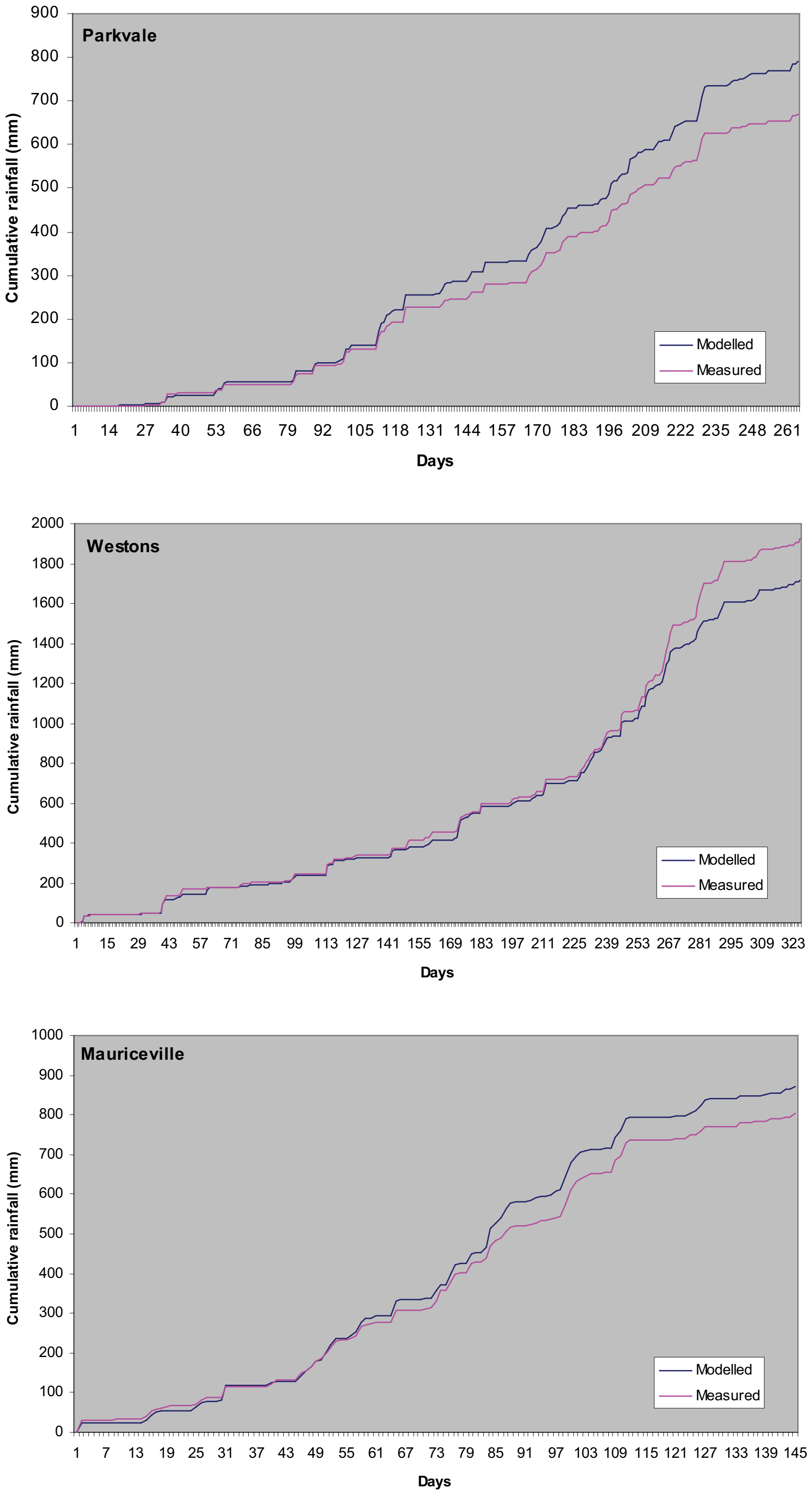


Figure A2.2: Cumulative measured and modelled daily rainfall graphs for three rainfall stations within or close to the Wairarapa Valley using available data (2007/08)

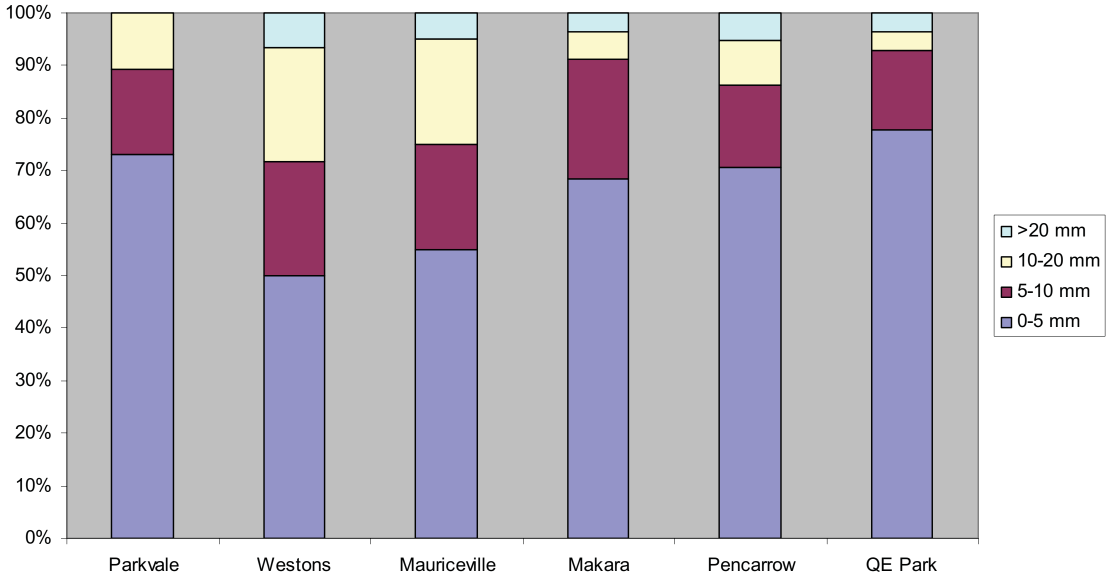


Figure A2.3: Weekly prediction errors for the NIWA 500 m^2 grid rainfall interpolation model for the Wellington region using supplementary data from six independent rainfall stations (excluded from the groundwater model)

Soil mapping and assignment of parameters

Soil moisture balance modelling requires knowledge of the spatial distribution of principal soil types and 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 Upper 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	61	0.7
2	o1c/o79a/o78a	Ruamahanga stony sand/Opaki black stony loam/Kohinui stony loam	Recent soils/Yellow-brown shallow soils	80	26	54	32	Well	45-60	66-81	0.7
3	o75b/o75a/o79a	Tauherenikau stony silt loam/ Tauherenikau shallow silt loam/ Opaki black stony loam	Yellow-brown shallow soils	110	40	70	42	Well	60-68	81-89	0.7
4	o75/o75a/o75b	Tauherenikau silt loam/Tauherenikau shallow silt loam/ Tauherenikau stony silt loam	Yellow-brown shallow soils	120	40	80	48	Imperfect-Well	68	86-89	0.7
5	o29/o29e	Pirinoa silt loam/ Bideford loam	Intergrades between yellow-grey earths and yellow-brown earths	220	120	100	45	Imperfect	74	86-95	0.7
6	o1b/o78/o76c	Ruamahanga sand/ Kohinui loam/ Carterton shallow silt loam	Recent soils/Yellow-brown shallow soils	280	110	170	70	Well	65	86	0.7
7	o2/o1/o106	Ahikouka silt loam/ Greytown silt loam and sandy loam/ Otukura silt loam	Recent soils/Gley soils	330	120-140	190-210	80-90	Well-Poor	65-74	86-95	0.7
8	o13d	Kokotau silt loam	Yellow-grey earths	340	230	110	55	Poor	74	95	0.7
9	o35b	Kaikouta silt loam	Yellow-brown earths	400	240	160	72	Imperfect	70	91	0.7
10	o99/o2	Moroa loam and stony loam/ Ahikouka silt loam	Gley soils/Recent soils	450	260	190	50	Poor	70-74	91-95	0.7

1: Original SCS curve number developed by Webb (2008)
2: Changed SCS curve number as used in the final model

The soil properties data were matched to mapped NZLRI soil polygons and then overlain on the 500 m^2 grid. Properties were assigned to each grid cell for the dominant soil type occurring within it.

Distributed recharge modelling

A computer script was developed to write the large FEFLOW transient recharge power function files for each 500 m^2 recharge cell. The application uses the time series NIWA climate data (Rainfall and PET) residing in an external database, and the soil data in the form of a shapefile containing the recharge model input parameters (TAW, RAW, WP, FC, Fracstor, and SCS number) for each cell.

Run-off calculation methods

Rushton et al. (2006) proposed a method of calculating run-off coefficients based on soil moisture deficit (SMD) and rainfall intensity. This is an ideal way of simulating run-off but is heavily dependent upon the availability of good field data from gauged catchments exhibiting a wide spectrum of different soil types, land use and slope conditions. This data allows the development of rainfall-runoff coefficients for different soil types, slope categories and land uses.

In the case of the Wairarapa Valley, very few catchments have downstream gauges with which to measure rainfall run-off relationships. This means that run-off coefficients could not be defined. The SCS method (USDA Soil Conservation Service runoff curve number model described in Rawls et al. (1992) was, therefore, used as an alternative.

Limitations to estimated recharge reaching the groundwater environment

Soil moisture balance modelling assumes all soil drainage below the soil root zone reaches the water table instantaneously. For a well-drained soil overlying a permeable aquifer with a water table relatively close to the surface, this assumption is realistic. However, in some situations, a thick and low permeability unsaturated zone (i.e. in which a number of clay loess deposits occur on older terrace sequences), the migration of percolating water below the root zone may be severely attenuated and recharge reaches the water table as a slowly moving wetting front over considerable time. The vertical hydraulic conductivity of the unsaturated zone therefore limits the maximum rate at which recharge can reach the water table. In such areas, groundwater level hydrographs do not show the usual short-duration, or even annual recharge peaks, but rather tend to exhibit smoothed trends which are more reflective of long-term rainfall patterns (e.g. the stratigraphic profile for Fernhill in the Middle Valley catchment contains several loess layers). Standard soil moisture balance modelling cannot account for such a situation and tends to apply recharge instantaneously. It can be taken into account by increasing run-off over certain units, and by applying a daily cap of maximum recharge in certain hydrogeological domains. Fortunately, the areas which display such characteristics are small and the bulk of the modelled catchments are underlain by a relatively permeable, thin unsaturated zone.

Recharge model verification

The accuracy of the Rushton soil moisture balance model was verified by comparing calculated recharge with lysimeter data from Canterbury, New Zealand. Lysimeter data for three sites were provided courtesy of Environment Canterbury. Other soil moisture balance models – SOILMOD and the Soil Water Balance Model (described by White et al. 2003) were also tested for comparison. Soil properties were kept consistent for the three models (Table A2.2) and are the same values as those used by White et al. (2003). No surface runoff was incorporated in these simulations.

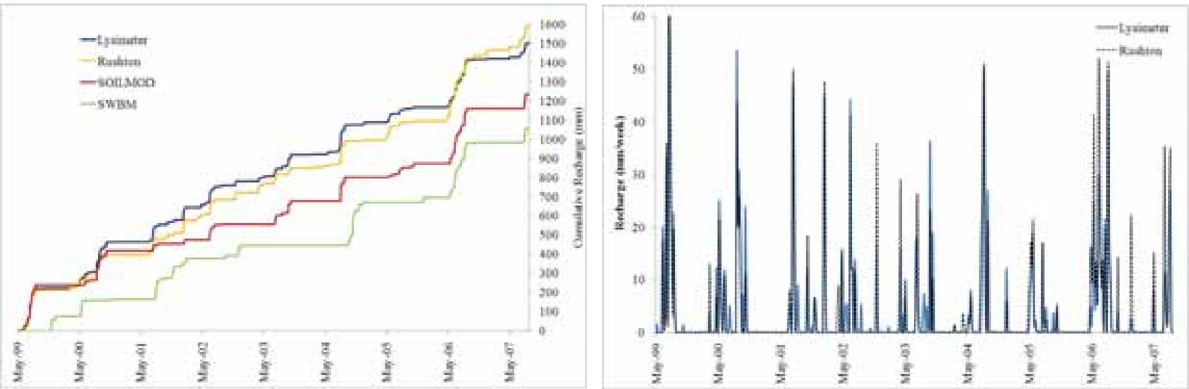
Table A2.2: Soil properties used for Canterbury recharge simulations

	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

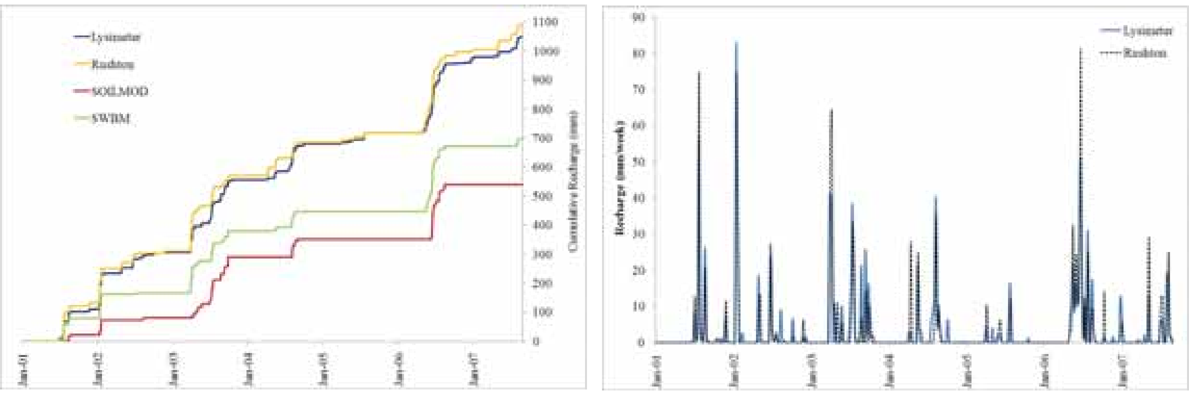
Results for the three soil moisture balance models are compared graphically with lysimeter data in Figure A2.4. Statistics to compare the three models are provided in Table A2.3. The Rushton model gives the most accurate estimation of weekly rainfall recharge of all the three models. Recharge at the 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

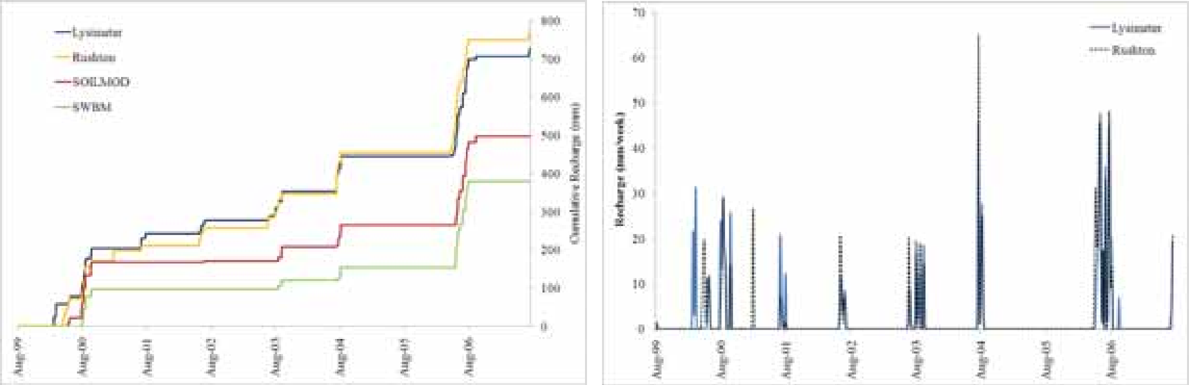


Figure A2.4: Hydrographs of cumulative recharge calculated by three soil moisture balance models (Rushton, SOILMOD and SWBN) compared to lysimeter data (left). Weekly recharge for the Rushton model compared with lysimeter recharge (right)

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

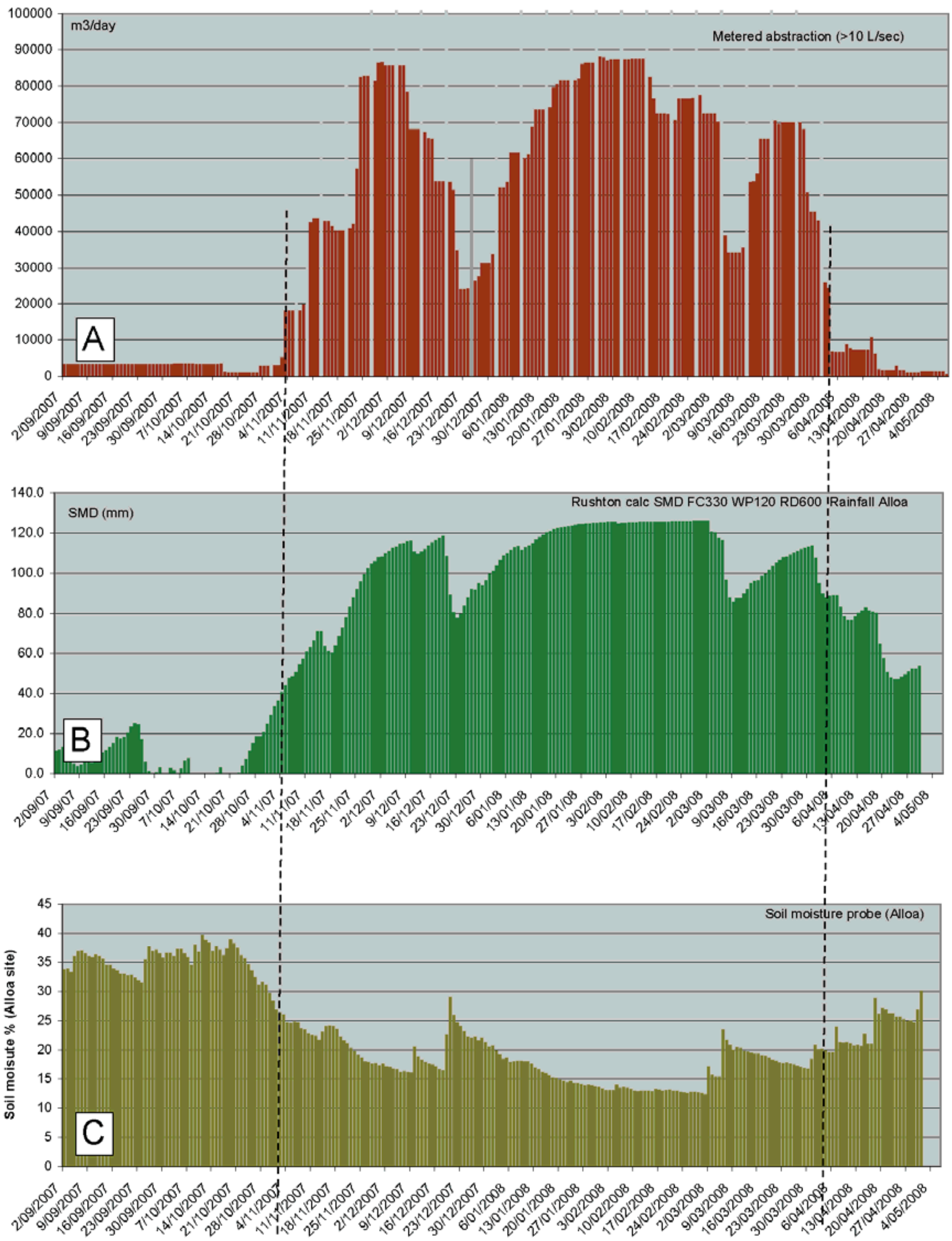

Figure A3.1: (A) Metered Lower valley catchment abstraction, (B) calculated soil moisture deficit, and (C) soil moisture monitoring data at Alloa, for the 2007/08 irrigation season

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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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

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[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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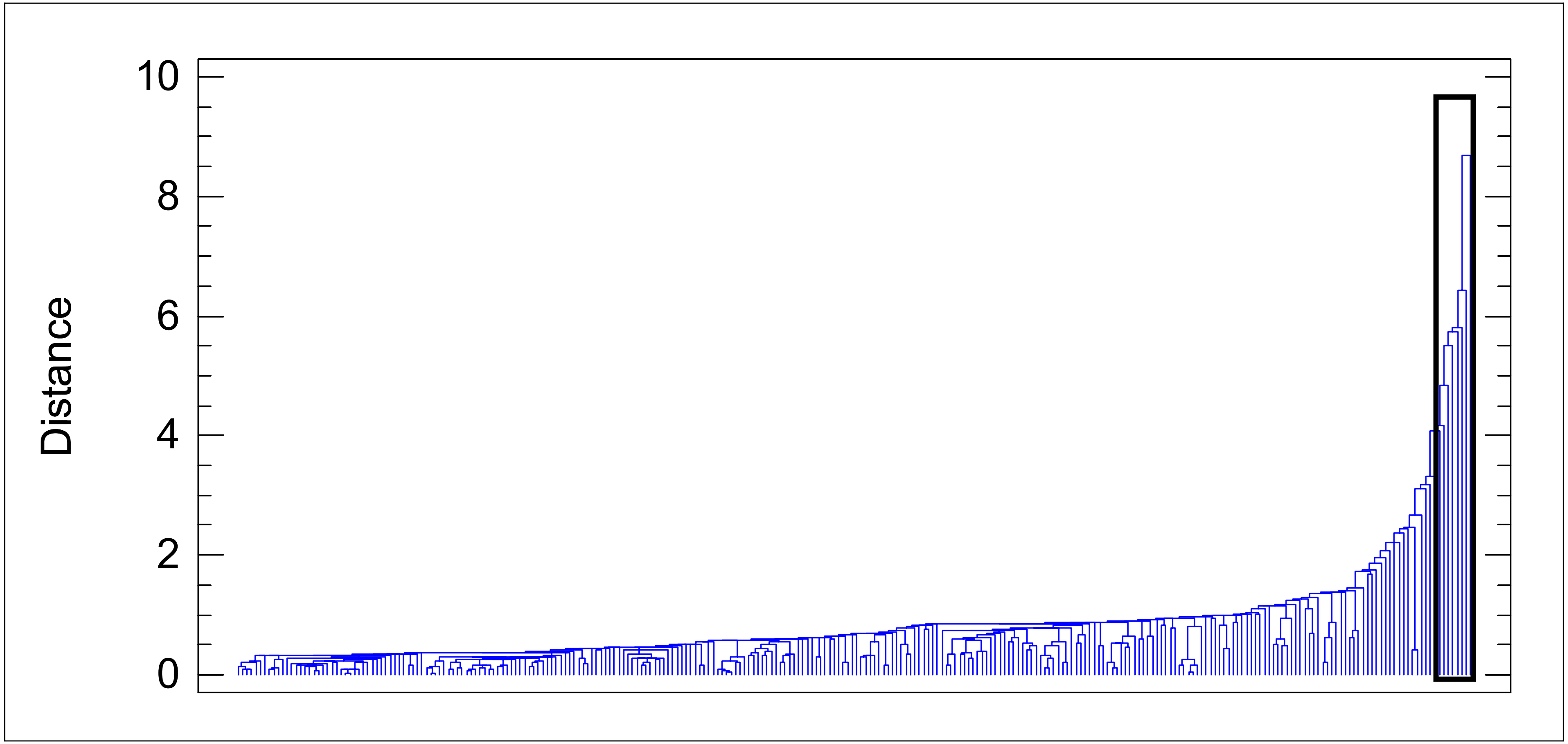

Figure 1. Hierarchical cluster analysis dendrogram, Nearest Neighbour linkage rule. The terminus of each vertical blue line represents a single monitoring site. Marked box identifies eight outlier (residual) sites.

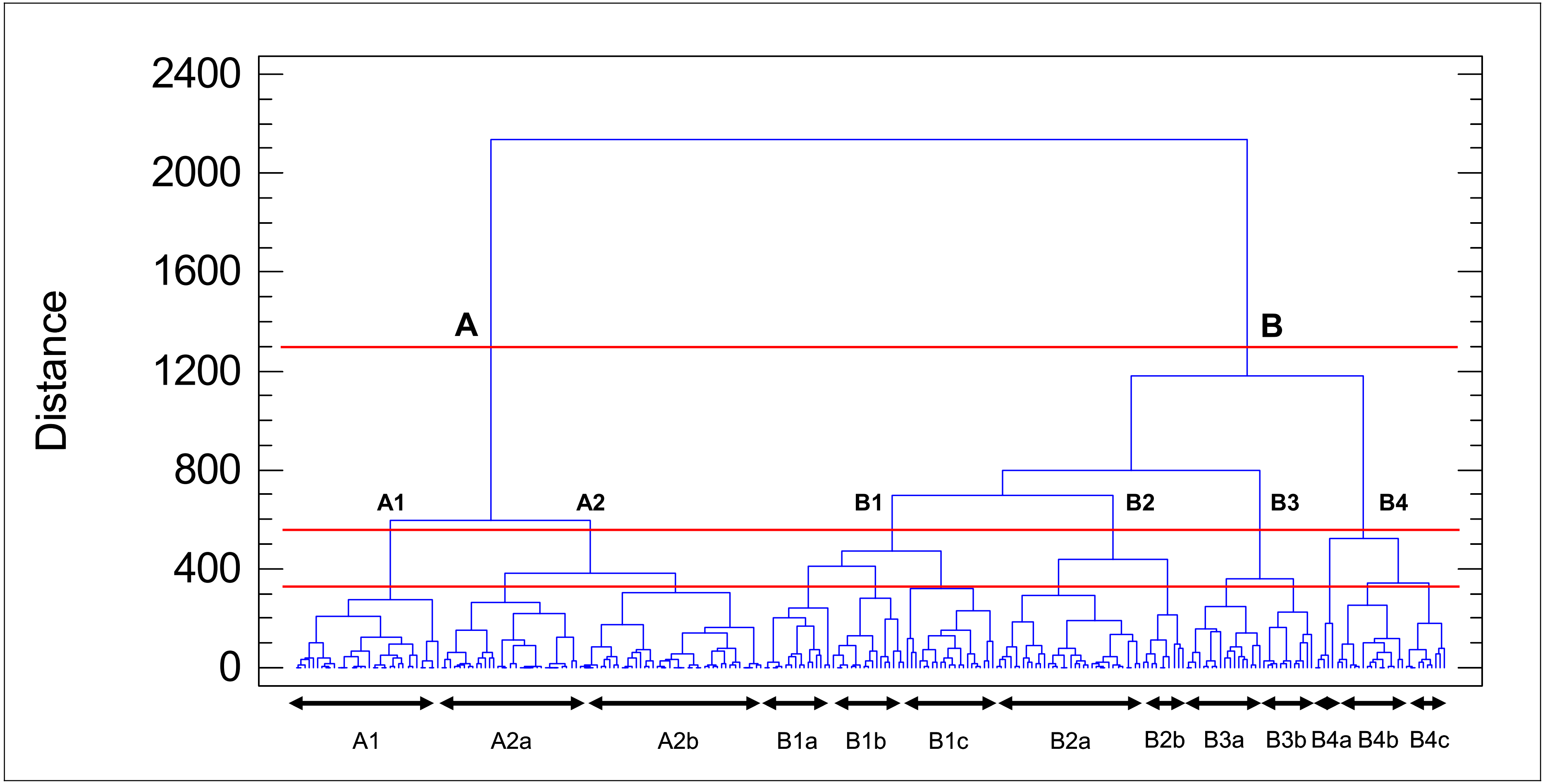

Figure 2. Hierarchical cluster analysis dendrogram, Ward's linkage rule. identifying two main clusters (A and B) at a separation threshold of ca. 1300, six subclusters (A1 to B4) at a separation threshold of ca. 550, and thirteen subclusters (A1 to B4c) at a separation threshold of ca. 350. The terminus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

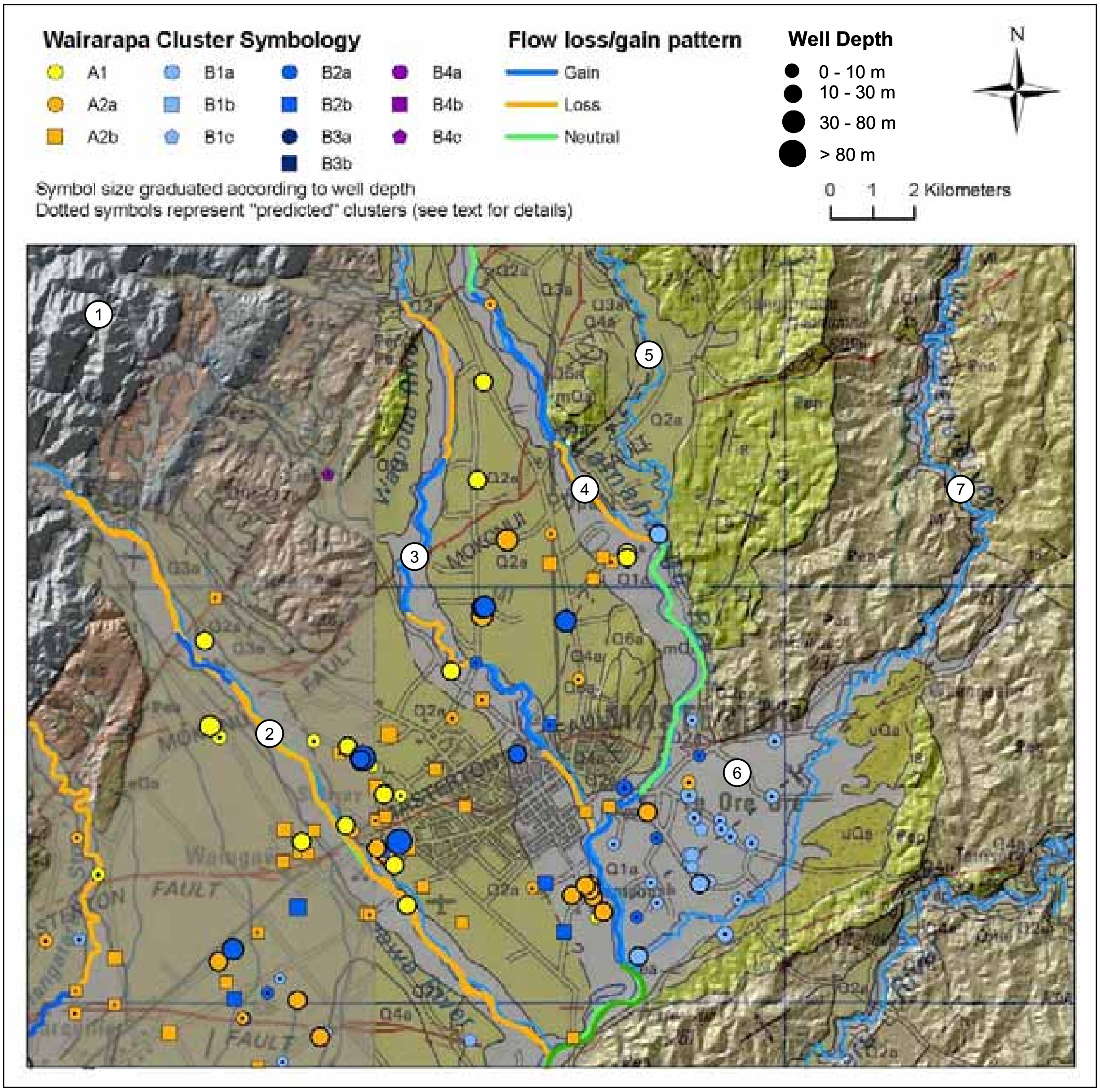

Figure 3. Cluster assignments, Upper Wairarapa Valley. Map base layer shows a digital terrain model in combination with surficial geology (Begg and Johnston, 2000; Lee and Begg, 2002). Circled numbers denote geographic features described in the text: 1) Tararua Ranges, 2) Waingawa River, 3) Waipoua River,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

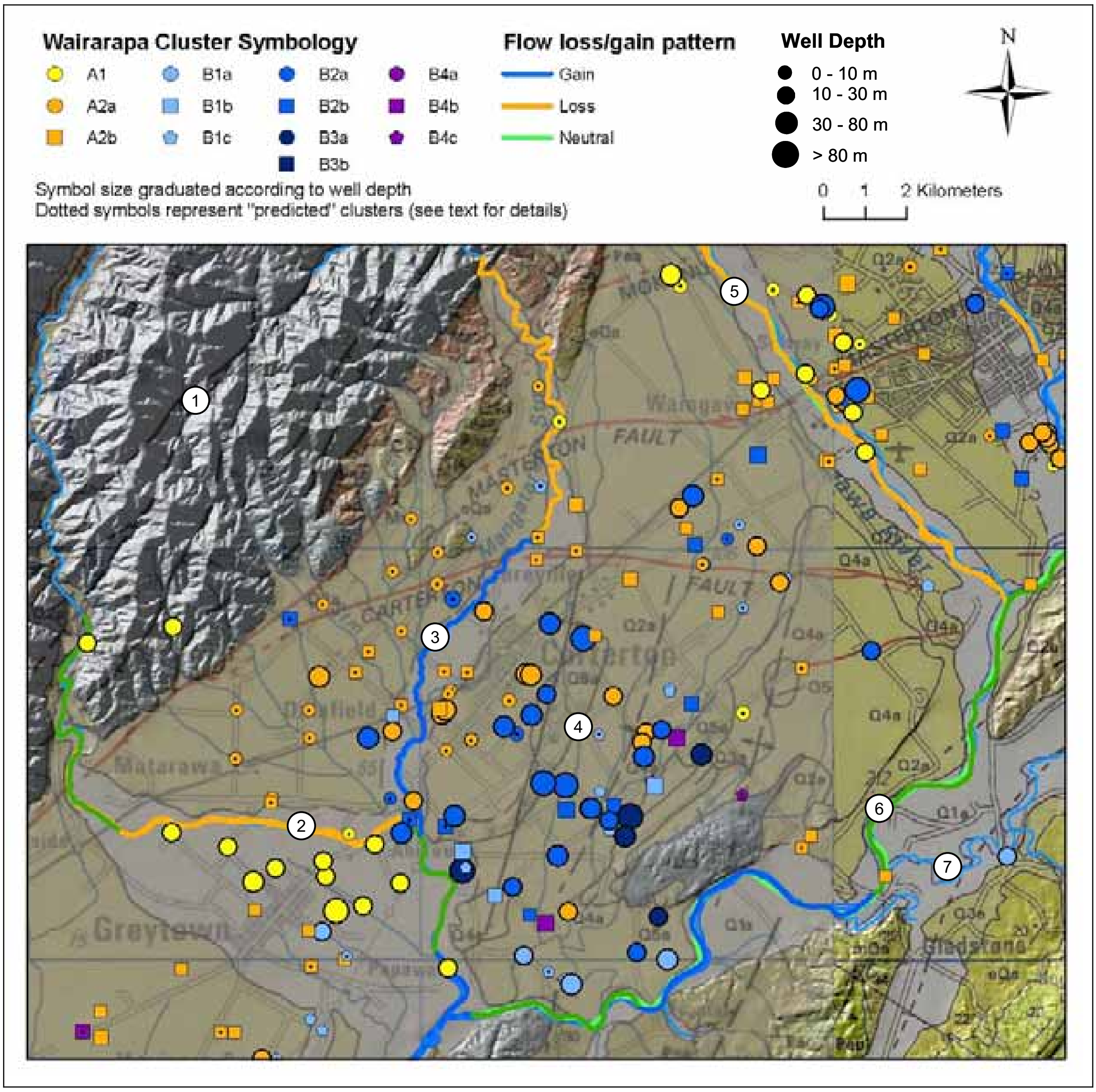

Figure 4. Cluster assignments, Middle Wairarapa Valley. Map base layer shows a digital terrain model in combination with surficial geology (Begg and Johnston, 2000; Lee and Begg, 2002). Circled numbers denote geographic features described in the text: 1) Tararua Ranges, 2) Waiohine River, 3) Mangatarere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

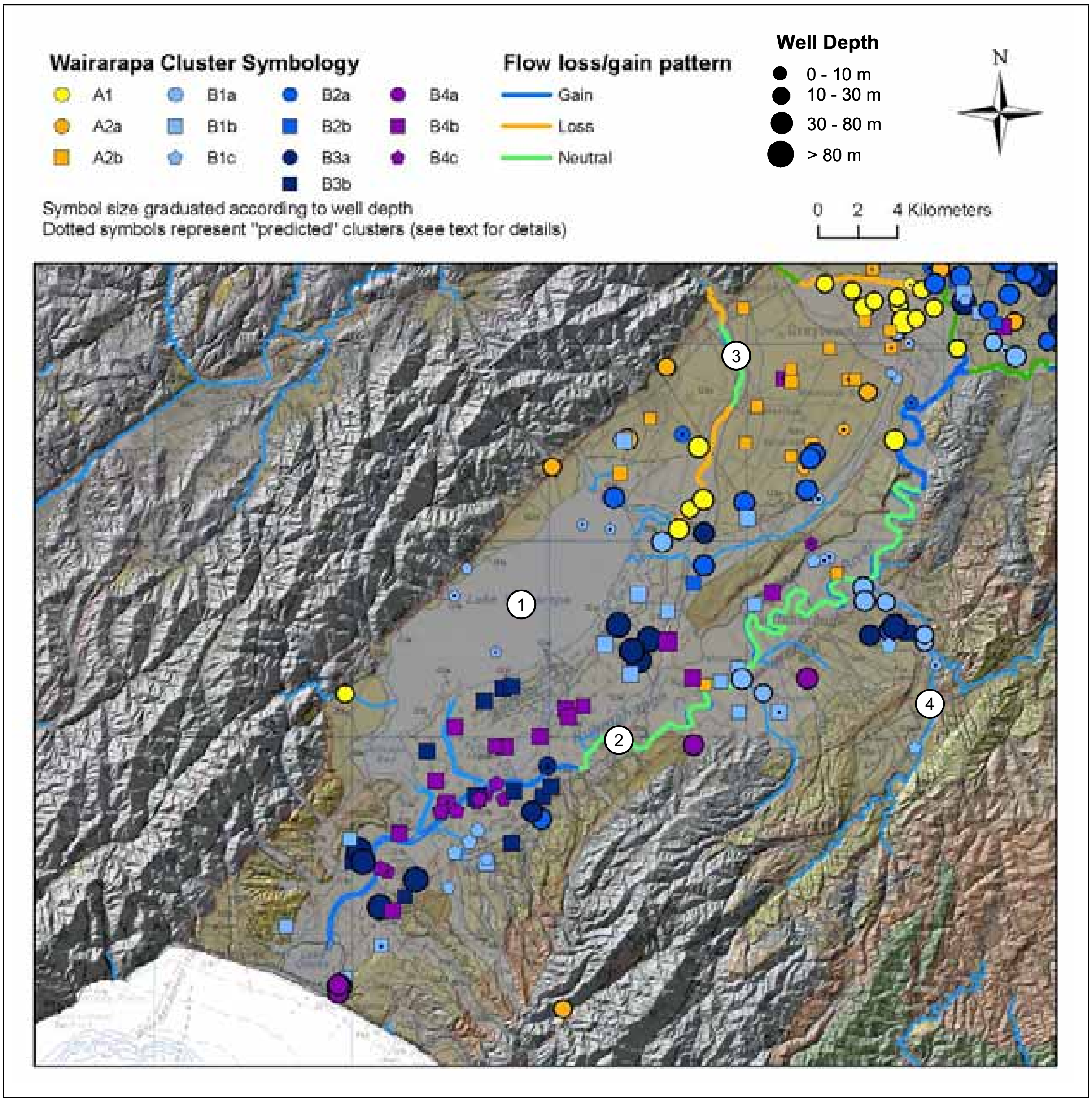

Figure 5. Cluster assignments, Lower Wairarapa Valley. Map base layer shows a digital terrain model in combination with surficial geology (Begg and Johnston, 2000; Lee and Begg, 2002). Circled numbers denote geographic features described in the text: 1) Lake Wairarapa, 2) Ruamahanga River, 3) Tauherenikau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

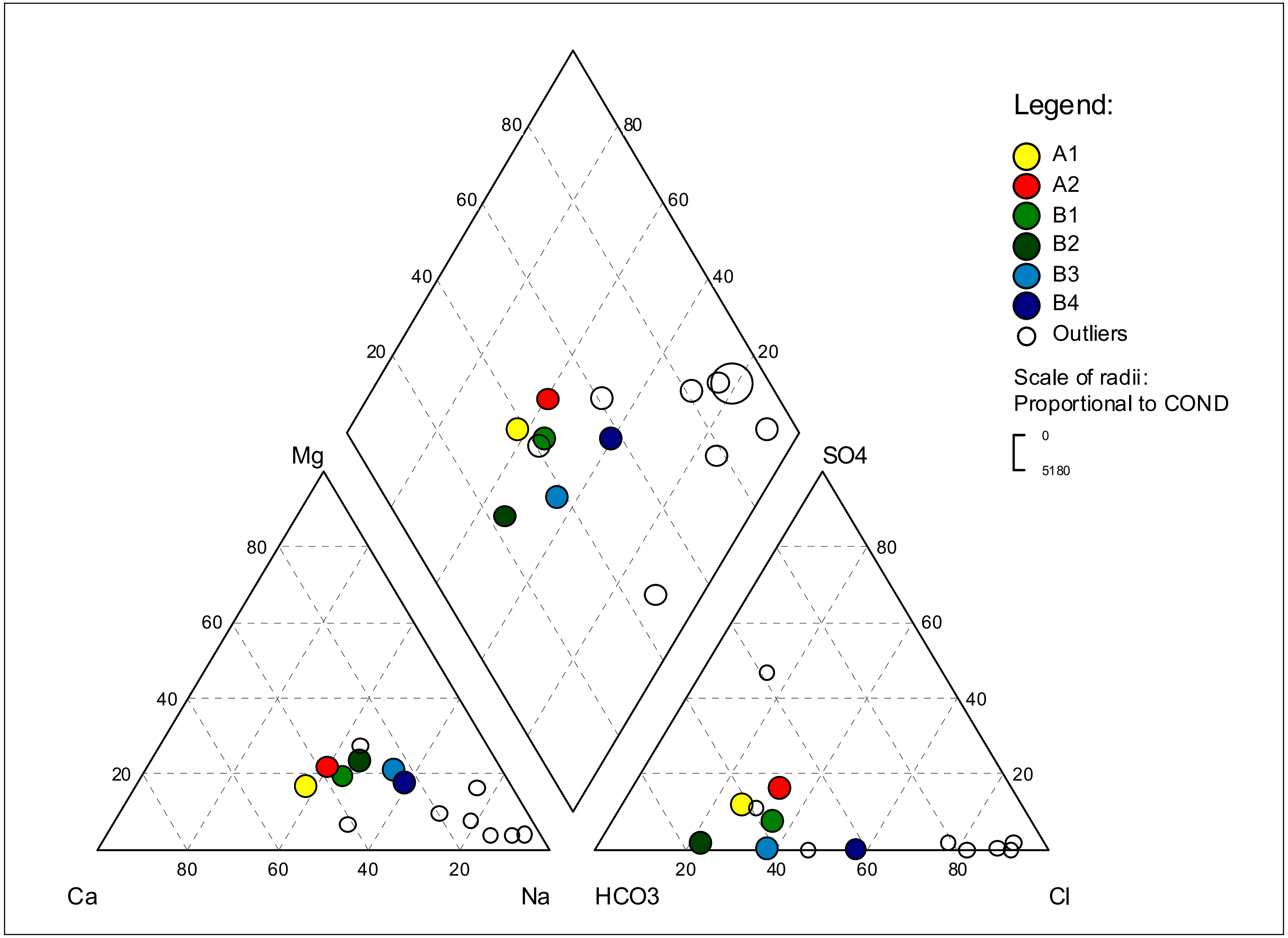

Figure 6. Piper diagram showing the variation of major ion ratios amongst the centroids of the six clusters defined by HCA at a separation threshold of ca. 500 (coloured symbols) and the eight outlier (residual) sites (unfilled symbols). The left and right triangular plots show the major cation and anion 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.

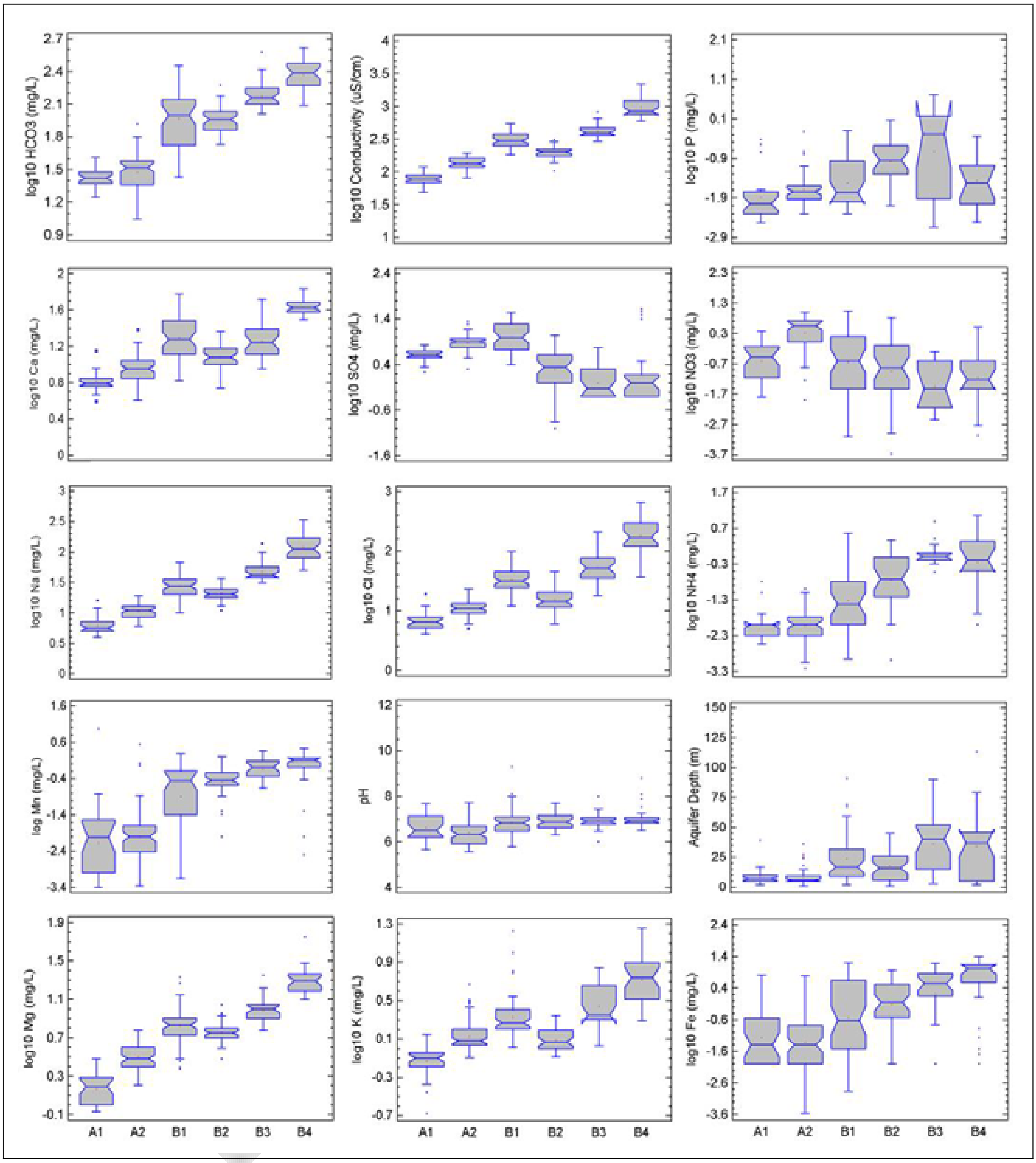

Figure 7. Box-whisker plots showing variation of selected parameters between six clusters defined by HCA. The rectangular "box" extends from the 25th to the 75th percentile, covering inter-quartile range, i.e. the centre half of each distribution. The horizontal line within the box shows the location 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).

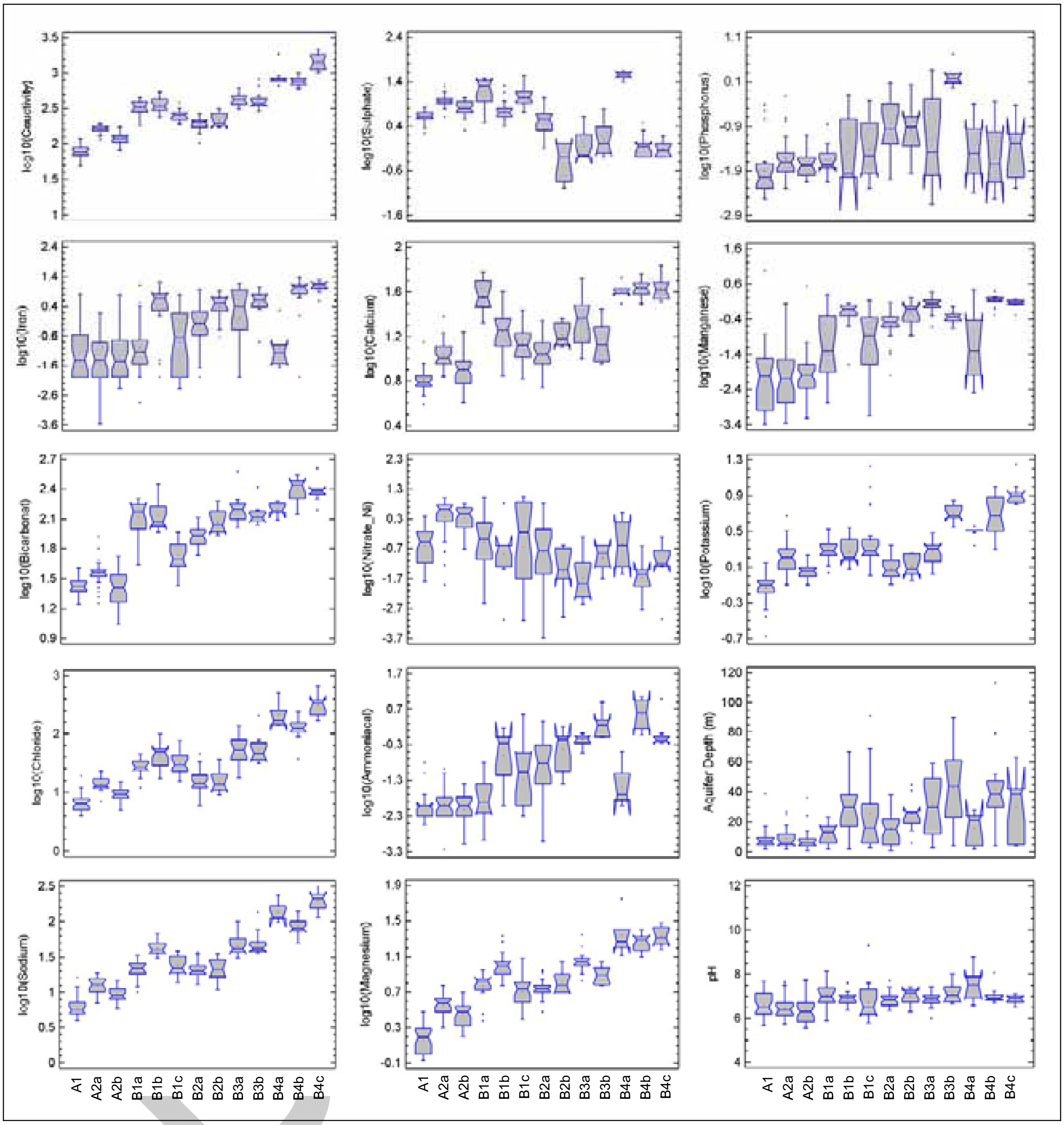

Figure 8. Box-whisker plots showing variation of selected parameters between thirteen subclusters defined by HCA. The rectangular "box" extends from the 25th to the 75th percentile, covering inter-quartile range, i.e. the centre half of each distribution. The horizontal line within the box shows the 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).

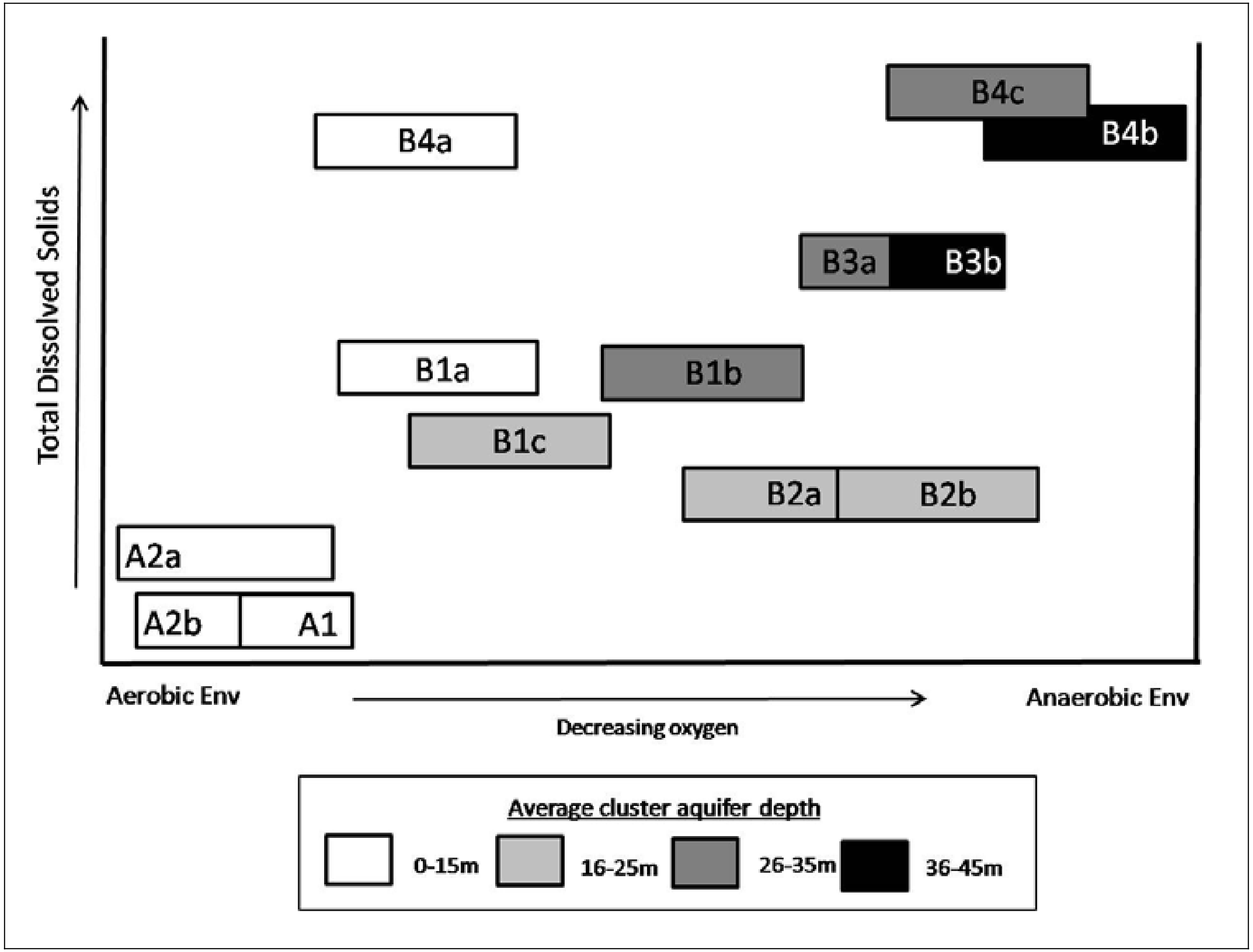

Figure 9. Simplified schematic representation of differences amongst the 13 subclusters (A1a-B4c) in relation to their total dissolved solids, aquifer depth and aerobic environment. Scale and axis is representative of increase only.

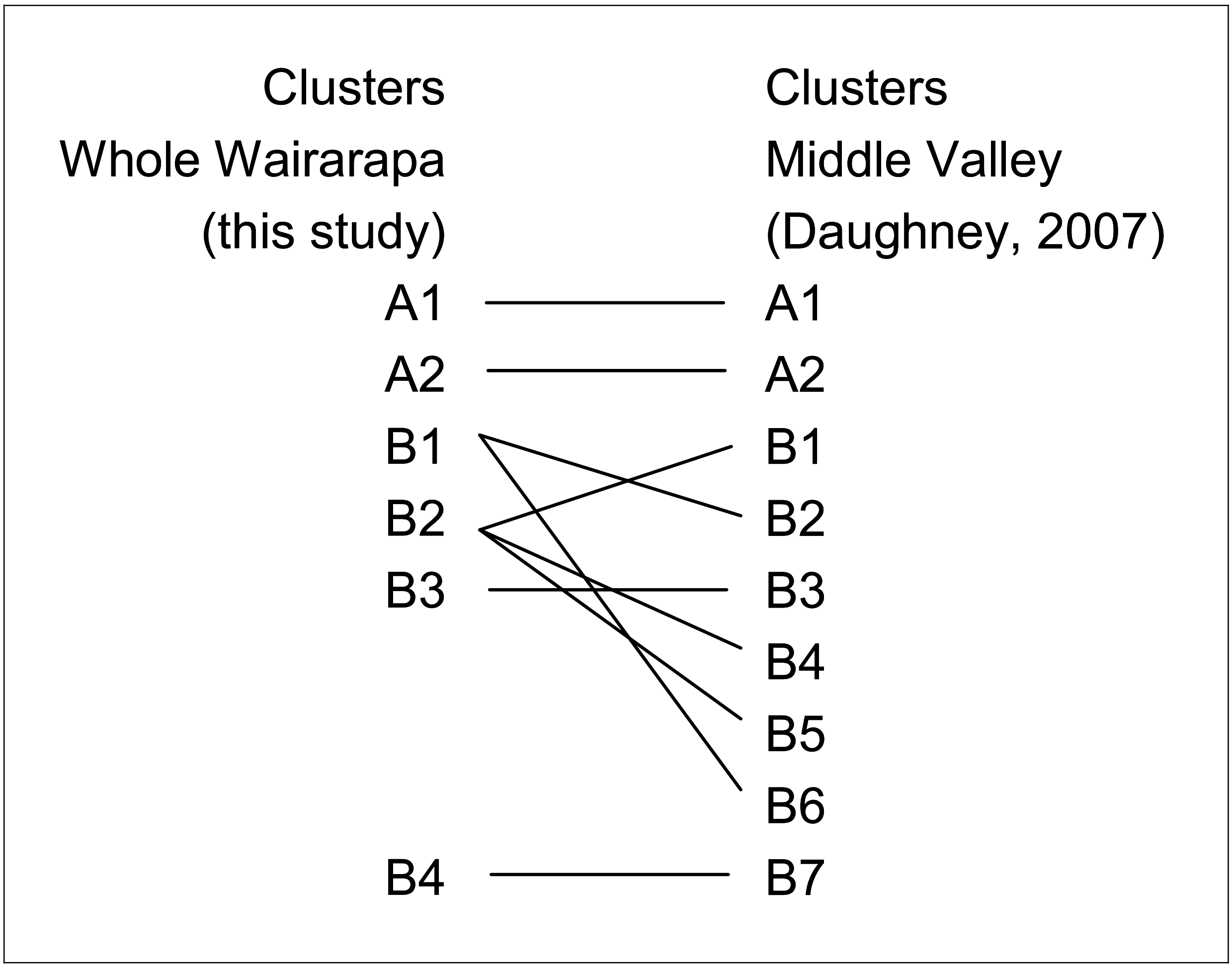

Figure 10. Correspondence of clusters defined for the Middle Wairarapa Valley (Daughney, 2007) with clusters defined for the whole Wairarapa Valley (this study).

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

MIKE11 surface water model

A MIKE11 surface water model was developed for the Upper 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 Upper Valley catchment surface water model consists of the Waingawa, Waipoua, Kopuaranga, and Whangaehu rivers, and the Ruamahanga River between the flow gauge at Mt Bruce and its confluence with the Waingawa River. The Waingawa River was used in both the Upper and Middle valley models as it forms the boundary between the models.

Input flow data

Flow data were available at a number of recorder sites located within or just outside the model area as listed in Table A5.1. The data are archived in Greater Wellington's hydrological database (Hilltop) and, for the purposes of this model, cover the period June 1992 to October 2008. The flow data were collated in Hilltop and exported to a suitable format for MIKE11.

Table A5.1: Mike11 flow data sources for the Upper Valley model

Site	Site No.	Map Reference
Ruamahanga River at Mt Bruce	29254	S25:293470
Waingawa River at Kaituna	58582	S26:226324
Waipoua River at Mikimiki	29257	S26:246375
Whangaehu River at Waihi	29244	T26:441378
Kopuaranga River at Palmers	29230	T26:353396

The Waipoua River at Mikimiki site has been operational at various times since 1979. The site was primarily used for flood warning purposes and only rated for medium to high stage heights, until February 2007 when it became fully rated. Therefore, a synthetic flow record for Waipoua River at Mikimiki had to be created for the period 1992 to 15 February 2007 based on a correlation developed between Mikimiki and the Mangatarere Stream (at Gorge). However, because the Mangatarere site only commenced operation in February 1999 a synthetic record for the Mangatarere prior to 1999 was also developed based on correlations with the Atiwhakatu River at Mt Holdsworth Road and the Waingawa River at Kaituna. The synthetic record for Waipoua at Mikimiki was therefore based on both the derived Mangatarere record prior to 08/02/99 and the actual Mangatarere flow record after that until 15 February 2007. The same correlation was used for both sections of data derived from the Mangatarere Stream at Gorge:

$$\text{Waipoua River at Mikimiki } (m^3/s)) = 1.9388\,(\text{Mangatarere Stream at Gorge } (m^3/s))^{1.0331}$$

This relationship was calculated by comparing flows at both sites for the period 15 February 2007 to 7 July 2009.

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.

Cross section data

River cross sections are surveyed by Greater Wellington as part of its flood protection role. The most recent cross section level data for the rivers in the study area were provided as detailed in Table A5.2. Because not all cross sections can be surveyed at one time there is a range of dates that cover each branch. A total of 190 cross sections with corresponding level data and location co-ordinates were incorporated into the model.

There were no cross section data available for the Whangaehu River so it could not be included in the MIKE11 model. However, flow inputs from this river to the Ruamahanga were simulated using a synthetic branch based on flow monitoring data on the Whangaehu River at Waihi (which is a long way upstream of the confluence with the Ruamahanga) and incorporating a lag time.

All the river cross section data used in the MIKE11 modelling were converted to the L&S Datum from the local Wairarapa datum (9.22 m subtracted). Figure 3.2 of the main report contains the longitudinal bed profiles of the modelled rivers.

Table A5.2: Cross section data

River	Survey date	Number of sections
Ruamahanga River	2006-2007	70
Waingawa River	2001	30
Waipoua River	2004	43
Kopuaranga River	2005	45
Whangaehu River	Synthetic	2

Hydrodynamic modelling

MIKE11 produces flow, velocities and water levels at nodes along a river system based upon the surveyed river cross sections and accounts for the dynamic effects of catchment inflows and channel storage. The MIKE11 model for the Upper Valley catchment consists of five branches (Ruamahanga, Waingawa, Waipoua, Kopuaranga and Whangaehu). A total of 199 points (Hnodes) were used in the model – corresponding to the 190 surveyed cross sections, plus interpolated sections at river confluences and model boundaries.

The only inflows to the model were at the upstream boundaries of the five branches as described above; these correspond to flow recorder locations. Since the downstream boundary of the Upper Valley catchment model and the top of the Middle Valley catchment model intersect, the boundary node records were matched to maintain continuity.

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 - except for the Kopuaranga River branch, which was set to 0.055 due to the narrow winding nature of the channel. The same value was used in the Middle Valley catchment model where it was found to be appropriate. No structures are 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 6:

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.

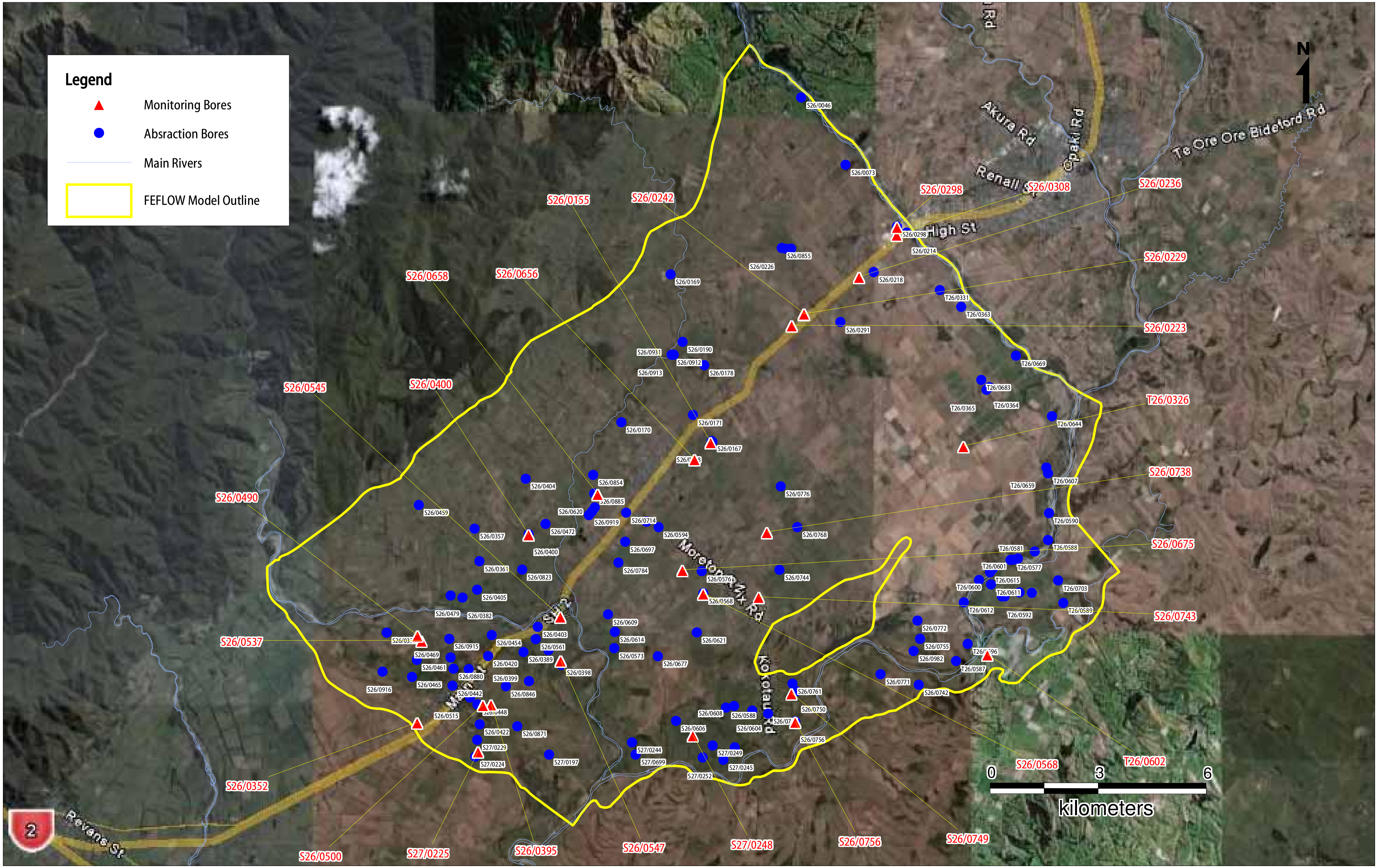

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Figure 1
GWRC REGISTERED GROUNDWATER BORES

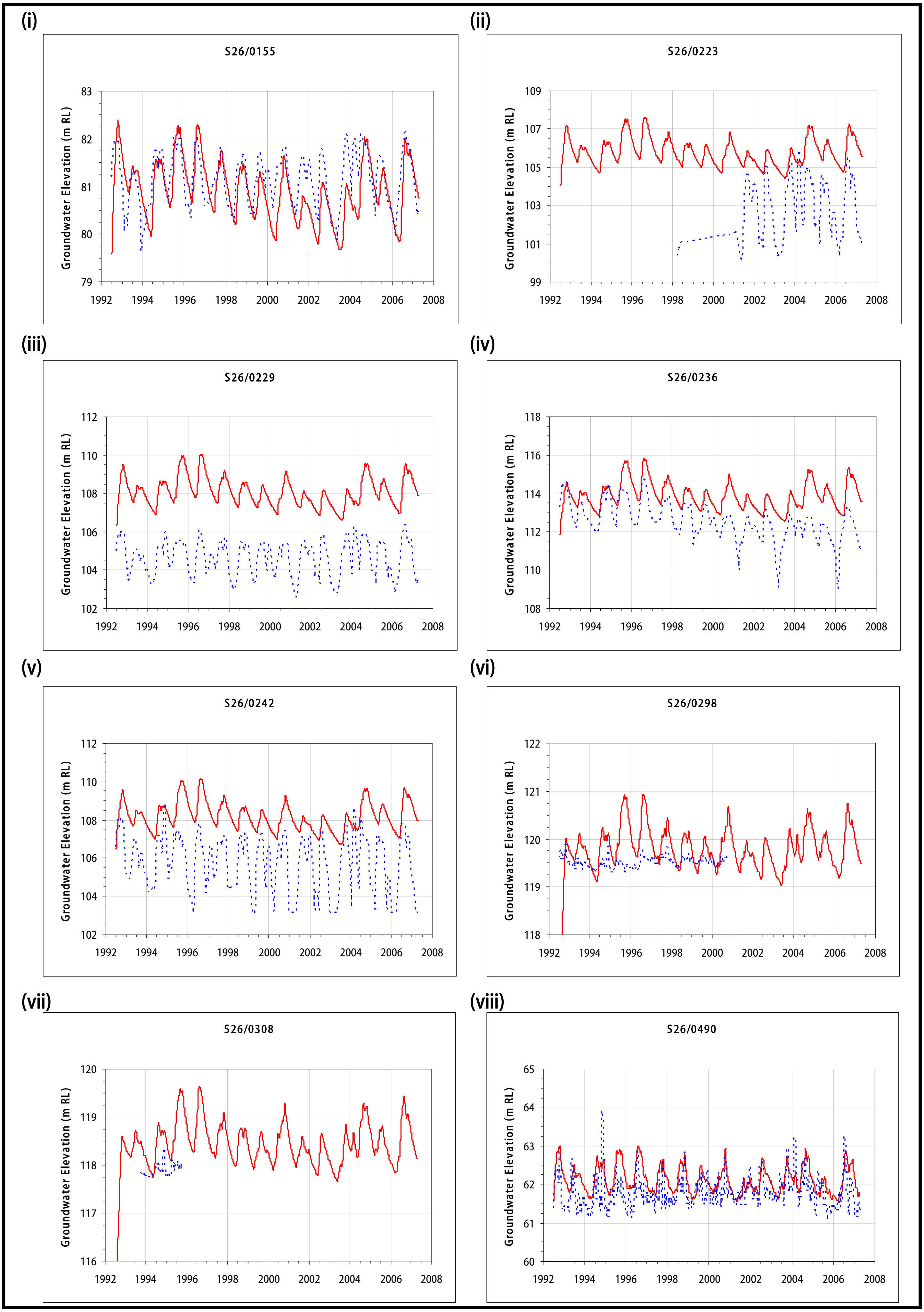

Figure 2
COMPARISON OF OBSERVED & SIMULATED HYDROGRAPHS (AFTER GWRC MANUAL CALIBRATION)

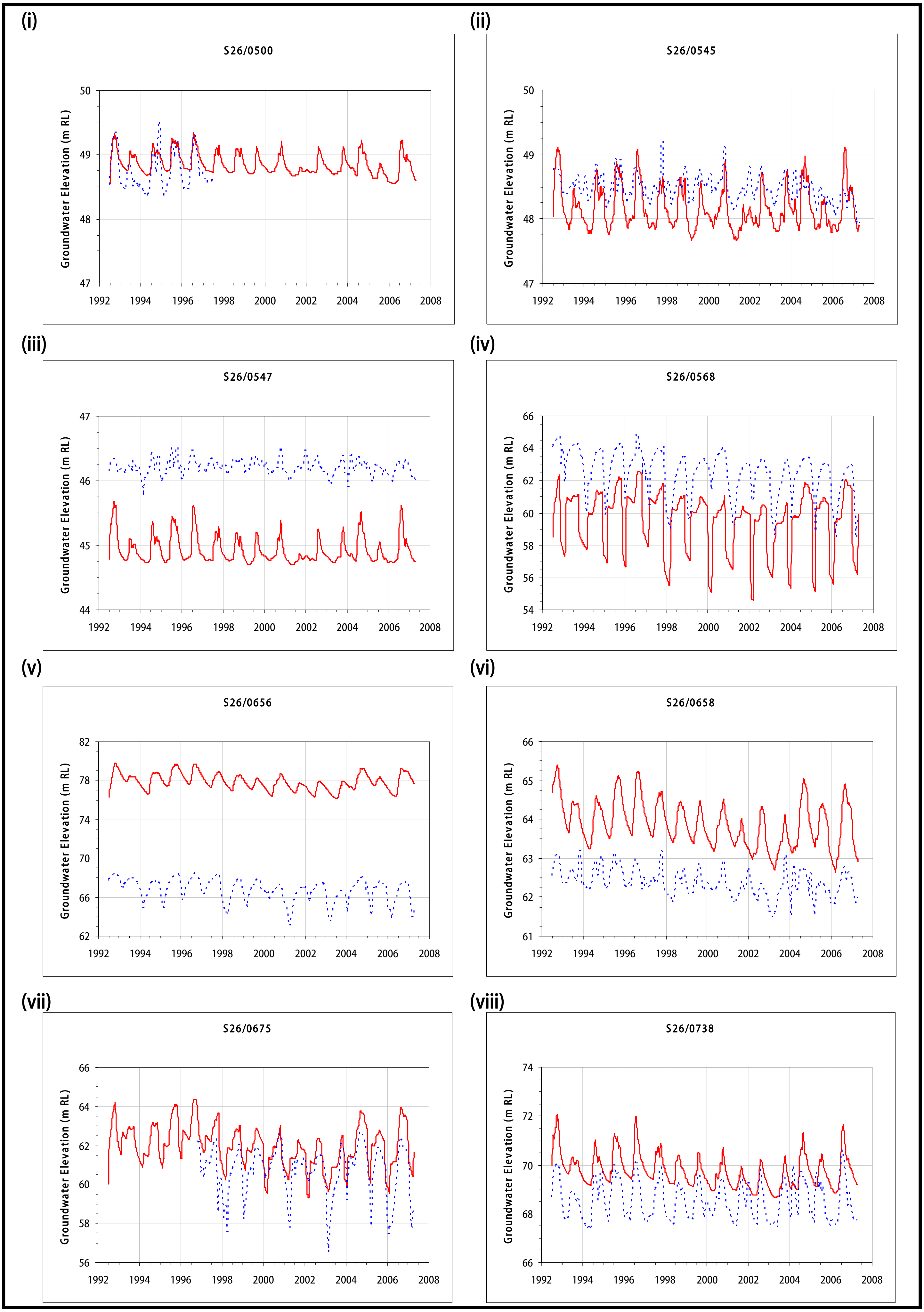

Figure 3
COMPARISON OF OBSERVED & SIMULATED HYDROGRAPHS (AFTER GWRC MANUAL CALIBRATION)

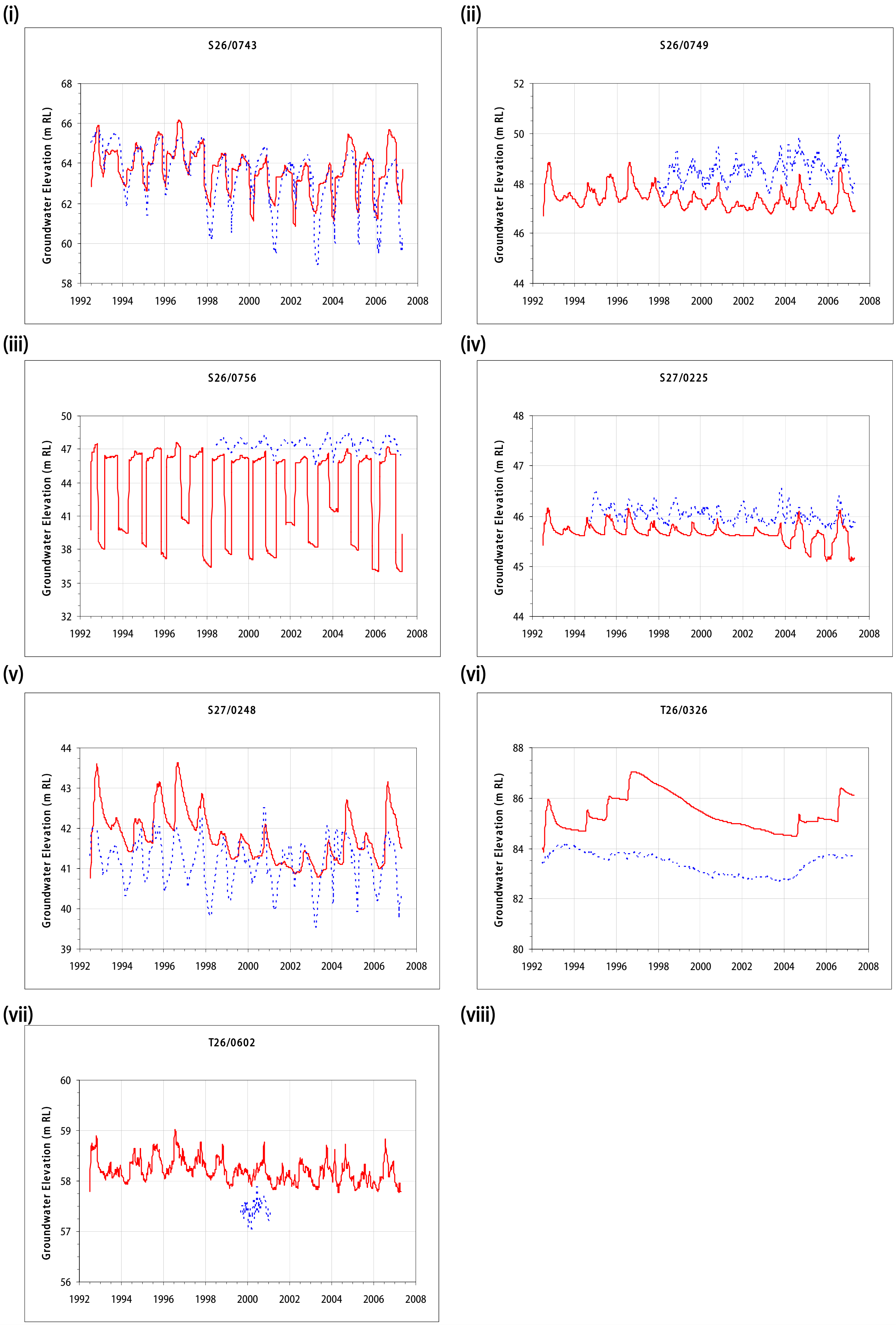

Figure 4
COMPARISON OF OBSERVED & SIMULATED HYDROGRAPHS (AFTER GWRC MANUAL CALIBRATION)

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	#

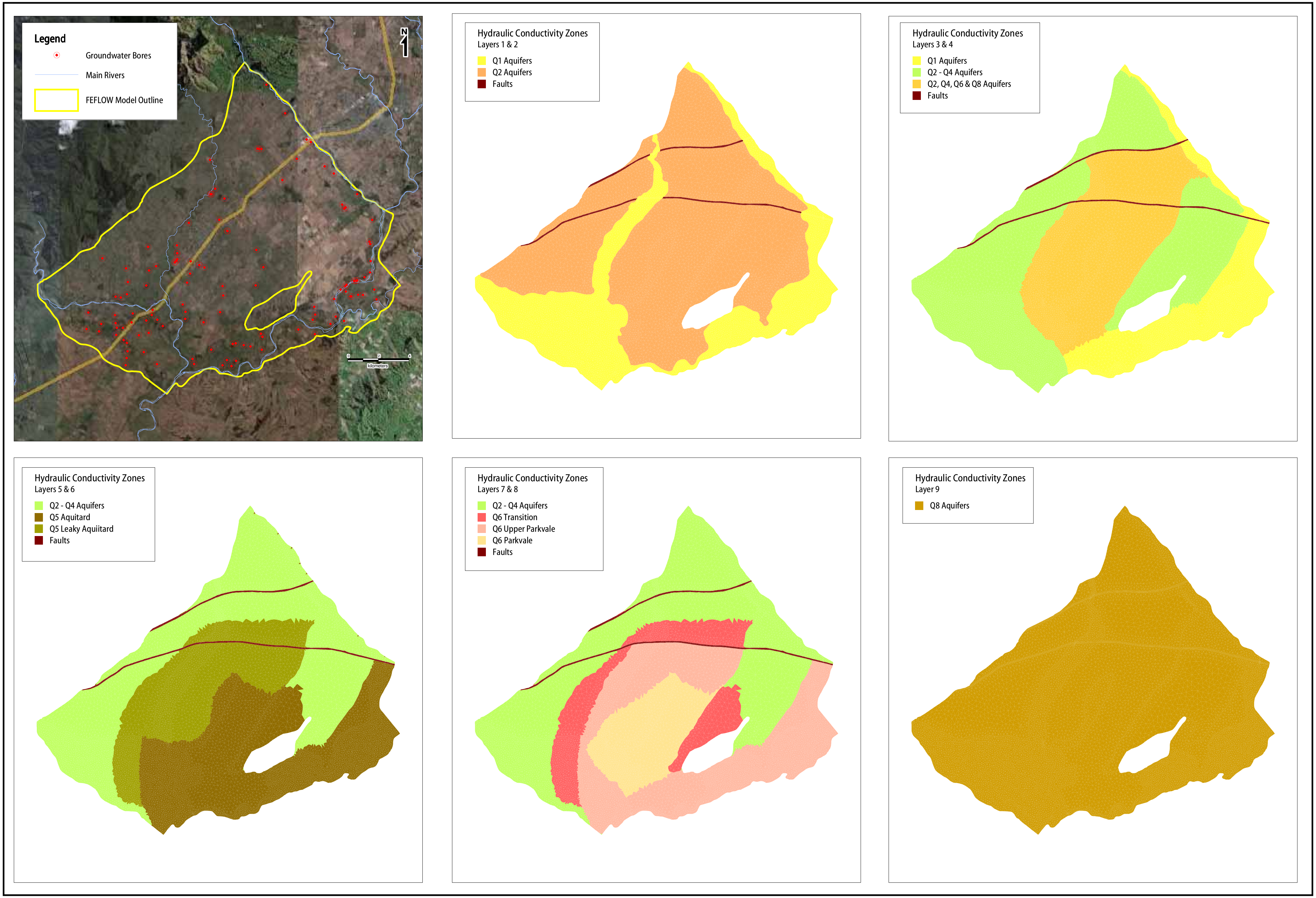

Figure 5
HYDRAULIC CONDUCTIVITY ZONATION

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).

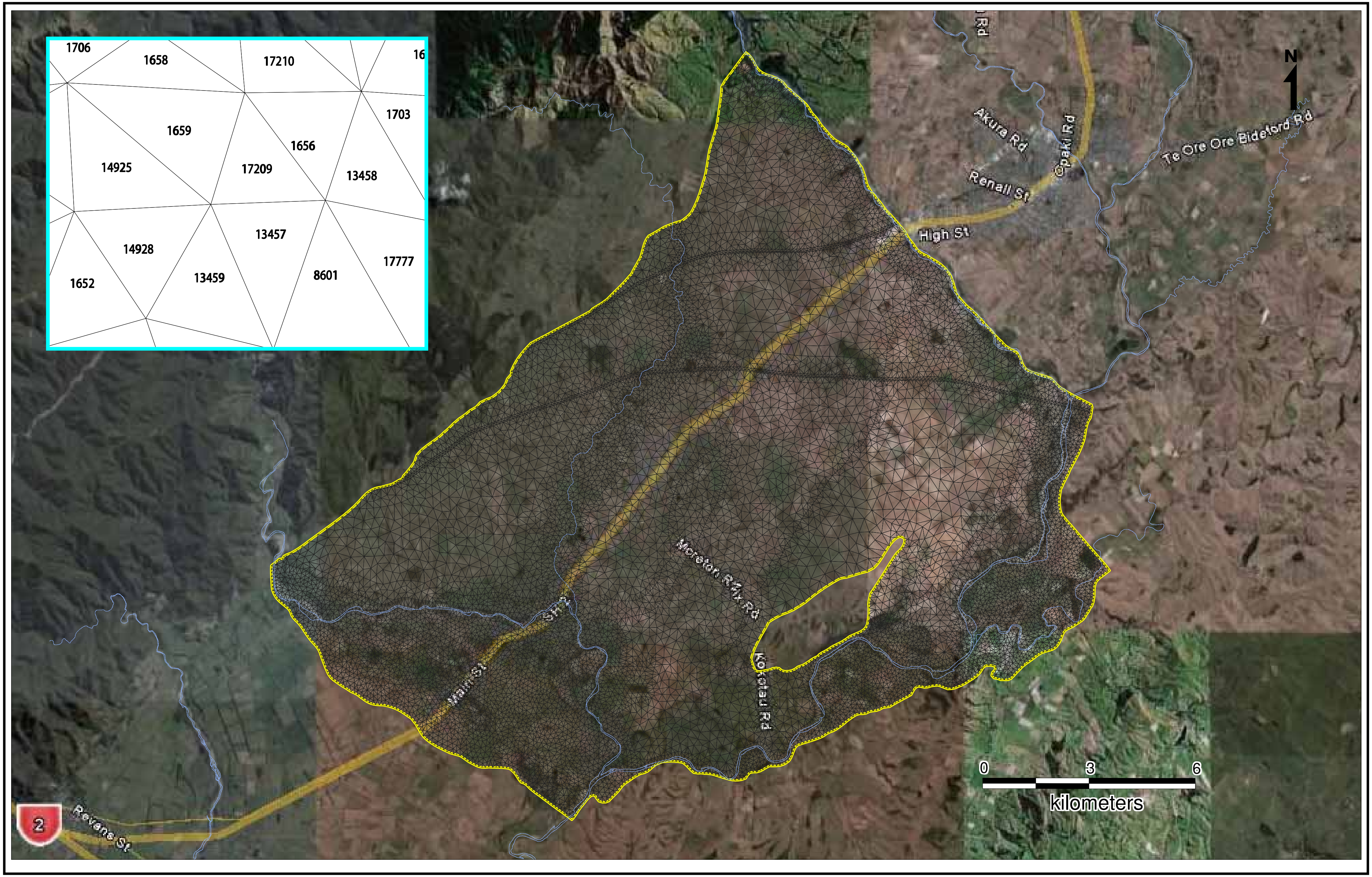

Figure 6
FEFLOW MODEL GRID AND ELEMENT NUMBERS IN LAYER 1

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

	Error (m)				Scaled Error			
Monitoring Bore	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	Coefficient of Determination
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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