2007

Mid-Mataura Groundwater Model

Environment Southland

Final Report

Phreatos Limited

Contents

1. INTRODUCTION

The mid-Mataura catchment has experienced a considerable increase in groundwater abstraction over the past five years. Between 2000 and 2005 groundwater demand in Southland increased eight-fold, driven primarily by the expansion of pasture irrigation in northern Southland. Demand for additional water supplies for irrigation continues to grow – particularly in the Riversdale area.

The shallow, productive alluvial aquifers of the mid-Mataura catchment are hydraulically connected with rivers and springs – groundwater and surface water are fundamentally a 'single resource'. This characteristic of the groundwater system has led to considerable focus being directed at the cumulative effects of groundwater abstractions on the surface water environment.

Management of the cumulative depletion effects of groundwater abstractions is driven partly by the requirements of the Mataura River Water Conservation Order (1997). The Order stipulates that at any point, 95% of the natural flow in the Mataura River must remain.

The sustainable management of groundwater allocation in the mid-Mataura catchment requires a reliable and scientifically robust understanding of the groundwater environment, and the dynamics of its interaction with surface water systems. Groundwater allocation in the Riversdale Groundwater Management Zone is currently approaching the 'first order' allocation limit set by Environment Southland.

At present the cumulative depletion effects of groundwater allocations is not fully understood. The stream flow depletion effects of individual takes are currently assessed by Environment Southland as part of the consenting process, but a more comprehensive examination of the cumulative effects is required.

Environment Southland has therefore commissioned a groundwater modelling study from Phreatos Limited to assist in the evaluation and management of groundwater allocations in the mid-Mataura catchment. Specific objectives of the study are as follows:

- Construction of a transient-flow groundwater model of the mid-Mataura catchment between Gore and Cattle Flat, focussed upon the Riversdale, Waipounamu, Wendon and Knapdale groundwater zones. The model is to be capable of accurately simulating the interaction between groundwater and surface water.

- Assess the cumulative effects of current abstractions on the Mataura River and spring fed streams in the Riversdale Groundwater Management Zone.

- Using insights derived from the modelling study, provide guidance and recommendations for the improved assessment and management of groundwater allocations.

- Provide training support to Environment Southland technical staff in the development, use and maintenance of the model. The conceptual and numerical model are to be developed in close liaison with ES staff to ensure that there is confidence in the reliability of the model for resource management purposes.

This report documents the first three objectives.

2. PREVIOUS WORK

Several phases of hydrogeological investigation have been commissioned by Environment Southland for the mid-Mataura catchment. Two numerical models have been produced by SKM (2003, 2005) which focused upon specific sub-regional 'groundwater management zones' .

The first model (SKM, 2003) resulted in a steady-state model for the Riversdale and Longridge groundwater management zones. Although limited as a resource management tool, the model served the valuable purpose of facilitating an initial conceptual hydrogeological understanding of the area through the collation of existing information. Identification of critical information gaps resulted in a field investigation programme which included the installation of groundwater monitoring sites and the establishment of a river and stream gauging programme.

A subsequent study resulted in the development of the 'Northern Southland Model' (SKM, 2005) which encompassed five groundwater management zones. This was a first attempt at a transient flow model using new information acquired from resource development work and environmental monitoring. The Modflow-based model helped to understand the dynamics of the groundwater environment around Riversdale and its interaction with the river and spring systems, and provided an initial water balance evaluation for the groundwater system. It also identified a number of information gaps and inadequacies in the conceptual understanding of the aquifer systems in some areas.

More recently, Environment Southland has completed a review of the surface water and groundwater relationships in the Mataura catchment above Gore (Wilson, 2007). This study provides a summary of the groundwater – surface water quantity relationships based on monitoring data gathered by Environment Southland over the past five years. The review has been a particularly important resource for the current study.

3. STUDY AREA DESCRIPTION

3.1 Location and topography

The study area is delimited by the Quaternary age fluvial deposits occurring within the mid catchment of the Mataura River between Ardlussa and Gore (Figure 1). The Waimea Plains and Waikaia River valley form the western and eastern boundaries respectively. Topographically, the area is generally flat adjacent to the Mataura and Waikaia rivers, ranging from about 80m amsl at Gore to about 170m around Ardlussa. A series of elevated river terraces occur in the north (Wendonside) and south (Longridge). The plains and terraces are surrounded by the hill ranges of the Hokonui in the south, and Mt Vernon and Mataura Ranges to the north.

3.2 Climate Overview

The Southland Region experiences a temperate climate with rainfall evenly distributed throughout the year, and modest evapotranspiration rates. However, Northern Southland may experience extended periods of below average rainfall. In general, the inland valleys are relatively dry receiving only between 800-1000 mm of rainfall per year. The mean annual rainfall recorded at Riversdale is 807mm.

The study area contains six rainfall stations (Table 1). Representative potential evapotranspiration (PET) data is also available from the NIWA site at Gore.

Name	Easting	Northing	Start	Finish	Duration (years)	Mean Annual Rainfall (mm)
Balfour	2167500	5476600	3-Jan-86	current	21.3	899
Gore PPN	2195800	5448200	1-Aug-86	1-May-01	14.8	952
Mandeville	2184450	5460693	26-Feb-88	current	19.2	876
Riversdale/Liv St	2179575	5470413	*3-Dec-02*	current	4.4	807
Waikaia	2186400	5490000	2-Aug-90	1-May-95	4.7	858
Wendonside	2175500	5487100	1-Jan-85	current	22.3	1026
Gore PET	*2195800*	*5448200*	*3-Jan-72*	*current*	*35.3*	

Table 1: Available rainfall and PET data within the project area.

The temporal rainfall pattern is illustrated by Figure 2 which shows the highest rainfall occurring during summer, and the lowest during winter and spring. There is generally one third less rainfall in the driest month (July) compared to the wettest month (December). Over summer and autumn, the Waimea Plains and Riversdale area receive less rainfall (mean annual rainfall for Liverpool St = 807mm) than the areas surrounding it. This is due to the hot, dry winds of the north-westerly weather systems which occur at this time. North-westerly winds rapidly reduce soil moisture which can lead to localised ‘drought’ conditions (Wilson, op cit).

The spatial and seasonal variability in average rainfall is shown in Figure 3. The four diagrams consistently show that Riversdale experiences a localised low-rainfall micro-climate which has important implications in terms of rainfall recharge.

3.3 Hydrology

The study area encompasses the middle reach of the Mataura River between Gore and Ardlussa (Figure 1). A major tributary, the Waikaia River, is located along the eastern edge of the study area. Both rivers have numerous minor tributaries, including the Waimea and Waikaka Streams. There are also a large number of smaller tributaries such as the Otama Stream, Tomogalak Stream, Otamita Stream and Pukerau Stream.

Environment Southland operate continuous flow recorders at a number of sites in the middle reaches of the Mataura River catchment. Table 2 lists the recorder sites within or around the study area and shows the 7-day mean annual low flow, five and ten year return period low flow, and lowest flow recorded for each site.

Flow Site	Low Flow Record Starts	7-Day Mean Annual Low Flow	5 Year Low Flow Return	10 year Low Flow Return	Lowest Measured Flow
Mataura River at Parawa	21-Jun-77	5.996	4.75	4.15	3.151
Mataura River at Gore	18-May-77	17.724	16.6	8.85	7.185
Waikaia River at Piano Flat	17-Jul-79	3.108	2.091	1.849	1.589
Waikaia River at Mahers Beach	16-Mar-84	5.794	3.831	3.346	2.443
Waimea Stream at Mandeville	20-Sep-83	0.374	0.276	0.2	0.107

Table 2: Hydrological Monitoring Sites and Low Flow Data (m^3/sec)

Environment Southland also monitor river stage only at Cattle Flat, Pyramid Bridge and in the Meadow Burn.

Figure 4 shows the mean monthly flows for the Mataura River at Parawa (just beyond the northern edge of the study area), and at the downstream end at Gore. Both sites exhibit the same temporal variability in mean monthly flow with the lowest flows occurring between February and April then steadily increasing throughout the year to reach a maximum in October. This pattern reflects the influence of snow accumulation and melt in spring in an alpine catchment. It does not seem to reflect rainfall in the catchment which is lowest between July and September (Figure 2). A similar pattern is exhibited by the Waikaia River at Mahers Beach (Figure 5).

The rivers exhibit distinct patterns of loss and gain to groundwater which is characterised by concurrent gauging flow data. The first of a series of concurrent gaugings were undertaken in 2003 on the Mataura and Waikaia rivers. Further gauging datasets are available for 2005 and 2007. The data have been used to identify and quantify significant gaining and losing river reaches thereby characterise the interaction between surface water and groundwater.

Reach	13/2/ 2003	20/3/ 2003	26/3/ 2003	4/4/ 2003	11/4/ 2003	29/4/ 2003	3/2/ 2005	10/2/ 2005	2/3/ 2006	18/2/ 2007	20/2/ 2007	6/3/ 2007
Mataura River												
Cattle Flat - Ardlussa	-1.157	+0.026				+0.15					-1.344	-0.574
Ardlussa – Riversdale Bridge	-1.864	-1.327		-1.444	-1.365	-1.449		-0.344			-1.193	-1.626
Riversdale Bridge – u/s Waikaia conf.											+0.914	+0.29
Pyramid Bridge – Otama Flat Rd				+0.566	+0.659	+0.203						
Otama Flat Rd – Dillons Rd (minus Meadowburn, Otamita Ck and other tribs)				+0.7	+0.9	+0. 4		+1.0			+1.15	+0.5
Dillons Rd – Otamita Br (u/s conf). Minus Waimea flow.					+0.31	+0.06		-0.668			-0.776	+0.088
Otamita Bridge – Gore *assumed flow in Otamita Stm 0.2m3/sec					-0.4*	+1.0*		+0.8*		+1.3*	+2.335	+2.3*
Waikaia River												
Mahers Beach – Freshford (minus Garvie Burn)											+0.032	-0.2
Mahers Beach – Waipon. Bridge *assumed flow at Garvie Burn 0.15m3/sec				+1.6*	+1.2*	+1.3*	+2.9*				+1.05	+0.56*
Freshford – Waipon. Bridge											+0.88	+0.7
Waipon. Br – Mataura Riv conf							+0.56				+0.98	+0.71

Table 3: Summary of concurrent flow gauging data for the Mataura and Waikaia rivers

Table 3 summarises the available concurrent flow gauging data from 2003 to 2007 to show the amount of river flow gain or loss between gauging sites. Locations of the gauging sites are shown on Figure 6.

The Mataura River between Cattle Flat and Riversdale Bridge looses about 1.5m^3/sec of its flow to groundwater (recharging the Riversdale groundwater zone), but then gains flow from groundwater drainage between Riversdale Bridge and Gore. Gauging work carried out in February and March 2007 show a gain in flow between Riversdale Bridge and Dillons Road of 1.6 and 2.3 m^3/sec when the Mataura flow at Dillons Road was 15 and 11 m^3/sec respectively. Below Dillons Road, the Mataura River seems to either loose or gain to groundwater depending upon seasonal fluctuations in relative groundwater and river level.

There are only three sets of concurrent gaugings on the Waikaia River which were carried out between 2005 and 2007. Despite the limited dataset, the results show there is significant flow gain over the reach between Mahers Beach and the Mataura River confluence (accounting for inputs from tributaries). The net gain is approximately 2m^3/sec when the Waikaia at Mahers Beach is at the 7-day MALF. During prolonged dry periods, this appears to reduce to about 1.3m^3/sec. At least 50% of the net gain in flow occurs in the short reach of the Waikaia River between Waipounamu Bridge Road and the confluence with the Mataura River, as shown in Table 4. This is probably due to the groundwater discharge from the Waipounamu Groundwater Zone.

Waikaia River Reach	Length (km)	Nett Flow Gain (L/sec)	Groundwater Drainage (L/sec/km)
Mahers Beach to Pyramid – Waiparu Road	4.3	32	7
Pyramid – Waiparu Road to Waipounamu Bridge Road	13.1	967	74
Waipounamu Bridge Road to Mataura River confluence	3.5	982	284

Table 4: Groundwater Drainage in the Waikaia River (based on 20-Feb-07 gaugings when Mahers Beach flow was 5.78 cumecs). Source: Wilson 2007

4. HYDROGEOLOGY

4.1 Conceptual Hydrogeology

Holocene and late Quaternary age fluvial terrace deposits comprise the principal aquifer unit in the study area. These are underlain by a Tertiary mudstone/sandstone/conglomerate /lignite sequence exhibiting poor groundwater resource potential. Together, these sediments fill structurally-controlled basins formed within the underlying basement Mesozoic sequence. Figure 7 shows an extract of the 1:250 000 scale geological map (Sheet 20; Murihiku) for the region.

The fluvial Late Quaternary sequence is dominated by moderately to poorly sorted gravels, with sand and silt. The younger post-glacial deposits (oxygen isotope ages Q1 and Q2-4) form low-lying terraces adjacent to the modern day courses of the Mataura and Waikaia rivers. These host a relatively thin (<20m thick) highly permeable unconfined aquifer. By contrast, the bounding older, higher terrace sequences (Q6 and Q8 surfaces in Figure 7) are the product of uplift and river entrenchment. These are comprised of considerable thickness of alluvial sediments and generally tend to have a much lower groundwater resource potential, being more compact and highly layered. The thick terrace deposits are regarded to contain a multiple aquifer sequence, from unconfined near the surface, to confined at depth. The Wendonside Terrace is a good example of a Q6 age elevated terrace.

Underlying Tertiary sediments exhibit low permeabilities and effectively form a 'groundwater basement' to the overlying Quaternary aquifer sequence. The Tertiary Gore Lignite measures of the East Southland Group are encountered at the base of the Quaternary fluvial sequence in the Riversdale area and comprise siltstone, sandstone, conglomerate and thick lignite seams.

The encompassing Mesozoic basement , exposed in the hills surrounding the Mataura plains, comprises a deformed and recrystalised sedimentary sequence with negligible primary porosity. Secondary porosity created by fractures and joints, particularly along major structural trends, may locally enhance the groundwater potential however. Mesozoic basement rises to the surface at Gore thereby 'closing' the upstream Quaternary groundwater basin.

The lower lying terrace sequences (Q1-Q4) adjacent to the Mataura and Waikaia rivers are intimately connected with the surface water environment and complex flow transfers occur between the rivers and aquifers adjacent to both the Mataura and Waikaia rivers. Highly permeable palaeochannels within the aquifer probably facilitate much of these flows. These aquifers are very productive and are the principal groundwater resource in the study area.

Flow losses from the Mataura River (Section 3.3) provide recharge to the lower terrace aquifers in the northern part of the study area (north of about Riversdale Bridge). The river provides a 'base' aquifer level to which groundwater levels fall during extended periods of low rainfall – the river in effect represents a constant head condition during low flow. Further to the south and above Gore, the Mataura River (and also the Waikaia River) receives discharge from the aquifer and thereby gains flow from 'aquifer drainage'. The aquifer also drains into a prominent spring system below Riversdale – the Meadow Burn being the largest spring-fed stream (c. 100-500 L/sec). The flow transfer rates and flow directions between groundwater and the Mataura River appear to be highly seasonal between Pyramid and Gore - being dependent upon the relative head gradients between the aquifer and the river. All groundwater in the Late Quaternary and Holocene aquifers must drain back to surface water above Gore since the basement rises to surface at Gore preventing any groundwater throughflow downstream. The groundwater basin is therefore a 'closed' system and all inputs from river flow and rainfall recharge to the Quaternary aquifers in the mid-Mataura catchment must balance the outflow in the Mataura River at Gore (minus net losses to groundwater and surface water abstractions).

Rainfall recharge is an important process which causes seasonal fluctuations in regional groundwater levels and provides an 'active' storage component above the river base levels. Rainfall infiltration is the principal recharge mechanism on the higher terrace surfaces (such as Wendonside). These terraces discharge slowly to the adjacent lower terrace sequences and ultimately to the river systems.

4.2 Aquifers and Groundwater Management Zones

Environment Southland has divided the fluvial terrace aquifers in the mid Mataura catchment into a number of groundwater management zones as shown in Figure 8. The zones, delineated on the basis of geological and hydrogeological characteristics, are hydraulically interconnected to variable degrees.

The study area and groundwater model domain incorporates six of the management zones – Riversdale, Waipounamu, Wendon, Wendonside, Knapdale and Longridge. It also partially covers the Waimea Plains and Cattle Flat zones. A brief description of the characteristics of each zone follows:

Riversdale Zone

The Riversdale groundwater zone covers about 10,300ha and occupies the recent floodplain terrace on the true right bank of the Mataura River between Ardlussa and the Otamita Bridge. The north-eastern zone boundary coincides with the main channel of the Mataura River and is a hydraulic recharge/discharge boundary. The south-western boundary with the Longridge and Waimea Plains groundwater zones follows the prominent Q8 alluvial terrace which marks the outer boundary of the Mataura floodplain. This boundary marks a significant change in formation hydraulic conductivity from the very permeable Riversdale zone gravels to the compact older terraces to the west. Flows across it are therefore regarded to be somewhat restricted. The outcrop of lignite measures (Meg) at the base of the Londgridge terrace (Figure 7) suggests that this zone has no hydraulic connection with the Riversdale zone and that groundwater discharges into springs before they cross onto the Riversdale plains.

The gravel deposits in the Riversdale Zone comprise moderately to poorly sorted gravel, clay-bound gravel, sand and silt, and extend to a depth of up to about 25m to the west of Riversdale village, but reduce to less than 10m towards Mandeville. Generally, the depth to the water table is less than 2m, varying within a 1m range in response to seasonal rainfall recharge patterns. These gravels generally have a very high permeability, as evident by the large scale irrigation in this zone, although there is some variability which reflects the heterogeneous nature of the gravels

Recharge to the Riversdale groundwater zone occurs through a combination of rainfall recharge and river recharge. There is also minor throughflow from the Waimea Plains groundwater zone.

Groundwater level fluctuations reflect the two major components of aquifer recharge. Flow loss from the Mataura River provides a ‘base’ aquifer level to which groundwater levels fall during extended periods of low rainfall, while rainfall recharge provides an ‘active’ storage component. During the winter months rainfall recharge events occur relatively frequently resulting in an overall increase in aquifer storage volume. During summer and autumn when soil moisture is below field capacity, groundwater levels gradually decline as water is progressively drained from the aquifer system.

Recharge from the Mataura River occurs upstream of Riversdale Bridge and has been observed to increase as the water table drops and the head gradient between the river and the aquifer steepens.

Groundwater discharge from the Riversdale groundwater zone occurs into the Mataura River and via five major spring-fed streams; the largest is the Meadow Burn. Discharge in the Meadow Burn increases progressively downstream reflecting the local drainage of groundwater from the surrounding unconfined aquifer.

Waipounamu Zone

The Waipounamu groundwater zone covers an area of about 3,200ha over the lower floodplain terrace on the northern side of the Mataura River between Ardlussa and the Waikaia River confluence. The northern boundary follows the base of the large elevated Wendonside gravel terrace to the north, while the southern boundary follows the Mataura River. This zone is comprised of coarse alluvial gravel and sand that forms a highly permeable unconfined aquifer which is hydraulically connected to the Mataura River. Recharge to the Waipounamu groundwater zone is dominated by leakage from the Mataura River and direct rainfall infiltration. Throughflow from the Wendonside terrace groundwater zone is regarded to be minor. Discharge from the zone occurs principally into the Mataura River and through the Wendon groundwater zone into the Waikaia River.

Wendon

The Wendon groundwater zone encompasses the floodplain terrace adjacent to the Waikaia River. The eastern boundary follows the base of the Umbrella Range including the Wendon Stream and Pyramid Creek catchments, while the western boundary follows the base of the large remnant Quaternary gravel terrace which forms the Wendonside groundwater zone. The sediment deposits of the Wendon groundwater zone are relatively poorly sorted containing a much higher percentage of fine mud and silt in the gravel matrix. In some locations semi-confined aquifer conditions are exhibited due to the presence of laterally continuous clay-bound gravel layers. The significant difference in the character of the gravel deposits of the Wendon compared to the Waipounamu groundwater zones may reflect the schistose geology of the Waikaia catchment compared to the greywacke-dominated headwaters of the Mataura catchment (Wilson, 2007).

Wendonside

The elevated Wendonside groundwater zone is comprised of mid-Quaternary (Q8 and older) compact gravels which have a much lower permeability than the more recent gravels in the Waipounamu and Riversdale groundwater zones. The thickness of the gravel deposits in the Wendonside groundwater zone is significantly greater than beneath the lower terraces and is highly variable and layered. Confined groundwater conditions occur at depth, and there is evidence that shallower aquifers are perched above the lower terrace (Waikaia, Waipounamu and Riversdale) aquifers. There is also evidence to suggest the occurrence of more permeable paleochannels running in a north-west – south-easterly direction.

Knapdale

The Knapdale groundwater zone encompasses the floodplain on the eastern side of the Mataura River between Pyramid and Gore. The northern boundary follows the large terrace that marks the older Quaternary gravel terrace remnants along the southern margin of the Chatton groundwater zone. The downstream extent zone occurs at Gore where the river is confined to a narrow channel cut into the basement rock of the Murihiku Terrane which comprises the Hokonui Hills. The aquifer thickness in the Knapdale groundwater zone becomes very thin towards Gore (<10m) and basement siltstones outcrop in the river bed near the town.

Cattle Flat

The Cattle Flat groundwater zone encompasses the narrow, confined valley upstream of Ardlussa to the Nokomai Gorge. There are few bore logs available for the area and even fewer pumping test data so aquifer yields and lithology are largely uncertain. The aquifer appears to consist of a sequence of sandy gravels overlying claybound gravels. While there is likely to be a significant degree of interaction between the Mataura River and adjacent riparian aquifer, throughflow to the Riversdale and Waipounamu groundwater zones is probably limited due to the channelling of the river between two basement outcrops immediately upstream of Ardlussa.

4.3 Regional Groundwater Flow Pattern

A regional groundwater level survey was conducted in March 2004 by Environment Southland. Figure 9 shows the water table map produced using this data to characterise the regional flow system. Regional groundwater flow occurs to the south-east, generally parallel to the Mataura River. The water table contours indicate no flow across the boundary between the Riversdale Zone with the Longridge and Waimea zones, and little flow between the Waipounamu and Wendonside zones (they intersect these boundaries at right angles). The hydraulic gradient through the Riversdale, Waipounamu, Wendon and Knapdale lower terrace zones is relatively low reflecting high hydraulic conductivity.

The Knapdale zone shows a more complex groundwater flow pattern with possible recharge sources occurring from side valleys to the north, such as the Otama Stream. Flows in this zone appear to focus on the Mataura River.

Groundwater levels and gradients within the older Wendonside terrace appear much higher with flow generally towards the Waikaia River. This is consistent with the lower hydraulic conductivity of the older terrace deposits. Monitoring bores are also probably screened within deeper confined aquifers which have limited connection with the water table.

4.4 Groundwater Levels

The Environment Southland groundwater monitoring network was established in 2000 and has since gradually been expanded in response to increasing resource utilisation. Table 5 shows a summary of the key monitoring bores in the study area.

Well Number	Grid Reference	Record Start Date	Monitoring Interval	Aquifer Type
Wendonside Groundwater Resource Zone				
F44/0018	F44:785-859	17-May-01	Monthly	**Unconfined (perched)**
F44/0069	F44:784-831	30-Sep-02	Monthly	**Confined**
F44/0139	F44:788-828	25-Mar-03	Monthly	**Unconfined**
F44/0077	F44:766-831	17-Jun-03	30 mins	**Semi-confined**
Waipounamu Groundwater Resource Zone.				
F44/0199	F44:830-733	24-Feb-04	Weekly	**Unconfined**
F44/0214	F44:812-744	06-Dec-04	30 mins	**Unconfined**
Longridge Groundwater Resource Zone				
F44/0006	F44:714-748	17-Mar-00	Monthly	**Unconfined**
Riversdale Groundwater Resource Zone				
F45/0167	F45:821-657	14-Sep-00	Monthly	**Unconfined**
F45/0181	F45:986-575	03-Dec-02	30 mins	**Unconfined**
F45/0174	F45:793-697	14-Sep-00	Monthly	**Unconfined**
F45/0370	F45:854-602	12-Feb-04	Monthly	**Unconfined**
Knapdale Groundwater Resource Zone				
F45/0172	F45:902-606	14-Sep-00	Monthly	**Unconfined**
F45/0168	F45:966-526	14-Sep-00	Monthly	**Unconfined**
Wendon Groundwater Resource Zone				
F44/0088	**F45:834-778**	**24-Feb-04**	**30 mins**	**Unconfined**

Table 5: Groundwater Level Monitoring Sites

Groundwater levels are generally highest during spring and lowest in autumn and appear to be closely controlled by the Mataura River as shown in Figure 10 which shows the groundwater level hydrograph for F44/081 (Liverpool Street) in the Riversdale groundwater zone, and also the Mataura River stage (measured at Parawa).

It is interesting to note that groundwater levels measured in monitoring wells sited some distance from the river, such as F44/0181 in Riversdale (some 3,200m from the river), closely mimic river stage.

Figure 11 shows a six-month detail for the F44/0214 hydrograph (Waipounamu groundwater zone) and the Mataura River stage. The plot demonstrates the presence of a relatively small time lag of 5-6 days between the peak in river stage and corresponding peak in groundwater level.

Elevated terrace aquifers (Longridge and Wendonside groundwater zones) are not in direct hydraulic connection with surface water systems but are important in maintaining surface water flows through springs formed at the base of the terrace where the water table intersects the land surface. These aquifers are recharged entirely by rainfall so groundwater levels mirror rainfall and soil moisture patterns. The magnitude of seasonal groundwater level fluctuations observed in terrace aquifers ranges from two to five meters depending on rainfall variability and spatial location of the monitoring bore within the aquifer system. Variability tends to decrease towards the terrace margins due to the constant head provided by spring discharge. Representative hydrographs for the Wendonside terrace are shown in Figure 12.

4.5 Aquifer Properties

Aquifer test data compiled from resource consent applications has enabled a general assessment of the hydraulic characteristics of the aquifers in the Riversdale, Waipounamu and Knapdale groundwater management zones. The data are however sparse in some areas, and interpreted transmissivity values are highly variable reflecting the heterogeneous nature of the fluviatile sediments. None of the tests are suitable for the derivation of a specific yield. Table 6 lists the available test interpretations in these zones.

Well Number	Easting	Northing	Q_{max} (m^3/day)	Transmissivity m^2/day
Riversdale				
F44/0080	2182902	5470444	4500	1,189
F44/0184	2176922	5473622	6220	1,250
F44/0059	2177761	5472427	2970	1,250
F44/0026	2180185	5472575	2938	650
F44/0113	2179223	5472618	4406	700
F44/0206	2179400	5473300	4752	8,000
F45/0419	2184260	5465320	4555	500
F45/0420	2183468	5467098	4555	750
F44/0218	2181920	5471752	3750	850
F44/0205	2179500	5471300	635	810
F44/0207	2179560	5471430	635	2,900
F45/0402	2184700	5463500	3572	750
F45/0403	2185131	5463465	3572	750
F44/0014	2177743	5470850	346	1,250
F44/0183	2176880	5473105	3560	1,600
F44/0223	2177400	5474400	2745	3,000
F45/0433	2184500	5464500	5270	8,582
F45/0452	2182000	5467900	3285	2,100
F44/0236	2177566	5471397		2,880
Waipounamu				
F44/0200	2181500	5473700	8380	12,000
F44/0217	2182298	5473343	3862	4,300
F44/0201	2180550	5474451	5214	21,000
F44/0075	2176976	5479702	2160	15,000
F44/0138	2173381	5480431	8470	15,000
F44/0198	2182467	5474184	182	10,000
F44/0109	2182349	5473984	182	10,000
F44/0228	2178563	5478665	6912	4,540
Knapdale				
F45/0398	2196200	5450400	1500	250
F45/0397	2196200	5450300	1500	250
F45/0394	2195717	5452285		50
F45/0463	2195791	5452168	5000	50
F45/0424	2191497	5457093	1650	3,830
F45/0458	2191100	5456700	1300	470
Wendon				
F44/0193	2191497	5457093		100
F44/0216	2191100	5456700		785

Table 6: Transmissivity values derived from pumping tests in the Riversdale, Waipounamu, Knapdale and Wendon groundwater management zones.

The data listed in Table 6 are spatially represented in Figure 13. Although there is a high degree of variability, Figure 13 shows that the Riversdale and Knapdale groundwater zones seem to have a similar transmissivity range of about 1,000-3,000m^2/day. This equates to a hydraulic conductivity of approximately 200-300m/day assuming partially penetrating wells sourcing water supplied by a 10m thick aquifer profile.

Higher transmissivity values are evident from the few aquifer tests in the Waipounamu groundwater zone where a range of 5,000-15,000m^2/day is observed - with one value at 21,000m^2/day (F44/0201). The hydraulic conductivity of the Waipounamu groundwater zone may therefore be double that of the Riversdale zone, although more data are required to confirm this. This could relate to the occurrence of recent Mataura palaeochannels between the present-day channel and the base of the Wendonside terrace.

Due to the heterogeneous nature of the aquifer deposits and consequent high variability in transmissivity values derived from pumping tests, a 'bulk' hydraulic conductivity value for each zone is regarded to be more representative for resource analysis purposes.

4.6 Groundwater Recharge and Discharge

4.6.1 Rainfall Recharge

Rainfall recharge is a major component of the water balance for the unconfined aquifer systems in the study area and quantification has been undertaken using a soil moisture balance method.

Climate data & rainfall distribution modelling

The investigation area contains six rainfall stations (Table 7). Representative potential evapo-transpiration (PET) data is available from the NIWA site at Gore.

Name	Easting	Northing	Tideda Number	Start	Finish	Duration (years)
Balfour	2167500	5476600	588511	3-Jan-86	1-Apr-07	21.3
Gore	2195800	5448200	681802	1-Aug-86	1-May-01	14.8
Gore PET	2195800	5448200	6819019	3-Jan-72	1-Apr-07	35.3
Mandeville	2184450	5460693	589710	26-Feb-88	10-May-07	19.2
Riversdale	2179575	5470413	401810	*3-Dec-02*	10-May-07	4.4
Waikaia	2186400	5490000	587801	2-Aug-90	*1-May-95*	4.7
Wendonside	2175500	5487100	587711	1-Jan-85	1-Apr-07	22.3

Table 7: Rainfall and PET data used for the recharge model.

Two of the rainfall sites, Waikaia and Mandeville, required an extension of the rainfall record in order to coincide with the groundwater model calibration interval by developing synthetic records using a linear regression with the intercept set to zero (Table 8).

Weekly Totals	Waikaia-Piano Flat	Riversdale-Mandeville
Coefficient	0.9077	0.8348
R^2	0.78	0.82
n	133	231

Table 8 Relationships used to extend the rainfall record at sites where the dataset is incomplete

Thiessen polygons were constructed to calculate the area of influence around each rainfall recorder site (Figure 14). Each polygon represents the area closest to its relevant site. To test whether the polygons should be weighted for orographic effects, the polygons were compared with contoured isohyets for the region. The comparison showed that Thiessen polygons adequately represent the rainfall distribution over the area.

Table 9 shows the mean monthly and annual rainfall statistics for each rainfall site. The data are also exhibited graphically in Figure 15.

Polygon	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Wendonside	101	99	90	79	87	80	60	69	64	87	99	104	1026
Riversdale	71	67	72	61	65	78	42	57	47	56	66	118	807
Mandeville	77	75	74	68	82	79	55	61	59	71	84	90	876
Gore	106	84	80	69	90	73	58	62	58	75	84	103	952
Balfour	125	78	91	64	75	67	67	70	55	70	65	103	899
Waikaia	89	59	49	67	71	79	46	67	59	80	94	96	858

Table 9: Mean monthly and annual rainfall for Theissen polygons

Soil Properties

Soil property data for the soil moisture balance was taken from the Southland Regional Council GIS database. The database separates the soils into four available water classes: Low/Moderate/Moderate-High/High. Table 10 shows the correlation between these classes and soil type, infiltration class and other soil parameters used in the soil moisture balance model (discussed below). Figure 16 shows broad soil drainage classes within each of the six Thiessen polygons.

Available water	Series	Soil type	Infiltration	TAW	RAW	FRACSTOR	SCS drainage group	SCS curve number
Low	Oreti	Stony fine sandy loam	Rapid	35	15	0.4	A	45
Moderate	Gore, Kaweku	Stony silt loam	Mod-rapid	50	25	0.55	B	55
Mod-high	Mataura, Fleming	Silt loam	Mod-slow	100	50	0.6	C	65
High	Otama, Otaraia	Silt loam to loamy silt	Slow	150	75	0.65	C	75

Table 10: Soil properties used for the soil moisture balance model.

Recharge Model

The recharge model is based upon a soil moisture balance method described by Rushton et al (2006). The 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 - parameters which depend on soil properties and the effective depth of the roots. The model introduces a new concept, near surface soil storage (FRACSTOR), to account for continuing evapotranspiration on days following heavy rainfall even though a large soil moisture deficit exists. The base data required for the soil moisture balance model are daily rainfall and potential evapotranspiration. Total and readily available water (TAW and RAW) for soil groups are also required.

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 has also been adapted for this study to take into account runoff using a the USDA Soil Conservation Service (SCS) runoff curve number model. The SCS runoff model is described in Rawls et al (1992).

Spreadsheet calculations for soil moisture balance have been set up to follow the algorithms given in the appendix of Rushton et al. (2006). The calculation involves 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) and *SOILSTOR* from the previous day.

3. Estimation of actual evapotranspiration (AET). PET is derived by the Penman-Monteith equation (Allen et al., 1998). A crop coefficient is not applied since the crop is assumed to be pasture (which is the reference crop for the Penman-Monteith equation). Most pastures in New Zealand 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 set to 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 daily soil moisture deficit. These parameters are described below, while values used for the Southland model are given in (Table 10).

SCS Curve Number: A curve number needs to be estimated for each soil, which is used to calculate maximum soil retention of runoff (this is the same method used for the HortResearch SPASMO model). The lower the curve number, the greater the soil retention threshold, which results in 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). The Southland model assumes that slope is always less than 5 degrees, and soil moisture is not considered.

Total Available Water (TAW): TAW is calculated from field capacity, wilting point, and rooting depth data. Typical values for field capacity and wilting point are given in Table 19 of Allen et al. (1998).

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 ET). For NZ conditions *p* should be around 0.4 to 0.6, typically 0.5 for grass. See Table 22 of Allen et al. (1998) for more values.

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, 2006, pg 388).

Note that values of TAW and RAW are specified as a range of representative values in the Environment Southland database. Values used in the recharge model are the mean of this range.

Recharge Model Outputs

The results of the recharge modelling are summarised in Table 11 and Figure 17 for dominant soil drainage classes within the main Theissen polygons. Also shown for comparison are recharge values calculated by Lincoln Environmental (2005) which lie in the same range as the Rushton model predictions.

Groundwater Management Zone (Theissen Polygon)	Rushton Model (this Study)	% Mean annual rainfall	Lincoln Recharge
Riversdale/Waipounamu (Riversdale Polygon)	201-227	25-28	281
Knapdale (Mandeville+Gore Polygons)	179-276	20-30	254
Wendonside (Wendonside Polygon)	285-380	27-36	315
Wendon (Waikaia+Riversdale Polygons))	170-228	21-28	205

Table 11: Summary recharge calculations using 'Rushton model'

The model outputs show that there is very little recharge between September and March/April. Although rainfall is higher during these month (see Figure 17), potential evapotranspiration is also high. The highest recharge occurs during May and June, with lower quantities in July and August corresponding to a decline in rainfall.

4.6.2 Recharge from Hardrock Catchments

Streams flowing off peripheral hardrock catchments often loose significant flow into alluvial fan deposits in many parts of the Southland Region. SKM (2005) suggest that hardrock catchments to the north of the Wendonside and east of the Wendon groundwater zones may provide additional recharge (i.e. side fluxes) into these zones. Since the catchments of these smaller catchments are largely impermeable, most rainfall is partitioned into runoff and when these streams reach the alluvial terraces they may recharge the aquifers. The Boundary Creek (which flows across the Wendonside Terrace) is a good example where the stream flow disappears a short distance after crossing the Wendonside gravels. Quantification of this recharge mechanism is difficult and has been attempted by SKM (2005), although no details of the methodology are documented.

It appears that the principal streams which may provide recharge input to the Wendon and Knapdale aquifers include the Wendon Stream, Pyramid Creek and the Otama Creek. SKM (op cit) calculate that the Wendon Creek, by far the largest side-flux recharge source, may supply over 50,000m^3/day of recharge into the Wendon groundwater zone.

4.6.3 River Recharge

Recharge from the Mataura River above Riversdale Bridge is regarded to be a dominant component of the groundwater balance for the Riversdale and Waipounamu groundwater zones. Section 3.3 and Table 3 provide a summary of the gauged losses (recharge) to groundwater. The Mataura appears to loose about 1.5m^3/sec to groundwater above Riversdale Bridge. Seasonal recharge to the shallow gravels in the Knapdale groundwater zone is also evident from the concurrent gauging data.

4.6.4 Groundwater Discharge

The lower part of the mid-Mataura catchment, east of about Riversdale village, is characterised by groundwater discharge (Figure 18) in the form of springs or groundwater discharge ('groundwater drainage') into the main river systems. Since the mid-Mataura aquifers above Gore occupy a 'closed groundwater basin' (the bedrock surfaces at Gore), all groundwater must discharge into rivers or springs above Gore.

A prominent spring discharge area occurs in the Riversdale Groundwater Zone between the Mataura and Waimea Plains terrace where several large springs emerge and flow eastwards to join the Mataura River. The total measured discharge from spring fed creeks in the Riversdale groundwater zone totalled 716 L/sec on the 17 January 2003. The largest of these is the Meadow Burn which rises near Riversdale and flows some 6.5km to the river. Smaller springs include the McKellar Stream and other un-named streams.

The Meadow Burn appears to gain flow along most of its length and where it crosses Fingerpost Pyramid Road, monitoring shows a variable flow of between 100-500 L/sec at this location (Figure 19). Gaugings near the source of the Meadow Burn in Riversdale during the 2006/07 summer show as groundwater levels drop (below 126.12 metres amsl in F44/0181), the Meadow Burn maintains a fairly constant discharge of 25 L/sec near its origin. Gauging near to the confluence of the Mataura River at Round Hill Road indicate a flow of 300-1000 L/sec – although there is no high flow data at this site because the Mataura River back-flows into the Meadow Burn during high flow events.

The Garvie Burn transects the Wendonside terrace along with numerous other streams which drain the southern slopes of the Garvie Mountains. These streams dry up almost immediately upon emerging onto the Wendonside terrace, presumably recharging the underlying aquifer. The Garvie Burn is the single major tributary in the Waikaia River catchment downstream of Mahers Beach. Available gaugings indicate a summer flow in the order of 100-200 L/sec near the confluence with the Waikaia River. A single set of concurrent gaugings on 1/2/2007 show it is a gaining stream, with 76 L/sec measured at Hurley Road near the base of the mountains, and 248 L/sec near the Waikaia River confluence.

4.7 Groundwater Abstractions

Table 12 shows the consented abstraction wells in the study area and the maximum consented pumping rate (Qmax) for each well. The maximum consented abstraction from groundwater in the study area is shown to be nearly 100ML/day (100,000m^3/d).

Seasonal abstraction for irrigation is regarded to occur over a 150 day period between November and March. For initial modelling purposes, in the absence of metering data, the first three months of seasonal abstraction are assumed to occur at about one-third of the maximum consented rate (Qmin), whilst abstraction in the remaining two months occurs at Qmax.

Well ID	GW Zone	Start Month	Qmax	Qmin
F44/0026	Riversdale	2/02	2831	1051
F44/0080	Riversdale	11/02	4500	1500
F44/0184	Riversdale	11/04	6220	2073
F44/0113	Riversdale	2/02	4406	469
F44/0059	Riversdale	11/99	2970	990
F45/0419	Riversdale	11/04	4555	1518
F45/0420	Riversdale	11/04	4555	1518
F44/0218	Riversdale	11/04	3570	1190
F45/0289	Riversdale	9/03	140	140
F45/0353	Riversdale	10/02	113	113
F44/0014	Riversdale	11/00	346	115
F44/0183	Riversdale	11/05	3560	1186
F44/0223	Riversdale	11/05	2745	915
F44/0097	Riversdale	3/01	173	173
F44/0056	Riversdale	10/02	224	224
		Sum Riversdale Zone	***40908***	***13175***
F44/0200	Waipounamu	11/04	8380	2793
F44/0201	Waipounamu	11/04	5214	1738
F44/0217	Waipounamu	11/04	3862	1287
F44/0075	Waipounamu	11/04	2160	720
F44/0138	Waipounamu	11/05	8470	2823
F44/0228	Waipounamu	11/06	6912	2304
F44/0109	Waipounamu	11/04	182	182
		Sum Waipounamu Zone	***35180***	***11847***
F44/0193	Wendon	11/04	3600	1200
F44/0216	Wendon	11/04	3600	1200
F44/0209	Wendon	11/03	1750	583
F44/0215	Wendon	11/03	1750	583
		Sum Wendon Zone	***10700***	***3566***
F45/0398	Knapdale	6/99	1500	1500
F45/0397	Knapdale	6/99	1500	1500
F45/0424	Knapdale	2/06	1650	1650
F45/0458	Knapdale	2/06	1300	1300
F45/0394	Knapdale	6/99	1913*	277*
F45/0463	Knapdale	6/99	1984*	1020*
		Sum Knapdale Zone	***9847***	***7247***
SUM ABSTRACTION m^3/day			**96,635**	**35,835**

*actual data from meter

Table 12: Consented Abstraction Wells

Qmin and Qmax = estimated maximum and minimum pumping rates for irrigations wells in m^3/day.
Qmax = maximum consented rate (m^3/day).

Figure 20 illustrates the estimated abstraction from the area between 1999 and 2007.

5. NUMERICAL MODELLING

5.1 Model Code

The USGS finite difference numerical code MODFLOW (McDonald and Harbaugh, 1988) was used to model the mid-Mataura aquifers. The 'Visual Modflow' data processing interface (Waterloo Hydrogeologic, 2006) was used to build the model, prepare input files, and process the output data.

5.2 Grid Design

MODFLOW uses a finite difference solution method that requires the use of a rectilinear, block-centered spatial grid and one or more layers. The model developed for the mid-Mataura aquifers has a grid domain of 47 x 30km, an active grid area of about 470km^2, and uniform cell size of 200m^2. The grid has been aligned to the principle northwest-southeast groundwater flow vector and parallel to the main reaches of the Mataura River upstream of the Waikaia River confluence and downstream of the Waimea Stream confluence.

The active model domain is delineated by the contact of the Quaternary age fluvial terrace deposits with Mesozoic and Tertiary age basement material, except along the south-western edge where the model boundary coincides with a topographic and hydrological divide. Figure 21 shows the model boundary and grid orientation.

5.3 Layer Configuration

The aquifers are represented by a single model layer and therefore only the aquifer base elevations and land surface topography are required. The aquifer base surface was generated using bore log data where the aquifer base was encountered. Such bores are located in the Riversdale, Knapdale and Waipounamu groundwater zones and therefore greater confidence in the modelled aquifer thickness can be attributed to these areas. Elsewhere, a conceptual interpretation of the Mataura River palaeo-topography was used. Figure 22 shows the modelled aquifer base.

The layer top elevation was derived from the LINZ 20m topographical contours supplemented by accurate elevation survey data for well locations and survey transects undertaken by Environment Southland.

The two surfaces allow the modelled gravel thickness to be visualised as shown in Figure 23. The layer represents the unconfined groundwater system to a thickness of about 30m in the Riversdale and Waipounamu groundwater zones, and up to 60m in thickness beneath the higher Wendonside terrace. In the Knapdale Zone, the gravel thickness appears to reduce significantly to 10m or less.

Layer 1 is assigned an unconfined (Modflow Type 1) aquifer condition.

5.4 Boundary Conditions

5.4.1 Rivers: Stream Boundary Type (STR).

River stage elevation is a critical model input parameter which controls groundwater-surface water fluxes and ultimately, the groundwater balance for the lower river terrace aquifers. It is therefore important to ensure that river stage data is assigned accurately to the stream boundary cells.

River boundaries have been simulated using the MODFLOW STR1 Package. Surveyed bed profiles of the Mataura and Waikaia rivers and river stage gauging data were used to assign the stage heights and gradients.

The river profiles were then divided into reach segments based the bed slope. Figure 6 shows the locations of the bed survey cross sections and the locations of gauging sites which were used to identify the riverbed morphology and divide it into a number of segments of equal gradient. Table 13 lists the gradient segments for both rivers, showing an example stage height for 7/6/1999.

	Location	Stage Height	Bed Height
Mataura River			
Seg1_startStage	Model edge/Bed Sect 93	185.769	182.615
Seg1_endstage	Bed Sect 86	164.901	163.745
seg2_endstage	Ardlussa	157.826	156.347
seg3_endstage	Morfield Farms	137.75	136
seg4_endstage	Pyramid	113.184	111.13
seg5_endstage	Bed Sect 31 Monaghans Beach	79.309	78.255
seg6_endstage	Gore	68.76	67.612
Waikaia River			
Seg1_startStage	u/s Mahers Beach	148.047	146.75
Seg1_endstage	Mataura confluence	119.75	119

Table 13: Modelled constant gradient segments on the Mataura and Waikaia rivers

Stage data are recorded at Parawa, Cattle Flat and Pyramid Bridge on the Mataura River, and at Waikaia and Mahers Beach on the Waikaia River. Environment Southland also maintain a manual gauging database with surveyed stage elevations.

Time series stage data for the Mataura River has been derived principally from the continuous flow record at Parawa (slightly upstream of the model edge) and Gore, supplemented by data from Cattle Flat and Pyramid Bridge, and also checked against other spot measurements. The surveyed bed gradients and river stage heights were used to extrapolate the transient stage data between the gauging sites. Stage data were averaged over the model stress periods (7 days).

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

$$C = K L W / M$$

The river width varies between about 20m and 30m based upon the estimated average river widths for each reach. Streambed vertical hydraulic conductivity values were originally set at 10m/day for all rivers which appeared to allow the correct (observed) flows between groundwater and the rivers. The vertical conductivity values derived during calibration equates to the streambed conductance of about 10,000-20,000m^2/day per 200m^2 grid cell.

5.4.2 Springs: Drain Boundary Type (DRN).

The major spring systems in the Riversdale groundwater zone have been simulated using the MODFLOW Drain (DRN) boundary condition. This type of boundary will only permit water to be taken out of the aquifer when the water table is modeled above the base of the drain cell (the spring elevation). When the water table drops below the base of the drain cell, flow into the spring ceases. Flow from the aquifer to the drain cells (spring flow) is controlled by the value used for the drain bed conductance and the drain bed elevation. The drain bed elevations were derived from survey data for the Meadow Burn and McKellar Stream. Levels for other springs were derived from the nearest spot height survey data or the topographic map. Bed conductance values were obtained through a trial and error process during calibration.

Figure 24 shows the surveyed 11km bed profile for the Meadow Burn from its source near York Road to the confluence with the Mataura River. Three distinct bed gradient segments are evident which have been used to set the drain boundary elevations in the model.

5.4.3 Abstraction Wells

Table 12 lists 32 consented wells within the model area extracting more than 10 L/sec. These have been incorporated into the model and pumping schedules created for each one, commencing when each particular abstraction was consented. The majority of wells abstract seasonally for irrigation purposes and it is assumed that abstraction occurs over five months between November and April with the abstraction rates occurring at about one third the maximum consented rate for the first two months, thereafter at the full consented abstraction rate until the end of the irrigation season. The combined pumping schedule used in the model shown in Figure 20. The locations of the abstraction wells are shown in Figure 25.

5.4.4 Rainfall Recharge

Section 4.6.1 describes the methodology adopted for calculation of rainfall recharge based on the Rushton model. Some 23 recharge zones have been delineated using the rainfall Theissen polygons and soil drainage classes as shown in Figure 26. Table 10 shows the soil parameters used for each soil class. Time series recharge data, averaged over each 7-day stress period, have been produced for each recharge zone.

5.5 Material Properties

The alluvial terrace aquifers are highly heterogeneous and probably possess a strong anisotropy resulting from fluvial depositional processes. The most appropriate way to represent such systems numerically is through defining areas of uniform hydraulic conductivity since the heterogeneity cannot be adequately characterised using the limited geological and aquifer testing data available. The groundwater model therefore assumes homogenous hydraulic conductivity domains based upon the conceptualisation of the area, geology, geomorphology, and upon pumping test data. Figure 27 shows the model hydraulic conductivity zones. Section 4.5 provides a discussion on the available hydraulic conductivity and transmissivity data derived from pumping tests.

Nine hydraulic conductivity zones were used in the model to represent distinct zones and these are shown in Figure 27. The zones correspond to the groundwater zones or mapped boundaries between different age terrace deposits. Table 14 shows the hydraulic conductivity values assigned to each zone following model calibration.

Hydraulic conductivity zone	Calibrated Value m/day	Observed m/day	Specific yield
1	5		0.15
2	100		0.15
3	50	20-50	0.2
4	100	10-80	0.15
5	50		0.2
6	400		0.2
7	700	600-700	0.2
8	300	200-300	0.2
9	300		0.15

Table 14: Calibrated Aquifer Parameters

Table 14 also shows specific yield values derived from published values for sand and gravel aquifers in the range of 15-20%.

6. MODEL CALIBRATION

6.1 Calibration Approach

Model calibration has entailed a two-step process of initial steady state calibration followed by a more intensive transient-time calibration process.

The steady state calibration has the main purpose of testing the conceptual groundwater model. It also provides a check on the boundary conditions and water balance estimation.

Upon satisfactory steady state calibration, further testing of the model under transient stresses has been performed and evaluated against time-varying water level monitoring and river/spring gauging data. The transient calibration involves input parameter adjustments and sensitivity analysis.

Calibration of the mid-Mataura groundwater model has involved the iteration of several stages of parameter estimation:

- Initial estimation of aquifer parameters and recharge within the ranges identified from field measurements and calculations, and manual (forward) steady-state calibration.
- Modification of parameters and manual calibration (forward) against steady-state groundwater levels in monitoring wells, and to water balance measurements (river losses and gains).

6.2 Calibration Targets

6.2.1 Steady state

Steady state calibration was initially performed using average groundwater level data. A full concurrent groundwater level monitoring dataset undertaken in March 2004 has been used to produce a representative (average) water table map for late summer conditions in the model area. This dataset is assumed to portray a 'pseudo' steady-state condition suitable for model calibration purposes.

Figure 9 shows the contoured groundwater level data for March 2004. In general, although there are small vertical gradients in most areas, when plotted together the data show a consistent flow pattern across the area. Further discussion of the regional flow regime is provided in Section 4.3.

Measured flow losses and gains in the rivers from concurrent gauging work (Section 3.3; Table 3), and spring flow measurements were also used as calibration targets. This data provide guidance on the location and magnitude of flows between the groundwater system and rivers to check that the model boundary conditions adequately simulate loosing and gaining reaches. Because there are so few gaugings to assess a representative 'steady state' condition, no attempt was made to calibrate the model exactly to this information.

6.2.2 Transient flow

Table 15 provides a list of monitoring wells used for the calibration of the transient flow model. Greater emphasis has been placed on using those with accurate surveyed elevation data. Monitoring wells on the Wendonside Terrace have been excluded since the aquifers in this area tend to be either perched or semi confined exhibiting limited continuity with the lower terrace aquifers.

Well Number	Grid Reference	Record Start Date	Monitoring Interval	Elevation Reliability
Waipounamu Groundwater Resource Zone.				
F44/0199	F44:830-733	24-Feb-04	Weekly	Survey
F44/0214	F44:812-744	06-Dec-04	30 mins	Estimate
Riversdale Groundwater Resource Zone				
F45/0167	F45:821-657	14-Sep-00	Monthly	Survey
F45/0181	F45:986-575	03-Dec-02	30 mins	Survey
F45/0174	F45:793-697	14-Sep-00	Monthly	Survey
F45/0370	F45:854-602	12-Feb-04	Monthly	Estimate
Knapdale Groundwater Resource Zone				
F45/0172	F45:902-606	14-Sep-00	Monthly	Estimate
F45/0168	F45:966-526	14-Sep-00	Monthly	Estimate
Wendon Groundwater Resource Zone				
F44/0088	F45:834-778	24-Feb-04	30 mins	Survey
Wendonside Groundwater Resource Zone				
F44/0018	F44:785-859	17-May-01	Monthly	Survey
F44/0069	F44:784-831	30-Sep-02	Monthly	Survey
F44/0139	F44:788-828	25-Mar-03	Monthly	Survey
F44/0077	F44:766-831	17-Jun-03	30 mins	Estimate

Table 15: Transient flow calibration wells

6.3 Steady State Head Calibration

Figure 28 shows a good correlation between observed March 2004 groundwater levels and modeled heads for the same period. This provides an initial degree of confidence that the conceptual model and boundary settings are reasonable. The model tends to under-predict heads on the Wendonside Terrace because aquifers in this area are regarded to be confined/semi-confined and possibly perched above the lower terrace aquifers. Since the single-layer model does not take this into account, it is not possible to match the groundwater heads in the Wendonside Terrace. This is not regarded to be a significant issue because the main focus of the calibration is the highly permeable lower terrace aquifers.

6.4 Transient Model Calibration

6.4.1 Calibration Period and Stress Period Design

The transient model run was determined by the available groundwater level monitoring and river gauging data as the period 1/6/1999 to 1/6/2007 (8 years). A weekly stress period was used over which all model stresses (river stage, recharge and abstraction) are averaged.

Because the aquifers exhibit a close connection to the river systems, calibration to a range of low flow conditions (particularly in the Mataura River) is considered important.

The period 1999-2007 contains a wide range of low flows and shown in Table 16. The lowest flow in the transient calibration period occurs in the 2000/2001 summer when the flow at Gore is just above the 10 year low flow return period. The flow at Parawa at the same time is equivalent to a 5 year low flow return period. Generally, the summer flow conditions are below the MALF for Gore, except for the wetter summers of 1999/2000 and 2005/2006.

	Gore	Parawa
MALF (7-day)	17.72	6.0
5 year return	16.6	4.75
10 year return	8.85	4.15
Model calibration window - summer low flows (7-day means)		
1999/2000	18.9	6.37
2000/2001	10.65	4.61
2001/2002	15.26	6.78
2002/2003	12.65	5.83
2003/2004	11.74	6.36
2004/2005	20.27	7.05
2005/2006	16.37	6.43
2006/2007	14.96	5.79

Table 16: Low Flow Statistics for the Mataura River and Seasonal Low Flows used for Transient Model Calibration

6.4.2 Transient Groundwater Level Calibration

Transient calibration hydrographs are provided in Appendix 1 which shows the modelled groundwater levels alongside observed levels. Simulated groundwater levels in the Riversdale Zone closely reflect both the magnitude and amplitude of groundwater level fluctuation shown by the observation data. Close calibration to monitoring well F44/0181 (Liverpool Street) proved difficult since when levels are closely matched, the calibration to all other wells in the Riversdale Groundwater Zone is compromised. The survey elevation of this well should be checked to ensure its accuracy.

Within the Waipounamu Groundwater Zone, F44/0199 calibrates closely to the short term monitoring record. However the modelled heads for F44/0214 apparently model slightly lower than the observed heads – although the wellhead elevation for this observation site is estimated so less emphasis was placed on calibrating closely to this observation data.

Modelled heads for the Knapdale and Wendon groundwater zones are also reasonable, and importantly, show that the model response to boundary stresses (recharge, river stage) closely matches the observed level responses in the unconfined aquifers.

Calibration to monitoring well records in the Wendonside groundwater zone has been achieved with variable success. A reasonable match is achieved for F44/0139 although the model is predicting head about 10m lower for F44/0077 – which is probably screened in a deeper semi-confined aquifer.

6.4.3 Transient Water Balance Calibration

The global water balance for the model was initially checked against the flow record in the Mataura River at Gore to ensure that the model was simulating the correct flows on a bulk scale. This proved possible since the groundwater system of the modelled area is effectively a closed basin and the (measured) flow at Gore should equal gauged river inflows across (into) the model boundaries (Mataura, Waikaia, and Waimea), plus discharge from groundwater in the form of fluxes to rivers and springs, minus groundwater abstraction. There are also minor tributary inputs (e.g. Wendon, Otamita, Tomogalak), but these are considered to be insignificant, particularly during the summer months.

Figure 29 shows the global water balance check against the measured flow in the Mataura River at Gore (as 7-day means) for the transient simulation period. There is a very close calibration during the summer months when the river is low indicating that the model is favourably simulating baseflow and groundwater drainage accurately. This provides confidence in the recharge modelling and also the set-up of the river and spring boundary conditions. The correlation between the Gore flow and model output during wetter, high flow period is not expected to be close since rainfall runoff becomes important, and minor tributary flow probably plays a larger role. The model does not simulate rainfall runoff – only the proportion of rainfall which infiltrates to groundwater.

Overall, the model water balance shows that the model is closely simulating dry/summer period water fluxes.

Appendix 2 contains a series of plots to check the simulated groundwater-surface water interaction against gauging data. The losses and gains associated with specific reaches of the Mataura and Waikaia rivers, and spring discharges in the Riversdale Groundwater Zone, are important calibration targets given that the intended purpose of the model is to assess the cumulative depletion effects of groundwater abstraction. The concurrent gauging data are shown in Table 3, and also graphically displayed on the plots in Appendix 2 for all river reaches, and for the Meadow Burn.

The plots in Appendix 2 relating to the Mataura and Waikaia rivers express net river losses to groundwater (+), and/or gains from the aquifer to the river (-). Between the western model edge upstream of Ardlussa and Riversdale Bridge, the simulated loss to groundwater closely matches the range derived from concurrent flow gaugings (red squares). Below Riversdale Bridge, the river begins to gain flow from groundwater down to about Dillons Road. The model appears to be simulating a smaller gain than the concurrent gaugings suggest between Otama Flat and Dillons Road. It proved unfeasible to increase the simulated gain by adjusting bed conductance or formation hydraulic conductivity, whilst maintaining the correct head distribution.

Below Dillons Road as far as about Monaghans Beach, the Mataura River appears to either gain or lose flow to groundwater depending upon the relative gradient between the aquifer and river stage. There are no reliable concurrent gauging data to verify the modelled interaction however. From Monaghans Beach to Gore, the model simulates gaining flow in the Mataura River of a similar magnitude (about 1 cumec) to the measured gain.

Appendix 2 also shows simulated spring flows for the Meadow Burn and McKellar Stream. The modelled springflow shows a very good correlation between the gauged flow in the Meadow Burn (York Road-Fingerpost Pyramid Road). It is however difficult to assess the accuracy of the simulated flow in the McKellar Stream , but the few gaugings that do exist agree fairly well with the model. The McKellar Stream appears to gain much of its flow from the neighbouring Longridge Groundwater Zone and may not actually gain very much flow from the Riversdale Groundwater Zone. Also shown in Appendix 2 is the predicted total spring flow for the Riversdale Groundwater Zone. There is only one gauging set to verify the model output; on 17/1/2003 Environment Southland reported a total spring discharge for the Riversdale Groundwater Zone of 716L/sec. This compares well with the simulated spring flow at this time.

6.4.4 Water Balance Outputs

Selected water balance outputs for three stress periods are shown in Table 17. The first output is for the lowest river flow condition in the transient simulation (March, 2001). The second output is for the last summer period (April 2007) to show the water balance at the highest abstraction rate. The final output shows the water balance for an average winter rainfall condition (June 2002).

Unit = m^3/day **Values represent 7-day means**	**27/3/2001** **Driest summer month**	**20/3/2007** **Max abstraction**	**25/6/02** **Average winter**
Output time (day)	665	2849	1120
IN			
Storage release	230,200	164,700	26,430
Steam Leakage/loss	312,300	395,000	322,750
Rainfall recharge	0.0	135,000	1,033,600
Total IN	*542,500*	*694,700*	*1,382,800*
OUT			
Storage gain	26	116,000	676,760
Wells	16,500	87,700	16,280
Springs/drains	33,900	25,200	114,200
Stream Leakage/gain	492,200	466,000	575,500
Total OUT	*542,626*	*694,900*	*1,382,740*
% Discrepancy IN-OUT	-0.01	-0.01	0.0

Table 17: Modelled water balances for selected stress periods

Table 17 shows that the dominant recharge process during winter is rainfall recharge, but that river leakage is dominant during summer months. Output from the closed groundwater system is primarily through leakage back into the main rivers. Spring discharges form a minor component of the water balance which is generally close to, or lower than, abstraction from wells during the summer. Summer spring flows appear to reduce to about 25% of the winter flows.

Stream/river losses appear to be about 100,000m^3/day (1.1 cumecs) higher in April 2007 compared to the very dry March 2001 condition. This probably relates to the very low river stage in 2001 and is indicative of the minimum loss to groundwater from the Mataura River upstream of Riversdale Bridge. It is interesting to note that spring discharge decreases in April 2007 even though recharge has increased which is reflected by increased drainage from groundwater back into the rivers. The cause of this may be the increased groundwater abstraction in the Riversdale Groundwater Zone.

7. SENSITIVITY ANALYSIS

The sensitivity of the model to various input parameters and boundary stresses has been evaluated during the model calibration process. A statistical analysis of model sensitivity has not however been performed, principally due to the paucity of river loss and gain flow calibration data for the Mataura River. These fluxes are regarded to be the most important observation parameters, alongside groundwater level data.

The model is most sensitive to river (stream) boundary condition settings – stage elevation data for the Mataura River being the principal control on groundwater heads throughout the Riversdale and Waipounamu groundwater zones. Considerable effort was therefore invested in ensuring the river and stage elevations matched survey data wherever available. River stage and bed survey data were generally of sufficient spatial and temporal distribution to obtain reasonably constrained boundary settings. The model proved somewhat less sensitive to river bed conductance values, particularly in the lower reaches of the river (below Pyramid Bridge) where there appears to be a high hydraulic connection between the river and the aquifer. Upstream of this locality, bed conductance values were derived through the calibration process to obtain the correct range of fluxes between the aquifer and river (derived from concurrent flow gaugings).

Hydraulic conductivity proved to be a moderately sensitive input parameter which principally controls throughflow in the Riversdale and Waipounamu aquifers, and consequently the discharge quantities into the springs and Mataura River downstream. Small changes in hydraulic conductivity appear to have relatively small impacts on groundwater levels because of the overall relatively high transmissivity of the lower terrace aquifers. River stage elevations tend to be the main controlling influence on head distribution.

The model is also insensitive to small changes in rainfall recharge, again due to the high transmissivity and storage properties of the lower terrace aquifers. Trials were conducted using the soil moisture balance model (Section 4.6) by varying the soil properties (RAW and TAW) within reasonable ranges for the soil types present in the study area. These resulted in negligible differences in groundwater heads in the lower terrace aquifers, but had a larger response over the older terrace sequences (such as the Wendonside Terrace).

Spring discharges using MODFLOW Drain cells are highly sensitive to bed elevation and bed conductivity. For the Meadow Burn, the bed elevation was well-constrained since there is good information regarding bed elevation along its entire reach. Bed conductance values were consequently derived through the calibration process. For the other springs, there is sparse survey data and elevations in most instances were derived approximately from topographic maps or nearby survey points.

Overall, the model is regarded to be robustly calibrated with the most sensitive input parameters being constrained using adequate field data.

8. ASSESSMENT OF GROUNDWATER ABSTRACTION EFFECTS

8.1 Approach

The primary purpose of the numerical model is to assess the cumulative effects of current groundwater abstractions as a basis for improving the management of the groundwater resource and to ensure that the requirements of the Mataura Conservation Order are not breached.

The focus of this assessment has been the Riversdale and Waipounamu groundwater zones since these contain most current large irrigation abstractions. Furthermore, rapid expansion of groundwater development is predicted to occur in the Riversdale Groundwater Management Zone. The effects of groundwater abstraction in the Riversdale and Waipounamu groundwater management zones on the flow in the Mataura River have been evaluated at Riversdale Bridge and Pyramid Bridge.

Depletion rates have been initially assessed for the climatic and river flows conditions occurring during the eight year transient model simulation (modelled as 7-day means). Table 16 provides information on the range of river flow conditions experienced during this period.

The following process was adopted to assess the impacts on current groundwater abstractions on flow in the Mataura River and spring-fed streams in the Riversdale Groundwater Management Zone:

1. The calibrated transient model was run with no groundwater abstractions to provide 'baseline' water balance data against which various abstraction simulations can be referenced. Calibration checking against groundwater level monitoring, gauged flow losses and gains in the Mataura River, and spring discharges was undertaken during this process.

2. The model was then run with all consented groundwater abstractions using average seasonal rates to provide an assessment of the maximum theoretical cumulative effect on river and spring flow (Scenario 1). The modelled flows in the Mataura River at selected locations, and spring discharges, were then compared to the baseline no-pumping simulation.

3. Groundwater takes assessed by Environment Southland[1] as having direct and high stream flow depletion (SFD) effects were switched off (Scenario 2). Many of these wells currently have consent conditions requiring them to turn off at specified low flows measured in the Mataura River at Gore. The model was then run to assess the cumulative effects of the remaining

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[1] Streamflow depletion assessment using analytical calculation following the method of Hunt.(1999)

consented wells – those having moderate-low SFD effects, in addition to wells abstraction less than 2 L/sec. These abstractions do not currently have low-flow restrictions.

4. Further abstraction scenarios (Scenario 3) were run to examine the effects of abstraction under different river flow conditions by applying the 2006/07 pumping rates for the unrestricted wells categorised as having a moderate-low SDF to the entire transient simulation. Further runs were also made by increasing the current cumulative take by various factors.

8.2 Modelled Effects of Current Abstraction

Scenario 1: All consented wells pumping, progressive abstraction 1999-2007 river flow and climatic conditions.

This scenario represents the progressively increasing pattern of groundwater abstraction which has occurred over the past eight years. The pumping rates used in the model are average daily rates calculated from the seasonal allocation amount (usually over 150 days).

Figures 30 to 34 show the results of a transient simulation from June 1999 to present, in which all consented wells are pumping. The maximum seasonal abstraction rate for the 2006-07 summer is about 90,000m^3/day for the entire model area, of which about 68,500m^3/day is taken from the Riversdale and Waipounamu groundwater management zones.

Figures 30 and 31 show that the modelled depletion at Pyramid Bridge peaks at about 43,000m^3/day during the 2006/07 summer. This equates to 60% of the abstraction rate from the Riversdale and Waipounamu zones which is equivalent to about 4% of the estimated flow in the Mataura River at Pyramid Bridge.

Figures 32 and 33 show the same outputs, but this time in relation to modelled flows in the Mataura River at Riversdale Bridge. The river experiences its lowest flows at this location, downstream of the major losing/recharging reach, and upstream of the Waikaia confluence and before the river starts to gain flow from groundwater. This is therefore the most vulnerable reach of river to depletion effects. The modelled flow reduction at Riversdale Bridge peaks at about 25,000m^3/day in 2006/07 which equates to about 6% of the natural flow in the river at this location.

The predicted effects of the abstraction on spring discharge from the Riversdale Groundwater Zone are shown in Figures 34 and 35. The total spring flow depletion is 8,000-9,000m^3/day, whilst the depletion of the Meadow Burn is about 70-80 L/sec.

The depletion modelled under this scenario would be realistic only in the absence of any low-flow restrictions on the direct-high SFD wells.

Scenario 2: Consented wells excluding direct-high SFD category wells pumping, progressive abstraction 1999-2007 river flow and climatic conditions.

This scenario assesses the cumulative depletion effects of low-medium SDF wells, and other (consented) wells pumping less than 2 L/sec. These wells currently account for a total abstraction of about

45,700m^3/day in the Riversdale, Waipounamu and lower Wendon groundwater zones (the lower Wendon takes are included as they probably impact on Mataura River flows). Wells categorised as having a direct and high SFD have been switched off since most of these are currently subject to low flow restrictions.

Figures 36 to 39 show the modelled depletion effects on the Mataura River at Pyramid Bridge and Riversdale Bridge. The model outputs show a marked reduction in depletion at Pyramid Bridge to 2% of the (7-day mean) flow, and about 3% at Riversdale Bridge during the 2006/07 summer. The depletion effects will however vary depending upon the low flow conditions in the river and this scenario provides an indication of the effects of current pumping rates during the 2006/07 summer only.

Figures 40 and 41 show the simulated effects of this abstraction scenario on spring flow. The effect on the Meadow Burn is estimated to be 40-50 L/sec over the past three summers.

Scenario 3: Seasonally constant abstraction (2006/07 rates and multiples), consented wells excluding direct-high SFD category wells, 1999-2007 river flow and climatic conditions.

Scenario 3 is designed to provide an insight into seasonal depletion variability under steady seasonal abstraction conditions. Since summer low-flow conditions vary between years with the potential occurrence of extreme low flows, it is considered necessary to examine the variability of effects under constant seasonal abstraction conditions.

The first model run under this scenario involved a constant seasonal (150 day) abstraction at the 2006/07 rates from all wells excluding direct-high SFD category wells. This was estimated to be 45,700m^3/day for the Riversdale, Waipounamu and lower Wendon groundwater zones.

Figure 42 shows the variability in depletion between years for the eight-year transient model run. Also shown on this plot are the 7-day mean flows modelled in the Mataura River at Riversdale Bridge. There appears to be a general pattern of increased depletion when flows are higher, and reduced depletion when flows are seasonally lower. But overall, the range in depletion is less than 500m^3/day between years (about 3-4% variability) suggesting that depletion volumes can be considered to be essentially ‘independent’ of river stage/flow condition.

Figure 43 shows the results of the model run for 2006/07 abstraction (Q_{av} 2007: 45,700m^3/day), and also two additional runs for which the abstraction rates for each well were multiplied by a factor of 1.5 (Q_{av} 2007 *1.5) and 2 (Q_{av} 2007 *2). The total (cumulative) seasonal rates are constant for each model run and the results presented as a percentage of natural (modelled) flow in the river at Riversdale Bridge. The analysis shows that the relationship between the river flow depletion rate and total abstraction rate is linear; depletion rates are: Q_{av}2007 = 14,000m3/day, Q_{av}2007 *1.5 = 21,000m^3/day, and Q_{av}2007 *2 = 28,000m^3/day.

The results presented in Figure 43 essentially represent a constant depletion rate for each irrigation season expressed as a percentage of flow in the river. The cumulative effects of current abstraction (excluding high-direct SFD category wells), is about 3-4% of the flow in the Mataura River at Riversdale Bridge, but rising to about 5% under very low flows.

Utilising the outputs from Scenario 3, Figures 44 and 45 shows the simulated relationship between total abstraction from the Riversdale, Waipounamu and lower Wendon groundwater zones, and flow in the Mataura River at Riversdale Bridge. Figure 45 shows the same relationship when the depletion rate in the river is 5% of the natural flow at Riversdale Bridge. This plot shows the minimum flow in the river required at Riversdale Bridge to ensure depletion does not exceed 5%. The 5% limit was chosen to correspond to the Mataura Conservation Order which specifies that abstractions from the river should not exceed 5% of the natural flow at any point.

The modelled effect under Scenario 3 abstractions on flow in the Meadow Burn are shown in Figure 46. Under current levels of abstraction and assuming an average pumping rate from each well, the depletion effect is predicted to be about 60-70 L/sec. The calculated depletion rate for Q_{av}2007 (current abstraction) is up to 40%.

9. ALLOCATION MANAGEMENT RECOMMENDATIONS

9.1 Current Management of Stream Flow Depletion

Groundwater allocations in the Mid-Mataura catchment are currently managed by Environment Southland for stream depletion effects (Policy 29 of the Proposed Regional Water Plan for Southland). Under this policy, abstractions of greater than 2 L/sec are assessed for their degree of hydraulic connection to surface water bodies and are ranked direct, high, moderate, or low depending upon the amount of stream flow depletion calculated using the Hunt analysis method.

Where there is a ‘direct’ connection, the take is managed as a surface water abstraction. If a take is categorised as having a ‘high’ connection, the calculated rate of stream depletion is managed as a surface water take and the remainder of the abstraction volume is included in the allocation volume for the relevant groundwater zone. Both direct and high connection takes are subject to surface water minimum flow restrictions in the Mataura River at Gore. It is understood that some older consents (and public supply wells) categorised as having a direct or high connection to surface water are not subject to low flow restrictions.

Takes having a moderate connection are managed the same way as ‘high’ connection takes, except they are not subject to low flow restrictions. Low connection takes are managed entirely as a groundwater abstraction, also with no low flow restriction.

9.2 Summary of Model Predictions

The Mid-Mataura Groundwater Model presented in this report investigates the cumulative effects of current groundwater abstractions from the Riversdale and Waipounamu groundwater zones on the surface water environment, focussing primarily upon depletion of flow in the Mataura River. It also investigates effects on the spring-fed Meadow Burn.

Since current policy adequately addresses the potential effects of those takes classified as having a direct or high stream flow depletion by way of low flow restrictions, the cumulative impacts of remaining abstractions have been examined.

In terms of assessing flow depletion in the Mataura River, the most vulnerable location is considered to be in the vicinity of Riversdale Bridge. This locality experiences the lowest flows in the mid-Mataura catchment because it is located at the downstream end of the main reach of river which recharges the Riversdale aquifer (the river looses flow to groundwater upstream of Riversdale Bridge and therefore flow gradually diminishes). Downstream of Riversdale Bridge, the Mataura River begins to gain flow again from groundwater discharge emanating from the Waipounamu, Riversdale and Wendon groundwater zones. The confluence of the Waikaia River is also a short distance downstream and therefore flows in the Mataura River increase significantly downstream of Riversdale Bridge. Riversdale Bridge is also immediately adjacent and downstream of most large current abstractions and potential future abstractions.

The model predicts a maximum cumulative depletion of flow in the Mataura River at Riversdale Bridge of between 3 and 5% (during the irrigation season) as a result of groundwater abstraction occurring from wells categorised as having a moderate and low hydraulic connection to surface water (and wells abstracting less than 2 L/sec). If all takes with direct and high connectivity are restricted during low flows, the effects of current levels of abstraction do not breach the Mataura Conservation Order for the range of flows experienced between 1999 and 2007.

It is probable, however, that the cumulative depletion effects of current (2007) groundwater abstractions would exceed 5% of the natural flow in the Mataura at Riversdale Bridge under extreme low flows (> than a 10 year return period at Gore, or 5 year return period at Parawa). Restriction of direct and high SFD category takes alone, based upon flows measured at Gore, is clearly insufficient to prevent excessive depletion of the most vulnerable reach of the Mataura River. This conclusion is amplified by the growing demand for groundwater in this area.

Significant spring flow depletion of the Meadow Burn is predicted by the model. The cumulative effect of current takes (excluding direct and high SFD category wells) is approximately 60 L/sec. This represents up to 40% of the flow during summer months.

9.3 Recommendations for Allocation Management

Location of Mataura River Flow Reference Site

It is recommended that Riversdale Bridge, being the most vulnerable reach of the Mataura River to the cumulative effects of groundwater abstractions, be established as a low-flow gauging site. Low flow restrictions attached to groundwater abstraction consents should be tied to this site (rather than Gore). Alternatively, if a good flow correlation can be established between Gore or Parawa and Riversdale Bridge, the Gore (or Parawa) flow record could be retained as a surrogate site for Riversdale Bridge low-flow restrictions.

Establishment of Minimum Groundwater Levels

There is difficulty in establishing minimum groundwater levels in the Riversdale aquifer, and it is considered more effective to constrain groundwater abstraction on the basis of river flow conditions. This is particularly relevant since aquifer levels, even at some distance from the river, are highly dependent on river levels (Figures 10 and 11) and drawdowns are ‘buffered’ by induced flow through the river beds (the river essentially represents a fixed head boundary condition). Therefore, very small changes in aquifer levels can equate to large changes in river flow depletion. Furthermore, monitoring wells used for resource management purposes can be influenced by local pumping effects, and also may be screened in an unfavourable part of the heterogeneous alluvial aquifer.

Establishment of minimum aquifer levels is therefore not regarded to provide an effective mechanism to manage stream flow depletion.

Low Flow Pumping Restrictions

The current methodology for classifying the wells according to their degree of connectivity to surface water bodies is considered to be practical, effective and easy to implement.

The results of the modelling suggest that it is necessary to apply low flow restrictions to all takes classified as having a direct or high connection to surface water in the Riversdale and Waipounamu groundwater zones. These takes have an immediate impact on surface water flows and therefore, all takes in the Riversdale and Waipounamu groundwater zones, including those older consents which currently have no restrictions, should be subject to low flow restrictions.

It is recommended that a ‘second-tier’ low flow restriction be applied to all new consents classified as having a ‘moderate’ SFD. Although these takes do not have such an immediate effect on surface water flows, the model shows that there is a longer term, cumulative impact on flow in the Mataura River. In this respect, it would be appropriate to tie ‘moderate’ SFD takes to a minimum river levels recorded at Riversdale Bridge. The model output (Figure 45) may be used to guide the selection of critical low flow limits at Riversdale Bridge (with consideration to the model limitations).

Minimisation of Effects on the Meadow Burn

Mitigation of depletion effects of abstraction on the Meadow Burn is difficult since the springs represent natural discharge from the Riversdale aquifer which is unavoidably reduced by upstream abstractions. The flow in the Meadow Burn is dependent upon groundwater levels, which are in turn influenced strongly by river conditions. The low-flow control at Riversdale Bridge of new moderate SFD takes, in addition to all direct and high SFD takes, in the Riversdale Groundwater Management Zone will reduce the depletion effects on the Meadow Burn. However, if the current level of depletion in the Meadow Burn predicted by the model (up to 40% of low flow) is considered unacceptable, it would be necessary to apply low flow restrictions to those larger (>10 L/sec) existing moderate SFD takes in the Riversdale Groundwater Management Zone.

10. MODEL LIMITATIONS AND RECOMMENDATIONS FOR FURTHER WORK

10.1 Model Assumptions and Limitations

The conceptual and numerical groundwater model constructed for the mid-Mataura catchment is based upon a limited amount of sub-surface information in the form of bore logs and aquifer testing. Much of this information is concentrated in the Riversdale and Waipounamu groundwater management zones due to the intensity of groundwater resource development in these areas. Assumptions have been made relating to the geometry and continuity of aquifer units to other parts of the basin using the published geological map and sparse bore log data to build a conceptualisation of the broader groundwater environment.

Specific limitations and assumptions are as follows:

- Regionalisation Assumptions: the model has been constructed to represent the regional groundwater environment and as such has the following limitations:

    - A relatively large cell size (200m^2): The model is designed to investigate the groundwater system, water balances and cumulative abstraction effects at an 'aquifer scale'. It is not capable of simulating local detail, such as drawdown around a pumping well.

    - Flow material averaging: the alluvial aquifers in the study area are highly heterogeneous mixtures of gravels, sands and silts which have a very complex small-scale hydraulic conductivity distribution. The model averages material property data such as hydraulic conductivity and storage properties over large 'domains' and present representative values for these areas based upon pumping test data and model calibration.

    - The three-dimensional conceptualisation of the aquifer systems is based upon available information and an understanding of the geological and hydrological evolution of the area. It is recognised that there are 'data gaps' in certain areas which require future refinements. Specific areas include the lower Waikaia River valley, and the Wendonside Terrace.

    - One-layer representation: The one layer representation of the Riversdale, Waipounamu, Wendon and Knapdale groundwater zones as a single unconfined aquifer is considered a reasonable assumption. However, problems are encountered with the older terrace sequences, such as the Wendonside Terrace, which are clearly more complex multi-layered aquifer systems.

- Temporal descretisation limitations: The model has been run using 7-day stress periods and thereby averages all boundary stresses (such as river stage and recharge) over this period. The model outputs and predictions therefore represent 7-day averages which may in some instances differ from instantaneous observation data (such as river flow gaugings). Depletion predictions on river and spring flows may therefore under-predict effects through the averaging process.

- Transient calibration window: The model has been calibrated to an eight year time period from 1999-2007. It therefore incorporates the climatic and hydrological variability experienced during this time only. The period does not contain extreme climatic or river flow conditions and as such the reliability of the calibration should be viewed accordingly. However, in conjunction with the sensitivity analysis, the calibration period does contain sufficient variability to assign a good degree of confidence to predictive capability of the model.

- Calibration data limitations: The model has been calibrated against a relatively restricted set of groundwater level and river gauging data. In particular, concurrent gauging data over some reaches of the Mataura and Waikaia rivers are sparse.

- Calibration problems: Calibration against water level and flow data in the Riversdale and Waipounamu groundwater zones is good. Calibration to relatively sparse gauged river losses and gains below Otama Flat in the downstream Knapdale Groundwater Zone presented some problems where the model tends to under-predict the groundwater flows to the river. Further fieldwork is required to investigate the behaviour of the river in this area and to characterise inputs from tributary streams.

10.2 Recommendations for further work

Field data collection:

It is important to build on the current surface water gauging database to build a more comprehensive understanding of the flow losses and gains to groundwater along the Mataura River. This data will enable the model calibration to be checked and refined if necessary. Further low flow concurrent gauging data are especially required between Cattle Flat/Ardlussa and the Otamita confluence.

Similarly, additional concurrent gauging data is required for the Waikaia River between Mahers Beach and the Mataura confluence.

There is currently only one estimate of total spring discharge from the Riversdale groundwater zone. Further spring gauging runs during both stable winter and summer groundwater levels conditions should be considered.

Surveying of river stage heights concurrently during low flow periods should be programmed for the Mataura and Waikaia rivers. This will facilitate the verification of modelled stage heights, many of which are extrapolated between survey points and measured at different times. Such a survey should be carried out 2-3 times during the summer months.

Wellhead surveys of those monitoring wells without accurate collar elevations should be undertaken. In addition, the survey elevation of existing monitoring well F44/0181 (Liverpool Street) needs to be undertaken since the calibration process indicated that the water table elevation at this site is not consistent with adjacent sites.

To improve the conceptual model in areas where there is limited confidence (such as the lower Wendon groundwater management zone and upper part of the Riversdale zone), further field investigation to confirm the aquifer geometry should be considered. This could take the form of geophysical surveying, using methods such as resistivity profiling.

Model refinement

The data recommendations listed above should be used to verify and refine the current model calibration as necessary.

Adaptation of the model to enable it to be used as a routine resource management tool should subsequently be considered. This model should be set up with carefully selected low flow boundary conditions to represent an appropriate drought return period, but also containing some input periods for which calibration data exists. This may entail the preparation of a synthetic river and rainfall record for part of this simulation. The model could be set up to run for a short duration (2-3 years) under a daily stress period to avoid the averaging limitations of a current weekly stress period length. Refinement of the model grid around areas of interest such as springs and concentrations of abstractions should also occur.

11. SUMMARY AND CONCLUSIONS

The mid-Mataura catchment has experienced a considerable increase in groundwater abstraction over the past five years. Between 2000 and 2005 groundwater demand in Southland increased eight-fold, driven primarily by the expansion of pasture irrigation in northern Southland. Demand for additional water supplies for irrigation continues to grow – particularly in the Riversdale area.

The shallow, productive alluvial aquifers of the mid-Mataura catchment are hydraulically connected with rivers and springs. Groundwater and surface water are fundamentally a 'single resource'. This characteristic has led to considerable focus being directed towards the cumulative effects of groundwater abstractions on the surface water environment, driven partly by the requirements of the Mataura River Water Conservation Order (1997).

Environment Southland has therefore commissioned a groundwater modelling study to assist in the evaluation and management of groundwater allocations in the mid-Mataura catchment.

The study provides a review of the conceptual hydrogeology of the mid-Mataura catchment as a basis for constructing a transient numerical groundwater flow model (the 'Mid-Mataura Groundwater Model'). A major focus of the review has been the characterisation of flow interactions between groundwater and surface water using field measurements (flow gaugings, groundwater level monitoring and surveying of river and spring levels).

The study has also resulted in a more accurate rainfall recharge distribution based upon a new soil moisture balance approach combined with spatial rainfall modelling across the catchment.

The Modflow-based groundwater model has been calibrated under transient stress conditions for the period 1999-2007 against both groundwater level and surface water gauging data to ensure a good representation of groundwater-surface water interaction under a range of stress conditions. It has then been used to investigate the cumulative effects of current groundwater abstractions from the Riversdale and Waipounamu groundwater zones on the surface water environment, concentrating primarily upon depletion of flow in the Mataura River. Effects on the spring-fed Meadow Burn have also been investigated.

Since current policy adequately addresses the potential effects of those takes classified as having a direct or high connection to surface water by way of low flow restrictions, the cumulative impacts of remaining abstractions have been examined.

In terms of assessing flow depletion in the Mataura River, the most vulnerable location is considered to be in the vicinity of Riversdale Bridge. This locality experiences the lowest flows in the mid-Mataura catchment because it is located at the downstream end of the main reach of river which recharges the Riversdale aquifer (the river looses flow to groundwater upstream of Riversdale Bridge and therefore flow gradually diminishes). Downstream of Riversdale Bridge, the Mataura River begins to gain flow again from groundwater discharge emanating from the Waipounamu, Riversdale and Wendon groundwater zones. The confluence of the Waikaia River is also a short distance downstream and therefore flows in the Mataura River increase significantly downstream of Riversdale Bridge. Riversdale

Bridge is also immediately adjacent and downstream of most large current abstractions, and potential future abstraction areas.

The model predicts a maximum cumulative depletion of flow in the Mataura River at Riversdale Bridge of between 3 and 5% as a result of groundwater abstraction occurring from wells categorised as having a moderate and low hydraulic connection to surface water (and wells abstracting less than 2 L/sec). If all takes with direct and high connectivity are restricted during low flows, the effects of current levels of abstraction do not breach the Mataura Conservation Order for the range of flows experienced between 1999 and 2007.

It is probable, however, that the cumulative depletion effects of current (2007) groundwater abstractions would exceed 5% of the natural flow in the Mataura at Riversdale Bridge under extreme low flows (> than a 10 year return period at Gore, or 5 year return period at Parawa). Restriction of direct and high SFD category takes alone, based upon flows measured at Gore, is clearly insufficient to prevent excessive depletion of the most vulnerable reach of the Mataura River. This conclusion is amplified by the growing demand for groundwater in this area.

Significant spring flow depletion of the Meadow Burn is predicted by the model. The cumulative effect of current takes (excluding direct and high SFD category wells) is approximately 60 L/sec. This represents up to 40% of the flow during summer months.

Allocation Management Recommendations:

Location of Mataura River Flow Reference Site

It is recommended that low flow restrictions for groundwater abstractions in the Riversdale and Waipounamu groundwater management zones be referenced to flow measured at Riversdale Bridge, rather than at Gore. Riversdale Bridge is considered to be the most vulnerable reach of the Mataura River to the cumulative effects of groundwater abstractions from these zones.

Establishment of Minimum Groundwater Levels

Establishment of minimum aquifer levels is not regarded to provide an effective mechanism to manage stream flow depletion.

Low Flow Pumping Restrictions

Low flow restrictions should be applied to all takes classified as having a direct or high connection to surface water in the Riversdale and Waipounamu groundwater management zones (including those older consents not currently restricted).

A ‘second-tier’ low flow restriction should be applied to all new consents classified as having a ‘moderate’ connection to surface water in the Riversdale and Waipounamu groundwater management zones.

Minimisation of Effects on the Meadow Burn

Low-flow restrictions tied to river flow at Riversdale Bridge of all new moderate connection takes, in addition to the restriction of all direct and high connection abstractions, will reduce the future cumulative depletion effects on the Meadow Burn. However, if the current level of depletion in the Meadow Burn predicted by the model (up to 40% of low flow) is considered unacceptable, low flow restrictions should be applied to larger (>10 L/sec) existing moderate connection takes in the Riversdale Groundwater Management Zone.

Recommendations for further work include ongoing fieldwork to expand the river gauging and stage/bed survey database. Spring gauging surveys are also recommended to further characterise the spring discharges from the Riversdale groundwater management zone. Improvement of the conceptual model and definition of aquifer three-dimensional geometry would benefit from further investigation, which may include geophysical surveying using appropriate techniques. The production of a more refined 'working' model for allocation management should be set up to investigate cumulative abstraction effects under a wider range of low flow conditions on a daily time step.

12. REFERENCES

Allen, R., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration: guidelines for computing crop water requirements, Irrigation and Drainage Paper 56. FAO, Rome, 300pp.

Hunt, B; 1999; Unsteady Stream Depletion from Ground Water Pumping; GroundWater, Vol 37, No. 1, pp 98-102

McDonald, M.G. and Harbaugh, A.W. 1984. A modular three-dimensional finite difference groundwater flow model: *US Geological Survey* Open-File Report 83-875, 528pp

Rawls, W.J., Ahuja, L.R., Brakensiek, D.L., Shirmohammadi, A., 1992. Infiltration and soil water movement. *In*: Maidment, D.R. (ed.), 1992. Handbook of Hydrology. McGraw-Hill, New York.

Rushton, K.R., Eilers, V.H.M., Carter, R.C. 2006. Improved soil moisture balance methodology for recharge estimation. Journal of Hydrology 318; 379-399.

Sinclair Knight Mertz, 2003. Riversdale aquifer management zone: Preliminary sustainable yield assessment. Report for Environment Southland.

Sinclair Knight Mertz, 2005. Northern Southland groundwater model development report. Report for Environment Southland.

Williams, J.R., 1991. Runoff and water erosion. *In*: Hanks, J., Ritchie, J. (eds.), Modelling plant and soil systems. Agronomy Monographs No 31, Crop and Science Society of America, Madison, Wisconsin.

Wilson, K. 2007. Surface water and groundwater relationships in the Mataura catchment above Gore. (Environment Southland, in prep).

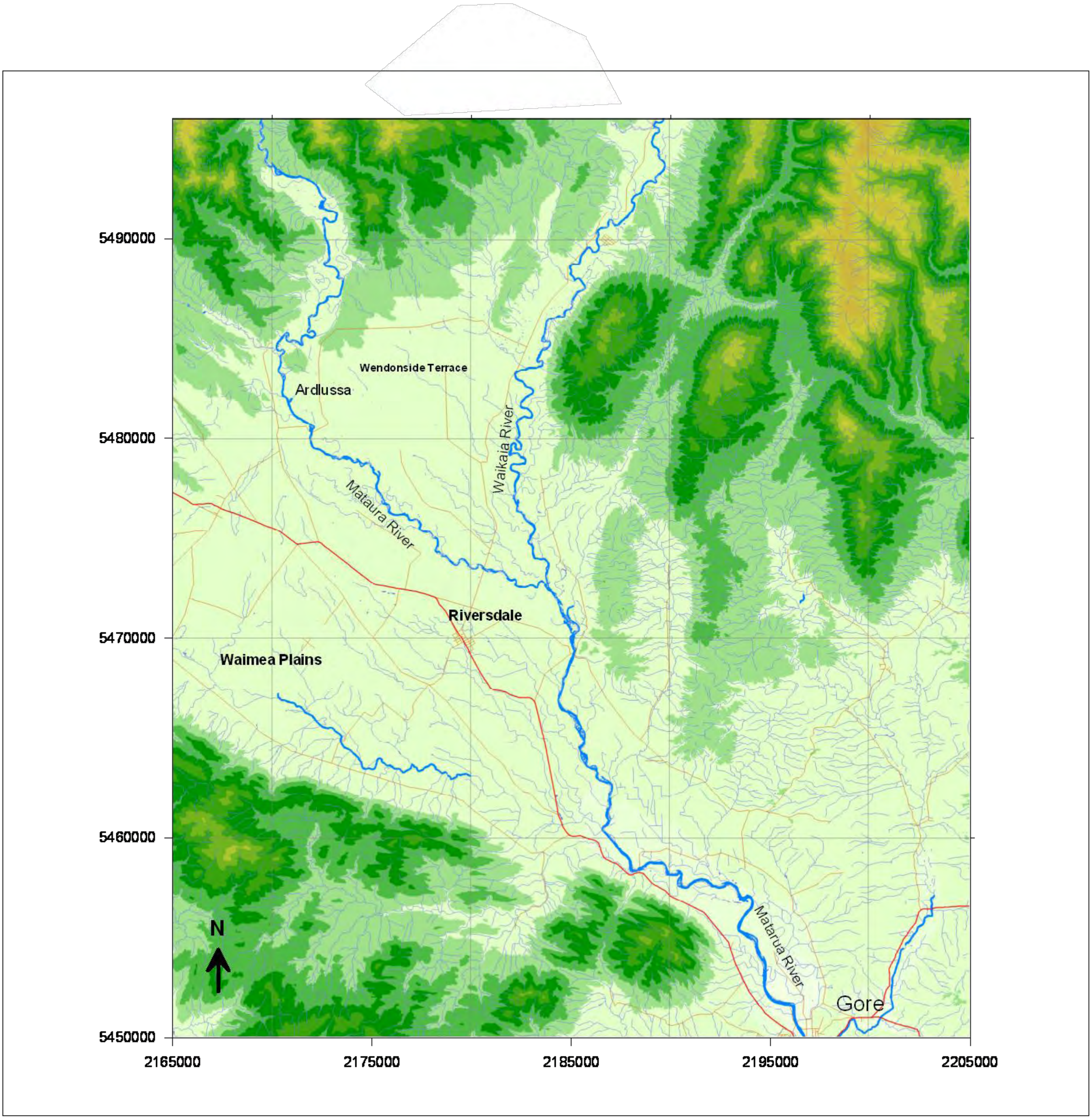


Figure 1: Location map

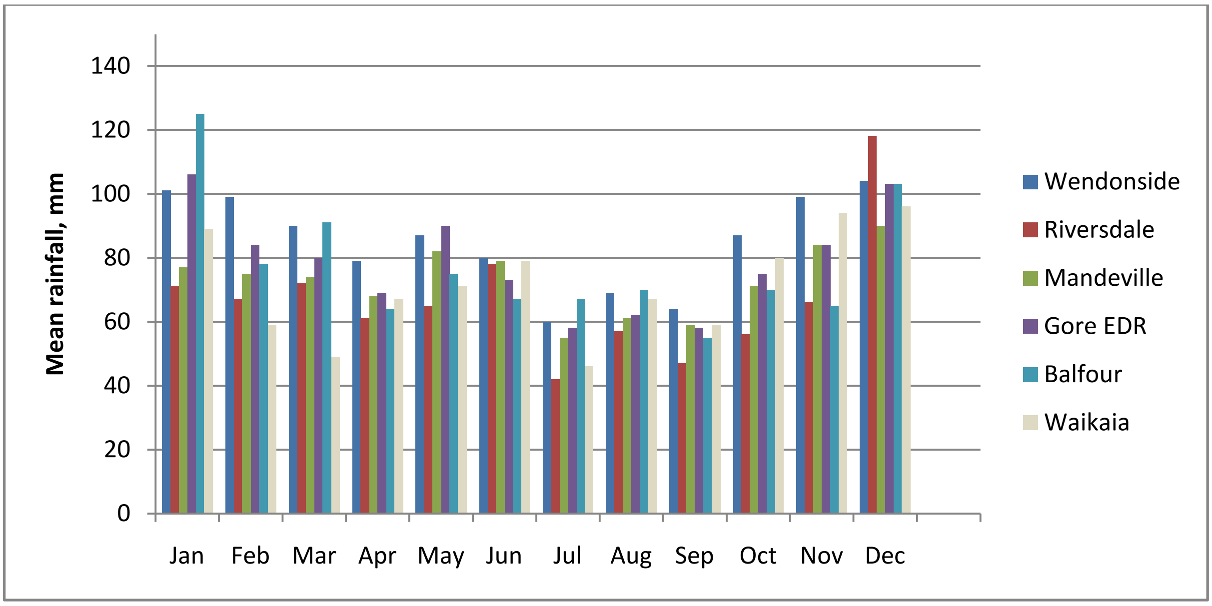
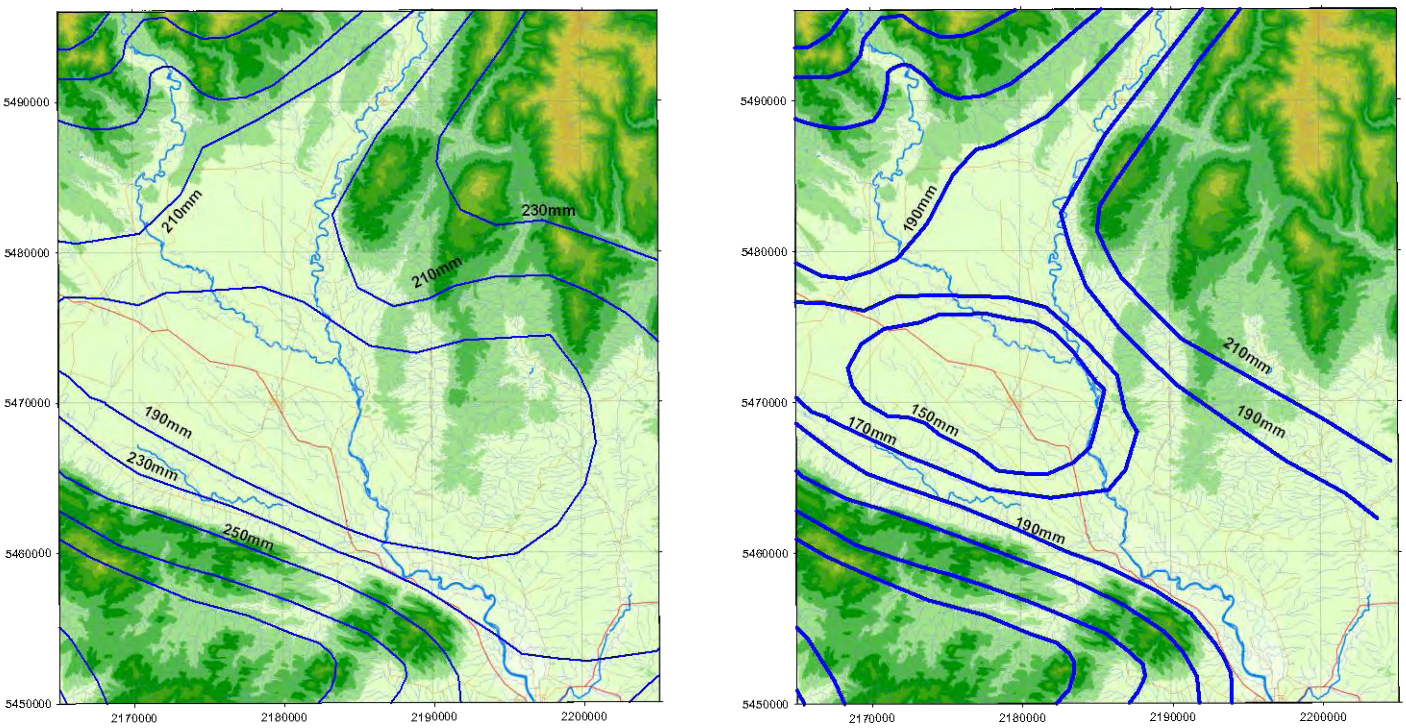
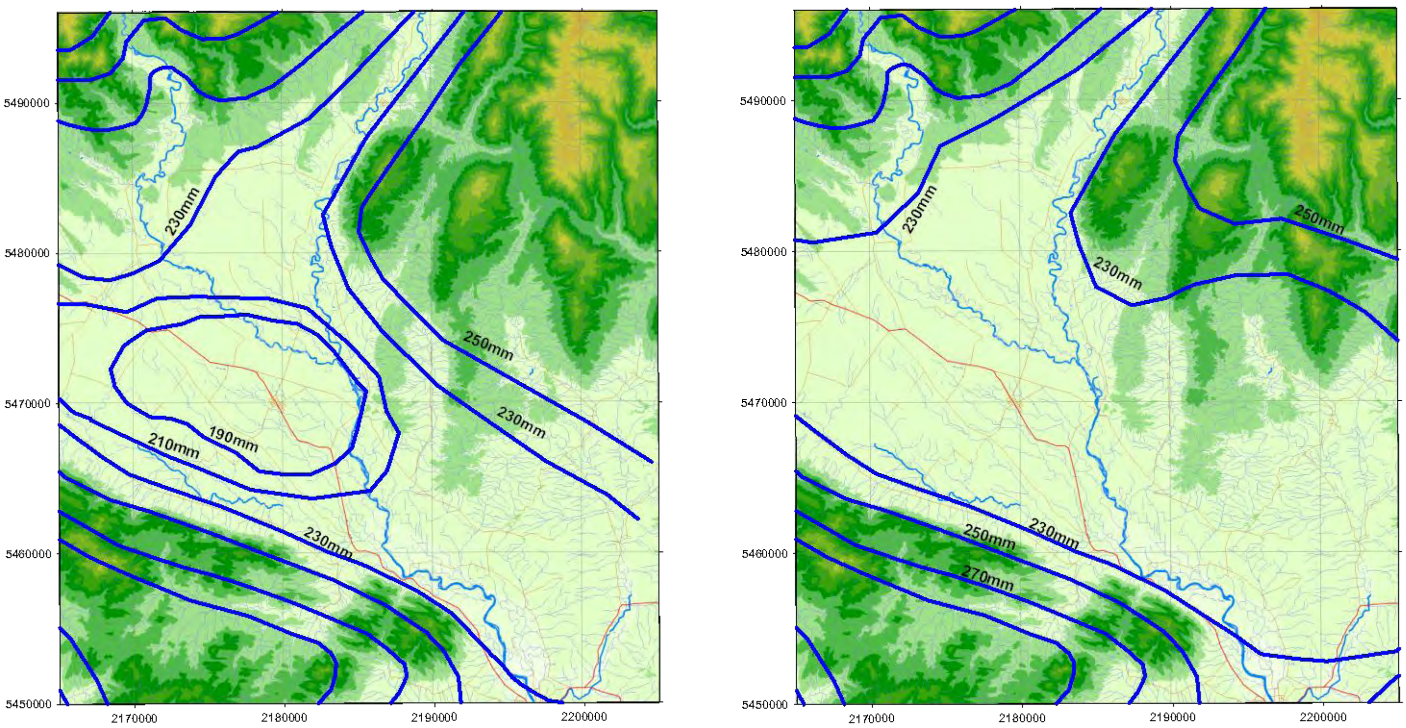


Figure 2: Temporal rainfall patterns relating to rainfall stations



A: Winter isohyets (3-month)

B: Spring isohyets (3-month)



C: Summer isohyets (3-month)

D: Autumn isohyets (3-month)

Figure 3: Seasonal rainfall isohyets

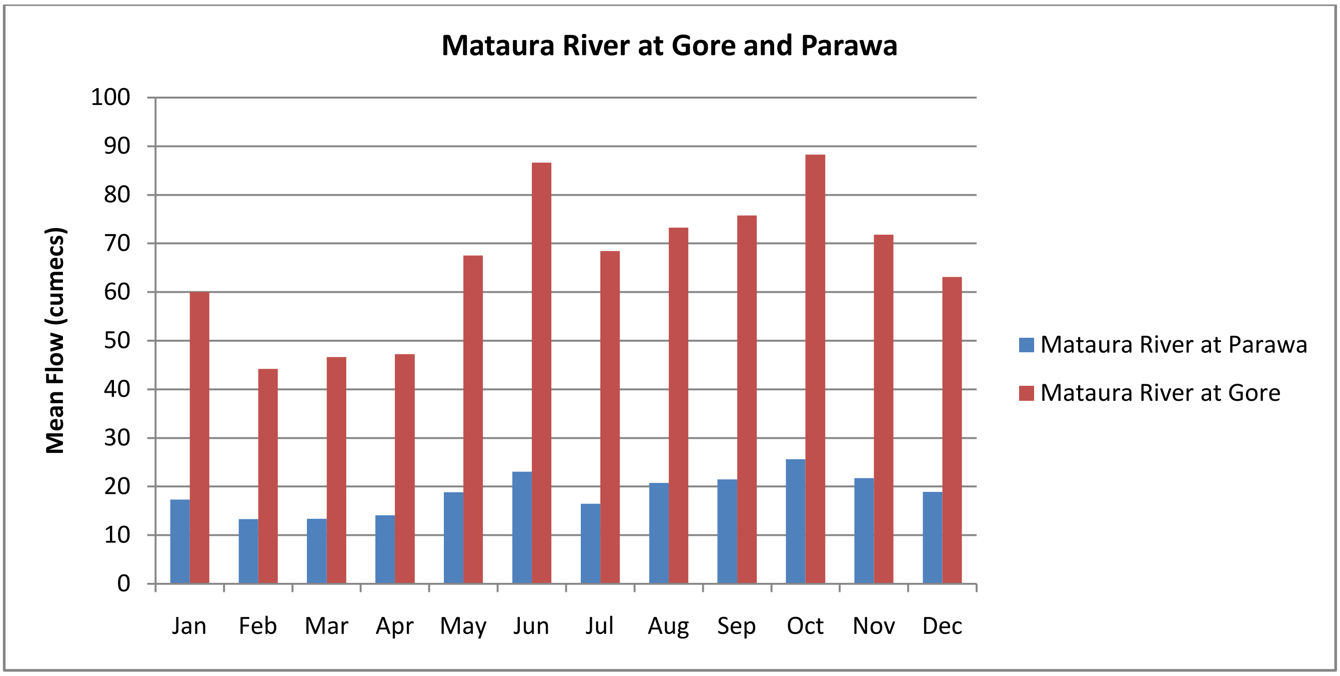


Figure 4: Mean monthly flows in the Mataura River at Gore and Parawa

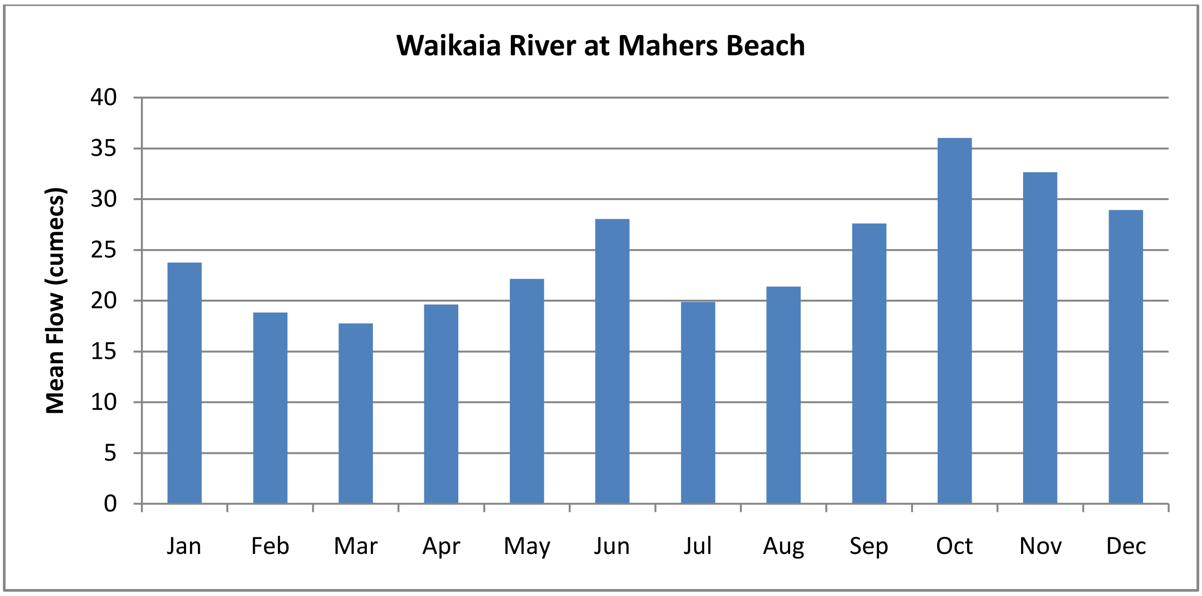


Figure 5: Mean monthly flow in the Waikaia River at Mahers Beach

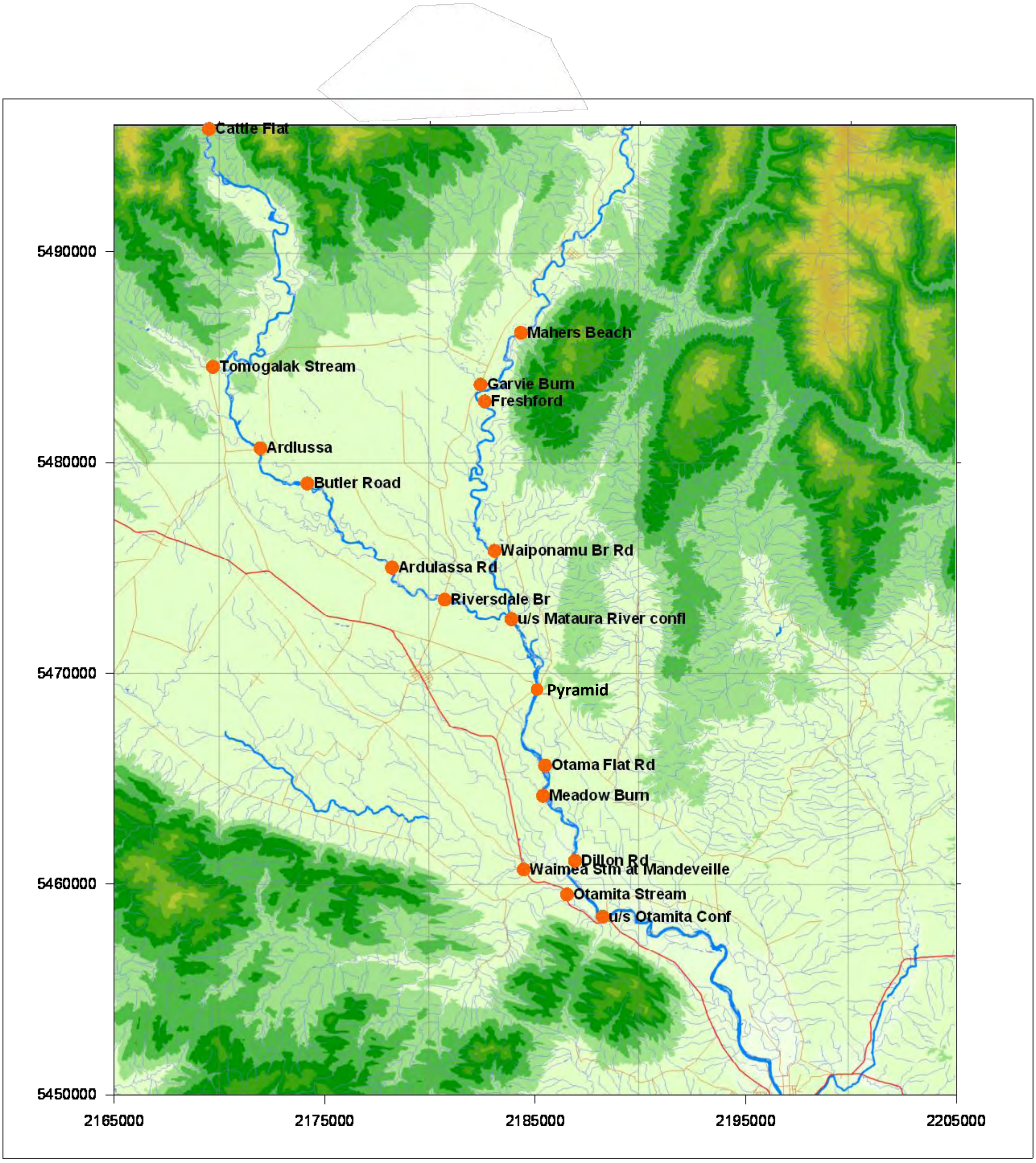


Figure 6: Flow gauging sites

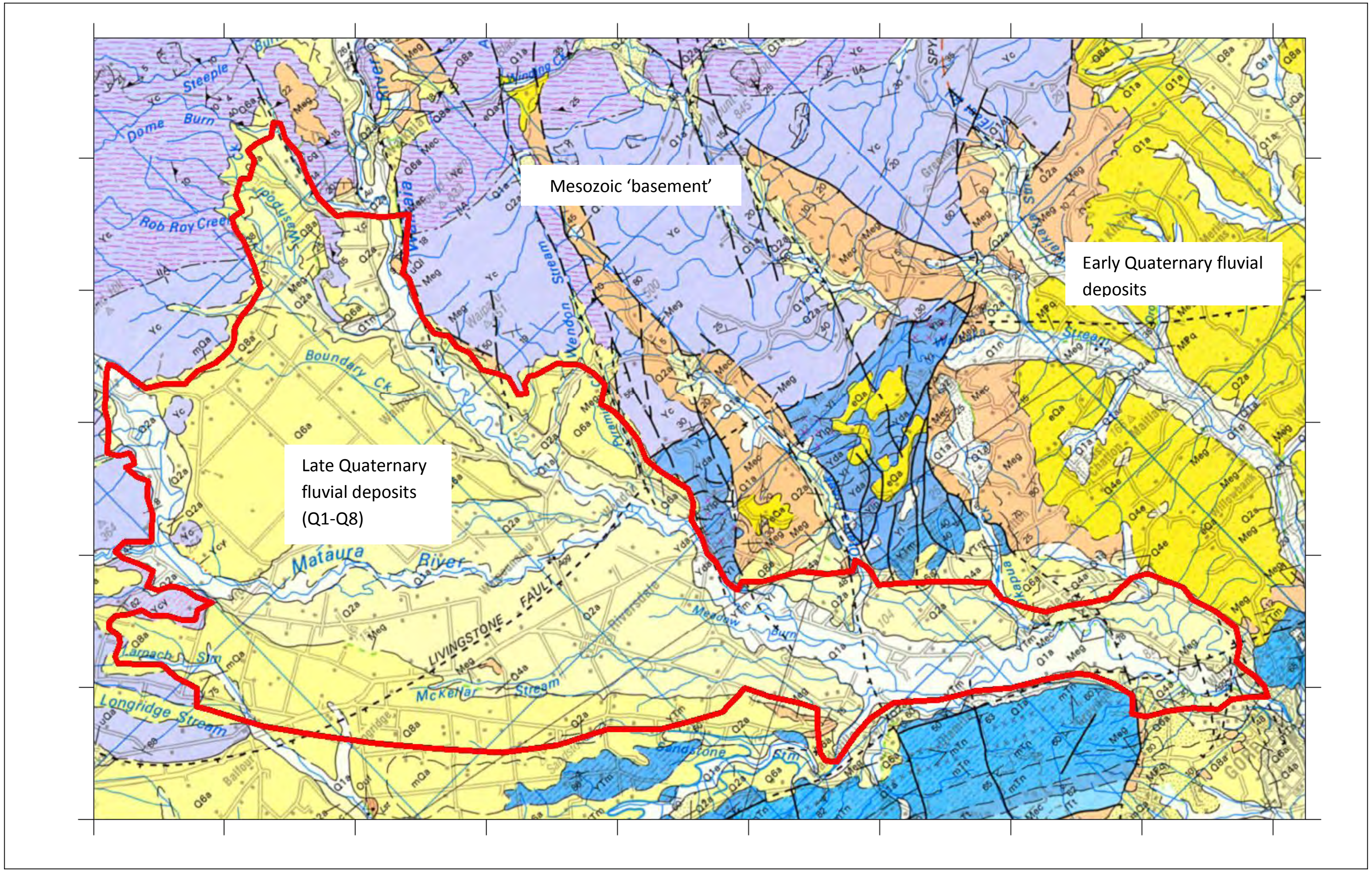


Figure 7: Geological map of study area (showing model boundary)

(source: GNS, 2003. Geology of the Murihiku area 1:2350,000 map 20)

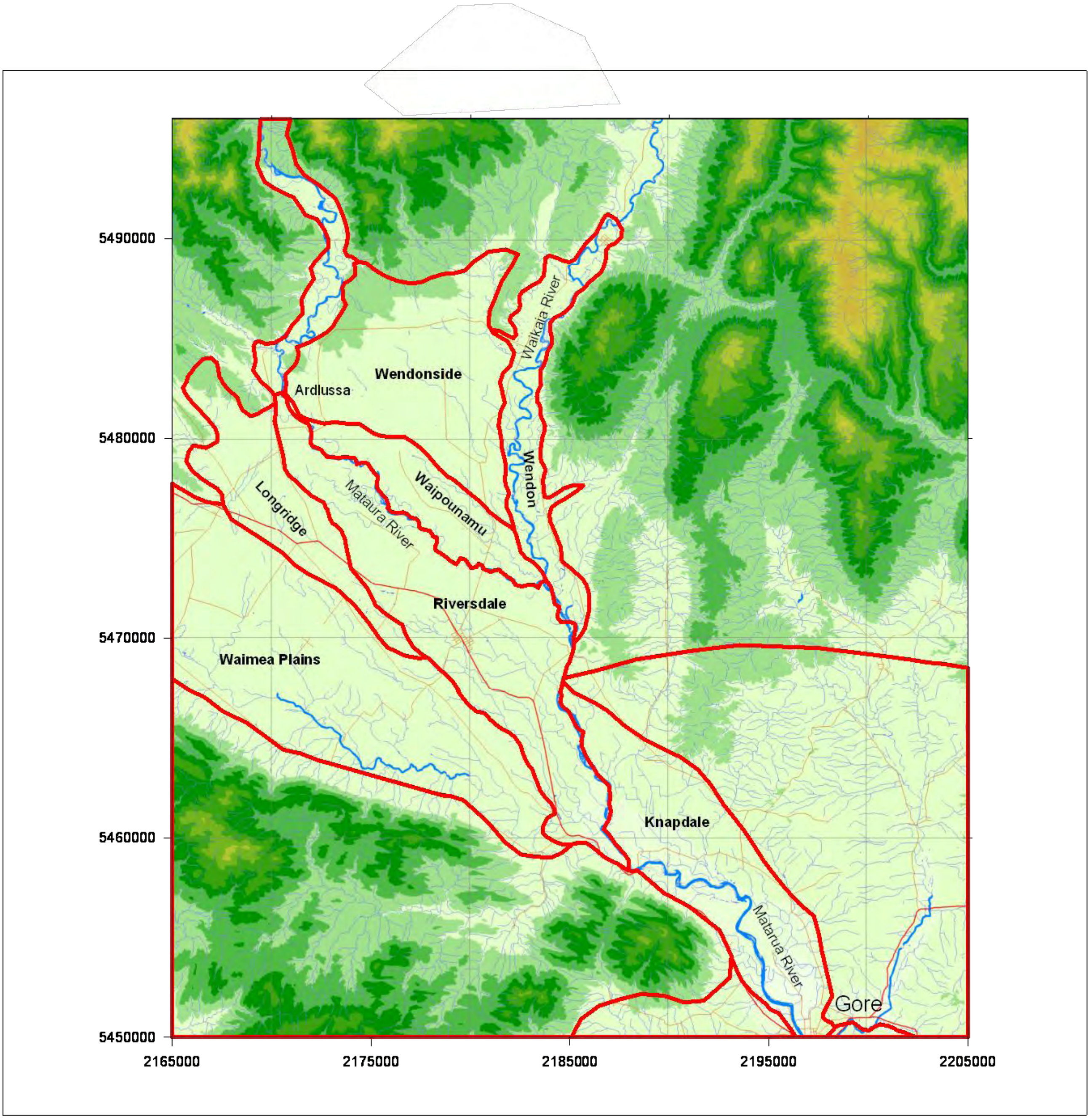


Figure 8: Groundwater management zones

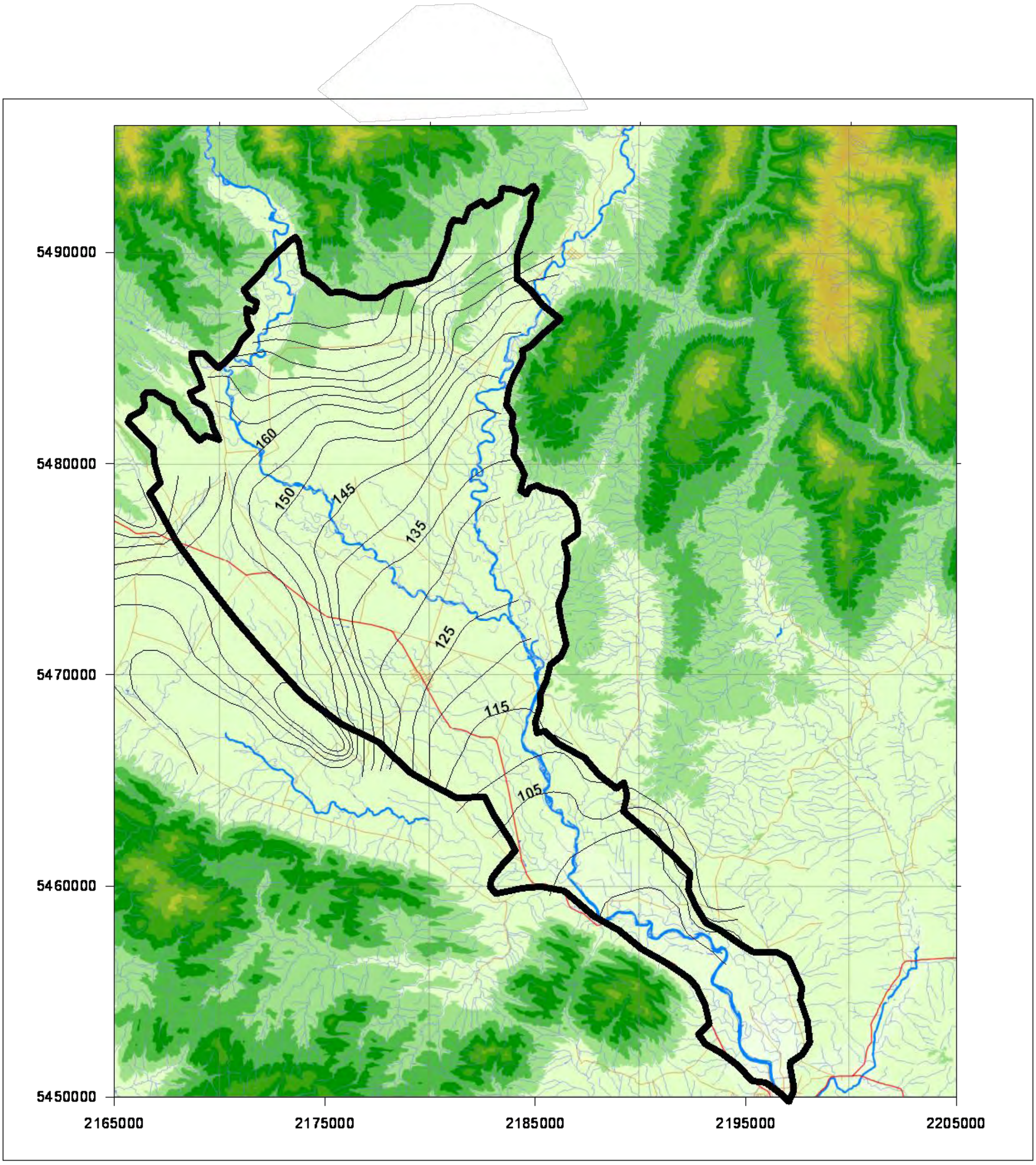


Figure 9: Water table contours (March 2004)

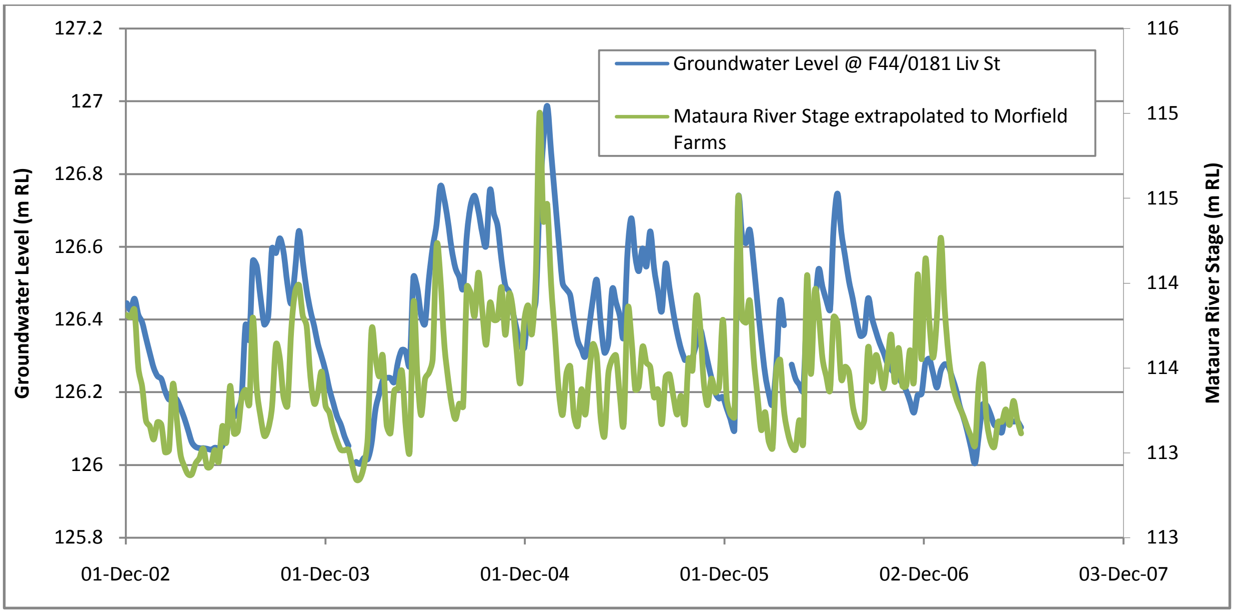


Figure 10: Groundwater level hydrograph for F44/0181

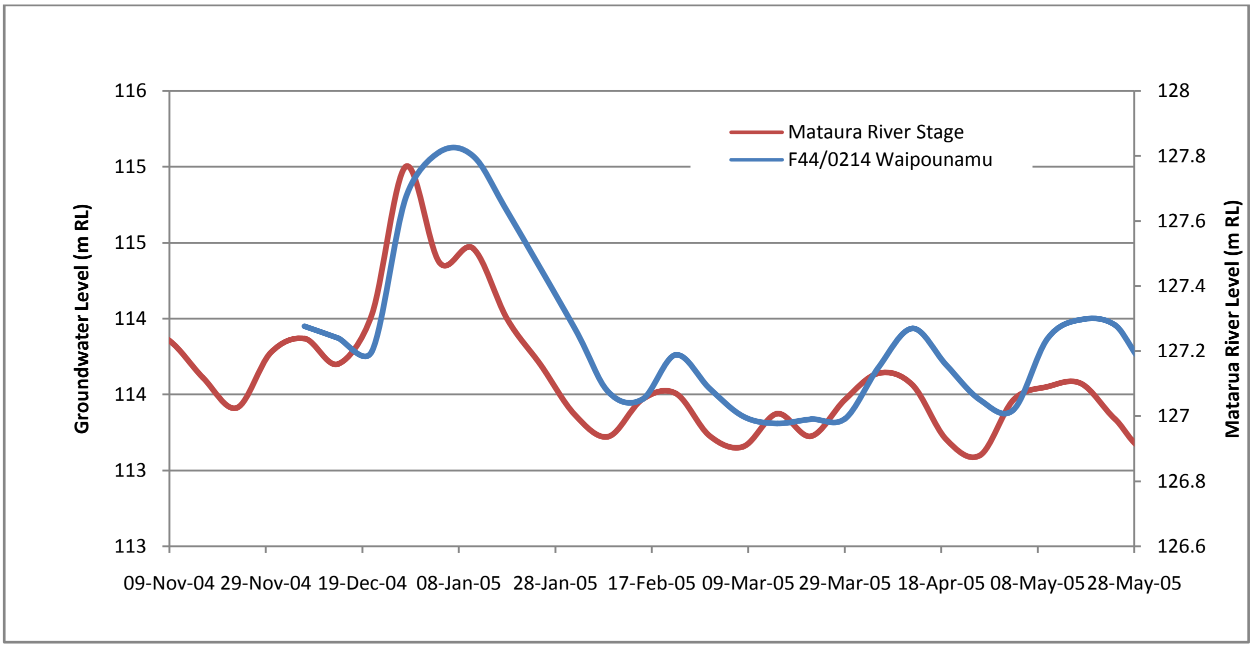


Figure 11: Six-month detail of F44/0214 hydrograph (Waipounamu Groundwater Zone)

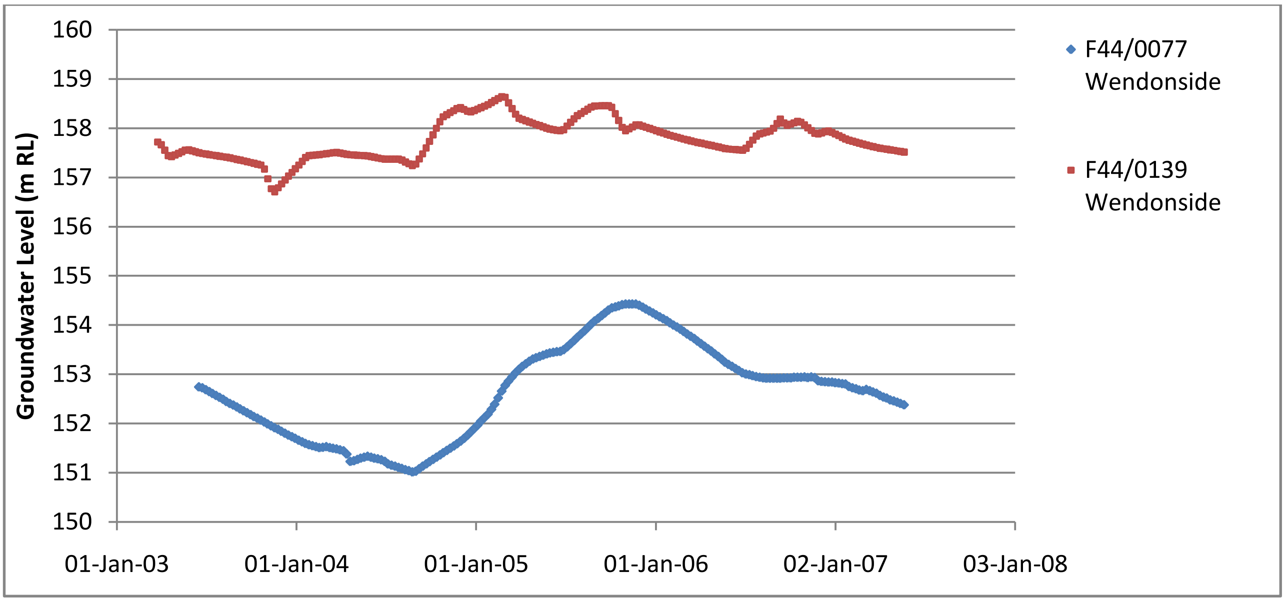


Figure 12: Groundwater level hydrographs for monitoring wells in the Wendonside Groundwater Zone

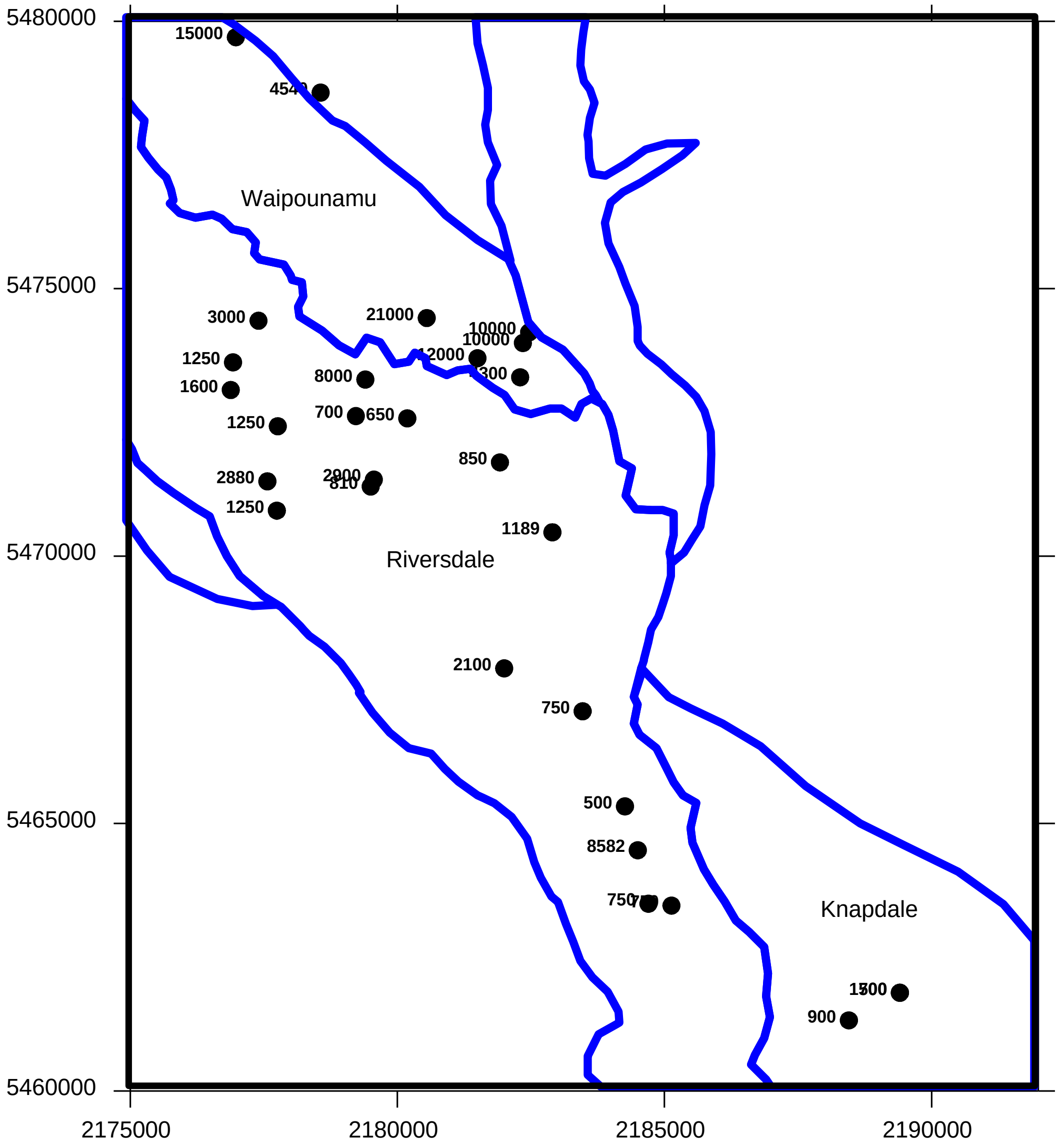


Figure 13: Transmissivity values for Riversdale, Waipounamu and Knapdale groundwater zones (values in m^2/day)

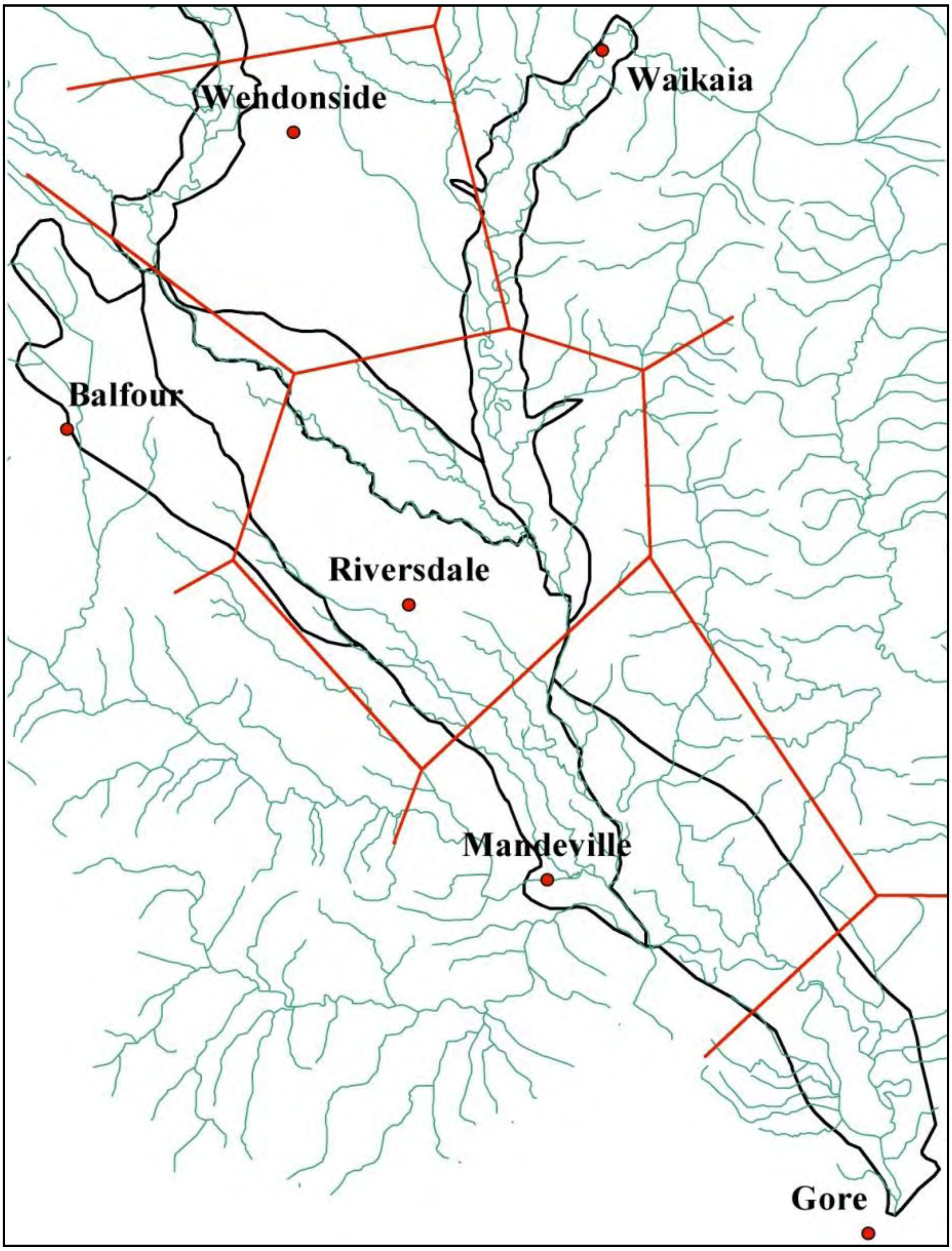


Figure 14: Rainfall recorder sites and associated Theissen polygons

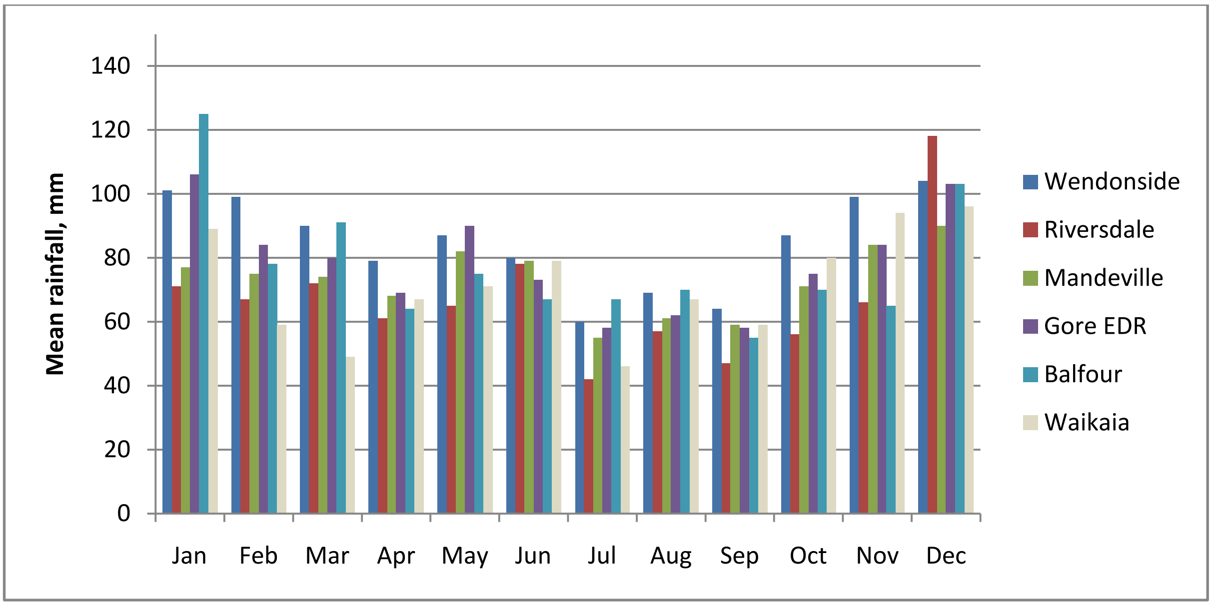


Figure 15: Mean monthly rainfall for rainfall recorder sites in model area

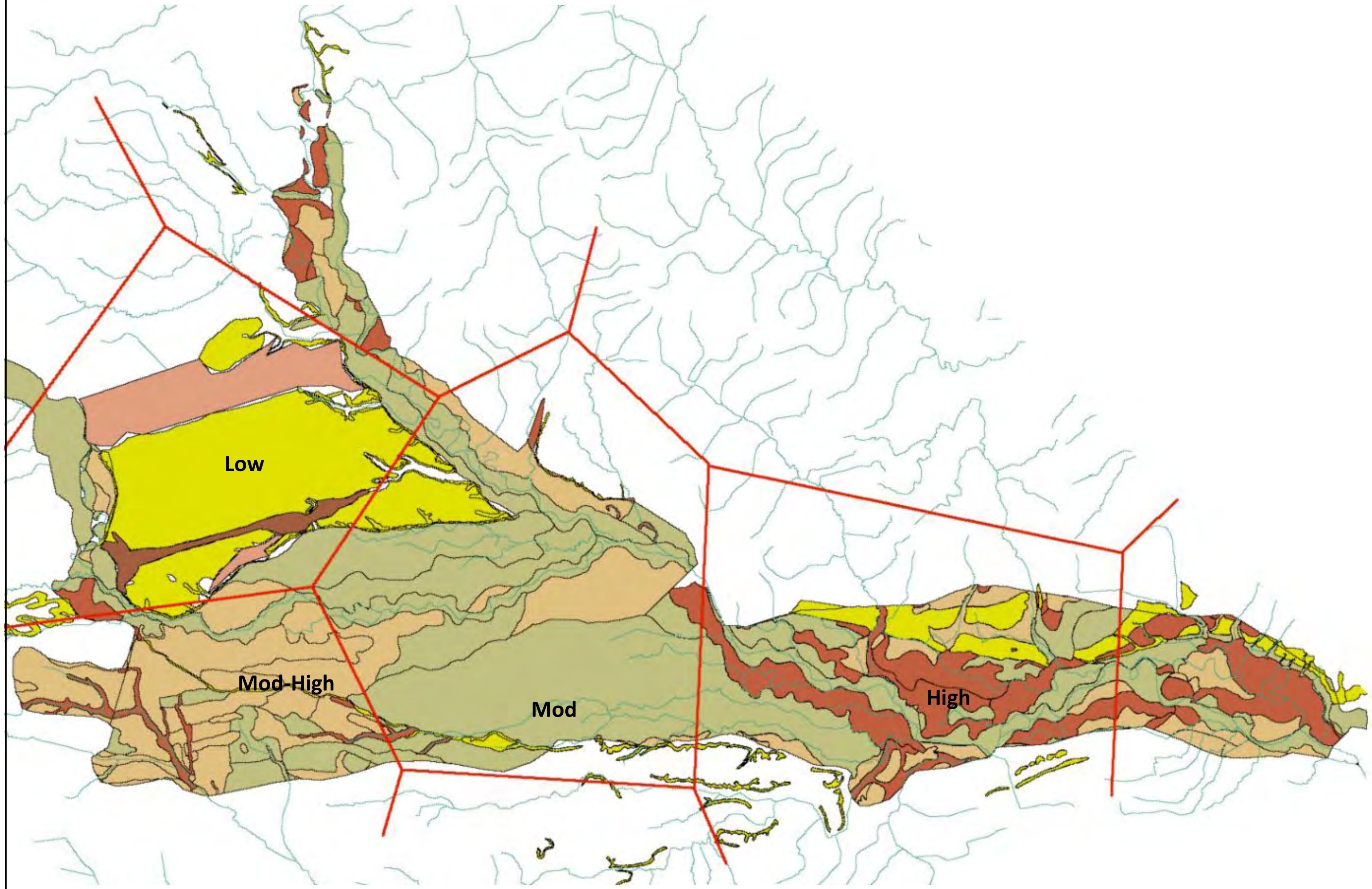


Figure 16: Soil drainage classes and Theissen polygons used for soil moisture balance model

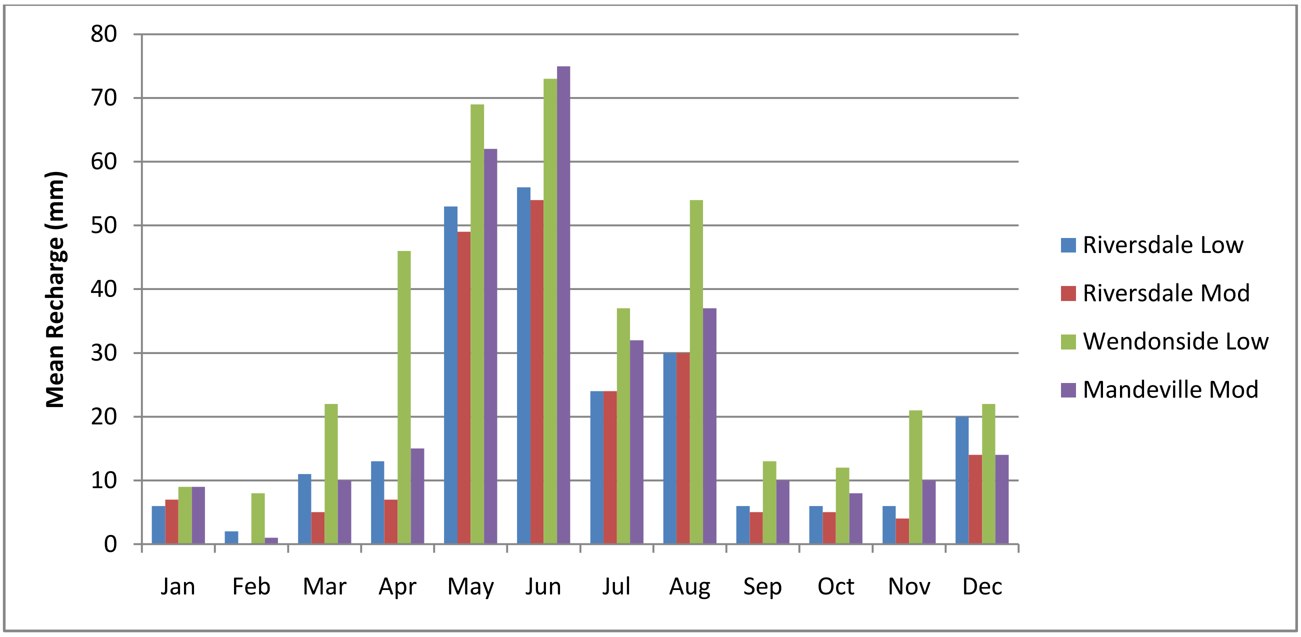


Figure 17: Calculated recharge using Rushton et al (2006) soil moisture balance model for Riversdale, Wendonside and Mandeville Theissen polygons and dominant soil drainage classes (Low + Mod).

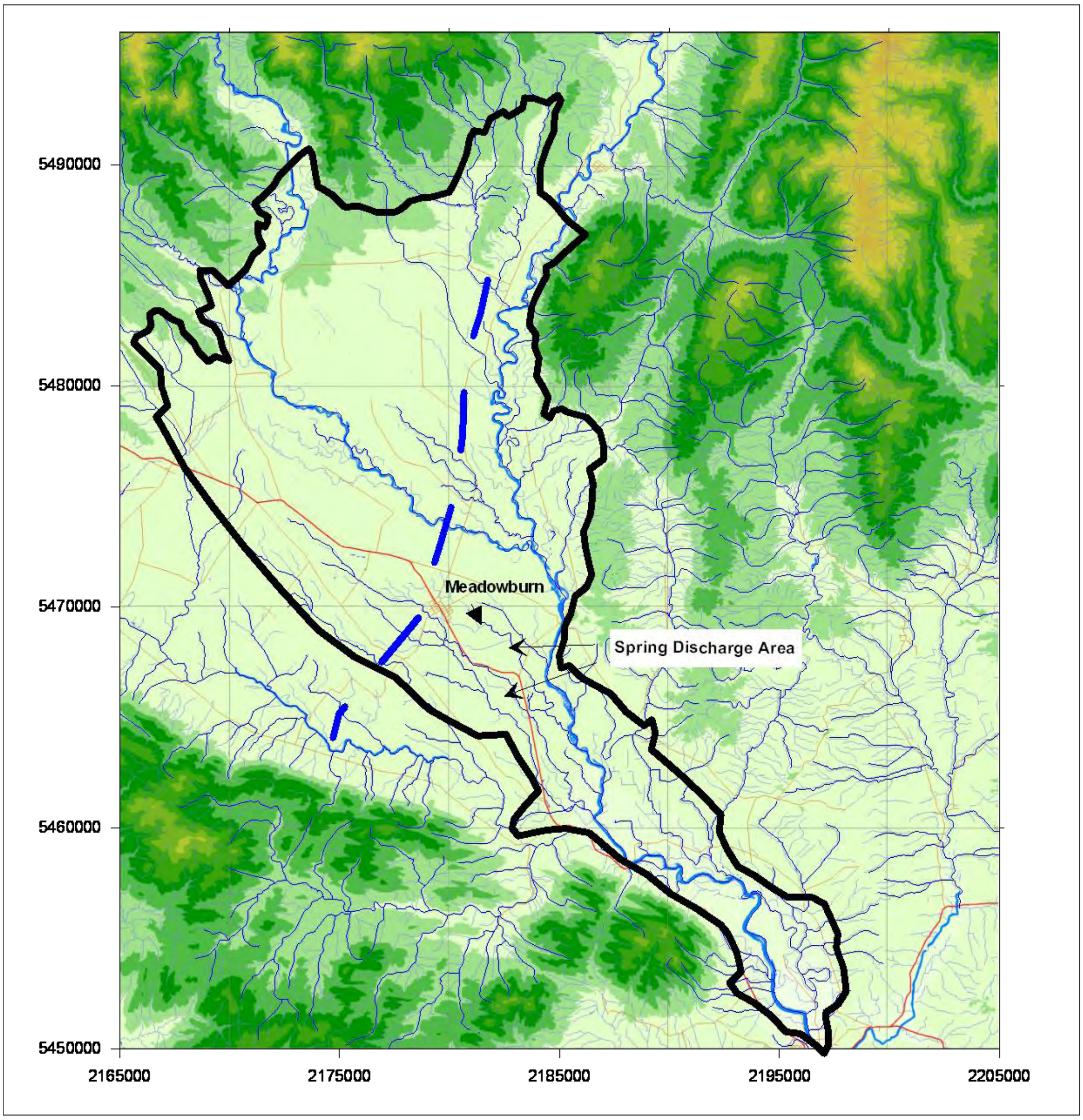


Figure 18: Groundwater discharge zone (occurs east of dashed blue line), and spring discharge zone around Riversdale

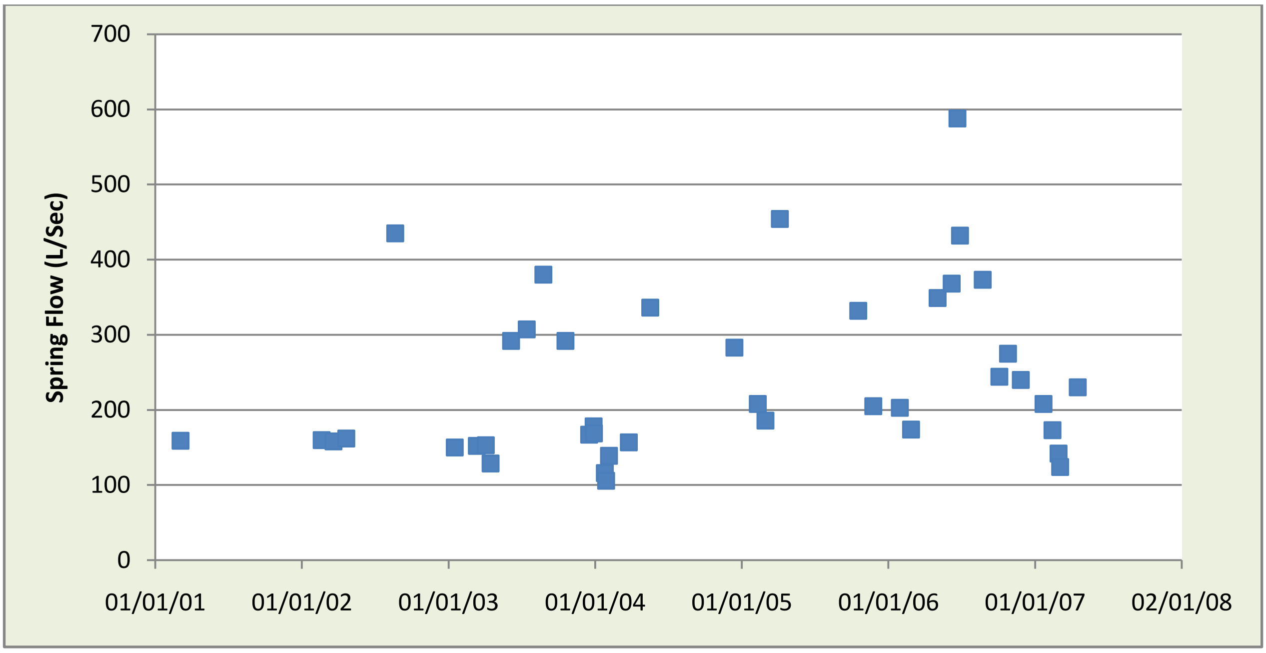


Figure 19: Flow gauging in the Meadow Burn at Fingerpost-Pyramid Road

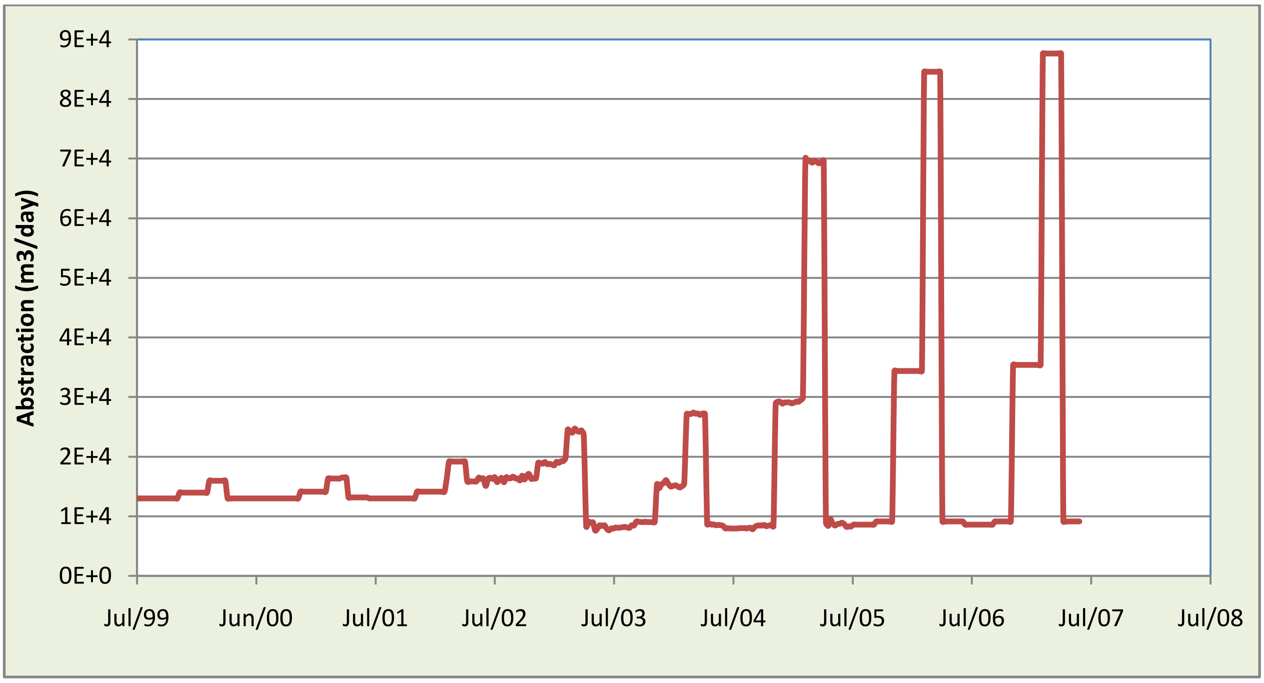


Figure 20: Estimated groundwater abstraction in the mid-Mataura catchment

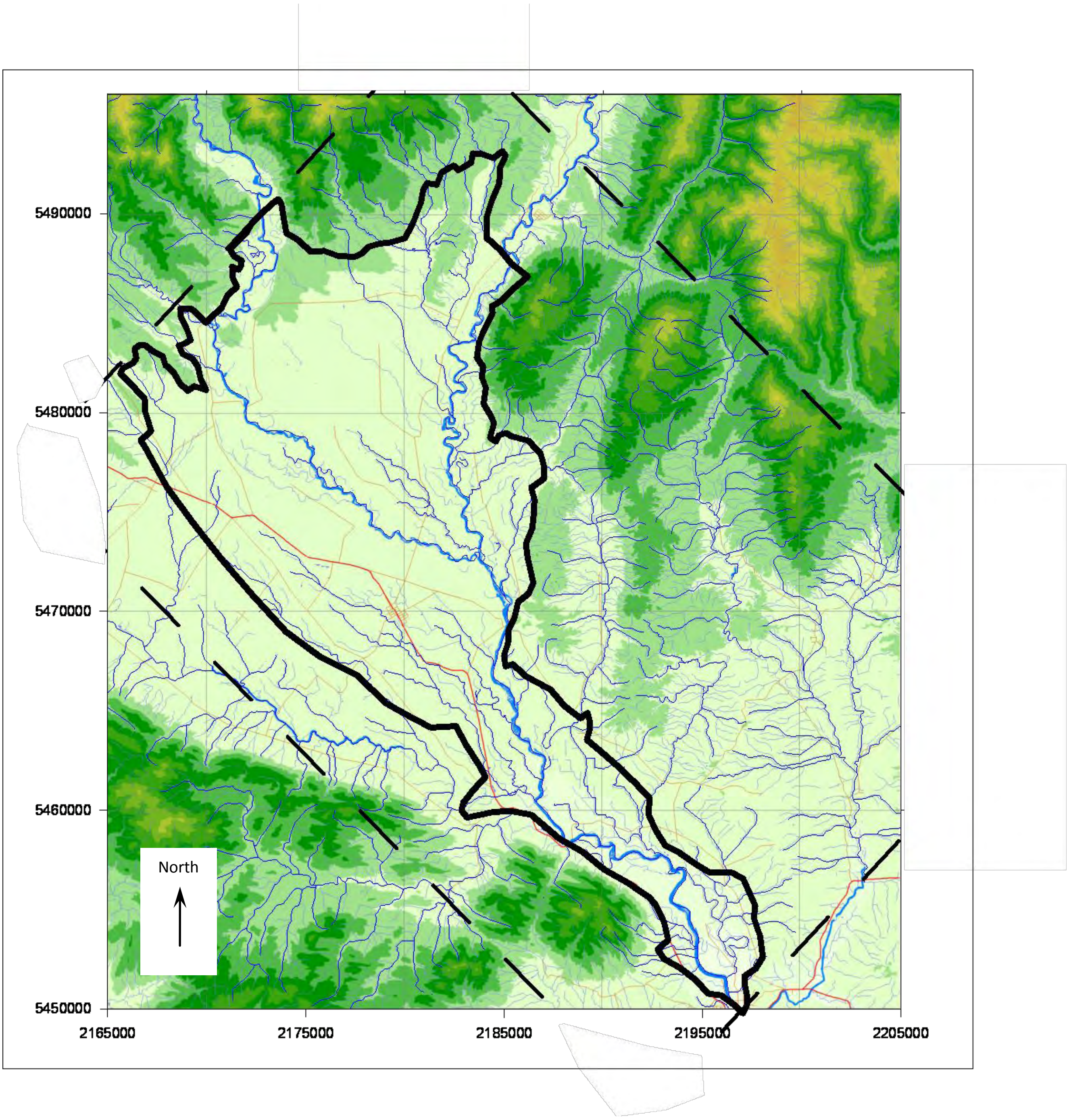


Figure 21: Grid orientation and model grid limits (dashed black line), and active model domain (solid black line)

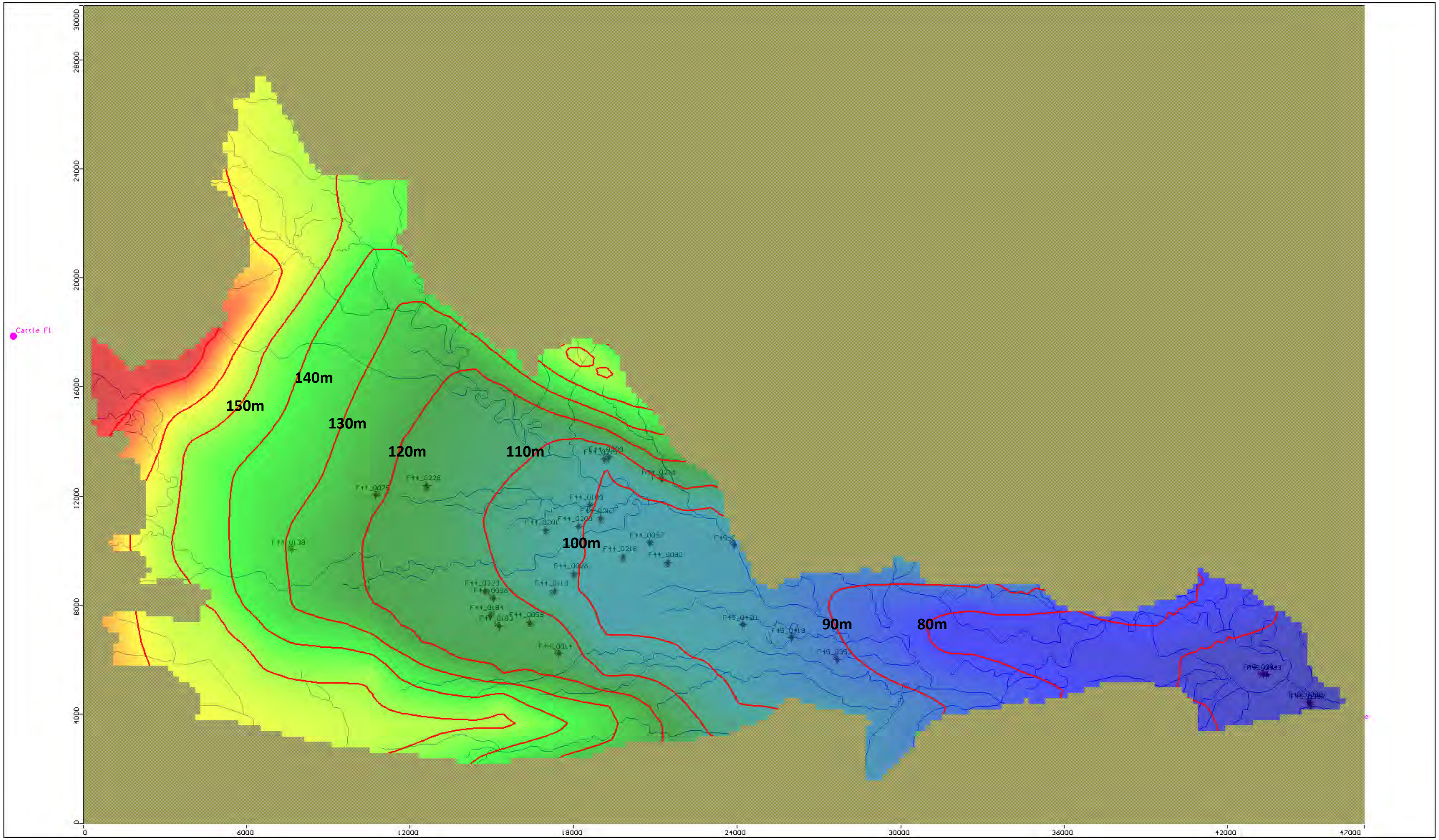


Figure 22: Modelled aquifer base

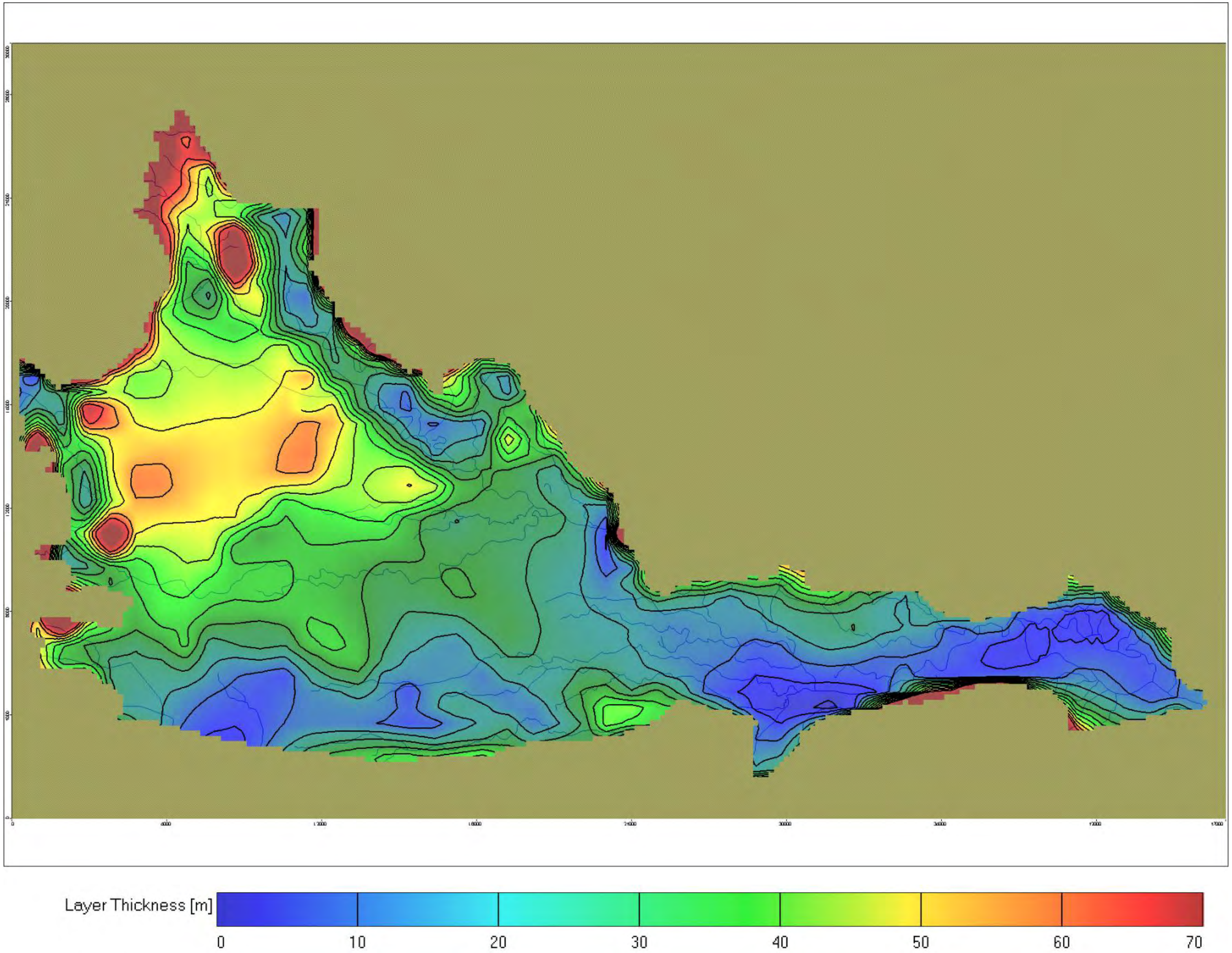


Figure 23: Layer 1 (aquifer) thickness

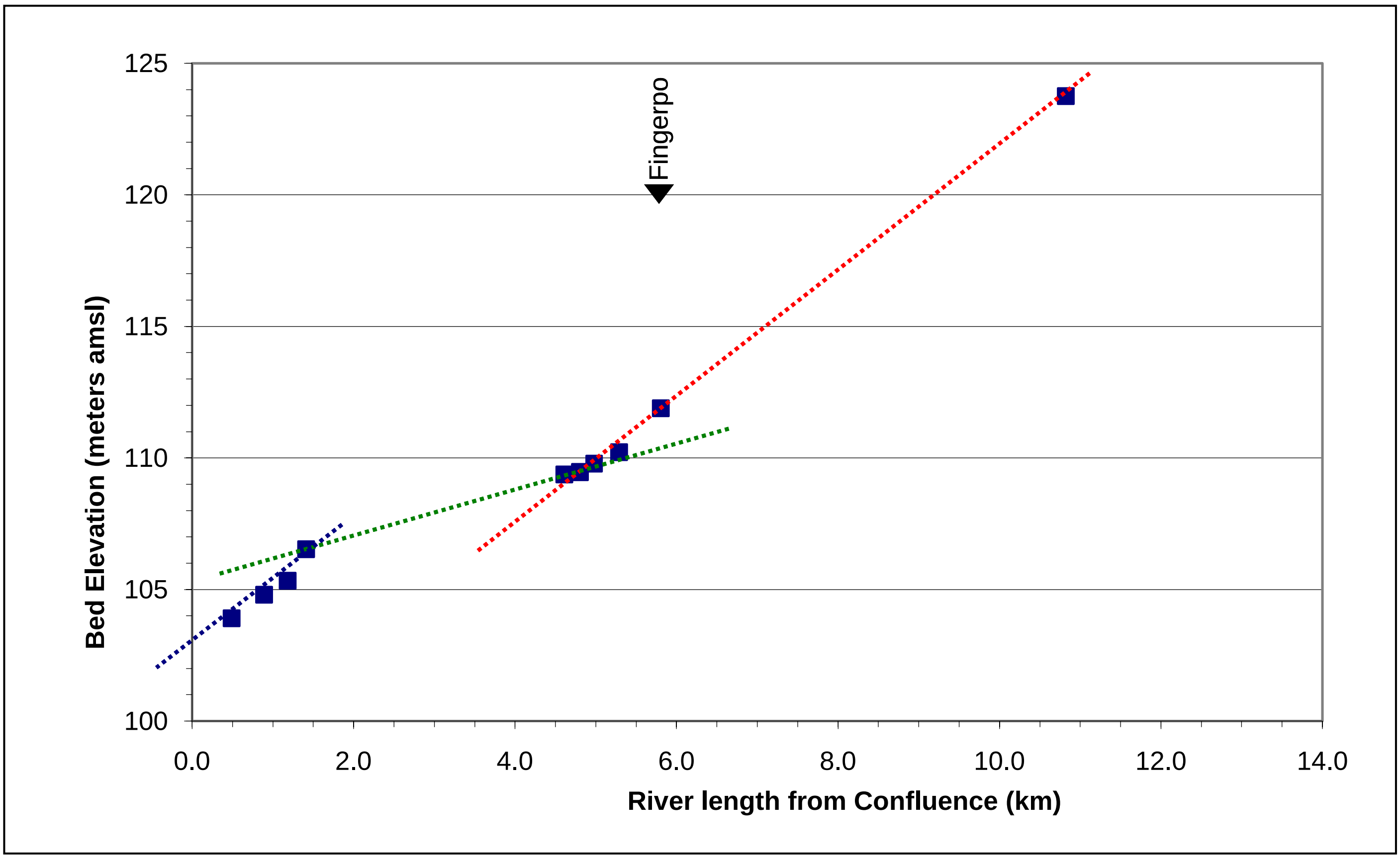


Figure 24: Surveyed bed elevations for Meadow Burn

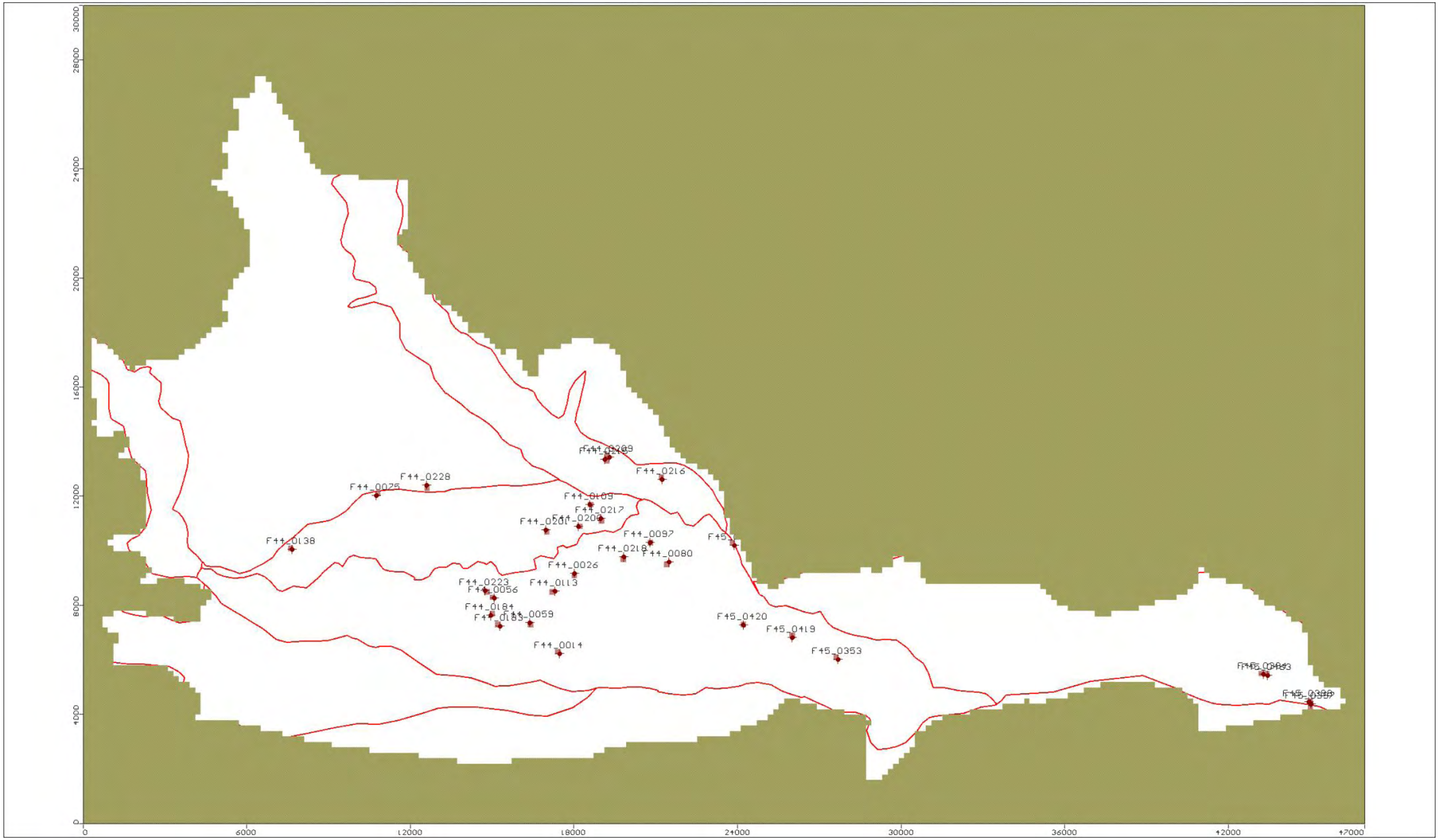


Figure 25: Location of pumping wells

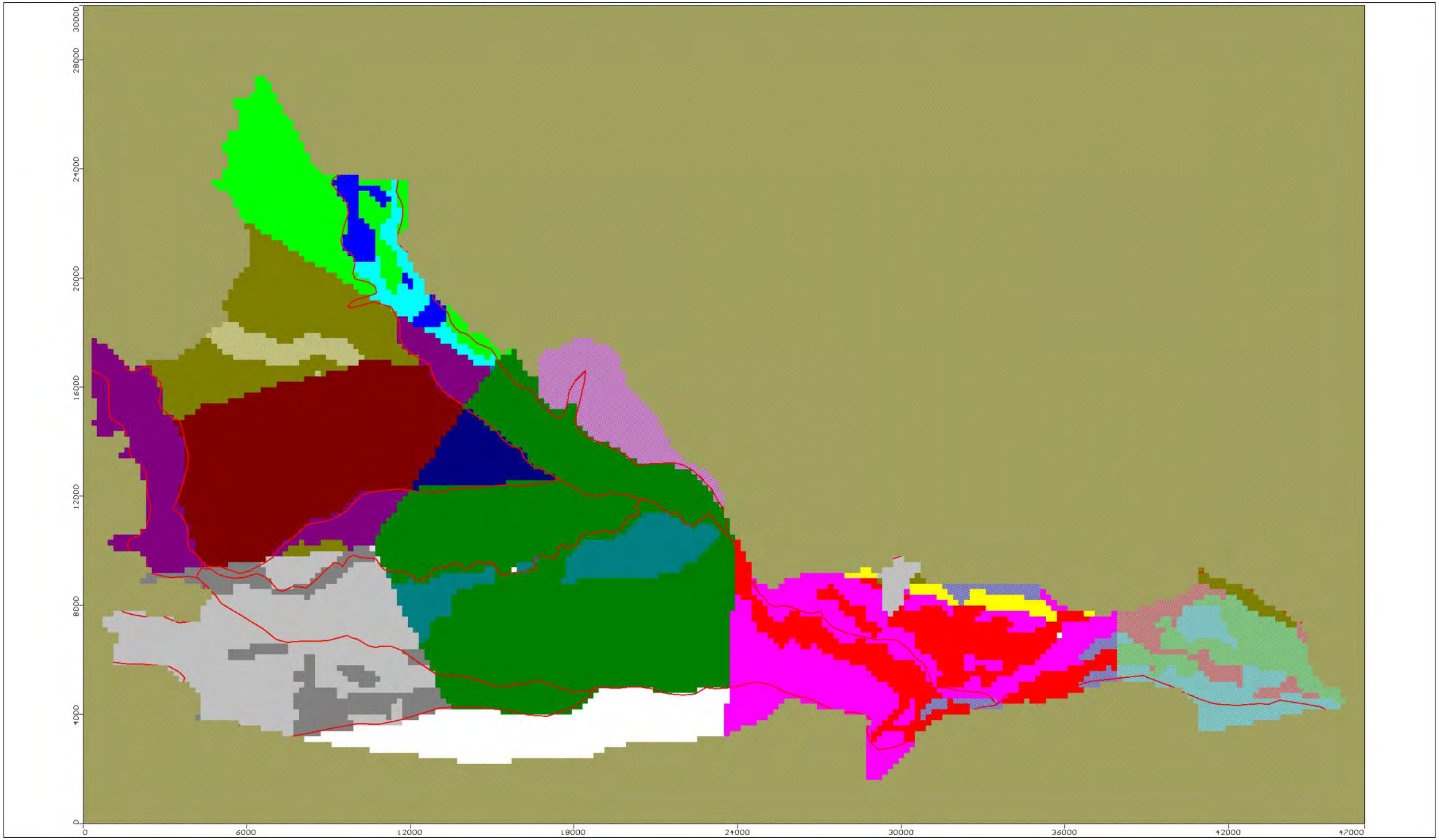


Figure 26: Recharge zones based on Theissen polygons for rainfall distribution and soil properties.

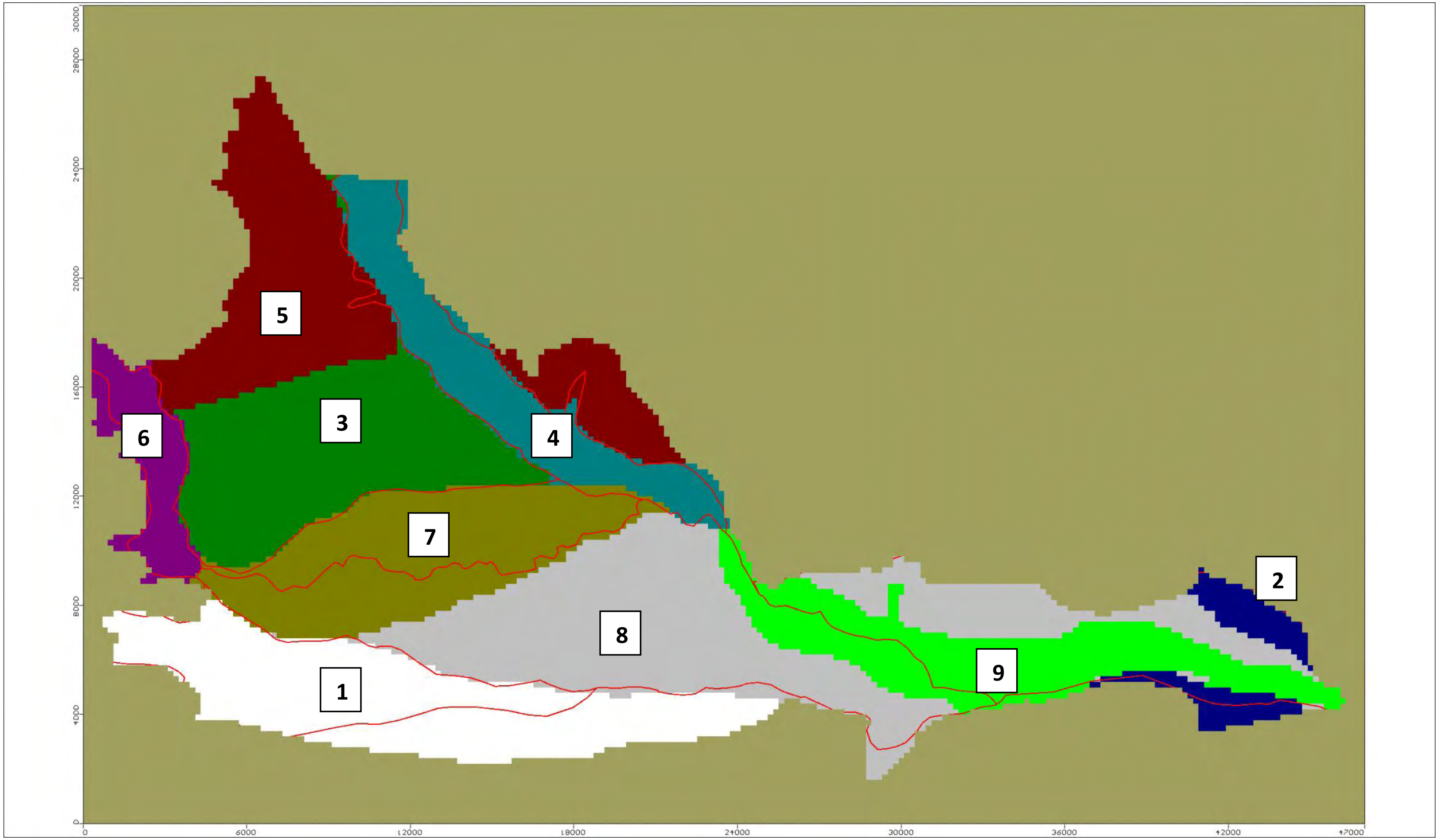
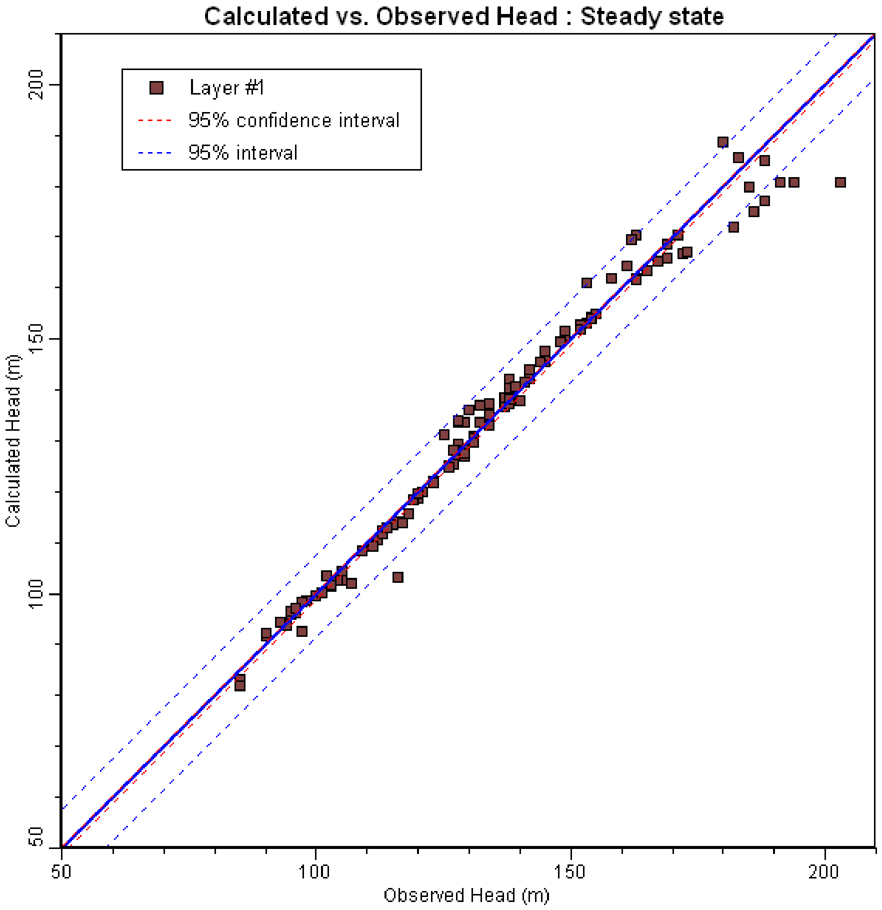


Figure 27: Hydraulic conductivity zones



Num. of Data Points : 122
Max. Residual: -22.084 (m) at F44_0061/1
Min. Residual: 0.023 (m) at F44_0173/1
Residual Mean : -0.467 (m)
Abs. Residual Mean : 2.587 (m)

Standard Error of the Estimate : 0.375 (m)
Root Mean Squared : 4.155 (m)
Normalized RMS : 3.521 (%)
Correlation Coefficient : 0.988

Figure 28: Steady state model calibration observed and modelled head comparison.

Figure 29: Simulated vs Gauged Flow in the Mataura River @ Gore

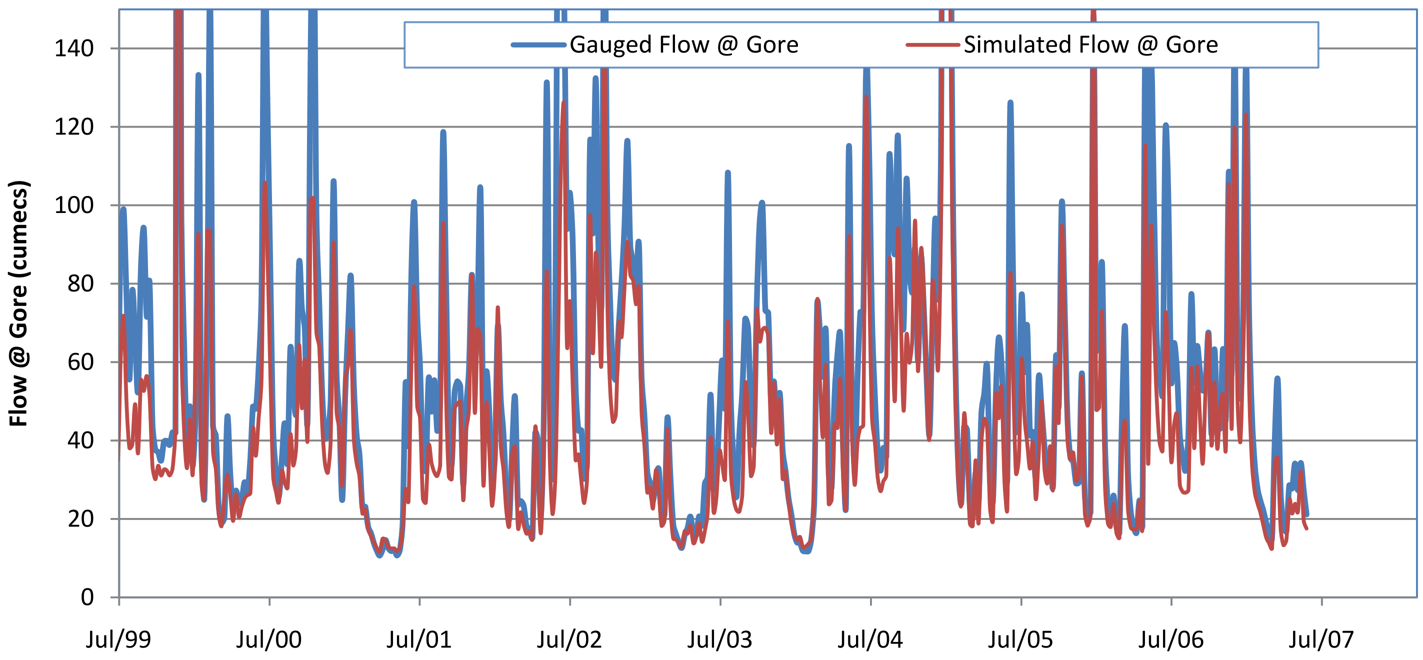


Figure 30: Simulated flow reduction at Pyramid Bridge - all wells pumping

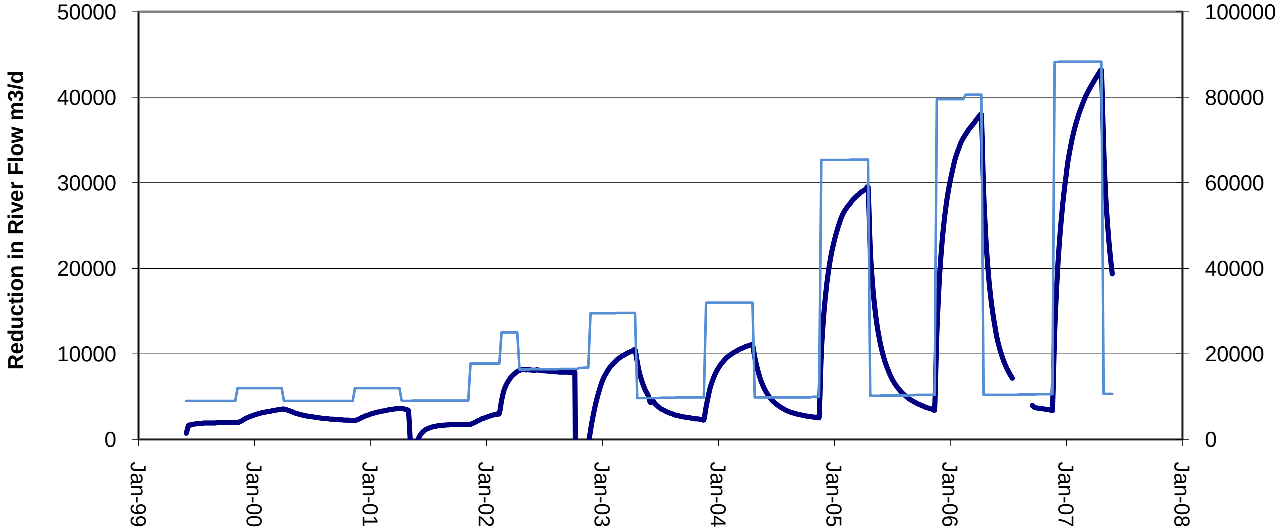


Figure 31: Simulated flow reduction at Pyramid Bridge as percentage of flow in the Mataura River - All wells pumping

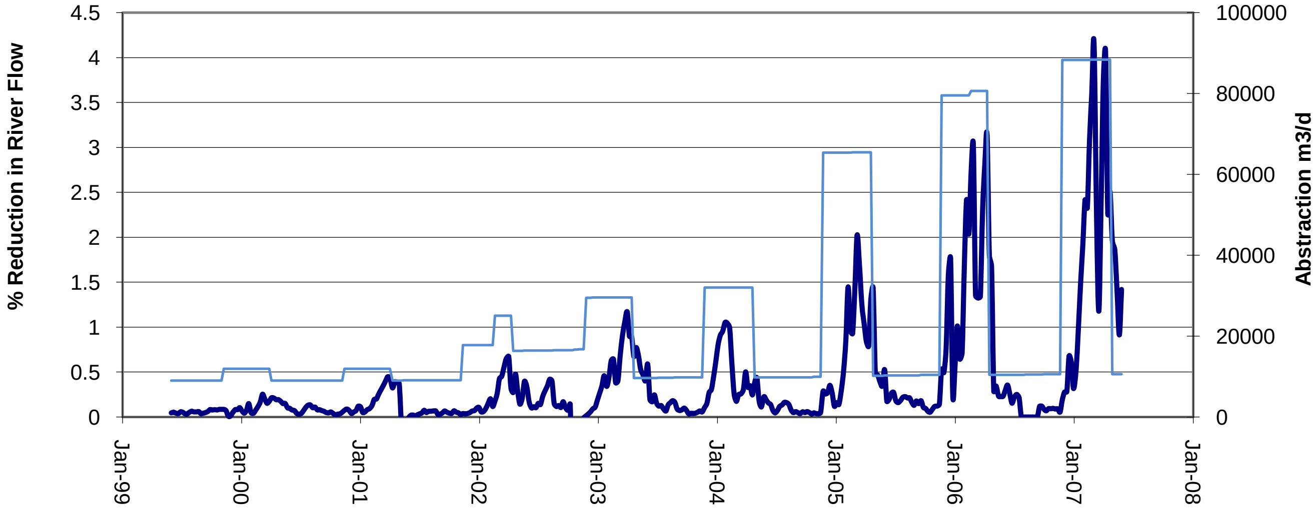


Figure 32: Simulated flow reduction at Riversdale Bridge - All wells pumping

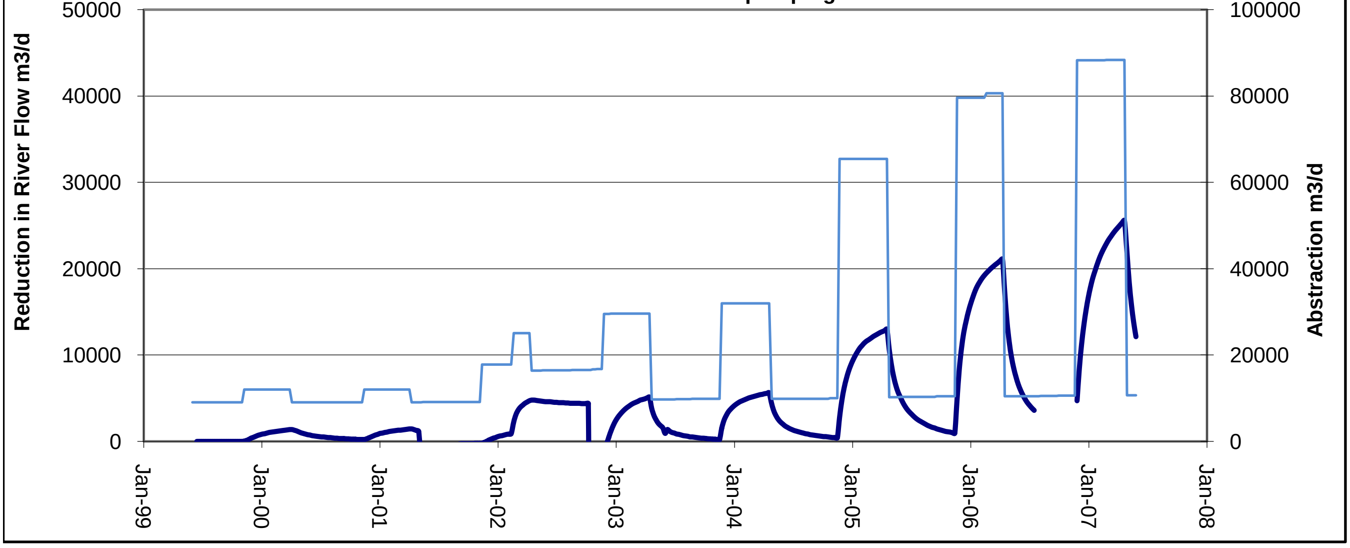


Figure 33: Simulated flow reduction at Riversdale Bridge as percentage of flow in the Mataura River - All wells pumping

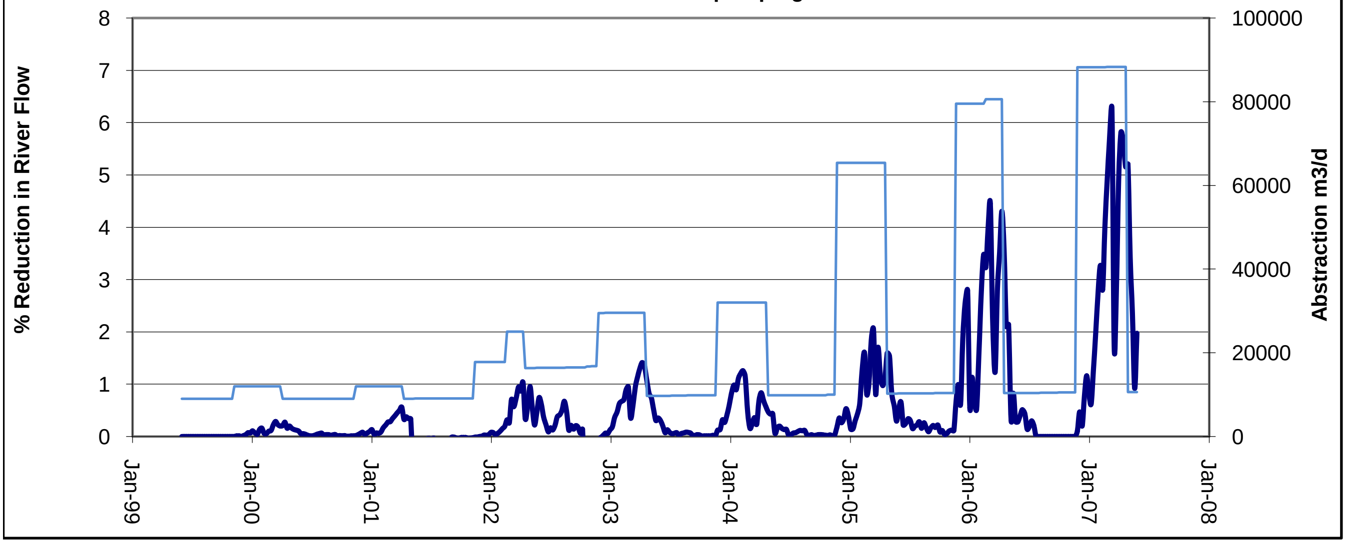


Figure 34: Simulated total springflow depletion in Riversdale GW Zone - all wells pumping

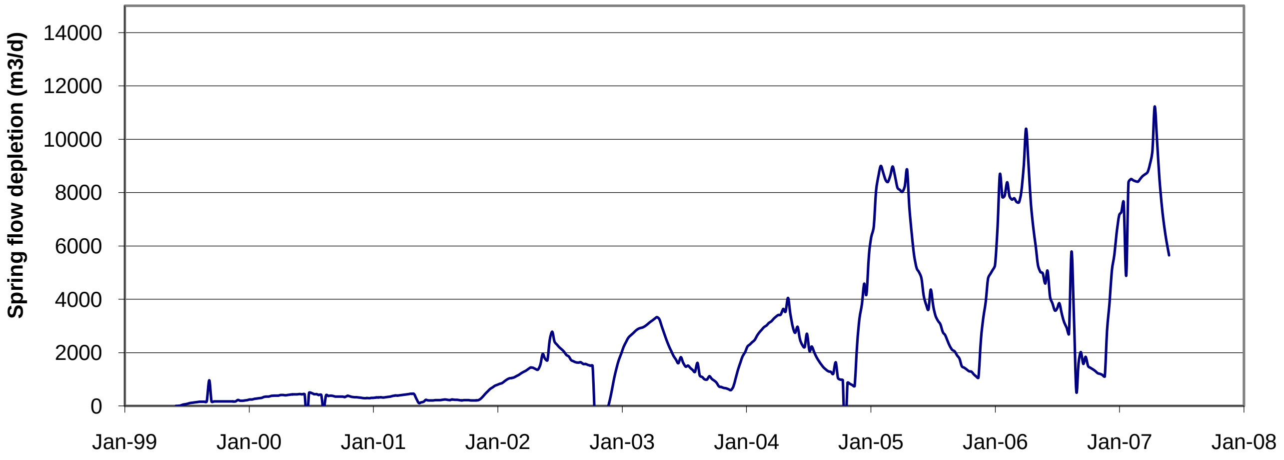
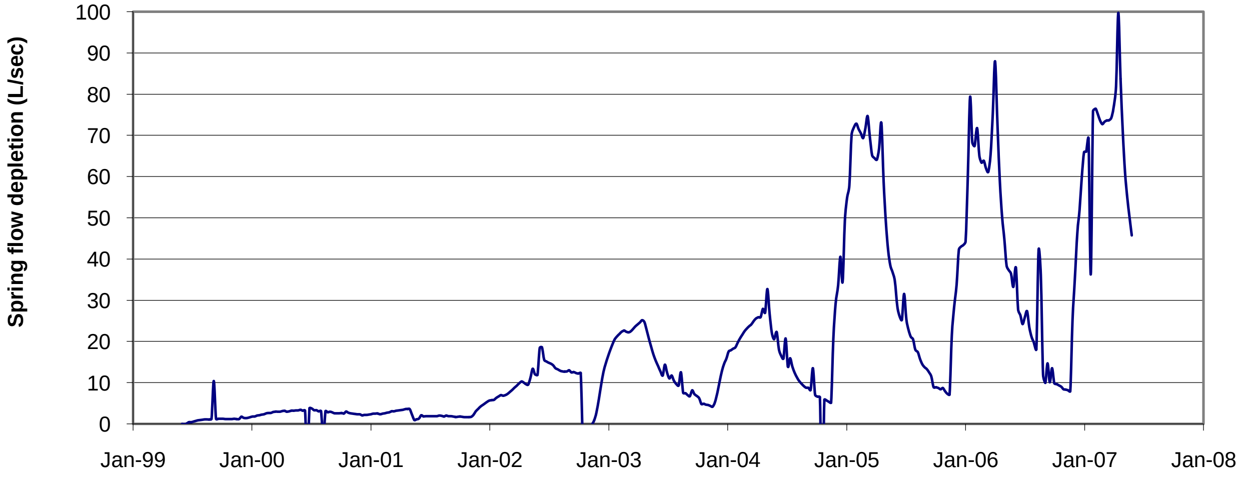


Figure 35: Simulated springflow depletion in Meadow Burn - All wells



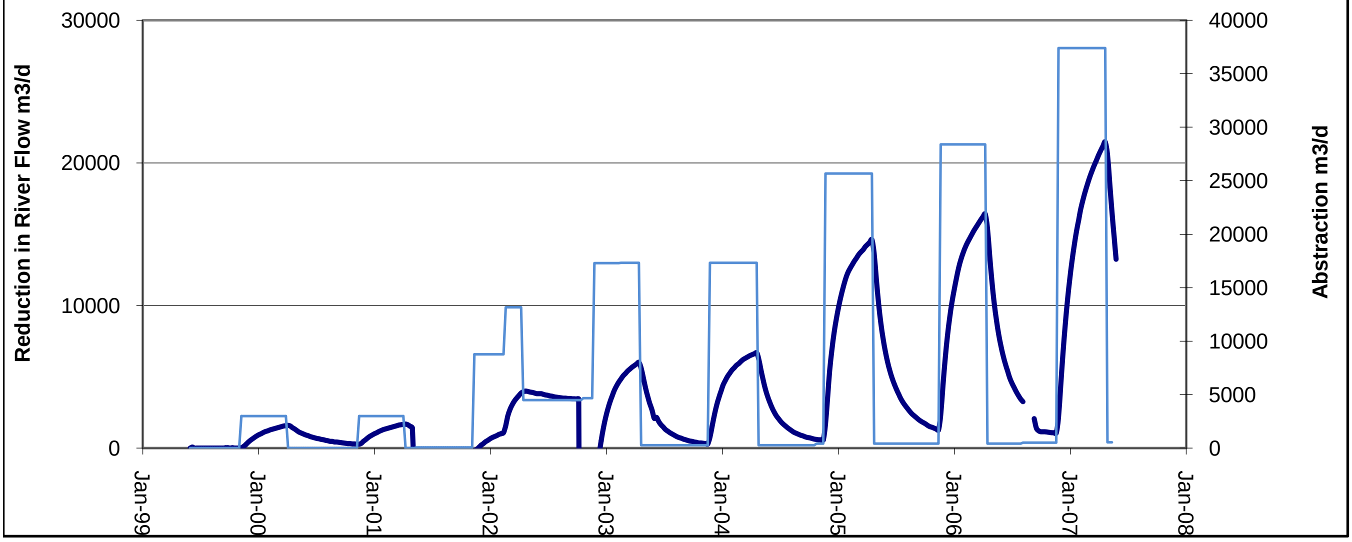


Figure 36: Simulated flow reduction at Pyramid Bridge - all wells except High/Direct SFD

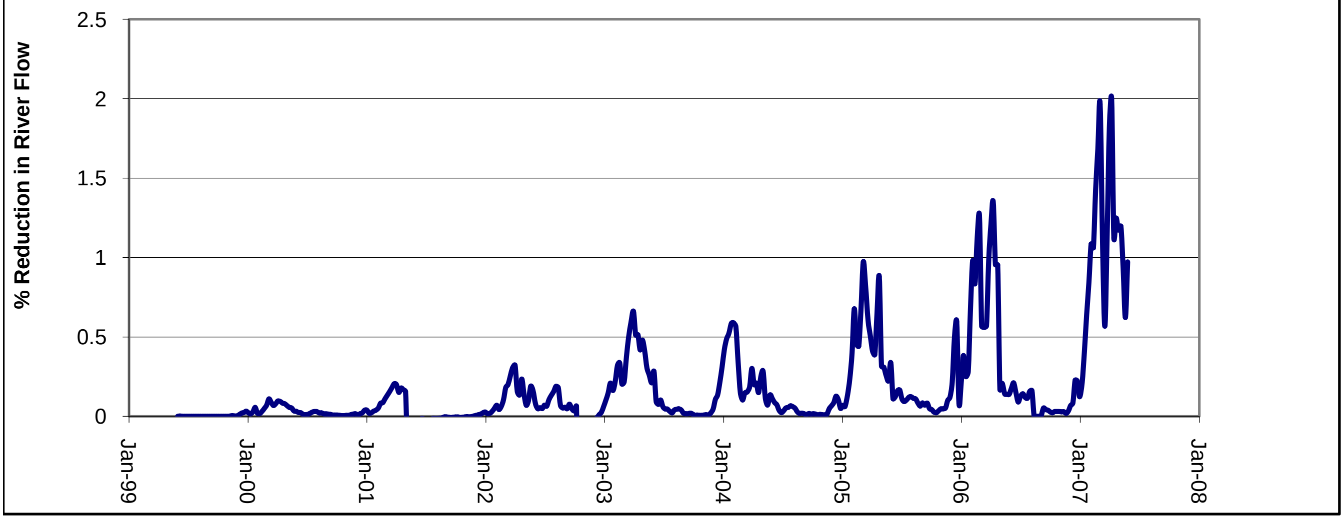


Figure 37: Simulated flow reduction at Pyramid Bridge as percentage of flow in the Mataura River all wells except High/Direct SFD

Figure 38: Simulated flow reduction at Riversdale Bridge - all wells except High/Direct SFD

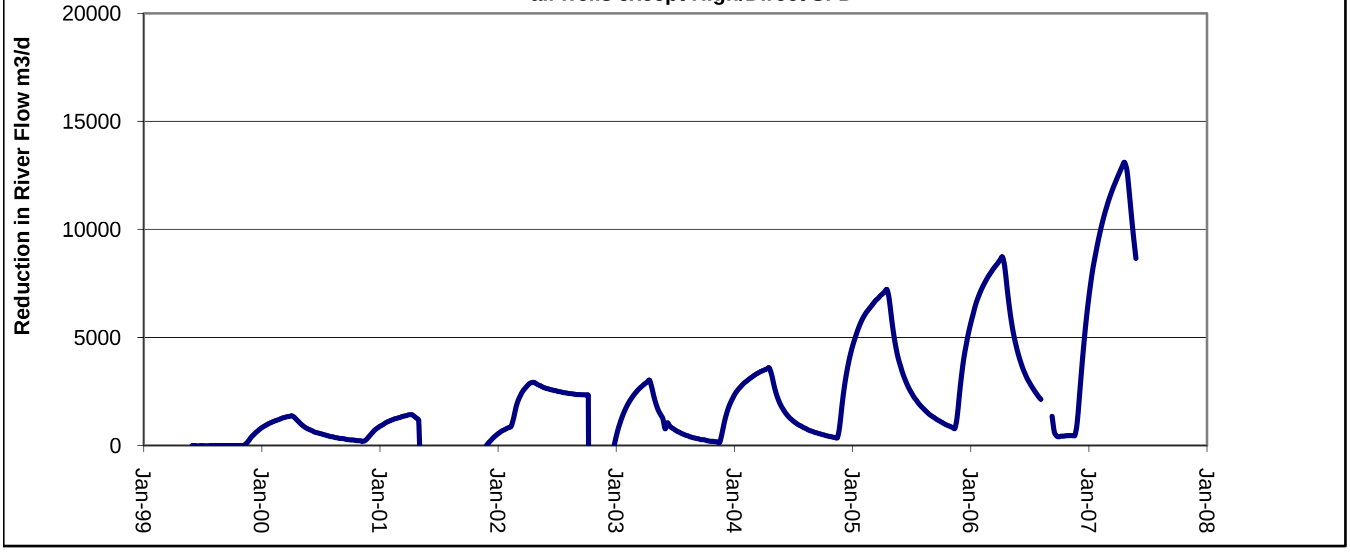


Figure 39: Simulated flow reduction at Riversdale Bridge as percentage of flow in the Mataura River - all wells except High/Direct SFD

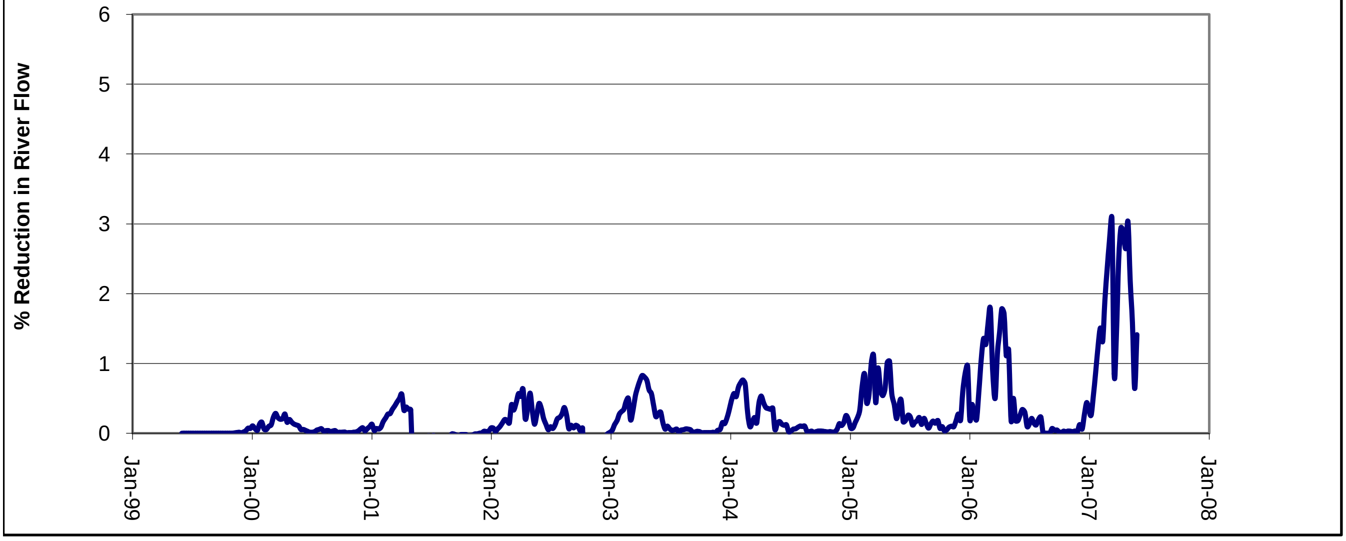


Figure 40: **Simulated total springflow depletion in Riversdale GW Zone all wells except High/Direct SFD**

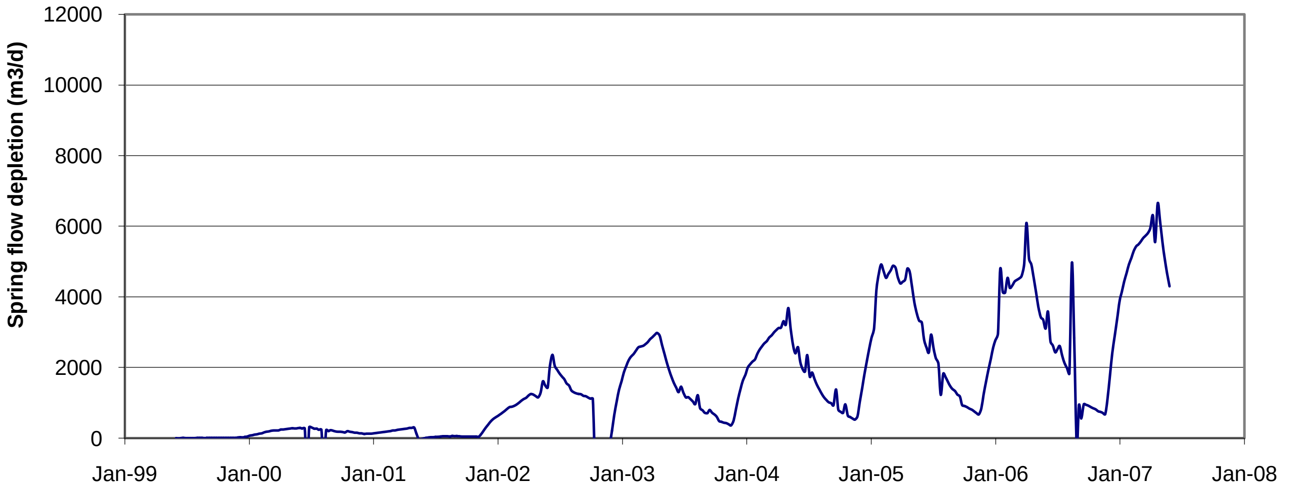


Figure 41: **Simulated springflow depletion in Meadow Burn all wells except High/Direct SFD**

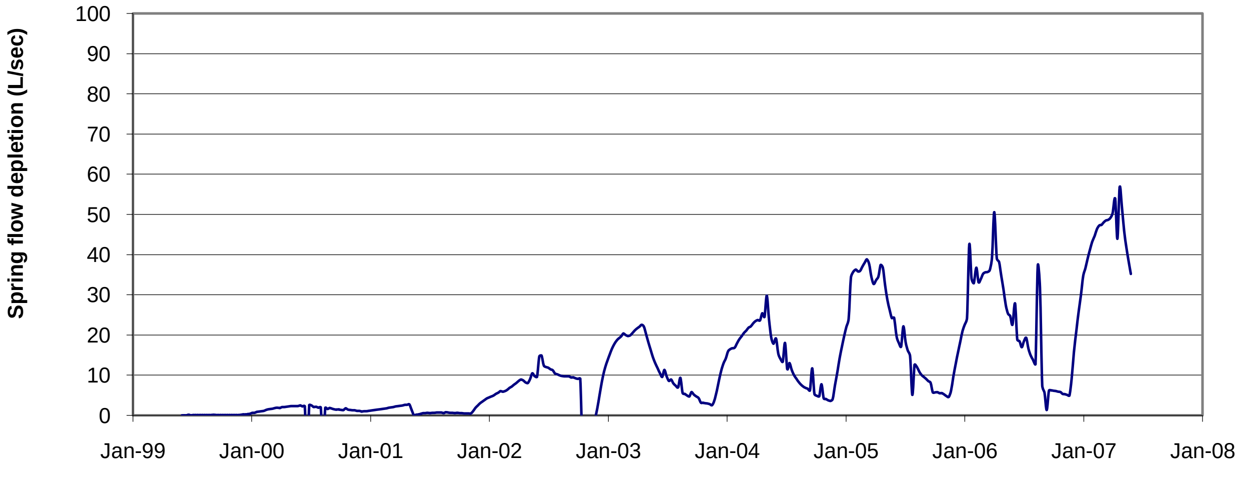


Figure 42: Simulated flow depletion at Riversdale Bridge: All wells except High/Direct SFD; pumping at 2006-07 rates

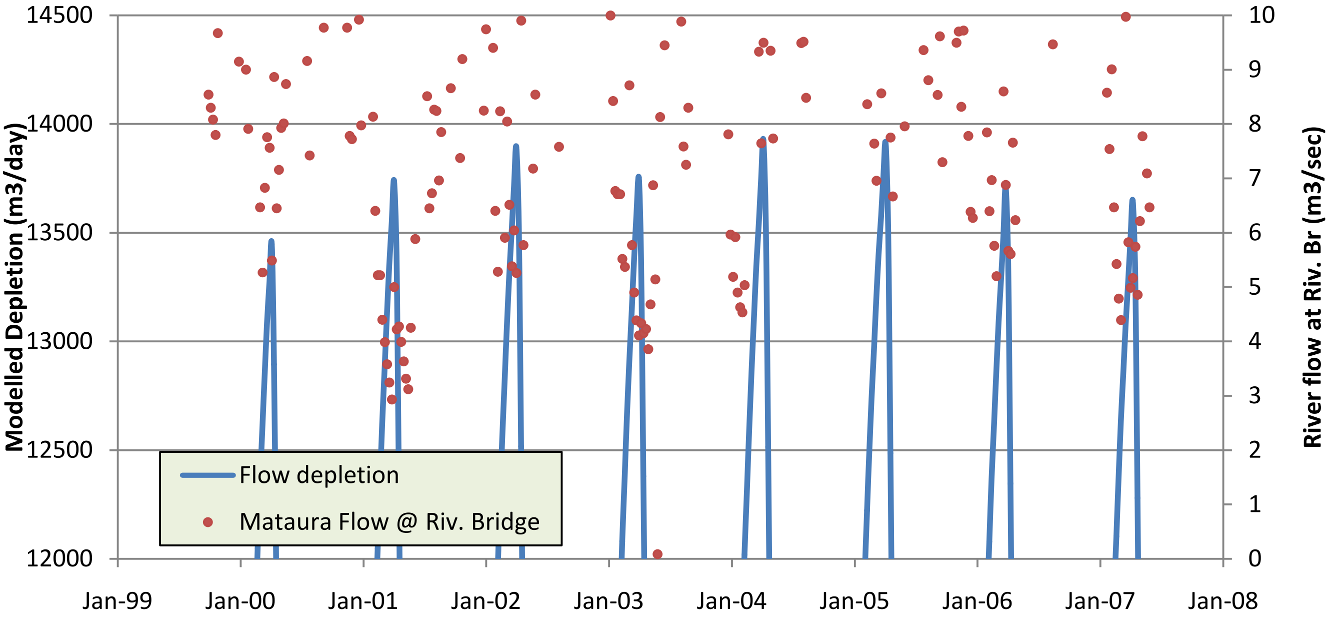


Figure 43: Calculated river flow depletion effects of current and increased abstraction from wells classified with moderate and low SFD, and <2L/sec wells

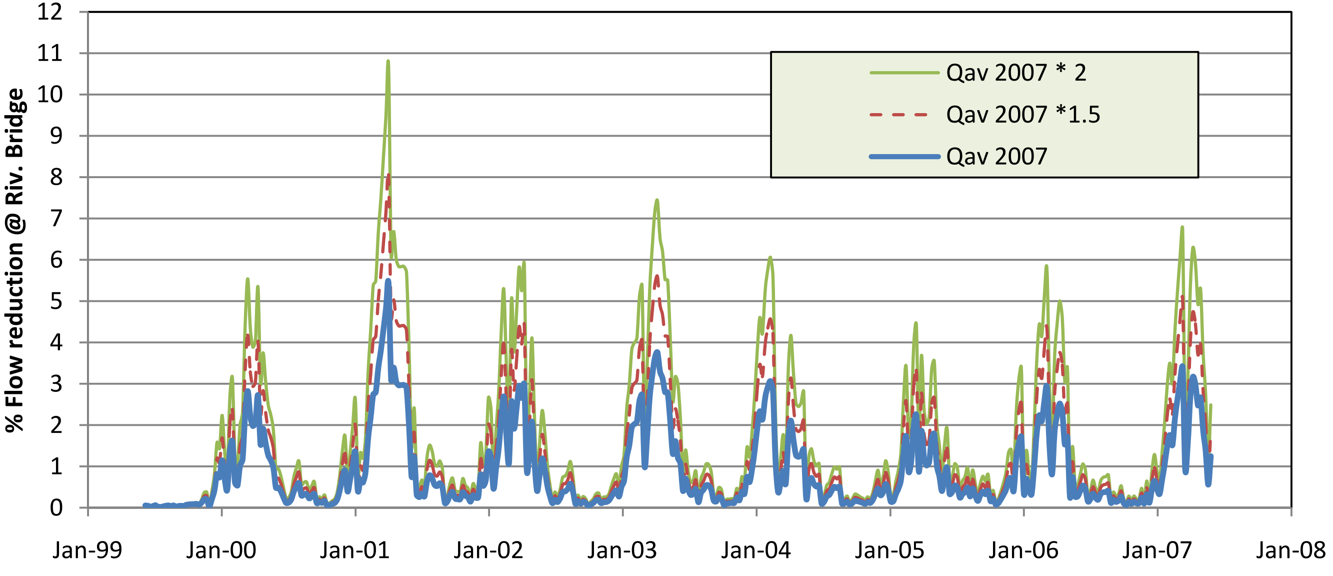


Figure 44: Cumulative depletion effects of 2006/7 groundwater abstractions on Matuara River flow at Riversdale Bridge (all bores except those with High/Direct SFD).

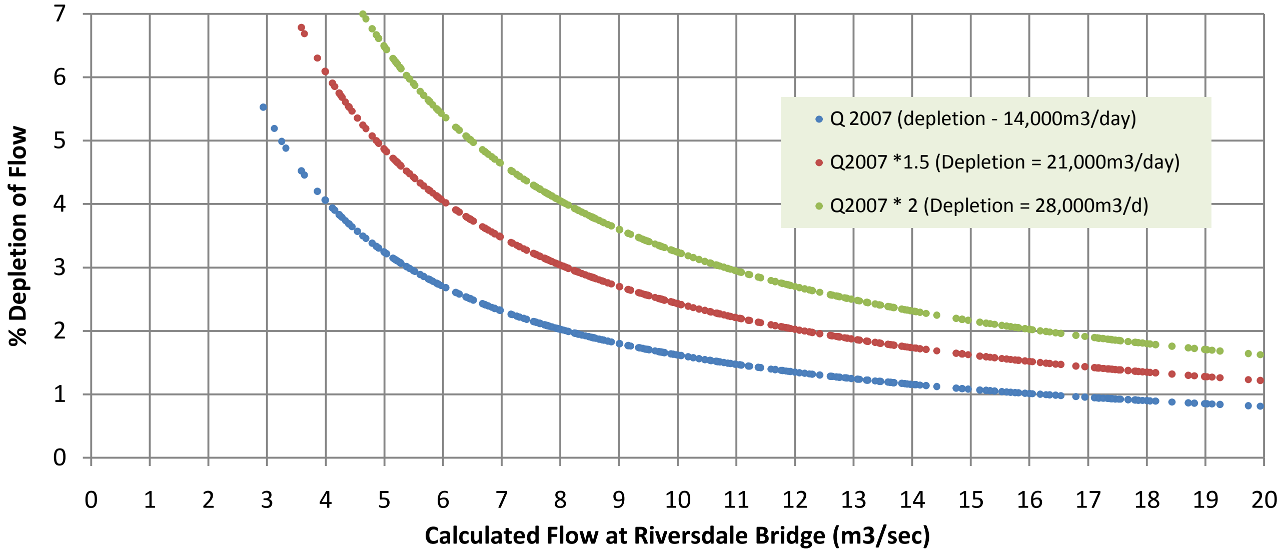
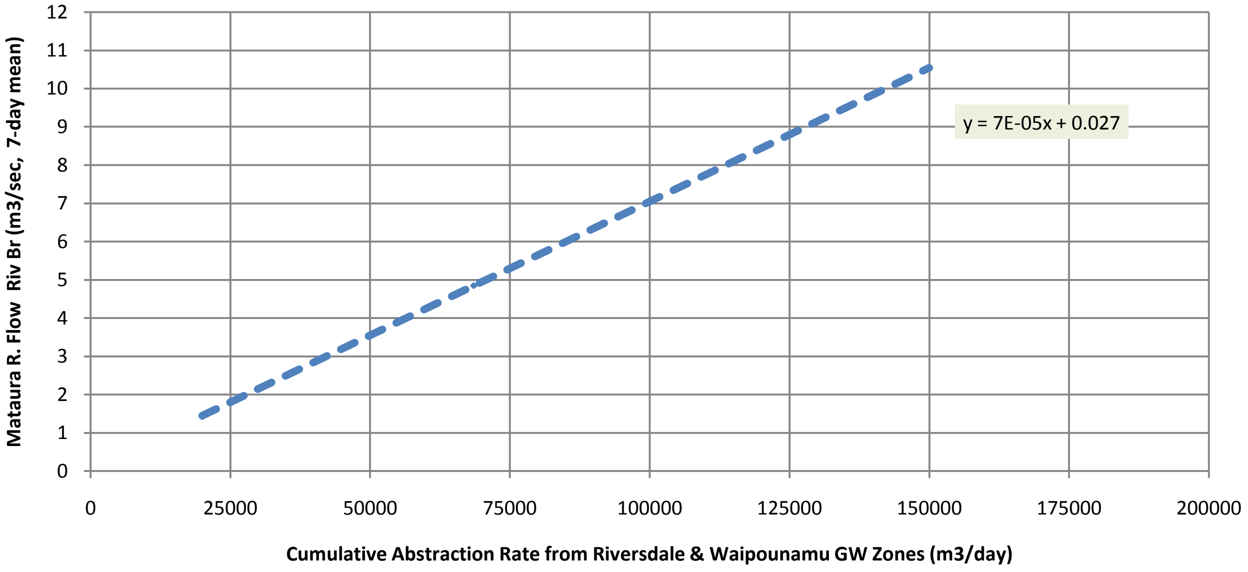


Figure 45: Simulated relationship between cumulative abstraction rate from Riversdale GW Zone and Mataura River flow at Riversdale Bridge when flow depletion = 5%. Plot shows minimum flow required at Riversdale Bridge to ensure depletion does not exceed 5%.



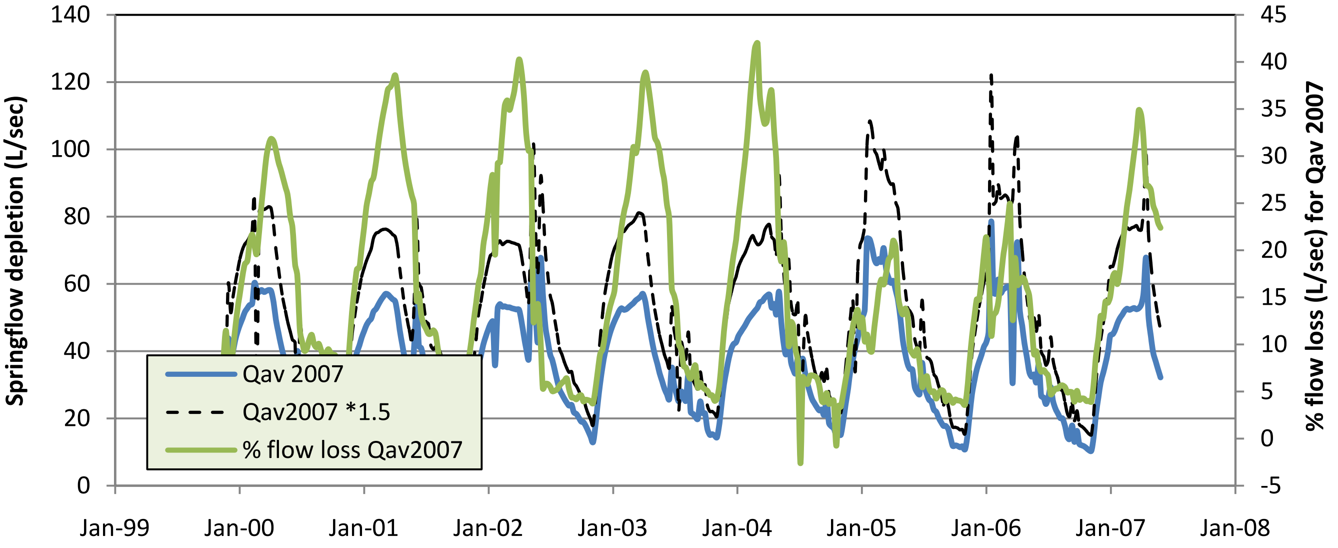
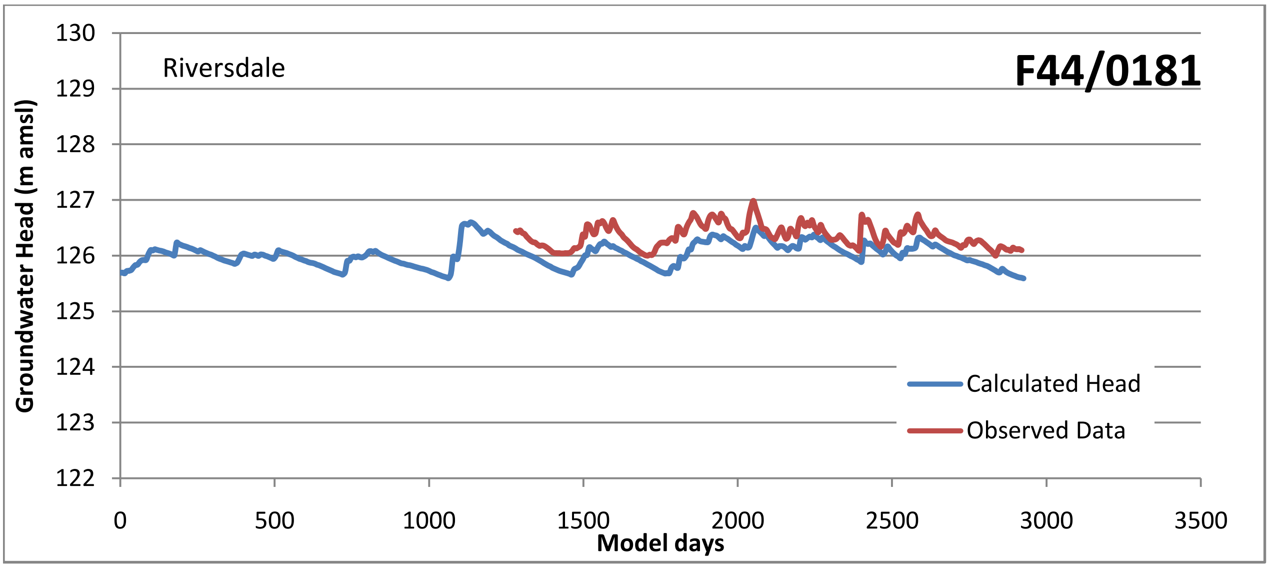
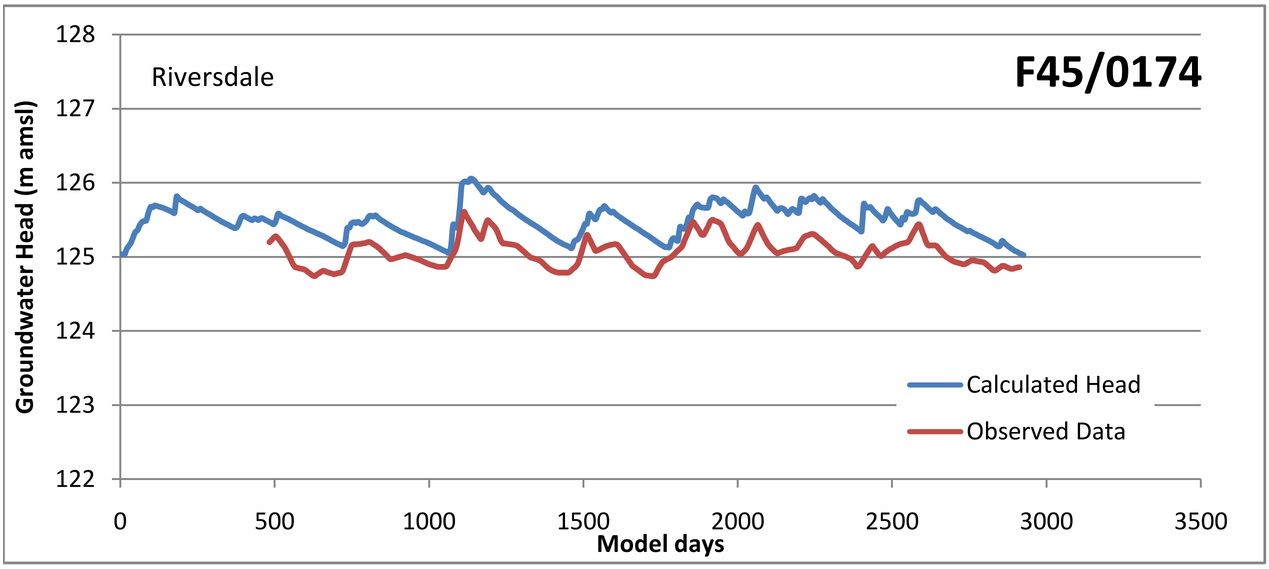
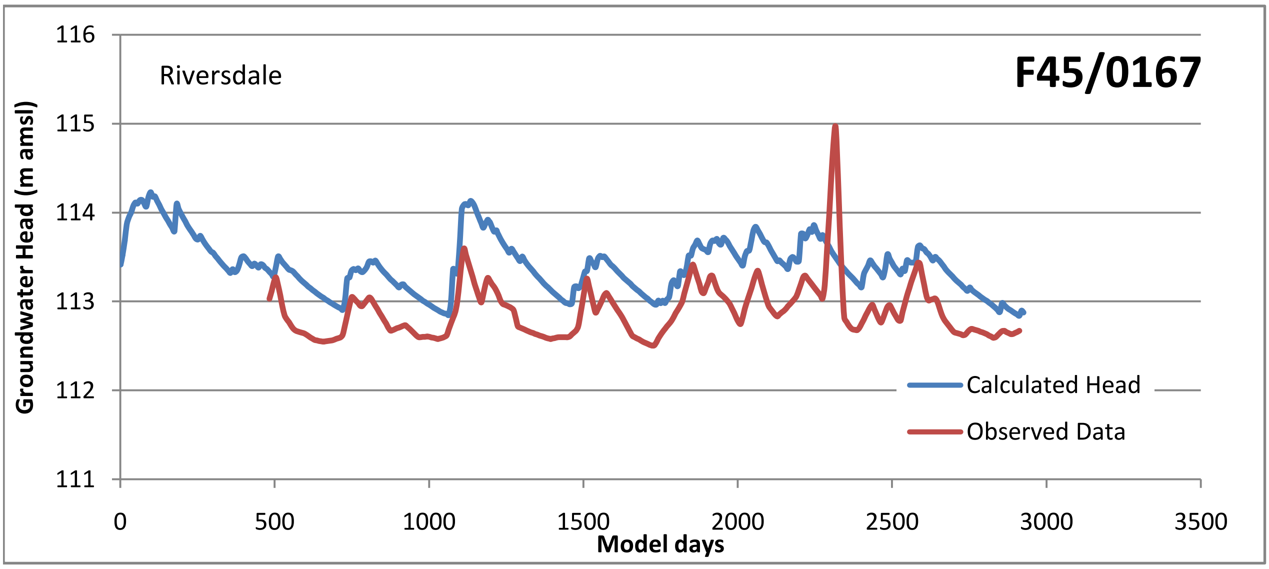


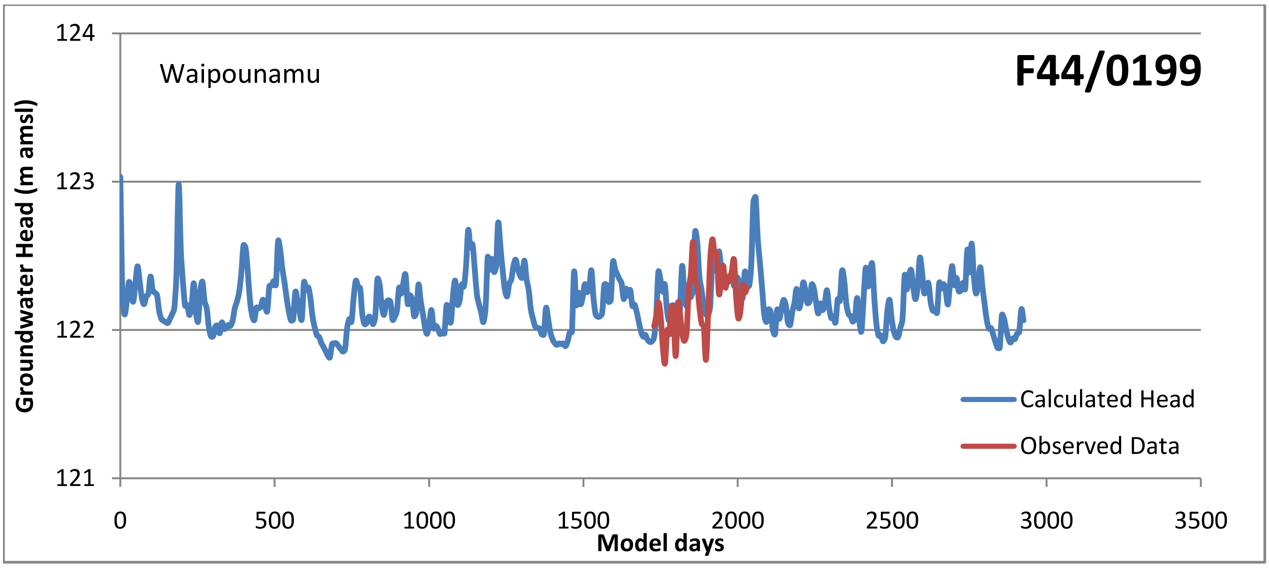
Figure 46: Modelled depltion of Meadow Burn - Constant seasonal abstraction all wells except high/direct SFD wells

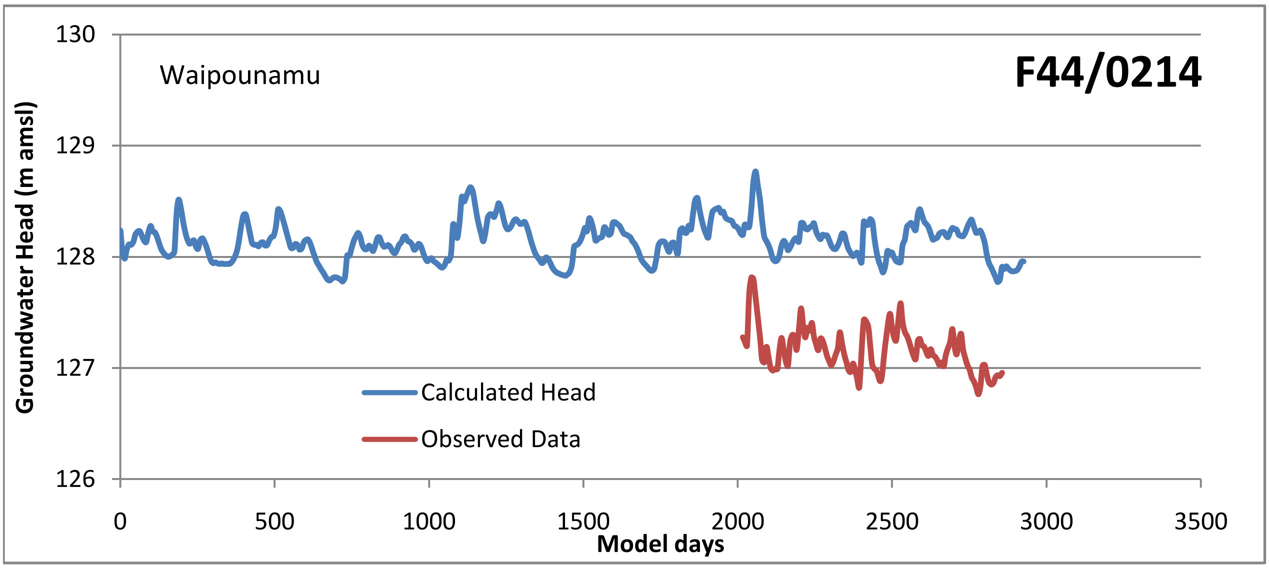


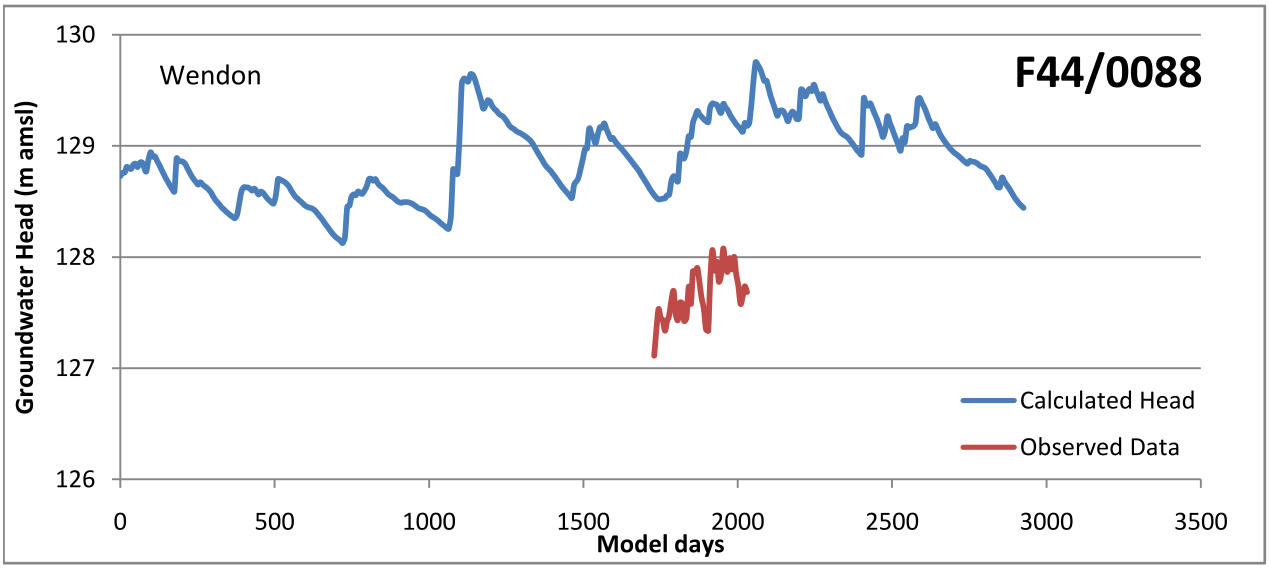




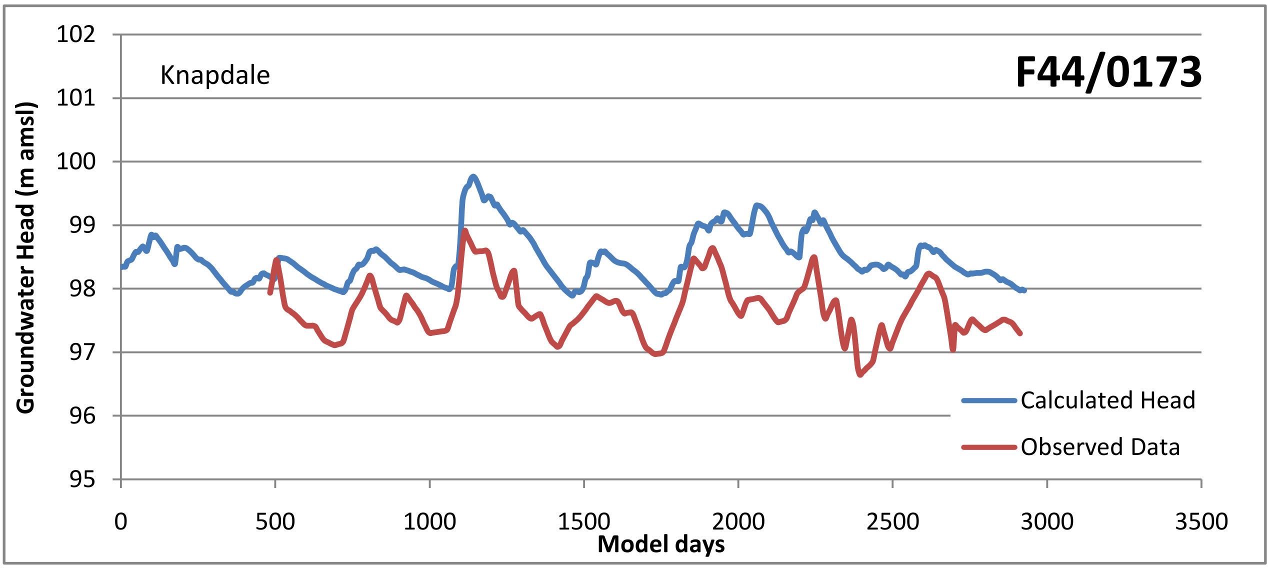
Appendix 1: Mid-Mataura Groundwater Model - Head Calibration Plots

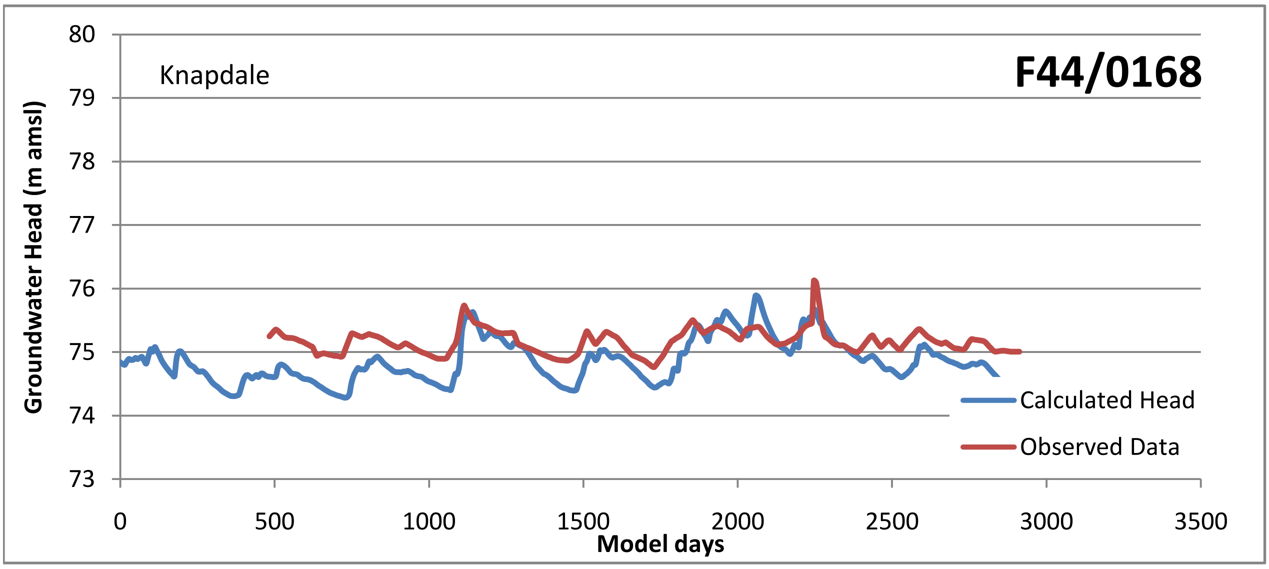


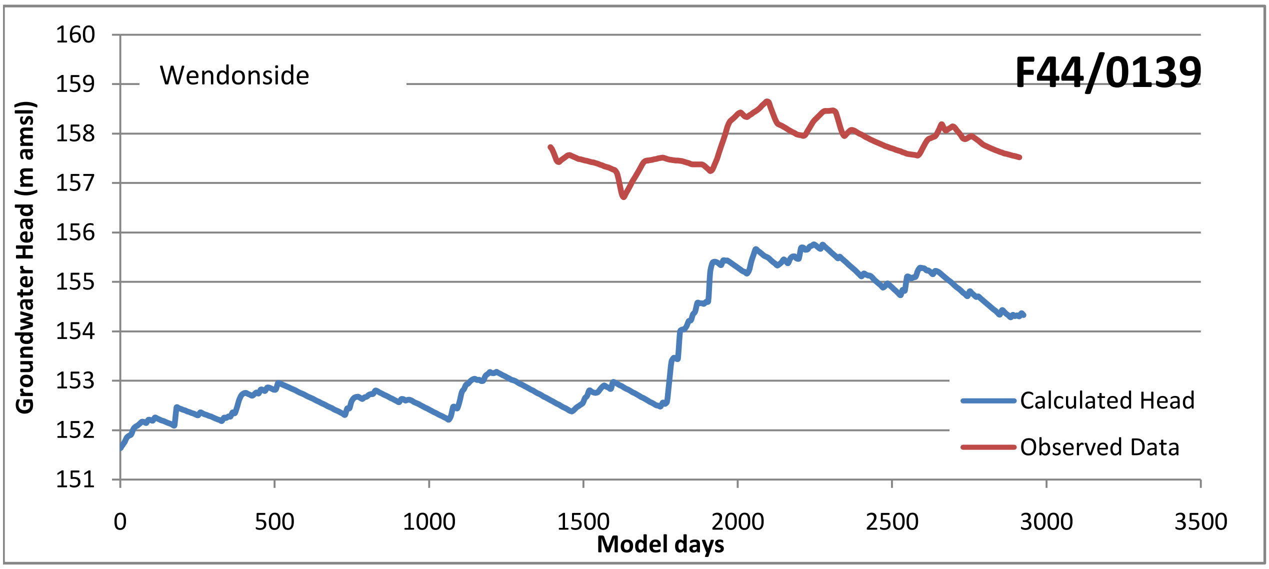


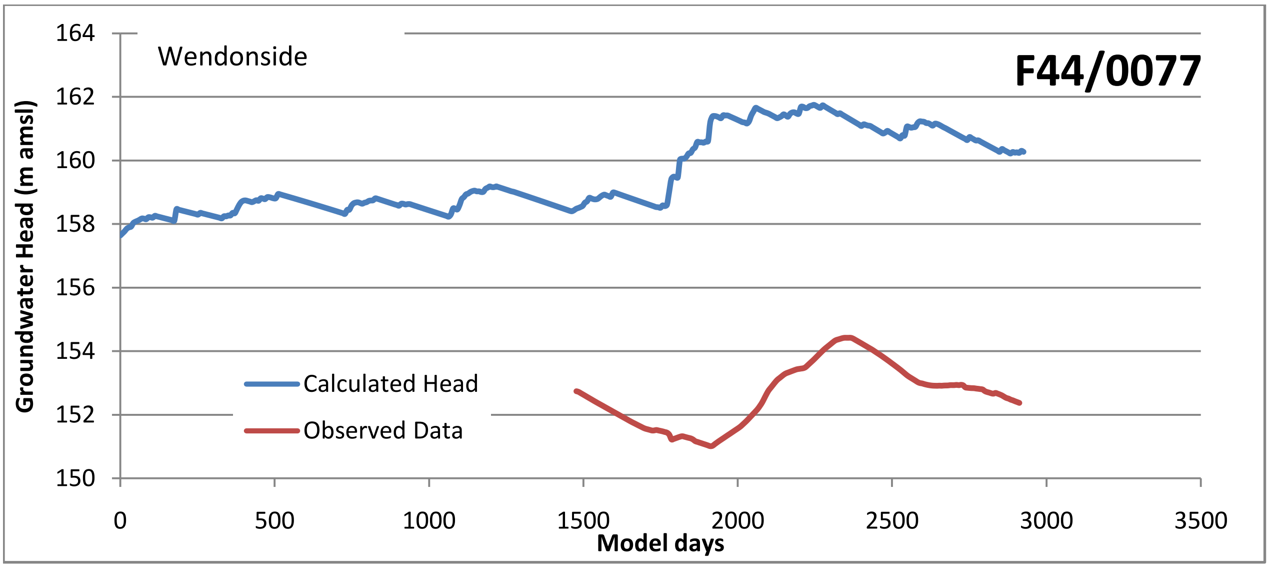


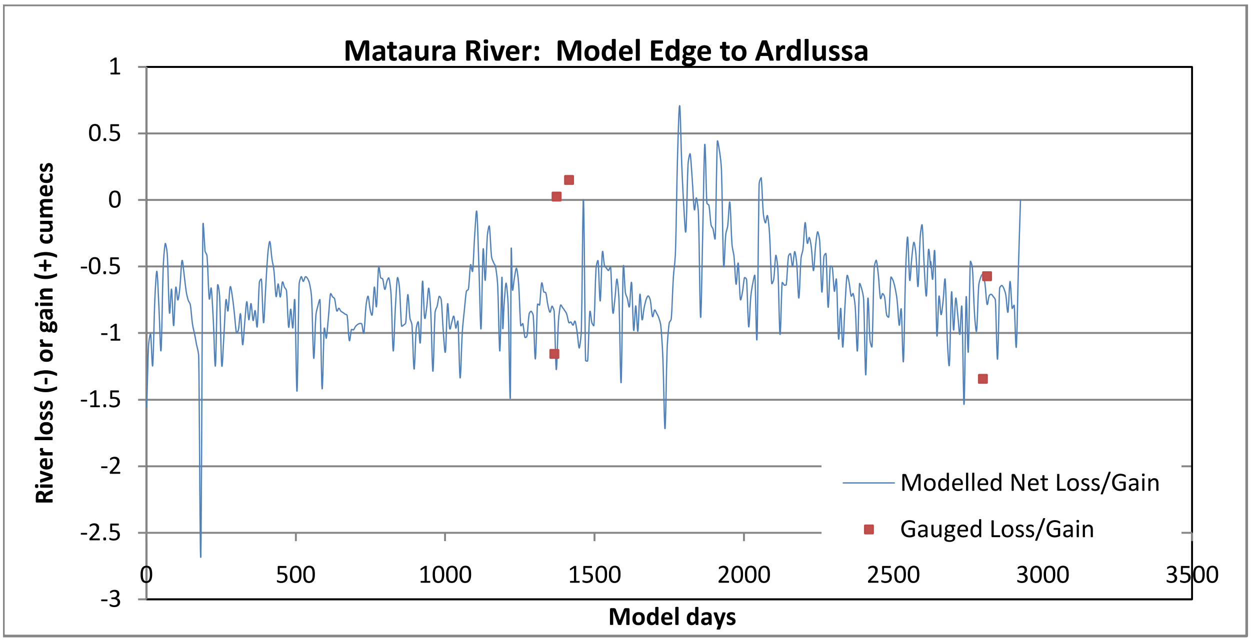
Appendix 1: Mid-Mataura Groundwater Model - Head Calibration Plots

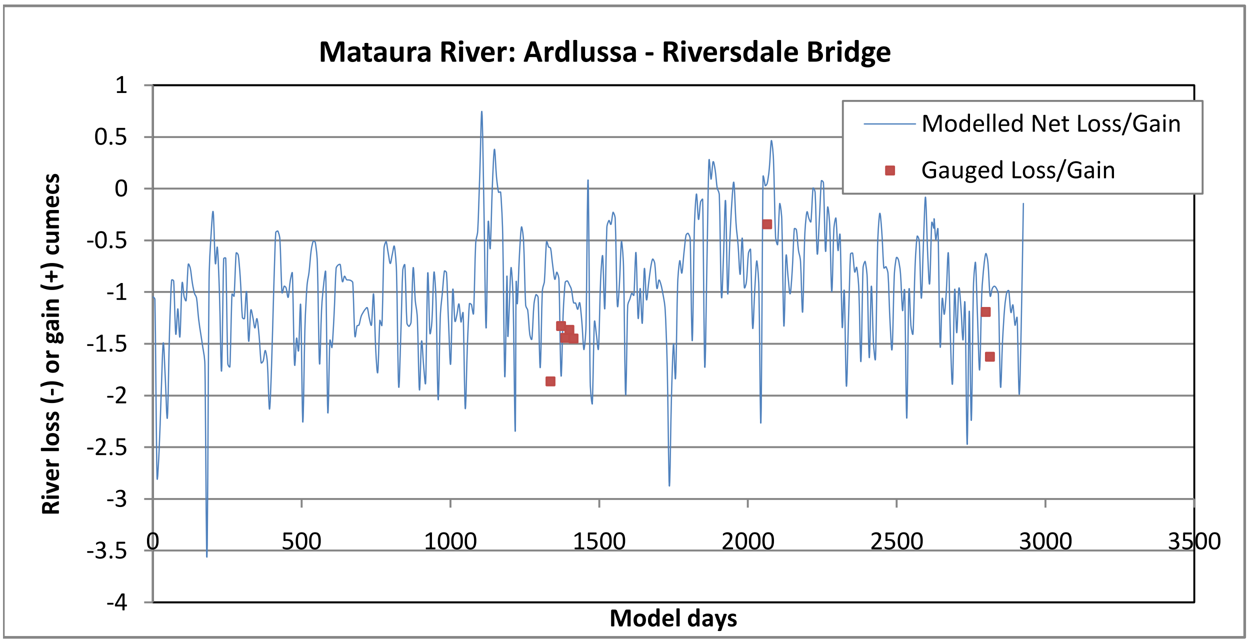

Knapdale
F44/0173
Groundwater Head (m amsl)
102
101
100
99
98
97
96
95
0
500
1000
1500
2000
2500
3000
3500
Model days
Calculated Head
Observed Data

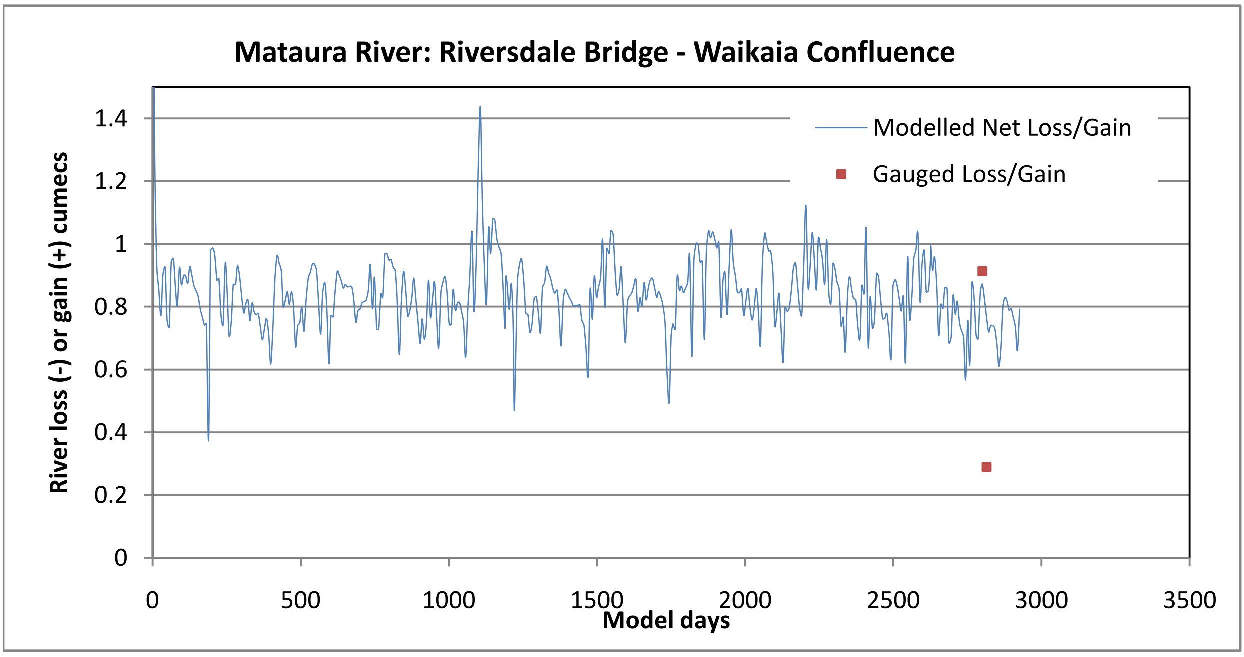

Knapdale
F44/0168
Groundwater Head (m amsl)
80
79
78
77
76
75
74
73
0
500
1000
1500
2000
2500
3000
3500
Model days
Calculated Head
Observed Data


Wendonside
F44/0139
Groundwater Head (m amsl)
160
159
158
157
156
155
154
153
152
151
0
500
1000
1500
2000
2500
3000
3500
Model days
Calculated Head
Observed Data

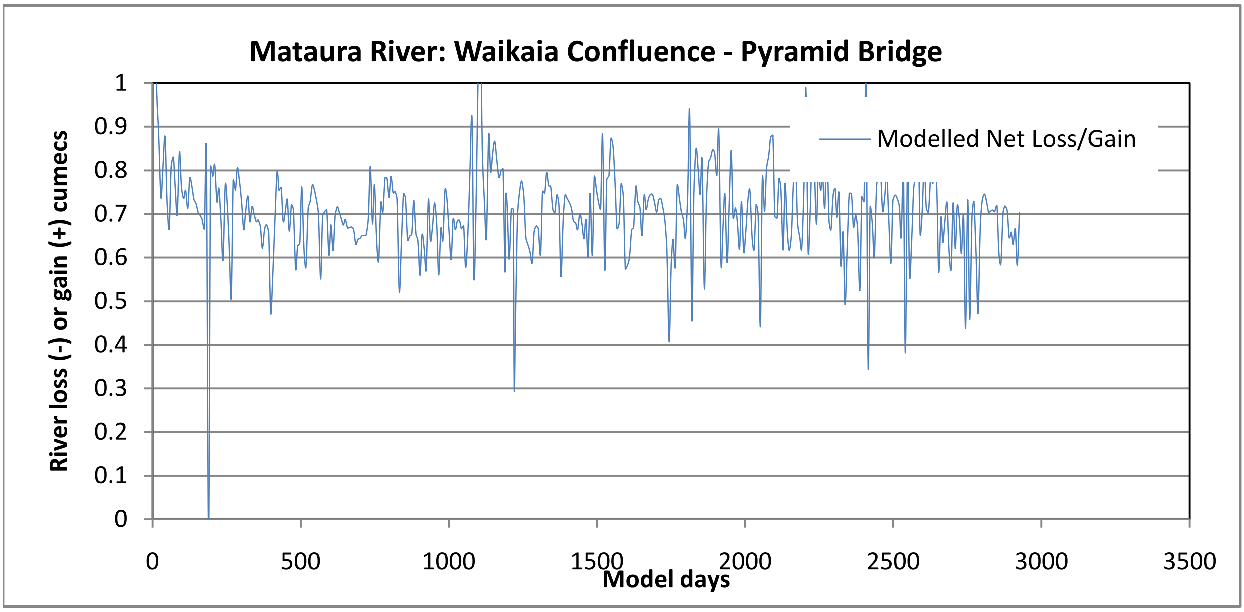

Wendonside
F44/0077
Groundwater Head (m amsl)
164
162
160
158
156
154
152
150
Calculated Head
Observed Data
0
500
1000
1500
2000
2500
3000
3500
Model days

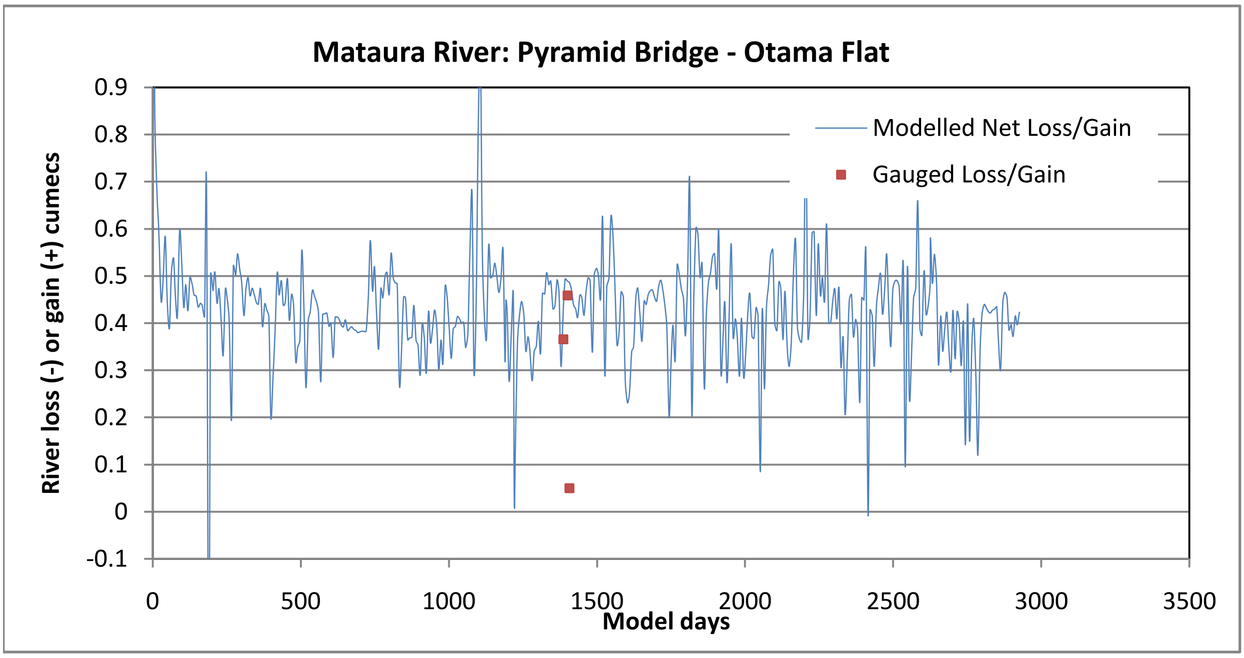


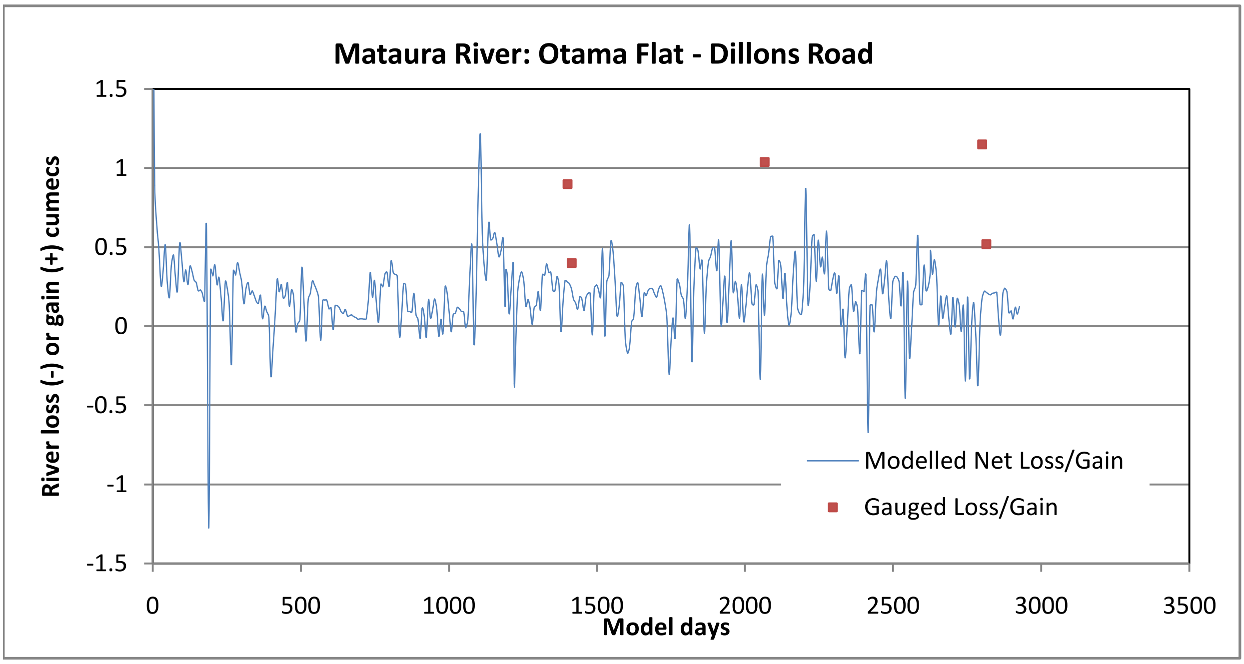




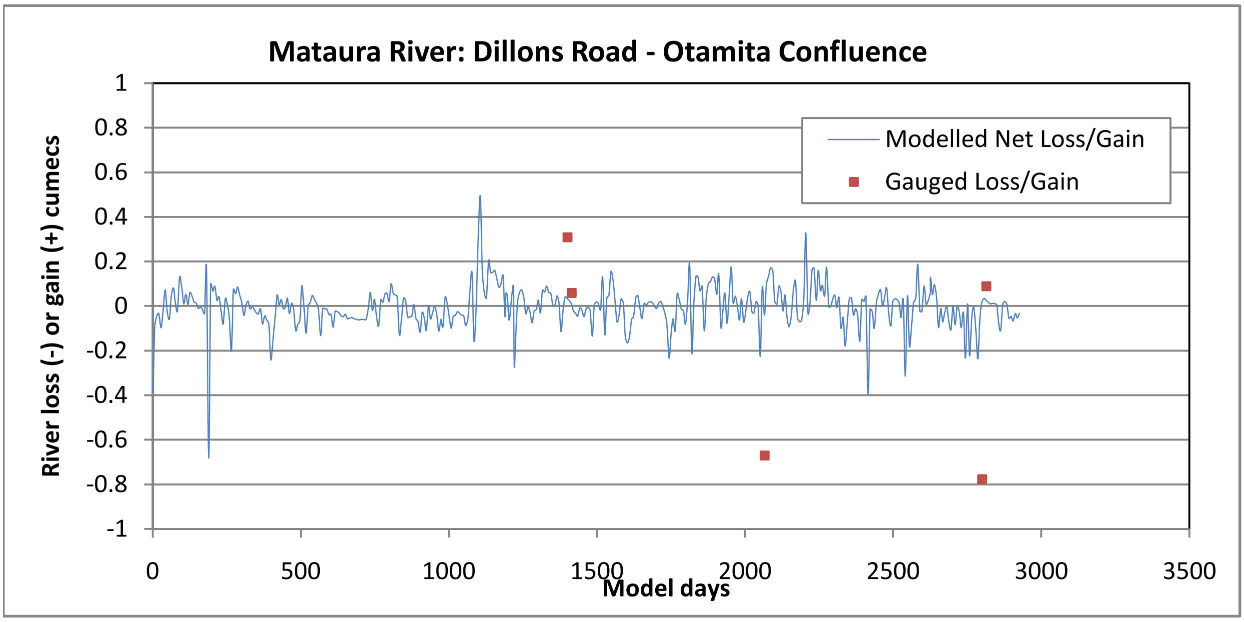
Appendix 2: Mid-Mataura Groundwater Model -Flow Calibration Plots

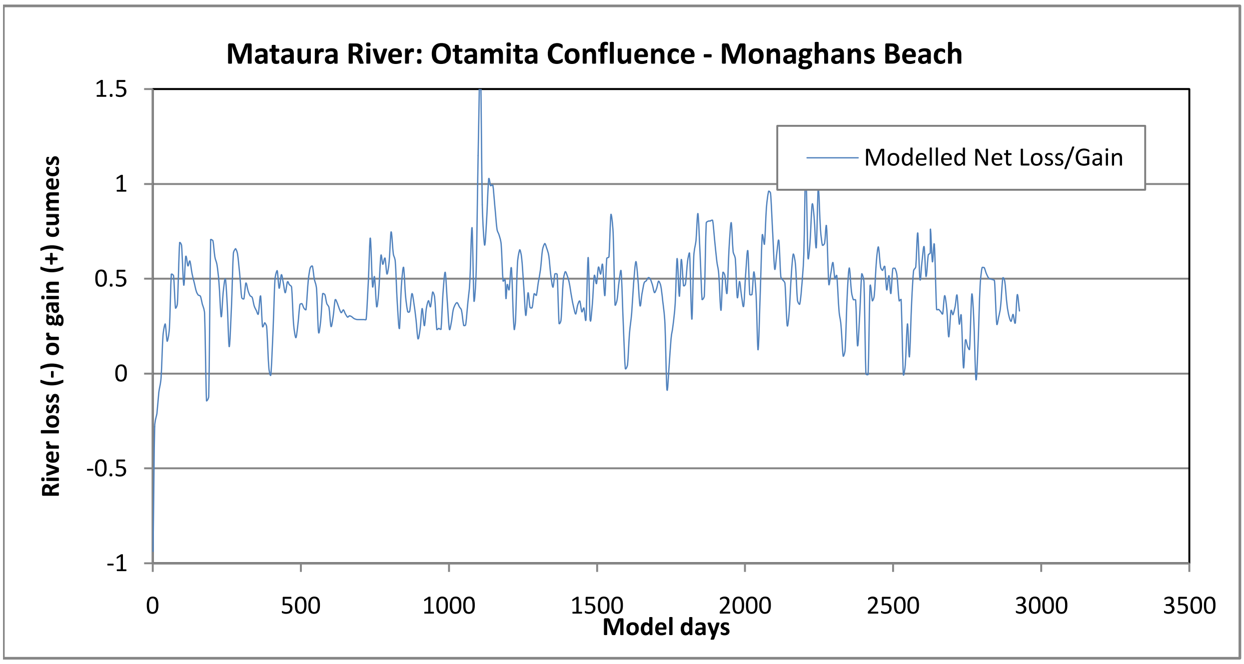


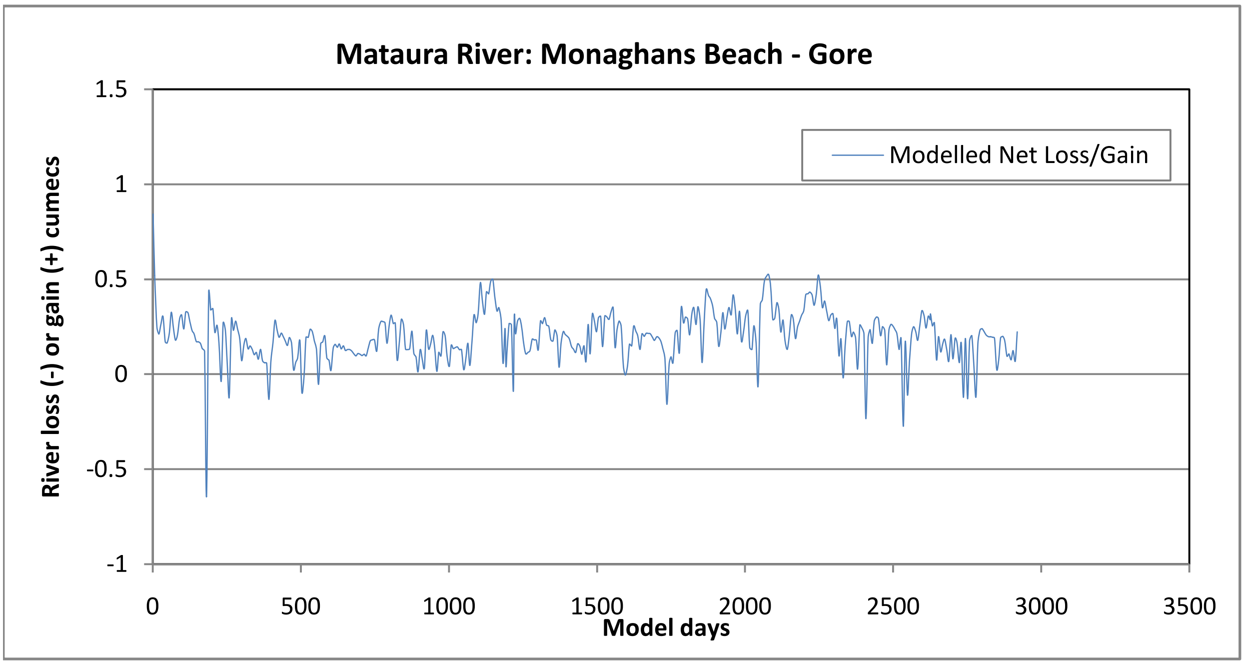


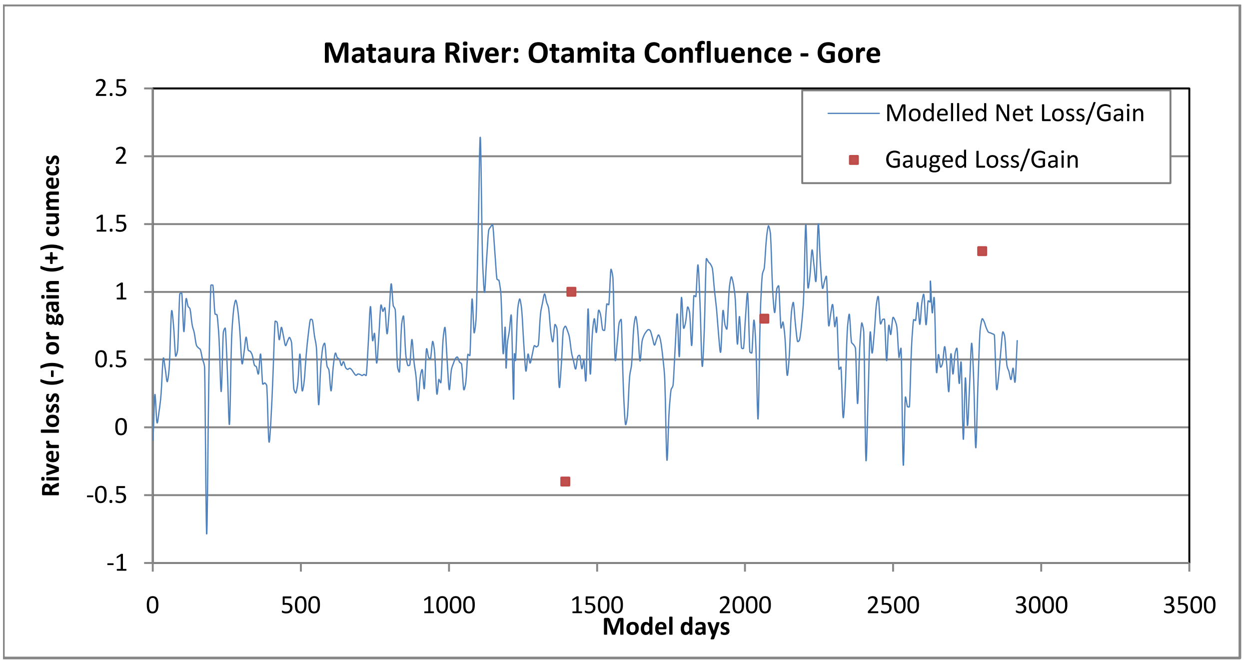


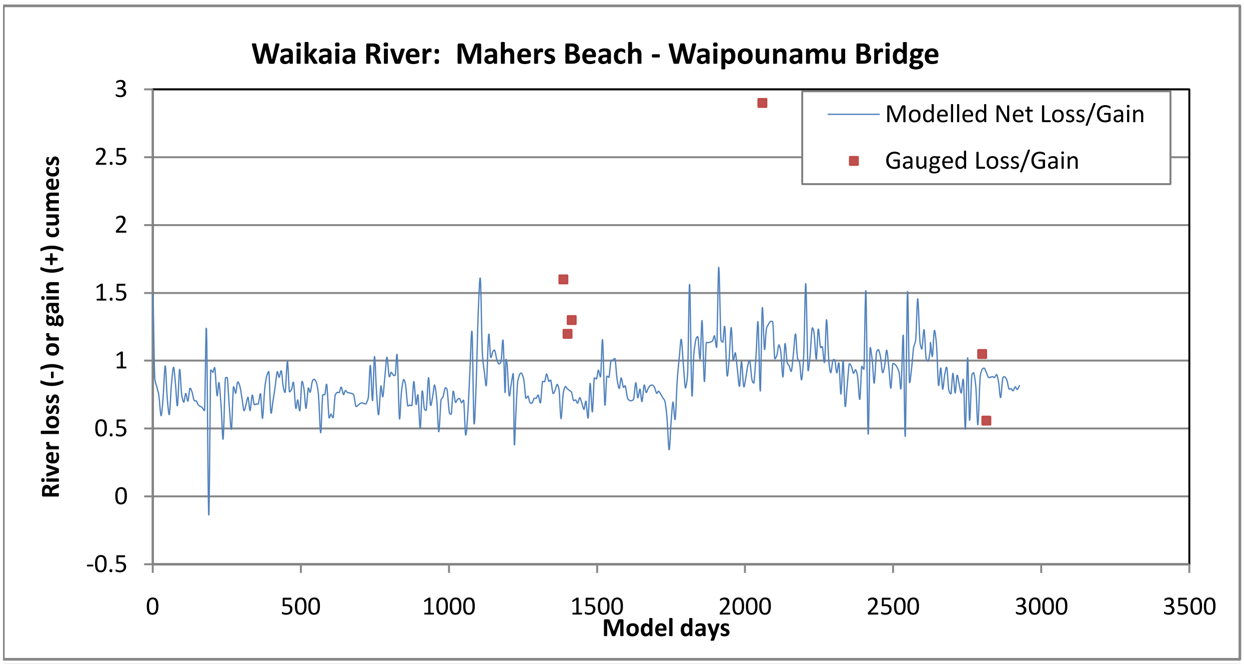
Appendix 2: Mid-Mataura Groundwater Model -Flow Calibration Plots

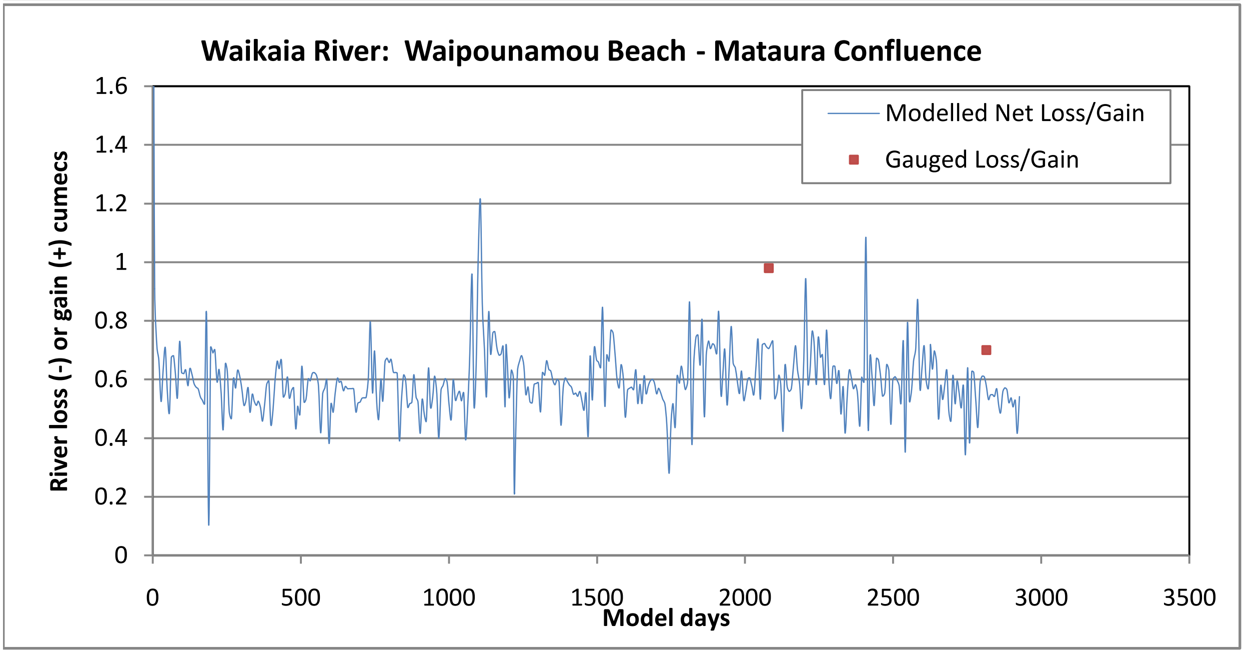

Mataura River: Dillons Road - Otamita Confluence
River loss (-) or gain (+) cumecs
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
0
500
1000
1500
2000
2500
3000
3500
Model days
Modelled Net Loss/Gain
Gauged Loss/Gain

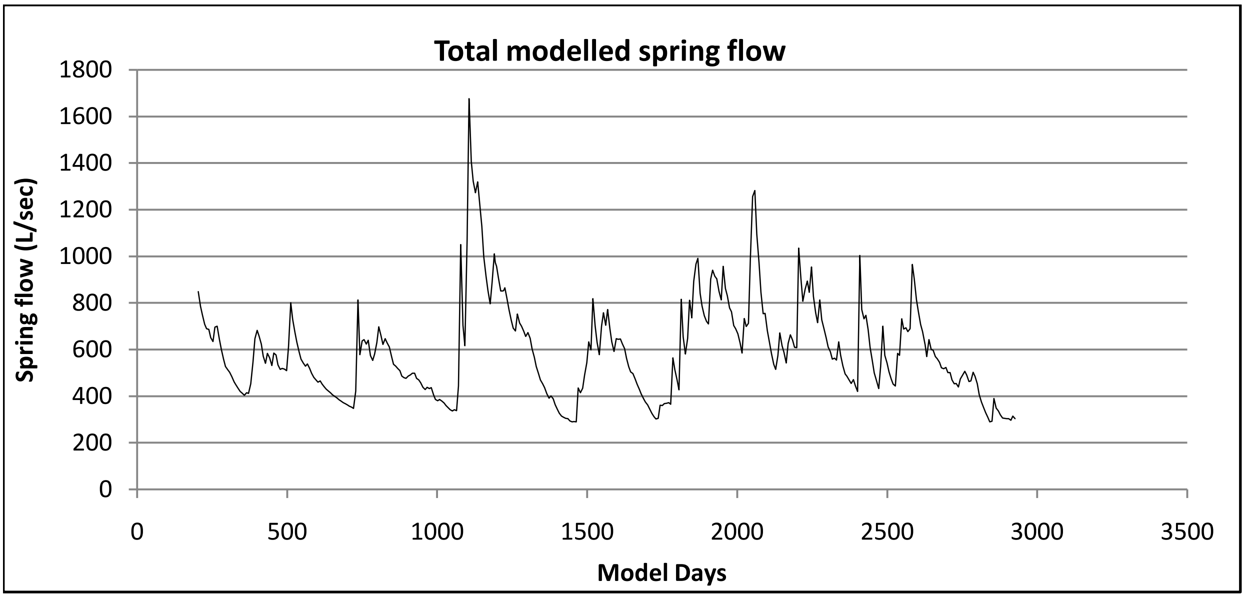

Mataura River: Otamita Confluence - Monaghans Beach
River loss (-) or gain (+) cumecs
1.5
1
0.5
0
-0.5
-1
0
500
1000
1500
2000
2500
3000
3500
Model days
Modelled Net Loss/Gain

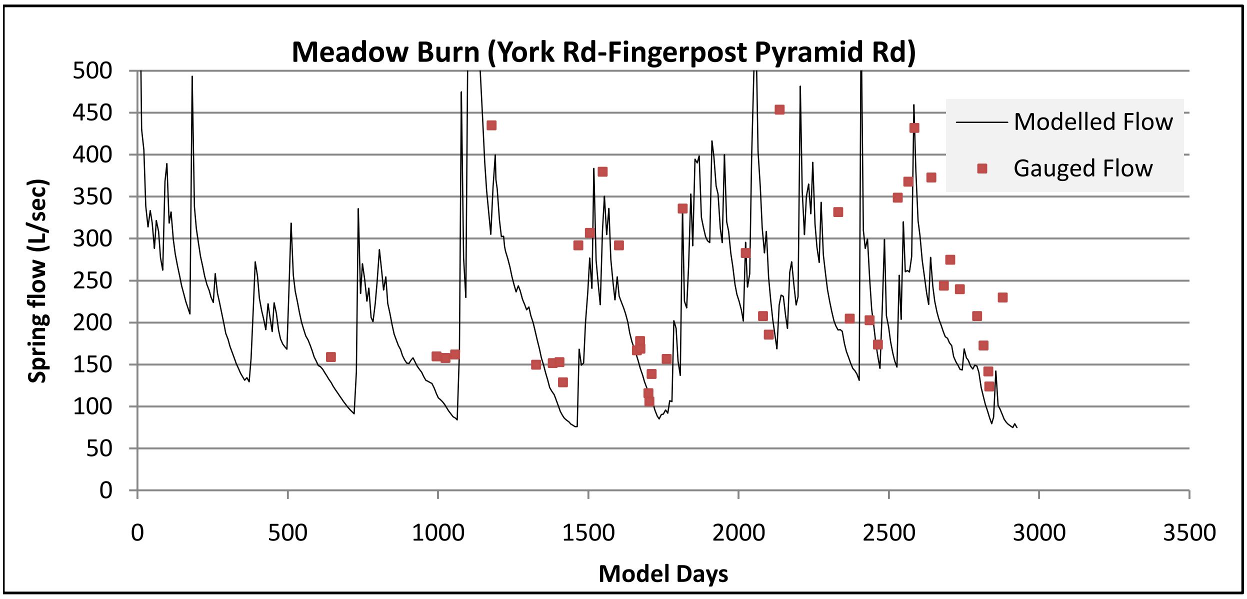

Mataura River: Monaghans Beach - Gore
River loss (-) or gain (+) cumecs
1.5
1
0.5
0
-0.5
-1
0
500
1000
1500
2000
2500
3000
3500
Model days
Modelled Net Loss/Gain

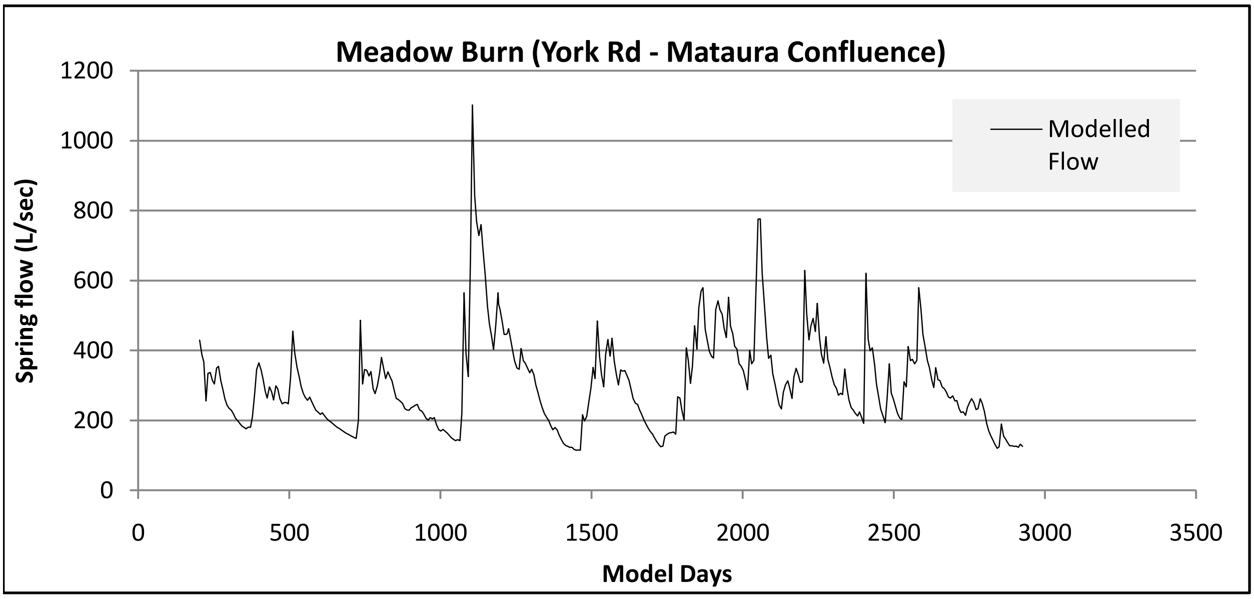

Mataura River: Otamita Confluence - Gore
River loss (-) or gain (+) cumecs
Model days
Modelled Net Loss/Gain
Gauged Loss/Gain
2.5
2
1.5
1
0.5
0
-0.5
-1
0
500
1000
1500
2000
2500
3000
3500

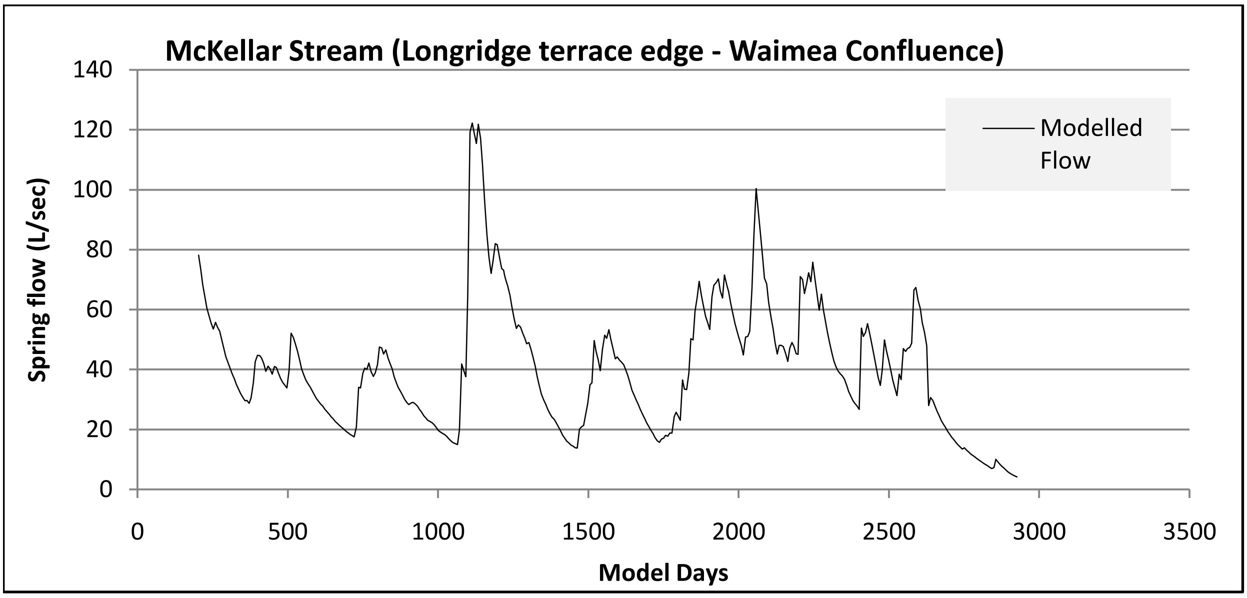

Waikaia River: Mahers Beach - Waipounamu Bridge
River loss (-) or gain (+) cumecs
Model days
Modelled Net Loss/Gain
Gauged Loss/Gain
3
2.5
2
1.5
1
0.5
0
-0.5
0
500
1000
1500
2000
2500
3000
3500


Waikaia River: Waipounamou Beach - Mataura Confluence
River loss (-) or gain (+) cumecs
Model days
Modelled Net Loss/Gain
Gauged Loss/Gain
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
500
1000
1500
2000
2500
3000
3500


Total modelled spring flow
Spring flow (L/sec)
1800
1600
1400
1200
1000
800
600
400
200
0
0
500
1000
1500
2000
2500
3000
3500
Model Days


Meadow Burn (York Rd-Fingerpost Pyramid Rd)
Spring flow (L/sec)
500
450
400
350
300
250
200
150
100
50
0
0
500
1000
1500
2000
2500
3000
3500
Model Days
Modelled Flow
Gauged Flow


Meadow Burn (York Rd - Mataura Confluence)
Spring flow (L/sec)
1200
1000
800
600
400
200
0
0
500
1000
1500
2000
2500
3000
3500
Model Days
Modelled Flow


McKellar Stream (Longridge terrace edge - Waimea Confluence)
Spring flow (L/sec)
140
120
100
80
60
40
20
0
0
500
1000
1500
2000
2500
3000
3500
Model Days
Modelled Flow