Riverlands Groundwater Model and Aquifer Sustainability Assessment

Prepared for Marlborough District Council

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EXECUTIVE SUMMARY

A numerical model of the Riverlands area has been calibrated for steady state and transient conditions. The model has been developed using the best available information, and the calibration is accurate and robust enough for predictive modelling.

The model provides insights into the dynamics of the confined aquifer. The model mass balance shows that the majority of aquifer discharge occurs through the aquitard to the west of Malthouse Road. There is only a minor component of offshore discharge, mainly because of the flat coastal hydraulic gradient. The model predicts that groundwater abstractions are mainly balanced by a reduction in aquifer vertical discharge, and an increase in leakage from aquitard storage.

Several different pumping scenarios have been run through the model to determine how the aquifer responds to an increase in water demand. The model predicts that there is high likelihood of seawater and connate water intrusion if 75% of the current 18,150 m^3/d allocation is used.

The model has also been used to determine a sustainable aquifer yield for the Riverlands area. Key conditions for sustainability are the retention of a positive regional hydraulic gradient towards the coast, and maintenance of coastal heads above 1.25m. Using these criteria, the sustainable aquifer yield has been estimated as being 10,000 m^3/d, or 11,600 m^3/d with seasonal restrictions.

In terms of the sustainability criteria, the aquifer has been over-allocated. This renders the aquifer vulnerable to changes in land use or water trading. It is therefore recommended that no further groundwater be allocated in the Riverlands area.

It is also recommended that the efficiency of water allocation be improved via the consent renewal process. At present only 36% of the allocation is being used. If the allocation system were adjusted to match the required use, the aquifer could be more fairly and sustainably managed.

1 INTRODUCTION

1.1 SCOPE OF THIS REPORT

The purpose of this report is twofold:

1. To document the calibration of a transient numerical model of the Riverlands groundwater system.

2. To present groundwater model predictions. The impact of increased water demand is assessed and sustainable aquifer yield is estimated.

A conceptual model of the Riverlands groundwater system is also covered briefly in this report. The conceptual model and additional background information is documented in more detail in a companion report "*Resource Evaluation of the Riverlands Groundwater System*".

1.2 RIVERLANDS STUDY AREA

This study is primarily concerned with confined groundwater in the Riverlands area. Of primary interest is the area south of Dillons Point Road, which is delineated in Figure 1. The groundwater model described in this report does extend beyond this area because a large buffer zone is required around the Riverlands area to cater for external pumping and boundary effects. However, the northern boundary shown in Figure 1 is somewhat arbitrary, and is not marked by any distinct change in hydrogeology.

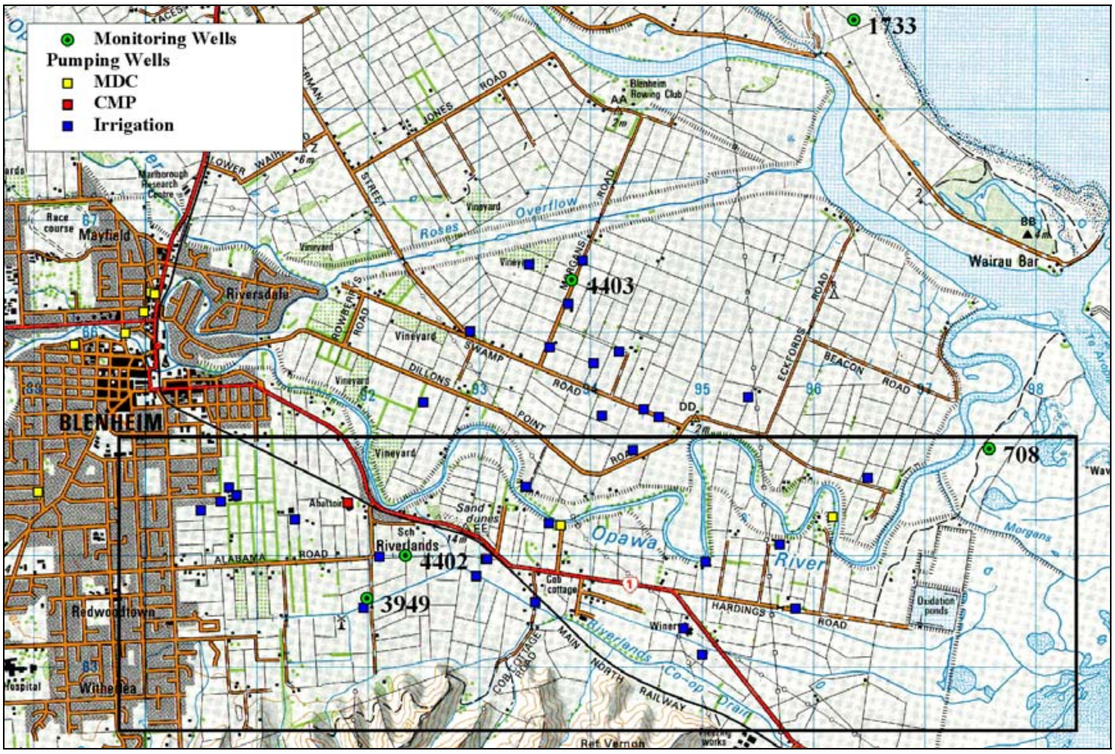

Figure 1 - Location map of the Riverlands area. The area that this report is primarily concerned with is indicated by a black box. Also shown are transient observation wells (labelled) and pumping wells used in the groundwater model.

2 CONCEPTUAL MODEL

2.1 AQUIFER DEFINITION

Groundwater abstraction in the Riverlands area is mostly derived from two distinct aquifers. The two main aquifer bodies can be seen in a map of estimated transmissivity values for the Wairau Plain (Figure 2).

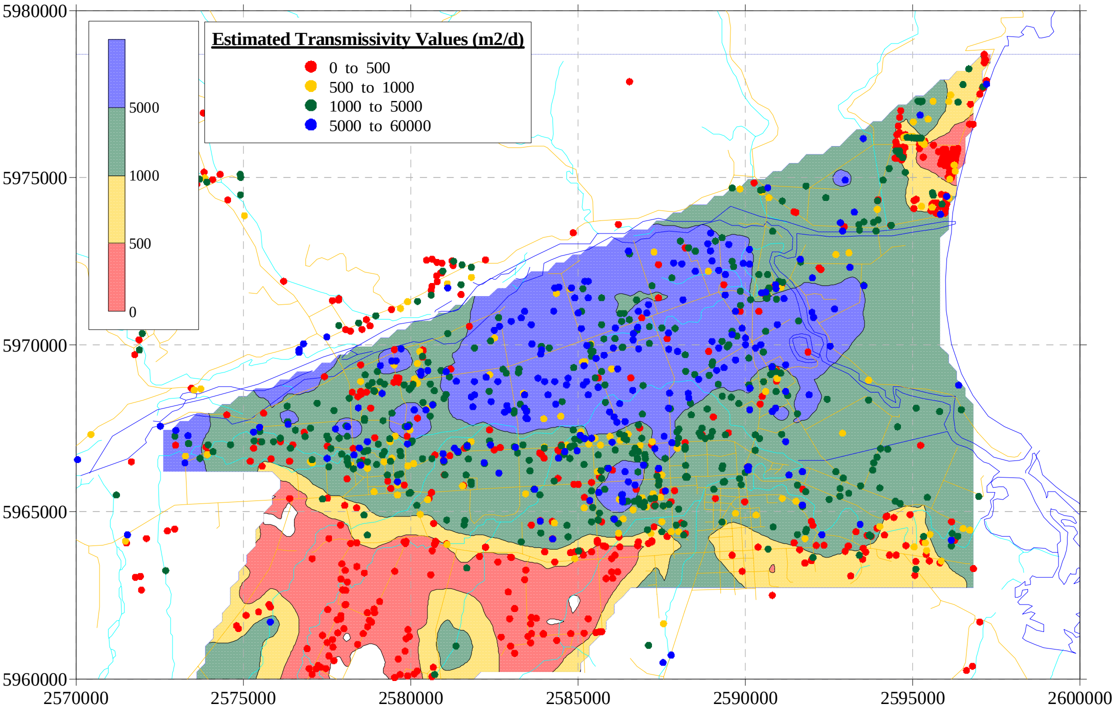

Figure 2 - Map of Wairau Plain showing the estimated distribution of aquifer transmissivity values.

The two aquifers are in hydraulic continuity, and are distinguished by characteristic yield characteristics. The southernmost of these two aquifers is seen in Figure 2 as a yellow zone east to the east of Blenheim, along the foothills of the Wither Hills. This zone is continuous with the Southern Valleys aquifers, and is characterised by similar low-yielding gravels. This area of low yielding gravels is here termed the “Riverlands Aquifer”. This aquifer is bounded to the south by the Wither Hills. To the north of the Riverlands Aquifer are the highly productive gravels commonly known as the Wairau Aquifer.

In the Riverlands and Lower Wairau areas, both the Riverlands and Wairau Aquifers are confined by an extensive aquitard. The aquitard is known as the Dillons Point Formation, which consists of marine and lagoonal silts and clays, and marine sands. Claybound gravels of the Speargrass Formation mark the base of the two aquifers.

There is insufficient drilling information to indicate how the thickness of both aquifers varies spatially. The reason for this is that drillers tend to only penetrate the upper three to five meters of the aquifer, so the Speargrass Formation is rarely intersected. Where the base of the aquifer has been intersected, thickness is approximately 8m ± 5m.

2.2 AQUIFER INFLOWS

2.2.1 Aquifer Flow

Aquifer recharge in the Riverlands is dominated by inflow from the upgradient, unconfined aquifers. This inflow can be considered to come from three sources:

1. Wairau Aquifer
2. Groundwater in the southern springs area, which comprises discharge from the Southern Valleys and Omaka River
3. Taylor River Riparian Aquifer.

The total recharge volume and how it is apportioned between these aquifers is unknown, but can be determined as an output from the numerical model.

2.2.2 Taylor River

The Taylor River loses all of its flow below the Taylor Dam to riparian gravels for approximately half of the year. During times of continuous flow to Athletic Park, baseflow at the Borough Weir is 60-70 l/s. At higher flows, approximately half of the river baseflow is lost to riparian gravels upstream of Athletic Park. Groundwater in these gravels recharges the Riverlands aquifer at its southwestern extremity near Burleigh Bridge.

2.2.3 Land Surface Recharge

Because of aquifer confinement, land surface recharge is not considered to contribute to aquifer storage in the Riverlands area. A soil moisture balance model was initially run for the Riverlands numerical model. Recharge to the aquitard only occurred on a few days a year, and caused unrealistic spikes in the model hydrographs. For this reason, land surface recharge was removed from the model. It is assumed that when the soil moisture reaches field capacity, additional rainfall either ponds on the surface, or is removed as runoff by the extensive drainage network in the area.

2.3 AQUIFER OUTFLOWS

2.3.1 Leakage

The majority of aquifer discharge is likely to be as leakage to the Aquitard. Aquifer heads become artesian to the east of Malthouse road and north of Alabama Road, indicating that there is less leakage in these areas. Leakage into the aquitard is compensated by discharge from the aquitard into rivers and surface drains. There is currently no flow information available in the Riverlands and Lower Wairau areas to estimate the rate of aquitard discharge.

2.3.2 Offshore Discharge

Discharge of the Wairau Aquifer to Cloudy Bay is likely to occur at some distance offshore via springs on the sea floor. However, at this stage there is no empirical evidence for offshore discharge. What is clear is that confined aquifer dynamics are controlled by pumping, leakage and recharge, with the balance being made up by changes in spring flow and river baseflow. The hydraulic gradient east of Malthouse Road is essentially flat, which suggests that if there is offshore discharge in the Riverlands area, it is only a minor component of the water balance.

3 NUMERICAL MODEL DESIGN

3.1 MODEL OBJECTIVES

The model objectives are as follows:

1. Establish a calibrated numerical aquifer model for the Riverlands area, incorporating all available data.
2. Determine the mass balance of the model, and how this changes through time.
3. Simulate aquifer response to different abstraction scenarios.
4. Evaluate the total exploitable groundwater resource.

3.2 SOFTWARE SELECTION

The model incorporates the MODFLOW 2000 finite difference numerical code developed by the USGS (McDonald and Harbaugh, 1984). Groundwater Vistas (Version 4) graphical interface package (Environmental Simulations Inc.) was used to set up the model and process the output data.

3.3 MODEL ASSUMPTIONS

- The model consists of two layers, representing the Dillons Point aquitard, and the Wairau and Riverlands aquifers. The underlying Speargrass formation is assumed to be impermeable.
- Layer 2, comprising the Riverlands and Wairau Aquifers, is assumed to have a constant 8m thickness.
- Aquifer properties are assumed to be isotropic for each cell (Kx=Ky=Kz).
- The aquitard is modelled using the MODFLOW Type 1 unconfined layer condition.
- The aquifer is modelled using the MODFLOW Type3 confined/unconfined layer condition. This allows for transmissivity and storage coefficient to vary throughout the model according to the saturated thickness of the cell. Thus, the aquifer becomes unconfined if the water level falls below the top of the model cell, and the storage component changes from specific storage to specific yield.
- There is aquifer discharged offshore to Cloudy Bay.
- There is no land surface recharge.

3.4 MODEL DOMAIN

The model extent is approximately 25 km east by 11 km north, covering an area of 273.5 km^2. The model domain origin is located just south of Omaka aerodrome, at 2587000E, 5962000N (see Appendix 1.1). The finite difference grid consists of 27 rows and 51 columns. Row spacing ranges from 250m to 740m, and column spacing ranges from 250m to 1100m. The grid has been refined from the Opawa River south to improve the accuracy of drawdown calculations in the Riverlands aquifer.

During initial model calibration phases the model extent was approximately half of the final model domain. The northern and eastern boundaries were extended outwards to avoid unrealistically large drawdowns during predictive modelling. The western boundary was also moved westward to coincide with the southern springs area. An increase in flux across this boundary during predictive modelling will therefore indicate a reduction in spring flow.

The top surface of the model has been derived from 10-foot topographic contours surveyed by Vickerman and Lancaster in 1924. This is the most detailed topographical information currently available for the area.

The top aquifer surface has been derived by contouring the aquifer depth, as indicated on bore logs, with the Surfer package (Golden Software Inc). These depths were subtracted from the topographic surface to obtain a reduced level for the upper aquifer surface. The aquifer has been set at a constant thickness of 8m across the whole model domain. Accurate variability of aquifer thickness is not available because boreholes do not tend to penetrate the entire thickness of the aquifer. Examination of boreholes that do penetrate the entire aquifer suggests that the aquifer is on average 8m thick.

3.5 MODEL BOUNDARY CONDITIONS

3.5.1 Constant Heads

Three constant or fixed head boundaries are incorporated into the model:

1. A coastal boundary set at a fixed head of 0m to allow aquifer discharge.

2. A head-dependant boundary along the western model margin north of Athletic Park. This allows inflow from groundwater upgradient of the model boundary. The heads along this boundary are based on the Substation and Athletic Park monitoring well records. The data was input as a line boundary using P28w/3954-0.2m and P28w/0949 respectively for the start and finish of the line.

3. A head-dependant boundary along the western model margin south of Athletic Park. This allows inflow from groundwater upgradient of the model boundary. Heads along this boundary are based on the Athletic Park monitoring well record (P28w/0949). The data was input as a line boundary using P28w/0949 and P28w/0949+7m respectively for the start and finish of the line.

The location of the fixed head boundaries in the model can be seen in Appendix 1.1 and 1.2.

3.5.2 River Boundaries

The numerical model contains three river boundaries. The river boundaries allow for surface water-groundwater interaction between the aquitard and the Opawa, Taylor, and Wairau Rivers. The Taylor-Opawa system is modelled as two separate reaches in order to accommodate the flattening of the bed gradient between Blenheim and the coast. The river package has been selected in preference to the stream package because of the lack of flow data within the model domain.

River stage data is available from recorders installed at the Wairau River at Tuamarina, and the Taylor River at Borough Weir and Hutcheson Street sites. All of these sites, except for Hutcheson Street, are outside of the model domain. As a result, stage for all river boundaries in the model has been estimated by extrapolation stage from the nearest recorder site. River boundary parameters are entered in the model as follows:

1. The Wairau River stage is extrapolated from the recorder at Tuamarina Bridge. Stage is calculated as Tuamarina-0.2m and Tuamarina-0.6m for the start and end of the reach respectively. Bed levels are estimated to be 1 and 0m. Bed conductance has been determined by parameter optimisation under steady state conditions.

2. The Taylor River has been simulated from Athletic Park to Sinclair St (SH1). Stage at Athletic Park is calculated as Borough Weir+1m. This simulates the winter period when the riparian gravels are fully saturated. The stage record at Hutcheson St Bridge has been used to simulate stage at Sinclair St.

3. The Opawa River is simulated from Sinclair St (SH1) to the confluence with the Wairau River. Stage at Sinclair St is simulated with the Hutcheson St Bridge record. Stage at the lagoons is calculated as Hutcheson St-0.2m.

3.5.3 Drain Boundary

Initial parameter optimisation runs overestimated aquifer heads in the Riverlands Aquifer, adjacent to the Wither Hills. Initially, the high heads were thought to be the result of unsteady conditions at the time of the potentiometric survey. However, the heads could not be reduced during subsequent transient calibration runs. To reduce heads in this area, the Riverlands Coop Drain was added to the model in the form of a drain boundary.

Bed levels for the drain boundary are derived from MDC survey data (0.2m at Alabama Road Corner, 0.1m at the old Freezing Works turnoff). Bed conductance is determined through the optimisation process.

3.6 MODEL INPUT PARAMETERS

3.6.1 Aquifer Properties

A summary of all available aquifer test data for the Riverlands and Lower Wairau areas is presented in Table 1. The test results indicate that transmissivity varies in a north-south direction, but not in an east-west direction.

Four transmissivity zones can be identified in the test record. The lowest transmissivity zone is found immediately adjacent to the Wither Hills, and may be representative of the Wither Hill gravels. The Riverlands Aquifer results are grouped in the ‘Low’ transmissivity group, and have a mean of 250 m^2/d.

At the northern edge of the Riverlands Aquifer is a narrow band of ‘Moderate’ transmissivity gravels, averaging 430 m^2/d. Wells within this zone are still screened within the Riverlands Aquifer, and have a slightly higher specific capacity. This indicates that the aquifer margin is slightly higher yielding, and the higher transmissivity recorded from pumping tests is not solely due to the recharge effect of the Wairau Aquifer to the north.

The final transmissivity zone is the high yielding Wairau Aquifer. Transmissivities in the Wairau Aquifer are an order of magnitude higher than the Riverlands Aquifer, and have a recorded mean value of 2,700 m^2/d.

Table 1 - Record of available pumping test data for the Riverlands area. Zones are grouped by transmissivity (H-high, M-medium, L-low, VL-very low)

Well	E	N	Depth	Scrn Top	Cs (m2/d)	T	S	Source	Zone
P28w/0716	2595900	5964700				3710	1.0E-04	Vol 2	H
P28w/0739	2591800	5964400	25.3	22.3	1640	3100	5.2E-05		H
P28w/0742	2591500	5964300	23.5			3100	1.0E-04	Vol 2	H
P28w/0743	2596500	5964300	41.8			3160	9.7E-05	Vol 2	H
P28w/0765	2596150	5963980	38.7	34.4	1138	2450	1.0E-04		H
P28w/0786	2596200	5963800				2450	1.0E-04	U040191	H
P28w/1119	2591820	5964470	25.4	22.2	882	1700	8.0E-05		H
P28w/1678	2593731	5964273	32.0	29.0	1536	2980	2.2E-04	U031249	H
P28w/1738						1870	1.0E-04	Vol 2	H
P28w/1739						2860	7.7E-05	Vol 2	H
P28w/1741						3300	3.1E-05	Vol 2	H
P28w/1742						4000	2.8E-05	Vol 2	H
P28w/1795						2500	3.3E-05	Vol 2	H
P28w/2500	2595037	5963945	38.8	36.9	260	3400	5.0E-04	U020465	H
P28w/4191	2591550	5964318	24.3	21.7	733	970		U041758	H
P28w/4339	2595511	5964322	38.5	35.6	318	1673	2.0E-04	U041517	H
P28w/0785	2591500	5963800	23.2			360	2.0E-05	U000989	M
P28w/2579	2595493	5963531	37.5	31.1	186	500	7.0E-06	U030074	M
P28w/3638	2591966	5963535	21.5	19.4	205	550	8.0E-05	U000989	M
P28w/4005	2592075	5963992	24.6	22.0	196	450	5.2E-05		M
P28w/4235	2593074	5963973	32.1	26.5	200	355	1.0E-04	U031313	M
P28w/4402	2592343	5963996	25.5	22.3	136	430	5.0E-05	MDC	M
P28w/4446	2595910	5963228	36.8	32.5	263	325	6.3E-06	U050668	M
P28w/1283	2591619	5963864	32.7	20.5	134	135	5.7E-05	Vol 2	L
P28w/1312	2593500	5963580	28.8	24.5	187	200	3.0E-04	U030920	L
P28w/3396	2593063	5963973	31.0	28.0	64	250	1.0E-04	U040691	L
P28w/3636	2591764	5963468	22.1	18.6	30	290	8.0E-05	U000989	L
P28w/3949	2591996	5963610	22.2	20.7	169	290	1.3E-04	U000989	L
P28w/4005	2592075	5963992	24.6	22.0	196	200	1.0E-05	U021132	L
P28w/4052	2595003	5963112	22.3	17.9	189	290	1.0E-05	U021199	L
P28w/4210	2593121	5963067	15.3	13.7	41	17	2.0E-04	U030827	VL
						Mean S	1.0E-04		
						Median S	8.0E-05		
						Max S	5.0E-04		
						Min S	6.3E-06		

The distribution of hydraulic conductivity zones within the model is shown in Appendix 1.3 and 1.4. Initial hydraulic conductivity estimates for the numerical model are presented in Table 2. It is important to estimate initial parameter values as accurately as possible, as optimum initial values improve the efficiency of parameter optimisation in the PEST routine.

Table 2 - Representative hydraulic conductivity values for the Riverlands area

Aquifer Transmissivity Zone	Model K Zone	Lower K Estimate	Upper K Estimate
Hi	1, 6 & 8	200	600
Mod	2	40	70
Low	3	20	40
Very Low	5	1	5
Inland Aquitard	4	0.01	1
Coastal Aquitard	7	0.0001	0.1

Pumping test data shows that storativity values for the Riverlands and confined Wairau aquifer average 1 x 10^{-4}. Observed values range from 6 x 10^{-6} to 5 x 10^{-4} with a median of 8 x 10^{-5}. There does not appear to be any spatial pattern to the storage distribution, except that there is a general tendency for storativity to increase to the east as aquifer depth increases.

3.6.2 Aquifer Observation Data

Observation data is available from continuous stage recorders and manual surveys. MDC has installed recorders on three monitoring wells that intersect the confined aquifer in the Riverlands and Lower Wairau areas (P28w/0708, 1733, and 4402). In addition to these records, three wells have been dipped at weekly intervals for a period of several months (3949, 4402, 4403). Of these wells, 4402 and 3949 are screened in the Riverlands Aquifer.

Spatial variability in aquifer head is provided by two regional water pressure surveys, carried out on 15 April 2004 and 13 June 2007. The potentiometric surveys have been corrected for tidal influences using the method of Ferris (1951).

3.6.3 Water Abstraction

Over 18,000 m^3/d or groundwater has been allocated from an area encompassing the Riverlands area. This area includes the Riverlands Aquifer, and the southern most kilometre of the Wairau Aquifer to 5965000 N. Of this allocated volume 9,550 m^3/d is allocated to MDC, and 1,200 m^3/d is allocated to Canterbury Meats Ltd (CMP). The remaining 7,400 m^3/d is for irrigation, which comprises 41% of the total allocated groundwater volume.

Daily water abstraction data is available for all MDC wells. CMP records weekly water use, which is typically up to 750 m^3/d. There is much less certainty in the actual volume used by irrigation consent holders. While the majority of wells have water meters installed as a requirement of their consent conditions, the water meter information is rarely recorded except during MDC surveys.

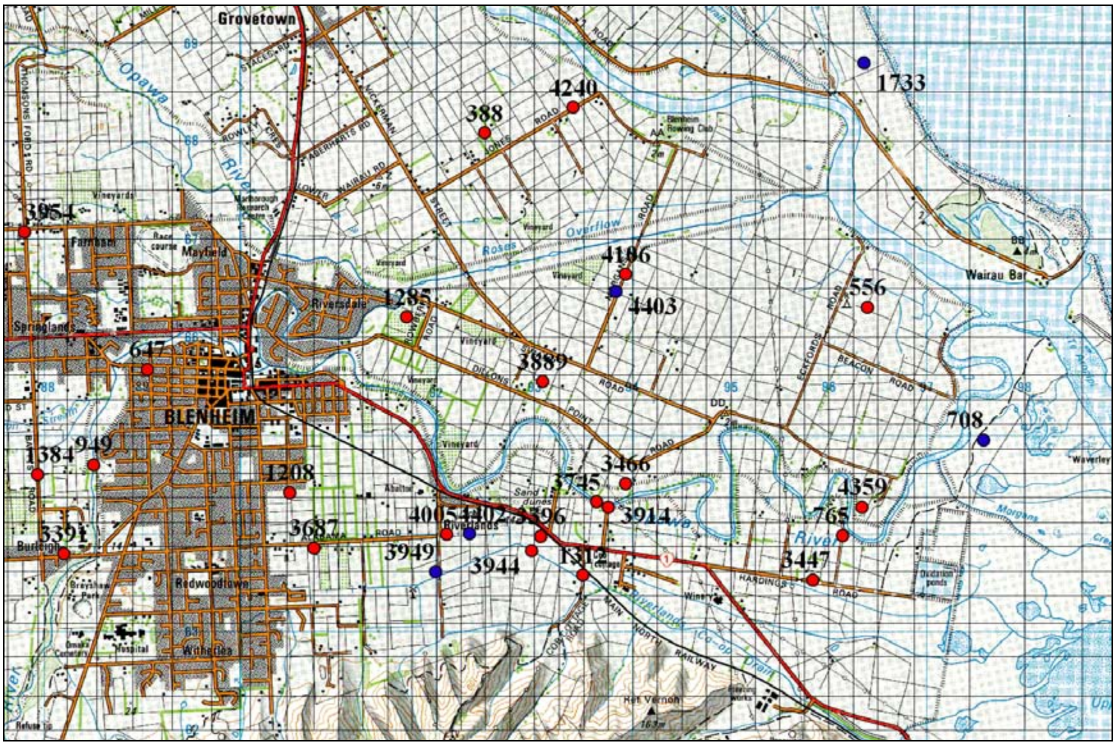

Figure 3 - Map showing the location of observation wells. Transient wells are shown in blue. The model grid is also visible.

A summary of the available water meter data for irrigation wells is provided in Table 3. Abstraction volume between different consent holders varies markedly. Also, the seasonal abstraction volume for each consent holder also varies from year to year. The high variability of use shows that it is difficult to predict abstraction rates for any single well in the Riverlands area unless the meter data has been recorded.

Table 3 – Available water meter data for irrigation wells in Riverlands and Lower Wairau

Well	Consent	Allocation (m^3/Ha)	Crop	Percentage of allocation used over 120 day season					
				Average	2002/03	2003/04	2005/06	2006/07	Other Year
1312	030920	21	Pasture	15				0	31
2500	020465	18	Vines	47				47	
2558	040014	22	Vines	3				3	
3396	040691	12	Vines	38					38
3405	011375	40	Pasture	86	86				
3447	030769	22	Vines	56				60	53
3638	000989	9	Vines	144				244	43
3745	010410	14	Mixed	39	100			0	18
3806	021159	17	Mixed	15				15	
3944	020001	13	Vines	50	63	19		60	60
4005	021132	18	Vines	69		28	130	54	65
4029	020318	50	Pasture	11	1			8	26

Where water meter data is available, this has been used to develop pumping records for the numerical model. Where water meter data is not available, the abstraction rates have been estimated. Assuming a 120-day irrigation season, the available data suggests that irrigators tend to use about 35-40% of their allocation.

A summary of allocation and peak demand for different water users is shown in Table 4. Note that demand for each of the water users varies throughout the year. Peak demand is expected to occur during late summer and vintage, and is estimated to be around 6,500 m^3/d.

Table 4 - Summary of water allocation and use in the Riverlands area

	Allocation (m^3/d)	Summer Demand (m^3/d)	% Use
MDC	9,550	3,200	34
CMP	1,200	750	63
Irrigation	7,400	2,960	40
Total	18,150	6,910	38

4 STEADY STATE MODEL CALIBRATION

4.1 CALIBRATION APPROACH

The initial step for calibrating a groundwater model is to represent steady state aquifer conditions. When an aquifer is in steady state, the inputs and outputs, and therefore the heads, remain constant through time. In reality, the steady state condition rarely occurs, but an aquifer can be assumed to be in steady state if head changes are fairly stable over a long period of time.

The advantage of the steady state assumption is that because inputs and outputs are constant, storage is not required as a parameter for model calibration. This limits the number of parameters required for optimisation, which gives greater confidence in the resulting calibration.

Calibration has been achieved by applying the inverse modelling routine PEST. The advantage of PEST over forward modelling is that it provides a statistical output of parameter sensitivity and covariance. This makes the optimisation process more efficient, and the final calibration more robust.

Parameters are optimised separately if they are strongly dependent, such as river conductance and aquitard hydraulic conductivity. PEST displays parameter covariance and correlation in the form of matrices, whereby parameter independence can be determined. Where a parameter has a high sensitivity and low covariance, its value can be considered to be uniquely defined. That parameter can then be fixed for ensuing PEST runs. The process is repeated until optimum confidence is arrived at for each parameter and a satisfactory calibration is achieved.

Aquifer hydraulic conductivity values are relatively well constrained by pumping test results, and do not require optimisation during initial model runs. Calibration was initiated by determining optimal values for river and drain conductance, and vertical conductivity for the aquitard. Later optimisation runs included aquifer parameters to refine the calibration.

Targets for the model calibration are observed head values, which were taken from the surveyed potentiometric surface of 13 May 2007. An exact fit between all the modelled and observed heads is not the intention of the steady state optimisation process. The objective is to represent the aquifer head distribution on a regional scale. There are many reasons for departures from a perfect fit, including:

- Temporal fluctuation of head within individual boreholes. Where fluctuations are considerable, the selection of an appropriate calibration target value for a borehole can be difficult.
- Local aquifer and aquitard heterogeneity
- Bore construction and deterioration
- The observed heads probably do not represent a steady state condition. Many of the observations are taken at different times over the course of a month.

4.2 STEADY STATE CALIBRATION RESULTS

A total of twenty-six calibration targets (head observations) were used for steady state model calibration (Appendix 2). The results of the steady state calibration are shown graphically in Figure 4. A summary of calculated heads and residuals is provided in Table 5.

The calibrated model shows a very good fit with the observed values. The residual sum of squares is less than 5m, with a residual mean of –0.03m. A positive residual value means that the model has predicted water levels in that bore too low. A negative value means that water level is modelled too high.

Of the twenty-six calibration targets used, only five have a residual (error) of greater than 0.5m. Four targets account for half of the residual total, which indicates that the calibration is not biased towards one or two targets.

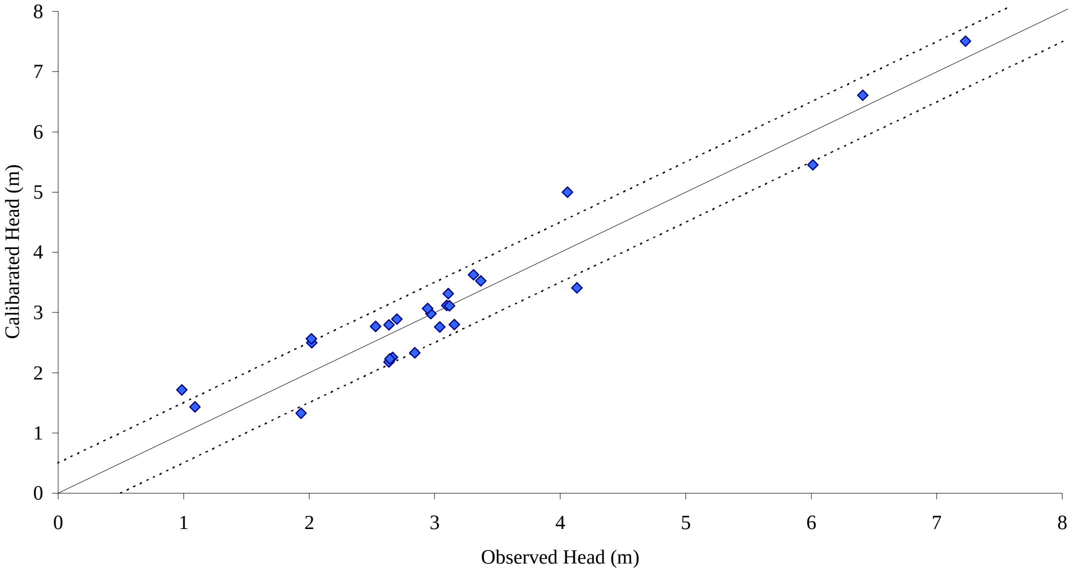

Figure 4 - Steady state model calibration results showing 0.5m error bands

The well with the largest residual is P28w/0647, MDC at Beaver Road (Table 5). This is an old well that is screened at a depth that is greater than expected for its location, which may explain its high calculated head. Other wells with residual greater than 0.5m are: P28w/0949 (Athletic Park), P28w/1285 (Blackmores), P28w/3687 (Newman) and P28w/3944 (Sileni). These wells are all situated adjacent to surface water bodies. This reflects the difficulty in accurately characterising groundwater heads along the whole length of each drain or river reach.

One calibration target, P28w/3391 (MDC at Burleigh Park), was removed during the calibration process. Heads in this well were calculated too low, which adversely influenced the parameter optimisation process. This well is screened at a depth of 25m within Taylor Fan deposits. The well is interpreted to have a poor hydraulic connection with the Riverlands aquifer.

Table 5 – Summary of steady state model calibration results. Wells in italics have also been used for the transient model calibration

Name	X	Y	Observed	Computed	Residual
P28w/0388	2592495	5968075	3.37	3.53	-0.16
P28w/0556	2596400	5966300	2.70	2.90	-0.20
P28w/0647	2589051	5965672	4.06	5.00	-0.94
P28w/0708	2597585	5964954	3.16	2.80	0.35
P28w/0765	2596150	5963980	3.04	2.76	0.28
P28w/0949	2588510	5964700	6.01	5.45	0.56
P28w/1208	2590506	5964415	3.31	3.63	-0.32
P28w/1285	2591700	5966200	4.13	3.42	0.72
P28w/1312	2593493	5963574	1.09	1.43	-0.34
P28w/1384	2588000	5964600	6.41	6.61	-0.20
P28w/1733	2596368	5968789	2.97	2.98	-0.01
P28w/3396	2593063	5963973	2.64	2.18	0.45
P28w/3447	2595845	5963529	2.02	2.50	-0.48
P28w/3466	2593929	5964508	2.53	2.77	-0.24
P28w/3687	2590752	5963852	2.02	2.57	-0.55
P28w/3889	2593083	5965549	2.94	3.07	-0.13
P28w/3914	2593756	5964268	2.84	2.34	0.51
P28w/3944	2592980	5963819	0.99	1.72	-0.73
P28w/3949	2591996	5963610	1.94	1.45	0.49
P28w/3954	2587762.2	5967031	7.23	7.51	-0.28
P28w/4005	2592109	5963989	2.67	2.31	0.36
P28w/4106	2593929	5966636	3.10	3.12	-0.03
P28w/4240	2593397	5968337	3.11	3.32	-0.21
P28w/4359	2596344	5964269	2.64	2.80	-0.16
P28w/4402	2592343	5963996	2.64	2.26	0.39
P28w/4403	2593830	5966459	3.12	3.11	0.00
		Residual Sum of Squares (phi)			4.51
		RMS Error			2.12
		Residual Mean			-0.03
		Abs. Res. Mean			0.35
		Min. Residual			-0.94
		Max. Residual			0.72

A plot of residual vs. observation (Figure 5) shows the relationship to be statistically random. This suggests that the model calibration is not spatially biased. However, when plotted on a map of the area, it can be seen that the model does have a tendency to underestimate heads locally (Figure 6). Clusters of lower calculated heads (positive residuals) can be discerned in the vicinity of surface water bodies, although this relationship is not always clear. It is likely that these localised variations are caused by local aquifer, aquitard and/or bed conductance heterogeneity. While detectable, the variations are small, and are not considered to significantly reduce model reliability given the scale of the model and the information available.

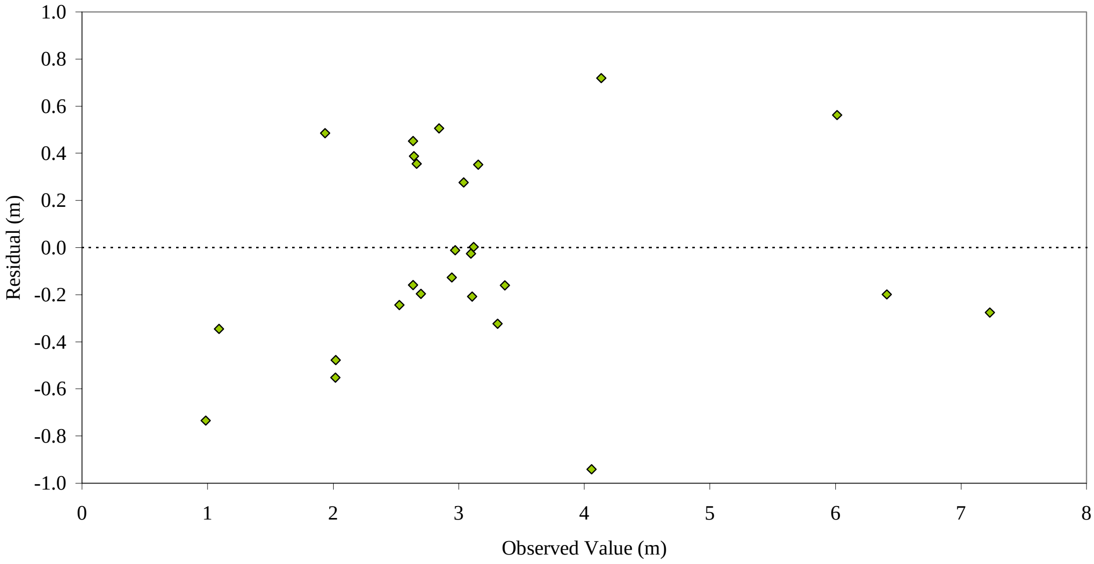

Figure 5 - Plot of observed vs. residual values for the steady state calibration

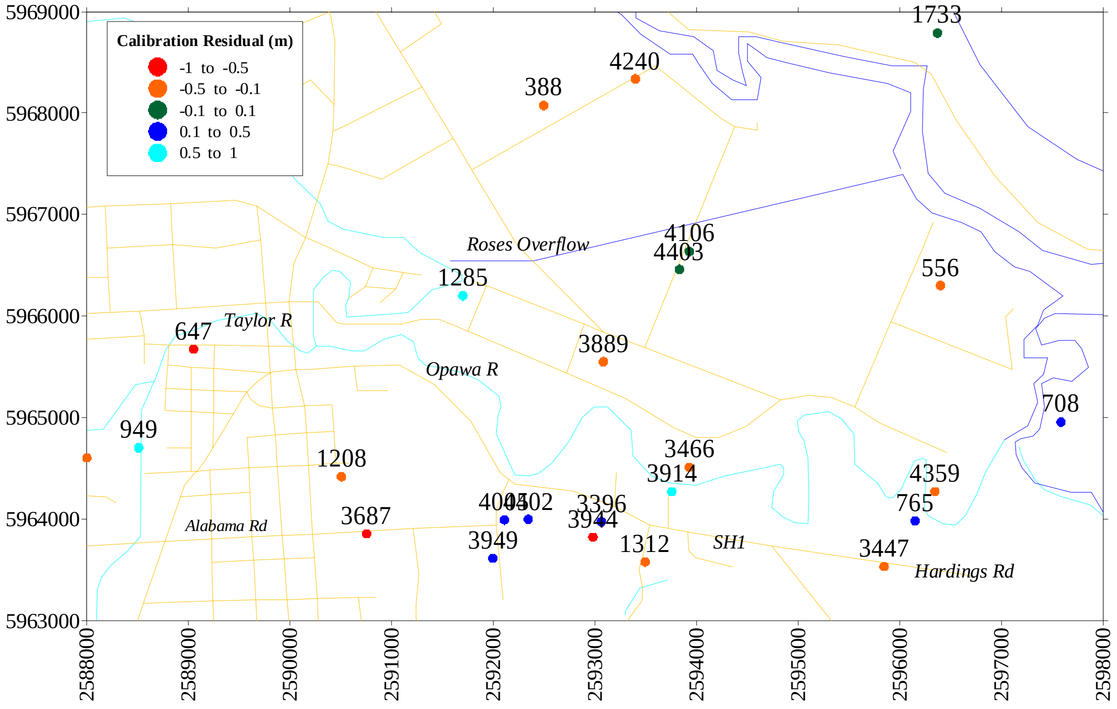

Figure 6 – Map of steady state calibration residual distribution. A positive residual indicates that the head calculated by the model is lower than the observed value.

4.3 STEADY STATE MASS BALANCE

The steady state mass balance is shown in Table 6. Inflows are dominated by upgradient flux from the Wairau Aquifer. Some inflow is also calculated to occur in the upper reaches of the Taylor River.

Outflows are dominated by losses to surface water bodies, with over half a cumec being lost to the Taylor and Wairau Rivers. The majority of this loss occurs in the Taylor River, as well as the upper reaches of the Wairau and Opawa Rivers.

Table 6 - Steady state mass balance

Boundary Condition	Inflow (m3/d)	Outflow (m3/d)	Inflow (l/s)	Outflow (l/s)
Constant Head	63,852	1,664	739	19
Rivers	4,425	49,242	51	570
Drain	0	3,000	0	35
Wells	0	14,371	0	166
TOTAL	68,277	68,277	790	790
	% ERROR	0	% ERROR	0

Unfortunately it is not possible to use the mass balance as a tool for model calibration or verification. This is because there is insufficient data available on river flows in the Lower Wairau area. However, river gains seem intuitively appropriate, and are not excessively high. Flow in the Riverlands coop drain also appears to be reasonably estimated, although actual flow in the drain has never been gauged.

4.4 OPTIMISED PARAMETER VALUES

Optimised values of hydraulic conductivity are presented in Table 7. The most significant changes made during optimisation were an increase in the inland aquitard value, and a decrease in the coastal aquitard value. All of the aquifer values were kept within the bounds recorded by pumping tests.

Table 7 - Optimised values for hydraulic conductivity

Model Conductivity Zone	Aquifer T Zone	Initial Value (m/d)	Optimised Value (m/d)
kx1	Wairau Aquifer	500	500
kx2	Moderate Riverlands	50	70
kx3	Low Riverlands	30	20
kz4	Inland Aquitard	0.1	0.9
kx5	Wither Hills	1	1
kx6	Wairau Aquifer	550	500
kz7	Coastal Aquitard	0.01	0.002

Optimised values of boundary conductance are presented in Table 8. All of the optimised values were increased from their initial values. Overall, the model calibration has predicted that the inland aquitard is considerably more leaky than originally expected.

Table 8 - Optimised values for boundary conductance

Boundary Condition	Initial Bed Conductance (m^2/d)	Optimised Bed Conductance (m^2/d)
Taylor River	1,000	2,610
Opawa River	500	1,500
Wairau River	2,000	60,000
Riverlands Coop Drain	50	1,000

4.5 STEADY STATE SENSITIVITY ANALYSIS

A groundwater model calibration is non-unique. Model parameters can be optimised at different values to obtain a similar head distribution. Confidence in a model calibration can be assessed through parameter sensitivity and covariance. The more sensitive a parameter is to change, the more confidence we can have in it's optimised value, depending on its covariance with other parameters.

A sensitivity analysis was performed on all model parameters by multiplying the calibrated values by the following factors: 0.1, 0.5, 0.75, 0.9, 1, 1.1, 1.25, 1.5, and 2. The residual sum of squares (phi) was used as a measure of parameter sensitivity for each of the iterations.

The results of the sensitivity analysis for optimised conductivity values are shown in Figure 7. The model calibration is most sensitive to Kx6, Wairau Aquifer conductivity in the middle of the Wairau Plain. The next most sensitive parameters are hydraulic conductivities Kx1 and Kx2, the southern Wairau Aquifer and Northern Riverlands Aquifer respectively. Parameters Kx3, Kx5, and Kz7 are fairly insensitive. Of all these parameters, Kx1, Kx2, and Kx3 can be considered to be well constrained by initial estimates obtained from pumping tests.

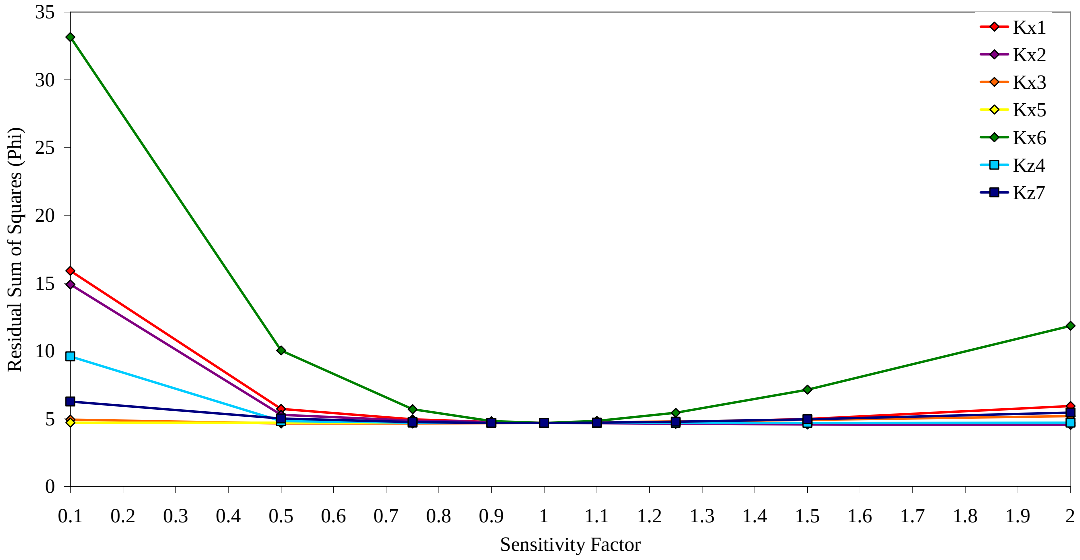

Figure 7 - Sensitivity analysis for hydraulic conductivity values

Confidence in the optimised value of any given hydraulic conductivity parameter can be determined from the covariance matrix derived by the PEST algorithm (Table 9). Confidence in the optimisation for any given parameter is shown along the matrix diagonal, shown in bold type. The lower the value on the diagonal, the greater confidence we can have in the parameter estimate. The covariance matrix shows that all horizontal conductivity parameters except for Kx5 are well constrained and we can have confidence in their estimated values.

Vertical conductivity value Kz7 (coastal) is well constrained, but there less certainty in the estimate for Kz4 (inland). The parameter correlation matrix shows that Kz4 has a high degree of dependence on horizontal conductance values (Table 10).
In conclusion, all of the hydraulic conductivity values can be considered to be well constrained except for Kx5 (Wither Hills), and to a lesser extent Kz4 (inland aquitard).

Table 9 - Covariance matrix for hydraulic conductivity

	kx1	**kx2**	**kx3**	**kz4**	**kx5**	**kx6**	**kz7**
kx1	**0.54**	-0.24	0.57	1.90	0.43	0.09	-0.24
kx2	-0.24	**0.55**	0.19	-0.05	-0.48	0.09	-0.01
kx3	0.57	0.19	**1.74**	3.57	-0.10	0.43	-0.43
kz4	1.90	-0.05	3.57	**13.42**	0.85	1.45	-0.36
kx5	0.43	-0.48	-0.10	0.85	**26.04**	-0.25	-2.30
kx6	0.09	0.09	0.43	1.45	-0.25	**0.25**	0.19
kz7	-0.24	-0.01	-0.43	-0.36	-2.30	0.19	**1.34**

Table 10 - Correlation coefficient matrix for hydraulic conductivity

	kx1	**kx2**	**kx3**	**kz4**	**kx5**	**kx6**	**kz7**
kx1	1	-0.45	0.59	0.70	0.11	0.26	-0.28
kx2	-0.45	1	0.19	-0.02	-0.13	0.24	-0.02
kx3	0.59	0.19	1	0.74	-0.02	0.66	-0.28
kz4	0.70	-0.02	0.74	1	0.05	0.80	-0.09
kx5	0.11	-0.13	-0.02	0.05	1	-0.10	-0.39
kx6	0.26	0.24	0.66	0.80	-0.10	1	0.34
kz7	-0.28	-0.02	-0.28	-0.09	-0.39	0.34	1

Sensitivity of the boundary conductance values is displayed in Figure 8. In general the model head distribution is less sensitive to drain and river boundaries than hydraulic conductivities. The main reason for this is that the rivers and drains have only a small localised effect on aquifer heads. The sensitivity analysis shows that optimum conductance values for the Opawa and Taylor Rivers have been determined. The Wairau River and Riverlands Coop Drain are fairly insensitive for factors greater than 0.5 times the optimised value.

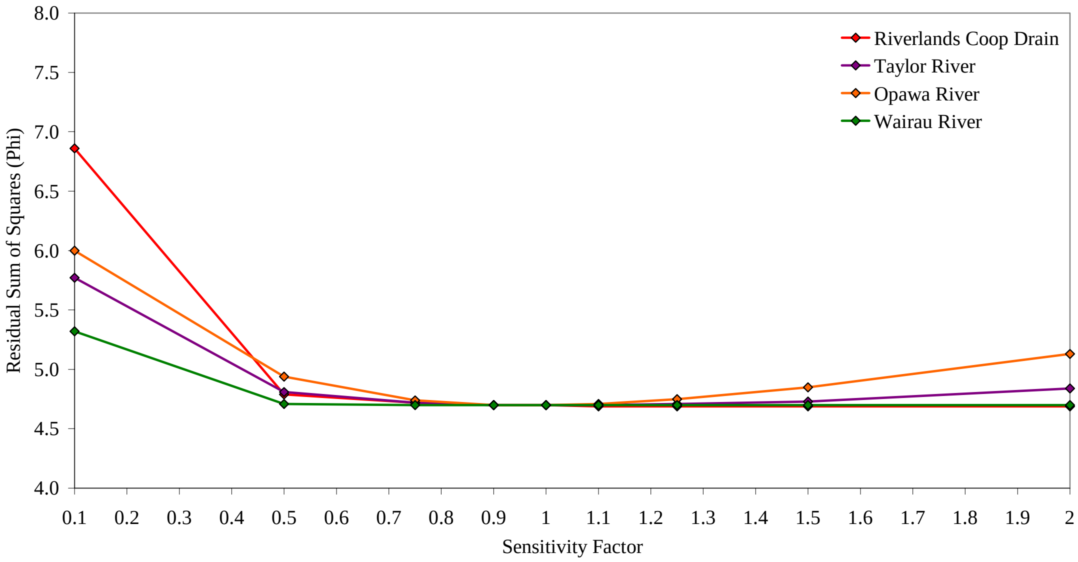

Figure 8 - Sensitivity analysis for river and drain bed conductance values

The parameter covariance matrix (Table 11) indicates that conductance for the Taylor, Opawa, and to a lesser extent Riverlands Coop Drain has been estimated with a high degree of certainty. We can have little confidence that the Wairau River bed conductance has been predicted with accuracy. However, the Wairau River is in the northern part of the model domain, and as such is considered to have little direct influence on heads in the Riverlands area.

Table 11 - Covariance matrix for bed conductance values

	Taylor River	**Opawa River**	**Wairau River**	**Riverlands Drain**
Taylor River	**0.26**	0.00	0.54	0.04
Opawa River	0.00	**0.35**	-2.84	-0.28
Wairau River	0.54	-2.84	**30.63**	1.31
Riverlands Drain	0.04	-0.28	1.31	**1.06**

5 TRANSIENT MODEL CALIBRATION

5.1 CALIBRATION APPROACH

The purpose of the transient model calibration is to verify that the steady state model can accurately simulate variations in aquifer stresses through time. The model is calibrated for transient conditions by fixing parameter values previously determined in the steady state model, and optimising for specific storage and specific yield. The calibration target is to match observed heads with heads calculated by the model over time. It has been assumed that storage properties do not vary within each layer across the model domain. There is currently insufficient information to discern any spatial variation in storativity within the Riverlands area.

There are five wells within the model domain with sufficient observations to use as transient calibration targets. These are Wairau Bar (P28w/1733), Lagoons (P28w/0708), Morgans Road (P28w/4403), MDC Huia (P28w/4402), and Diamond (P28w/3949).

Initial heads for the transient model are imported from the calibrated steady state model. Thus, the transient starting heads contain an initial error associated with the steady state residual calculated for each borehole. Initial heads were continuously improved for each model run by replacing the initial head input values with the output from the previous model run.

5.2 TRANSIENT STRESSES

Time-variant stresses included in the model are abstraction, river and drain stage, and the western fixed head boundary.

A time series record for the western fixed head boundary has been constructed from head observations at the Substation (P28w/3954) and Athletic Park (P28w/0949) wells. River time series records have been derived from stage recorders on the Taylor and Wairau Rivers (see Section 3.5.2).

Water use is recorded at MDC wells on a daily basis, and at Canterbury Meats on a weekly basis. Thus, time series records are available for around 55% of the groundwater abstraction in the Riverlands area. Abstraction records for the remaining 45% of water users (all irrigation takes) have been estimated.

The start and end of each irrigation season has been set to accord with the timing of drawdown and recovery in the MDC coastal wells at the Lagoons (P28w/0708) and Wairau Bar (P28w/1733). Irrigation is assumed to only occur within this period. Where water meter data is available, it has been averaged over the course of the irrigation season to match the measured abstraction rate. Where water mater data is not available, a constant abstraction rate of 40% of allocation was applied over the irrigation season. Irrigation is assumed to commence the summer following the granting of each consent.

The abstraction record used in the model has a peak demand in the Riverlands area of 6,460 m^3/d. This is 36% of the total allocation for the area. The highest demand occurs during vintage in April each year.

5.3 TIME DISCRETISATION

The transient calibration runs for a duration of seven years, from July 2000 to June 2007. This period has a good record of aquifer head observations, and includes the 2000-2001 drought.

The selection of appropriate stress periods and their duration in a model depends on the availability of data, as well as the variability of the record through time. A large number of stress periods will cater for temporal variability, but will take the model a long time to run. If insufficient stress periods are chosen, important fluctuations in head will not be accounted for in the model.

With these considerations in mind, the seven-year model record has been divided into 364 stress periods of one-week duration. This decision reflects the quality of data available, and provides sufficient temporal variability for calibration.

5.4 TRANSIENT CALIBRATION RESULTS

Optimised values of specific storage and specific yield are listed in Table 12. Specific storage for the aquifer was fixed at a value representative of aquifer test results (refer to Table 2). Note that confined storage values are normally quoted as storativity values. The MODFLOW routine uses specific storage, which is storativity divided by aquifer thickness.

Table 12 - Optimised storage values for the Riverlands model

	Specific Yield	Specific Storage	Storativity
Aquitard	2.5×10^{-4}		
Aquifer	1×10^{-2}	5×10^{-6}	4×10^{-5}

The transient calibration required that some values previously optimised in the steady state model be altered. These were:

- Drain bed conductance be decreased from 2 to 0.2 m/d
- Wairau Aquifer hydraulic conductivity increased from 500 to 550 m/d
- Inland aquitard vertical conductivity increased from 0.9 to 1.1 m/d

Inserting these revised values into the steady state model makes very little difference to the steady state calibration.

Calibrated model heads for the available monitoring wells are provided in Appendix 3. Overall, the model hydrographs show agree very well with the observation records, especially considering the poor availability of abstraction records from irrigation wells.

Emphasis of the transient calibration has been placed on fitting heads in the Riverlands area of the model. For this reason, the heads in the Bar well (P28w/1733) do not fit as closely as wells in the Riverlands area. The Bar well and Morgans Road well (P28w/4403) have been included in the calibration to ensure that the flow field surrounding the Riverlands area is appropriate. The hydrographs for these two wells are still calibrated well in terms of mean head, and the magnitude of winter peaks and summer drawdown.

The hydrograph with the best fit is the Lagoons well (P28w/0708). This well has an extensive observation record. The model data fits the observation record best for the last two to three years of model record. This is the period for which the best water meter data is available. The first half of the record does not fit quite as well, and this is mainly due to uncertainties in abstraction rates.

The model hydrograph for the Huia well (P28w/4402) also fits the observation data well, particularly for the last year record when abstraction rates are better known. The model does underestimate drawdown slightly for summer 2005-2006. The model hydrograph for this well can be improved by decreasing the specific yield of the aquitard, although doing this creates excessive drawdown in wells further north. It is uncertain whether the underestimated drawdown is the result of inadequate pumping records or local variation in storage properties.

The Diamond well (P28w/3949) shows the poorest fit of all the Riverlands wells. This well is used for domestic supply. As a result, there are large drawdowns apparent in the observation record that are not incorporated into the model. It is also clear from the hydrograph that the synthetic abstraction developed record for nearby wells is not accurate. Despite these discrepancies, the model hydrograph does fit the general trend of the observed data, particularly for the period between late 2003 and late 2004.

5.5 TRANSIENT MODEL SENSITIVITY ANALYSIS

The model is mildly sensitive to changes in aquitard specific yield, and is relatively insensitive to changes in aquifer storage values. The covariance matrix for storage properties (Table 13) shows that aquitard specific yield is optimised with a high degree of certainty.

Aquifer specific storage is optimised to a lesser degree of confidence. However, the availability of aquifer test results allows us to have good confidence in the value used in the model. Aquifer specific yield is the parameter with the least certainty. The reason for this is that aquifer heads are not drawn below the aquitard during model calibration, so the aquifer is always subject to confined conditions.

Table 13 - Covariance matrix for storage model parameters

	Aquifer Ss	Aquifer Sy	Aquitard Sy
Aquifer Ss	2.91	-4.67	0.05
Aquifer Sy	-4.67	11.36	-0.12
Aquitard Sy	0.05	-0.12	0.03

5.6 MODEL FLUXES

5.6.1 Transient Mass Balance

Figure 9 shows the water budget for one year as a percentage of inflow and outflow. Inflow is dominated by groundwater flux across the constant head boundary along the western edge of the model. River recharge only accounts for 5-10% of model inflow. Outflow is dominated by river losses, and to a lesser extent groundwater pumping. Discharge to the sea is calculated as being negligible.

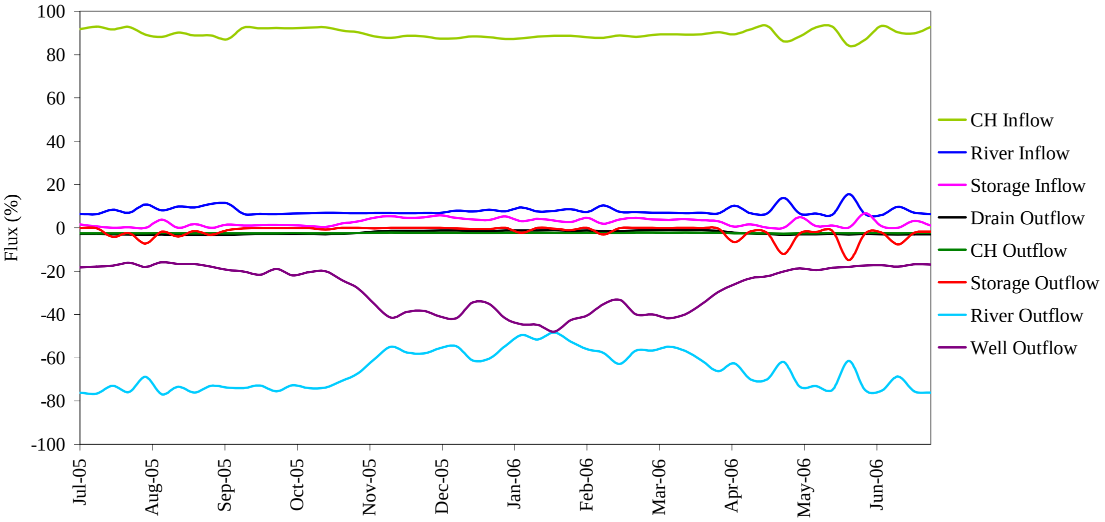

Figure 9 - Water budget for one year of the Riverlands model shown as a percentage of outflow and inflow

It is interesting to study how the water balance changes in response to pumping. While pumping contributes up to 40% of aquifer outflow, the associated change in aquifer storage is 5% or less. The additional water is provided by a reduction in groundwater discharge to rivers via the aquitard. This supports the idea that if heads (and hence spring flow) along the western edge of the confined aquifer can be managed, then groundwater abstractions will be sustainable.

The reduction in discharge to rivers also illustrates the importance of correctly characterising surface water groundwater interaction in the model. If the model was calibrated with a lower bed conductance in the surface water bodies, then the model would more reliant on aquifer storage during pumping.

5.6.2 Aquifer Leakage

Figure 10 presents the change in vertical aquifer flux throughout the year. Aquifer storage has not been plotted, as its contribution is insignificant compared to the other fluxes. Note that abstraction is approximately 50% of the recharge flux across the western boundary.

During summer when groundwater demand is high, most of the pumping demand is met by a reduction in vertical leakage to the aquitard. There is also a significant increase in the volume of storage removed from the aquitard, and a very slight increase in flux across the western boundary. Note that the reduction in flux across the western boundary will be largely met by a flow reduction in the southern springs area.

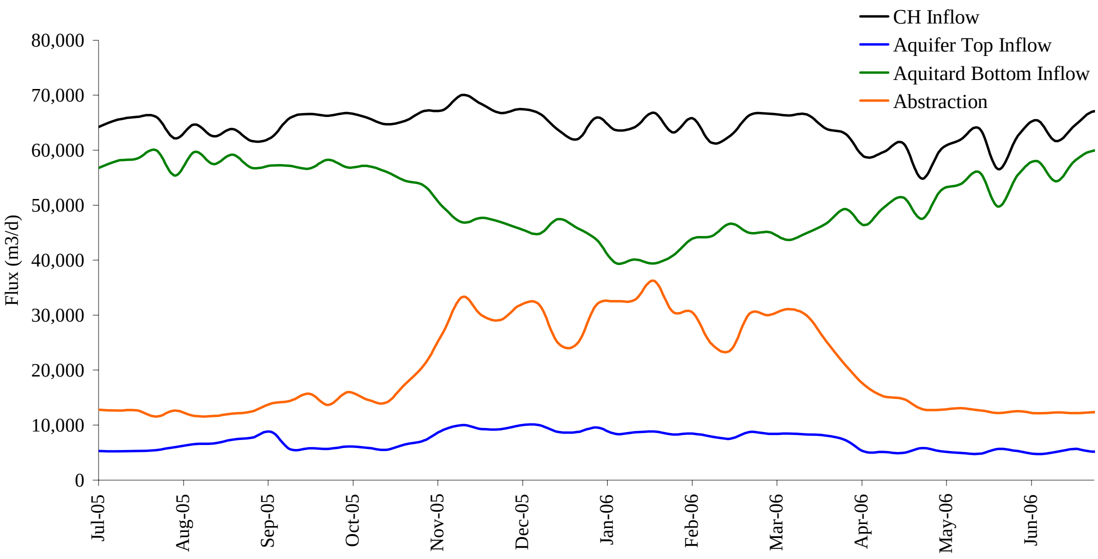

Figure 10 – Plot showing change in flux between aquifer and aquitard throughout the year

5.6.3 Groundwater inflow

Groundwater inflow along the western model boundary changes little throughout the year. The groundwater flux south of New Renwick Road is negligible, which is attributed to the low transmissivity of these gravels. Within the Wairau Aquifer, north of New Renwick Road, aquifer inflow is 5.5 to 6 m^3/d per metre. This means that the Wairau Aquifer south of Middle Renwick Road has approximately 9,000 m^3/d of groundwater flowing through its gravels.

For comparison, this is a similar volume to the discharge from the Doctors Creek spring system during periods of low flow. Note that while the flow in Doctors Creek may be typically over five times this volume during winter, the groundwater flux within the confined aquifer does not increase. The reason for this is that the springs represent the discharge of excess pressure within the confined aquifer.

6 MODELLED SCENARIOS

6.1 INTRODUCTION

The Riverlands model calibration has been shown to be accurate and robust enough to be used for predictive modelling. The model can be used to test how the Riverlands and Wairau aquifers respond to different conditions and stresses.

The most pressing issue to be tested by the model is an increase in water demand. It is clear from the available water use data that the current allocation of water in the Riverlands area is under utilised. However, there is potential for new consent applications to be made, and also for existing consent holders to use a higher proportion of their quota. This may come about through a change in dominant crop type from grapes to crops or pasture, or an increase in industrial demand.

To test the impact of increased demand, several high-demand scenarios were run through the groundwater model:

1. Irrigation wells at 2/3 capacity, MDC and Canterbury Meats Ltd (CMP) wells at calibrated rates.

2. MDC Riverlands wells at full capacity, all other wells at calibrated rates.

3. Full demand scenario, irrigation wells at 2/3 capacity, MDC Riverlands wells at full capacity

4. An estimate of the sustainable yield for the Riverlands area

The scenarios were modelled by applying additional demand to the calibrated abstraction records. The results for each scenario are plotted as hydrographs (Appendix 3), and also as profiles through the aquifer (Appendix 4). Contours of the Potentiometric surface for the day of greatest overall drawdown, typically 20 April 2007, are also presented for each scenario.

The primary area of focus for these simulations is the Riverlands Aquifer, and includes a 1km buffer zone in the Wairau Aquifer to 5965000 N. This is the area delineated with a black box in Figure 1. The extent of the buffer is somewhat arbitrary, although a buffer of at least this distance is required to avoid excessive drawdowns in the vicinity of Hardings Road. This focus area essentially encompasses abstractions south of Dillons Point Road, where drawdowns are expected to be concentrated.

The impact of each scenario is measured specifically in the following wells:

1. *MDC monitoring well P28w/0708, Wairau Aquifer.* This is a coastal observation well installed to monitor water level and conductivity. Water

levels should be kept above 1.25m RL to avoid seawater intrusion[1]. A 50% reduction in pumping rate is recommended for wells in the Hardings Road area when water level in this well reaches 1.5m RL.

2. *Diamond well P28w/3439, Riverlands Aquifer*. Some wells in the Riverlands Aquifer have consent conditions relating to a threshold on this well at -4.7m RL (6m below ground level)

3. *MDC monitoring well P28w/4402, Riverlands Aquifer*. The -4.7m RL threshold at Diamond is equivalent to -0.25m RL at the MDC well

4. *MDC Malthouse Road well P28w/1678, Wairau Aquifer*. This community supply well requires head to remain above -12m RL for continuous operation.

5. *Canterbury Meats (CMP) wells P28w/0739 & 4191, Wairau Aquifer*. Current available drawdown is at least 11.5m, allowing 7m for a submersible pump. Head at this well should be kept above –6.5m RL to maintain continuous operation of the plant.

6. *Butter Factory Corner, Wairau Aquifer*. There are a number of private domestic supply wells in this area. The lifting head of surface mounted pumps limits available drawdown for these wells. Low performance pumps are expected to struggle if heads in this area fall below -2m RL.

When studying the simulated hydrographs, it is important to note that drawdown for the Malthouse Road and CMP production wells is underestimated by MODFLOW. The reason for this is that MODFLOW averages the drawdown in the within the model cell containing the well across the whole area of the cell.

6.2 SCENARIO 1: Irrigation wells at 2/3rds of allocation

The first scenario predicts the impact if all irrigators were to use two thirds of their quota during the irrigation season. The MDC and CMP abstractions are retained at their calibrated abstraction rates. This scenario is intended to simulate existing land use with a high water demand brought on by prolonged dry or drought conditions. Peak demand in the Riverlands area for this scenario is 8,300 m^3/d, occurring in mid to late April 2007.

The resulting potentiometric contours for April are plotted in Figure 11. An overall hydraulic gradient to the coast is retained in this scenario. However, there is an area of concentrated drawdown at the end of Hardings Road. Surrounding this is a fairly extensive area where heads have been drawn down by half a metre below their calibrated values to 1m RL.

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[1] This calculation is based on the Ghyben-Herzberg approximation (Freeze and Cherry, 1979). Well P28w/0708 does not penetrate the entire Wairau Aquifer. The base of the aquifer is expected to be at 48.3m below sea level, assuming an average aquifer thickness of 8m. The required head to maintain the saltwater interface at the coast is therefore 48.3/40 = 1.21m, or 1.25m above msl including a safety buffer. This safety buffer takes into consideration the fact that there are deeper wells nearby.

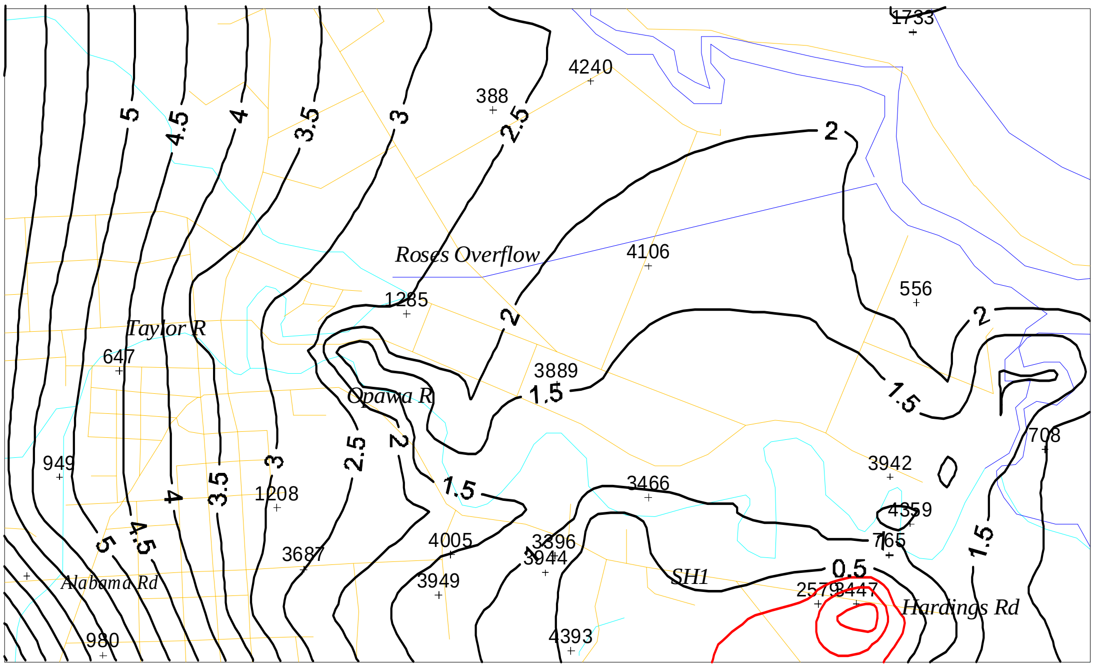

Figure 11 - Potentiometric contours during April for Scenario 1, high irrigation water demand. Contours where aquifer pressures are at or below sea level are shown in red.

The modelled hydrographs for this scenario indicate that there are no serious problems with respect to sustainability for this scenario (Appendix 3). The main issue for this scenario is the possibility of drawing connate water from the southeast into wells along Hardings Road, thereby increasing groundwater salinity.

The most significant impact of this scenario is at the Lagoons well (P28w/0708), where there is up to 1.5m of additional summer drawdown. Heads in this well fall close to the recommended 1.5m initial threshold. An additional drawdown of up to 1.45m is recorded at the Huia well (P28w/4402). Head is at this well is similar to the Lagoons well, which is an indication that the overall hydraulic gradient remains flat, but is not reversed.

6.3 SCENARIO 2: MDC at high demand

This scenario concerns two MDC abstractions, which are primarily for industrial use. The two abstractions comprise over 50% of the total volume of groundwater allocated within the Riverlands area:

1. Malthouse Road (P28w/1678), allocation 3,900 m^3/d
2. Hardings Road Wellfield (P28w/1147 & 1148). Total allocation is 5,650 m^3/d, partitioned into 2055 m^3/d for irrigation and 3595 m^3/d for industrial use

The Malthouse Road well is MDC's primary supply well in the Riverlands area, supplying water for domestic use and the Riverlands Industrial Estate. Peak demand is during vintage in April each year. So far, up to 80% of the daily allocation has been used, and overall demand has doubled since 2001 (Figure 12).

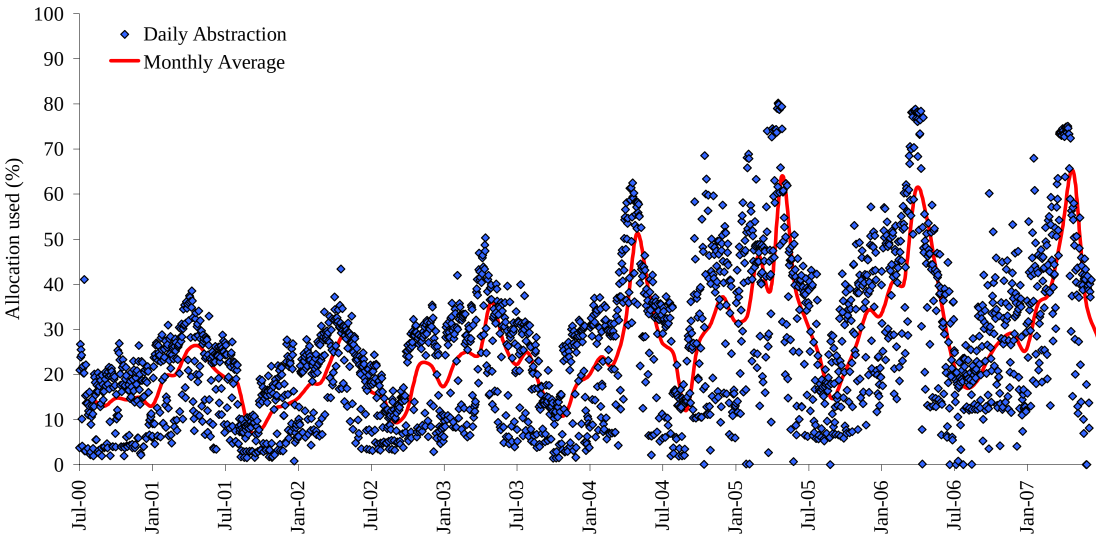

Figure 12 - Abstraction at MDC Malthouse Road well as a percentage of allocation

The Hardings Road wellfield has been largely dormant since PPCS closed their operation in the late 90's. The wellfield started pumping again in August 2006, but abstraction has typically been less then 100m^3/d. This wellfield represents the largest portion of the allocated volume that has yet to be exercised.

Synthetic pumping records have been developed to assess the impact of high demand from the MDC wells (Figure 13). Abstraction rates for both of the MDC wells were adjusted to match the weekly demand shown by the Malthouse Road well for the year starting July 2006. A factor was applied to each of the wells to bring the peak demand up to 100% of the industrial use quota. The irrigation portion of the quota for the Hardings Road well was set at 2/3rds of the consented allocation, and applied on a seasonal basis. The collective peak water use for this scenario is 12,245 m^3/d.

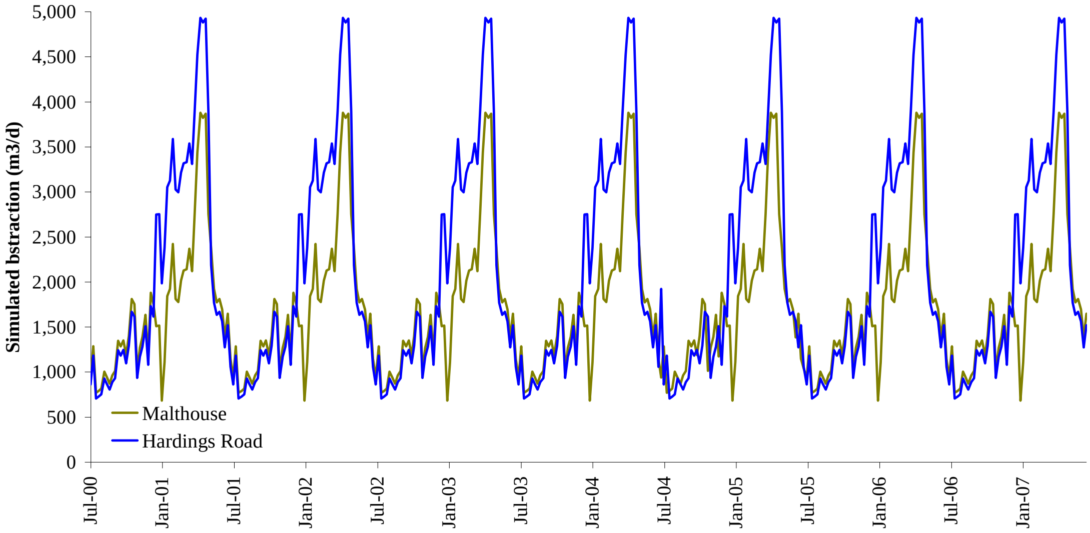

Figure 13 - Synthetic abstraction record for MDC Malthouse Road and Hardings Road wells. The record is expected to simulate high demand conditions.

Hydrographs for this simulation show that heads remain high for the wells situated inland, CMP, Butter Factory Corner, P28w/4402, and P28w/3949. The impact is most pronounced at the Lagoons and Malthouse Road wells. The Lagoons well P28w/0708 is drawn down from calibrated levels by up to 0.85m. Heads in this well reach the 50% threshold for a brief period in April 2007.

The Malthouse Road well also shows large drawdowns, with heads falling below sea level in 2007. However, there is still over 10m of available drawdown in the well, and the extent of the large drawdown is fairly localised. Heads in monitoring well P28w/4402 remain above 1.25m, and the overall hydraulic gradient from Blenheim to the coast is not reversed.

The profiles in Appendix 4 show that the overall magnitude of drawdown is very similar to Scenario 1. It is important to note that the degree of drawdown observed depends not only on the instantaneous abstraction rate, but also the duration of the demand. For example, if the peak rates for the above scenario are applied for the whole year (4,930 m^3/d for Hardings and 3,880 m^3/d for Malthouse), then water level in P28w/0708 falls to a predicted minimum of 1.17m. The 1.5m threshold is breached during summer from 2003 onwards, and the 1.25m threshold is breached for the last two years of the simulation.

The potentiometric contour plot for this scenario (Figure 14) shows that the largest drawdown is in the Hardings Road area. The extent and magnitude of the drawdown in this area is not as significant as it was for Scenario 1. However, the reduction in head in this area may still create problems with increased groundwater salinity and would require close monitoring.

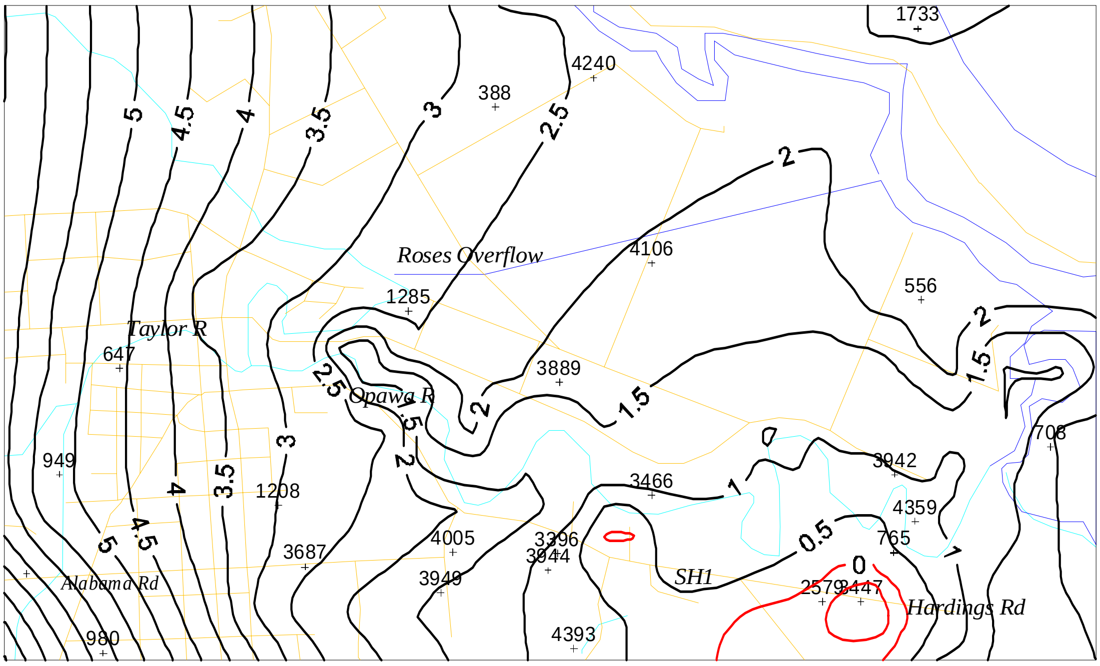

Figure 14 - Potentiometric contours during April for Scenario 2, high MDC water demand. Contours where aquifer pressures are at or below sea level are shown in red.

6.4 SCENARIO 3: High demand scenario

Peak demand in the Riverlands area for this scenario is 13,940 m^3/d, during early to mid April. The modelled hydrographs predict that heads will remain high at Canterbury Meats and Butter Factory Corner. Head at Malthouse Road drops to –1m RL, although there is still plenty of available drawdown in this well.

The drawdown at the Lagoons well falls below 1.5m on an annual basis, and also falls below the 1.25m seawater intrusion threshold for most seasons. At the Huia well, P28w/4402, head falls below 1.25m for most years. This indicates that the regional hydraulic gradient is reversed, indicating that seawater intrusion is likely to be a problem under high demand.

Aquifer profiles for this scenario (Appendix 4) show that drawdown is approximately twice that of Scenario 1 and 2 overall. Drawdown is most pronounced at the end of Hardings Road.

The modelled potentiometric contours (Figure 15) show that an extensive area around Hardings Road to Malthouse Road is drawn below sea level during periods of peak demand. There is a high probability that groundwater salinity will increase in this scenario, either through the drawing of connate water inland, or via movement of the seawater interface. The model predicts that a high demand scenario for groundwater in Riverlands is unsustainable with the current volume of allocation.

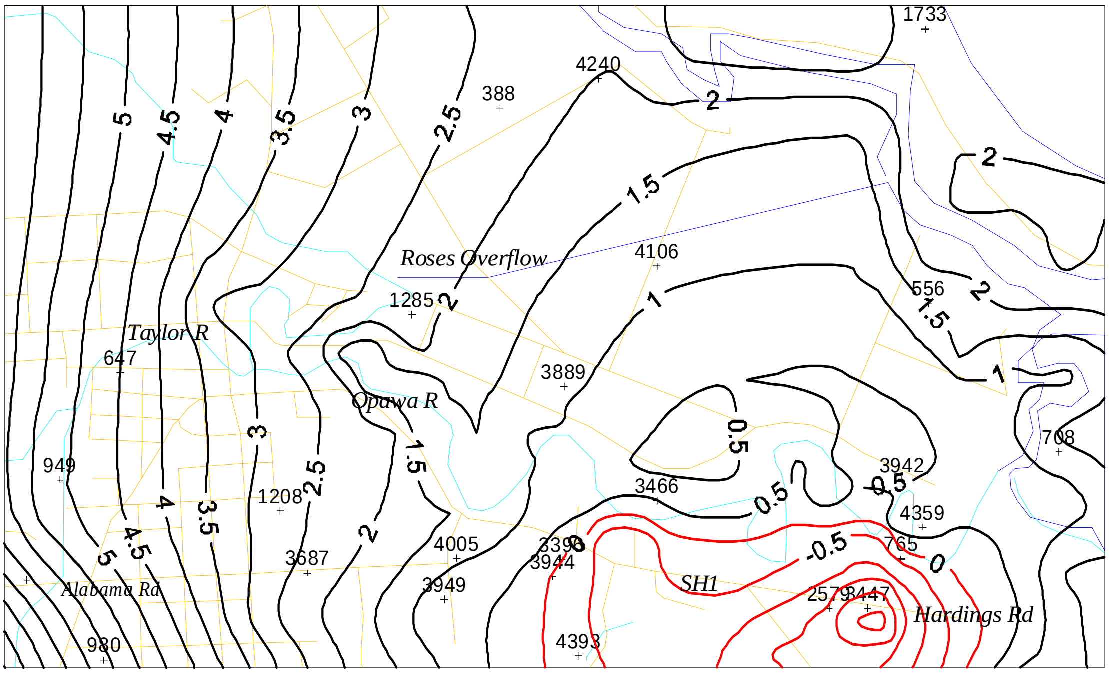

Figure 15 - Potentiometric contours during April for Scenario 3, high overall water demand. Contours where aquifer pressures are at or below sea level are shown in red.

6.5 SUSTAINABLE AQUIFER YIELD

A sustainable aquifer yield depends on the conditions that are intended for protection. Some potential issues are:

1. Drawdown of head below limit for surface mounted pumps (mostly affecting domestic users)
2. Inland movement of the seawater interface
3. Inland movement of the connate water interface
4. Reduction in spring and river flow

From a hydrogeological perspective, the most serious of these issues to be addressed is the deterioration of water quality caused by migration of the saline groundwater inland. The initial modelling scenarios indicate that this issue will be the limiting factor for sustainable groundwater abstraction in the Riverlands area. The high demand scenario suggests that seawater and connate water intrusion are likely to occur if 75% of the current allocation is exercised.

A reversal of flow across the Cloudy Bay constant head boundary (representing the saline interface) does not occur in any of the modelled scenarios. The reason for this is that the constant head boundary in the model is set at a large distance offshore so as to not interfere with drawdown predicted by the model scenarios. In reality, the position of the saline interface is unknown. However, it is likely that the interface position is much closer to the shoreline than set in the model, a conclusion that is supported by measured specific conductance and chloride values.

Because the exact position of the seawater interface is unknown, the level of risk needs to be assessed in terms of regional head distribution rather than changes in discharge flux. To maintain the position of the saline interface, it is recommended that two conditions be preserved:

1. The aquifer hydraulic gradient towards the coast should not be reversed on a regional scale. The calibrated hydraulic gradient between the coast and Malthouse Road/Alabama Road area is very flat. Also, because aquifer discharge is dominated by vertical leakage, aquifer velocity towards the coast is very low. A reversal of gradient could easily increase salinity in the Hardings Road area.

2. Heads in coastal monitoring well P28w/0708 should be maintained above 1.25m RL to avoid seawater intrusion. When water levels in this well reach a level of 1.5 m above sea level, pumping restrictions of 50% of allocation should be imposed.

The aquifer sustainable yield in the Riverlands area is therefore the maximum rate of abstraction that can occur without transgressing these two criteria. Obviously the sustainable yield will differ depending on the distribution of pumping wells and abstraction rates within the aquifer. Previous simulations have shown that the critical factor for allocation is the degree of drawdown in the Hardings Road area.

For the purpose of this analysis it has been assumed that the arrangement of wells stays at its current distribution. The sustainable yield has been determined by applying an equal factor to all pumping wells in Scenario 3. The demand is gradually reduced until the above conditions of sustainability are met.

Based on the existing arrangement of wells, the model predicts the sustainable yield of the Riverlands area to be 10,000 m^3/d. This allocation will maintain heads above 1.5m at P28w/0708, and will also maintain a hydraulic gradient towards the coast. It is expected that restrictions would not be required for this yield, although consent conditions are still advised as a safety measure.

An allocation limit greater than 10,000 m^3/d is predicted to draw the head in P28w/0708 below the 1.5m threshold. If this occurs, periodic restrictions will be required to maintain aquifer heads, particularly in the Hardings Road area. The model predicts that to maintain heads above 1.25m in well P28w/0708 requires an allocation limit of around 11,600 m^3/d.

One aspect of sustainability that also needs to be considered is the issue of climate change. More frequent and prolonged periods of drought will increase water demand on the Wairau Plain. However, it is difficult to determine the effect that climate change will have on water use in the Riverlands area. The reason for this is that sea level rise will bring the aquitard water table closer to the surface, so irrigation demand may actually decrease.

The critical factor for sustainability in the future will be the position of the seawater interface. The uncertainty in the exact position of the interface makes it difficult to model a sea level rise scenario with a high degree of confidence. What is certain is that sea level rise will cause the interface to move further inland, and coastal wells will potentially become contaminated. It is important to continue monitoring salinity levels in coastal sentinel wells and production wells in order to detect any encroachment of seawater.

7 RECOMMENDATIONS

7.1 RESEARCH RECOMENDATIONS

There are several areas of further research that can be carried out to further our knowledge of groundwater in the Riverlands area. Confidence in both model calibration and sustainable aquifer management can be further improved by obtaining more water use data. It is regrettable that the availability of water use data is not better, considering that all wells are fitted with meters, and that the recording of water use is a standard consent condition.

Future models can be improved by increasing our knowledge of how groundwater interacts with the Taylor River. This will give greater confidence in the characterisation of surface water-groundwater interaction in the model calibration. There are several ways in which further information can be obtained:

- A temporary flow recorder could be installed opposite Athletic Park where there is negligible weed growth.
- Concurrent gaugings could be carried out between Athletic Park and Omaka Aerodrome to characterise flow losses and/or gains to the aquifer.
- A streambed conductance survey could be carried out in the bed of the Taylor River between Hutcheson Street Bridge and Athletic Park.

Aquifer discharge is dominated by losses to the Dillons Point Formation. This loss is compensated for at the surface by discharge to the surface waterways. At present there is no flow data available for drains in the Riverlands and Lower Wairau areas. This data is important, as it can be used to refine model calibration. Further work could be carried out to:

- Carry out a well controlled aquifer test to determine the aquitard leakage coefficient
- Gauge flow in the larger of the surface drains
- Gauge any gain in flow down the Taylor and Opawa Rivers, particularly the upper reaches, west of Riverlands

7.2 RECOMMNEDATIONS FOR GROUNDWATER ALLOCATION

A summary of the demand for each modelled scenario is provided in Table 14. The recommended sustainable yield for Riverlands is 10,000 m^3/d. This is 55% of the current consented allocation. If consent holders accept that restrictions will occur, the sustainable yield can be increased to 11,600 m^3/d. This is 64% of the current consented allocation. It is clear that in terms of sustainability the aquifer has been over-allocated.

The main reason for over-allocation is that consent holders are only using 36% of the quota on average. This renders the aquifer vulnerable to a future increase in demand through a change in water use, or through water trading. *It is therefore recommended that no further groundwater be allocated in the Riverlands area.*

Table 14 - Summary of Riverlands water abstraction for modelled scenarios

Scenario	Peak Demand	% of Allocation
Current use	6,460	36
1: High irrigation demand	8,300	46
2: High MDC demand	12,245	67
3: High Demand for all wells	13,940	77
Sustainable yield	10,000	55
Sustainable yield with restrictions	11,600	64
Total Riverlands Allocation	**18,150**	**-**

Furthermore, to maintain a limit on water use in the Riverlands area, *it is recommended that the consent process be improved to encourage more efficient allocation of water*.

Over 60% of the sustainable resource is currently “locked up’ in existing consents and is not being used. The main reason for this is that consent applications are normally granted the maximum rate for irrigation that is specified in the Proposed Wairau Awatere Resource Management Plan (1998).

Future consent renewals should focus on the actual volume of water required for the applicant’s land use. The volume of water required by the applicant can be determined either from historical use, or by applying a crop-based soil moisture balance approach. An example of this is the SPASMO model that has already been developed for MDC.

If an improvement in the efficiency of water allocation is carried out, the resulting water demand is expected to be close to the sustainable aquifer yield. Any surplus groundwater allocation that remains after this process can then be granted to new consent applicants.

8 REFERENCES

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Freeze, R.A. and Cherry, J.A. 1979. Groundwater. Prentice Hall, New Jersey, 604 pp.

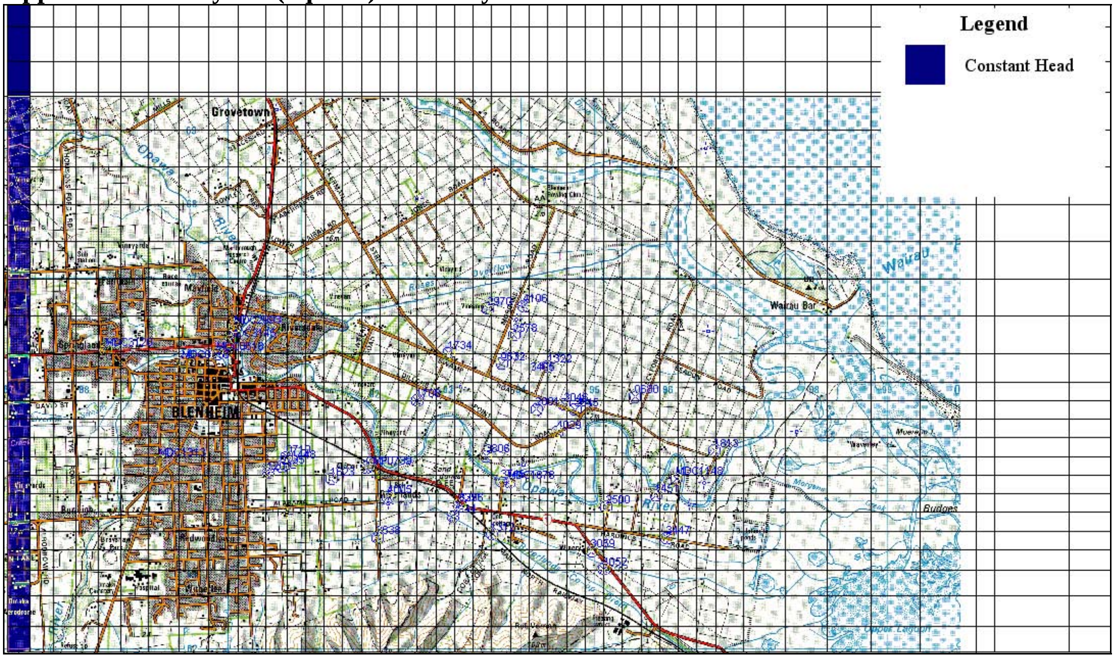
McDonald, M.G. and Harbaugh, A.W. 1984. A modular three-dimensional finite difference groundwater flow model. US Geological Survey Open File Report 83-875.

9 APPENDICES

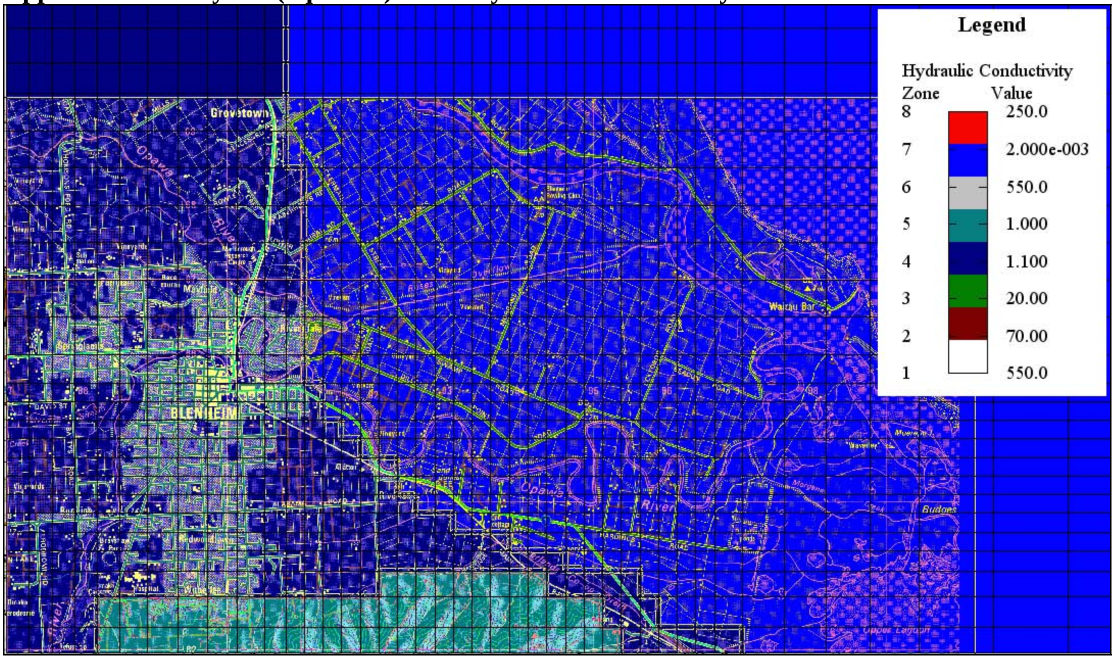
APPENDIX 1: MODEL DOMAIN PLOTS

Appendix 1.1 – Model domain and layer 1 (aquitard) boundary conditions

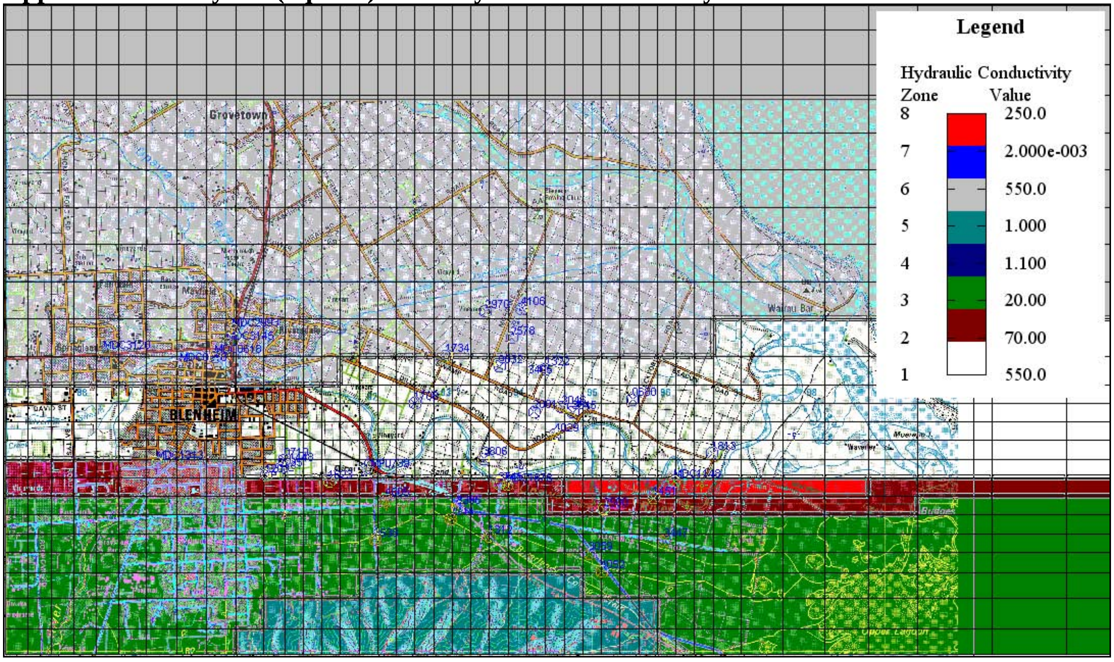
Appendix 1.2 – Layer 2 (aquifer) boundary conditions



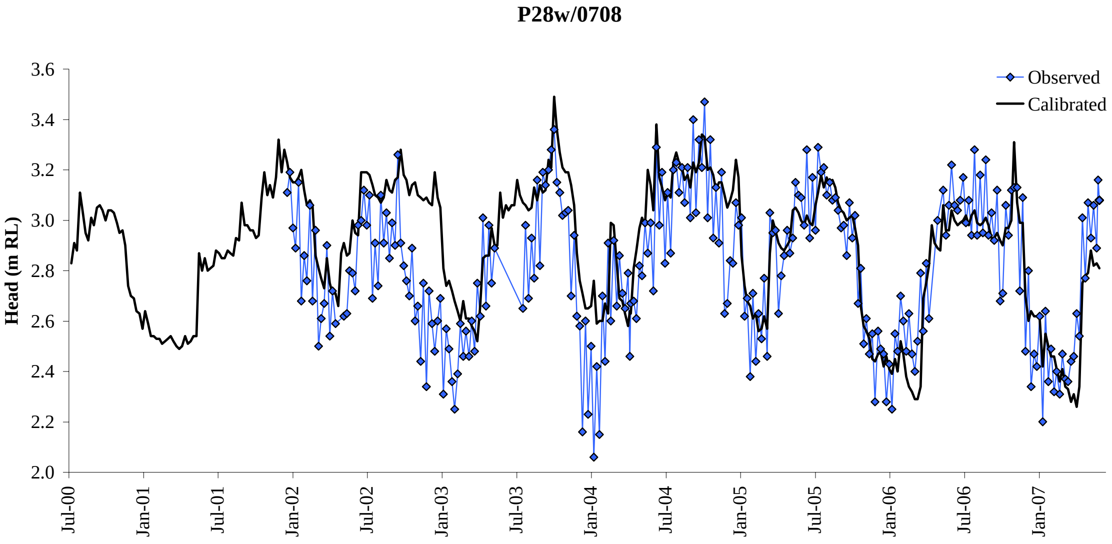
Appendix 1.3 – Layer 1 (aquitard) model hydraulic conductivity zones

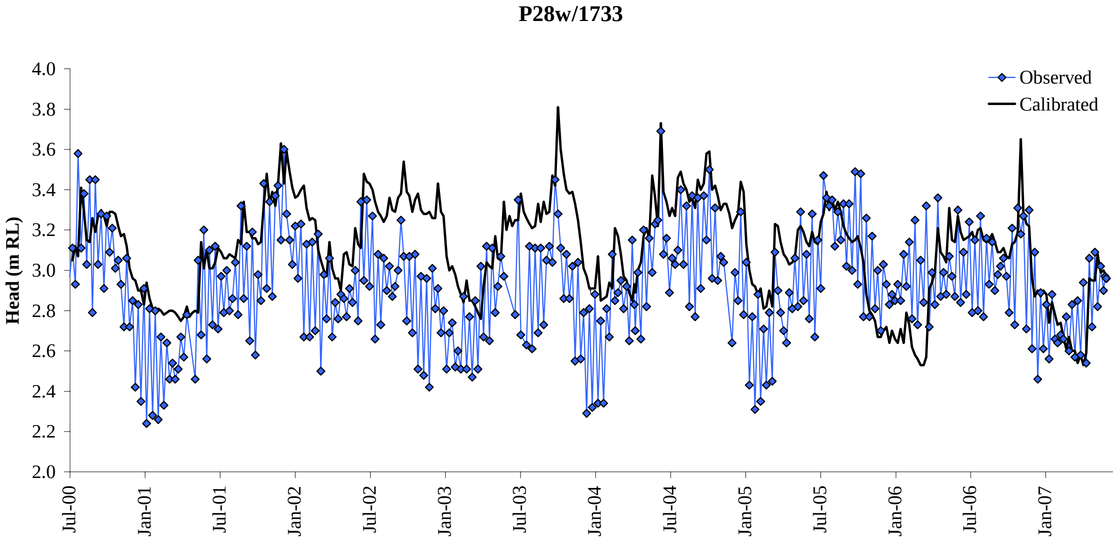


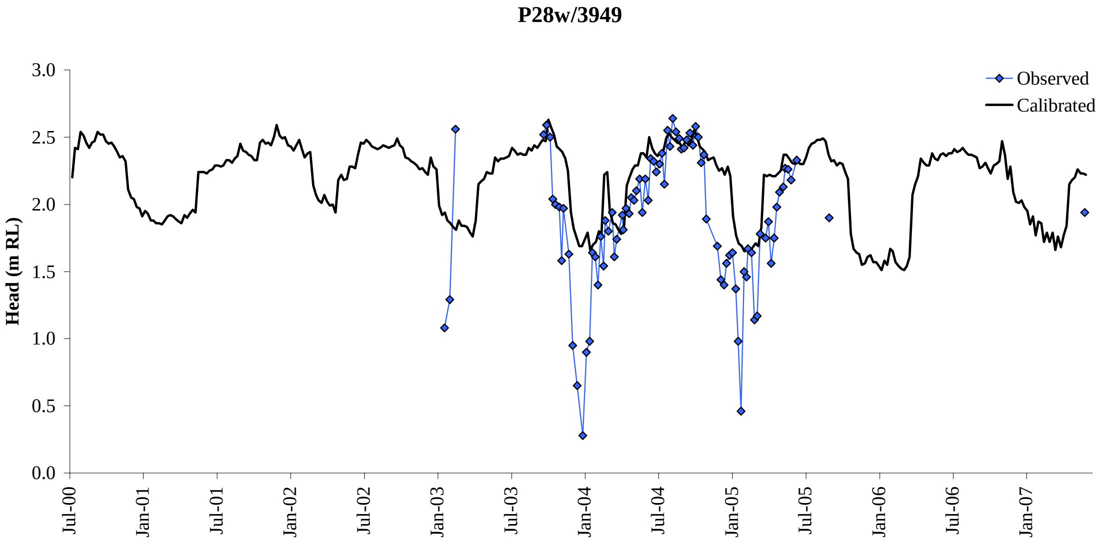
Appendix 1.4 – Layer 2 (aquifer) model hydraulic conductivity zones



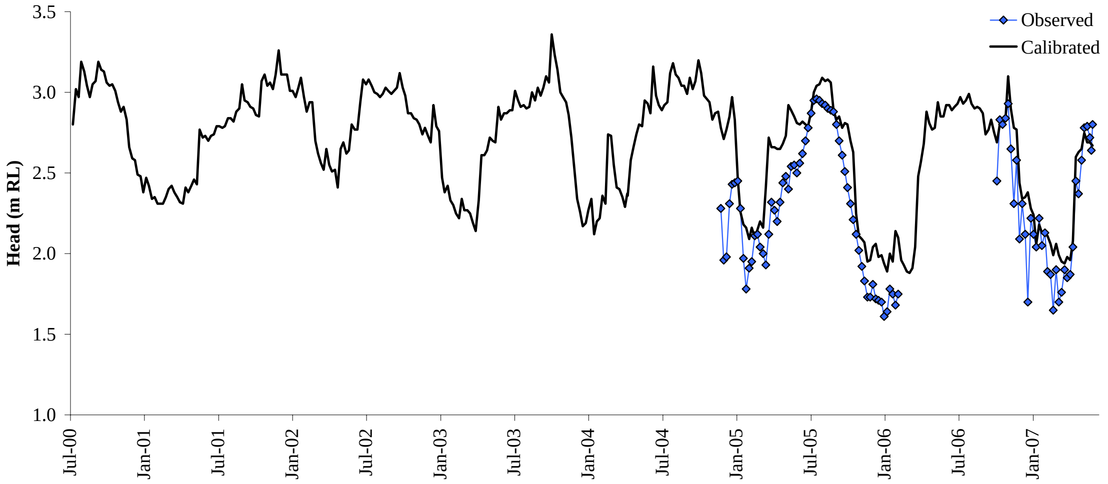
APPENDIX 2: TRANSIENT CALIBRATION HYDROGRAPHS







P28w/4402



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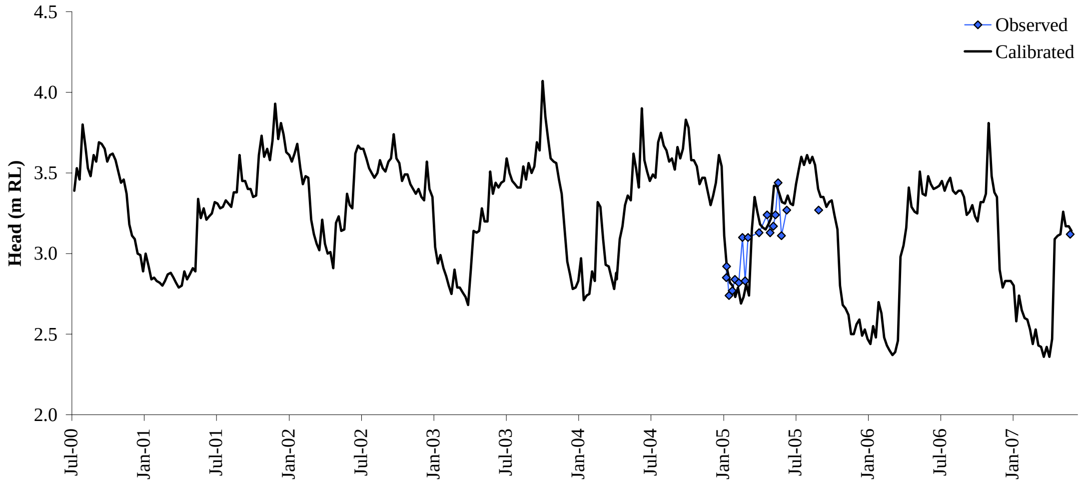
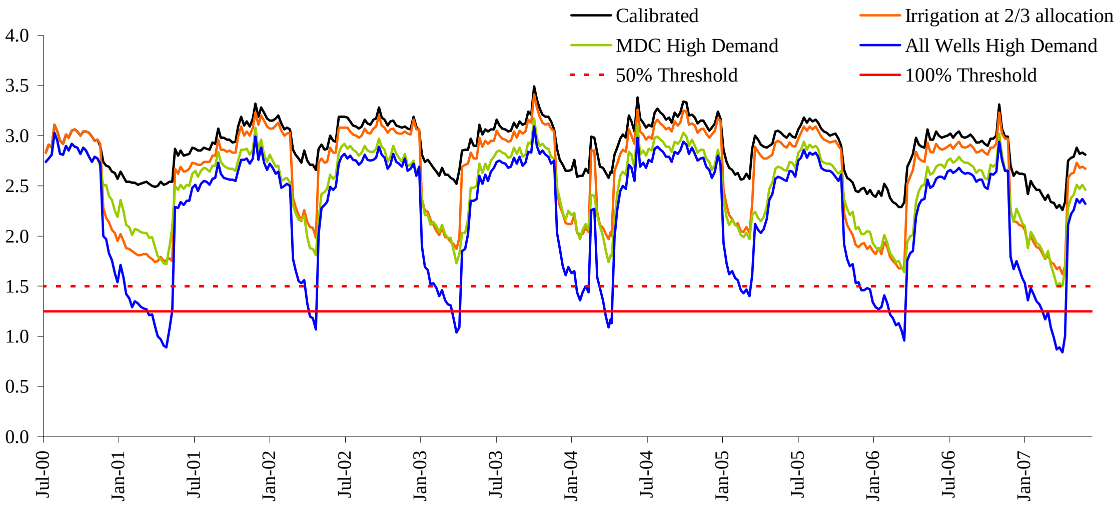


APPENDIX 3: MODELLED SCENARIO HYDROGRAPHS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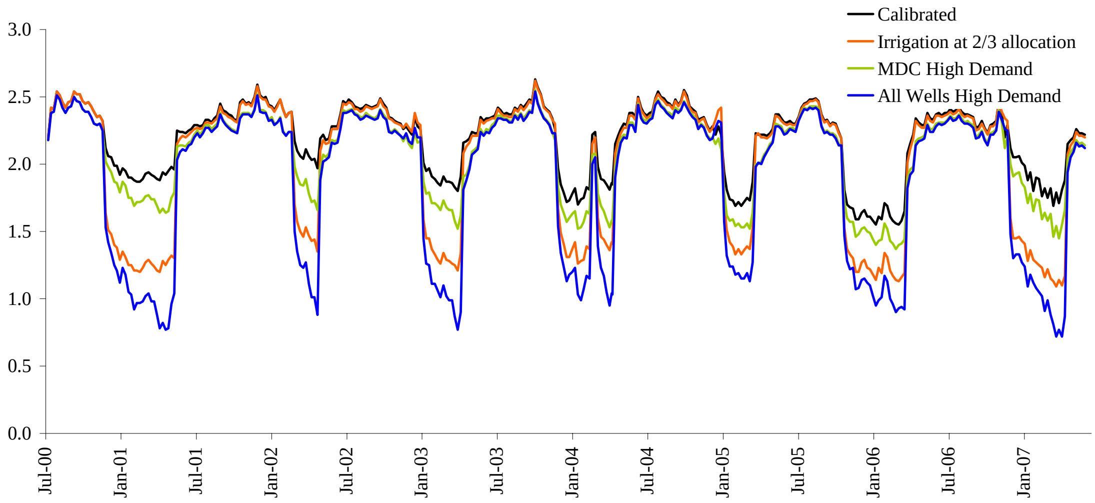
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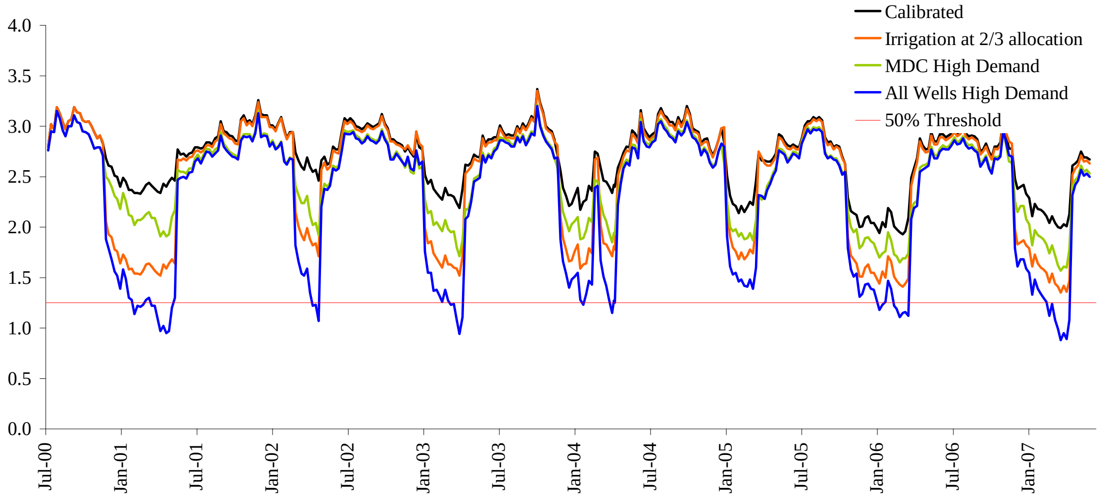
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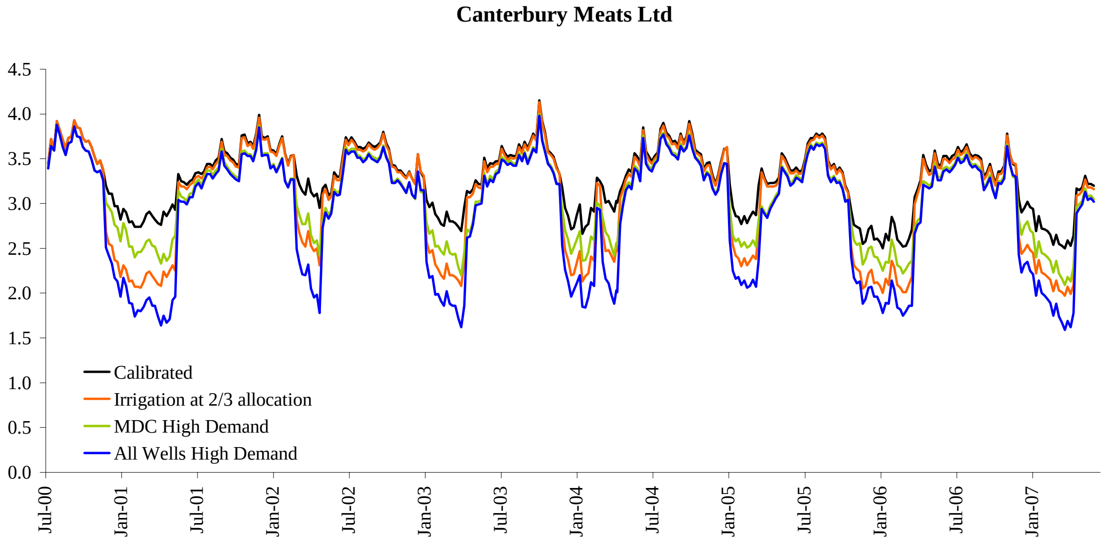
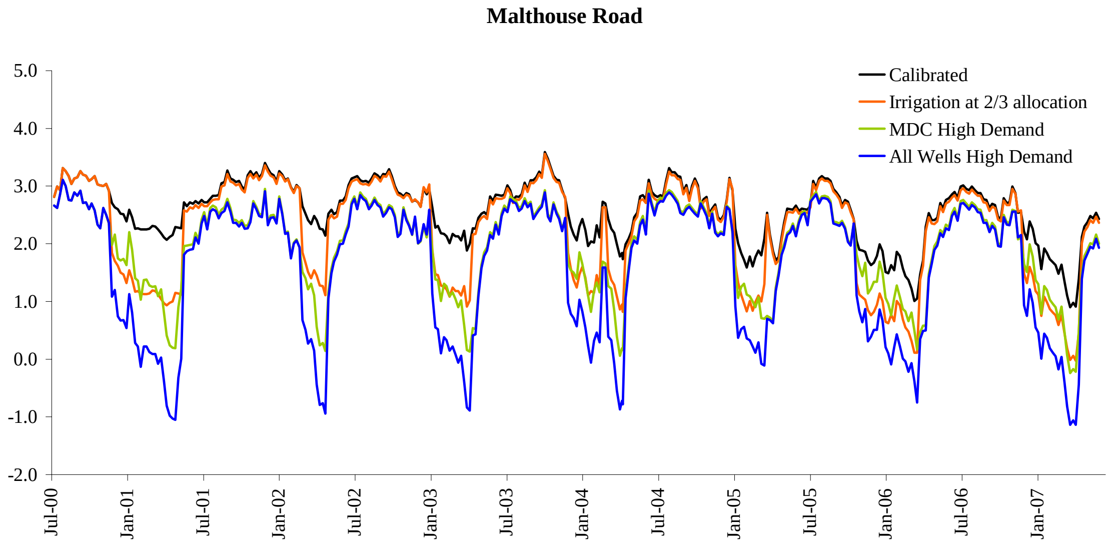
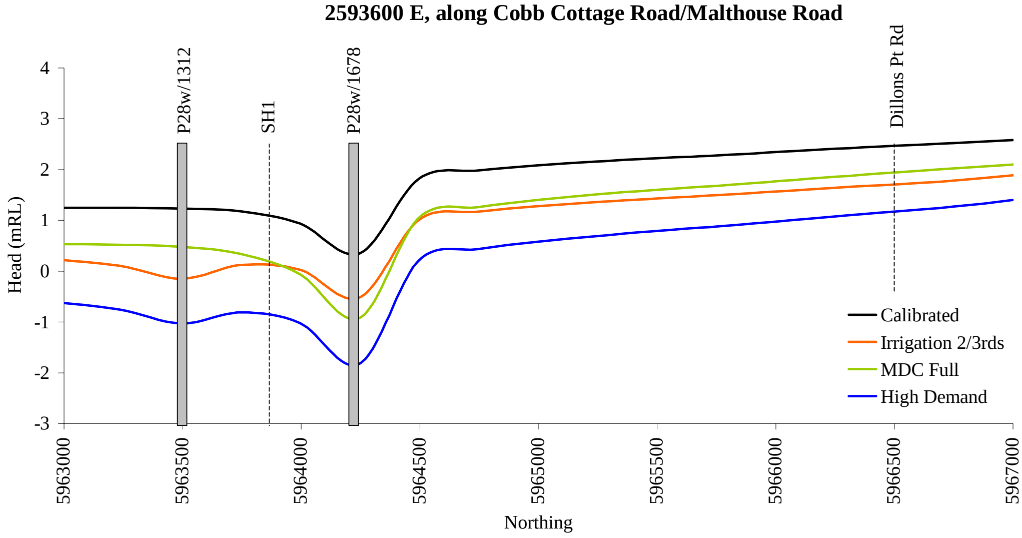
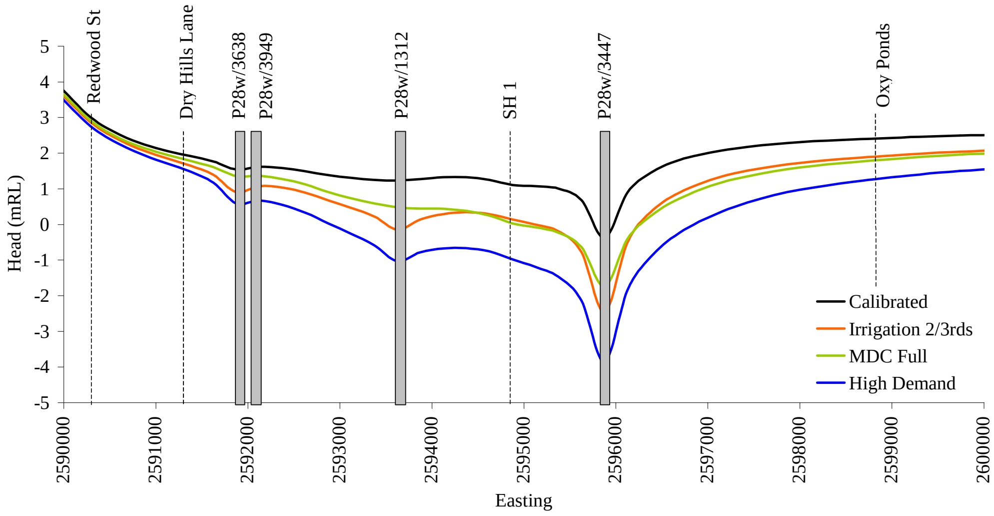
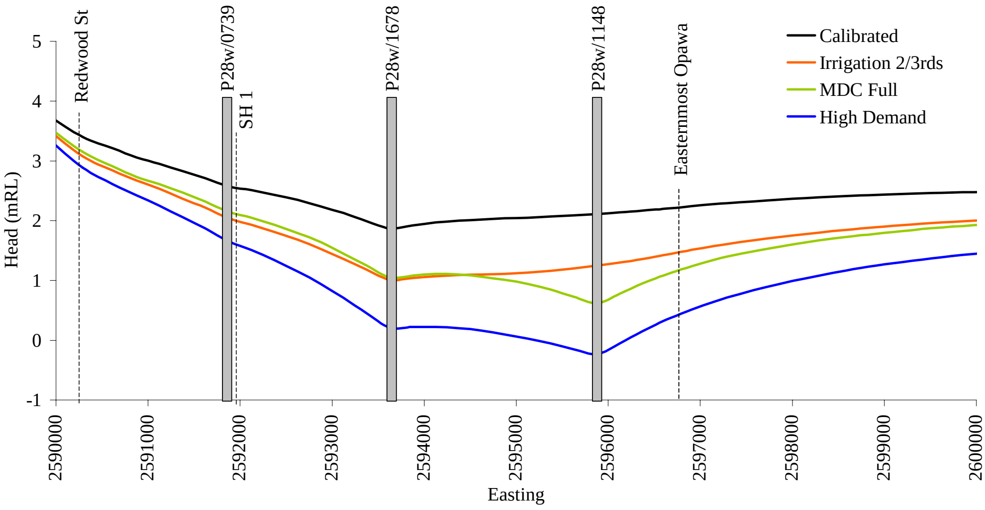

Canterbury Meats Ltd
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Calibrated
Irrigation at 2/3 allocation
MDC High Demand
All Wells High Demand
Jul-00
Jan-01
Jul-01
Jan-02
Jul-02
Jan-03
Jul-03
Jan-04
Jul-04
Jan-05
Jul-05
Jan-06
Jul-06
Jan-07


Malthouse Road
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
Calibrated
Irrigation at 2/3 allocation
MDC High Demand
All Wells High Demand
Jul-00
Jan-01
Jul-01
Jan-02
Jul-02
Jan-03
Jul-03
Jan-04
Jul-04
Jan-05
Jul-05
Jan-06
Jul-06
Jan-07

APPENDIX 4: PROFILES OF MODELLED HEAD


2593600 E, along Cobb Cottage Road/Malthouse Road


5963500 N, along Hardings Road


5964500 N, through CMP and MDC production wells