Wairau River-Wairau Aquifer Interaction

Report 1003-5-R1

Scott Wilson, Thomas Wöhling

Lincoln Agritech Ltd

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MEASURE. MODEL. MANAGE.

Registered company office:

Lincoln Agritech Limited

Engineering Drive, Lincoln University

Lincoln 7640

Christchurch

New Zealand

PO Box 69133

Ph: +64 3 325 3700

Fax: +64 3 325 3725

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Action	Name	Date
Prepared by	Scott Wilson	10 Feb 2015
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EXECUTIVE SUMMARY

This report presents initial findings from an investigation into understanding the nature of transient recharge from the Wairau River to the Wairau Aquifer. This investigation has been a year-long collaboration between Marlborough District Council (MDC), the Water & Earth System Science Competence Cluster (WESS) at University of Tübingen in Germany, and Lincoln Agritech.

The intention of this phase of the Wairau Aquifer recharge project is twofold:

- To review our conceptual understanding of the river and aquifer, and identify knowledge gaps
- To develop a numerical model to quantify the river-aquifer exchange based on that conceptual understanding

Historical flow gauging data shows that approximately 7.5 m^3/s is recharged from the river to the Wairau Aquifer between Rock Ferry and Wratts Road at flows less than 20 m^3/s. Temporary flow sites have been established at Rock Ferry, SH6 and Wratts Road, and a good flow-rating curve has been established at Rock Ferry. The difference between flows at Rock Ferry and SH1 indicates that aquifer recharge increases as the river flow increases. The preliminary evidence suggests that 15 m^3/s or more may be lost as recharge pulses during high flow events, although further work is required to correct flow for time lags in the river which will improve these estimates.

One of the key findings of this report is that the river appears to be perched above the Wairau Aquifer across its main recharge reach. This means that there is a vertical hydraulic gradient between the river and aquifer where most of the recharge occurs, which theoretically simplifies the calculation for estimating transient recharge rates.

Another key finding is that the hydraulic nature of the aquifer is more complex than our previous simple unconfined aquifer conceptual model. Groundwater monitoring records and aquifer test data indicate that the aquifer is highly stratified. This stratification explains the observation that the aquifer may be perched. The reason for this is that a strong vertical to horizontal anisotropy in permeability enables groundwater to potentially drain faster than it can be recharged by the river. There is also the possibility of distinct upper and lower aquifer horizons, although this needs to be explored further.

The implication of aquifer stratification for estimating river recharge is that the groundwater monitoring sites are representative of quite localised conditions. Therefore, for the prediction of recharge rates, groundwater data can be used to constrain hydraulic parameters within our numerical model, but it is preferable to calculate recharge rates based on river observations rather than changes in groundwater levels at a particular site. Furthermore, if the is indeed river perched over its main recharge reach, as the available evidence suggests, the prediction of transient recharge rates will be largely determined by river geometry, and the relationship between stage and wetted river bed perimeter.

A steady state numerical model has been built and calibrated to accord with our conceptual understanding. A combination of groundwater level observations and surface water fluxes were used for calibration targets. The best-fit "compromise" solution resulted in data fits that are well within the measurement uncertainty ranges. One of the key findings of the model was that the river was required to be perched to enable calibration, which supports field evidence outlined in this report.

Further work for 2015 will involve a more intensive field program to improve our understanding of the relationship between river flows and groundwater levels immediately adjacent to and beneath the river. Transient calibration of the numerical model will also begin, and we intend to use the final calibrated model to estimate transient aquifer recharge rates.

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INTRODUCTION

STUDY OBJECTIVES

The main objective of this study is to understand the process of recharge from the Wairau River to the Wairau Aquifer. This includes understanding the factors that the river-groundwater exchange is most sensitive to. An additional objective is to develop a steady state numerical model of the river and aquifer to quantify the exchange fluxes. The steady state model is a critical step for testing the conceptual model and developing a transient model.

SCOPE & NATURE OF THE SERVICES

The scope of the study is specified in the project brief of 7 March 2014 and is as follows:

- A review of the model development process, the assumptions used and a description of the model structure
- Discussion of the lessons learnt through the modelling process in terms of the drivers of Wairau Aquifer recharge from the Wairau River. Where to next in terms of research or other approaches to try if there are no firm conclusions
- Assess whether it is practical to measure the real time recharge rate for allocation purposes using measurements of:

  a) driving head in conjunction with aquifer permeability

  b) driving head in conjunction with wetted area, recharge reach length and channel bed permeability

- Evaluate whether the Wairau River is perched above the Wairau Aquifer or is hydraulically embedded within it

HYDROLOGICAL SETTING

The Wairau River is classified as a braided river system. A braided river forms in an environment where there is an abundant supply of sediment or in a situation where the slope of the land is high, such as an alluvial fan. One of the main characteristics of a braided river is its ability to erode the surrounding sediments. A stream with cohesive banks that are resistant to erosion will form narrow, deep, meandering channels, whereas a stream with highly erodible banks will form wide, shallow channels, resulting in the formation of braids. The combination of bank erosion with a large sediment load results in a highly dynamic river bed morphology. Sediments in the active channel are continuously being mobilised by the river, particularly during high flow events.

While the Wairau River is considered to be a braided river, its character has been modified immensely by river flood works since the early 1900s. The history of river control works on the Wairau Plain is documented in Rae (1987). One of the major early developments was to stem the flow of flood water from the Wairau River onto the plain via the Opawa River (originally a major braid channel of the Wairau) by the building of the Conders Groyne in 1914-1926. By the 1960s a stop-bank network had been built to form a defined floodway with a purpose to constrain flow during flood events. This network flood control system has remained in more or less in the same position to the present day.

The river engineering works have resulted in fairly radical changes to the way the river operates, and also how groundwater recharge occurs. Prior to the river works, the river had the freedom to widely across the Wairau Plain so that the location of the channel was highly mobile. This freedom also meant that the location and volume of recharge from the river to the Wairau Aquifer shifted considerably in space and though time.

Prior to the onset of engineering works, the river bed would have been much wider than its current form. Its greater width would have potentially allowed a higher rate of flow loss than the present day. It is not inconceivable that the river was historically ephemeral, with all of its flow lost during dry periods to the unconfined aquifer prior to reaching the springs and wetlands along the edge of the Dillons Point Formation aquitard. By contrast, the recent creation of a restrictive floodway river has trained the river into a comparatively narrow and channelised form. The result of this training of the river has been to decrease the effective width of the river, which turn has likely to have reduced the volume of recharge to the Wairau Aquifer.

Despite the controlling effect of the flood-works, the river remains braided in character, and this poses a number of problems for characterising its flow and recharge to the aquifer. The braided nature of the river, and the high permeability of sediments associated with the active channel make it extremely difficult to measure the flow at any point in the river. Indeed the record of historical concurrent flow gauging surveys on the Wairau Plain is limited to low flow conditions, and at points in the river where there are fewer braids. For this reason, it has not been possible to measure the rate of recharge to the aquifer at flows above 20 m^3/s (the median flow at SH1 is 60 m^3/s).

Flow recorders in New Zealand's braided rivers were originally installed for flood prediction purposes, and were placed in relatively stable positions at the upper and lower extremities of alluvial plains. One of the important components of this study is the installation of river stage recorders at key points along the alluvial floodplain. To do this requires the development of flow rating curves at each site. Recent advances in flow gauging techniques have allowed higher flows to be measured more accurately and safely. For this study, three temporary recorders were installed, at Wratts Road, SH6, and Rock Ferry. Visually, these sites appear to be stable (Figure 1), however the mobility of the riverbed has posed a particular challenge for the installation of recorders since the morphology of the river bed changes upon high flow events. This means that the flow rating curve is only valid for a brief period of time while the bed morphology is stable. However, these flow records do provide the first monitoring data available to enable us to study how flow losses change within a braided river system over time.

Figure 1 The Wairau River at a relatively stable reach at SH6

STEADY STATE AQUIFER MASS BALANCE

Table 1 shows the estimated mass balance for the Wairau Aquifer. The only components of the mass balance that are directly measured are the Spring Creek and Urban Springs discharge, which are the main discharge contributions. The values of the other components are calculated from indirect measurements or estimated based on the best available information.

Table 1 Estimated representative average annual and summer water balances

Annual recharge	**(m^3/s)**	**Annual discharge**	**(m^3/s)**	**Summer recharge**	**(m^3/s)**	**Summer discharge**	**(m^3/s)**
Wairau River	7.5	Abstraction	0.75	Wairau River	7	Abstraction	2
Rainfall & irrigation	0.3	Deep outflow	0.5	Rainfall & irrigation	0.1	Deep outflow	0.4
Southern Valleys inflow	0.75	Spring creek flow	3.5	Southern Valleys inflow	0.1	Spring creek flow	3
		Grovetown springs	0.5			Grovetown springs	0.2
		Urban springs	3.0			Urban springs	1.5
		Return river flow	0.3			Return river flow	0.1
Total recharge	**8.55**	**Total discharge**	**8.55**	**Total recharge**	**7.2**	**Total discharge**	**7.2**

One of the large uncertainties in the mass balance is the variability of recharge from the Wairau River, and how the annual recharge rate differs from observed summer conditions. River losses are by far the main contribution to aquifer recharge. The summer river recharge rate is quite well constrained by flow loss observations, so we can use this value to estimate the total discharge volume through the springs and confined aquifer flow towards the coast. The measured loss of flow in the river does match quite well with the observed total discharge in the springs. Because river recharge and spring discharge are the main components of the mass balance, the match between the two provides confidence in the mass balance components, as well as the total flux.

There is also uncertainty over what the flow losses and gains measured within the Wairau River represent for the purposes of the mass balance. For example, it is unknown how much of the observed flow gain and loss is accounted for by hyporheic flow within the active channel deposits. Furthermore, there are a number of North Bank streams that flow into the Wairau River between the top of the unconfined Wairau Aquifer at Rock Ferry, and its lower point near Tuamarina. These streams, the Onamalutu River, Are Are Creek, Storeys Creek, Gibsons Creek and the Waikakaho River, are expected to add half a cumec (m^3/s) during summer conditions, and considerably more during winter. To understand the impact that the North bank has on river flows, we need to look at the transient mass balance of the river as measured at the long term and temporary stage records.

TRANSIENT RIVER MASS BALANCE

Temporary flow recorders have been installed at Rocky Ferry, SH6, and Wratts Road. This new monitoring network allows us to gain an understanding of how the river relates to the aquifer dynamically, and is a new initiative for a braided river in New Zealand. Figure 2 shows the location of the temporary river sites as well as the long term monitoring site at SH1 and the groundwater level monitoring network.

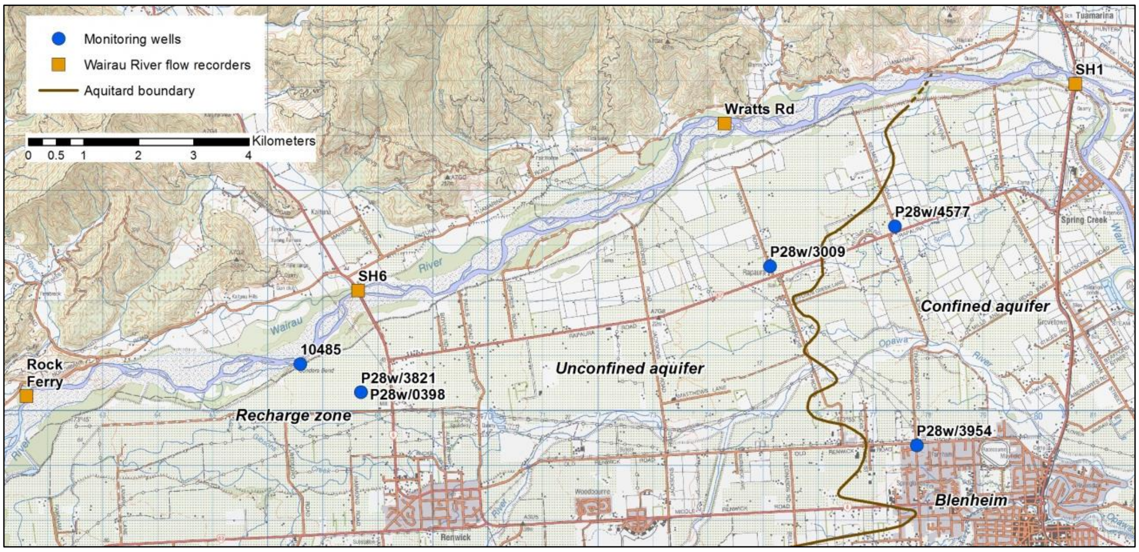

Figure 2 Location of MDC flow and river stage recorder sites

At the time of writing this report a reliable flow rating curve has only been developed for a short period of record at Rock Ferry. The reliability of the rating curve is limited to the range of flows that have been measured at the site, so the site is only valid for flows less than 100 m^3/s. The availability of flow data for Rock Ferry allows some analysis of the dynamic change in flow across the Wairau Plain. To complement the Wairau River sites we also have flow data from recorders on the Onamalutu River and Are Are Creek, which constitute (half to two thirds of the north bank inflow), as well as aquifer discharge at Spring Creek.

Figure 3 shows the daily flow difference between Rock Ferry and SH1 compared to North Bank and Spring Creek flows. The flow difference between Rock Ferry and SH1 is quite erratic compared to Spring Creek and the North bank. The flow in Spring Creek is quite stable because any fluctuations in groundwater recharge from the river are attenuated by storage in the aquifer. This results in a slow seasonal variation with no significant response to individual flow events.

The highly fluctuating nature of the flow difference between Rock Ferry and SH1 is due to the travel time of the river, which averages about 4 hours but changes at different flows. During periods of unstable flow, the daily recession rate is of a similar value to the flow difference between the sites. This means that a change in the lag time can significantly affect the flow difference, particularly during periods of steep flow recession.

Figure 4 shows the recent time-series data for river flow and the flow difference between Rock Ferry and SH1. The calculated river flow loss ranges from approximately 5 m^3/s to 15 m^3/s. The average flow loss for September to January is 9.8 m^3/s, which is slightly higher than the average of 7 m^3/s previously measured during concurrent low flow gauging runs. These values include inflow from the Northbank, which is expected to contribute 1 to 1.5 m^3/s for most of the period plotted.

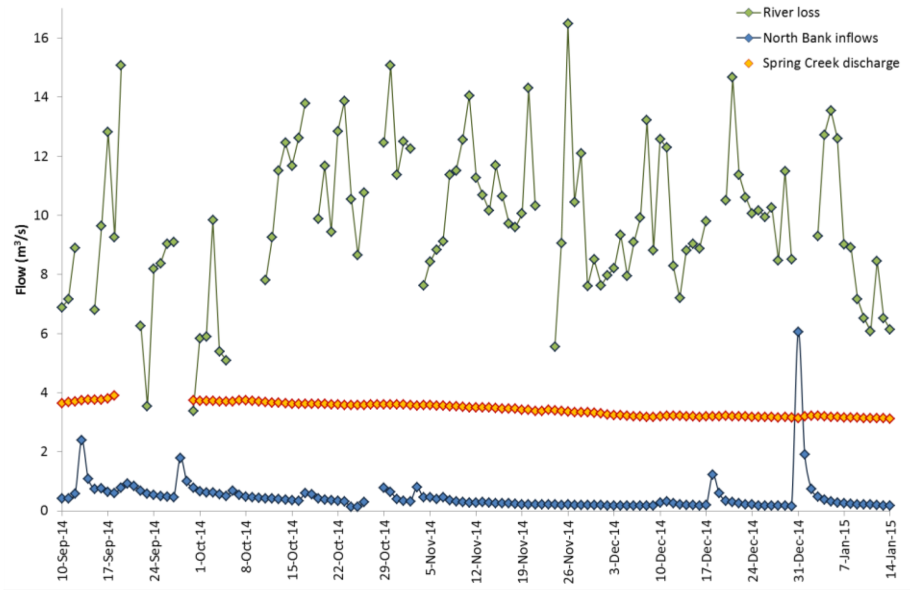

Figure 3 Time series of surface water inflows and discharges

One of the features of the flow difference curve plotted in Figure 4 is a marked shift before and after November. During September and October the flow is consistently above 20 m^3/s, and the flow difference recorded at this time is small relative to that recorded in December. Theoretically we would expect river losses to be greater during high flows, however if we plot flow versus flow difference we see that the flow difference decreases at higher flows. The reason for the discrepancy is that the travel time between the two sites is quicker at higher flows, and the steep recession curve produces an error in our calculations. This means that the flow difference is most accurately represented by low flow conditions.

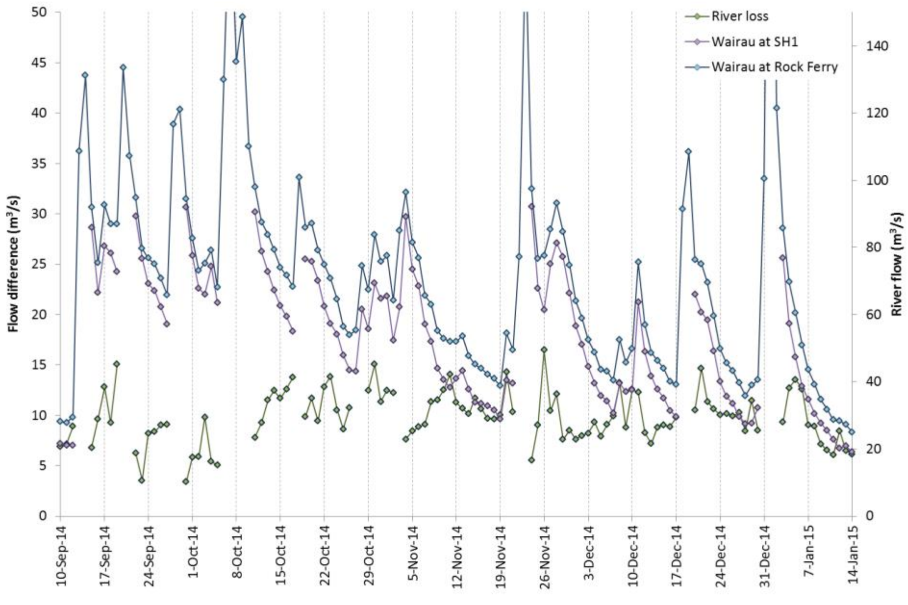

Figure 4 Flow difference between Rock Ferry and SH1 compared to flow

The flow data collected during December, when flows were lower and more reliable, indicates that flow losses from the river increase at higher flows. If North Bank inflow is accounted for during this period, we can make a preliminary estimate of aquifer recharge to be 6 to 14 m^3/s during low and high flows respectively (average of 9 m^3/s). More accurate calculations of flow loss can be made by making an adjustment for the time lag between the sites.

The observed variability of recharge with flow during December suggests the possibility of up to 15 m^3/s being recharged to the aquifer as pulses during high flow events. These recharge pulses account for the higher rates of discharge springs that are observed during winter conditions. These higher flows must be sourced from river recharge since there are no other possible external recharge sources. These recharge pulses also explain the groundwater response to high flow events, and are a verification that groundwater recharge pulses do occur at high flows.

The methods that can be used to estimate river recharge depend on the hydraulic relationship between the river and the adjacent aquifer. A summary of the steady state hydrological relationship between rivers and groundwater is given by Brunner *et al*. (2011). A river can be thought of as being hydraulically connected and gaining, or losing flow to groundwater, or hydraulically disconnected (perched) and losing flow to groundwater. Figure 5 shows theoretical diagrams of these three different regimes.

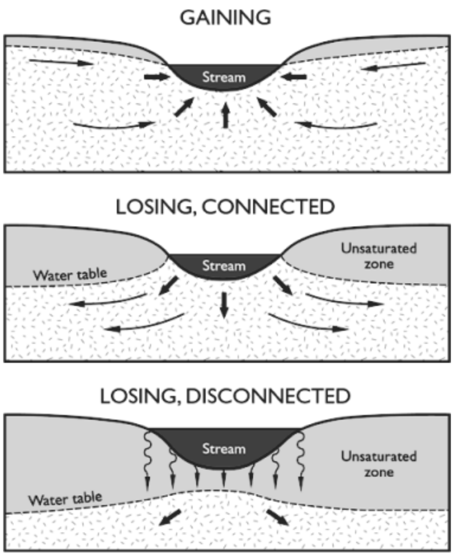

Figure 5 Different flow regimes between surface water and groundwater (figure based on Winter *et al*. 1998; Brunner *et al*. 2009a).

Figure 6 shows the theoretical nature of the transition from hydraulically connected to disconnected under steady state conditions. The curve shows how the infiltration rate reaches a maximum when the river is hydraulically disconnected from the aquifer. This is because the hydraulic gradient reaches unity (becomes vertical) when the river is disconnected.

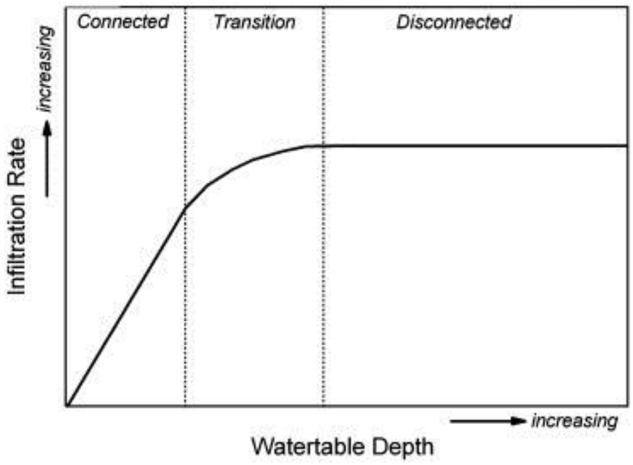

Figure 6 Theoretical flow exchange between surface water and groundwater (from Brunner *et al*. 2009a).

One of the simplifying assumptions made in Figure 6 is that the river bed has a clogging layer which has a lower hydraulic conductivity than the underlying aquifer, and this limits the rate of infiltration though the river bed. An alternative possibility is that there is no clogging layer, and that the rate of loss is determined by the vertical and horizontal hydraulic conductivities of the aquifer.

Aquifers tend to be anisotropic in that their hydraulic conductivity values vary in different directions, which are usually expressed as K_x (longitudinal), K_y (lateral), and K_z (vertical) flow vectors. In most aquifer environments we expect $K_x > K_y >> K_z$. This tendency to anisotropy is particularly true for braided rivers due to the layering of sediments of differing permeability intrinsic in their formation. If the horizontal hydraulic conductivity of the aquifer is significantly greater than the vertical, the aquifer has the potential to drain faster than it can be replenished by the river. This could cause the river to become perched above the aquifer, and a river bed clogging layer need not be present for this to occur.

In the case of a hydraulic disconnection, an inverted water table is thought to form beneath the riverbed, and represents the base of the saturated layer associated with the river (Xie *et al*. 2014). The thickness and shape of the inverted saturated zone depend on the river stage, channel geometry, and bed sediments (Wang *et al*. (2011). Wide rivers require a small water depth for a hydraulic connection to be maintained with the aquifer (Xie *et al*. 2014). This is because for a wide infiltrating water body, the wetted area of the river is greater, so the lateral flow rate in the river bed is small relative to the downward rate. However, anisotropy increases the likelihood of disconnection because it enhances preferential lateral flow.

Historically, the Wairau River has been considered to be hydraulically connected with the aquifer as it crosses the Wairau Plain. The river has been known to lose approximately 7.5 m^3/s between Rock Ferry and Wratts Road, with a small flow gain occurring between Wratts Road and the flow recorder at Tuamarina. This report presents evidence that the river upstream of Giffords Road may be hydraulically disconnected from the Wairau Aquifer, or at least in a transitional state. The disconnected river is a special case where an unsaturated zone exists between the river bed and the groundwater table, creating an inverted water table beneath the river. For a transitional state, the hydraulic gradient between the river and aquifer approaches a vertical value, and there is some hydraulic connection via a capillary fringe.

It is difficult to prove conclusively that a river is hydraulically disconnected from the regional water table, since direct evidence is not easily to obtain. The process is hidden beneath the surface, and drilling into the river bed is unlikely to prove the presence of an unsaturated zone because of sediment disturbance, leakage into the casing, and difficulties in measuring the saturated water content within the piezometer. For this reason we are reliant on a number of indirect lines of evidence to determine the hydraulic status of the connection.

The management implication for a disconnected river is that changes in the water table do not affect adjacent river flows. The use of saturated flow equations for characterising the linkage between river flows and the aquifer is also not a suitable approach because the unsaturated zone needs to be considered. However, the rate of river recharge to the aquifer can be calculated if the river bed conductance, reach geometry and stage-wetted perimeter relationships are known. The transient estimation of aquifer recharge can then be based primarily on knowledge of river characteristics rather than the groundwater response.

DEFINITIONS

It is important to identify the nature of the hydraulic connection between the river and groundwater. This is because in a hydraulically disconnected situation, analytical solutions that relate groundwater response to a change in river conditions are not appropriate because of the presence of an unsaturated zone.

The definition of a disconnected river has been suggested by Brunner *et al*. (2012) as where an unsaturated zone exists between the river bed and the regional water table. The key implication of this definition is that changes in the regional water table do not affect the rate of infiltrated recharge from the river. A drop in the water table does not change the infiltration rate from the river because the hydraulic gradient is vertical. It follows from this definition that a disconnected river can only be confirmed in the field by the presence of an unsaturated horizon, or a lack of river response to groundwater level changes, both of which are very difficult to measure.

Most studies on groundwater-surface water exchanges assume the presence of a clogging layer beneath the river bed. In a braided river system, the presence of a clogging layer is problematic because it is difficult to distinguish a clogging layer from any low permeability horizon within the alluvial deposits underlying the river bed. We suggest that it is a reasonable assumption for the bed conductance term to be representative of the vertical hydraulic conductivity between the regional water table and the river bed. It is therefore appropriate to replace the concept of river bed hydraulic conductivity with the saturated vertical hydraulic conductivity in the unsaturated zone and shallow aquifer.

HYDROGEOLOGY

This section looks at how the geology of the aquifer influences the way it interacts with the river. The way that sediments are deposited by the river has a strong control over aquifer properties. The internal structure imparts a strong influence on water table fluctuations seen in monitoring bores, and also how the river relates to the aquifer.

AQUIFER STRUCTURE AND PROPERTIES

AQUIFER INTERNAL STRUCTURE

The internal structure of the Wairau Aquifer influences how it interacts with the Wairau River. Traditionally the Rapaura Gravels, which constitute the host sediments of the aquifer, have been thought to produce unconfined conditions in the Conders-Rapaura area. Recent aquifer test analyses have indicated that unconfined conditions prevail at shallow depths, although much of the Wairau Aquifer may be best considered as a leaky-confined system. The reason for this is that the aquifer is layered at a fine scale (stratified), and this layering creates a marked difference between horizontal and vertical permeability (anisotropy).

Differences between the horizontal and vertical hydraulic conductivity of an aquifer can be formed during deposition of gravels and silts in an alluvial system. Brown (1981) established the type section for the Rapaura Formation at Foxes Island Quarry. A photograph of the Rapaura Formation exposed at the quarry face is shown in Figure 7. Two depositional features can be seen in the photograph:

- Imbrication, which is formed by the alignment of disc-shaped cobbles and sand particles so that they lie flat on the riverbed. Cobbles also tend to be stacked in the direction of river flow during deposition so that they overlap slightly.

- Stratification, which is the inter-bedding of finer and coarser sediment fractions. For example, a prominent sand or silt lens is evident, situated just above the hammer. Brown (1981) notes that in the quarry type-section, “rare sand lenses, up to 10cm thick, are generally less than 1m in length”.

Figure 7 Photograph of the Rapaura Formation at Foxes Island Quarry (from Brown, 1981)

These depositional features produce a hydraulic anisotropy within the aquifer, by forming a greater permeability in the horizontal direction than in the vertical. This anisotropy has two important implications for understanding how the aquifer functions:

- The aquifer can drain in a horizontal direction more readily than it can be recharged in a vertical direction. This mechanism allows the possibility for the river to become perched above the aquifer.

- The vertical transmissivity and storage coefficient of the aquifer decrease rapidly with depth (Figure 8). The reason for this is that permeable flow pathways become more tortuous as the depth is increased. This resistance to vertical flow means that water is preferentially routed horizontally along shallow pathways.

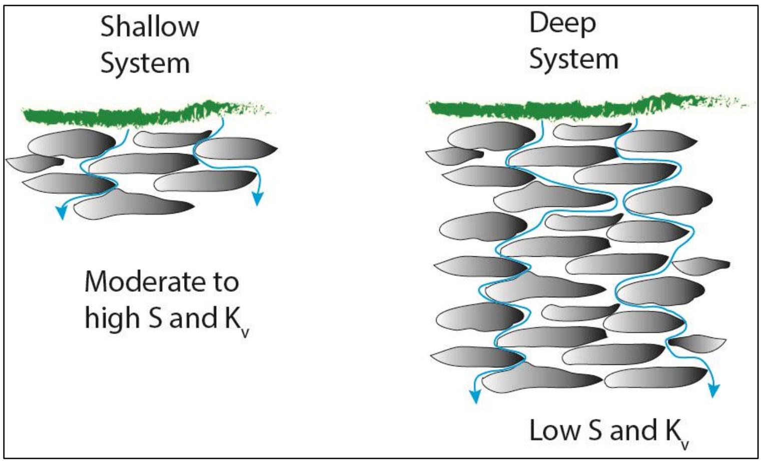

Figure 8 Illustration of the compounding effect that anisotropy has on vertical flow with depth

AQUIFER STRATIFICATION

The base of the Wairau Aquifer is usually identified as being at the base of the Rapaura Formation (or top of the underlying Speargrass Formation). The surface of the Rapaura-Speargrass contact is not well defined, but it has been broadly mapped from intercepts in exploration bores (see Brown, 1981). Based on observations from the exploratory bores, the Wairau Aquifer can be considered to have a thickness of 20- 30m over much of the Wairau Plain. The thickness does thin to the west where the Speargrass Formation outcrops at the surface around the Waihopai River. The aquifer also thins to the east of Hammerichs Road where the confining sediments of the Dillons Point Formation thicken as the coast is approached.

Drillers' logs tend to report variations in sand and gravel with various clay contents which change with depth. There is no clear or consistent pattern between individual bore logs, but perhaps what is notable is the fact that variability has been observable by the drillers. The drilling logs also indicate a change in the water content of the subsurface, and a log may include good and poor water-bearing horizons as well as clay-bound gravels with negligible water.

Water levels in many bore logs tend to change with depth, although in some logs the water levels are recorded as being stable with depth. However, there is a tendency for the upper 10-15m of saturated aquifer to show falling water levels with depth. This suggests that unconfined conditions prevail within this upper part of the aquifer.

The rate of head loss with depth within the shallow saturated gravels is likely to be related to proximity to the Wairau River. An example of a rapid fall in water table with depth is bore P28w/3950, which is situated adjacent to the Wairau River at the end of Pauls Road. This bore has a 1.8m head difference between shallow and deeper water-bearing horizons. The upper water-bearing gravels have a similar water level to the river, which is 70m away, so it is most likely that this upper layer represents recent channel deposits. The deeper gravels (from 16.4m) appear to represent the main Wairau Aquifer, and have a water level 2.3m below the top of the river (measured from the DEM). The stratification seen in this bore is similar to that of the recharge bore (10485), and these two bore logs suggest the possibility of an unsaturated zone between the river and regional water table.

Most of the aquifer tests on the Wairau Plain have been planned and analysed by Pattle Delamore Partners (PDP) on behalf of private clients. For the purposes of analysing aquifer test results, PDP have in recent years considered the aquifer as a two-layer system, an upper unconfined system, and a deeper leaky-confined system (PDP 2009, PDP 2014).

The concept of a stratified system is shown schematically in Figure 9. One of the possible explanations for a two-layer system is that there was a change in the climate or depositional environment between the shallow and deeper layers. This shift may represent the transition between the early and late Holocene, with the earlier sediments consisting of more silty outwash gravels that were formed prior to stabilisation of sea levels and the deposition of the Dillons Point Formation. Under this scenario, the earlier deposits would have consisted of more primitive outwash material from the last glacial period which has been deposited quite rapidly. The more recent sediments would therefore be subjected to more alluvial reworking because of the stabilisation of the sea level. An alternative explanation is that the deeper sediments represent Pleistocene gravels of the Speargrass Formation, although these deposits are thought to be present at depths of about 30 meters. MDC intends to review the geology of the Conders area in 2015 by using the 3D geological model developed by GNS (White and Tschritter, 2009) to focus on the upper part of the Wairau Plain.

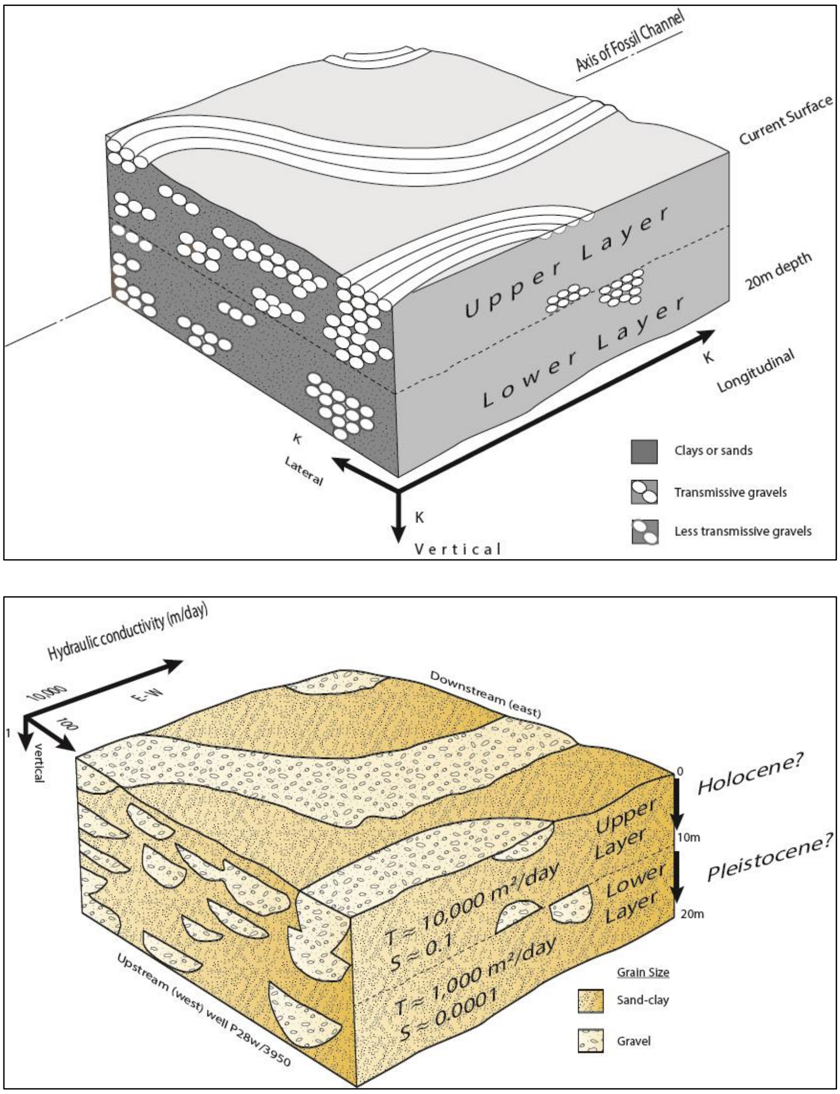

Figure 9 Schematic diagram showing how the Wairau Aquifer is stratified

CONDERS MONITORING BORES

MDC monitors two bores in the Conders area, P28w/0398 or 'Conders shallow', and P28w/3821 'Conders deep'. The Conders deep monitoring bore was drilled in late 2001 to replace water level monitoring in the existing adjacent shallow bore, which has been used for long term water quality monitoring. The shallow bore was deepened from 2m to 10m depth in mid-2012. This resulted in a small drop in water conductivity from 6.5 mS/m to 5.7 mS/m, suggesting that the deeper gravels are subject to a smaller land surface recharge source.

The bore log for P28w/3821 records alternating lenses consisting of various mixtures of shingle, sand and clay. The static water levels show a gradual falling of the water level with depth, followed by an abrupt increase at 20m depth (a saturated depth of about 15m). This pattern suggests that a structural control is creating leaky-confined conditions at that depth.

Intermittent periods of overlapping monitoring records are available for the shallow and deep bores, with the best records available for January 2011 onwards. Figure 10 shows a comparison of the two records, and it is evident that the water level is higher in the deeper bore by about 0.15m. Also, water levels in the two bores converge during a recharge event, and diverge during a recession. This indicates that the upper gravels are more dynamic and are recharged and drained more rapidly. Also, P28w/0398 shows no response to pumping from the nearby Pernod Ricard abstraction, which is screened near the base of the Rapaura Formation gravels. So it seems likely that the deeper gravels are recharged by leakage from overlying sediments in response to pumping, which buffers the drawdown response in P28w/0398.

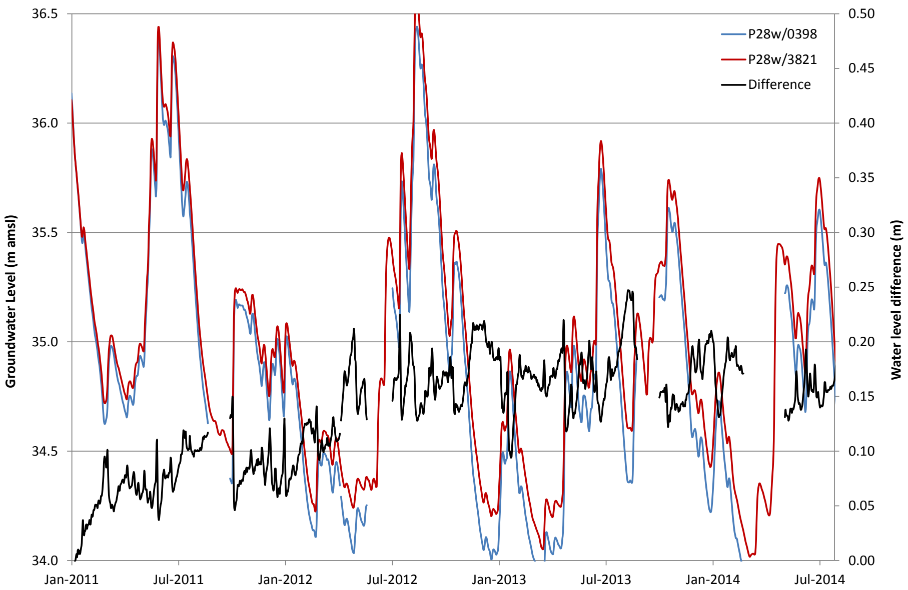

Figure 10 Monitoring records for Conders bores P28w/0398 and P28w/3821

The groundwater levels in P28w/3821 can be adjusted by 0.15m to create a continuous groundwater record at P28w/0398 that extends back to 1982. Figure 11 shows the resulting composite hydrograph, and it is evident that groundwater levels have been steadily falling over time. The current groundwater level is on average 0.6m lower than it was in the early 1980s even though the river flow has not significantly declined during this period. An obvious explanation for this decline would be to suggest that increased groundwater allocation has drawn groundwater levels down. However, while this is feasible, it does seem an unlikely cause given the small contribution that pumping makes to the mass balance.

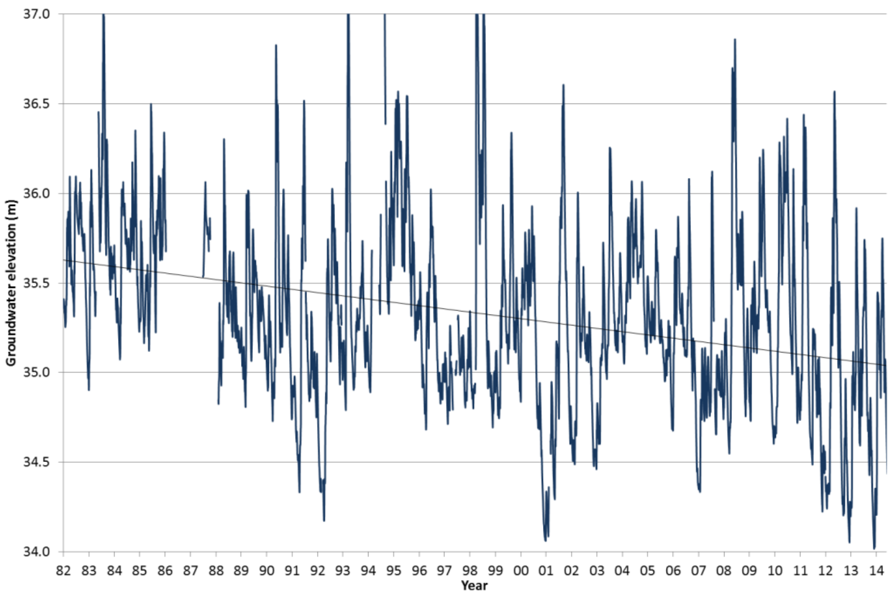

Figure 11 Composite long term groundwater level at P28w/0398

The most likely explanation for declining groundwater levels is that there has been a reduction in the rate of aquifer recharge from the river. There are several ways in which this could occur. One explanation is that there has been a change in the frequency of high flow events. Analyses of the relationship between flow or stage and wetted river bed perimeter show that they follow a power law. This means that a small increase in river stage can potentially provide a large increase in groundwater recharge. So the number of high flow events is expected to be a key factor in recharge to the aquifer. If high flow events become less frequent, there would be less potential for recharge pulses in the aquifer to occur, so groundwater levels would decline.

Figure 12 shows the mean annual Wairau River flow at SH1, which gives a good indication of long-term climate conditions since 1982. A comparison between Figure 12 and Figure 11 shows that mean annual flows do not align very well with the trend in groundwater levels. The pattern suggests that long-term flow alone cannot explain the drop in groundwater levels at Conders. However, this does not rule out the possibility that declining groundwater levels are related to the frequency of high flow events, since these events will not necessarily lead to large mean annual flow values.

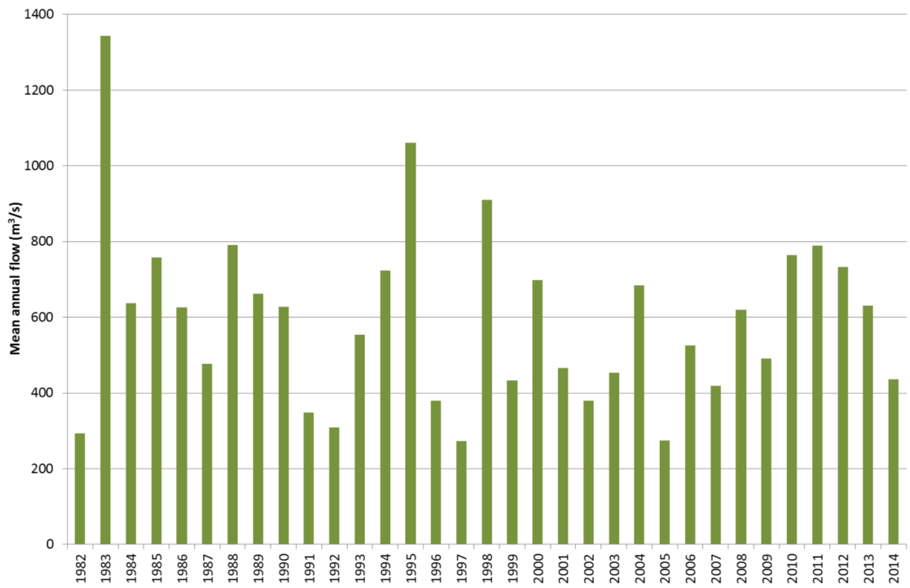

Figure 12 Mean annual Wairau River flow at SH1

Since 1998 there have been less flow events exceeding 1,000 m^3/s, and this does coincide with a drop in the water table. There is also a moderate positive correlation between mean annual flow and groundwater levels at Conders, which follows a power law relationship (Figure 13). This relationship does open the possibility that the decline in groundwater levels at Conders could be related to fewer high flow events in the river. However, there is an inflection in the curve at 50 m^3/s, indicating that groundwater is more responsive to river recharge during lower flow events. There is also a lessening of the groundwater response for mean monthly flows of 100-150 m^3/s onwards. Both of these factors suggest that there may be a structural rather than a climatic control on the relationship, although further work is required to substantiate this.

Alternative explanations for the decline in Conders groundwater levels relate to the morphology of the river itself, although groundwater levels may be sensitive to other contributing factors which we don't yet know about. For a scenario where the river is hydraulically connected to the aquifer, a decline in bed levels over time would reduce the hydraulic gradient and therefore the rate of river loss to the aquifer. For a scenario where the river is disconnected from the aquifer, the rate of groundwater recharge could be reduced by altering the wetted perimeter of the river bed. This would happen in a situation where the river becomes more entrenched or channelised over time, requiring higher flow events to generate a significant wetted river width. The evidence we have available suggests that the river is perched above the regional water table in the Conders area, so stabilisation of the river channel is a viable explanation for the observed long term decline in groundwater levels at Conders.

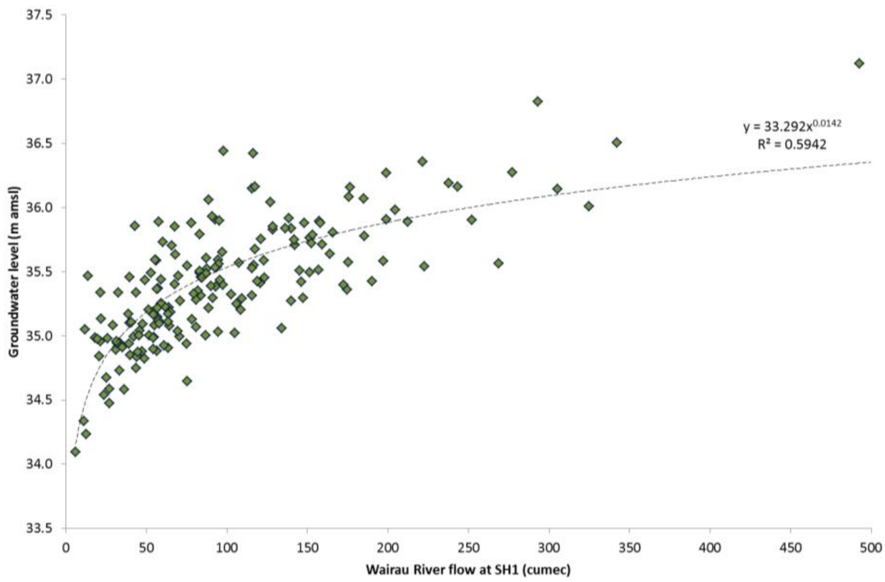

Figure 13 Relationship between mean monthly river flow and groundwater level at Conders

AQUIFER PROPERTIES

Historically, a total of 15 aquifer tests have been carried out in the unconfined Rapaura Formation. Locations for these tests are shown in Figure 14 (orange) along with the positions of MDC monitoring sites (blue). The results of these tests are reported in Cunliffe (1988), or as evidence submitted for resource consent applications. These historical test results indicate that aquifer transmissivity in the Rapaura-Conders area can be quite variable, from 320 to 15,000 m^2/d (mean 4,800 m^2/d). These values are equivalent to a bulk hydraulic conductivity of 20 to 2,800 m/d (mean 590m/d).

Very few tests have been carried out using observation bores, so there is little empirical information about aquifer storage coefficients. Historical tests that have been carried out using observation piezometers have returned values of 0.1 to 0.15, for bores screened at depths less than 10m (see Cunliffe, 1988). Consultants have typically assumed values of around 0.2 when assessing long-term drawdown predictions.

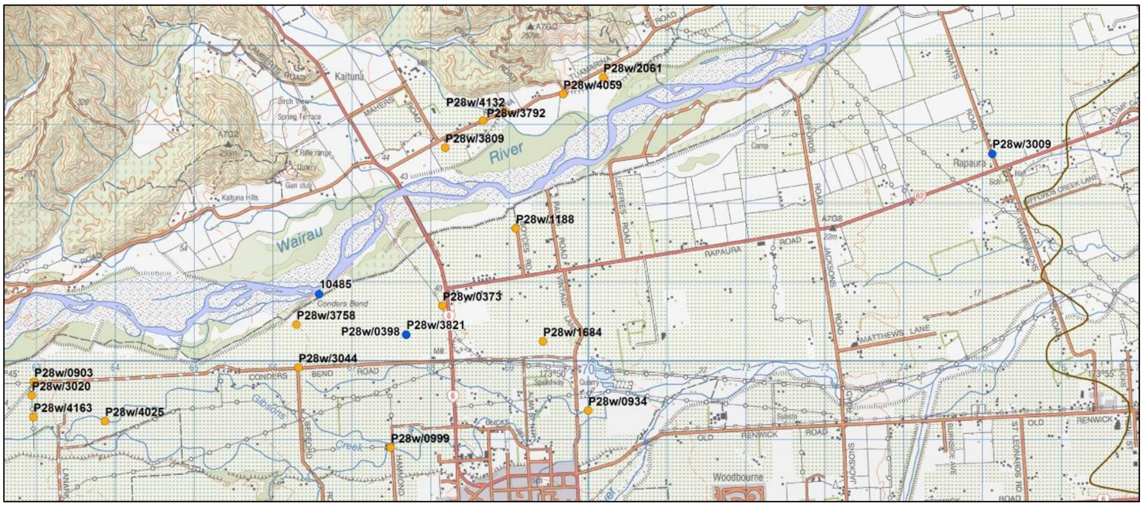

Figure 14 Locations of aquifers tests in the unconfined Wairau Aquifer

Tests carried out in recent years tend to provide more information about the aquifer because there have been improvements in bore logging and data recording. With the advancement of test analysis procedures in recent years, the use of observation bores has also become a more widely accepted practice. One of the outcomes from these recent developments is the ability to partition drawdown into upper and lower layers with their respective hydraulic conductivities and storage coefficients, including the ability to determine vertical leakage and hydraulic conductivity. The results of the three most recent tests are summarised in the following section of this report, and a summary of the analysed parameters is provided in Table 2.

Results from the three most recent aquifer tests suggest the Wairau Aquifer may be best considered as a stratified system which becomes increasingly confined with depth. An aquifer test carried out on P28w/3758 at Conders Bend returned a surprisingly low storage coefficient of 1×10^{-4} (PDP, 2001). This bore is thought to be screened near the base of the Rapaura Formation, from 23.5 to 27.5m depth, and has been the first indication that the Wairau Aquifer may not be a simple uniform unconfined aquifer system.

Table 2 Recent aquifer test results for the Rapaura area

Test	Pumped bore	Static water level (m bgl)	Top of screen (m bgl)	Pumped Horizon		Overlying Sediments	
				K_x	S	S_y	K_v
Montana	P28w/3758	6	23.5	1,400	1×10^{-4}	0.15	0.1
Oyster Bay	P28w/4537	4.9	26	720	2×10^{-3}	0.08	0.1
MDC Matua	P28w/4867	4.4	16.5	320	8×10^{-5}	0.03	0.5

Aquifer properties for the Conders Bend production bore P28w/3758 have been re-assessed by analysing its pumping record together with the drawdown observed at Conders monitoring bore P28w/3821. Bore P28w/3738 is located about 230m from the Wairau River, and is screened below 23.5m, with an overlying depth of saturation of 17.5m. The Conders monitoring bore is located 1,400m away from the pumped bore, 1,155m from the river, and screened below 20.2m, with a 14m depth of saturation. Interestingly, the adjacent Conders shallow monitoring bore (P28w/0398) shows negligible drawdown in response to pumping at P28w/3738. This suggests that drawdown between the deeper and more shallow gavels are being buffered by an additional source of storage, either from the overlying gravels, or recharge from the river.

The monitoring record for the Conders bore shows a drawdown of 10mm in response to a 50 l/s abstraction at P28w/3758. Analysis of the drawdown curve gives a storage coefficient of 0.0005, a hydraulic conductivity for the whole profile of about 1,400 m/d, and a vertical hydraulic conductivity of 0.2, a ratio of 1:5,800.

It is interesting to note that the Recharge bore (10485), which is only 480m from the pumped bore and 45m from the river shows a response of less than 1mm. This bore is screened below 10.6m, which is considerably shallower depth than the other two bores. Thus, it is difficult to know whether the poor response at the recharge bore is due to the recharge effect of the river, or due to its shallower screen depth.

The Oyster Bay test showed hydraulic conductivity values of 700-750 m/d and a storage coefficient of 0.004 to 0.0007 for a water bearing horizon screened at 16.5-20m depth. When the leakage rates from the test are converted to vertical K values for the aquifer saturated thickness, values of 0.05 to 0.15 are returned.

A more recent aquifer test carried out on bore P28w/4867 with two nearby piezometers (PDP, 2014) is the most intensive test to be carried out in the Rapaura area. The pumped bore was screened below 16.5m depth, which gives approximately 12m of saturated gravels above the screen. The shallow gravels above the screen appeared to bear less water than those within the screened horizon, so conditions in the aquifer were interpreted to be best represented by a two-layer system.

Analysis of the drawdown curves from the aquifer test at P28w/4867 indicates storage coefficients for the shallow and deep layers to be 0.025 and 8×10^{-5} respectively. When the modelled transmissivity results are corrected to layer thicknesses, the hydraulic conductivities of the upper and lower layers are 810 and 324 m/d respectively. The leakage coefficient for the top layer was interpreted to be 0.025 d^{-1}, which corresponds to a vertical hydraulic conductivity of 0.5 m/d. This gives a high anisotropy ratio of vertical to horizontal hydraulic conductivity at 1:1,600.

A characteristic of the recent aquifer tests is that if aquifer anisotropy is assumed, the drawdown curves can be fitted by various methods (stream depletion, two-layer, multilayer). For drawdown in the pumped bore to be simulated, it simply requires the influence of an overlying reservoir of some kind, such as a stream or shallow layer. The source of this reservoir is open to interpretation, but is guided by the conceptual model of the hydrological system. However the type of reservoir or conceptual model that is selected does determine the drawdown model used, and this ultimately influences the result of the drawdown analysis.

It is also possible that an apparent stream depletion signature could be created by the recharge effect of the river in a scenario where the river is perched above the regional water table. The resulting drawdown curve could be interpreted to represent stream depletion even though no stream depletion is actually occurring. This highlights the importance of verifying the conceptual setting of the aquifer test prior to analysis of the drawdown curves.

DISCUSSION

The internal aquifer structure of the aquifer is an important consideration for interpreting the response of groundwater levels to river flow events. If the aquifer was unconfined and homogeneous, we could safely assume that the response seen at each monitoring bore is a reflection of the timing and magnitude of river recharge that it receives. However, if each monitoring bore is representative of different aquifer conditions, then it is very difficult to compare the response at each monitoring bore. The key factor that influences the groundwater response is the storage coefficient, since this is the characteristic which controls the timing and magnitude of a peak event.

The term 'storage coefficient' was defined by Theis (1935) as the amount of water released from storage from a cylinder of aquifer, caused by a unit decline in head. Theis also proposed that storage is influenced by aquifer drainage in unconfined aquifers (known as specific yield), or aquifer compression in confined aquifers (known as storativity). The two processes differ in their characteristics in that the specific yield is independent of aquifer thickness, whereas the storage coefficient of a confined aquifer is proportional to aquifer thickness.

A key assumption that is made for drawdown analysis is that aquifer storage at the well screen is released instantaneously upon a reduction in pressure. However, in a case where the vertical hydraulic conductivity is considerably smaller than the horizontal, the reduction in permeability produces a time delay for the release of storage. The assumption of an instantaneous release of storage therefore results in an underestimation of the real storage characteristics of the aquifer.

RIVER FLOW AND STRUCTURE

The Wairau River has a complex form, which is evident in Figure 15. This photograph shows the upper section of the aquifer recharge reach from Conders Bend to Rock Ferry. The number of river channels increase and decrease over a short distance, and where multiple channels are present, they each have a slightly different elevation and slope. To complicate matters, we can also see the formation of new channels within the active gravels of the river bed, indicating that there is water coming and going from the river at shallows depth within the active channel sediments (hyporheic flow). These factors make it difficult to locate monitoring sites or to carry out concurrent flow gauging runs.

Figure 15 Aerial photograph of the Wairau River upstream of Conders Bend

MDC have monitored river stage at Barnetts Bank at the SH1 bridge, Tuamarina since July 1960. The river channel at the SH1 site is set within marine and marginal-marine sediments of the Dillons Point Formation aquitard. This geological setting has provided a relatively stable river channel, which has allowed a good flow-rating curve to be developed. The long term mean and median annual flows at this site are 100 and 60 m^3/s respectively.

For this study, the SH1 site has been complimented by temporary river stage recorders at Wratts Road, SH6 Bridge, and Rock Ferry. These sites are located in parts of the river where a single channel has formed, making them suitable for developing flow-rating curves. Despite this, the monitoring of river flows is practically difficult due to the changing position of the river channel, and the movement of river bed sediments in response to high flow events.

FLOW PROFILES

A summary of concurrent low-flow gauging results carried out prior to this project is shown in Figure 16. What is remarkable about these profiles is the consistent shapes of the curves over a period of 31 years. It is important to note that some of the low flows have occurred mid-year, so there is no possibility that they are due to pumping. This evidence confirms that flow losses to the aquifer are a natural process.

The rate of river loss is represented in Figure 16 by the slope of the curve, the steeper the curve the greater the flow loss. It is evident in Figure 16 that the location of river recharge to the aquifer doesn’t change much through time and at different flow rates. Sometimes slightly more water is lost upstream of SH6, sometimes downstream of SH6, but the overall pattern is very consistent. The consistency of the flow profiles suggests there is some structural control over the rate of losses within each of the reaches, and that this structural control has remained quite stable through time.

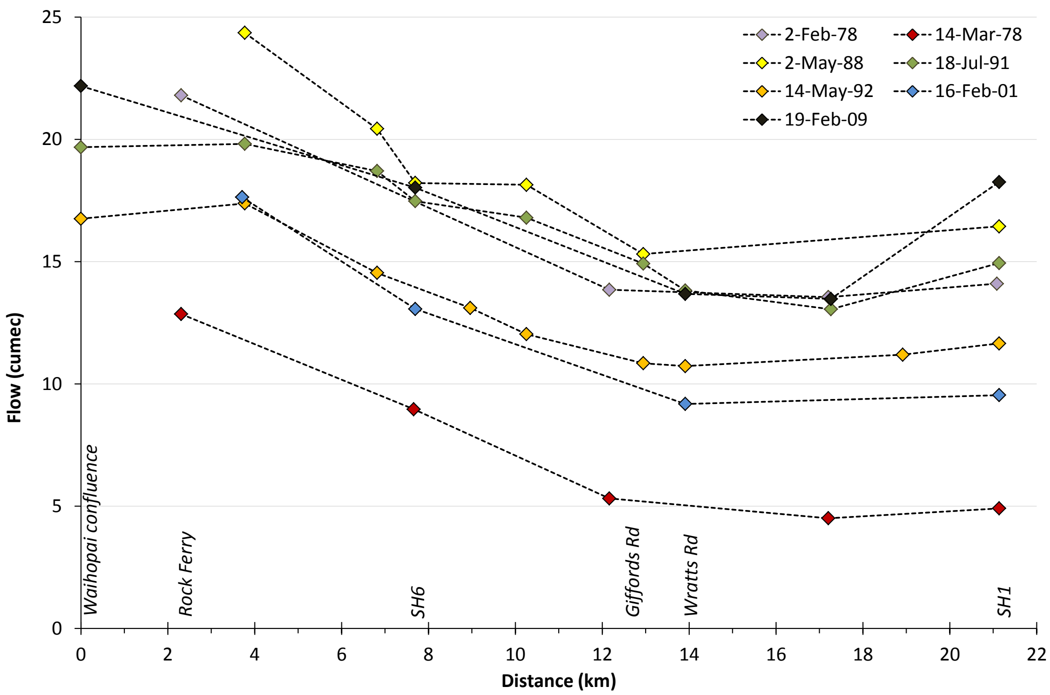

Figure 16 Historical flow gauging profiles down the Wairau River

The rate of loss between Rock Ferry and Giffords Road represents the total rate of river recharge to the Wairau Aquifer. In general, the rate of loss is slightly greater upstream of SH6, and appears to peak between Conders Bend and SH6. The change in magnitude of the loss between surveys is difficult to see in Figure 16, but it varies upstream of SH6 from 0.5 $m^3/s/km$ in Feb 2009 to 1.5 $m^3/s/km$ in July 1991. The river reaches an equilibrium with the aquifer between Giffords Road and Wratts Road, and a small gain occurs downstream of Wratts Road.

A summary of the gauging runs is tabulated in Table 3, and the flow balances are plotted against SH1 flow in Figure 17. Unfortunately we can't be very precise about river water budgets because of the braided nature of the river. The magnitude of the flow losses and gains is also to some extent influenced by the number and position of the gauging sites between Giffords Road and Wratts Road. Furthermore, there are uncertainties about the amount of North bank flow entering the river, and any hyporheic flow that needs to be accounted for. Almost all of this water can be accounted for once the river crosses the Dillons Point Aquitard, downstream of Selmes Road.

Despite the uncertainties, the majority of river flow does occur as inflow within the main channel, so the summary does give a good indication of the values that we can expect. Flow losses vary from 6.65 to 9.54 m^3/s, and Figure 17 shows that the river typically loses more water at larger flows (about 70 l/s per m^3/s increase in flow).

Table 3 Summary of historical concurrent flow gaugings on the Wairau River

Date	SH1 Flow (m^3/s)	Gaugings	Total loss (m^3/s)	Total gain (m^3/s)	Flow balance (m^3/s)
2-Feb-78	14.10	4	-8.25	0.55	-7.70
14-Mar-78	4.91	5	-8.35	0.40	-7.95
9-Feb-82	18.81	4	-9.54	2.39	-7.15
2-May-88	16.44	6	-9.05	1.13	-7.92
18-Jul-91	14.94	9	-6.76	2.03	-4.74
14-May-92	11.66	9	-6.65	1.55	-5.10
16-Feb-01	9.54	4	-8.46	0.36	-8.09
19-Feb-09	18.26	5	-8.71	4.78	-3.93
Min	**4.91**	**4**	**-9.54**	**0.36**	**-8.09**
Max	**18.81**	**9**	**-6.65**	**4.78**	**-3.93**
Mean	**13.58**	**6**	**-8.22**	**1.65**	**-6.57**

The flow balance is largely influenced by the flow gain component at higher flows, which appears to have an exponential increase with total river flow. This relationship suggests that the flow gain values may be related to inflows from north bank tributaries such as the Waikakaho. The observed increase in river flow loss at higher flows is not apparent if the total flow balance alone is studied because of the increased influence that total flow gains have during high flow conditions. The influence of the North Bank tributaries increases as flow increases, indicating that input flows from the North Bank will needed to be accounted for in transient model simulations.

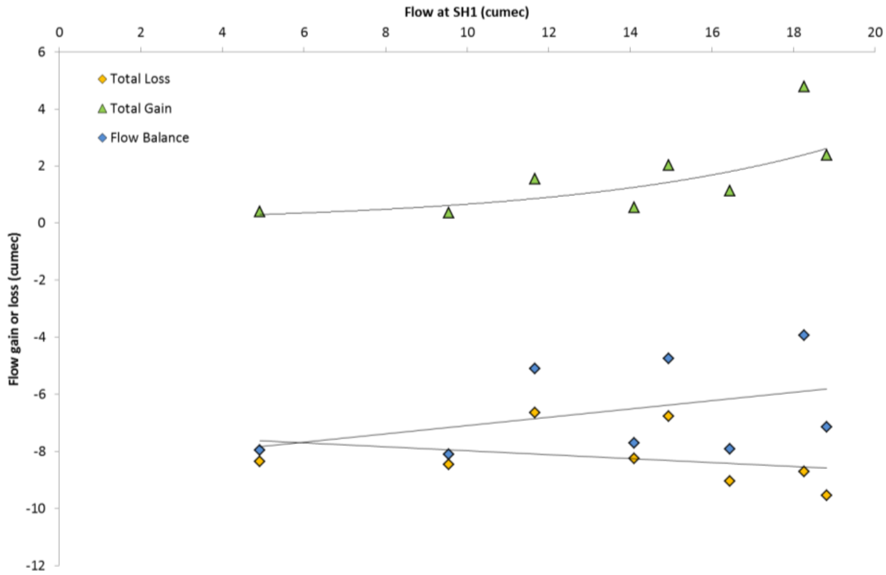

Figure 17 Summary of historic Wairau River concurrent flow gauging surveys

FLOW TIME LAGS

It takes a few hours for water in the Wairau River to travel across the length of the Wairau Plain. However, the time lag between sites varies with different flows, and whether the river is on a rising or receding phase. A statistical analysis tool was written in Matlab to determine the dynamic time lags between river stages recorded at four sites along the river. The cross-correlation technique used compares the offset between two sites in the daily cycle generated by storage and release of water from the Branch River reservoir operated by Trustpower. Flow peaks generated by the operation of this scheme are used to calculate time lags and corresponding probabilities.

The time lag with the highest probability is the selected for a specific site and flow condition (Figure 18). The results of this analysis suggested a 2 ½ hour time lag from between Rock Ferry and Wratts Road, and a 4 hour lag between Rock Ferry and SH1 at flows of about 20 m^3/s. These times lessen as the river flow rate increases.

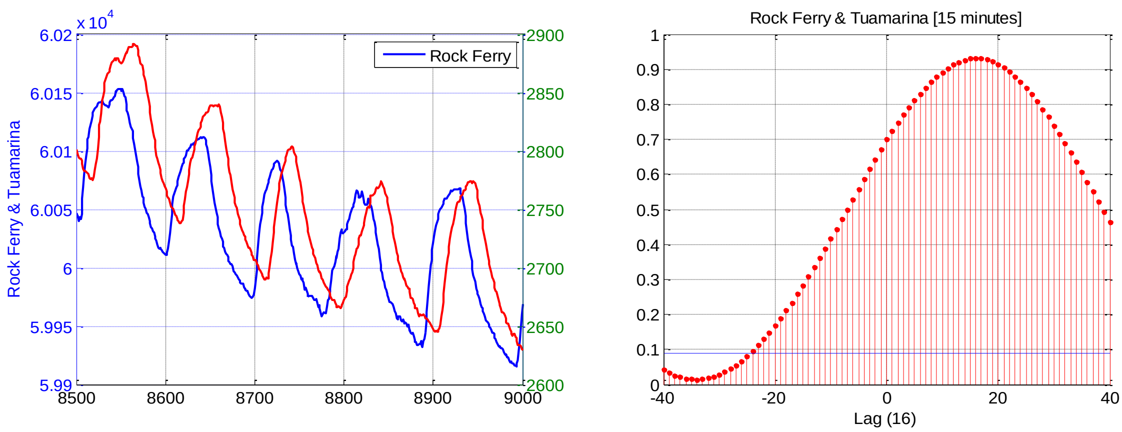

Figure 18 Graphical example of the probability approach for predicting time lags

RIVER STRUCTURE

This section describes our current understanding of the nature of the hydraulic connection between the river and underlying Wairau Aquifer.

One of the important datasets to become available in recent years is Lidar imaging. Lidar is a remote sensing technique that measures distance by analysing the light reflected by a laser, and it provides a high resolution survey image of the land surface. Because the method is based on surface reflectance, the image also provides elevations for the surface of water bodies. The resulting image therefore gives us the first available detailed map of the Wairau River surface and it's adjacent topography. A Lidar image was captured for the Wairau Plain on 23 to 28 February 2014. An example of the resulting image is shown in Figure 19 with the active river channel drawn in blue for the purposes of clarity.

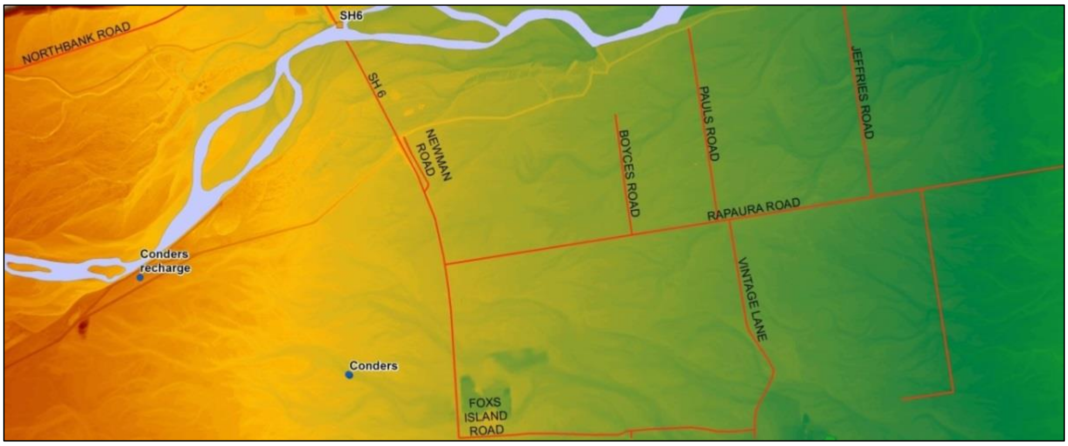

Figure 19 Example Lidar image of the Conders area

RIVER AND AQUIFER SURFACES

One of the powerful aspects of the Lidar image is that it gives us the ability to compare the river surface with groundwater level surveys. Figure 20 shows a piezometric survey across the Wairau Aquifer using data from various sources in order to appreciate a complete picture of the hydrology. The assumption made in generating this map is that vertical fluctuations over time are small compared to spatial changes in elevation. River elevations were taken from the 24 February 2014 Lidar survey (light blue points) and stage recorders for the same date (orange), when the flow at Tuamarina was approximately 10 m^3/s.

The groundwater survey data was taken from a comprehensive piezometric survey of the Wairau Plain carried out on 23-24 February 1987 (points shown in blue). The river flow at the time of the survey was approximately 20 m^3/s at Tuamarina. These data were supplemented by static water levels for boreholes on the north bank of the river which have had their bore collars surveyed (green points).

What is evident in Figure 20 is the distortion of the water table around the river. The river level is consistently higher than the adjacent water table between Onamalutu Road and Wratts Road. While the contours are largely informed by the position of the measurement sites, it is still apparent that the hydraulic gradient is very steep adjacent to the river in this area. In fact the offset is so marked in locations where groundwater sites are located close to the river, such as upstream and downstream of SH6, that the river appears to be perched above the regional water table. Further upstream at Rock Ferry, and also below Wratts Road the river level is very similar to the regional groundwater table. This suggests that the two water bodies are hydraulically connected and in close equilibrium in these areas.

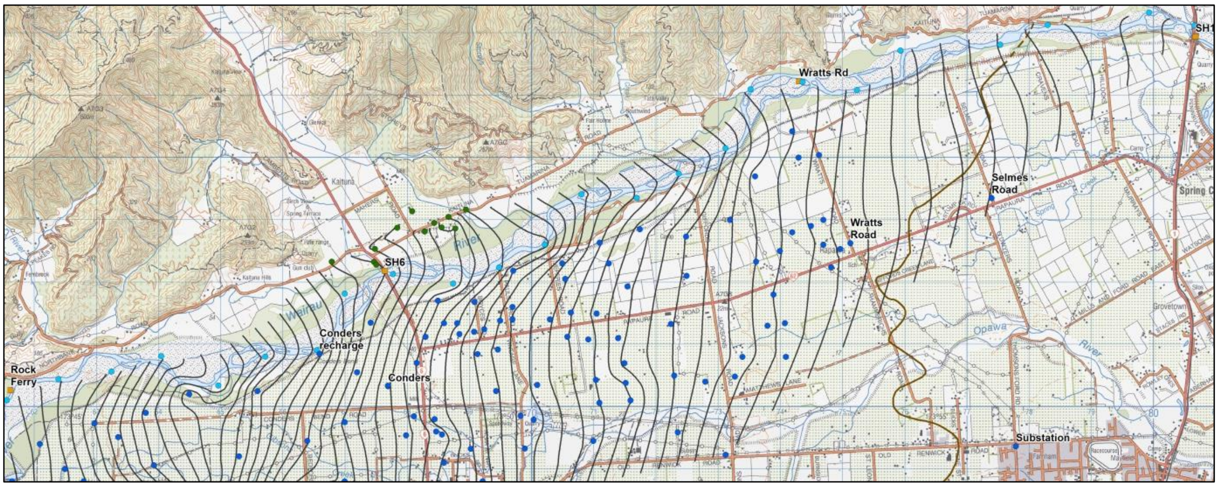

Figure 20 Composite piezometric survey across the Wairau Aquifer including river elevations

Another method of studying the relationship between the river and aquifer is to project the groundwater piezometric surface beneath the river and study the vertical difference between the two. Figure 21 shows the result of this exercise as a longitudinal profile. Three groundwater interpolations have been made beneath the river, the detailed piezometric surveys carried out in February 1987 and May 1988, and a surface generated from all static water levels in the MDC database (to give a better spatial resolution). The longitudinal profile is supplemented with historical observations made in riparian bores P28w/1692, 1696, 1697, and 1699 for a range of hydrological conditions to indicate the variation in the water table.

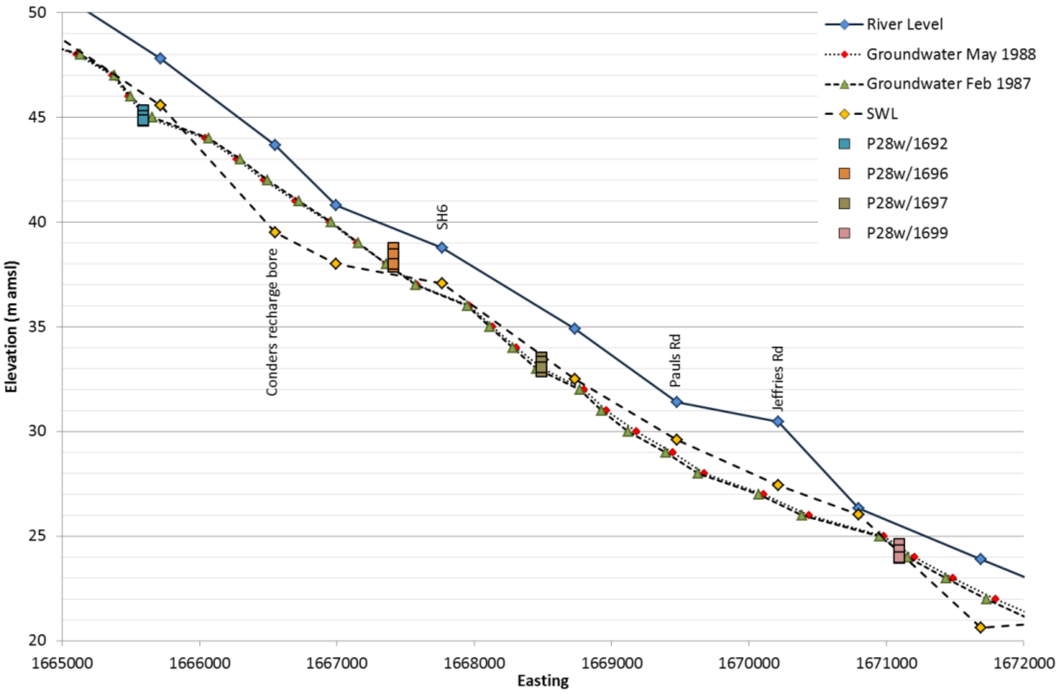

Figure 21 Longitudinal hydrological profile along the Wairau River from Conders to Giffords Road

The longitudinal profile shows that the river is consistently 2-3 m above the regional water table for most of this reach. The river and regional water table do converge downstream of Jeffries Road, just up-gradient of the Neal bore P28w/1685. It is difficult to know whether this is an area of higher permeability, or if the convergence is an expression of the anastomosing of the river in this area.

A simplified summary of the entire Wairau Plain longitudinal profile is shown in Figure 22. This plot includes the low flow profile down the river from a fairly comprehensive concurrent flow gauging run that was carried out in May 1992. The length of river that shows the most losses, from Rock Ferry to Wratts Road, coincides with the length of river that is significantly higher than the regional groundwater table. The river losses and separation distance are both fairly consistent from Rock Ferry to Jeffries Roads. Between Jeffries and Giffords Roads the river level and regional water table start to converge (the hydraulic gradient flattens) and there is a corresponding reduction in the flow loss. Downstream of Wratts Road the river approaches the Dillons Point Formation aquitard, and a small flow gain is observed as groundwater from the unconfined aquifer become squeezed back into the river.

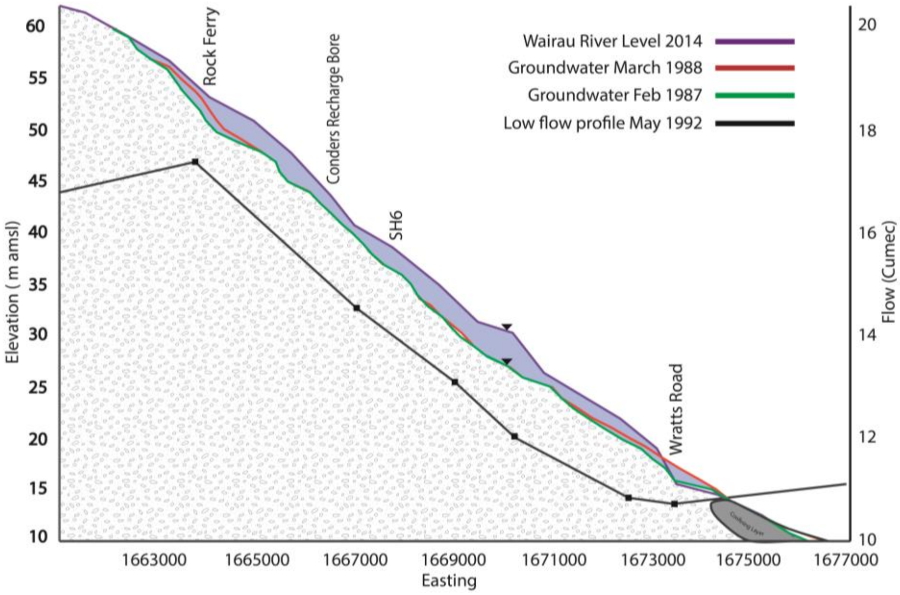

Figure 22 Simplified longitudinal profile for the whole Wairau Plain

Comparison of river and groundwater levels along the river indicates that the hydraulic gradient between the two is very steep and possibly vertical over the main recharge reach. In the case of a vertical hydraulic gradient, the hydraulic relationship between the two is either disconnected or transitional. Furthermore, the vertical separation is much greater than the fluctuations seen in the aquifer, which suggests that the hydraulic relationship across the main recharge reach does not alter during the year. This is a significant insight, because it suggests that the recharge rate does not vary significantly with changes in the hydraulic gradient. The recharge rate can be estimated if the subsurface vertical and horizontal hydraulic conductivities can be constrained, and the source area of recharge (e.g. wetted river perimeter) is known.

The hydraulic relationship at the up-gradient and down-gradient ends of the main recharge reach is expected to change from hydraulically connected when groundwater levels are high to a transitional state when groundwater levels are low. It is not known how much this transition zone migrates up and down the river in response to high and low groundwater levels.

GEOLOGICAL CONTROL ON RIVER LOSSES

The Lidar image shown in Figure 19 clearly shows the presence of older river channels that were formed prior to the river being constrained to its present position by flood protection works. Apart from a small entrenchment of the modern river channel compared to the surrounding plain, no clear distinction can be made between the active river channel gravels, and the adjacent, older alluvial deposits. Form a hydrological perspective, the gravels can be considered to be a single entity of varying internal structure and permeability (anisotropy and heterogeneity).

Traditional approaches to calculating stream-aquifer exchanges include a bed conductance term to allow clogging to occur in the stream bed. Such a term is undoubtedly appropriate for a meandering river or a spring where a distinct clogging layer may be observable. However, in a braided river depositional environment, there is a constancy of sediment re-deposition or re-working through time. We also see a spatial repetition of the surrounding and underlying deposits, so that no obvious distinction can be made between the sediments in the active river channel and those that adjacent or underneath. This calls to question the relevance of a stream bed conductance term for a braided river environment.

It is perhaps more appropriate to consider that the sediments associated with the active river channel are more permeable that the surrounding sediments. This is because the more recent deposits are likely to have been subject to more reworking by the river, particularly since the training of the river position by flood works. We suggest that a bed conductance term is not required for a braided river environment, although existing analytical techniques such as Modflow do require a bed conductance to be formulated. Instead, it is more appropriate to consider river flow to be determined by the horizontal and vertical hydraulic conductivity values within the shallow aquifer.

It is also valuable to consider the effect of enhanced permeability within the active river channel gravels. How we define the active river channel boundaries will inform our predictions for the wetted area of the river. It is apparent from aerial photos of the river that river braids can appear and disappear at some distance from the active river. We do not know if these braids are caused by localised high permeability channels (underflow) or whether they are a representation of the regional water table or even the shallow table associated with the river. Indeed, at this stage there is little known about the hydrology beneath braided rivers, and this should be considered as a topic for further study by drilling investigation bores in the river bed, perhaps using geophysical survey methods.

RIVER GEOMETRY

The bed of the Wairau River has been surveyed every few years at transects perpendicular to the river. The latest survey results from 2012-2013 consist of 22 survey sections spaced at intervals of approximately 800m along the river. Unfortunately, the river stage level for each river transect was not measured during the survey, but we do have a snapshot of river stage from the Lidar survey. We also have transient stage records for SH1 and the three temporary recorder sites at Wratts Road, SH6 and Rock Ferry.

Relationships have been established between stage, flow and wetted river bed perimeter for the purposes of providing input data for the 22 cross sections employed in the numerical model. In theory, if the horizontal and vertical hydraulic conductivity of the near-surface sediments can be constrained, the rate of recharge for a hydraulically disconnected river is simply a function of wetted perimeter. Simple power-law functions were derived to relate river stage, h, and width, w, to river flow, Q:

$$h(Q) = aQ^b \qquad \text{and} \qquad w(Q) = cQ^d,$$

Where a, b, c, d denote empirical fitting parameters.

To generate these formulas, several steps were undertaken. Firstly, the 22 surveyed cross sections along the river were analysed. Relationships of river stage and width to the cross-sectional wetted area, A, were derived from the river geometry data and fitting of parametric functions to these data.

For the river-gauging station at SH1, simultaneous measurements for both river water level and river flow were available (bottom middle panel in Figure 23). Therefore, the equations for h(Q) at SH1 have been measured directly and a function was fitted to the data. The equation for w(Q) was calculated from the cross-sectional area, A as follows (Figure 23):

$$Q \text{ in } h(Q) \rightarrow h; \;\; h \text{ in } h(A) \rightarrow A; \;\; A \text{ in } w(A) \rightarrow w; \;\; \rightarrow w(Q)$$

Unfortunately, little river flow information was available for the other cross sections. The h(Q) relations for these cross-sections were derived using the known h(Q) and Q(A) relationships at SH1, and the assumption of (on average) normal flow along the various river sections. This leads to the assumption of constant velocity (but variable in time since it is a function of flow), and allows us to establish h(Q) and w(Q) relationships at all other cross-sections while preserving conservation of mass.

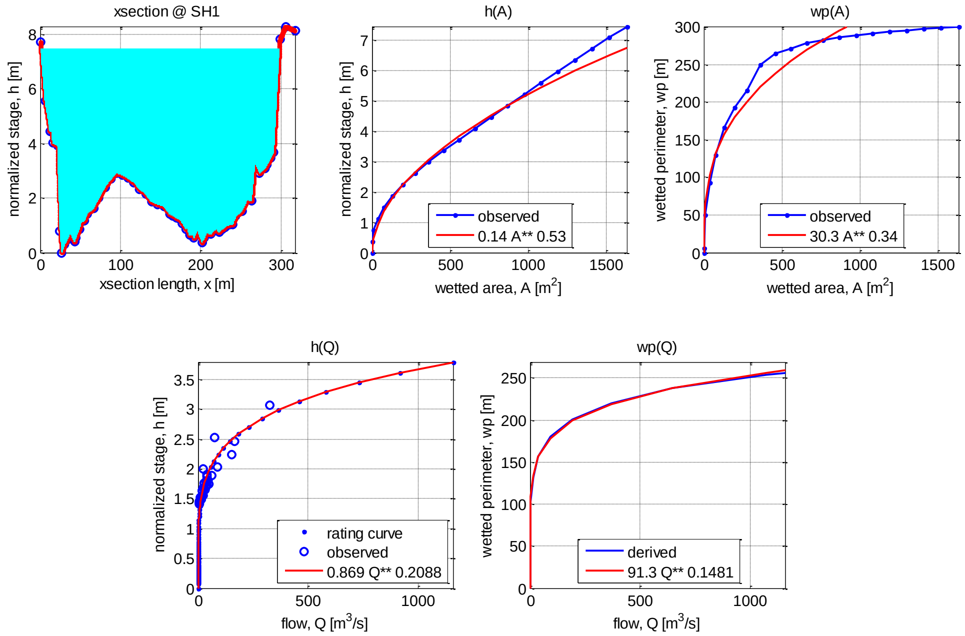

Figure 23 Relationships between stage (h), flow (Q), cross-sectional area (A), and wetted perimeter (wp) at the SH1 recorder site

GROUNDWATER OBSERVATIONS

HYDRAULIC REPONSE TO FLOW EVENTS

The responsive of groundwater to flow events in the river depends on the proximity of the monitoring bore to the river. Figure 24 shows the groundwater and flow hydrographs for the summer to autumn 2014 period, a period of quite stable hydrological conditions. The water levels at each site have been adjusted to allow the individual responses to be compared with each other. It can be seen that the recharge bore mimics river flow quite closely, and is very responsive. Small flow events (e.g. 20 m^3/s flow increases) are recoded in the recharge bore, but are not registered by Conders bore in particular. The reason for dissipation of the small flow events is probably that much of the increase in flow is incorporated into storage within the vicinity of the river.

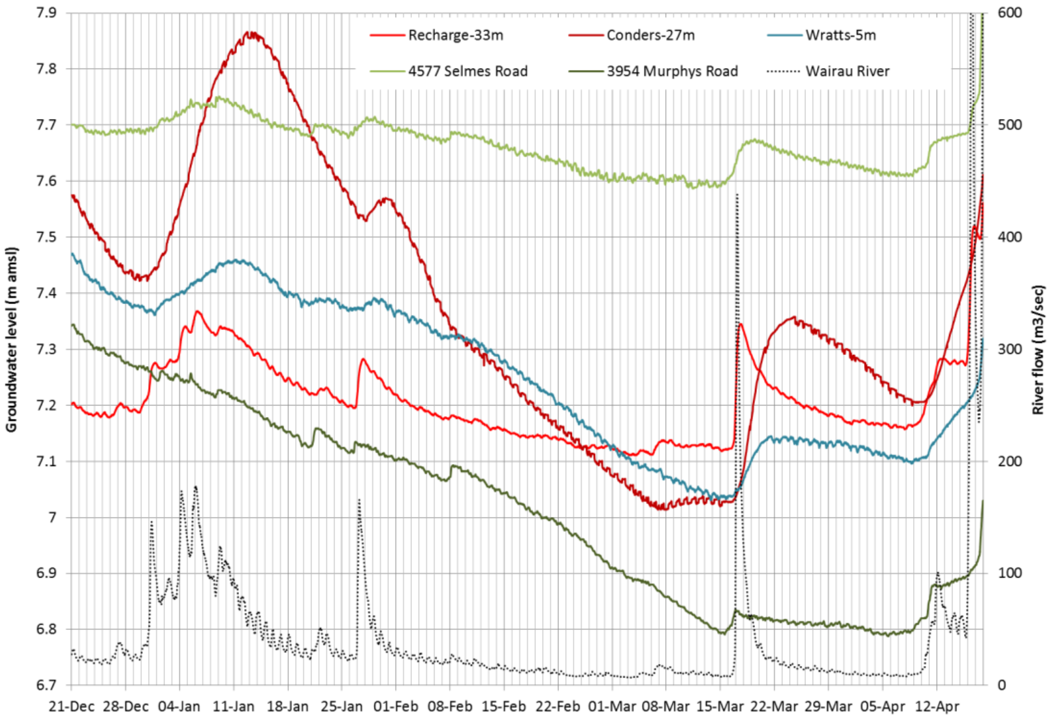

Figure 24 Groundwater and river flow hydrographs for the summer-autumn 2014 period

One of the useful aspects of the monitoring record shown in Figure 24 is the presence of a >400 m^3/s fresh in the river with clean recessions before and after the event. Figure 25 focuses on the aquifer response at each of the MDC monitoring sites to this flow event. The groundwater response to the flow event can be considered as composed of three characteristics, the magnitude of the response, the delay to the onset of the event, and the peak delay. The way that each site responds to these characteristics depends on the proximity of the river, the hydrogeological setting of the site (degree of confinement), and the local aquifer hydraulic properties.

The site with the fastest event response is the recharge bore because of its close proximity to the river. This is closely followed by a response in the Conders monitoring bore. The Selmes Road bore is very responsive, and shows a very rapid peak, and also exhibits fluctuations from the Trustpower scheme. The reason is that this bore is situated in a confined environment which results in a low storativity value.

Perhaps the most interesting response is seen at the Conders bore, which shows the largest groundwater rise, but has a much delayed peak. To some extent the sluggish response will be caused by its confined-leaky geological setting. The rise in groundwater levels is imparted by the overlying unconfined gravels, which gives the long delay.

However, the main reasons for the delayed response and large magnitude of the rise will be caused by the bores central position within the Conders recharge area. Because the river runs at an acute angle to the main direction of groundwater flow, the Conders bore is subject to a large number of flow paths from the river. What we effectively see in the hydrograph is the interference effect caused by multiple flow paths reaching the Conders bore at different times.

One of the conclusions to be drawn from analysing the aquifer structure and the hydrological responses is that the monitoring bores represent quite localised groundwater conditions. Because the aquifer is traditionally considered to be unconfined, there is a tendency to think that a bore is representative of a particular area. However, we now know that due to aquifer stratification, the groundwater response is very much a function of anisotropy and screen depth, and can be even more complex when heterogeneity is considered.

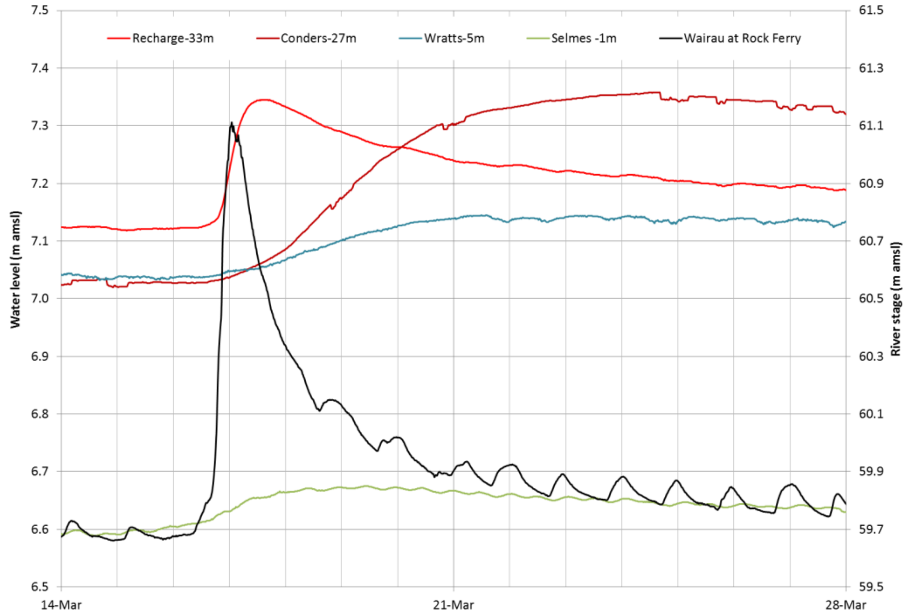

Figure 25 Response at groundwater monitoring sites to a flow event during stable conditions

RIPARIAN BOREHOLES

There are few boreholes that have been drilled in close proximity to the Wairau River. MDC drilled a network of Wairau Aquifer bores along the river stop-bank in early 1987. Several surveys were undertaken although the results were not written up. The surveys were undertaken during different seasons from 1987 to 1992, and the results are shown in (Table 4). The surveys show a groundwater fluctuation of 0.5 to 0.9m, with the greatest fluctuation seen at Conders Forest. Assuming that the river bed level has remained stable over time, the river is projected to be over 2m above the groundwater level at each site. The exception is at P28w/1699, which has a lowest observed head difference of 1.5m.

Table 4 Historical riparian monitoring bore records and adjacent river level from Lidar survey

Well	Location	E	N	24-Feb-87	7-Oct-87	2-May-88	16-Jul-91	15-May-92	Lidar river level
1692	Conders Bend	1665591	5406251	45.22	45.33	45.07	44.83	44.85	47.6
1696	Conders Forest	1667409	5407346	38.37	38.75	38.44	37.86	38.00	40.9
1697	SH6-Boyces Rd	1668491	5407700	33.10	33.53	33.33	32.84	33.04	35.9
1699	Ds Jeffries Rd	1671094	5408632	24.10	24.62	24.31	23.97	24.00	26.1

CONDERS RECHARGE BORE

The first discussions about the nature of the relationship between the Wairau river and aquifer resulted from the drilling of the “recharge bore” 10485. This bore was drilled 43m from the river at Conders Bend and was drilled specifically to monitor the effect of river flows on the Wairau Aquifer. The bore log shows that water-bearing gravels, which are here interpreted to be productive gravels, are not encountered until 10.1m depth. Clean gravels are also encountered at a shallow depth (at a similar elevation to the active channel deposits), but these are not shown as being productive in the bore log.

The monitoring record for the recharge bore indicates that the level of the river is always at least 3.3m higher than the groundwater level. The surveyed cross section at this location indicates that the groundwater level remains at least 1.8m below the lowest point in the river bed throughout the year.

The large difference between the river level and adjacent groundwater level produces an uncharacteristically steep hydraulic gradient adjacent to the river. Two possible conceptual interpretations may be considered for this steep gradient, either that the aquifer is hydraulically connected to the river, and its effect on groundwater levels is restricted to the immediate vicinity of the river, or that the river is hydraulically perched above the river. These two scenarios are shown schematically for the Conders recharge bore in Figure 26.

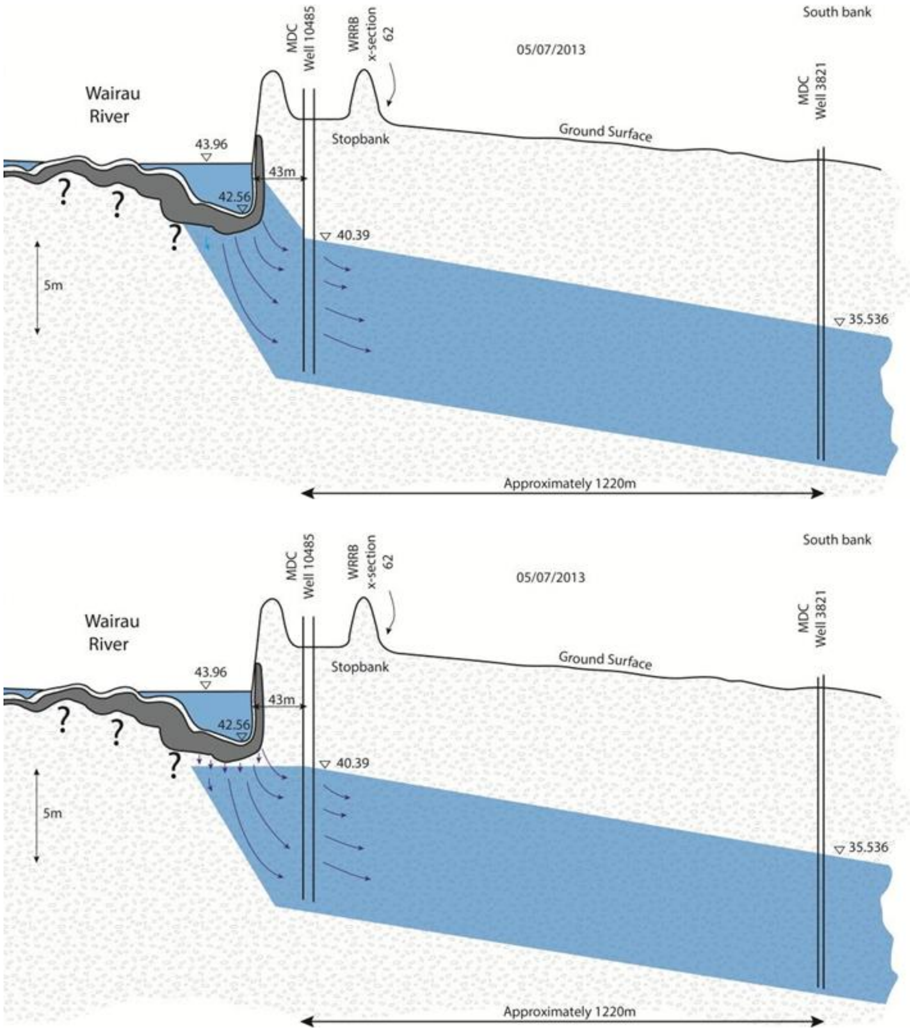

Figure 26 Schematic representation of hydraulically connected (above) and disconnected (below) scenarios at the Conders recharge bore

PAULS ROAD

There are very few existing boreholes that have been drilled close to the river. One noteworthy bore is P28w/3950 at the end of Pauls Road. This bore is located 70m from the river at the end of river survey cross section 54. Figure 27 shows the stratigraphic log for this bore, which shows the presence of two productive horizons separated by 7.9m of lower permeability sediments. What is most interesting about this bore log is the large difference in static water levels recorded by the two productive horizons.

Depth To Strata Top (m)	Bottom (m)	Strata Thickness (m)	Static Level (m)	2579509 – 5969854 Strata Description	Strata Picture
0.00	0.50	0.50		Black topsoil	
0.50	8.50	8.00	3.80	Brown coarse gravels, some yellow clay, water bearing	
8.50	16.40	7.90		Brown and grey cobble to medium sand, yellow clay bound	
16.40	18.60	2.20	5.60	Brown and grey coarse gravel, coarse sand, good water bearing	

Figure 27 Stratigraphic log for bore P28w/3950

The upper water-bearing gravels have a similar water level to the river level as measured from the Lidar image. It seems likely that this upper layer represents the active alluvial deposits associated with the river, and that the water level represents hyporheic flow associated directly with the river. The deeper gravels have a water level 2.3m below the top of the river, and this horizon most likely represents the unconfined Wairau Aquifer and its associated regional water table.

The significance of this bore log is that it provides the first direct evidence that there may be an unsaturated zone between the river and regional water table. The setting and lithological of the Pauls Road bore is very similar to that observed at the Conders recharge bore (10485), although the recharge bore does not record a near-surface saturated horizon.

The drilling of a nested piezometer in the Pauls Road area is planned for 2015. The piezometer will test whether the shallow two-layer system observed P28/3750 is laterally extensive adjacent to the river. The bore will be screened with the shallow and deeper horizons to study the dynamics of the two by aquifer testing and water level monitoring.

RIVER-AQUIFER RELATIONSHIP

1-D ASSESSMENT

Brunner *et al*. (2009) proposed that the status of the hydraulic connection could be assessed with a simple 1D model where disconnection occurs if:

$$\frac{K_c}{K_a} \leq \frac{h_c}{d + h_c}$$

Where K_c and h_c are the hydraulic conductivity and thickness of the river clogging layer (or sediments between the regional water table and river bed).The parameter K_a is the horizontal hydraulic conductivity of the aquifer, and d is the depth of the river. It is therefore appropriate to consider the 1D equation as a balance between river water depth and aquifer anisotropy. We can apply the 1D equation to the Conders recharge bore by inputting parameter values based on observations made in the aquifer (Table 5).

Table 5 Representative parameter values for assessing hydraulic connectivity

Parameter	Minimum	Maximum	Mean
River depth	1.5	4.4	2.3
Clogging thickness	1.7	2.4	2.2
K_c (K_v)	0.1	1	0.5
K_a (K_x)	20	2,800	600

The value of h_c to river depth is fairly consistent, and ranges from 0.3 to 0.6. The results of aquifer tests indicate that K_c/K_a aquifer anisotropy is the most likely control on the hydraulic connection because of the large observed variability in hydraulic conductivity, and because of the large difference between observed horizontal and vertical hydraulic conductivity values. For the aquifer hydraulic conductivities that have been returned from aquifer tests, the vertical hydraulic conductivity would need to be between 6 and 840 m/d, or a k_x/k_v ratio of 3:1 or less for a hydraulic connection to occur. The largest values of vertical hydraulic conductivity obtained from aquifer tests have been 0.5 m/d.

The vertical hydraulic conductivity of the river bed between Rock Ferry and Jeffries Road has been estimated by PDP (2001) as being 1 to 400 m/d, assuming a 100m channel width. This is certainly within the range of values required for a hydraulic connection to occur, although the hydraulic conductivity of the river bed was estimated to decrease downstream.

It is possible to apply a qualitative test to see whether the hydraulic gradient between the river and aquifer is vertical (or at least steep). To do this we can study the relationship between the wetted river of the perimeter and the head difference between the two, which has been plotted for the Conders recharge bore in Figure 28. We know from observations along the river that there is a power function relationship between river stage and wetted river perimeter. If there is a significant change in the hydraulic gradient we would expect to see considerable scatter around the trend line. The relationship between the head difference in Figure 28 is very good (r^2 0.92), which suggests that the hydraulic gradient is being maintained at a constant value, and is therefore most likely to be vertical.

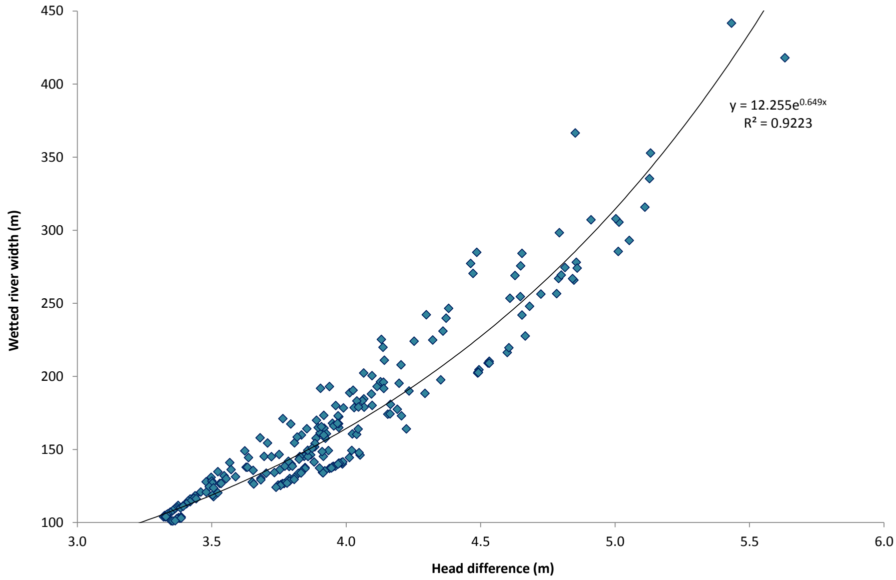

Figure 28 Relationship between wetted perimeter width and river-aquifer head difference at the recharge bore

OXYGEN ISOTOPES

Oxygen Isotope data can provide valuable insight into the source of recharge to groundwater. Figure 29 shows a composite of median ^{18}O values taken from Stewart (2008) and Taylor (2004). The ^{18}O data in Figure 29 has been colour coded according to the thresholds suggested by Stewart (2008). Sites coloured blue (values of -8.6 to -9.2) are representative of high altitude recharge that is typical of the Wairau River. The dark green coloured sites (values of -6.8 to -7.4) are representative of recharge from local rainfall. Sites coloured orange and light green indicate that the groundwater is a mixture of Wairau River and local rainfall recharge.

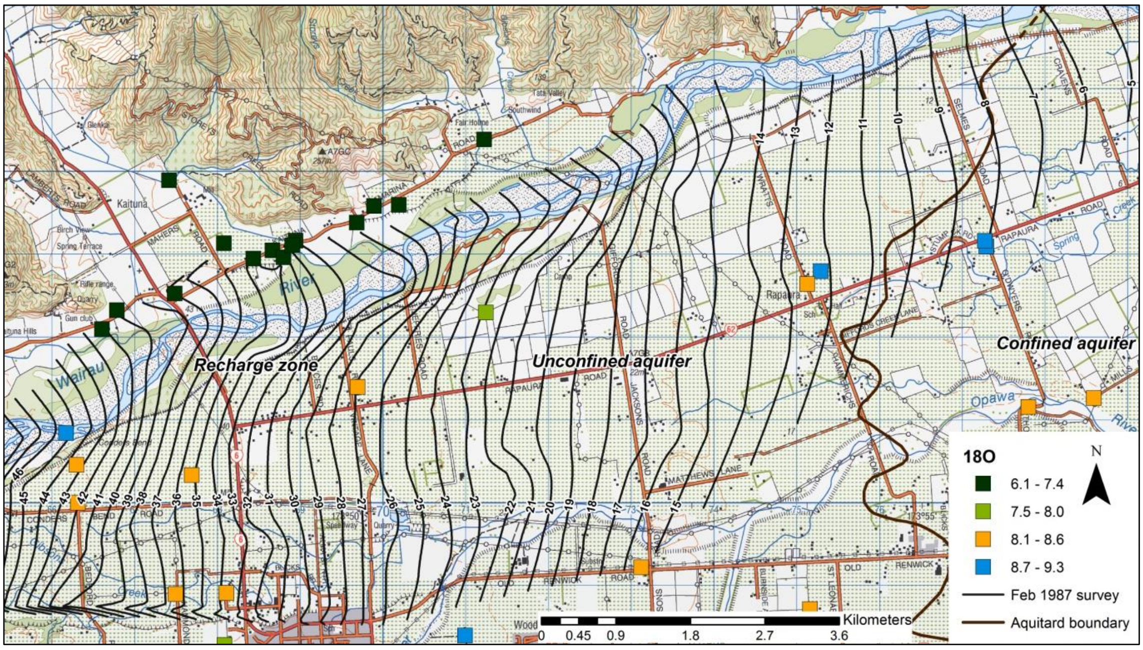

Figure 29 Map of median Oxygen-18 isotope values

The distribution of ^{18}O values on the Wairau Plain shows an interesting and unexpected pattern. Sites on the south bank of the river show a significant influence from local land surface recharge, even though they are close to the Wairau River. The river is known to contribute 95% or more of the recharge in the aquifer mass balance, so we would expect these bores to have ^{18}O values very similar to the river. For example, the Neal bore P28w/1685 shows an ^{18}O signature that suggests a particularly high local recharge component and yet it is very close to the river, and situated within the known river recharge reach.

A possible explanation for the presence of significant local recharge on the south bank is that the river is not acting as a groundwater flow divide because it is perched above the regional water table. This hypothesis is a departure from previous thinking, since the Wairau River has traditionally been considered to be hydraulically connected to the aquifer. While the ^{18}O data does suggest the possibility of north bank water flowing under the river, the evidence is not conclusive and requires further testing.

If there was a hydraulic connection between the aquifer and river, the river would tend to act as a hydrological boundary, and any drainage from the north bank would most likely be intercepted by the river. If the river is perched above the regional water table, it opens the possibility for groundwater from the north bank to pass beneath the river and mix with groundwater on the south bank. Under this scenario, the Wairau River would contribute recharge onto the water table by vertical drainage, but it would not act as a flow divide. Figure 30 schematically illustrates these hydraulically connected (left) and disconnected (right) scenarios.

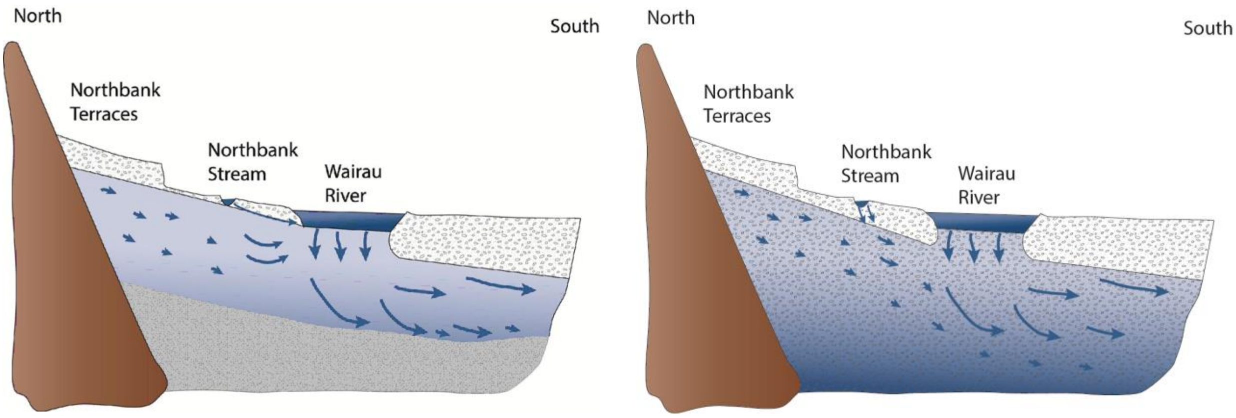

Figure 30 Schematic profiles across the SH6 area showing hydraulically connected and disconnected scenarios

Down-gradient of Wratts Road, the river recharge signature becomes more dominant at bores P28w/0208 and P28w/0222, and also in Spring Creek. In contrast to bores situated in the main river recharge area of the aquifer, these bores are located a long way from the river. If the river was hydraulically connected to the aquifer, we would expect these sites to have a greater local recharge component than those situated in the Conders area. It is most likely that the river is hydraulically connected to the aquifer along the flow paths that contribute to this part of the aquifer, and therefore acts as a flow divide and captures North Bank groundwater.

In summary, the spatial distribution of ^{18}O values suggests that the river is hydraulically disconnected from the regional water table upstream of Giffords Road, and hydraulically connected somewhere between Giffords and Wratts roads. This supports the indirect evidence provided in other sections of this report that the Wairau River is perched above the aquifer in the main recharge reach from Rock Ferry to Giffords Road. There is a possibility that North Bank water may flow beneath the river into the Wairau Aquifer, although to confirm this requires further investigation.

TEMPERATURE RECORDS

Temperature loggers were installed at eleven groundwater sites in the Wairau Aquifer in August 2014. The preliminary results of this monitoring are shown graphically in Figure 31. Long term temperature monitoring of the river shows a cyclic pattern with temperatures ranging from around 6°C in June-July to about 21°C in January, which closely follows the air and shallow earth temperature. Accordingly, high flow events result in a temporary drop in water temperature.

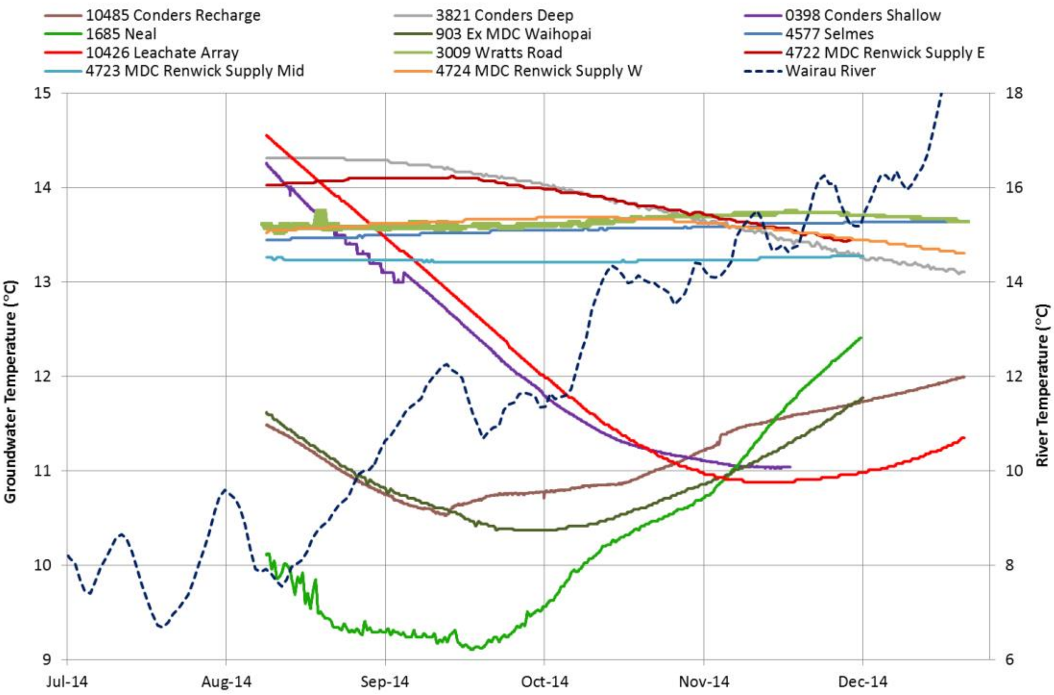

Figure 31 Groundwater and Wairau River temperature monitoring records

Figure 31 shows that the temperature response varies quite markedly within the aquifer. In general, four characteristic responses can be seen which range from rapid (~2 months), to seasonal (~4 months), to sluggish (>5 months), to weak or unresponsive sites. The more responsive sites show temperature rise events during more prolonged flow recession events in the river. The details for each site and their response are listed in Table 6.

Table 6 Temperature monitoring sites and their characteristic responses

Well	Depth (mbgl)	SWL (mbgl)	Screen top (mbgl)	Saturated depth (m)	Distance to river (m)	Temp range (°C)	Response
1685	10	5.9	10	14.2	1,000	3.3	Rapid
0903	7	3.35	7	3.7	650	1.4	Rapid
10485	17	7.3	10.6	3.3	40	1.2	Rapid
10426	14	5.6	14	12.2	2,500	3.7	Seasonal
0398	10	6.2	10	3.8	1,500	3.2	Seasonal
3821	21	6.7	20.2	13.5	1,500	1.0	Sluggish
4722	15	4.95	21.4	16.5	2,600	0.67	Sluggish
4724	20	6.5	21.1	14.6	2,600	0.24	Weak
4577	14	1.65	14	12.4	4,500	0.19	Weak
3009	6	2.0	5	3.0	3,800	0.16	Weak
4723	30	5.7	28	22.3	2,600	0.07	Weak

The response at each site depends on both the distance from the river, and the screen depth (or depth of saturation). The range in temperature observed at each site is a function of the seepage velocity compared to the volume of media that the incoming groundwater is flowing through. Sites that show a large range in temperatures are therefore expected to have a greater seepage velocity, particularly if they are located at some distance from the river. The groundwater site that shows the largest range in temperatures is the Neal bore (P28w/1685), which suggests that the aquifer transmissivity may be greater in this area (assuming a uniform effective porosity in the aquifer).

The time lags shown at each site are a function of the seepage velocity of the aquifer. Sites that show a rapid response to river temperature are located within a kilometre of the river and their temperatures follow the annual river temperature cycle with a short time lag of approximately two months. Two of the sites, P28w/1685 and 10485, also show a response to individual rapid warming events with a time lag of approximately one month.

Sites that show a seasonal response show a large but delayed seasonal fluctuation in water temperature, and do not show a response to individual warming events. These two sites, P28w/0398 and 10426, are screened in the shallow productive gravels and are located within 2,500 m of the river.

Sites with a sluggish and attenuated seasonal response are greater than 1,500 m from the river and are screened into the deeper, leaky-confined part of the aquifer. Sites that are located more than 2,500 m from the river tend to show a weak response to seasonal changes in temperature regardless of the depth of the bore screen. This is a significant observation because it suggests that the temperature fluctuations observed at sites closer to the river are primarily caused by recharge temperatures rather than changes in shallow earth temperature.

The temperature response observed in the aquifer appears to be a function of both depth and distance from the river. Close to the river, the depth does not appear to influence the temperature greatly. The responsiveness seen at P28w/1685, which is a relatively deep bore, suggests that deep recharge is occurring adjacent to the river. Further away from the river, we see a greater response in more shallow bores than deeper ones. For example, the paired Conders monitoring bores P28w/0398 and P28w/3821 show quite different responses, reflecting their respective unconfined and leaky-confined settings. The implication is that the transmissivity of the aquifer is considerably greater at shallow depths than in the deeper sediments. This supports the hypothesis that the aquifer permeability is highly anisotropic, and suggests that most of the flow is occurring close to the water table.

NUMERICAL GROUNDWATER FLOW MODEL

A steady state Modflow model focusing on the recharge area of the Wairau Aquifer was developed at the University of Tübingen in Germany. The model was developed using the ModelMuse graphical user interface and calibrated using a Matlab© -based multi-objective global parameter optimisation method. The period represented by the steady state model was summer to autumn conditions in 2014, since this is the period for which sufficient data was available to fully quantify the boundary conditions.

The objectives of the model were to:

- Better understand the hydraulic relationship between the river and aquifer
- Calibrate the hydraulic parameter field of the aquifer in the recharge zone
- Prepare for modelling transient conditions

This section gives a brief summary of the model setup and outlines the insights gained during the steady state model calibration.

MODEL SETUP

MODEL STRUCTURE AND EXTENT

The main elements and extent of the model domain are shown on Figure 32. The model was constructed to account for the whole recharge reach of the river, and extends from Rock Ferry in the West to the MDC monitoring wells within the confined aquifer at Selmes Road (P28w/4577), and Mills and Ford Road (P28w/4404). The model grid is aligned West-East. To accommodate the southern extent of the model, a no-flow boundary was assumed along Gibsons Creek, which is located just north of the contact between the Rapaura gravels and Speargrass Formation over the western part of the Wairau Plain. A no-flow boundary is also assumed to the west of Rock Ferry, and also along the North bank hills. At the eastern boundary, groundwater is allowed to discharge through the confined Wairau Aquifer.

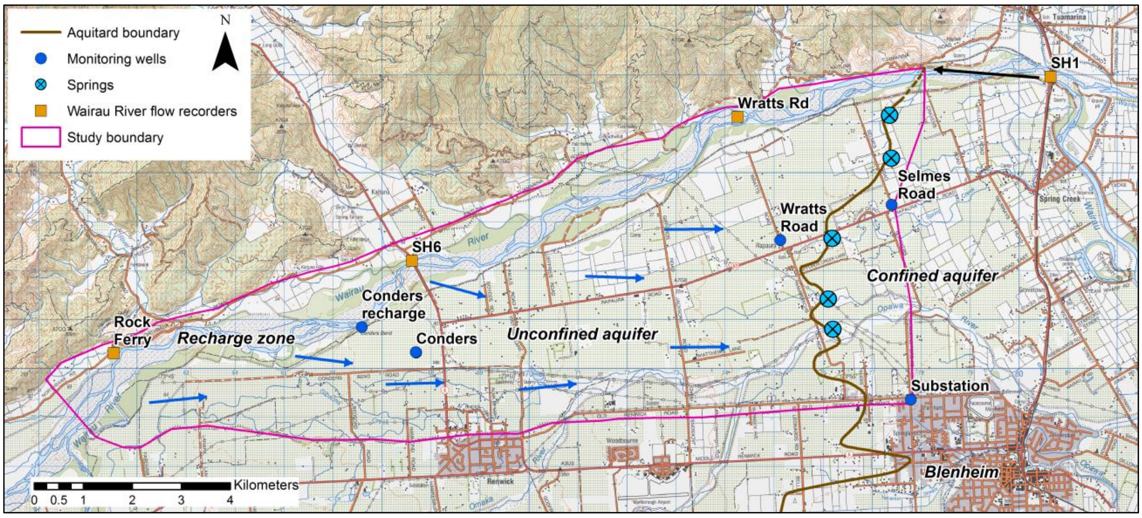

Figure 32 Map showing the main elements for setting up the Modflow model

Data for the land surface elevation was taken from the Lidar survey, which was interpolated onto the regular grid used in the model. The base of the aquifer was taken from the contours of the top of the Speargrass Formation as generated by Brown (1981), and represents a lower no-flow boundary.

Flow within the Wairau Aquifer is simulated in the Modflow model by a 170 x 70 cell rectangular finite difference grid with a 100 m^2 cell size. The aquifer was separated into twenty computational layers which were generated by non-uniform horizontal interpolation between the upper and lower bounding elevations, allowing for finer grid resolution at the land surface. This setup was chosen to get a higher grid resolution in areas of likely water-level fluctuations in the top layers, while the bottom layers are always saturated, allowing for a lower resolution towards the base of the aquifer.

BOUNDARY CONDITIONS

The model is constrained by five flow boundary conditions: land surface recharge, pumping demand, river exchange fluxes, drains (springs), and down-gradient discharge through the confined aquifer in the Spring Creek-Grovetown area.

Land surface recharge and pumping demand

Land surface recharge and irrigation demand were calculated using a modified version of the Rushton model (Rushton *et al*. 2006). A daily soil moisture balance was calculated for different combinations of soil hydraulic properties on the Wairau Plain. The results of this daily model were averaged over the Summer-Autumn period for input to the steady state numerical model.

There was very little land surface recharge during the Summer-Autumn 2014 period covered by the steady state numerical model. Irrigation demand during this period was calculated by applying 2.2mm of water when the soil moisture store for each recharge zone reached a nominal value of 70% of the TAW. The demand record was also averaged over the Summer-Autumn 2014 period to provide input values for the steady state numerical model.

River Exchange Fluxes

From the selection of Modflow packages for river simulation, the Stream-Flow Routing package (SFR2 package) was chosen to represent the Wairau River in the model. The SFR package routs the water flow through a series of continuous cells, while interaction with the groundwater (loss or gain of water) affects the flow for each cell. The SFR package also allows for unsaturated flow to occur beneath the river bed.

Power functions are used in the SFR package to relate both river head and width to flow at the 22 surveyed river cross sections that lie within the model domain. These were input to the model as 22 river segments, each with a bed thickness, bed elevation (at segment start and end), bed hydraulic conductivity and w(Q) and h(Q) power functions that were fitted to the data as explained above. The first segment at Rock Ferry also needed information about the inflow into the river, which was an average flow of 32.2 m^3/s during the steady state modelling period.

Since river loss estimates were available from consecutive flow gaugings at the four gauging sites during the low-flow period used for the steady-state model, these were implemented into the model calibration as flux targets which also helped to constrain river bed conductance values at the various stream segments.

Springs

Spring flow was modelled using the Drain package. Since the model grid with its 100 x 100m resolution was too coarse to reproduce the indentation of the springs in the real topology into the model topology, the model surface along the drain cells was deemed too high to lay the drains on top of it. Since altering the model geometry was not easy and this inaccuracy had no further negative effect on the model, it was instead chosen to simulate the spring elevation by assigning the drain cells to the deeper fourth layer which represented better the true elevation of the spring channels.

Drain bed conductance values for five spring channels considered in the model were set as parameters to be optimised during the calibration process. For Spring Creek, flows were measured and an average discharge of 3.2 m^3/s was used as a flux target in the calibration.

Confined aquifer discharge

The down-gradient discharge boundary of the aquifer was set as a constant flux boundary in the model. An appropriate flux rate of 500 l/s was set by estimating the rate of leakage through the aquitard east of the model domain. The estimates were derived by multiplying the head difference between the confined aquifer and shallow water table by a representative vertical hydraulic conductivity for the aquitard. A value of 0.005 m/d was used, as based on the results of aquifer test analyses from bores in confined aquifer located east of SH1.

For any point in the coastal area the rate of vertical leakage rate is estimated to be about 20-25 m^3/d (0.23-0.29 l/s). This leakage rate can be used to estimate the total aquifer discharge across the eastern margin of the model domain. The area down-gradient of the model domain to the coastline is approximately 16 km^2, which gives a total discharge flux of approximately 54,000 m^3/d, or 625 l/s. This value compares well with the 500 l/s estimate of discharge derived from total spring flow discharges in the Lower Wairau.

OBSERVATIONS

Head observations were used in the model to constrain the shape of the water table and to calibrate the uncertain model parameters. Head targets were set for groundwater levels at the MDC monitoring bores located within the model domain. The sites used were Conders recharge (10485), Conders (P28w/3821), Wratts Road (P28w/3009), Selmes Road (P28w/4577), and Mills and Ford Road (P28w/4404). Other observations used for model calibration were the flow at spring creek and the river-groundwater exchange fluxes derived from the differential flow gaugings described above.

PROPERTIES

Wairau River bed conductance

Conductance values for the river bed have been estimated from aquifer tests as being in the range between 150 m^2/d and 1,500 m^2/d. This is equivalent to bed hydraulic conductivities of > 50 m/d. Since these values are highly uncertain and strongly dependent on the assumptions made in aquifer test analysis, bed conductance values were given wide bounds during model calibration.

Hydraulic conductivity

Little is known of the 3D hydraulic conductivity structure of the aquifer. A 2D-horizontal conductivity field was assumed and hydraulic conductivity values at spatial regularisation locations ("pilot points") were estimated by calibration. Data from aquifer tests was used to derive suitable starting values, and to constrain pilot point values at locations where test data exist.

The hydraulic conductivity of the aquitard in the springs belt was assumed to be isotropic. Optimal values of 5-10 m/d were determined by the model calibration process.

MODEL CALIBRATION

The hydraulic conductivity field of the Rapaura formation, the ratio of horizontal to vertical conductivity, the river bed conductance, and drain conductance values were uncertain parameters to be calibrated. Objective functions used for model calibration were based on fits to groundwater head data, spring creek flow, two river exchange flux values for the river sections between Rock Ferry, SH6, and Wratts Road, and two regularisation functions to ensure smoothness of the hydraulic conductivity field and the river bed conductivity sequence.

The parameter calibration was carried out using the Matlab©-based multiobjective global parameter optimisation method AMALGAM. The calibration was carried out in two phases, an initial run using a linear field of aquifer hydraulic conductivity values, and a second run using hydraulic conductivity fields constrained by pilot points. For both approaches, vertical hydraulic conductivity values in the aquifer were represented by a single optimised K_{xy}/K_z ratio. The ratio was assumed to be unity within the aquitard.

As the name suggests, the linear method generates a hydraulic conductivity field of linearly increasing values from west to east. Field observations and preliminary modelling results suggested that this hydraulic conductivity distribution might be plausible.

The second method of parameterisation for the steady-state model calibration assumes a medium-scale heterogeneous conductivity field. To generate a hydraulic conductivity field according to this assumption, spatial variability in the hydraulic conductivity has to be resolved in the parameters. A common approach to this problem is to use pilot points, whereby a number of points are spread over the model area, each representing a single parameter. The hydraulic conductivity field is generated from these points by interpolation.

Model tests runs using different setups suggested that a total number of forty pilot points were sufficient to introduce heterogeneity into the conductivity field without a strong drawback of over-parameterisation. The pilot points were distributed evenly across the model domain, and were supplemented by points at aquifer test locations and several auxiliary points along the edges.

MODEL INSIGHTS

The steady-state model with pilot point parameterisation could be well calibrated to fit the available groundwater level and stream flux targets. The trade-off between the fits to the different calibration objectives was rather small. The best-fit "compromise" solution resulted in data fits that are well within the measurement uncertainty ranges. The model allowed the analysis of the river-groundwater exchange fluxes and their spatial distribution along the length of the Wairau River. The model realisation of simulated river exchange fluxes along the Wairau River providing the best-fit "compromise solution" parameter set is shown in Figure 33.

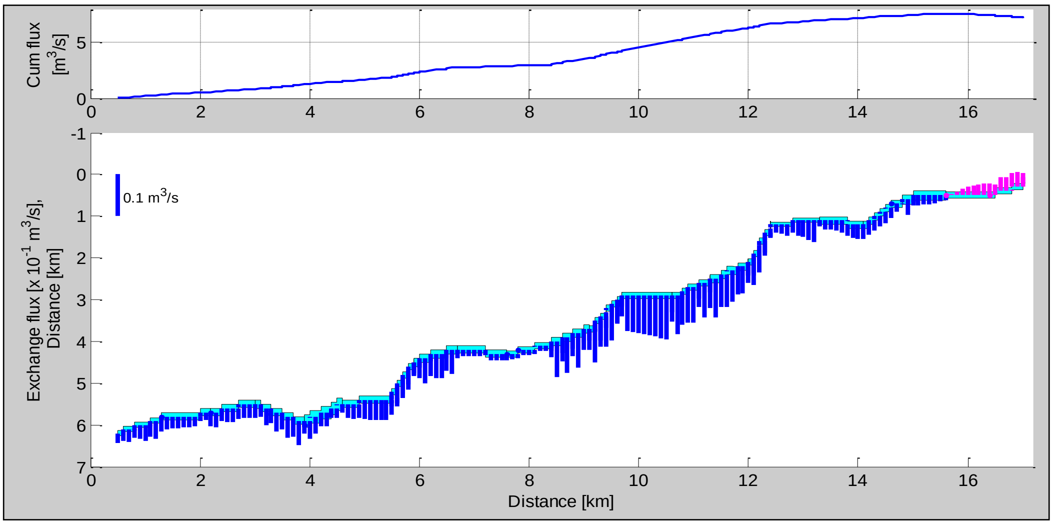

Figure 33 Simulated river exchange fluxes along the Wairau River as estimated with the best-fit parameter set

Model calibration is a way to integrate available data in a best-fitting way that is constrained by fundamental (flow) laws. The simulations with the calibrated model suggest perched conditions of the Wairau in the upper recharge domain of the aquifer which is in agreement with observations from field data. The direction of flow from the river to the aquifer is reversed in the lower, eastern part of the river, where groundwater is connected with the river and is flowing back into it (Figure 33). The return flow consistently occurs close to the boundary to the confining sediments where, further to the South, springs emerge at the Plains. The hydraulic conductivity field is variable and exhibits large conductivity values exceeding 1,000 m/d, particularly in the eastern margins of the unconfined aquifer, which is in agreement with earlier qualitative assessment of higher transmissivity values in this area.

The stochastic calibration exercise allows also for a rough estimation of parameter uncertainty which was generally small. Given the calibration setup, there was little variability in the conductivity fields which suggests that the model does not suffer a lot from non-uniqueness which is often an issue in over-parameterised models. Elevated variability of conductivity values was only observed at the western part of the model domain and the eastern corners. This has to be expected, since the model was constrained by fewer observations in these regions.

Using the linear conductivity field for aquifer property parameterisation performs quite well in terms of fitness to the calibration data. However, this approach does lead to an implausible spatial distribution of the river exchange fluxes. This justifies the need for explicit spatial parameterisation of the hydraulic conductivity field.

A sensitivity analysis for the best-fit parameter set showed that parameter sensitivities were generally lower for heads than for surface water exchange fluxes. Also, the aquifer hydraulic conductivity field and river geometry coefficients were the most sensitive parameters with respect to the river losses and spring creek flows. This finding accords with our hypothesis that recharge rates can be calculated from river geometry if the shallow aquifer hydraulic conductivity vectors can be constrained.

FUTURE WORK

The collaboration between MDC, WESS/University and Lincoln Agritech will continue into 2015 with transient calibration of the transient Modflow model. The next phase of the model is intended to improve optimisation of near-surface horizontal and vertical hydraulic conductivity values so that transient recharge rates can be predicted. One of the key areas of study will be to develop flow rating curves for all of the Wairau River sites, and to derive empirical relationships between them to account for the change in time lags with flow. This will enable us to get a more accurate assessment of how losses from the river change with flow.

In addition, MDC have outlined a field program, which will focus on gathering more information about the aquifer structure, including the possibility that north bank groundwater may flow to the south bank, and also the nature of saturation and recharge in close proximity to the river. Figure 34 shows the intended surface water-groundwater exploratory network, consisting of existing bores (green), permanent monitoring sites (pink), temporary piezometers (red), and surface water survey sites (blue).

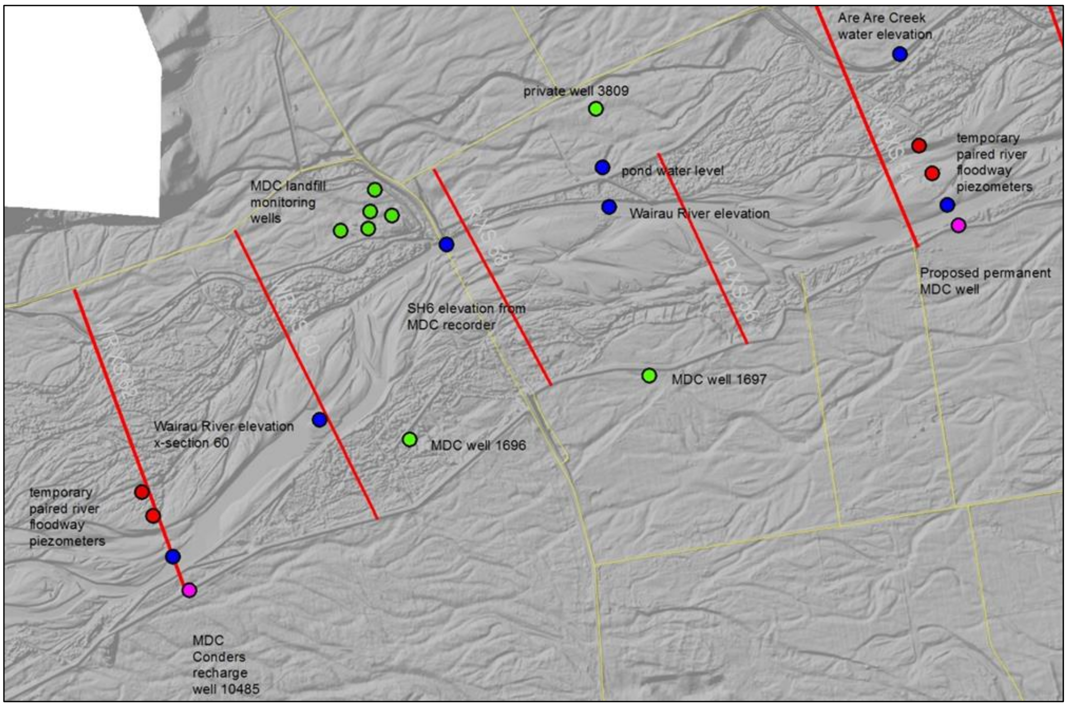

Figure 34 Proposed MDC test sites and Wairau River/groundwater elevation survey arrays

The intention of the expanded network is to more intensively study the key recharge reach of the river in order to improve our understanding of the recharge process. The temporary and surface water monitoring sites have been chosen to coincide with survey cross sections where we have records of river be morphology.

A key component of the field program is the drilling of a new nested piezometer at the end of Pauls Road (shown in pink on Figure 34). The testing and monitoring of this bore will improve our knowledge of the structure and recharge dynamics of the aquifer immediately adjacent to the river. This bore, together with temporary bores installed in the river bed will hopefully resolve the issue of whether an unsaturated zone exists between the river and the underlying regional water table.

Other potential studies that are likely to be carried out to complement our program are:

- Detailed analysis of geological model in the recharge area to improve understanding of structure (GNS)
- Analysis of groundwater and river temperature records to calculate aquifer seepage rates (ESR/GNS)
- Geophysical surveys in river bed to map out the shallow water table (Victoria University)

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Appendix 1: Historical Flow gauging data

Gauging Site	Easting	Northing	Date	Distance (km)	Flow (m^3/s)	Flow change ($m^3/s/km$)
Rock Ferry	2572360	5968030	2-Feb-78	2.3	21.802	
Giffords Rd	2581900	5971300	2-Feb-78	12.2	13.852	-807
Selmes Rd	2586530	5973300	2-Feb-78	17.2	13.552	-59
SH1	2590540	5973740	2-Feb-78	21.1	14.100	141
Rock Ferry	2572360	5968030	14-Mar-78	2.3	12.858	
SH6	2577820	5969400	14-Mar-78	7.7	8.966	-727
Giffords Rd	2581900	5971300	14-Mar-78	12.2	5.320	-810
Selmes Rd	2586530	5973300	14-Mar-78	17.2	4.509	-161
SH1	2590635	5973631	14-Mar-78	21.1	4.910	102
Narrows	2567922	5965399	9-Feb-82	3.0	25.963	
Giffords Rd	2582559	5971742	9-Feb-82	12.9	17.806	-822
Selmes Rd	2586575	5973342	9-Feb-82	17.3	20.194	553
SH1	2590635	5973631	9-Feb-82	21.1	18.813	-357
Rock Ferry	2573775	5968649	2-May-88	3.8	24.360	
Conders Forest	2577046	5969064	2-May-88	6.8	20.435	-1,289
SH6	2577702	5969738	2-May-88	7.7	18.220	-2,518
Jeffries Rd	2580243	5970333	2-May-88	10.3	18.144	-30
Giffords Rd	2582559	5971742	2-May-88	12.9	15.310	-1,054
SH1	2590635	5973631	2-May-88	21.1	16.443	138
Waihopai Confluence	2570802	5966327	18-Jul-91	0.0	19.682	
Rock Ferry	2573775	5968649	18-Jul-91	3.8	19.818	36
Conders Forest	2577046	5969064	18-Jul-91	6.8	18.707	-365
SH6	2577702	5969738	18-Jul-91	7.7	17.475	-1,401
Jeffries Rd	2580243	5970333	18-Jul-91	10.3	16.800	-264
Giffords Rd	2582559	5971742	18-Jul-91	12.9	14.922	-699
Wratts Rd	2583461	5972095	18-Jul-91	13.9	13.826	-1,133
Selmes Rd	2586575	5973342	18-Jul-91	17.3	13.055	-230
SH1	2590635	5973631	18-Jul-91	21.1	14.944	488
Waihopai Confluence	2570802	5966327	14-May-92	0.0	16.756	
Rock Ferry	2573775	5968649	14-May-92	3.8	17.382	166
Conders Forest	2577046	5969064	14-May-92	6.8	14.542	-933
Boyces Rd	2579032	5969873	14-May-92	9.0	13.109	-668
Jeffries Rd	2580243	5970333	14-May-92	10.3	12.036	-829
Giffords Rd	2582559	5971742	14-May-92	12.9	10.846	-443
Wratts Rd	2583461	5972095	14-May-92	13.9	10.731	-119
Cravens Rd	2588244	5973651	14-May-92	18.9	11.197	93
SH1	2590635	5973631	14-May-92	21.1	11.657	207
Rock Ferry	2573775	5968549	16-Feb-01	3.7	17.637	
SH6	2577702	5969738	16-Feb-01	7.7	13.066	-1,147
Wratts Road	2583461	5972095	16-Feb-01	13.9	9.182	-625
SH1	2590635	5973631	16-Feb-01	21.1	9.544	50
Waihopai Confluence	2570802	5966327	19-Feb-09	0.0	22.186	
SH6	2577702	5969738	19-Feb-09	7.7	18.027	-540
Wratts Road	2583461	5972095	19-Feb-09	13.9	13.683	-699
Selmes Rd	2586575	5973342	19-Feb-09	17.3	13.479	-61
SH1	2590635	5973631	19-Feb-09	21.1	18.258	1,234