Modelling of Temperature in Wairau Aquifer

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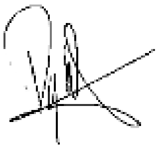

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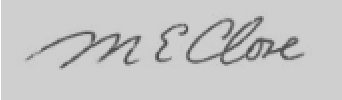

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DISCLAIMER

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EXECUTIVE SUMMARY

Groundwater temperature logging has been carried out on 14 wells in the recharge zone of the Wairau Aquifer during 2014 and 2015, with three additional monitoring points added to the network from January to April 2016. The Marlborough District Council (MDC) requested ESR to carry out analysis of these temperature data using analytical techniques, as well as preliminary numerical modelling which can provide greater spatial detail of hydraulic property variation, to provide insight into river recharge processes.

The wells were located at distances ranging from 20 to 5000 m from the river, with sinusoidal temperature responses ranging in amplitude from 0.19 to 15.1 °C. The temperature range of the Wairau River over the study period was 15.8 °C. The lags in the timing of temperature maximum and minimum values compared to the Wairau River ranges from 1 day for a well located 20 m from the river to 327 days for a well located 5 km from the river. The analytical approach involved plotting the variation of temperature range in each well against distance from the Wairau River using an exponential decay function, and also plotting the variation of lags in temperature peaks compared to the Wairau River using a linear equation. These plots identified outliers which, in this situation, can be interpreted as indicating wells with higher than, or lower than average recharge, thus providing a qualitative description of relative recharge. This analysis is based on curve-fitting and therefore both approaches identified outliers well in the middle areas of the plots where the fitted curves were defined by a larger number of data-points but were limited at the extremes of the plots where there were only one or two data-points.

Preliminary numerical modelling of heat transport was carried out using MT3DMS, in conjunction with the steady-state groundwater flow model of the Wairau Plains shallow aquifer developed by Lincoln Agritech (Wilson and Wohling 2015). Observed temperatures, in addition to flow and groundwater head data, were used as a basis for a partial model calibration (note that the calibration process was halted prematurely to meet reporting time frames). Simulated recharge rates from 12 river reaches were analysed.

On the basis of the preliminary numerical modelling, simulated temperature time series displayed a moderate correlation to observed temperature time series, with the simulated and observed variability in temperature generally showing better agreement (mean absolute error of 3.19 °C) compared to that of the simulated and observed temperature averages (mean absolute error of 3.88 °C). Credible parameter values for spatially distributed hydraulic conductivity (K) and porosity (θ) were obtained through model calibration process. On average, the river recharge rates per reach simulated on the basis of the calibration-constrained numerical model and the origninal Lincoln Agritech model were generally similar, although some significant absolute differences (e.g., >100%) were apparent. For example, for reaches 2, 3 and 11, the recharge rate resulting from the calibration of the heat transport model was 278%, 5500% and 266% larger than that resulting from the calibration of the flow model, respectively. Higher recharge rates (13.7% to 22.7% of the total recharge) occurred for reaches 1, 11 and 12, with much lower recharge rates (<1.8% of total recharge) occurring for reaches 2, 4, and 8.

For reaches that permitted comparisons, there was general agreement between inferred relative recharge rates from the analytical results and those derived from the numerical modelling. However, the relative nature of the recharge estimates from the analytical approach limits the possible comparisons and are at best, only qualitative. The key advantage of the analytical approach is its low cost and time requirements. The numerical modelling approach can provide more quantitative estimates of river recharge and the groundwater flow paths indicated by the model shows which river reaches contribute recharge in the vicinity of any particular well. However, the disadvantages of numerical modelling are the much higher time and computational resources required (e.g. this work was not able to run to completion during this current project that is discussed in this report). The analytical approach may provide a useful preliminary analysis, prior to a more complex numerical modelling approach depending on the importance of the management decisions and the value placed on the water resources.

1. INTRODUCTION

Many groundwater systems in New Zealand gain a large amount of recharge from rivers. This recharge provides storage of water within the groundwater system, sustains flows to groundwater-dependent streams, and is used for many purposes including domestic and stock water supply, irrigation and industrial use, with the major use by far being irrigation. There is significant uncertainty in the estimates of rate of recharge from rivers, particularly large braided systems, as precise river flow gauging can only be carried out under low flow conditions and measurement errors can be large. Regional councils in New Zealand have the responsibility to manage water resources and to allocate water. This is difficult when there is uncertainty in estimating both the quantity and variability of recharge. Water temperature provides a useful means by which to infer river - groundwater interactions and can potentially be applied to reduce the uncertainty of aquifer recharge estimates. The Wairau Aquifer is a very important water resource in the Marlborough region. Monitoring shows that in the past 30 years the groundwater levels in the aquifer have dropped by about a metre. This project focuses on the use of the natural variation in temperature to gain insights into the recharge processes for the Wairau River.

ESR has a large number of downhole temperature loggers that had been obtained and used for an intensive groundwater temperature tracing experiment at the Burnham experimental well array. These were made available to carry out temperature logging at a number of wells in the recharge zone of the Wairau Aquifer. Measurements were carried out during 2014 and 2015 on 14 wells. A further three wells that were recently drilled and/or added to the network were monitored for temperature from January to April 2016 to provide additional data. The Marlborough District Council (MDC) has requested ESR to carry out analysis of the temperature data using analytical, as well as preliminary numerical modelling approaches. A comparison of the two approaches was expected to provide further insight into recharge processes. This report provides the results and interpretation of using temperature as a natural tracer to study aquifer recharge from the Wairau River to the Wairau Aquifer system near Blenheim.

2. METHODOLOGY

2.1 HYDROGEOLOGY AND WELL SELECTION

The Wairau Aquifer underlies a land area of around 26,000 ha and is the predominant groundwater system underlying the Wairau Plains. It is a highly permeable sandy gravel aquifer (Rapaura formation) and supplies drinking water for Blenheim, Woodbourne and Renwick, as well as irrigation water for the extensive viticulture industry. The braided Wairau River provides significant recharge to the Wairau Aquifer in the vicinity of Conders Bend (Davidson and Wilson, 2011). River loss gaugings show that around 7 m^3/s are lost from the river between the Waihopai confluence and opposite Selmes Rd. Monitoring shows that in the past 30 years the groundwater levels in the aquifer have dropped by about a metre. There is a need to know the causes of this drop and any implications regarding future recharge amounts to the aquifer.

Wells within 6 km from the river were selected in the zone where the Wairau River is known to recharge the Wairau Aquifer system. A range of well depths were selected, sometimes at the same location to provide an indication of the differences in flow paths with depth. At well 3821 sensors were located at 2 different depths (12.7 and 19.0 m bgl) and at Pauls Rd two wells, 7007 and 10608, were drilled close to the river at different depths. A total of 17 wells were monitored although not all temperature records could be used for analysis because some wells were located too far from the river and the temperature signal was too weak (this does provide an effective limit for the temperature signal).

The Wairau River at the Barnetts bank site near SH1 has a long term record of temperature and this was used as the input signal for the recharge water. The well locations wells are shown in Figure 1 and details of the sampling sites and period of temperature monitoring are given in Appendix 1. Temperature measurements were recorded in the wells, usually at 15-minute intervals, using automatic water temperature loggers (HOBO Pro V2). Mean daily values were used to estimate temperature range and lags between the wells and the Wairau River. Mean monthly temperature was used as input observations for the numerical modelling.

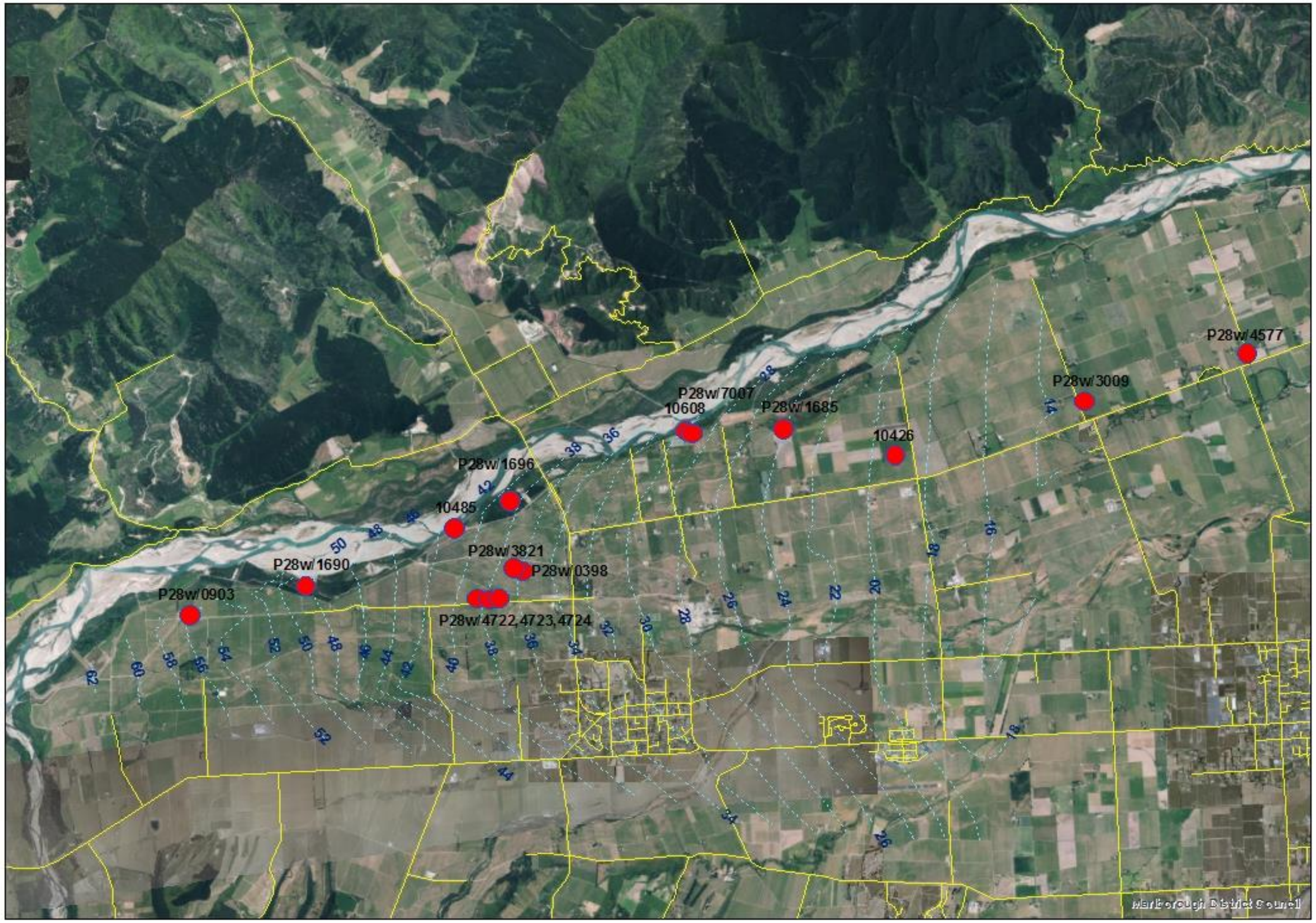

Figure 1: Location of wells monitored in the study together with piezometric groundwater levels.

It should be noted that there are some concerns about the Wairau River monitoring site at Barnetts Bank (Peter Davidson, pers. comm. May 2016). The concerns are whether the temperature sensor is located sufficiently in the main flow of the river and that there could be some effects at low flows. A possible difference with temporary temperature sensor at the Wairau River Rock Ferry site has been noted, with the Rock Ferry location showing slightly lower temperatures in winter. These differences are being investigated but, for the purposes of this study, the temperature record for the Wairau River at Barnetts Bank was taken as the input signal to the aquifer.

2.2 DATA ANALYSIS

High quality temperature records were obtained for 14 wells with an additional depth being measured for one well that resulted in 15 temperature records being available for analysis. Most data records were for about 12 months and displayed a sinusoidal pattern typical of a seasonal influence. The temperature records from the wells were grouped by the range in observed measurements and plotted both as a data quality control measure and guide for data analysis (Figures 2 to 6). The large downwards spike in well P28w/4723 temperature (Figure 5) was caused by the sinker falling off the temperature sensor due to corrosion of the wire. This caused the sensor to float on the top of the water table. This well was omitted from the data analysis due to the uncertainty in the temperature record from this well, plus the availability of data from an adjacent well about 150 m away. Well P28w/3009 was also omitted from the data analysis as the temperature record had only a small temperature variation (< 0.6 °C) with multiple peaks without a typical sinusoidal pattern (Figure 6). This suggests that the observed temperature variations were probably from a source other than the Wairau River. Although well P28w/4577 had a lower temperature range (0.2 °C), it had a sinusoidal pattern and fitted well with the relationships for range and lag, indicating the source of the variation was the Wairau River.

The distance of each well from the river edge (Table 1) was measured along the estimated groundwater flow direction as inferred from local piezometric gradients and topography. The width of the Wairau River ranges along the study reach from about 300 to 800 m and recharge from the river to the groundwater could originate from any location within the riverbed. For this analysis it was assumed that the recharge occurred at the river edge. The significant variability in the orientation of the Wairau River bed relative to the regional groundwater flow direction (Figure 1) introduces additional uncertainty in the distance estimates.

Table 1: Summary of temperature statistics from monitoring period

Site number	Distance from river (m)	Sensor depth (m bgl)	Temperature Range (°C)	Date of Max. Temp.	Date of Min. Temp.	Mean lag (days)
Wairau R @ Barnetts bank	0		15.77#	20/1/2014 3/2/2015 1/2/2016$	27/7/2014 29/7/2015	
P28w/0398	1700	9.7	5.63	21/5/2015	15/11/2014	109
P28w/0903	1300	6.6	6.15	15/4/2015	26/9/2014	66
P28w/1685	1000	9.3	9.45	29/3/2015	10/9/2014	50
P28w/1696	300	6.4/ 10.4*	11.33	17/2/2016	19/8/2015	19
P28w/3009	4000	3.9	-			
P28w/3821	1700	12.7	3.69	25/6/2015	24/12/2015	145
P28w/3821	1700	19.0	1.60	9/8/2015	8/2/2015	192
P28w/4577	5000	13.6	0.19	10/1/2015	21/5/2015	327
P28w/4722	2300	13.6	1.38	13/9/2014	19/3/2015	236
P28w/4723	2150	18.6	-			
P28w/4724	2000	12.6	0.96	7/10/2014	6/4/2015	257
P28w/7007	20	8.7	15.14	8/2/2016	15/7/2015	1@
10426	2500	8.7	5.89	20/5/2015	14/11/2014	108
10485	40	11.0	5.01	8/5/2015	12/9/2014	71
10608	20	15.2	8.53+	9/2/2016	-	2@

Note: * both periods of data used to estimates lags and range.

This is the range in mean daily temperatures for 1/10/2013 to 18/5/2016.

$ The times of the peaks are approximate (within ~7 days) due to daily fluctuations in the river temperature.

@ determined by lag analysis of daily data

+ value is an under-estimate because of short data record

The time of occurrence of the minimum and maximum temperatures in each well record were determined along with the temperature range. The temperature records for most of the wells were smooth and the timing of the minimum and maximum temperature values was easily determined. However the temperature records for the Wairau River and the Pauls Rd wells (P28w/7007 and 10608) showed considerable variability in mean daily and mean weekly temperature records. For these cases the timing of the minimum and maximum values was determined by fitting a 5th degree polynomial to the data. The uncertainty in the times for the minimum and maximum values was approximately 7 to 10 days for the Wairau River and Pauls Rd wells and approximately 3 to 5 days for the remainder of the wells.

An exponential decay curve with an intercept of 16, corresponding to the range in temperature for the Wairau River, was fitted to the temperature range data (see Figure 9).

Range (°C) = 16 exp(-kd)

where k = decay coefficient (fitted as 0.0009)

d = distance from Wairau River (m)

The mean lag (from a comparison of timing of both minimum and maximum temperature values) between the wells and the Wairau River was plotted against the distance and was fitted with a linear relationship with the intercept going through the origin.

Mean lag (days) = 0.074d

Wells that plot above the line in Figure 8 indicate that the range is higher than would be expected for that distance implying that the rate of recharge is higher in the vicinity of this particular well. The converse is true for wells that plot below the line. Similarly, wells that plot below the straight line in Figure 9 indicate that the lag is less than average for that distance and that the rate of recharge from the river is higher than average in the vicinity of this well.

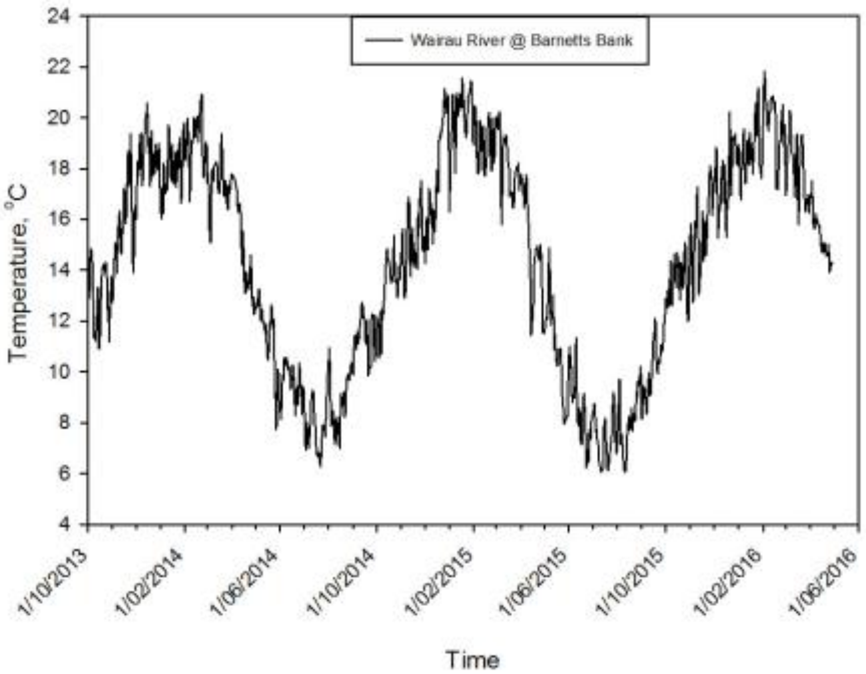

Figure 2: Mean daily temperature for Wairau River at Barnetts bank (near SH1) for the period October 2013 to April 2016.

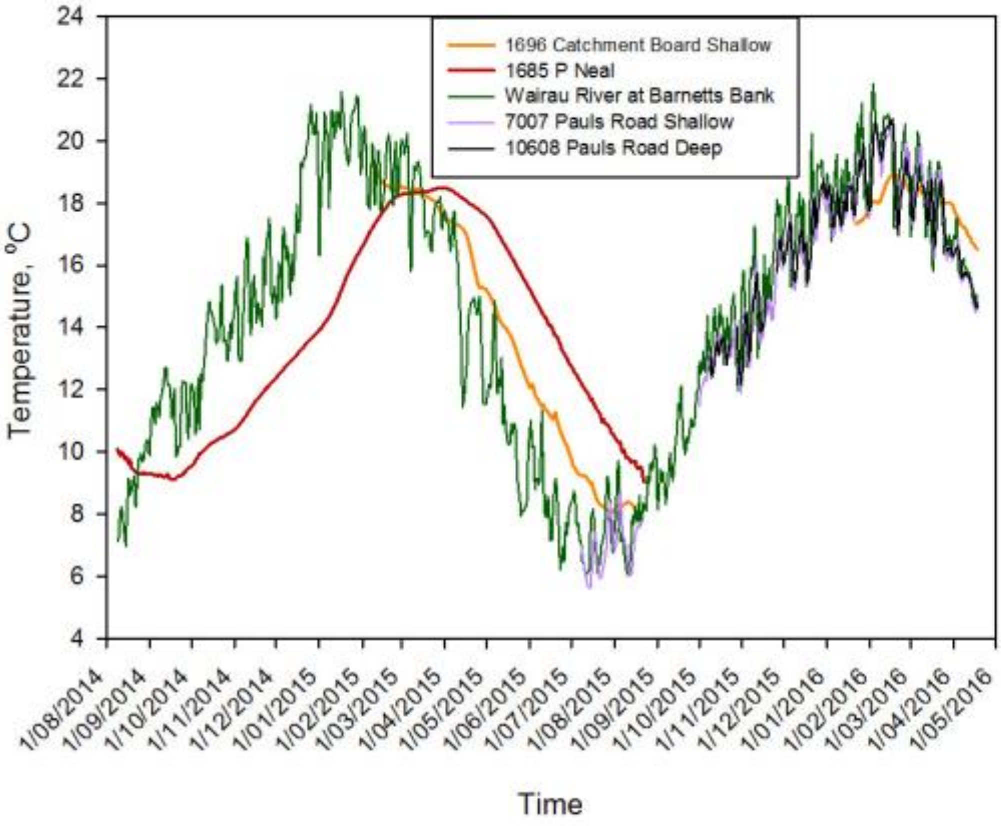

Figure 3: Mean daily temperature for sites with a temperature range between 9 and 16 °C.

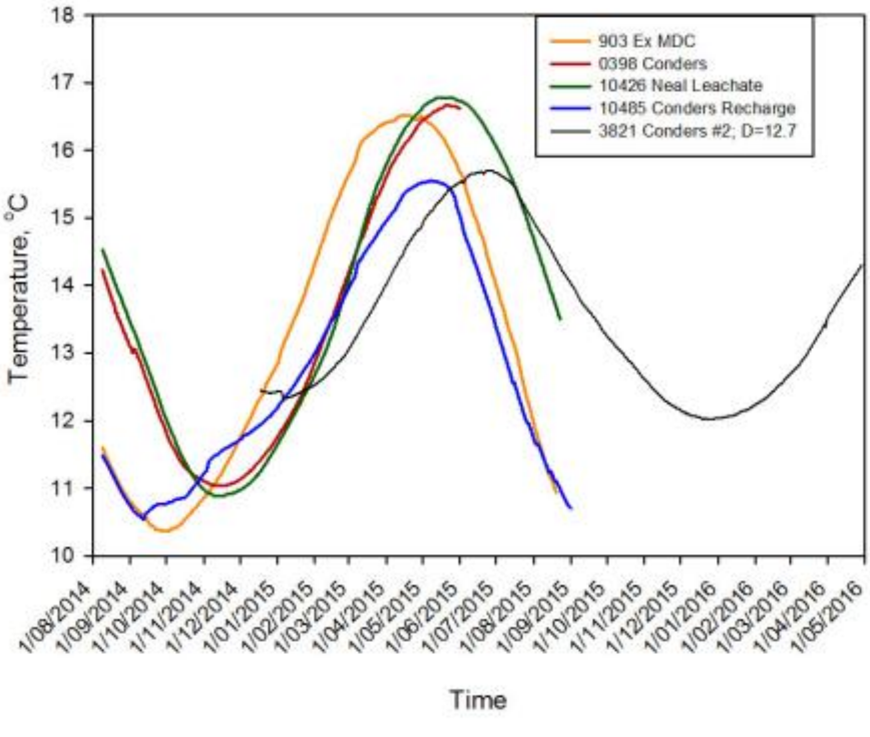

Figure 4: Mean daily temperature for sites with a temperature range between 3.5 and 6.5 °C.

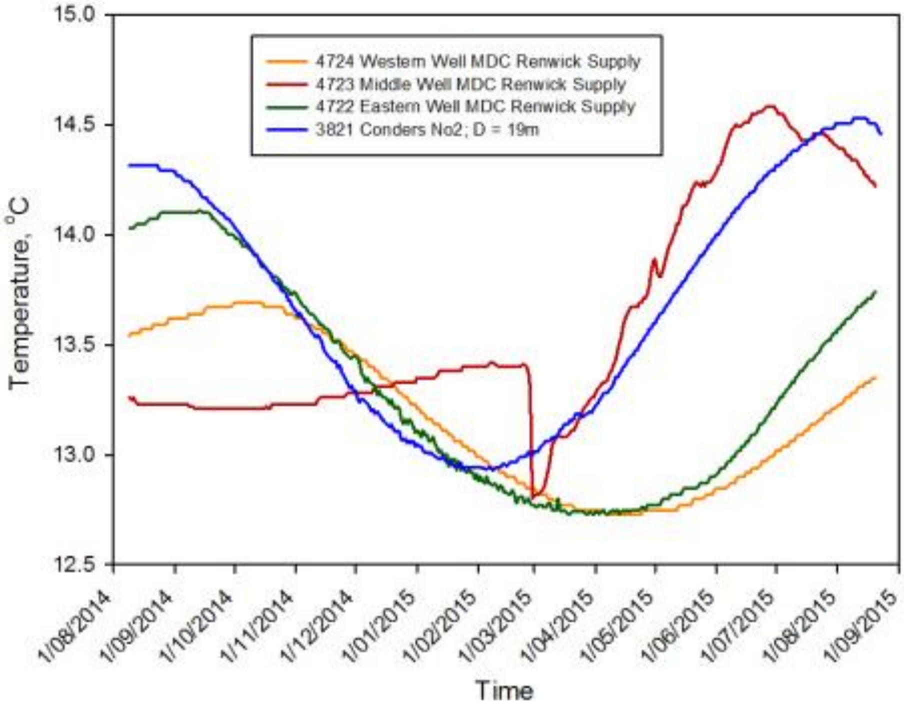

Figure 5: Mean daily temperature for sites with a temperature range between 0.9 and 1.8 °C.

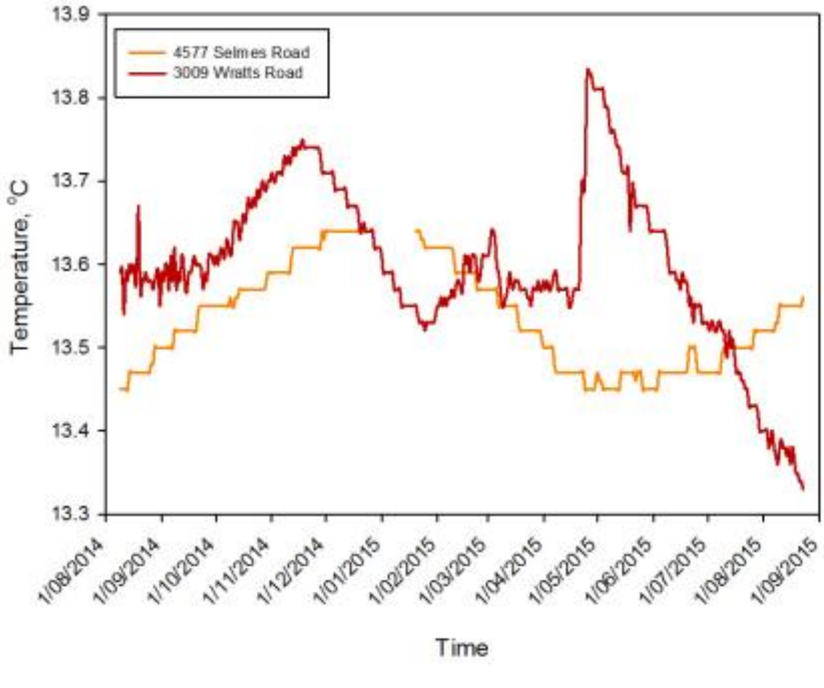

Figure 6: Mean daily temperature for sites with a temperature range less than 0.6 °C.

2.3 NUMERICAL MODELLING

The steady-state groundwater flow model of the Wairau Plains shallow aquifer developed by Lincoln Agritech (Wilson and Wöhling, 2015) was used as a basis for the numerical modelling undertaken in the current study. The model grid consists of 36 rows, 98 columns, with a uniform horizontal grid size of 200 m × 200 m, and 12 layers, as shown in Figure 7a. Model river reaches are also shown in Figure 7a. The reader is referred to Wilson and Wöhling (2015) for further details pertaining to the model. MODFLOW-NWT (Niswonger et al., 2011) was used to simulate groundwater flow under steady-state conditions. Simulation of thermal transport was achieved using MT3DMS (Zheng, 2010) according to Ma and Zheng (2010) by substituting: (1) temperatures for concentrations, (2) thermal distribution coefficients (which is related to water-sediment temperature exchange; K_d, Table 2) for solute distribution coefficients, and (3) bulk thermal diffusivities (D_m, Table 2) for molecular diffusion coefficients. Transport parameters adopted in the MT3DMS model are given in Table 2.

Given that MT3DMS is presently incompatible with the streamflow routing (SFR) package (Niswonger and Prudic, 2005), which is used in the original MODFLOW model, the use of the stream (STR) package (Prudic, 1989) was deemed to be a necessary modification to the original model. It follows that the Manning's equation (assuming a rectangular channel) was used for calculating stream water-level. The resulting flow model was (re-)calibrated on the basis of head and flow data to estimate hydraulic conductivity (K), stream conductance (C_{STR}) and vertical anisotropy (K_{xy}/K_z) using PEST (Doherty, 2016). K, C_{STR} and K_{xy}/K_z were parameterised using pilot points (a single K field was specified for all model layers), a single value per reach, and a single value, respectively, as per Wilson and Wöhling (2015). Figure 7b shows distributed K and C_{STR} values estimated through calibration of the flow model. The estimated K_{xy}/K_z value was 3.95.

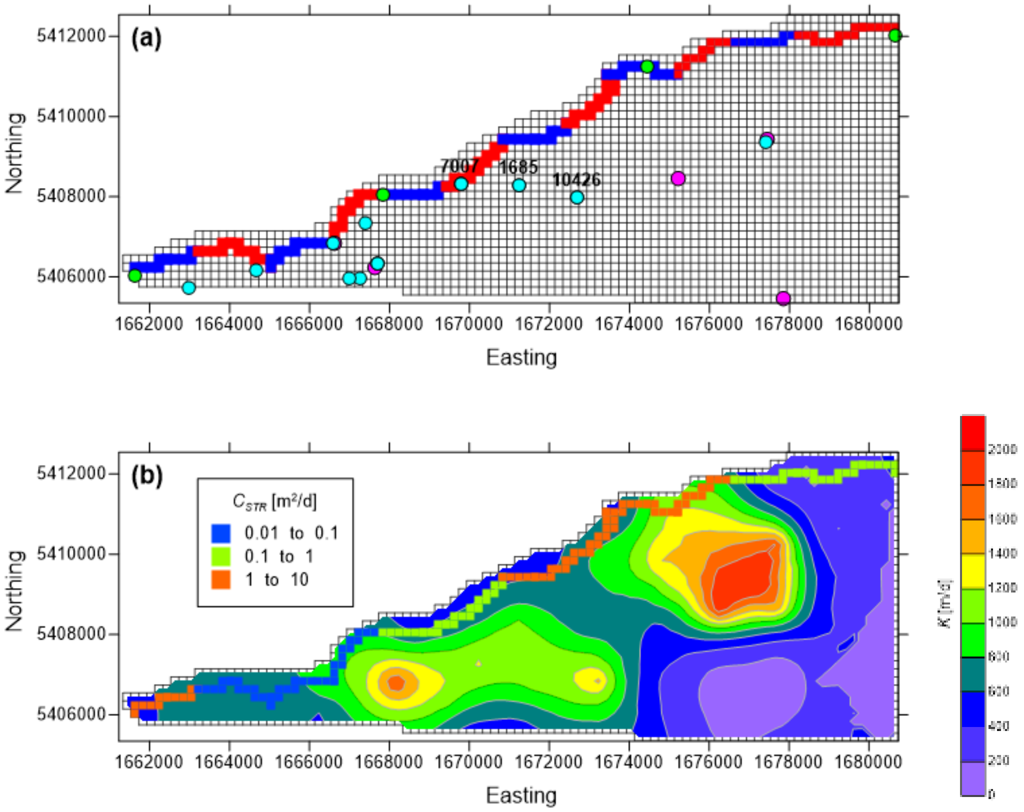

Figure 7: a) Model grid, river reaches (shown by alternating red-blue colours), and observation wells with groundwater-level data (purple circles), flow data (green circles), and temperature data (blue circles). (b) Spatially distributed hydraulic conductivity (K) and stream conductance (CSTR) values estimated through calibration.

Following calibration of the flow model, calibration of the flow-and-thermal transport model was also used to estimate K, C_{STR} and K_{xy}/K_z, as well as effective porosity (θ), bulk density (ρ_b) and the thermal distribution (or retardation) factor (K_d). The parameterisation of K (pilot points) and C_{STR} (single value per reach) was equivalent to that of the flow-model, except that K-pilot points were assigned to each model layer (i.e., K fields were allowed to vary between layers) and K_{xy}/K_z is parameterised on a layer-by-layer basis. Pilot points were also used to parameterise porosity as a spatially distributed property unique to each model layer, with spatial interpolation factors equivalent to those used for the spatial variability in K. The parameters governing the thermal conductance, i.e. bulk density ρ_b and the thermal distribution factor K_d were parameterised as a single value for each model layer; as the estimation of the spatial distribution of these parameters would have otherwise posed an impractical computational expense, for the current study.

Table 2: MT3DMS transport parameters.

* Represents initial (i.e., pre-calibration) value.

Parameter	Units	Value	Basis for value
Effective porosity θ	-	0.17*	Dann et al (2009)
Longitudinal dispersivity α_L	m	10	Schulze-Makuch (2005)
Horizontal transverse dispersivity α_T	m	1	Schulze-Makuch (2005)
Vertical transverse dispersivity α_{VT}	m	1	Schulze-Makuch (2005)
Thermal diffusivity D_m ($=\kappa_o/\theta\rho_w c_w$)	m^2/d	1.9891×10^{-1}*	Calculated
Bulk thermal conductivity κ_o ($=\theta\kappa_w+(1–\theta)\kappa_s$)	W/(m°K)	1.9246	Wagner et al (2014)
Solid thermal conductivity κ_s	W/(m°K)	2.2	Wagner et al (2014)
Fluid thermal conductivity κ_w	W/(m°K)	0.58	Wagner et al (2014)
Fluid density ρ_w	kg/m^3	1000	SI standard value
Heat capacity of fluid c_w	J/(kg°K)	4180	Hecht-Mendez et al. (2010)
Bulk density ρ_b	kg/m^3	1700*	Dann et al (2009)
Thermal distribution/retardation factor K_d ($=c_s/c_w\rho_w$)	J/(kg°K)	1.00×10^{-6}*	Calculated
Heat capacity of sediment c_s	J/(kg°K)	715	Ma et al. (2012)

3. RESULTS

3.1 ANALYTICAL MODELLING

The temperature record for the Wairau River showed significant fluctuations on a daily and weekly basis, reflecting the short-term variation in temperatures and flows (Figure 2). Most of the wells showed little short-term variation in temperature; instead these variations were dampened out and were dominated by the seasonal signal from the Wairau River. An exception is well P28w/7007, which is a shallow well located 20 m from the Wairau River. The temperature record in this well exhibits the same short-term variations that are seen in the Wairau River. Well 10608 (Pauls Rd deep), located at the same site but 6.5 m deeper, also showed the same short term variations in temperature. It should be noted that only a single summer maximum was able to be determined for this well as the reliable record only began in October 2015. The temperature range of 8.53 °C for this well is presumably under-estimated as the minimum temperature is likely to occur in late July or early August, given the similarity of the temperature variability in this well to the Wairau River and well P28w/7007 - Pauls Rd shallow well (Table 1). A subset of the temperature record from July 2015 to April 2016 for the Wairau River and wells P28w/7007 and 10608 is plotted in Figure 7 to better show the correlation between the wells and the Wairau River. There is a very high correlation (r=0.99) between the wells indicating very little influence of the depth difference of 6.5m. There is also a very strong correlation between the Wairau River and the Pauls Rd wells. Analysis of the lags (Table 3) that well P28w/7007 had a lag from the Wairau River record of 1 day whereas well 10608 had a lag of 2 days from the Wairau River. The additional information contained in the daily and weekly temperature for these records allows a more accurate estimation of the lags.

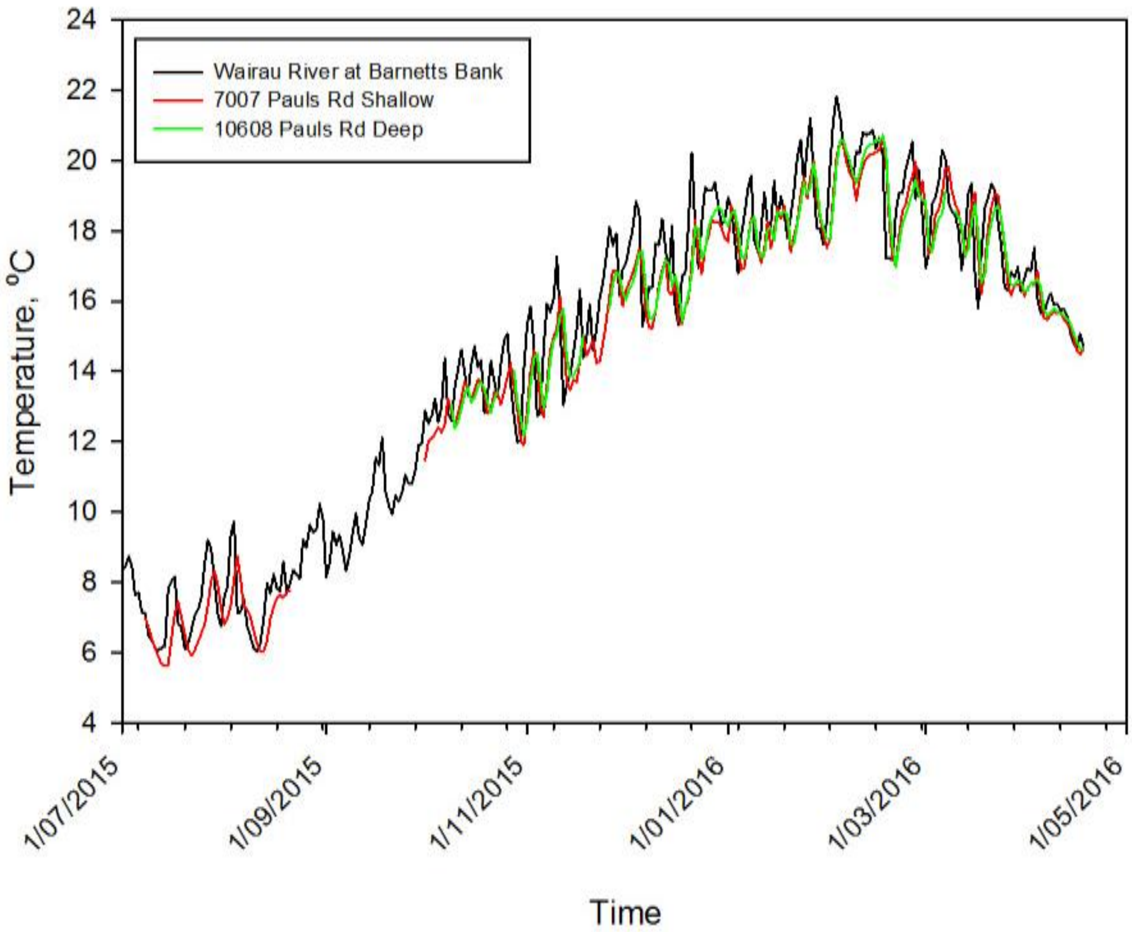

Figure 8 Mean daily temperature for the Wairau River @ Barnetts bank, well P28w/7007 and well 10608 for the period July 2015 to April 2016.

The timing of minimum and maximum temperatures, temperature range and lag from the Wairau River are summarised for each well in Table 1. The temperature ranges observed in the wells vary from 15.1 C°, which is nearly the same as that observed in the Wairau River, to 0.19 °C in well P28w/4577 located about 5 km from the Wairau River. It should be noted that even this low level of temperature variation is significant and clearly distinguishable from background (Figure 6). The depth below the water table had a variable effect on temperature response. There were 2 sets of wells with sensors located at depths differing by approximately 6.5 m (Table 1); well P28w/3821, which had sensors at 12.7 and 19 m bgl and the two Pauls Rd wells which had sensors located at 8.7 and 15.2 m bgl, for wells P28w/7007 and 10608, respectively. The two Pauls Rd wells showed very similar temperature responses (Figure 8) whereas well P28w/3821 showed very different responses for the 2 depths (Figures 4 & 5; Table 1).

Table 3: Correlation coefficients (r) for daily temperature data between Wairau River and Pauls Rd wells

Well	Lag - 0	Lag - 1 day	Lag - 2 days	Lag - 3 days
P28w/7007	0.976	0.994	0.988	0.972
10608	0.874	0.958	0.966	0.904

The variation of temperature range with distance from the Wairau River is shown in Figure 9. The exponential decay equation fits the data fairly well with r^2 = 0.74. It allows the identification of outliers, which in this situation are interpreted as representing wells with higher than, or lower than average recharge. Thus it provides a qualitative description of the pattern of recharge. The variation of lags in temperature peaks compared to the Wairau River is shown in Figure 10. The linear equation fits the data reasonably well with an r^2 = 0.75. Both Figures 9 and 10 identify outliers well in the middle range of distance from river. Near the origin even areas with very high recharge are limited to the maximum temperature range shown by the river and the minimum lag close to zero. The two Pauls Rd wells are examples of this as they have ranges similar to the river and lags of 1 to 2 days but it is not possible from this sort of analysis to determine whether their recharge is average or above average. Wells located at the large distance from the river may exert an undue influence on the plotted best-fit equation, which may represent that well as more "average" than is perhaps the case. Well P28w/4577 located 5 km from the Wairau River is an example of this situation. It plots on the fitted curve for the temperature range but is slightly below the line for the lags, indicating higher than average recharge. Because the well is located at the end of the regression line, it causes the regression line to plot closer to itself and thus the well probably experiences even higher recharge than indicated from the graph. The indications for relative recharge from this analysis are given in Table 4, with those wells very close or very far from the Wairau River noted in the table. The river reach where recharge is likely to originate for each of the wells is estimated based on the piezometric contours in Figure 1. For some wells, especially those at greater distances from the river, it was difficult to determine which reach the recharge was likely to originate from and a range of reaches is given in Table 4. There was generally good agreement between estimates based on temperature range compared to those based on temperature lags.

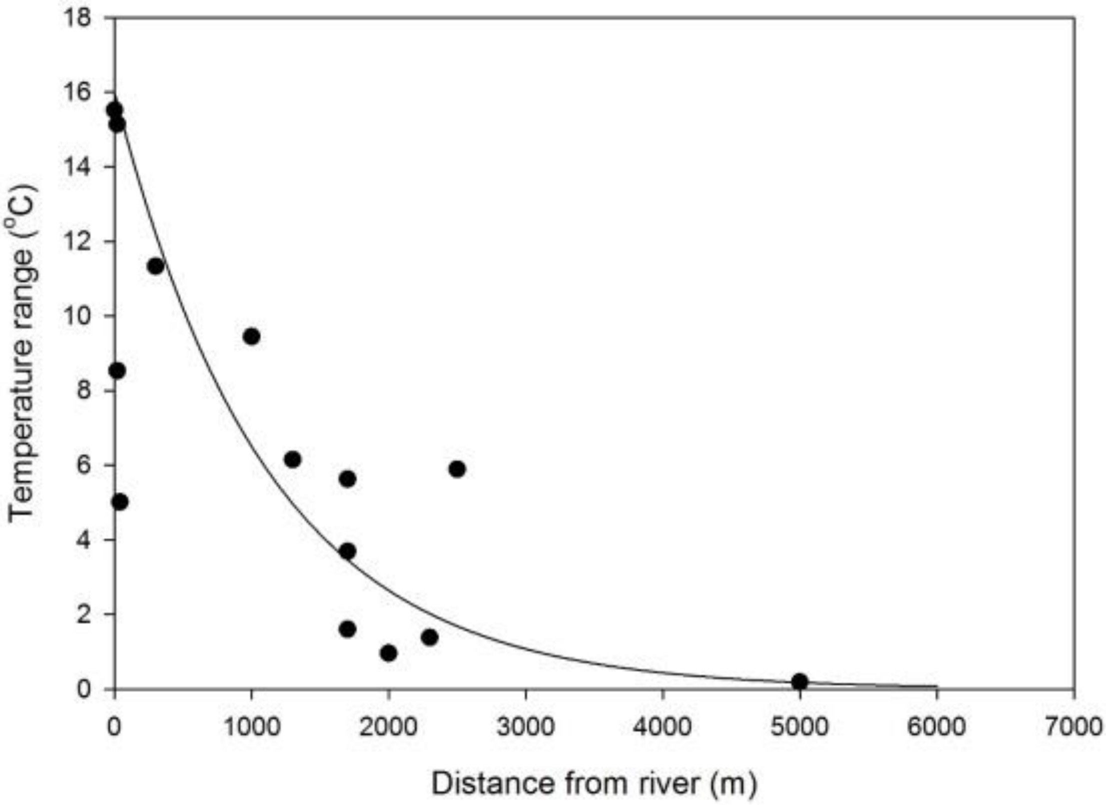

Figure 9: Variation of annual temperature range with distance from the river.

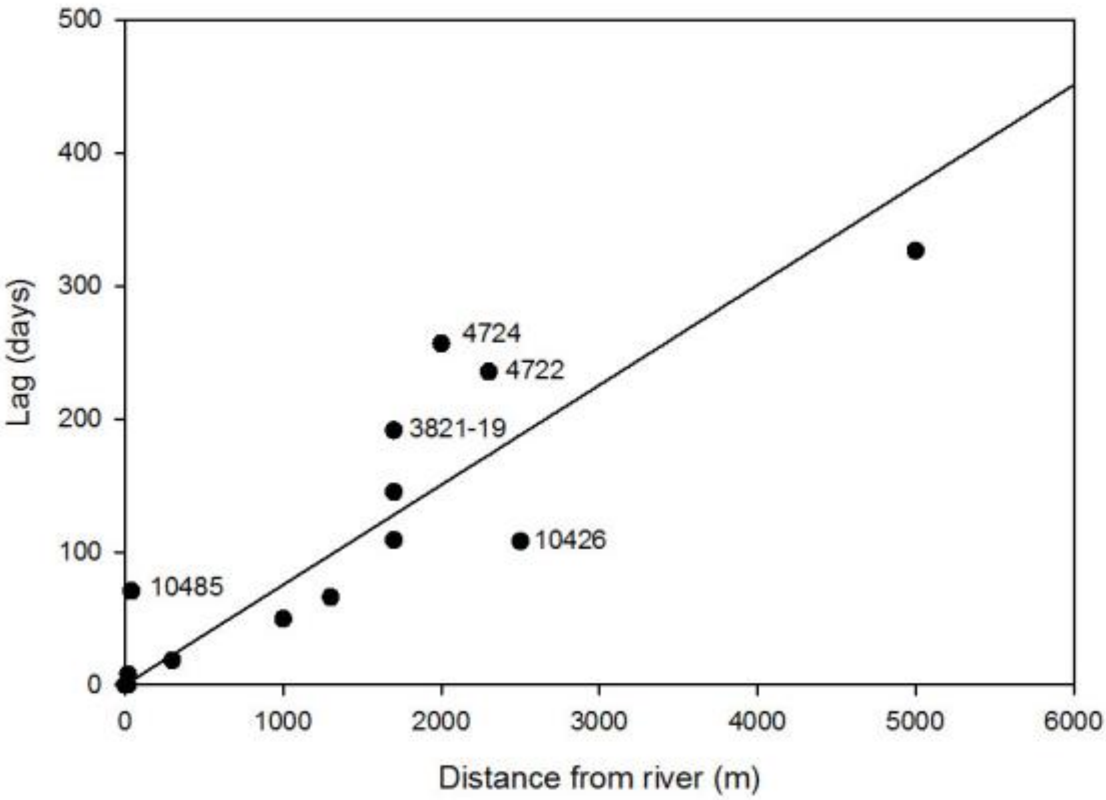

Figure 10: Variation of mean lag in temperature with distance from Wairau River.

Table 4: Summary of recharge indications from temperature range and lag analysis. The wells located near to the river (close) or at a long distance from the river (far) are noted in the recharge columns.

Note: ? indicates that there is uncertainty about the origin of recharge

Site number	Distance from river (m)	Recharge section	Recharge amount from lag	Recharge amount from range
P28w/0398	1700	3?	Mean	High
P28w/0903	1300	1	Mean to high	Mean to high
P28w/1685	1000	6	Mean to high	High
P28w/1696	300	4	Mean: close	Mean: close
P28w/3009	4000	6 to 7	NA	NA
P28w/3821-13	1700	3?	Mean	Mean
P28w/3821-19	1700	3?	Low	Low
P28w/4577	5000	5 to 8	Mean to high: far	Mean: far
P28w/4722	2300	2 to 3	Mean to low	Mean
P28w/4723	2150	2 to 3	NA	NA
P28w/4724	2000	2 to 3	Low	Mean to low
P28w/7007	20	6	Mean: close	Mean: close
10426	2500	5 to 6	High	High
10485	40	4	Low	Low
10608	20	6	Mean: close	NA

3.2 MT3DMS NUMERICAL MODELLING

Simulated temperature time series displayed a moderate correlation to observed temperature time series (mean error of -2.62 °C (negative value indicates model under-estimation), mean absolute error (MAE) of 3.18 °C, and normalised root-mean-squared-error of 29%, for the 14 wells). The simulated and observed variability in temperature (i.e., deviation from mean temperature) generally showed better agreement (e.g., MAE of 3.19 °C for all wells) compared to that of the simulated and observed temperature averages (e.g., MAE of 3.88 °C for all wells). Figure 11 shows simulated versus observed temperature for four wells of particular interest (P28w/7007, P28w/1685, P28w/3821 and 10426; locations given in Figure 7a). Of these wells, the best match (e.g., MAE of 2.02 °C) was obtained for P28w/1685, followed by P28w/7007 (e.g., MAE of 2.11 °C), P28w/3821 (e.g., MAE of 3.00 °C) and 10426 (e.g., MAE of 5.11 °C), which is located furthest from the river.

Spatially distributed hydraulic conductivity (K) and porosity (θ) values estimated through calibration (showing spatial averages of 721 m/d and 0.17 for all layers, respectively) were considered to be reasonable with respect to hydrogeological field data (Dann et al. 2008; 2009). This was expected due to the incorporation of expert knowledge pertaining to K and θ in the form of parameter bounds and the use of preferred homogeneity regularisation. The K and C_{STR} distributions obtained on the basis of the flow-and-heat transport model calibration displayed some similar features to those obtained on the basis of the flow model calibration (e.g., the presence of K values >1500 m/d near well 3821 and in the east of the domain; Figure 11b). Estimated K_z/K_{xy} values range between 0.85 (layer 2) and 0.036 (layer 10). These values are consistent with literature, i.e., K_z typically ranges between 0.01 and 1 times K_{xy} (e.g., Fetter, 2001). Estimated values of ρ_b and K_d range between 1269 and 2039 kg/m^3, and 6.803×10^{-7} to 1.234×10^{-6} J/(kg°K), between layers, respectively. These values are also considered reasonable with respect to literature values for sand/gravel aquifer settings (e.g., Ma et al., 2012). The calibration process was particularly sensitive to the ρ_b and K_d parameters which govern thermal conductance.

Table 5 lists simulated river recharge rates per reach arising from calibration of the flow model and the flow-and-thermal transport model, and the recharge rates are also shown graphically in Figure 12. On average, distributed river recharge rates simulated on the basis of these models were generally similar (transport model produces 13% higher recharge rates per reach on average). However, some significant absolute differences (e.g., >100%) are apparent. For example, at reaches 2, 3 and 11, the recharge rate resulting from the calibration of the transport model was 278%, 5500% and 266% larger than that resulting from the calibration of the flow model, respectively. Differences can be attributed to the role of the temperature data in constraining the model and its parameters beyond that was achievable with the flow model (constrained by groundwater-level and flow data only). Where no significant difference in recharge rates between the two models is obtained (e.g., differences of -9.6%, -17.3%, -20.7% and -15.8% for reaches 1, 7, 9 and 10, respectively), the temperature data does not provide unique insight into model parameters compared to that on the basis of groundwater-level and flow data. Relatively high recharge rates (13.7% to 22.7% of the total recharge) occurred for reaches 1, 11 and 12, with much lower recharge rates (<1.8% of total recharge) occurring for reaches 2, 4, and 8.

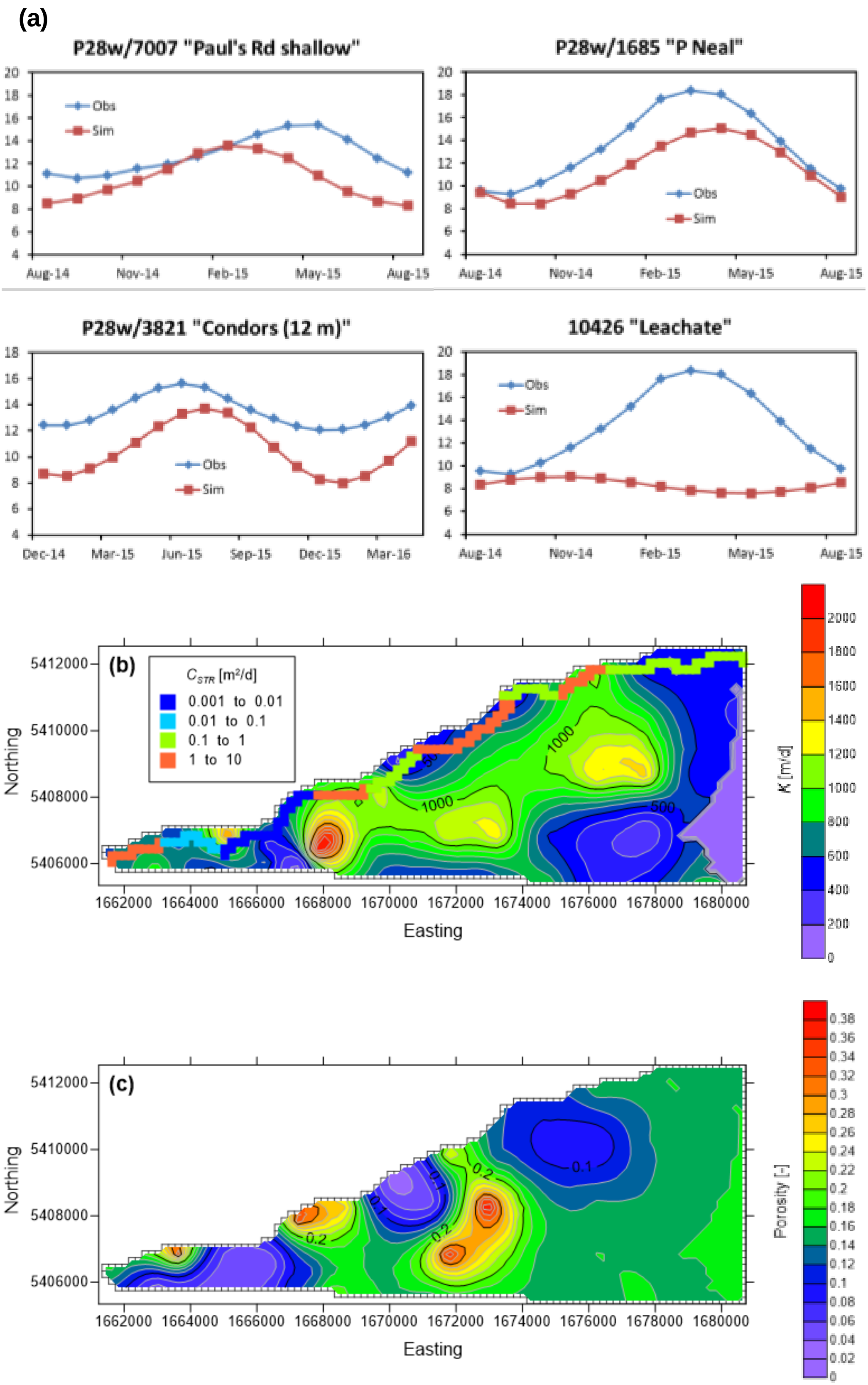

Figure 11: (a) Observed versus simulated temperature (°C) for wells P28w/7007, P28w/1685, P28w/3821, and 10426" (located 20, 1000, 1700, and 2500 m from river, respectively; Figure 1, Table 2), and spatially distributed (b) K for layer 11; ie., the layer in which P28w/7007 and P28w/3821 targets are specified, and CSTR, and (c) θ values for layer 11 estimated through calibration.

Table 5: River recharge rates (m3/d) for each reach from the flow model and the flow-and-heat transport model.

Notes: *See Figure 7a for river reach locations.
%Difference is (thermal − flow) divided by flow.

Reach*	Simulated river recharge (m^3/d) Flow model	Flow & heat transport model	% Difference	Reach % recharge (for heat model)
1	1.22×10^{5}	1.11×10^{5}	-9.58	22.7
2	4.31×10^{2}	1.63×10^{3}	278	0.33
3	5.21×10^{2}	2.92×10^{4}	5500	5.99
4	4.75×10^{3}	3.19×10^{3}	-32.9	0.65
5	4.14×10^{4}	2.96×10^{4}	-28.6	6.07
6	4.57×10^{4}	5.79×10^{4}	26.6	11.9
7	4.06×10^{4}	4.76×10^{4}	17.3	9.77
8	4.00×10^{4}	8.82×10^{3}	-78.0	1.81
9	4.02×10^{4}	3.19×10^{4}	-20.7	6.54
10	3.47×10^{4}	2.92×10^{4}	-15.8	6.00
11	1.82×10^{4}	6.67×10^{4}	266	13.7
12	3.63×10^{4}	7.09×10^{4}	95.2	14.6

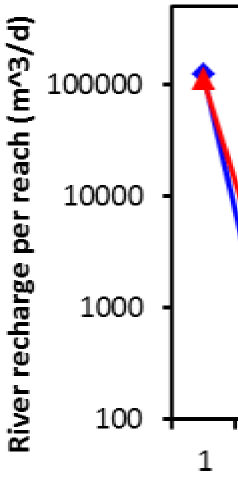

Figure 12: River recharge rates (m3/d) for each reach from (a) the flow model (blue line), and (b) the flow and heat transport model (red line).

3.3 COMPARISION BETWEEN ANALYTICAL AND NUMERICAL MODELLING RESULTS

There was general agreement between the relative indications of recharge from the analytical results (Table 4) compared to the numerical modelling (Table 5) for reaches that permitted comparisons. For example, wells P28w/4722 and P28w/4724 down-gradient of reach 2 (the lowest recharge rates from the numerical modelling) had low or mean to low relative recharge rates from the analytical approach. Well P28w/0903 down-gradient from reach 1 (the highest recharge rate from the numerical modelling) had mean to high recharge indicated from the analytical results.

The monitoring wells were located mainly down-gradient of reaches 1 to 6, with the exception being well P28w/4577 (Selmes Rd) which may have received recharge from reaches 5 through to 8 depending on the exact direction of the flow path. Hence there was no information from monitoring wells for reaches 9 to 12 and only one well that may relate to reaches 7 and 8.

4. DISCUSSION

Although there was general agreement between the outcomes of the analytical and preliminary numerical modelling approaches, the relative nature (higher or lower than an average value) of the river recharge estimates from the analytical approach limits the comparisons able to be made. The relative recharge estimates depend on a comparison to a best fit regression line and are thus dependent on, and limited to, the data collected and included in the analysis. This means that this sort of comparison is, at best, only qualitative. In addition the uncertainty of estimating the distance from the river and from which reach a particular well is likely to receive recharge needs to be considered in such a comparison. The key advantage of the analytical approach is its low cost and time requirements.

The numerical modelling approach can provide more quantitative estimates of river recharge and the groundwater flow paths indicated by the model shows which river reaches contribute recharge in the vicinity of any particular well. However, the disadvantages of numerical modelling are the much higher time and computational resources required. The analytical approach could provide a useful preliminary analysis, prior to a more complex numerical modelling approach depending on the importance of the management decisions and the value placed on the water resources.

The first attempt at the flow-and-heat transport model calibration used the same K and C_{STR} parameterisation schemes adopted for the existing steady-state model (e.g., the same K field was employed in every model layer). This initial parameterisation was combined in two different ways. Firstly, a single θ value for all model layers was estimated. Next, the coefficients of a linear regression relationship between log(K) and log(θ) were estimated, which allowed a greater degree of θ heterogeneity to be represented in the model. Both of these calibration exercises achieved similarly good representation of the flows and heads as the original model, but the fit to the observed temperatures in the wells was poor. This indicated that there was much more heterogeneity in the aquifer system than was being represented in the model and that this was important for fitting the temperature data. A third model calibration was then embarked on, that adopted a separate suite of pilot points for K and θ in every model layer, plus a vertical hydraulic conductance term in each model layer (a total of 1232 parameters being calibrated). While this provides greater flexibility within the model parameterisation (e.g., spatial variability in θ that is independent of the spatial variability in K) to allow for better matches to temperature (and flow and head) data, and can therefore provide greater insight into river recharge variability in space, the degree to which temperature data could be matched was still somewhat limited. However, by also estimating K_d and ρ_b through calibration (albeit as a constant value per layer), significant improvements were afforded in terms of fitting temperature data. It is expected that further improvements in temperature-data matching could be achieved at all well locations across the Wairau Plains following the estimation of the spatial distribution of ρ_b and K_d (e.g., using pilot points). Future work should undertake such inverse modelling activities.

It cannot be inferred directly that the addition of temperature data into the calibration of the flow-and-transport model produces improved estimates of river recharge (i.e., relative to those obtained on the basis of the flow-only model constrained by head and flow data). To evaluate the worth of temperature data, the change in parameter/prediction uncertainty on the basis of calibration datasets that include/exclude temperature data would need to be quantified (e.g., Moore, 2006; Dausman et al., 2009; Wallis et al., 2014). Future work could include such investigations.

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APPENDIX A: SUMMARY OF SITE AND MONITORING INFORMATION.

Site number	Easting	Northing	Site name/ owner	Sensor depth (m bgl)	Start date	Finish date
Wairau R @ Barnetts bank	1680224	5412302			1/10/2013#	18/5/2016
P28w/0398	1667686	5406335	Conders shallow	9.7	9/8/2014	20/8/2015
P28w/0903	1662969	5405735	Ex MDC	6.6	9/8/2014	20/8/2015
P28w/1685	1671240	5408299	P Neal	9.3	9/8/2014	1/9/2015
P28w/1690	1664674	5406157		8.7	5/2/2016	18/4/2016
P28w/1696	1667405	5407349	Catchment Bd	6.4/ 10.4*	7/2/2015 2/1/2016	20/8/2015 18/4/2016
P28w/3009	1675125	5408625	Wratts Rd	3.9	9/8/2014	23/8/2015
P28w/3821	1667691	5406330	Conders No2: perm	12.7	18/12/2014	29/4/2016
P28w/3821	1667691	5406330	Conders No2: temp	19.0	9/8/2014	23/8/2015
P28w/4577	1677395	5409349	Selmes Rd	13.6	9/8/2014	23/8/2015
P28w/4722	1667273	5405960	Renwick eastern	13.6	9/8/2014	20/8/2015
P28w/4723	1667123	5405954	Renwick middle	18.6	9/8/2014	20/8/2015
P28w/4724	1666977	5405946	Renwick western	12.6	9/8/2014	20/8/2015
P28w/7007	1669780	5408324	Pauls Rd shallow	5.7/ 8.7$	8/7/2015 1/10/2015	21/8/2015 18/4/2016
10426	1672711	5408016	Neal Leachate	8.7	9/8/2014	23/8/2015
10485	1666584	5406847	Conders recharge	11.0	9/8/2014	1/9/2015
10608	1669796	5408320	Pauls Rd deep	15.2	9/10/2015	18/4/2016

Note: * both periods of data used to estimates lags and range.

data record is longer but this was the start of the data period used.

$ only the second data period was used for the estimation of lags

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