Memorandum

Date: 17 June 2025

To: Peter Davidson, MDC

From: Scott Wilson & Patrick Durney

RE: Wairau Aquifer Temperature Modelling

We have calculated travel times, Darcy and pore fluid velocities for all suitable temperature records for the Wairau Aquifer. Hydraulic conductivities have been calculated for pairs of piezos that lie along the same flow path.

Data sources

The use of temperature for modelling requires a source signal, in this case river recharge or a well that receives river recharge, and a downgradient receptor signal. The temperature record for the Wairau River source extends from April 2010 to the present day, with a gap in the record from Aug 2019 to May 2023. This gap was partially filled using sensors installed in the river at our MBIE project field site between Jeffries and Giffords Roads. This enabled early time and late time records to be created for the river, spanning from 11 April 2010 to 21 Aug 2019, and 21 Oct 2020 to 21 May 2025 respectively. Piezo temperature records are available for shorter duration than the river records, and so become the limiting factor in the duration of record available for modelling. A period of 1.5 years is recommended to provide sufficient data to have confidence in the results. We have therefore discarded shorter duration records. Time series of the input observations are shown in Figure 1.

Sediment thermal property values used were based on measurements made on Wairau Aquifer drill core samples in the lab using a Tempos thermal properties analyser (Table 1). These measurements were used to calculate effective thermal diffusivity (m^2/s), the key parameter in temperature modelling.

Table 2. mean and standard deviation for physical properties used in the modelling

Parameter	mean	sd	unit
grain density	2650	15	kg/m^3
Porosity	0.14	0.2	-
grain heat capacity	1063	62	J/Kg.C
grain thermal condy	1.77	0.044	W/m.C

Modelling approach

The modelling was done in three batches:

1. Between pairs of piezometers that lie along the same flow path
2. Sites with data prior to 2020 (early time)
3. Sites with data after 2020 (late time)

The idea of using pairs of piezometers was to reduce uncertainty of the distance between the source signal and receptor, since the distance between piezos can be accurately determined, whereas there

is some uncertainty of the exact position of a river source signal. This gave us the opportunity to determine if we required different thermal properties to be used for each site, or whether the same thermal property values could be used for the whole modelling exercise.

Modelling approach

Previous modelling of Wairau Aquifer temperatures has applied the Stallman analytical equation to fit a modelled response curve to an observed response curve. The Stallman approach involves fitting both the source signal amplitude attenuation and phase lag are used in the curve fitting. The Stallman equation was intended to be used to estimate vertical flow beneath a stream. An important modification to the Stallman equation was made by Hatch et al. (2006)[1], and it is this modification that we have adopted for our temperature modelling. The key modification made was to separate the Stallman equation into separate components for making estimates based on *either* the amplitude attenuation *or* the phase lag. For our purposes this separation into the two different signal components is important because these two components are physically controlled by different processes. The signal amplitude attenuation is controlled primarily by diffusion, which is appropriate for slow velocities (vertical seepage), whereas phase lag is controlled primarily by advection. The most appropriate equation to use for the high-velocity Wairau Aquifer is therefore the phase lag calculation, which can be applied to lateral or vertical flow. The inclusion of signal amplitude attenuation in the calculation, where it be via the Stallman or Hatch approaches results in an unrealistically low velocity estimate.

We have also used a Bayesian approach to estimate Darcy velocities, implemented in python via the DREAMzs algorithm. This approach enables us to include uncertainty in the model input parameter values: heat capacity, thermal conductance, grain density, porosity, and distance. An added advantage of this approach is that is provides likelihood values for each parameter after the model has been run (posterior distributions). These Darcy velocities are then used to determine travel time and pore fluid velocity using estimates for distance and porosity.

Assumptions

The position of individual river channels varies over time, and it's difficult to capture the position of a source signal channel over the duration of the modelling period. This affects the velocity estimate because velocity is related to distance. We have therefore assumed that the source signal position is located at the margin of the braidplain aquifer. This assumption holds when a river channel is positioned against the braidplain margin. If the source channel position is at the furthest braidplain margin, it could introduce a delay of up to in the source signal due to travel through the braidplain aquifer. This estimate is based on radon sampling within the braidplain aquifer and adjacent Wairau aquifer carried out in the MBIE programme. We have also not endeavoured to separate lateral and vertical flow components. For this exercise, flow is assumed to be lateral.

Results

[1] Hatch CE, Fisher AT, Revenaugh JS, Constantz J, Ruehl C, (2006). Quantifying surface water-groundwater interactions using time series analysis of streambed thermal records: Method development. *Water Resource Research 42 (10)*

The model velocity and lag time results for piezo pairs are shown in Table 2. The travel times are the pore fluid velocity divided by distance, which enables comparison with other tracers. A hydraulic gradient was calculated for these pairs by determining the median water level over the period of modelling and dividing this by the distance between the wells to derive the gradient. Hydraulic conductivity could then be estimated by dividing the Darcy velocity by the gradient. The derived values compare well with typical values of 2000 m/d calibrated for the Wairau Aquifer model. The results for well 3821 also enable a vertical hydraulic conductivity to be estimated by looking at the difference between the shallow and deep source wells. The vertical K estimate is 3.5 m/d, with an equivalent anisotropy ratio of ~1:600.

Table 2. median and standard deviations for velocity estimates, travel times, and hydraulic conductivities between piezos

Source	Receptor	Distance	Velocity (thermal)		Velocity (Darcy)		Velocity (pore)		Travel time (days)		K (m/d)	
well	well	(m)	med	SD	med	SD	med	SD	med	SD	med	SD
10485	3821	1230	11.6	0.1	8.0	0.3	58.8	9.4	153	5	2069	130
w12	20185	4110	6.2	0.0	4.3	0.1	31.4	5.0	964	155	1421	81
w14	w22	690	19.2	1.6	13.3	1.2	96.8	17.4	52	9	2792	727
20184	3821	1230	7.5	0.0	5.2	0.2	37.9	6.2	238	39	562	30
20186	3821	1740	9.1	0.1	6.3	0.2	46.3	7.6	276	45	732	36
w30	w12	320	18.1	3.9	12.5	2.7	92.7	24.7	26	7	2632	1301
7007	10426	2950	6.1	0.1	4.3	0.1	31.1	5.0	166	28	1097	71

River to piezo estimates in Table 3, with Darcy velocities ranging from ~4 to ~13 m/d. Sites with multiple records are annotated with “a” for early time and “b” for late time. We have also only used piezo pairs to estimate hydraulic conductivity, since this approach has the least uncertainty associate with it. When mapped (Figure 2), the results indicate that velocities are higher near the river. This is likely due to higher permeability sediments in that area, combined with a more dynamic hydraulic gradient.

Table 3. median and standard deviations for velocity estimates, travel times from the river

Receptor	Sensor	Distance (m)		Velocity (thermal)		Velocity (Darcy)		Velocity (pore)		Travel time (days)	
well	depth (m)	med	SD	med	SD	med	SD	med	SD	Med	SD
w0398	9.7	1570	20	15.08	0.89	10.44	0.70	76.93	13.67	150	10
w0903a	6.6	1030	50	13.75	0.95	9.52	0.71	70.02	12.36	108	10
w0903b	6.6	1030	50	14.63	1.10	10.12	0.82	74.79	13.28	102	10
w10426	8.7	2500	100	5.18	0.15	3.58	0.15	26.35	4.37	698	41
w11	4.98	320	20	21.07	7.90	14.54	5.45	106.61	43.98	22	8
w12	6.2	390	10	14.40	3.09	9.96	2.17	72.85	19.15	39	9
w1685	9.3	1050	50	19.55	1.91	13.54	1.37	98.74	18.88	78	9
w1690	8.7	150	50	1.47	0.30	1.01	0.21	7.41	1.90	148	58
w1696	6.4	170	20	12.18	7.19	8.43	4.98	61.59	37.90	20	12
w20185	24	4300	200	6.18	0.19	4.26	0.18	31.04	5.05	1008	63
w21	4.8	350	50	8.39	1.42	5.81	0.99	42.43	9.94	60	13
w22	3.915	900	100	16.46	1.88	11.40	1.33	84.06	16.50	79	13
w3821a	12.7	1580	20	8.36	0.18	5.79	0.21	42.65	6.94	273	11
w3821b	12.7	1580	20	7.81	0.16	5.40	0.20	39.43	6.42	292	12
w4722	13.6	2300	250	9.63	0.69	6.66	0.51	48.77	8.78	345	46

w4724	12.6	2200	200	8.50	0.51	5.88	0.39	42.67	7.30	374	42

Note that two most distant sites (10426 and 20185) initially gave very high velocity results, indicating that the fitted thermal lag was too low. We subsequently constrained the travel time for these two sites by an additional year to derive results in line with the other sites.

Discussion

Because flow in the Wairau Aquifer is dominated by advection, thermal properties cannot be resolved through Bayesian inference. As a result, we have resorted to using our measured thermal properties as means and bounds for the modelling. Another finding is that the prediction uncertainty increases with proximity to the river, and we have only reported results for sites >100m from the river in Table 3.

A comparison with radon measurements is made in Table 4. An issue with the use of radon travel time estimates is the need to choose a source and equilibrium activity to use with the sample activity. The equilibrium activity is particularly uncertain and has a large bearing on the travel time estimates. The results do not compare well, with radon estimate being much greater than temperature. To some degree this will be due to the validity of the methods. Temperature is best applied at distances >100m from the river, and radon at distances <100m from the river. Note that the results for both methods will be affected by depth, and for the temperature modelling we have only accounted for lateral distance. While more uncertain, radon estimates are independent of depth or direction travelled.

Table 4. travel time estimates for temperature and radon

Receptor	Sensor depth	Distance (m)	T time (days)		Radon time (days)	
			median	SD	Median	SD
w25	3.9	7	0.5	0.5	3.1	0.7
w7007	8.7	15	0.8	0.5	0.6	0.3
w20184	6.2	60	50.4	21.4	5.3	1.2
w20186	4.6	60	4.5	3.4	6.4	1.5
w30	7.2	75	5	3.1	3.9	0.9
w14	4	80	12.3	11.7	4.5	0.4
w11	5	320	22	8.4	8.7	2.3
w21	4.8	350	60.3	13.4	24.8	13.6
w22	3.9	900	79	12.8	15.2	5.6

One of the issues with the 1D approach is the need for prior information to help constrain velocity estimates at larger distances from the river (>2km). This is highlighted by the addition of a year to the travel times at 3009 and 10426. For the majority of piezos, we have a continuous downgradient spacing of wells and can be confident about the number of annual temperature cycles held in the data. This is not the case for the Renwick water supply wells, and there is some uncertainty about whether the phase lag in those wells is 50 days, or 415 days. We think temperature data will give better travel time estimates for water up to 2 years old than any other tracer method (eg tritium). However, this is only the case if there is information available to constrain the number of phase cycles to be accounted for.

Figures

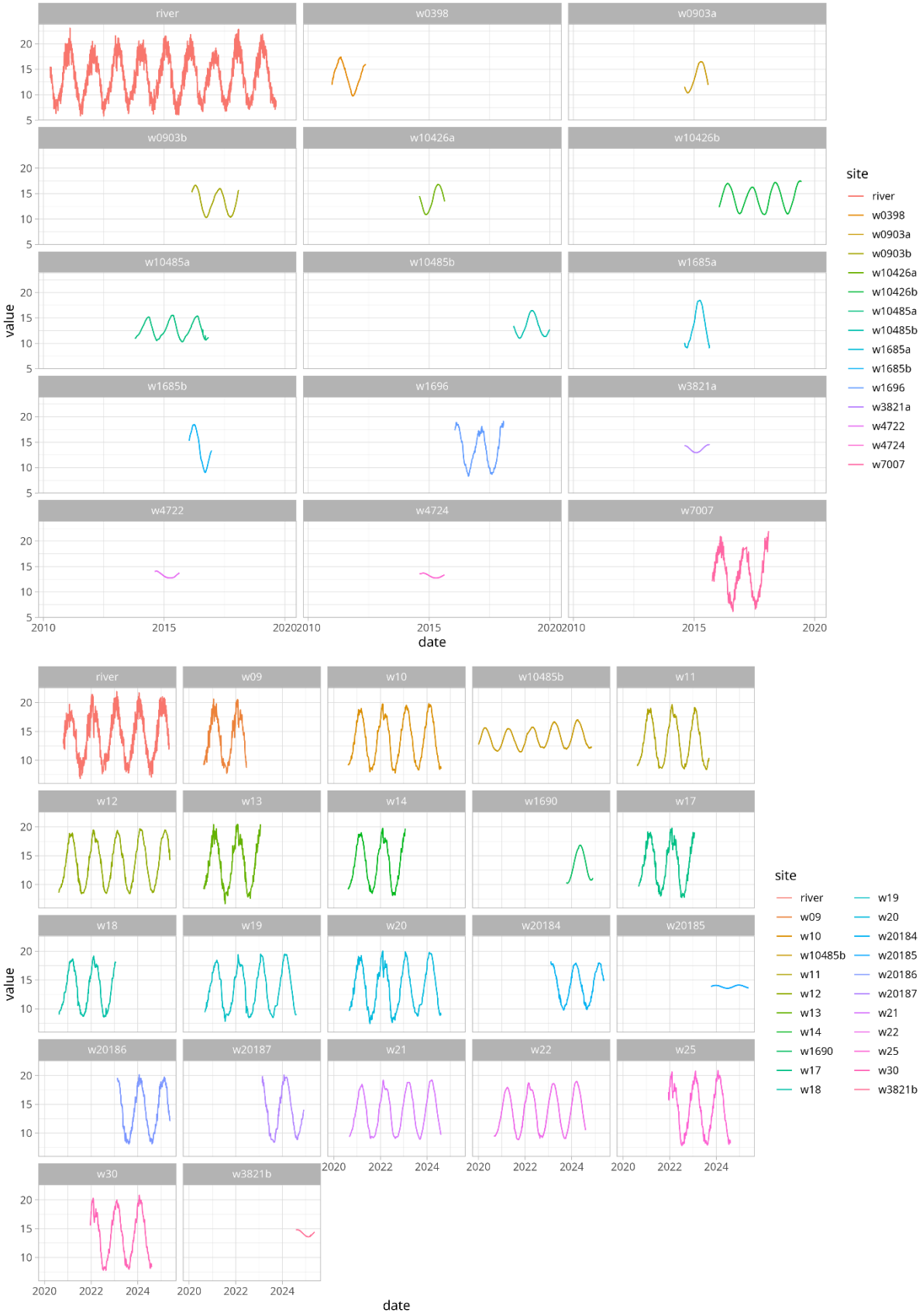


Figure 1. Time series of temperature observation data, early time (above) and late time (below).



Figure 2. Map showing the pore fluid velocity distribution