Analysis of Radon data from the Wairau River and adjoining Wairau Plains Aquifer February 2014

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May 2014

Murray Close
ESR

Client Report
CSC14001

ANALYSIS OF RADON DATA FROM THE WAIRAU RIVER AND ADJOINING WAIRAU PLAINS AQUIFER FEBRUARY 2014

Prepared by

M. Close
May 2014

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Executive Summary

In February 2014 ESR, together with Peter Davidson, Marlborough District Council (MDC), carried out sampling of dissolved radon gas in the Wairau River and shallow groundwater adjacent (within 5 km) to the river. The purpose of the study was to gain information on surface water - groundwater interactions and the likely amounts and variability of recharge to the groundwater system. Radon-222, a radioactive decay product (half-life = 3.82 days) of naturally occurring radium-226, is present in many groundwater systems. It degasses from surface water so is low in concentration and increases to an equilibrium value as it recharges a groundwater system. Field parameters, such as temperature, dissolved oxygen and pH, which might also be expected to differ between the river and shallow groundwater were also measured.

The wells were grouped into two zones and analysed separately. Wells in the southern group (Zone 1) showed an increase in radon concentration with increasing distance from the river and fitted the ingrowth equation well. There were only three wells in the northern group (Zone 2) and all were a reasonable distance from the river. The data analysis indicated that the radon concentrations had already reached equilibrium values and hence only an equilibrium radon value and a maximum groundwater seepage velocity could be estimated. The estimated groundwater seepage velocities were 94 and < 25 m/day, for Zones 1 and 2 respectively. The differences between the zones are likely to relate to differing hydraulic conductivities in the groundwater system and variability in the riverbed conductance along the recharge reach.

The temperatures measured in the Wairau River in mid-February were much higher than in the groundwater and the groundwater temperatures decreased with increasing distance from the river. The patterns were generally consistent with the spatial distribution of radon concentrations. Analysis of the continuously measured (0.25 to 1 hourly) temperature in the Wairau River and in a well located close to the river (10485) indicates that the groundwater temperatures do not respond to the diurnal temperature variation in the river or even to floods lasting about 2 weeks but rather show a slow seasonal response over a period of months. The data from well 10485 indicates that the groundwater temperature was still increasing in mid-March and therefore the maximum sensitivity for using temperature data to delineate groundwater recharge patterns could be in March or April and the corresponding winter

recharge period 6 months later. Additional groundwater temperature measurements would assist in these interpretations.

The concentration of radon in the groundwater were significantly lower (maximum radon concentration = 10.4 Bq/L) compared to those observed in a recent Canterbury study (maximum radon concentration = 47 Bq/L). As the analytical percentage error increases at lower radon concentrations it would be an advantage for future studies in this area to count the samples for longer to reduce the analytical errors for these relatively lower levels of radon. There are also errors in estimating the distance from the river along the groundwater flowpath for each well and a combined analysis of radon and temperature data together with piezometric data, could resolve some uncertainties in the flow path estimations.

Both the radon and temperature data indicate that significant recharge occurs in the study reach of the Wairau River. It is likely that more recharge occurs in the southern zone although only three wells were measured in the northern zone so that conclusion should be treated with caution at this stage.

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 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 chemistry provides a useful means by which to infer knowledge about river - groundwater interactions and can potentially be applied to constrain aquifer recharge estimates.

Radon gas (Rn or Rn-222), a radioactive decay product of naturally occurring radium-226, is present in a dissolved state in many groundwater systems with concentrations depending largely on the lithology (Shaw and Eckhardt, 2012). A study of radon in New Zealand alluvial greywacke gravel aquifers indicated concentrations ranging from 10 – 50 Bq/L (Gregory, 1980). Radon degasses from surface water and concentrations in surface water are close to zero which provides a means to examine surface water interactions with groundwater. Elevated concentrations of radon in river water can signify effects of groundwater discharge. In contrast, low radon concentrations measured in groundwater can indicate local river recharge effects but more importantly can permit estimation of flow rates. Surface water infiltrating into groundwater should initially contain low radon concentrations, but would start accumulating radon as it flows through the aquifer, reaching equilibrium in approximately 6 half-lives (22.9 days; $T_{1/2}$ = 3.82 days). Close et al. (2014) have recently carried out a study using radon concentrations in two well arrays adjacent to the Waimakariri River, Canterbury, to estimate groundwater seepage velocities and gain information about groundwater – surface water interactions.

The Marlborough District Council (MDC) requested ESR to carry out sampling for radon and to interpret the results to provide insight into recharge processes. This report focuses on using radon gas as a natural tracer to study aquifer recharge from the Wairau River to the Wairau Plains aquifer system near Blenheim.

Methodology

Well Selection

Wells suitable for the investigation of surface water recharge to groundwater using radon need to be: shallow; positioned on the groundwater flowpath, and; located in suitable proximity to the river (within 2-3 weeks effective transport distance). Eleven wells that met those criteria were selected (Figure 1) and were sampled on 11 - 12 February 2014. The Wairau River was sampled at 4 locations along the reach of likely recharge to the groundwater system (Figure 1). Details of the sample sites and sampling time are given in Appendix 1.

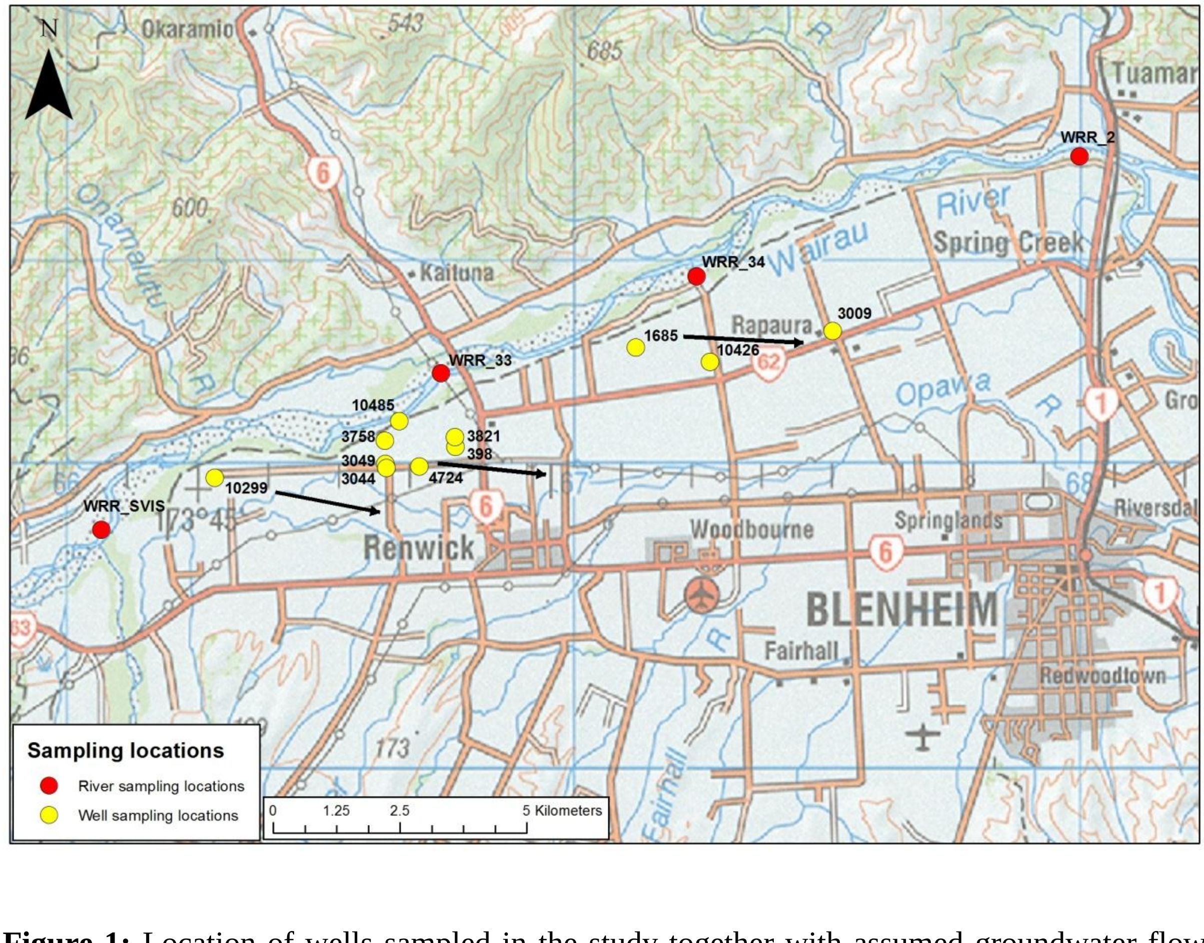

Figure 1: Location of wells sampled in the study together with assumed groundwater flow direction shown by the black arrows. Well P28w/3821 is located very close (< 5m) to well P28w/0398 so is offset 200 m north in the figure for display purposes.

Sampling and Analysis

Samples were collected using installed irrigation pumps or the MDC portable Grundfos MP1 sampling pump. The bores were flushed for at least three well volumes where possible. Field parameters, namely pH, dissolved oxygen saturation (DO_{sat}), conductivity and temperature, were measured using field meters (Table 1) and the radon samples collected after these field parameters had stabilised. The radon samples were collected by directing the water through tubing inserted into the bottom of the one-litre polyethylene sample bottle, and overflowing to thoroughly flush the bottle. Care was taken to avoid aeration, with low flow (< 0.1 L/s) and a total lack of bubbles. Bottles were filled completely with no air gap, capped securely, stored in a cool environment, and transferred to the laboratory for analysis. Where possible, groundwater levels were measured before pumping commenced.

Samples were analysed at the National Centre for Radiation Science (Christchurch) using standard liquid-scintillation counting (LSC) techniques. The water samples were clear and no pre-treatment was necessary. For each measurement an 8 mL aliquot of water was mixed with *Optiphase HiSafe 3* liquid scintillation cocktail in a standard 20 mL scintillation counting vial. The mixture was allowed to stand for 4 h for reduction of any chemiluminescence, and ingrowth of radon decay products, before analysis with a 60 min counting time with a *Wallac 1400* LSC, with α- and β-emitting members of the radon decay series in equilibrium. A blank correction was made by purging a water sample of radon using nitrogen gas. The instrument was calibrated using a radium solution of accurately known activity with decay products in radioactive equilibrium. The detection limit for these counting conditions was around 2 Bq/L and the 95% confidence limit was 20% for a radon concentration of 10 Bq/L.

Data analysis

In a closed system radon concentrations build up to an equilibrium value where the rate of decay is matched by the rate of production. The rate of buildup, known as ingrowth, is described by the following equation (Hoehn and von Gunten, 1989).

$$A_t = A_e(1-e^{-\lambda t}) \qquad (1)$$

Where A_t = Rn activity at time t;

A_e = Rn activity at equilibrium;

λ = radioactive decay constant for Rn (0.18 day^{-1})

Equation 1 indicates that radon concentrations will reach 72%, 92% and 98% of the equilibrium radon value after 7, 14 and 21 days, respectively. This provides an effective window of about 2 weeks of groundwater travel time for the radon build-up to provide useful information on groundwater recharge characteristics. As the groundwater velocity is usually unknown (and its estimation is the objective of this radon technique), the equivalent distance for locating wells will be an estimate at the beginning of the study. The application depends on the following main assumptions (Hoehn and Gunten 1989):

1. the average distribution of the radon parent compounds (uranium and radium) in the aquifer material is homogeneous on a macroscopic level;
2. the equilibrium radon concentrations measured at sites remote from the river are representative of the groundwater flow path under investigation (similar minerals and particle size distributions);
3. losses of radon from the groundwater to the unsaturated zone and the atmosphere are constant;
4. the infiltrating water does not mix with older groundwater or water rapidly infiltrating from another source such as a water race. Note that land surface recharge usually occurs over time intervals greater than a month and after the water has been in the groundwater system for more than three weeks the radon will be at equilibrium concentrations; and
5. the flow distance of the water to a sampling well is constant even in the case of varying water table elevations.

The equilibrium radon value will be influenced by the type of minerals present, the level of radon precursors in those minerals, and the particle size (smaller particles have more surface area per volume).

To analyse the radon data from the wells, equation 1 was transformed into a distance relationship (using v=d/t), to give:

$$A_d = A_e(1 - e^{-\lambda d/v}) \qquad (2)$$

where A_d = Rn activity at distance d (m);

v = groundwater seepage velocity (m/day)

The distance of each well from the river edge was measured along the best estimate of groundwater flow direction, 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. As our analysis assumes recharge from a line source somewhere within the riverbed rather than a planar source corresponding to the entire riverbed width, an offset distance from the edge of the river to a hypothetical location of the line source was used so that $d_{total} = d + d_{offset}$. The radon data for each array were fitted to equation 2 and used to estimate the values of A_e, v and d_{offset} using the Solver package in Microsoft Excel. As recharge to the sampled wells would have taken place over a distance of approximately 10 km, the wells were divided into 2 zones and analysed for each zone and for all wells together. Well 10299 could possibly be put into a separate zone by itself but as there would be only one sample for this zone it was analysed with Zone 1.

Results and discussion

Estimation of Groundwater Velocity from Radon data

The measured radon concentrations and field parameters are given in Table 1 and the spatial distribution of the radon data is shown in Figure 2. There is a marked difference between the water chemistry for river and groundwater system for radon, pH, DO and temperature. The sampling was carried out in February which would maximise the differences for pH, DO and temperature and the river flow was stable and moderately low (mean flow for 11th and 12th February = 19 m^3/s). The differences for pH and DO are due to photosynthesis by algae and the difference in temperature is due to the heating of the moderately low river flow in mid-summer. The reason for the difference in radon concentrations is described in the introduction and data analysis sections and is expected to remain similar throughout the year. Figure 2 clearly shows the general trend of increasing radon concentrations away from the river but also illustrates the variability that is present in the data.

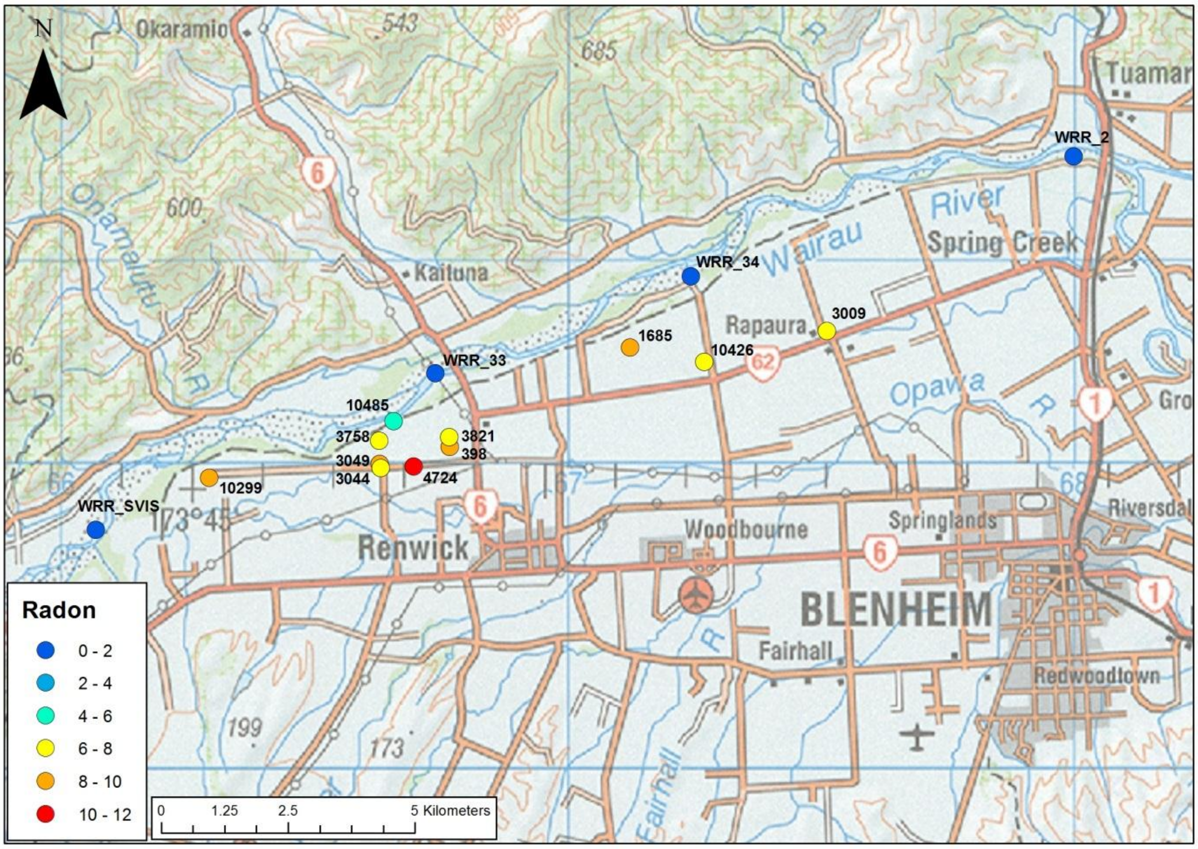

Figure 2: Spatial distribution of radon concentration data. Well P28w/3821 is located very close (< 5 m) to well P28w/0398 so is offset 200 m north in the figure for display purposes.

The data were fitted to the ingrowth model (equation 2) by optimising the equilibrium radon concentration (A_e), the groundwater velocity and the offset distance. This model fitting was carried out for all the wells and for the zones separately. The optimised parameters are given in Table 2 and the fit of the model to the data is shown in Figures 3 and 4 for zones 1 and 2, respectively. Well P28w/3044 is located close (< 10 m) to the north branch of Gibsons Creek and since it is very likely to be affected by recharge from the creek, it was omitted from the model fitting. Figure 2 shows that this well plots below the fitted line consistent with recent recharge from surface water.

The residual sum of squares divided by the number of samples (RSSE/n) indicates that the data fitted the ingrowth equation better when divided into zones (Table 2). The values for A_e are fairly similar for all equations and range from 7.6 and 9.2 Bq/L. These are similar to the maximum radon value of 10.4 Bq/L found in well P28w/4724, which provides a degree of confidence in the model fitting results. The maximum radon values found in this survey were significantly lower than some of the radon values observed in a study around the Waimakariri River - Christchurch city area (Close et al. 2014). Many of the radon values in that study were around 20 to 30 Bq/L, with a maximum value observed of nearly 50 Bq/L. The likely cause of the lower radon levels would be some differences in mineralogy and particle size distribution.

Table 1: Summary of radon concentrations and measured field parameters for each sampling location.

Well number	Zone	Distance to river edge (m)	Radon (Bq/L)	Radon error (Bq/L)	pH	DO (% sat)	Cond. (mS/m)	Temperature (^{o}C)
WRR-SVIS	River	0	< 2.8	#	8.09	107	6.66	19.0
WRR-33	River	0	< 2.7	#	9.24	124	6.80	22.3
WRR-34	River	0	2.0	1.6	8.78	119	6.70	21.0
WRR-2	River	0	< 2.6	#	8.00	112	6.80	19.8
Mean river		0	1.5#		8.50	116	6.74	20.5
P28w/0398	1	2050	7.0	1.7	6.64	73	6.52	13.9
P28w/1685	2	1450	9.2	2.0	6.90	71	6.40	14.9
P28w/3009	2	4740	6.8	1.9	6.70	71	6.92	14.0
P28w/3044	1*	1300	6.9	1.7	6.38	83	6.55	14.3
P28w/3049	1	1320	8.5	2.0	6.99	74	6.54	13.5
P28w/3758	1	650	6.7	2.1	7.03	72	6.42	14.9
P28w/3821	1	2050	9.6	1.9	6.65	67	6.47	13.7
P28w/4724	1	1850	10.4	2.0	6.56	67	6.50	13.8
10299	1	1100	9.6	2.2	6.74	67	6.63	15.3
10426	2	3290	6.9	2.1	6.60	73	6.33	13.9
10485	1	150	4.9	1.7	7.06	74	6.59	14.8

* well omitted from model fitting as recharge from nearby (10 m) Gibsons Creek was suspected.

samples were less than the detection limit (DL); a value of 0.5 DL was used for estimation of the mean river radon concentration.

Table 2: Summary of parameters from the model fitting. A_e is the equilibrium radon concentration; RSSE is the residual sum of squares.

Zones	A_e (Bq/L)	GW velocity (m/day)	Offset distance (m)	RSSE	RSSE/n
Both zones	8.27	52	103	20.3	1.69
Zone 1	9.09	112	320	13.5	1.50
Zone 1 ex 3044	9.21	94	228	10.7	1.34
Zone 2	7.63	< 25	Not sensitive (0)	5.9	1.48

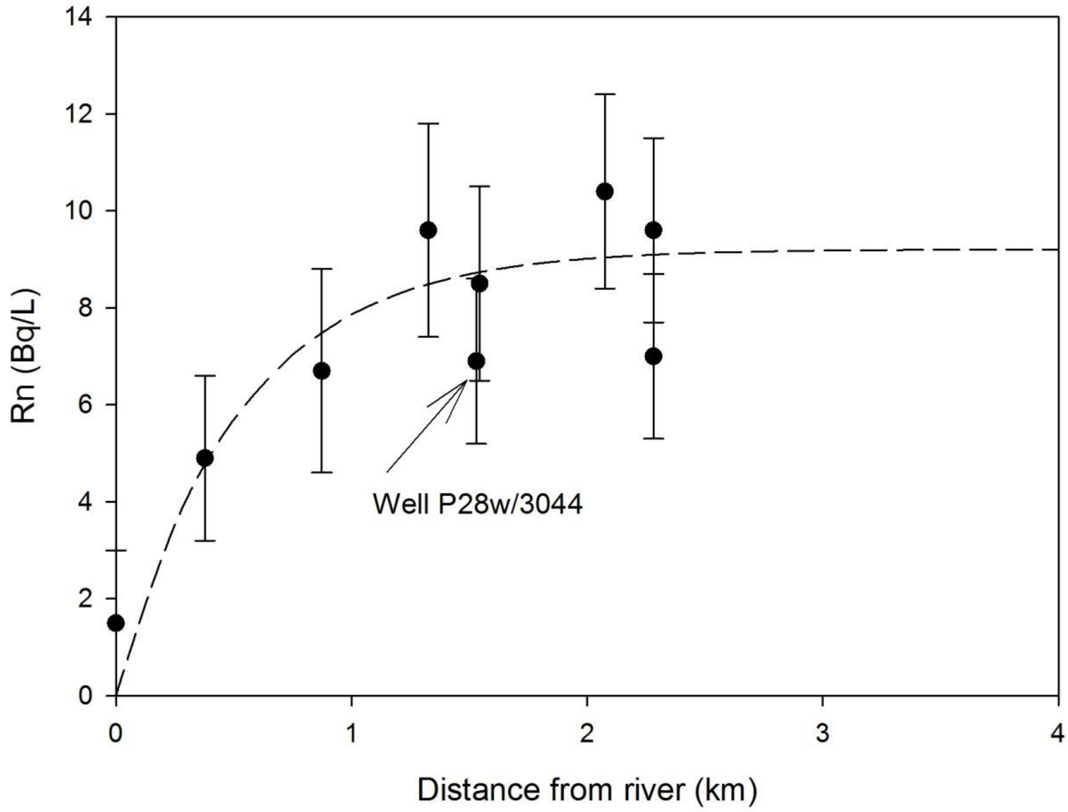

Figure 3: Fit of observed to simulated radon data for Zone 1wells using parameters given in Table 3. The error bars correspond to the analytical error and do not include variability of sample replicates or errors in estimation of distance along the groundwater flow path. Distance from river is the estimated distance from the river edge plus the offset distance. Well P28w/3044 was omitted from the model fitting but is indicated on the figure.

The variability in the radon data is clearly shown in Figures 3 and 4. The analytical error is shown on the figures as vertical error bars. The percentage error is greater at low radon concentrations and, as mentioned above, the radon concentrations observed in this study were lower than those observed in the Christchurch study. If further radon samples were to be collected in the future from this area then the radiation laboratory would be requested to count the samples for a longer period to reduce the analytical error. The errors in the

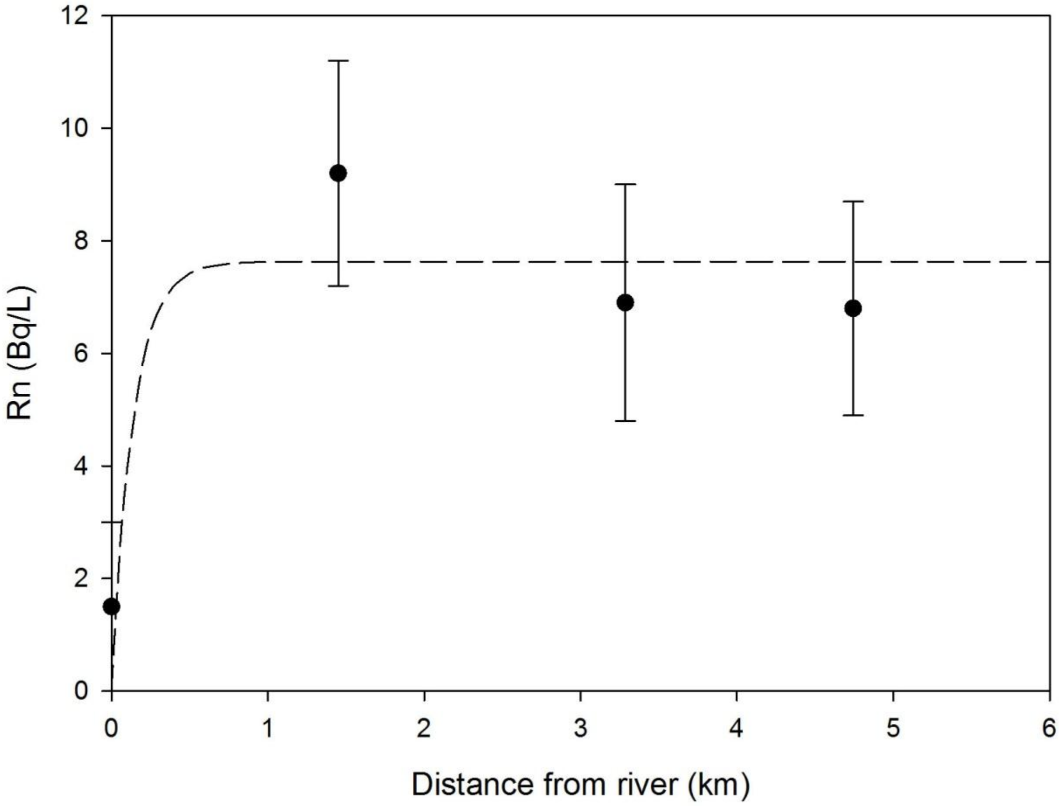

Figure 4: Fit of observed to simulated radon data for Zone 2 wells using parameters given in Table 3. The error bars correspond to the analytical error and do not include variability of sample replicates or errors in estimation of distance along the groundwater flow path. Distance from river is the estimated distance from the river edge.

estimated distance from the river are not shown in Figures 3 and 4 but could be substantial. The flow direction has been assumed from available peizometric contours but the groundwater flow direction can vary at a local (100 to 500 m) scale quite significantly from the regional flow paths due to local heterogeneity and a meandering flow deposition process

(Dann et al. 2008; Pang et al. 1998). As the angle between the river and the assumed peizometric contours (groundwater flow direction) is quite small, this means that a slight difference in the assumed flow direction can result in a reasonably large difference in the estimated distance from the river. The meandering nature of the Wairau River adds to the error. The error is difficult to quantify but could be up to 400 m for some wells.

There were only 3 wells in Zone 2 and all were a reasonable distance from the river. In addition the closest well (P28w/1685) had a slightly higher radon concentration compared to the two other Zone 2 wells. This meant that all 3 wells were analysed as being in equilibrium and thus the model was only sensitive to the A_e value which was fitted as 7.63 Bq/L. The groundwater seepage velocity was constrained as being < 25 m/day and the model was insensitive to the offset distance which was taken as zero. The estimated groundwater seepage velocity is strongly influenced by the radon level observed in well P28w/1685 and therefore should be treated with caution until additional data can be obtained. The data could be re-analysed if additional wells were able to be sampled in this area, particularly closer to the river.

The estimated groundwater velocities are quite different for the two zones (94 and < 25 m/day for Zones 1 and 2, respectively). The zone 1 velocity is reasonably high but falls within the range of velocities estimated by others who have conducted natural gradient tracer tests in similar alluvial gravel aquifers within the Canterbury Plains aquifer system (Pang et al., 1998; Sinton and Close, 1983; White, 1988) and is lower than the groundwater velocities estimated in the Christchurch radon study of around 370 m/day adjacent to the Waimakariri River. White (1988) has estimated the highest groundwater velocities, around 800 m/day, by conducting a salt-tracing experiment close to the river bed of the Rakaia River, which is a large braided river. The lower groundwater velocity estimated for zone 2 would most likely relate to lower hydraulic conductivities in the groundwater system and in the riverbed conductance. However, as noted above, this value is very dependent on the radon concentration observed in a single well.

The Wairau River and unconfined groundwater system is low in ionic strength (conductivity = 6 to 7 mS/m (60 – 70 µS/cm) and has a low buffering capacity. It would be expected that pH would adjust quickly to the groundwater environment and may not exhibit much of a river signature. All the wells have pH values between 6.5 and 7.1 and there is a weak trend of decreasing pH with increasing distance from the river. There were high levels of dissolved oxygen measured in the Wairau River but, apart from well P28w/3044 which was likely to be influenced by Gibsons Creek, all the wells have DO_{sat} values between 67 and 74% (Table 1).

The temperature data (Table 1; Figure 5) clearly shows a decrease in temperature with increasing distance from the river. As these measurements were taken in summer the river temperatures are higher than the groundwater. Similar measurements in winter should exhibit

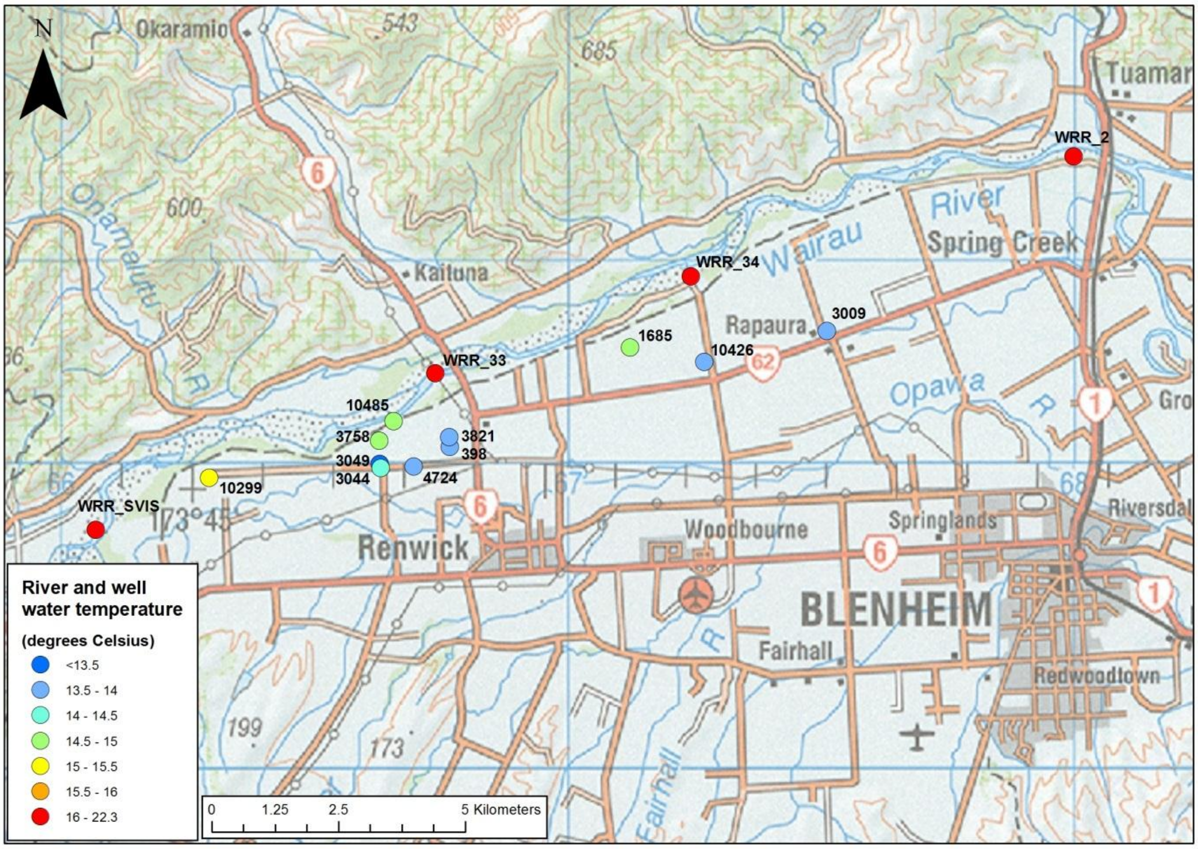

Figure 5: Spatial distribution of temperature data. Well P28w/3821 is located very close (< 5 m) to well P28w/0398 so is offset 200 m north in the figure for display purposes.

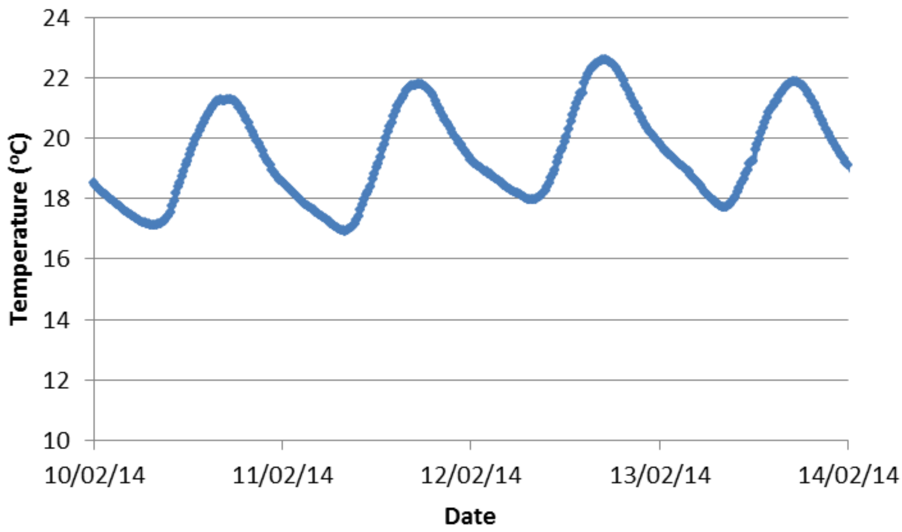

Figure 6: Temperature record every 15 minutes for Wairau River at Barnetts Bank from 10th to 14th February 2014.

the reverse trend. Figure 6 shows the diurnal variation in Wairau River temperature over the sampling period, which varies from about 17 to 22.5°C and is consistent with the measured river temperatures shown in Table 1. MDC have a continuous (hourly) temperature probe installed in well 10485 (Figure 7) that indicates that even a well located close to the river does not respond to the diurnal temperature variation in the river or to floods lasting about 2 weeks but rather shows a slow seasonal response over a period of months. When plotted against the estimated distance from the river (Figure 8), the observed well temperatures in mid-February decreased with increasing distance up to a distance of around 2.5 km and then showed no further decrease. Figure 7 indicates that the well temperatures were still increasing in mid-March and therefore the maximum sensitivity for using temperature data to delineate groundwater recharge patterns could be March or April. This could be confirmed by examining further data from well 10485 and by deploying more temperature probes in other wells to give a better spatial coverage. A simple linear trend is plotted in Figure 8 to allow a preliminary analysis, although a non-linear trend would be more correct. This shows a couple of wells (10299 and P28w/1685) plotting above the line which could indicate more recharge to these wells. Another possibility is that the estimated distance from the river is higher than it should be. Wells P28w/3044 and P28w/3049 are located reasonably close to each other. Well P28w/3044 is thought to be influenced by recharge from Gibsons Creek (about 10 m from the well) which is consistent with a measured well temperature 0.8°C higher than well P28w/3049. The fact that the higher well plots on the trend line possibly relates to the difficulty of determining an appropriate trend line with limited data. Collection of additional temperature data from the wells to confirm these single observations and combined interpretation of the temperature and radon data should result in resolution of some uncertainty in the likely estimated flow paths and improved estimates of recharge and its variability in this section of the Wairau River.

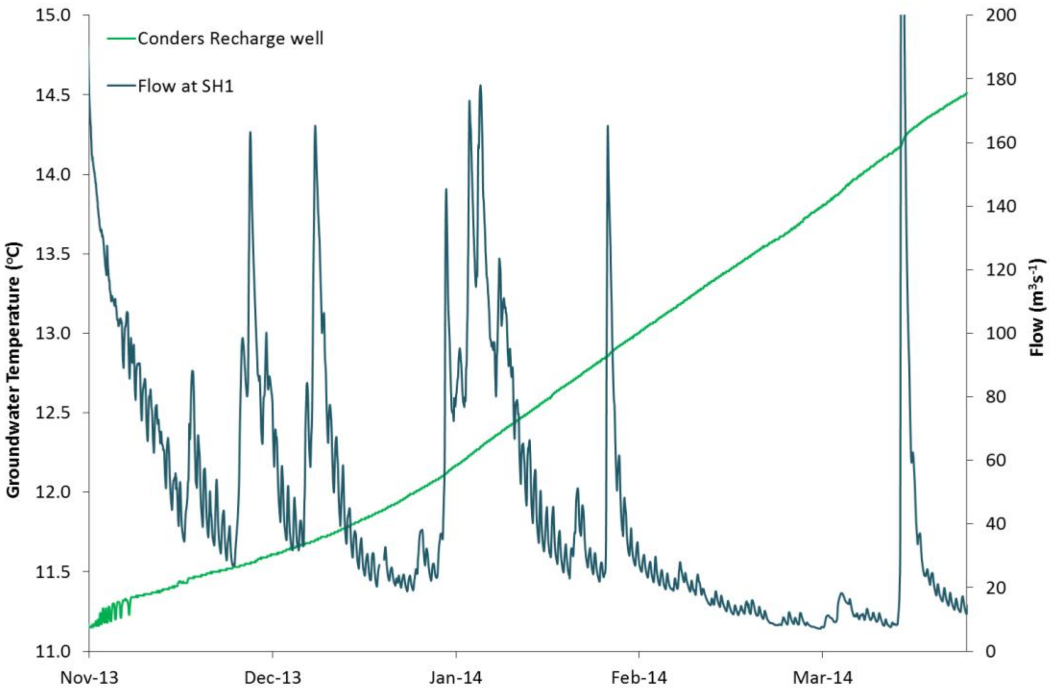

Figure 7: Hourly temperature record for Conders Recharge well (10485) from November 2013 to March 2014.

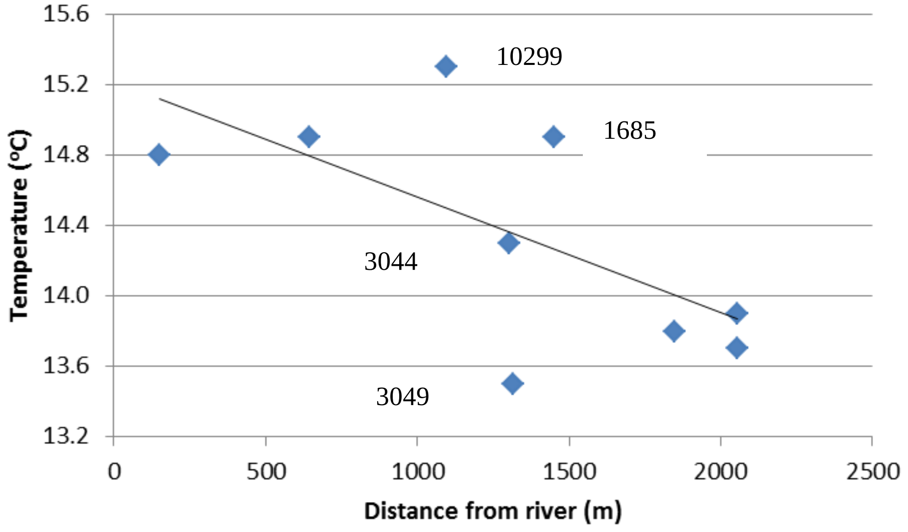

Figure 8: Observed groundwater temperature with estimated distance along the groundwater flowline from river.

Recommendations

1. Consider resampling the wells for radon and analysing the samples with increased counting times to give reduced analytical errors.
2. Deploy additional heat sensors in more wells in the recharge area to gain more information through the next year. The sampling frequency need not be hourly (as is the case for well 10485) but could be reduced to 12 or 24 hourly monitoring with no loss of information.
3. Carry out a combined interpretation of the updated radon and temperature datasets to reduce uncertainties in the estimated distance from the river along groundwater flowpaths and to refine estimates of groundwater seepage velocities.

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Appendix 1: Summary of site and sampling information.

Site number	Easting	Northing	Well screen (mbgl)	Sample date	Sample time	GW level (mbgl)
WRR-SVIS	1660707	5404697		11/2/14	11:20	
WRR-33	1667404	5407783		11/2/14	12:07	
WRR-34	1672446	5409703		11/2/14	12:27	
WRR-2	1679996	5412070		11/2/14	12:51	
P28w/0398	1667686	5406335	11	12/2/14	08:45	6.246
P28w/1685	1671240	5408299	20 - 24	11/2/14	15:15	6.235
P28w/3009	1675125	5408625	5 - 6	11/2/14	13:30	2.63
P28w/3044	1666323	5405915	7 - 9	12/2/14	12:02	6.36
P28w/3049	1666309	5406002	16 - 21	11/2/14	10:30	6.667
P28w/3758	1666296	5406460	24 - 28	11/2/14	09:50	6.070
P28w/3821	1667691	5406330	20 - 22	12/2/14	10:00	6.684
P28w/4724	1666977	5405946	21 - 25	12/2/14	13:20	7.522
10299	1662947	5405722	6 - 9	11/2/14	11:12	4.04
10426	1672711	5408016	18 - 19	11/2/14	14:00	6.059
10485	1666584	5406847	11 - 14	12/2/14	11:05	7.411

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