From Rain through River Catchment to Aquifer: The Flow of Water through the Wairau Hydrologic System

U Morgenstern P Davidson DB Townsend PA White
RW van der Raaij MK Stewart M Moreau C Daughney

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U Morgenstern, GNS Science, PO Box 30368, Lower Hutt 5040, New Zealand
P Davidson, Marlborough District Council, PO Box 443, Blenheim, New Zealand
D Townsend, GNS Science, PO Box 30368, Lower Hutt 5040, New Zealand
P White, GNS Science Wairakei Private Bag 2000, Taupo, 3352, New Zealand
R van der Raaij, GNS Science, PO Box 30368, Lower Hutt 5040, New Zealand
M Stewart, GNS Science, PO Box 30368, Lower Hutt 5040, New Zealand
M Moreau, GNS Science Wairakei Private Bag 2000, Taupo, 3352, New Zealand
C Daughney, MFE, PO Box 10362, Wellington 6143, New Zealand (formerly GNS Science)

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4.0 RESULTS AND DISCUSSION – GROUNDWATER PROCESSES AND FLOW DYNAMICS

In this section, the surface water and groundwater tracer results of the techniques listed above are interpreted with respect to groundwater dynamics from recharge to discharge; interaction with surface water; recharge sources; catchment storage and retention processes; and understanding of the processes that control groundwater hydrochemistry (quality), including sources and expected loads of nutrients. The techniques are complementary, and the results improve significantly by integrating all techniques.

4.1 Water Age

Age tracers are used in the vicinity of the Wairau Plain to establish a) mean residence times (MRT) of the water at sampled locations in the Wairau Plain groundwater system and b) mean transit times (MTT) of the water through the catchments and groundwater systems into the rivers and streams.

4.1.1 Groundwater Residence Time

In this section we use three types of tracers to establish residence times: age tracers with long-term time-dependent tracer input concentrations in the atmosphere or that exhibit radioactive decay allowing groundwater dating in the age range 1–100 years, tracing the seasonal variability signals from the source through the aquifer for dating over shorter time scales of 0–1 years, and radon build-up in groundwater for dating periods of up to several weeks.

4.1.1.1 Age Tracer Results

Utilising convolution integral Equation 1 for conversion of tracer concentrations into water ages requires application of groundwater mixing models and, in absence of sufficient time-series or multi-tracer data, assumptions about mixing parameters. Regardless of the choice of model parameters, the raw tritium ratios already show a clear pattern of the groundwater flow dynamics in the Wairau Plain. Figure 4.1 shows tritium ratios of samples collected after 2005, the time at which the impact of the bomb-tritium had diminished that otherwise would cause elevated tritium concentrations in old water.

In groundwaters of the Holocene gravel fans, tritium ratios are similar to those of rain water (c. 2 TU, Figures 4.1 and 4.2), indicating very young water. This also includes a shallow well in the unconfined Quaternary beach deposits and a shallow well in the Holocene deposits of the Omaka River. Intermediate tritium ratios in the confined aquifer north-east of Blenheim indicate intermediate groundwater ages. In contrast, low tritium ratios in the northern and southern part of the confined aquifer near the coast indicate old water. In the Quaternary beach deposits south of Rarangi, the Rarangi Shallow Aquifer, (Figure 4.1 insert) relatively high tritium ratios indicate young groundwater and, in the most northern well, medium tritium ratios indicate medium age and a more sluggish flow close to the boundary of the beach deposits.

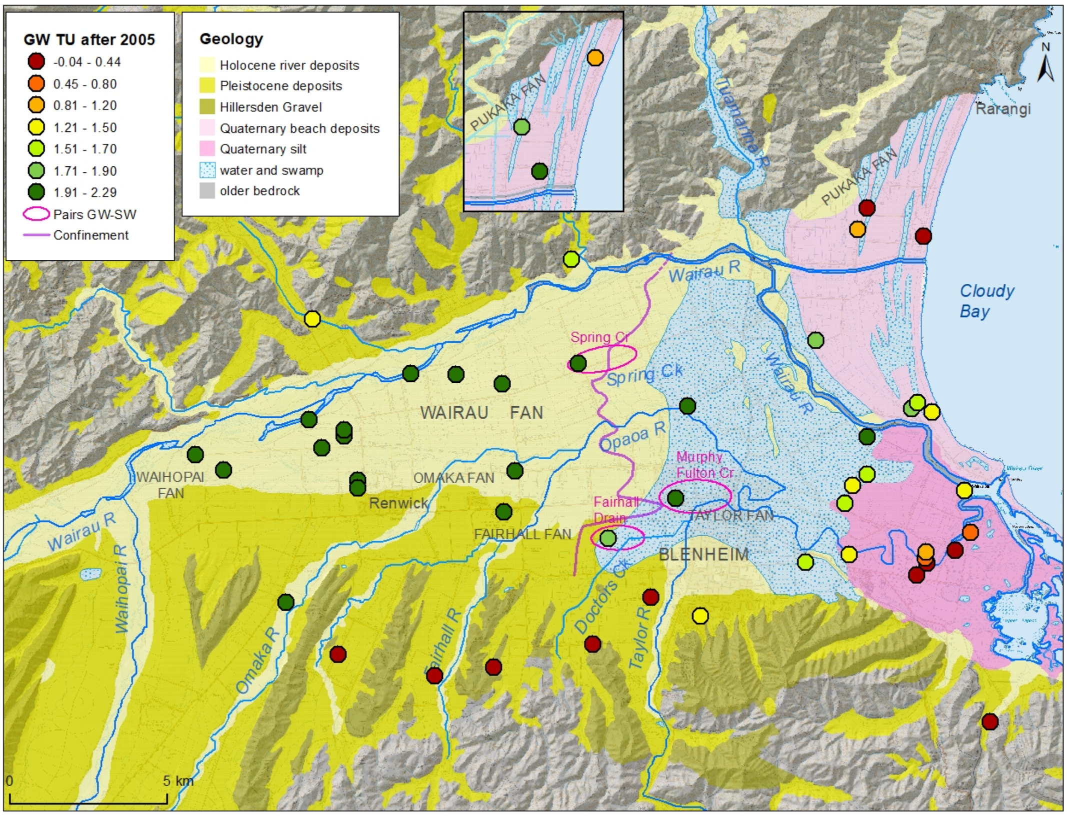

Figure 4.1 Tritium ratios (in TU) for groundwaters sampled after 2005. The insert on the top shows TU for the Rarangi Shallow Aquifer, while the main figure shows TU only in the confined aquifer in this area.

For the interpretation of age tracers, it is important to keep in mind that gas tracers in groundwater samples can be contaminated due to air contact during sampling or in the well head, and in the aquifer due to anthropogenic sources in the recharge area (Section 3.1). About 20% of the sites on the Wairau Fan up to the Quaternary silt deposits show CFC contamination, indicating the presence of local contamination sources. These elevated point-source CFC concentrations can be used to identify recharge from local rain, as elevated CFC concentrations do not occur in river water.

Tritium, as the most robust age tracer, was given the most weight for age interpretation, with SF_6 data being used in a complementary way. For the very young water (c. 1 year), the SF_6 data generally showed a slight mis-match to tritium, indicating a slightly older water age. However, the young tritium ages are confirmed by the presence of seasonal variability of temperature and stable isotope composition (Section 4.1.1.2).

Utilising convolution integral Equation 1 for identification of water age requires knowledge of the tritium input for both high-altitude rain for the river recharge and low-altitude rain for local rain recharge within the Wairau Plain. A continuous tritium record (monthly data since 1960) is available from Kaitoke from the foothills of the Tararua Ranges north of Wellington (Figure 2.2). For the high-altitude Wairau River catchment, Taylor et al. (1992) proposed an elevated tritium input compared to that of Kaitoke because of a contribution of precipitation from the high troposphere.

Recent groundwater tritium data indicated that the low-altitude local rain in the Wairau Plain must also have a higher tritium input compared to Kaitoke, as it was not possible to match tritium ratios of young Wairau Plain groundwater with the Kaitoke input for any combination of model parameters. To establish the scaling factor of the Kaitoke tritium record for the Wairau Plain hydrologic system, we set up a rain collector in Blenheim (location in relation to

Kaitoke shown in Figure 2.2) and measured tritium in monthly rain samples over a period of two years (Figure 4.2). The results clearly show higher tritium ratios in Blenheim rain by a factor of 1.22 on average compared to nearby Kaitoke. This demonstrates the general influence of the mountain ranges in shielding the Wairau Plain from direct precipitation of low-tritium oceanic moisture, but with occasional periods of similar or lower tritium concentrations indicating periods of dominance of tritium-diluted oceanic moisture via NE weather systems (Section 2.2).

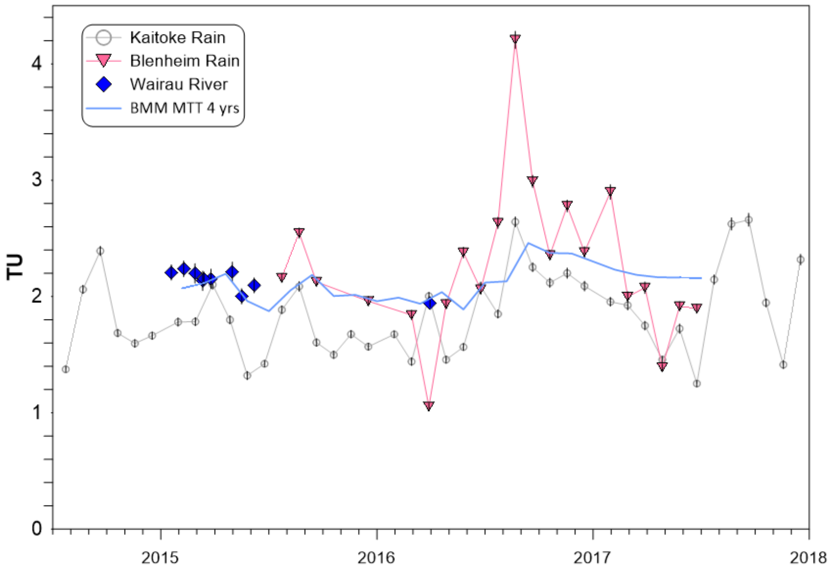

Figure 4.2 Tritium ratios in rain of Kaitoke and Blenheim (Figure 2.2) measured in monthly samples and from the Wairau River sampled at SH 6 (Figure 2.3).

Figure 4.2 also shows tritium ratios for the Wairau River for comparison, with similar tritium ratios for Blenheim rain and the Wairau River. To provide a better overlap between the Wairau River and Blenheim rain data, the fit to the river tritium data (Section 4.1.5) is also shown in light blue. The high-altitude Wairau River catchment is expected to exhibit even higher tritium concentrations than Wairau rain, as indicated by its significantly higher altitude catchment (Figure 2.2), in accordance with its more negative stable isotope signature (Taylor et al. 1992). However, passage of the water through the upper catchment groundwater reservoir provides storage that is sufficiently large that the Wairau River water is delayed and thus already significantly tritium-decayed when it arrives at the Wairau Plain. The decay is such that the tritium ratio in the Wairau River water matches that of the local Wairau Plain (Section 4.1.2; Figure 4.2). The scaling factor of 1.22 can therefore be applied to both – to the local rain input over the Wairau Plain, and to the groundwater recharged from the river into its Holocene gravel fan.

For most of the wells in the Wairau Plain, sufficient tritium time-series data were available to constrain both parameters of the age distribution (refer to Section 3.1). Figure 4.3 shows examples of the model fits to the measured data.

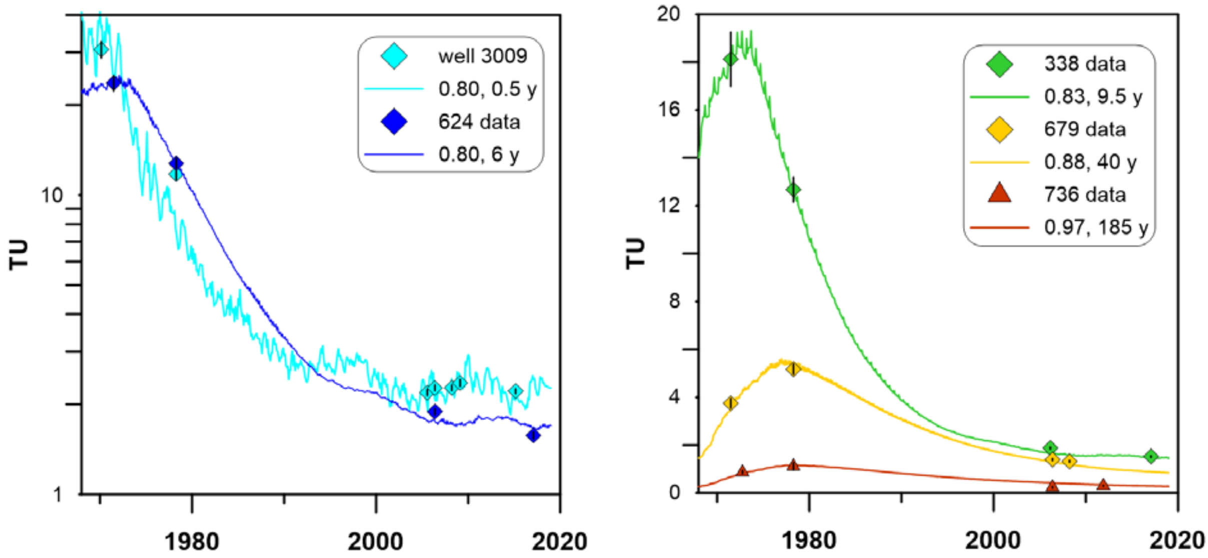

Figure 4.3 Typical time-series tritium data (error bars one-sigma) with matched outputs of the exponential piston flow model for very young (left) and older (right) water. Note the log scale in the left and linear scale in the right figure. The legends show well ID, together with the matching age distribution parameters. The first parameter is f, the fraction of the exponential (mixed) flow volume within the total flow volume, and the second parameter is the MRT in years.

The MRTs are listed in Appendix 1 and shown in Figure 4.4, together with well depth (outer circle) for context. The entire data set, including tracer concentrations, is attached in electronic form.

Throughout the unconfined Wairau Fan, we observed only very young groundwater (0–1 years), even in the deeper wells (> 20 m). Along the southern boundary, between the Holocene and the Pleistocene gravel deposits, groundwaters are slightly older, about two years. In major contrast, all groundwaters within the Pleistocene gravel deposits are very old (> 100 years). Groundwaters in the Deep Wairau Aquifer south of the Fairhall Fan and Blenheim are extremely old, up to 39,000 years (Morgenstern et al. 2008), indicating they are trapped and not part of the current active groundwater flow. The southern-most shallower wells also contain old water, as well as a small contribution of young water. The shallow well in the Holocene deposits of the Omaka River also contains very young water, indicating connection to the river.

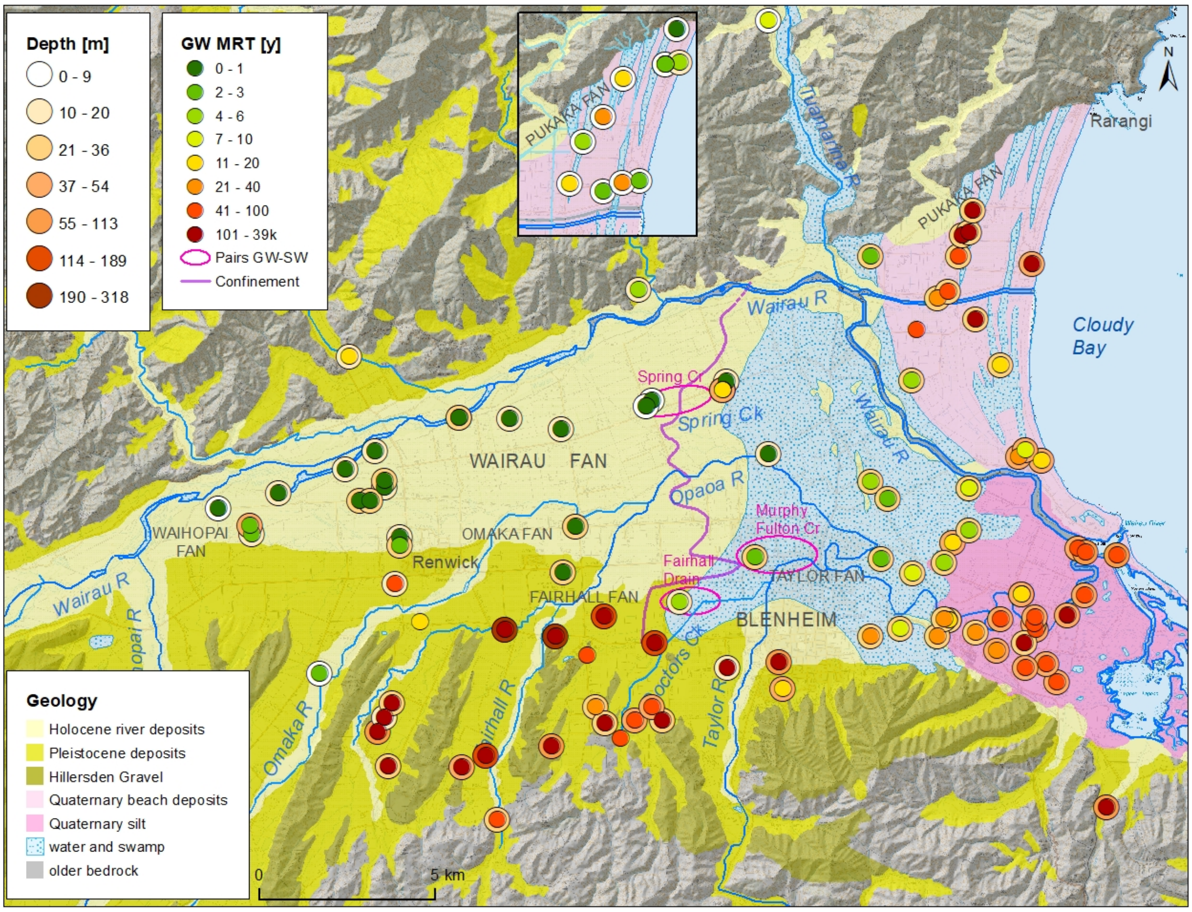

Figure 4.4 Map of groundwater mean residence time (MRT) in years (inner circle). Well depth in metres (outer circle) is shown for context. Aquifer confinement is shown in Figure 2.7. The insert on the top shows MRT and depth for the Rarangi Shallow Aquifer, while the main figure shows the data only in the confined aquifer in this area.

In the confined part of the gravel deposits in the centre of the valley (confinement boundary indicated by the purple line in Figure 4.4) groundwaters are older, from two years near the boundary to 10–40 years near the coast in the centre of the valley. This relatively young groundwater near the coast indicates active groundwater flow to this part of the confined aquifer.

Groundwater in the confined aquifer near the coast is much older toward the northern and southern boundaries of the valley, in the range of 100 years. Groundwater there also shows an age increase from west toward the coast, but also becomes progressively older toward the boundaries of the valley, indicating increasingly sluggish flow, likely due to increasingly finer deposits toward the northern and southern ends of the valley.

In the Quaternary beach deposits south of Rarangi overlying the confined aquifer, groundwater is relatively young (Figure 4.4 insert). This groundwater is recharged from local rain (Section 4.3.1), and the variable ages indicate partially confined flow conditions (Section 4.3.2).

Increasing groundwater ages from the start of confinement towards the coast along the area slightly off-centre to the south, with relatively young groundwater near the coast, is consistent with gravel lens deposits of paleochannels of the Wairau River, as modelled from lithologic well-log descriptions by Raiber et al. (2012). The results from multivariate statistical techniques of hydrochemistry indicative of evolutionary pathways (Raiber et al. 2012) are, in principle, consistent with our groundwater ages as determined from the age-tracer signature of the water.

4.1.1.2 Results from Seasonal Signals

Tritium data and highly variable stable isotope and temperature data measured in the past suggest extremely young groundwater of around one year or less across the Holocene Wairau Fan. Such young groundwaters across the entire fan from the recharge area up to the main discharge area, Spring Creek, and in wells up to 50 m depth, was unexpected. To confirm and refine such young water ages, tracers with a variable input signal were applied, including temperature and stable isotopes.

Temperature Logger Records

Close et al. (2017) logged groundwater temperature in 14 wells in the recharge zone of the Wairau Aquifer during 2014 and 2015. We added three additional monitoring points to the network from January to April 2016. Figure 4.5 shows typical records. Using an analytical approach, Close et al. (2017) determined lagged responses of the sinusoidal temperature variation between those measured in the wells and those in the river, ranging in amplitude from 0.19 to 15.1°C and in lag from 1 day near the river to 325 days 5 km down-gradient. They modelled the temperature responses using a numerical approach in order to provide insight into river recharge processes.

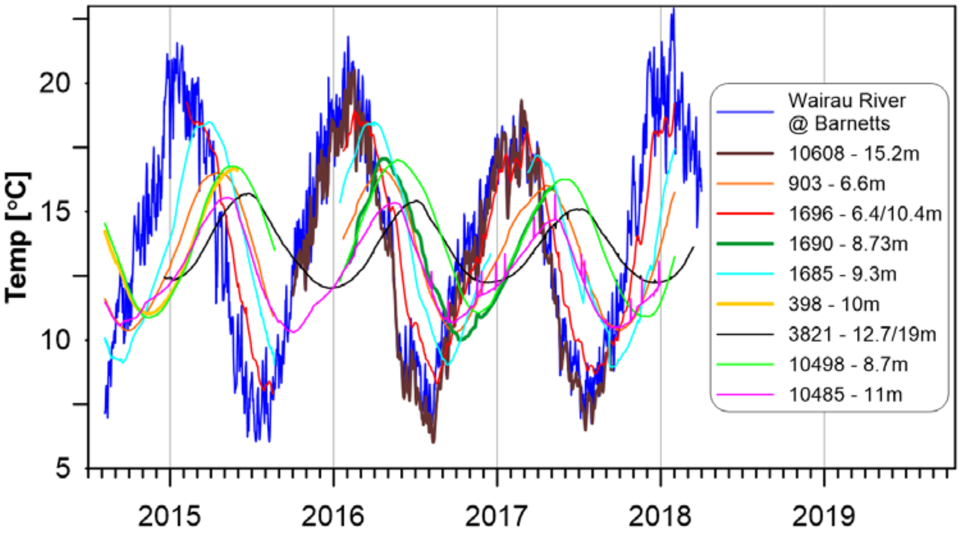

Figure 4.5 Mean daily temperatures of groundwater sites, showing the lagged temperature response in the wells in relation to the Wairau River, the main recharge source. Legend shows well ID, with locations shown in Figure 2.7 (red outer circle) and temperature logger position below the ground surface. Temperature data up to mid-2016 from Close et al. (2017).

Differences between logged temperatures and those measured in the pumped water during sampling at a different well, 3009, by about 1°C and with less variability in the pumped water, raised concern of potential interference with the temperature loggers by heat flux from the surface at the well site. Even though the temperature logger at this well was placed at the shallowest depth (3.9 m) of all wells, at this depth the surface temperature interference is still expected to be insignificant. The temperature difference between the logger (unpumped well) and the temperature in the pumped water is likely to be because, during pumping, deeper groundwater with less temperature variability is drawn to the surface.

A number of facts provide further indication that the temperature variability observed in the wells is a response to the temperature variability of the input signal of the water from the river through the aquifer. Close et al. (2017) show a reasonable correlation between temperature lag time and distance to the recharge source, the river. If the surface temperature was the driver for the temperature variability in the wells at these depths, no such correlation would be observed. At several sites, two more facts rule out the possibility that the observed temperature variability is caused by heat flux from the surface: too short a lag and too high a variability at great depth. Well 10608 shows a lag time of only 2 days at a depth of 15 m. Well 7007 (in Close et al. 2017) shows a logged temperature range of 15°C, similar to that of the river water, at a depth 8.7 m, and well 3821 shows a logged temperature range of 3.7°C at 12.7 m depth.

Even though temperature is not a conservative tracer due to buffering of the signal by the thermal mass of the aquifer material, the lag of temperature variation in the aquifer can at least provide a maximum water age. The retardation of the temperature signal, defined as the ratio of observed temperature lag to the true water age, can be established from conservative tracers, for example, the stable isotope lag time.

Wairau River Seasonal $\delta^{18}O$ Variability

With such distinct temperature variability signals in the groundwater across the Wairau Fan, we also expect that the more conservative seasonal variability of stable isotope ratios from the river source is present in these groundwaters and that their lag can be used to determine true groundwater travel times.

Water stable isotope ratios in rivers generally exhibit seasonal variability, with more negative ratios during the colder seasons and less negative ratios during the warmer seasons. Stable isotope variability was also observed in the Wairau Aquifer in near-river groundwater wells (Taylor et al. 1992; Stewart 2008), indicating the potential of using the stable isotope variability and subsequent damping as a tracer of the groundwater flow. To establish the $\delta^{18}O$ input signal of the Wairau River water into the aquifer, including the amplitude of the seasonal variability and the mean ^{18}O ratio, the river had been sampled monthly over several annual periods over the recent decade.

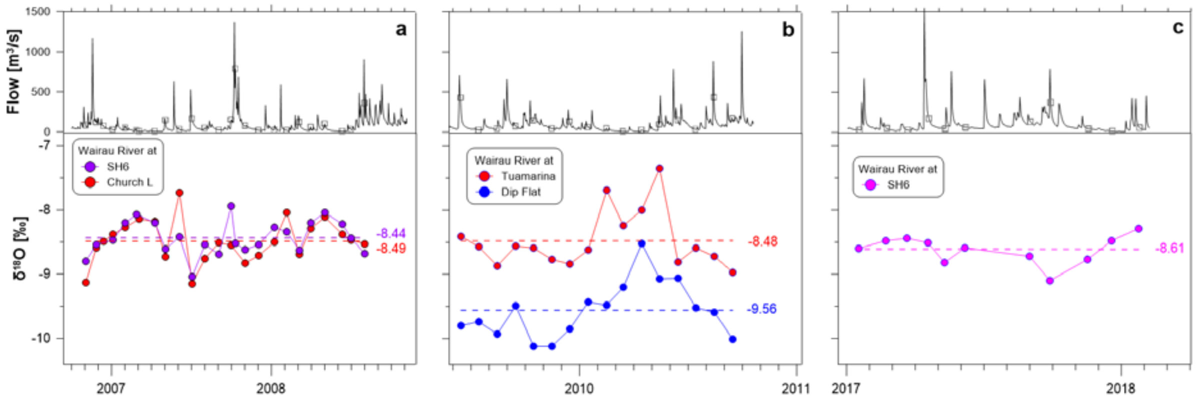

Figure 4.6 Seasonal variability of $\delta^{18}O$ of the Wairau River water over three periods at various locations (Figures 2.2 and 2.3). Upper figures show river flow at Barnetts gauging station (SH 1), with grey squares indicating the flow at approximately the time of sampling. Dotted lines show the averages, with their numerical values at the right.

Figure 4.6 shows the seasonal variability of $\delta^{18}O$ in the Wairau River over three periods, together with river flow. Samples were collected through a) an earlier MDC survey of river–groundwater interaction on paired surface water and groundwater sites during 2006–08, b) the Isoscapes project (Baisden et al. 2016) during 2009–10 and c) this project in 2017. The sampling site at Dip Flat lies in the upper catchment where the river leaves the mountains (Figure 2.1), and Tuamarina, Church Lane and SH 6 are within or close to the stretch where the river recharges the aquifer (Figure 2.3).

The Dip Flat data (Figure 4.6b) represent the undiluted $\delta^{18}O$ ratio of the headwater catchment of the Wairau River, which has a higher rain contribution from upper tropospheric moisture (Section 2.2). Its mean $\delta^{18}O$ ratio is -9.56‰, about 1‰ more negative than at the downstream Tuamarina site, which has a mean $\delta^{18}O$ ratio of -8.48‰ over the same period due to contribution of water from lower altitude catchments. The mean $\delta^{18}O$ ratios at the low-altitude sites Tuamarina, Church Lane and SH 6 (Figures 4.6a–c) are reproducible throughout the different periods and sites, with an overall average of -8.51‰. This value represents the $\delta^{18}O$ ratio of the recent river water input to the Wairau Aquifer.

An amplitude of the seasonal $\delta^{18}O$ variability of approximately 1‰ was observed through the three sampled periods (Figure 4.6). Only during the summer of 2010 did the available $\delta^{18}O$ data show a distinct peak of less negative ratios significantly exceeding the amplitude of 1‰. The river was approximately at baseflow during this time (Figure 4.6b, upper panel), indicating that these peaks were not a result of individual storm events but rather due to enhanced input of oceanic moisture, for example, through more pronounced NE weather systems.

Matching $\delta^{18}O$ variability observed in groundwater samples from the Wairau Fan confirms that these groundwaters are very young, with MRTs of less than one year. The tritium concentrations also suggest MRT < 1y.

Groundwater Seasonal Variability

To obtain further insight into the age range of such young groundwater in the Wairau Fan unconfined aquifer, over the period of one year we collected samples from and measured field parameters in the river, six wells and Spring Creek (headwater), one of the main discharges of this aquifer. Figure 4.7 shows the observed $\delta^{18}O$ ratios together with measured field parameters.

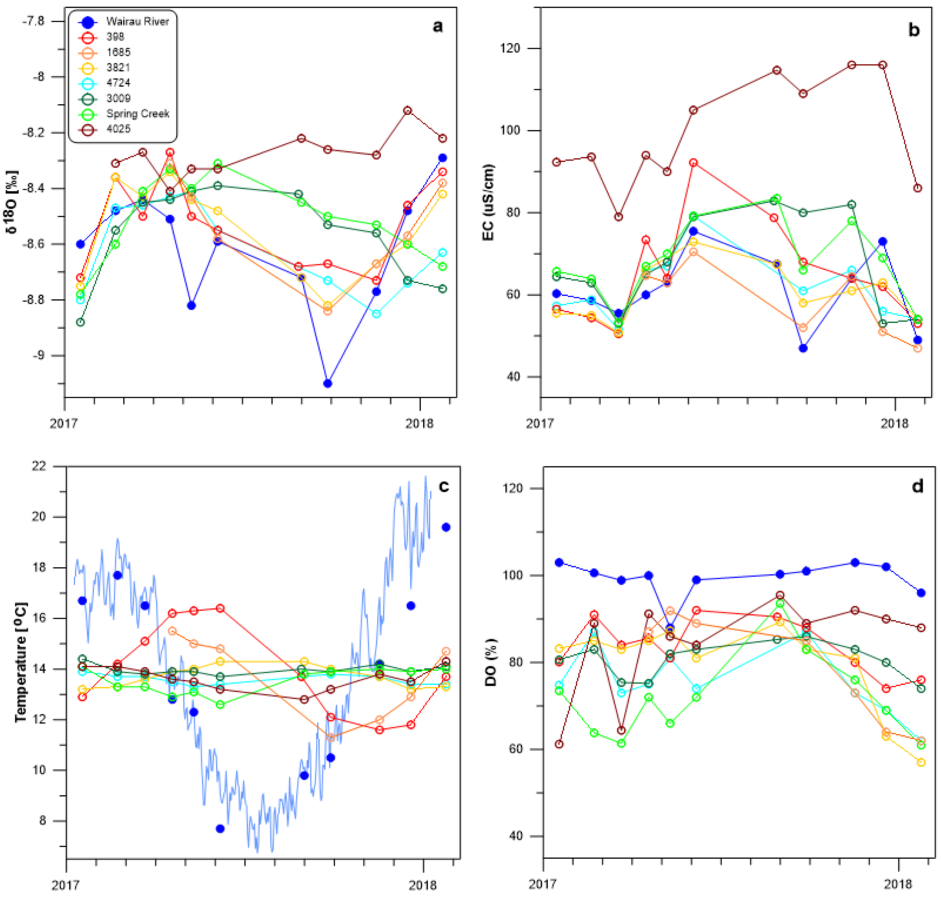

Figure 4.7 $\delta^{18}O$, electric conductivity (EC), temperature, and dissolved oxygen (DO) in the river, spring and groundwater. For temperature, daily means (light blue lines) are added to the temperature measured during sampling (dark blue points).

The Wairau River exhibits the most negative $\delta^{18}O$ ratios (Figure 4.7a). The less negative $\delta^{18}O$ ratios of all groundwaters indicate that all groundwaters have an additional contribution from local rain water. Well 398, a shallow well next to the Wairau River within the area where river water is lost to the aquifer, shows a variability that is nearly in phase with that of the river. Well 3821, a deeper well at the same location, and well 1685 show a $\delta^{18}O$ variability out of phase to that of the river by c. 0.04 years, and well 4724 by c. 0.08 years. The variability signals of Spring Creek and well 3009 further down-gradient are more out of phase to that of the river by c. 0.33 years. The $\delta^{18}O$ variability of well 4025 appears to be poorly correlated with that of the Wairau River. However, as its $\delta^{18}O$ ratio is significantly more negative than -8‰ but less negative than that of the Wairau River, this well's main water source is likely to be the Waihopai River – the well is located just downstream of the Waihopai Fan. Tritium indicates a MRT of about 1.5 years, and also the more damped $\delta^{18}O$ signal indicates older water than the other wells, so the different trend of $\delta^{18}O$ is likely to represent the damped Waihopai River pulse from the previous year.

Electric conductivity (EC), dissolved oxygen (DO), temperature and pH are not conservative tracers, as they change due to water-rock interaction and microbial reactions or are buffered by the thermal mass of the aquifer. However, a few conclusions can be drawn from the seasonal trends of this data.

For EC (Figure 4.7b), wells 3821, 1685 and 4724 have outputs approximately in phase with that of the river. Well 3009 and Spring Creek have outputs very similar to each other but slightly elevated compared to the river, confirming similar evolutionary pathways and impact by land use for these two groundwater discharges, and indicating slightly longer residence times in the groundwater system compared to the wells that are more in phase with the river. The highest EC in well 4025 may also confirm the older age of this water. The data for well 398 are inconclusive, but elevated concentrations during the recharge season may point towards impacts of local land use.

Measured temperatures of the pumped groundwaters (Figure 4.7c) generally confirm the logged temperatures (Figure 4.5) despite their significantly lower resolution and potential interference by the pumping. The wells that showed high amplitudes and short lag times in the logged temperature variability (wells 1685, 398, 3821) show similar lag times to that of the river in the measured temperatures. Measured temperature variability during pumping in all other wells that were sampled is too small at this low resolution to establish lag times. The presence of a large amplitude of temperature variation at well 398 confirms the immediate link of this well to the river. However, the delay of the temperature summer peak by about 2.5 months, not indicated by $\delta^{18}O$, the direct tracer for flow time, indicates the large lag due to the thermal mass of the aquifer buffering the temperature signal.

DO in the groundwater is a reflection of the availability of electron donors in the aquifer matrix to facilitate microbial reactions that consume the oxygen. All analysed groundwaters are slightly depleted in DO (Figure 4.7d), with the least depletion during winter. This likely reflects slower microbial reactions due to colder conditions in the groundwater recharge zone near the river and less efficient exposure of the water to microbial reactions due to faster groundwater flow in that zone during winter, caused by higher river discharge into the aquifer at higher river flows. Spring Creek water is the most depleted in DO during summer, consistent with this being some of the oldest water in the Wairau Fan with the longest exposure to microbial oxygen uptake. The water in well 4025 is the least depleted in DO, despite its older age, likely reflecting ‘cleaner’ gravels at the top of the fan that contain less organic matter to provide electron donors for microbial oxygen depletion. The variability in DO may reflect seasonality of oxygen uptake in the shallow groundwater system but does not allow the identification of lag time of the groundwater flow.

The pH (not shown) of groundwater tends to increase over longer time scales (years, decades, centuries) due to water-rock interaction reactions. Over short time scales (days/months) of transition from the river to the groundwater environment, we expect the pH of the water to decrease due to uptake of soil CO_2 in the aquifer. The water from wells 1685 and 3821 showed only slightly decreased pH, while the waters from well 3009 and Spring Creek have the lowest pH, confirming the findings from the $\delta^{18}O$ variability that these discharges represent the youngest and oldest waters, respectively, of this sample set. Well 4025 shows inconsistently low and high pH.

Even though temperature input variability is buffered due to the large thermal mass of the aquifer material, its retardation with respect to the groundwater flow can be established by the ratio of the temperature to the $\delta^{18}O$ lag. Three wells had overlapping temperature and stable isotope data, providing retardation factors of 9.1, 7.0 and 8.7. The mean of 8.3 was used to convert the lags of the logged temperature signals (Figure 4.5) to groundwater residence time.

Continuous groundwater temperature logs are simple to obtain and, once calibrated by the conservative stable isotopes, their temperature lags provide an easy means to establish water travel time for very young groundwater (< 1 year). Stable isotopes are conservative tracers for the water flow but require discrete sampling and analyses, and therefore stable isotope records usually have significantly less resolution.

MRTs for these very young groundwaters, as deduced from age tracers and calibrated seasonal temperature variability on a scale of 0–10 years, are shown in Figure 4.8. Wells down-gradient, in close proximity to the river (distance < 1 km), contain extremely young water of < 0.03 years. Slightly further down-gradient (2–3 km from the river) groundwaters are slightly older, 0.04–0.1 years. Groundwater and the spring discharge near Spring Creek have residence and transit times of 0.1–0.33 years. These are all extremely young waters, considering their groundwater travel distance of several kilometres from the river recharge zone. Further down-gradient, in the confined part of the Wairau Fan, groundwaters are becoming older but are still < 10 years near the coast in the centre of the valley.

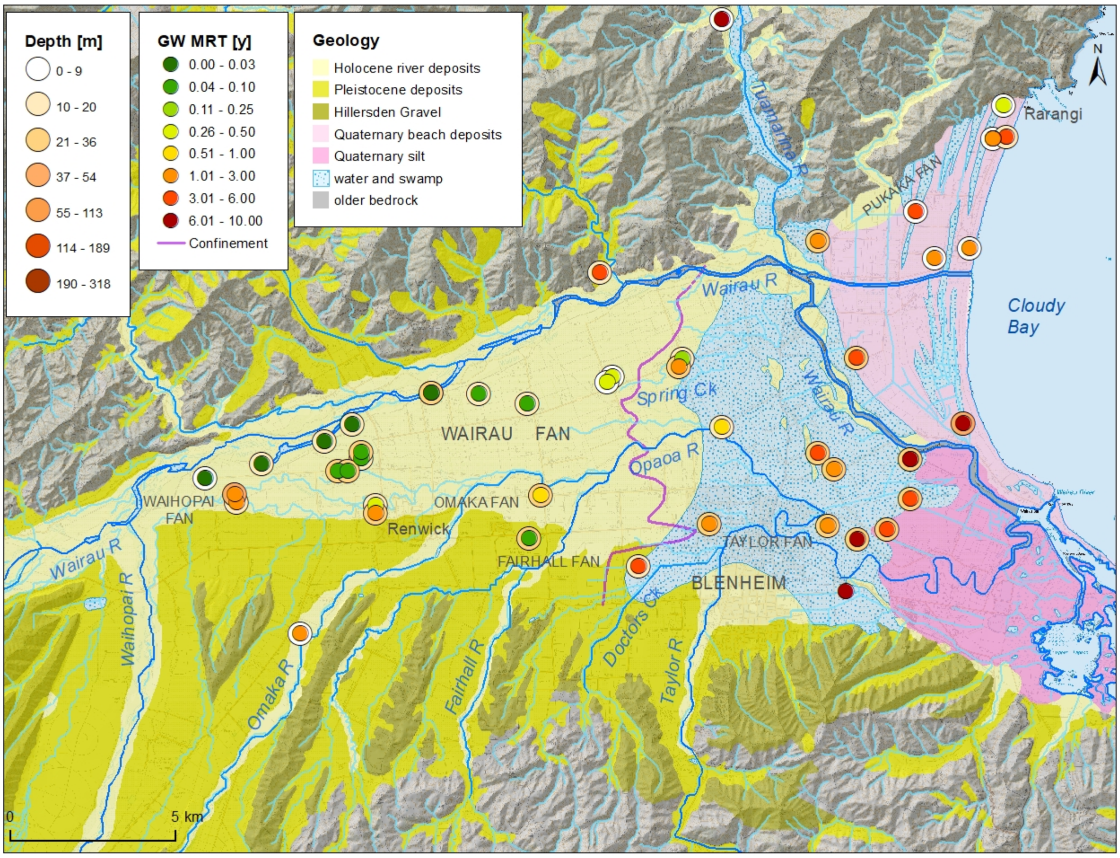

Figure 4.8 Map of mean residence times (MRT) for young groundwater in years (inner circle). Well depth in metres (outer circle) is shown for context. Aquifer confinement is shown in Figure 2.8, with the extent of the confining layer of the Wairau Fan indicated by the purple line.

The unconfined Wairau Fan has a relatively large extent, and MRTs of several years were expected in its down-gradient part. However, these results show that the groundwater flow is extremely fast in this aquifer, with transit times of only 0.33 years at its main discharge, Spring Creek.

4.1.1.3 Results from Radon-222

Radon-222 (^{222}Rn) concentrations in surface waters are low, and it takes several weeks for the ^{222}Rn to equilibrate to the ambient concentration of the groundwater (Section 3.1). Therefore, low ^{222}Rn concentrations may indicate very young groundwater.

The spatial distribution of ^{222}Rn is shown in Figure 4.9. Groundwaters older than a few weeks indicate that ambient groundwater ^{222}Rn concentrations in the Wairau Fan gravels approximately vary between 5 and 20 mBq/L. Two wells next to the river north-west of Renwick have unusual low ^{222}Rn concentration, confirming the young age of the water.