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

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ATTACHMENTS

Marlborough: Age tracer results……(Attached in PDF)

4.3 Groundwater Flow Dynamics

4.3.1 Recharge Source of Groundwater and Connection to Surface Water

Spring Creek and the spring-fed Blenheim urban streams (Figure 4.3) are highly valued for their sparkling clear water and aquatic life. For management of the water quality and minimum flows in these streams, it is crucial to understand the source of these springs and their dynamic connection to the groundwater flow. The isotopic signature and the age of the stream water, and comparison to surrounding groundwater, allows for an improved understanding of the flow sources and connections.

Useful tools for distinguishing between potential groundwater recharge sources are provided by the hydrochemical composition of the water, in particular chloride, with contrasting concentrations between high-altitude inland river water and coastal local rain. With no significant sources in the groundwater system, chloride is also a conservative tracer, enabling low concentrations to indicate river recharge without ambiguity (Figure 4.19).

Another conservative tracer with contrasting concentrations between high-altitude river water and low-altitude local rain is $\delta^{18}O$. Taylor et al. (1992) and Stewart (2008) estimated ranges of $\delta^{18}O$ that indicate river recharge, local rain recharge, and a mix of the two. They concluded that mean values are required because the river water and groundwater close to the river showed significant temporal variability.

We have now obtained a better understanding of these temporal variabilities from Wairau River data covering three annual cycles (Section 4.1.1.2). The Wairau River at the Wairau Fan has a long-term mean $\delta^{18}O$ ratio of -8.51‰, with a seasonal $\delta^{18}O$ variability of approximately 1‰ (Figure 4.6). Figure 4.26 shows the spatial distribution of mean $\delta^{18}O$ in the Wairau Plain aquifers. In contrast, the $\delta^{18}O$ ratios of locally recharged precipitation in the Wairau Plain are represented by the $\delta^{18}O$ ratios found in the shallow wells in the northern part of the Quaternary beach deposits near Rarangi (green circles in insert) with a mean of -6.64‰ (nine samples).

A number of groundwaters in the unconfined Wairau Fan, and most of the groundwaters in the confined aquifer, have $\delta^{18}O$ ratios that match those of the Wairau River, indicating the river as their recharge source. This recharge pattern is corroborated by the nitrate and chloride data (Section 4.2.4).

The upstream part of the Wairau Fan borders onto Waihopai Fan. The wells in this area, both shallow and deep, contain groundwater with slightly less negative $\delta^{18}O$ ratios, indicating the Waihopai River as their recharge source, and good hydraulic connection between the two fans.

Where multi-depth wells are available close to the Wairau River north of Renwick, the shallower wells match the river signature and the water of the deeper wells has slightly less negative $\delta^{18}O$ ratios, indicating that Wairau River-recharged groundwater south of the Wairau River overlies a flux of groundwater recharging into the Wairau Fan from the northern hill discharges. The situation is similar downstream of Waihopai Fan; the deeper well has a slightly less negative $\delta^{18}O$ ratio, indicating a flux of groundwater recharged from the Waihopai River into its fan further upstream that underlies the water flux recharged from the Wairau River.

The wells close to the boundary between the Holocene and Pleistocene deposits, and the shallow well in the Holocene deposits of Omaka River, contain groundwater with significantly less negative $\delta^{18}O$ ratios towards those of coastal rain near Rarangi, indicating local rain and southern tributaries as the main recharge source. These groundwaters are also characterised by the highest NO_3-N concentrations, confirming the recharge pattern obtained from ^{18}O.

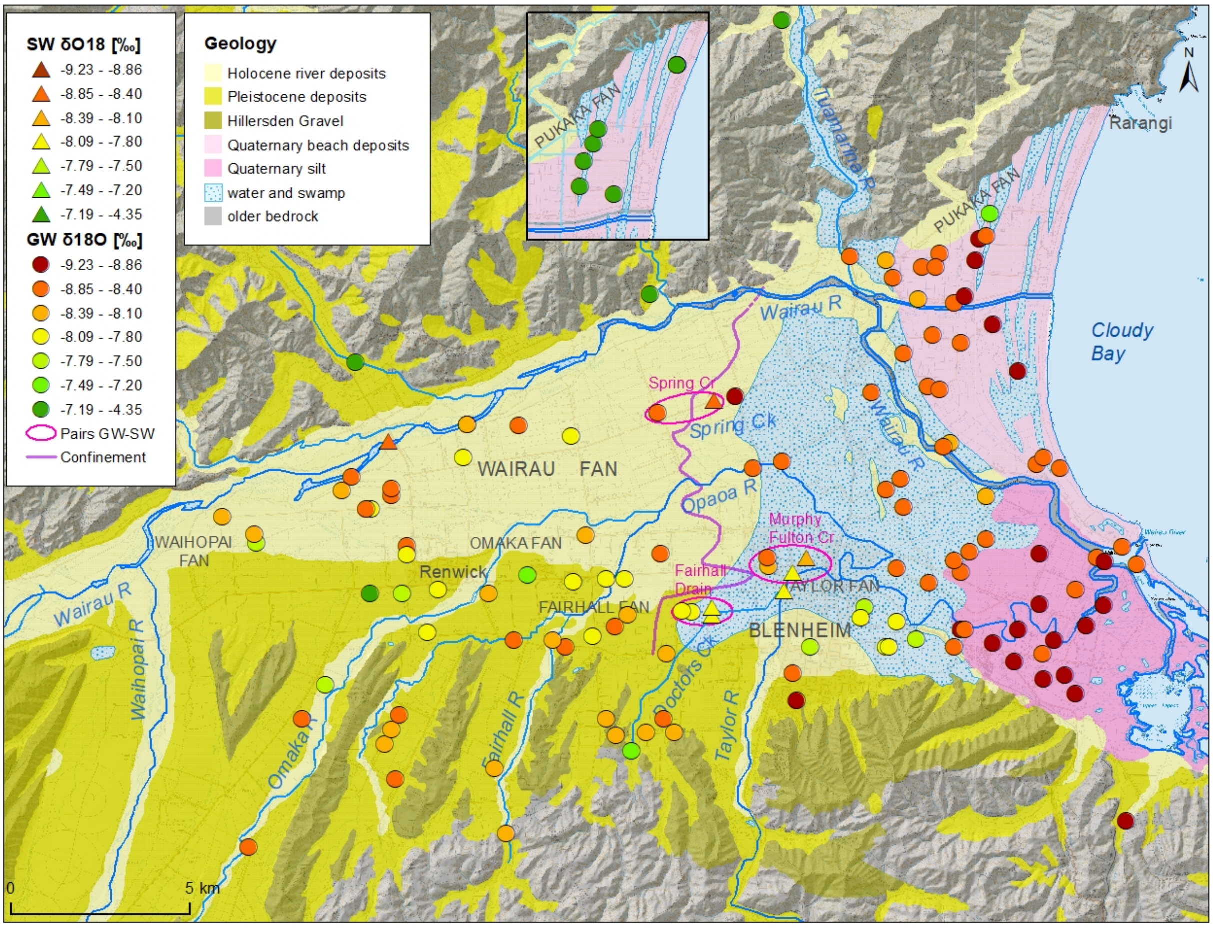

Figure 4.26 Spatial distribution of $\delta^{18}O$ of surface water and shallow groundwater in the Wairau Plain. Symbols: triangles for surface water, circles for groundwater. Red ellipses show areas of paired sampling of surface and shallow groundwater. The insert on the top shows $\delta^{18}O$ for the Rarangi Shallow Aquifer, while the main figure shows the $\delta^{18}O$ only in the confined aquifer in this area.

The wells in the Pleistocene deposits south of the Holocene Wairau Fan contain water with mixed $\delta^{18}O$ ratios within the more negative half of the spectrum. Chloride also shows mixed concentrations. NO_3-N is generally very low, as expected in such anoxic groundwaters. The $\delta^{18}O$ ratios are not consistent with those of current local rainfall but may be consistent with rain or river recharge during previous climatic periods. These groundwaters are generally very old.

The Wairau River ^{18}O signature extends from the Wairau Fan into the confined aquifer in the central part up to the coast, indicating that the water source there is the current Wairau River. In the northern and southern part of the coastal confined aquifer, the stable isotope signature of the groundwaters does not match those of the Wairau River, indicating that the water in these parts of the aquifer does not originate from the current Wairau River. Furthest in the north, the less negative $\delta^{18}O$ ratio indicates recharge from the northern tributary via the Pukaka Fan, and therefore connection of the Pukaka Fan to the confined aquifer.

The two clusters of wells in the confined aquifer in the northern and southern part of the coastal aquifer contain water with $\delta^{18}O$ ratios more negative than -8.85‰ (dark red circles), which is significantly more negative than the current mean for the Wairau River. Most of these groundwaters contain some tritium; they are decades old, but not hundreds or thousands of years old. It is therefore unlikely that these very negative δ^{18}O ratios are a result of recharge during a cooler climate. The artesian nature of these wells also makes mixing of small fractions of young water with very old deeper water unlikely. At this stage there is no explanation for these low δ^{18}O ratios, and we recommend re-sampling these wells to confirm these low δ^{18}O ratios and collecting data that can provide an explanation for the observed pattern, potentially involving leakage of pressurised very old Deep Wairau Aquifer water moving to the surface under a strong vertical pressure gradient (potentially fault-related).

The shallow wells in the northern part of the Quaternary beach deposits near Rarangi contain groundwater with significantly less negative δ^{18}O ratios (> -7.5‰, green symbols in insert) which, as it cannot be Wairau River water, must be recharge from the local coastal rain. The groundwater north of the Wairau River, also recharged by local rain, has similar δ^{18}O ratios.

Spring Creek is fed by shallow groundwater recharged from the Wairau River, as indicated by matching δ^{18}O ratios. Doctors Creek and Fairhall Drain are fed by discharge from the southern hills around Fairhall River, as indicated by their less negative δ^{18}O ratios (Figure 4.26). Murphy and Fulton Creeks are fed by a mix between these southern hill discharges and Wairau River-fed groundwater, as indicated by δ^{18}O ratios between those of the Wairau River and local rain.

Close connection between shallow groundwater and the main spring discharges near the start of confinement is demonstrated by matching δ^{18}O ratios between the spring-fed streams and nearby shallow groundwater. Pairs of samples from the main surface water discharges and shallow groundwater are indicated in Figure 4.26 by red ellipses.

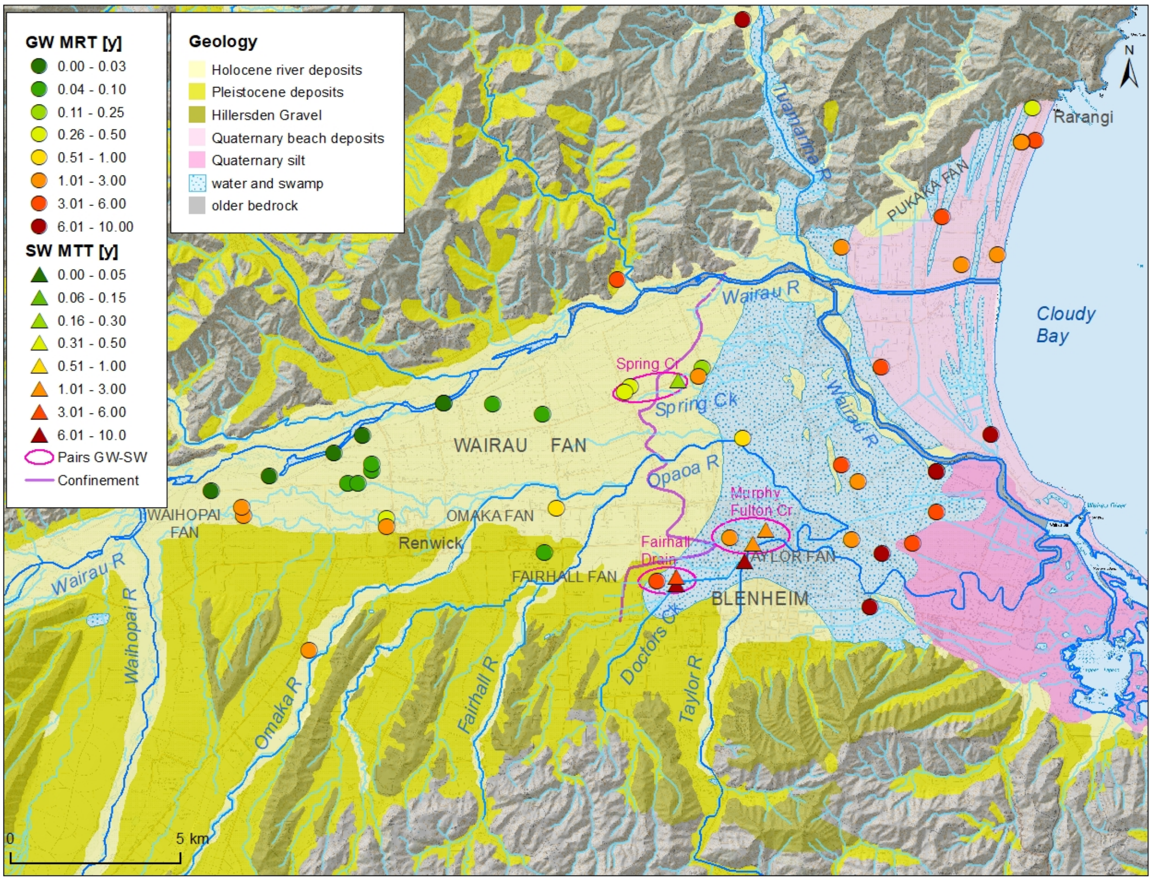

Figure 4.27 Spatial distribution of the mean transit time (MTT) of surface water and the mean residence time (MRT) of shallow groundwater in the Wairau Plain. Symbols: triangles for surface water, circles for groundwater. Red ellipses show areas of paired sampling of surface water together with shallow groundwater.

Close connection between shallow groundwater and the main spring discharges near the start of confinement is indicated not only by matching δ^{18}O ratios but also by matching water ages (Figure 4.27). Water ages match between Spring Creek and the Blenheim urban streams and their surrounding shallow groundwater (pairs of surface water and shallow groundwaters indicated by red ellipses in both figures).

The ^{18}O and groundwater age data indicate a clear pattern of recharge source and connection of the Wairau River and spring discharges to the groundwater system. NO_3-N and Cl concentrations (more useful than the HCA clusters due to better spatial coverage) are consistent with the recharge patterns derived from ^{18}O and groundwater age.

4.3.2 Vertical Flow and Local Recharge

Unconfined recharge situations result in stratified groundwater ages and the vertical recharge rate can be estimated from the age-depth relationship of the groundwater (Cartwright and Morgenstern 2012; Morgenstern et al. 2009). Figure 4.28 shows groundwater age versus depth for the Wairau Plain groundwaters.

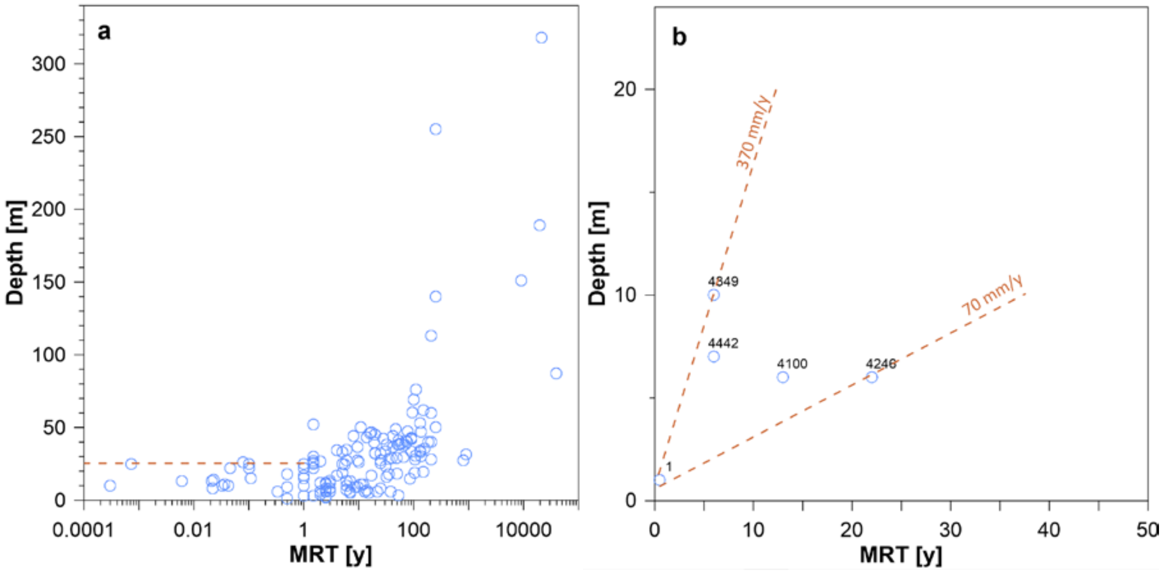

Figure 4.28 Groundwater MRT vs. depth for a) all wells and b) the Rarangi unconfined aquifer. Labels in b) refer to IDs in Figure 2.7 and Appendix 1. Age vs. depth trends for vertical recharge rates of 70 and 360 mm/y are indicated by orange broken lines (assuming a porosity of 0.25).

There is no unique trend overall between groundwater age and depth, indicating confined conditions throughout large parts of the aquifer and the dominance of recharge via Wairau River water. Old groundwater with MRTs of up to 50 years at shallow depth (< 10 m) clearly indicates confined conditions in those parts of the aquifer.

The data for MRTs younger than one year are from the unconfined Wairau Fan and show the presence of very young water (<< 1 year) at great depths; up to 25 m (Figure 4.28a, orange broken line). This is consistent only with the dominance of recharge by river water. Such rapid groundwater flow to a depth of 25 m indicates extremely high hydraulic conductivity of the Holocene gravels down to that depth. Note that such rapid groundwater flow also appears to occur through lenses of deposits, causing highly anoxic conditions (Section 4.2 1).

For the Rarangi Shallow Aquifer near the coast overlying the confined aquifer (Figure 2.7), the available groundwater age and well depth data are shown in Figure 4.28b. The poor correlation between groundwater depth and age indicates the presence of lenses of finer sand, clay and peat, the remnants of wetlands (Davidson and Wilson 2011), which can act as partial confinement in parts of the aquifer. The recharge rates to the deeper groundwater system (> 5m), deduced from the available data using an assumed porosity of c. 0.25, spans the bracket between 70 and 360 mm/y. This range overlaps with the estimate of 320 mm/y made with soil balance models (Davidson and Wilson 2011). However, the average of recharge rates as deduced from age-depth data is significantly lower, which is expected because transfer of the water into the deeper groundwater system depends, in addition to soil hydraulic properties, on the hydraulic properties of the deeper aquifer layers.

The very old age (up to 40,000 years) of the water in the Deep Wairau Aquifer, west of Blenheim in the Pleistocene deposits, indicates very low recharge into this aquifer, i.e. less than 5 mm/y. For the sites with the oldest water, the recharge probably occurred mainly at the time of lower sea levels and their related higher hydraulic gradients, so the current recharge into the deep Wairau Aquifer is probably negligible.

Land surface recharge in the unconfined Wairau Fan can be estimated using the contrasting $\delta^{18}O$ ratios between the water of the Wairau River and that of local rain recharge. Local rain recharge over recent decades has a mean $\delta^{18}O$ ratio of -6.64‰ (Section 4.3.1), in contrast to that of the Wairau River of -8.51‰ (Section 4.1.1.2).

In Spring Creek the main discharge of the Wairau Fan, the mean $\delta^{18}O$ ratio through an annual sampling cycle, is similar to that of the Wairau River (Figures 4.7 and 4.26), implying that the contribution from land surface recharge in the unconfined Wairau Fan is small. However, the land surface recharge is not negligible. Figure 4.7 shows that Spring Creek and all the Wairau Fan groundwaters within the same sampling period have slightly less negative $\delta^{18}O$ ratios compared to the Wairau River.

The few available data do not allow calculation of progressive addition of land surface recharge along the flow path in the unconfined Wairau Fan because the $\delta^{18}O$ ratios are slightly variable, likely related to seasonal variability in this very young water and spatial variability in hydraulic parameters. In the main flow system, Spring Creek and the central confined aquifer, with discharges more averaged over space and time, $\delta^{18}O$ ratios are relatively uniform and match that of the Wairau River.

The contribution of local rain recharge to the Spring Creek discharge can be calculated by applying the $\delta^{18}O$ mass balance to the time series of $\delta^{18}O$ ratios (Figure 4.7a). To compare the $\delta^{18}O$ ratios of the Wairau River and Spring Creek water over the same period, the mean $\delta^{18}O$ ratios for the Wairau River were calculated for the sampling period 31/3/16 to 1/9/17, and for Spring Creek for the sampling period 11/5/17 to 24/1/18, to account for the four months transit time (lag) at Spring Creek compared to the Wairau River. Shifting the $\delta^{18}O$ ratio of -8.59‰ in Wairau River to -8.50‰ in Spring Creek requires 4.5% of local rain water, containing a $\delta^{18}O$ ratio of -6.64‰. The 4.5% represents the total contribution of land surface recharge along the flow paths between the Wairau River and the Spring Creek discharge.

Water balance modelling for the whole unconfined Wairau Fan resulted in a land surface recharge of less than 4% of the total recharge into the Wairau Fan (Wöhling et al. 2018), in good agreement with the $\delta^{18}O$ mass balance result of 4.5% for the Spring Creek flow part. While this small land surface recharge contribution shifts the ^{18}O signature at Spring Creek only marginally, for NO_3-N from surface applications that small water contribution is enough to flush the NO_3-N that is not taken up by the plants into the aquifer. Hence, NO_3-N concentrations significant increase (Figure 4.20), but nearly constant $\delta^{18}O$ ratios (Figure 4.26) occur in the groundwater downstream in the Wairau Fan.

4.3.3 Horizontal Flow Rates

Figure 4.29 provides a schematic summary of the conceptual flow of the Wairau Plain aquifers that builds on the age, chemistry and stable-isotope data, and their interpretations, that are presented in the previous sections. Groundwater flow rates in the aquifer were estimated from horizontal groundwater age gradients. Piezometric contours from a survey in 1991 (Davidson and Wilson 2011) are included in Figure 4.29 as a guide to flow direction.

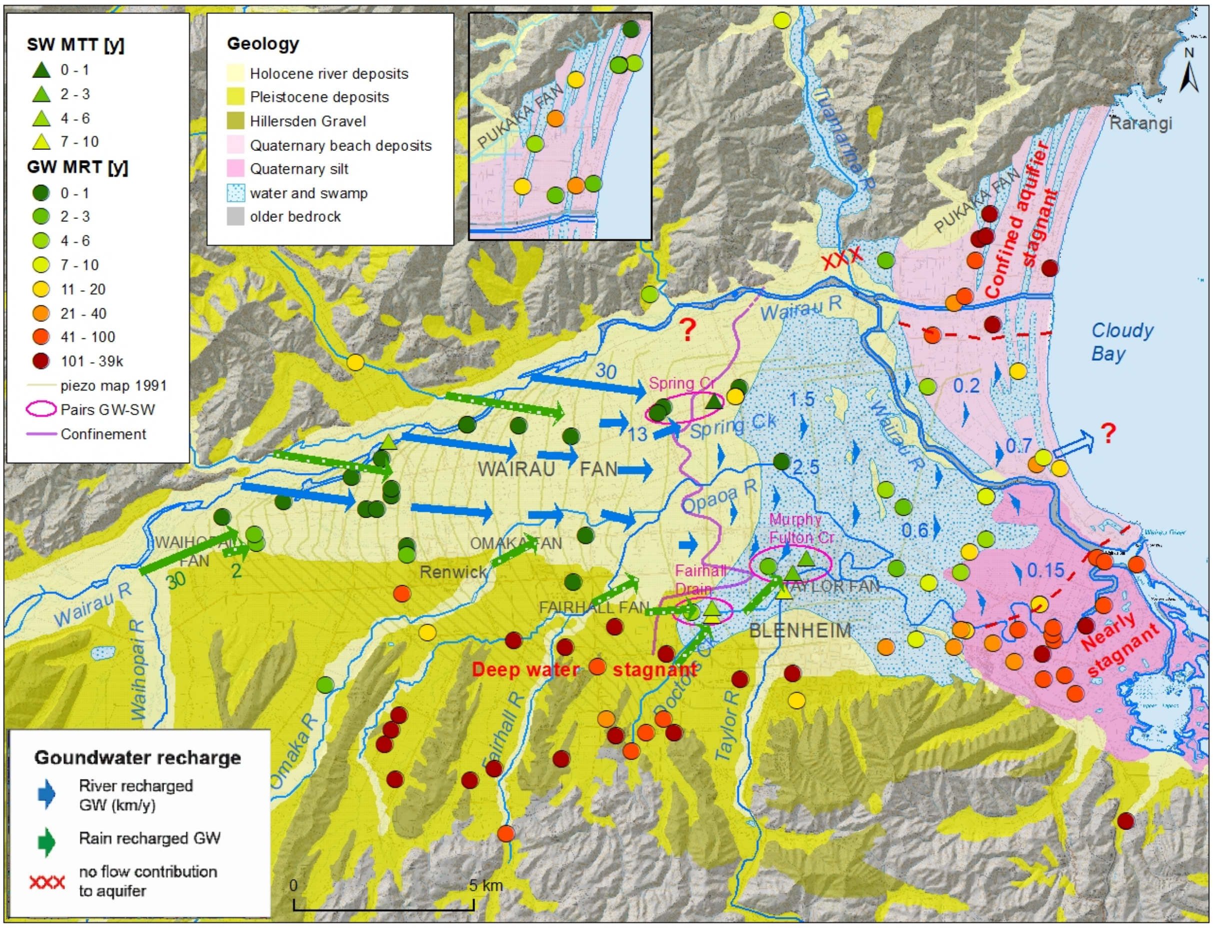

Figure 4.29 Groundwater dynamics in the Wairau Aquifer inferred from groundwater ages (circles). Active groundwater flow in the confined aquifer occurs in the centre of the valley between the two broken red lines near the coast. Blue arrows indicate Wairau River-recharged groundwater flows, and green arrows indicate groundwater recharge from southern and northern local low-altitude tributaries. The length of the arrows is approximately proportional to the groundwater flow rate (numbers in km/y). Dotted green arrows indicate only flow contribution in general, without information on flow rate. Flow rates decrease strongly from the recharge area toward the coast, from c. 30 km/y near the river in the west to 0.7 km/y near the coast in the centre of the valley. The hollow blue arrow there indicates potential for groundwater flow out to sea from the confined aquifer. Groundwater flow rates off-centre near the coast are significantly lower, c. 0.2 km/y in the north and 0.15 km/y in the south. There is also a slight contribution of local rain water from the surface into the unconfined aquifer downstream in the Wairau Fan, but this could not be shown visually. Red crosses indicate no connection of tributary river to the confined aquifer. Red question marks indicate unknown flow due to lack of data. Red ellipses indicate main spring discharge areas from the aquifer near the confinement boundary. The insert on the top shows the MRTs for the Rarangi Shallow Aquifer, while the main figure shows the MRTs only in the confined aquifer in this area. Piezometric contour lines 2 m.

In the upper half of the unconfined Wairau Fan, the Wairau River is well connected to the Wairau Fan. All wells next to the river in this area contain extremely young water, with MRT <0.03 years. Extremely high flow rates, as deduced from the age gradients, of c. 30 km/y in this area indicate extremely high hydraulic conductivity in these Holocene deposits near the river. A similar flow rate is also observed in the Waihopai Fan for groundwater recharged from the Waihopai River. In the Wairau Fan, such extremely young groundwaters, indicating high hydraulic conductivity, occur down to a depth of 25 m and through highly anoxic layers.

Towards the coast, the flow rates reduce considerably, with c. 13 km/y halfway toward the boundary of the confinement, and thereafter slowing further to 0.7 km/y near the coast in the centre of the valley. The reduction in flow rate near the coast, by a factor of > 20, is related to the flow loss from the aquifer, mainly to the spring belt and through abstraction.

Compared to the extremely high flow rates near the Wairau River, the flow rates near the coast appear low, but c. 0.7 km/y is still a relatively high flow rate. The presence of such young water (< 10 years) near the coast indicates active groundwater flow to this part of the aquifer. There is no data yet to distinguish between the two potential causes for this active flow: |aquifer leakage to the surface near the coast, or submarine discharge from the confined aquifer.

Flow rates off-centre near the coast decrease to < 0.2 km/y to the north and south. The northern and southern parts of the confined aquifer near the coast contain old water, indicating near-stagnant flow conditions. This is confirmed by the different δ^{18}O ratios and chloride concentrations in these parts of the aquifer on both sides of the valley near the coast. Restricted flow is also confirmed by lower well yields due to thinning gravel layers that are increasingly clogged with clay (Davidson and Wilson 2011).

Most of the groundwaters in the Pleistocene deposits south of the Wairau Fan are very old, indicating near-stagnant flow conditions. This is confirmed by the very low yields of the wells in these Southern Valley aquifers due to higher clay content (Davidson and Wilson 2011). In the Deep Wairau Aquifer in the Pleistocene deposits, groundwater ages are up to tens of thousands of years, indicating stagnant flow conditions in this formation.

In the north at Tuamarina River, the isotopic signature of the groundwater indicates limited, or non-existent, connection of the river to the confined aquifer. The δ^{18}O ratios of the Tuamarina Valley of > -7‰ are not observed in the groundwater downstream of the confluence between the Tuamarina and Wairau rivers. This is expected because the confluence lies in the confined zone. The lack of connection of the Tuamarina River to the confined aquifer is indicated by red crosses in Figure 4.29.

Green arrows in Figure 4.29 indicate the areas where the tracer signature indicates the presence of recharge from low altitude rain, locally derived and from the adjacent hills. For the Waihopai Fan, the source of the water is the Waihopai River, with groundwater flow rates similar to those observed in the Wairau Fan near the Wairau River. At the boundary to the Pleistocene deposits, flow rates are considerably lower, c. 2 km/year. Dotted green arrows indicate flow contributions from adjacent hill run-off, but because the recharge area is not known, no estimates of flow rates can be made. Increasing contribution of water from the surface into the unconfined aquifer downstream in the Wairau Fan is indicated by increasing nitrate concentrations (Figure 4.20).

The results for the spring-fed streams at the confinement boundary, which are the main natural discharge of the aquifer, are encircled in the red ellipses in Figure 4.29 with those of shallow groundwaters. The stream waters in the spring areas and surrounding shallow groundwaters have identical age and δ^{18}O ratios (Figures 4.26 and 4.29), indicating that the shallow groundwater is the source of the springs and streams.

4.3.4 Hydraulic Parameter and Aquifer Limits

Using the observed flow rates in the Wairau Fan, hydraulic parameters can be estimated to help identify the aquifer flow limits. Thorpe (1992) describes, according to Darcy's law, that hydraulic conductivity K = q/L, where q = flow rate and L = piezometric gradient and provides a K-range of 150–86,000 m/day for gravel aquifers. The piezometric gradient through the Wairau Fan is about 0.007 in the west near the river in its upper half, 0.003 in its centre and 0.002 near the confinement boundary in the east (Davidson and Wilson 2011).

With the estimated flow rates of c. 30 km/y, the hydraulic conductivity in the unconfined Wairau Fan near the river is estimated to be c. 11,700 m/day. With a flow velocity of c. 13 km/y, the hydraulic conductivity in the central part of the unconfined Wairau Fan is estimated to be 11,900 m/day, indicating similar hydraulic conductivity throughout the unconfined Wairau Fan. Near the coast in the central part of the confined aquifer, the estimated flow velocity of c. 0.7 km/y leads to a hydraulic conductivity of 800 m/day. These values are within the expected range.

With the flow rate of c. 30 km/y and an estimated porosity of 0.25, the seepage velocity can be estimated to c. 20 m/d in the recharge area of the Wairau Fan near the river. The groundwater flow through this part of the Wairau Fan, mainly through recharge from river flow loss, is estimated to 7 m^3/s (Davidson and Wilson 2011). The required cross-section to maintain that flow volume at that flow rate is c. 30,000 m^2 and, with an aquifer width perpendicular to the flow of 5.5 km, the water column depth to maintain that flow is estimated to be c. 5.5 m. With the porosity of 0.25, this implies that groundwater to a depth of c. 22 m below the water table is required to take part in this active groundwater flow. This is in agreement with the observed extremely young groundwater age at well 10608 at this depth.

The flow rate further down the Wairau Fan is significantly lower, c. 13 km/y halfway toward the spring discharges near the confining layer, resulting in a seepage velocity of c. 8.7 m/d. A cross-section to maintain the flow of 7 m^3/s of c. 70,000 m^2 would require an aquifer depth of c. 50 m to participate in this active flow. This exceeds the depth of the Holocene gravel aquifer (Section 2.3).

The above hydraulic parameters, estimated from the flow rates obtained from the groundwater age gradients, allow understanding of the declining water levels in the unconfined Holocene Wairau gravel fan (Figure 2.8) and pinpoint the limiting factor in the groundwater flow system.

The main recharge source of the Wairau Aquifer, the Wairau River, has never dried up throughout the recorded period (Figure 4.12). Availability of water for increased aquifer recharge should therefore not be a limiting factor. However, the observed declining water levels in the Wairau Fan indicate that, somewhere in the flow system, there is a limit reached to compensate increased abstraction; a limit either in water transfer from the river into the Wairau Fan or in transmission of water through the aquifer.

Water transfer from the river into the Wairau Fan is unlikely to cause the flow restriction because the extremely young water at well 10608 at 25 depth, next to the river, indicates that the surface flow is well connected to a large gravel 'underflow' and therefore, even at low river flows with decreased area of wetted gravel on the surface, the transfer of water through the large surface of the 'underflow' is not expected to cause a limitation in the flow system.

As discussed above, the Wairau Fan becomes less transmissive downstream because of decreasing piezometric gradients. This is likely to cause the restriction in the flow system. With the decreased flow rates through the gravels observed downstream in the Wairau Fan, the cross-section to provide for an increased flow exceeds the total aquifer thickness. While these transmissivity values are estimates based on only few data, the estimated transmissivity near the river seems realistic and matches flow, aquifer thickness and the observed extremely young water at 25 m depth. With decreasing piezometric gradients downstream, it is also realistic that this part of the aquifer becomes the limiting part in the flow system. Despite similar hydraulic conductivities throughout the Wairau Fan, the lower piezometric gradient downstream is the likely cause for the flow restriction. The 'choking point' in the flow system of the unconfined Wairau Fan appears to be not the recharge zone near the river but the lower Wairau Fan due to its lower transmissivity by a factor of two (Figure 4.30).

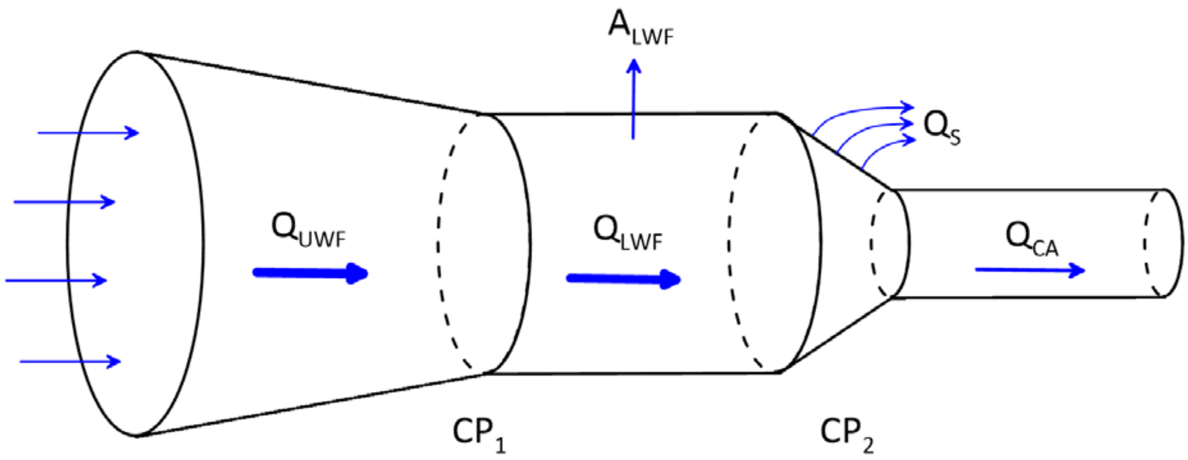

Figure 4.30 Conceptualisation of the water flow through the Wairau Aquifer. The Wairau River loses approximately 7 m^3/s of water into the Wairau Fan. The Wairau Fan is well-connected to the river and the flow through the upper Wairau Fan Q_{UWF} could exceed the current flow. However, the lower Wairau Fan has a lower transmissivity by a factor of two, causing the first choking point (CP_1) and restricting the total flow to that of the flow through the lower Wairau Fan Q_{LWF}. At the start of the confinement, the flow becomes further restricted to that of the flow through the confined aquifer Q_{CA}, causing the second choking point (CP_2). The spring belt is the overflow of the unconfined Wairau Fan – of what does not fit through the confined aquifer, with the spring flow $Q_S = Q_{LWF} - Q_{CA}$. Abstraction in the lower Wairau Fan A_{LWF}, past the first choking point, cannot be compensated by additional recharge from the river, causing a decline in spring flow ($A_{LWF} = -\Delta Q_S$).

This limitation in flow likely existed naturally in the past. In equilibrium with throughflow through the lower Wairau Fan, the springs would have discharged steady amounts of water; the overflow of the Wairau Fan system – of what does not fit through the confined aquifer. However, increasing water abstraction from the lower Wairau Fan in the recent past is likely to have caused a decline in the overflow – the spring flows.

In addition, despite the apparent restriction in groundwater flow through the lower Wairau Fan, aquifer recharge northeast of Renwick may have been supplemented from extensive surface flooding before establishment of continuous stop banks and closure of a previous natural Wairau River flood channel in the upper Plain (Figure 2.3). To re-enable such supplementary water flow along the surface of the lower Wairau Fan, increasing flow diversion from the Waihopai or Wairau Rivers into Gibson Creek for direct supply of irrigation water to minimise abstraction from the lower Wairau Fan, or for artificial recharge into the lower Wairau Fan, may therefore be able to prevent further decline in spring flow.

Water levels in the highly conductive central part of the confined aquifer have not yet decreased significantly (Figure 2.8). The urban spring belt is the overflow of the Wairau Fan system and, as long as there is overflow via the spring belt, the pressure in the confining system is not expected to drop significantly unless there is over-abstraction, meaning abstraction above what can be compensated by flow through the aquifer. In the less conductive northern part of the coastal confined aquifer, water levels are dropping due to abstraction (Davidson and Wilson 2011).

Increased water takes from the highly conductive gravels near the river are likely to be compensated by increased supply from the river, but therefore are likely to directly influence the river flow. Increased water abstraction downstream in the Wairau Fan, on the other hand, is likely to cause further decreases in water levels due to the restricted flow through the aquifer and subsequently decreases in spring flow (Figure 2.8).

4.3.5 Groundwater Storage

The hydrogeologic properties of geologic formations, such as the ability of the rainwater to enter a groundwater system, can be characterised by the mean transit time (MTT) of the water discharge from these formations. The MTT is the time between rainfall and discharge of the water, for example, via springs and seeps into rivers and streams. A longer MTT shows a larger contribution of deeper groundwater flow paths, associated with larger dynamic groundwater volumes, the storage. Catchments with long transit times contain long-lived stores of water; streams in those catchments are likely to be more resilient to droughts.

Usually water drains from an area through a combination of shallow quick flow run-off and slow flow deeper groundwater systems with larger water storage that maintain water flow in the rivers during dry periods. The dynamics of the water movement through catchments, as a result of the interaction between these processes, depend on the hydraulic properties of the geologic formations, such as transmissivity and porosity, and are generally still poorly understood in New Zealand and internationally.

In general, younger clastic sediments, including sand and gravel, have the highest transmissivity and porosity. However, in many places these young permeable rocks may be thin (e.g. alluvial gravels may be up to a few metres thick). Tertiary sandstone and limestone have moderate to high transmissivity, whereas finer grained or poorly sorted sediments such as silt, clay and mud have lower transmissivity. Lithified or indurated rocks may have high or low transmissivity, depending on jointing and fracture density; more joints allow more connected pore space, thus higher transmissivity.

The age of the water in stream and river discharges is linked to the age of the water in the groundwater reservoir that feeds the rivers and streams (e.g. Berghuijs and Kirchner 2017). Most groundwater is exchanged only slowly with the surface and is therefore relatively old. Tritium concentrations of the water in rivers and streams can be used to estimate the groundwater volume (storage) that actively feeds these rivers and streams.

The active groundwater storage (S), defined here as the water stored in the subsurface that is mobile and flowing toward a stream or river, is related to groundwater flow (Q) and groundwater MTT via the fundamental equation $S = Q \times MTT$ (e.g. Maloszewski and Zuber 1982; Morgenstern et al. 2010). Flow rate and MTT at a certain point provide the storage of groundwater that is actively contributing to the flow of the rivers and streams at that discharge point.

The Wairau River was sampled for tritium over a wide range of flow conditions, which overall are representative of average flow (Figure 4.12). Therefore, the derived MTT of four years (Section 4.1.2) is representative of average flow. Using the average flow of 51 m^3/s, the groundwater storage that feeds the Wairau River upstream of the Wairau Plain is estimated to be approximately 6,400M m^3 (Table 4.4). The relatively large water storage in the Wairau River catchment, which causes a significant lag of the water through the catchment, is likely to be related to the extensive cover with scree deposits that infill the valleys of the upper Wairau catchment (Figure 2.1). These Holocene deposits with high hydraulic conductivity, as shown for the Wairau Fan (Section 4.1.1), provide sufficient pathways for the water through a significant groundwater storage. The U-shaped glacial valleys infilled with scree and alluvium were also identified by Taylor et al. (1992) as playing an important hydrological role by retaining water and releasing it slowly to the rivers.

Table 4.4 Catchment groundwater storage as estimated from the mean transit time (MTT), and flow at the time of age-tracer sampling.

	Flow (m^3/s)	MTT (y)	Storage (M m^3)
Wairau River at SH 1	51	4	6,400
Spring Creek	2.8	0.33	29
Doctors Creek	0.23	7	51
Murphys Creek	0.64	1.5	30
Fulton Creek	0.25	1.5	12

Flow and MTT data are also listed in Table 4.4 for the streams. The streams were sampled during low-flow conditions (Figure 4.12). Doctors and Fulton Creeks had no flow data measured at the time of tritium sampling. However, they have previous flow data that enabled the construction of flow duration curves. For calculation of storage for these streams flows were used that represent 92% of their flow exceedance, similar to Murphys Creek, which was sampled at the same time.

The flows of Spring, Murphys, and Fulton Creeks do not vary significantly, so the results can be considered to be reasonably representative of average flow conditions. For Doctors Creek, with significant flow variation, the estimated storage only represents that of low baseflow.

For better comparison of the different groundwater storage volumes of the streams, their volumes are shown in Figure 4.31 as boxes, with their sizes proportional to the volumes. Total annual flow volumes are also shown for comparison (boxes with broken lines) to illustrate the ratio between annual flow volume and groundwater storage.

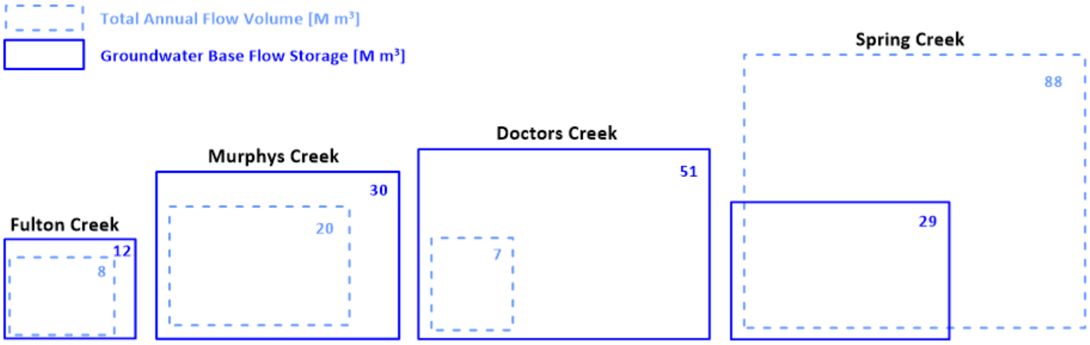

Figure 4.31 Groundwater storage volumes and total annual flow volumes for the streams.

Spring Creek, considering its relatively high flow, has a very low water storage of 29M m^3 in the Wairau Fan because of its short transit time of only 0.33 years. Its flow is therefore very dependent on continuous recharge from the Wairau River, and it is likely to mimic the Wairau River flow very closely in the event of extended drought, similarly to the southern valley tributary fans where the water levels drop quickly when these ephemeral rivers stop flowing in summer.

Murphys Creek has a similar storage of 30M m^3 and, with its MTT of 1.5 years, would be buffered against a drought of up to a year, but not of more than a year. The drought buffer is similar for Fulton Creek, with a storage of 12M m^3. The estimated storage of 51M m^3 for Doctors Creek is that representative of low baseflow. This is the storage which would be able to sustain such low baseflow over years.

5.0 CONCLUSION

This study demonstrates the effectiveness of groundwater age, stable isotope and hydrochemistry data in determining and quantifying water transit times and related hydraulic parameters to help understand interactions between surface and groundwaters, groundwater recharge mechanisms, groundwater flow pathways, available baseflow groundwater storage and time lags between land-use change and impact on water quality in order to mitigate critical water management issues, such as declining water levels and stream flows, and water quality.

Through systematic monitoring of the groundwater system by Marlborough District Council, including levels, flows, temperature, hydrochemistry, isotope and age tracers, a dataset has been created that allows the identification of large-scale and local water flow patterns in the Wairau Plain from rain through the river catchment to, and through, the aquifer.

New tracer input and output data provided the basis for expanding upon the insights from previous studies, resulting in a large-scale perspective on the dynamics of the Wairau Plain groundwater system. For most of the groundwater well sites with age-tracer data, it was possible to obtain groundwater ages, allowing the identification of areas of recharge (defined by young water) and flow direction and flow rate (gradient of groundwater age). The flow rates provided the hydraulic parameters to understand the restriction of flow in the aquifer.

Key hydrochemical data, together with age data, indicate that the impact on groundwater quality by high-intensity land use is minor in the Wairau Plain groundwater system. Only a few groundwater samples display nitrate and sulphate concentrations slightly above those indicative of high-intensity land use. However, some older groundwaters have NO_3-N concentrations high enough to cause environmental issues once discharged to the surface.

The extensive dataset employed in this study has provided a basis for many new insights into groundwater processes and dynamics in the Wairau Plain. By systematic application of the multi-tracer methods, the full potential of these tools can be realised for understanding of the groundwater dynamics, which is not possible with other techniques.

The main focus of this study was understanding the transit time and storage of the water through the Wairau River catchment and Wairau Plain aquifers to the spring-fed stream belt, and understanding of the groundwater recharge sources, residence times, and hydrochemistry processes in the Wairau Plain aquifers, including aquifer recharge via rivers and aquifer discharge into streams. The findings are summarised below.

- The mean transit times (MTT) of the water through the catchments of the Wairau and Tuamarina Rivers, deduced from long-term tritium data, are 4 and 8 years, respectively.
- For the spring-fed stream belt in the Wairau Plain, the MTT through the Wairau Plain aquifers is 0.3 years for Spring Creek, 1.5 years for Murphys and Fulton Creeks, and 7 years for Doctors Creek.
- The Wairau River and the discharge from the southern and northern hills contribute to the Wairau Plain Aquifer, but not the Tuamarina River.

- The stream belt at the boundary of the confining layers in the Wairau Plain is fed by shallow groundwater. The $\delta^{18}O$ ratios and water ages are identical between the shallow groundwater and the surface water around their springs. Spring Creek is fed by shallow groundwater recharged from the Wairau River. Doctors Creek and Fairhall Drain are fed by discharge from the southern hills around Fairhall River, and Murphy and Fulton Creeks are fed by a mix of these southern hill discharges and Wairau River-fed groundwater.
- The groundwater storage in the upper Wairau River catchment is approximately 6,400M m^3. This large storage is likely to be related to the scree-infilled valleys in the upper Wairau catchment, which release the water slowly to the river.
- The groundwater storage of the Wairau Plain Aquifer that feeds Spring Creek is very low, approximately 30M m^3, providing very little buffer to long-term drought. The groundwater storage that feeds Murphys Creek is approximately 30M m^3, which would buffer its flow against drought of up to a year. The drought buffer is similar for Fulton Creek, with a storage of 12M m^3. The estimated low baseflow storage for of 51M m^3 Doctors Creek would be able to sustain the low baseflow over years.
- Throughout the Holocene Wairau Fan, we found extremely young groundwater of less than one year, to a depth of tens of meters. In the coastal deposits, groundwaters are typically up to a hundred years old. In the Pleistocene deposits south of the Wairau Fan, we found extremely old groundwater of up to 40,000 years, indicating no water circulation in these deep aquifers. The old ages of the groundwater in the coastal and Pleistocene aquifers indicate low hydraulic conductivity in these parts of the aquifer.
- Recharge from the Wairau River into the Wairau Fan occurs all along the upper half of the river within the unconfined Wairau Fan, as evident by extremely young groundwater all along this part of the river.
- Slightly elevated nitrate occurs only in young groundwater, indicating land-use activities as the nitrate source.
- We have been able to develop and employ a new method for dating very young water by tracking the seasonal temperature variability through the groundwater system, calibrated by the stable isotope variability.
- Extremely young groundwater ages in the Wairau Fan indicate extremely high hydraulic conductivities throughout the fan. Despite these extremely high hydraulic conductivities, the lower piezometric gradient downstream is the likely cause for the flow restriction. The ‘choking point’ in the flow system of the unconfined Wairau Fan appears to be not the recharge zone near the river but the lower Wairau Fan due to its lower transmissivity by a factor of two.

6.0 RECOMMENDATIONS

To cover existing data and knowledge gaps, we recommend the following investigations to Marlborough District Council:

- Carry out a combined assessment of the groundwater age and chemistry in the whole Marlborough District.
- Carry out baseline radon surveys in stream and river reaches that are gaining through groundwater seepage. Such groundwater contributions to surface flows are important contributors to baseflow but difficult to assess. In the light of increased abstraction and potential decrease of precipitation, decreased radon concentrations in future radon surveys would then unambiguously indicate a decrease in groundwater seepage.
- Perform a targeted survey in the unconfined Rarangi Shallow Aquifer to obtain the age-depth relationship of groundwater to enable assessment of local rain recharge rates. Depth-specific sampling for groundwater age and hydrochemistry may also provide better understanding of the sources and mobilisation of arsenic observed in the Rarangi Shallow Aquifer.
- Undertake five-yearly age tracer monitoring for the wells with water older than several years, including the Deep Wairau Aquifer, to detect changes in flow dynamics; for example, through changing abstraction or climate.
- Continuous monitoring of the temperature in some critical wells in the unconfined Wairau Fan through one annual cycle and measurement of the stable isotopes (including the river) once every two weeks. This allows robust calibration of the easily obtainable temperature signals to groundwater age and provides a tool to detect changes in groundwater age for the very young groundwaters. The following wells are recommended: 10485, 3821, 10608, 7007, 1685, 3009, 4404 and 10498, and the Wairau River. This would also allow for robust identification of Wairau Fan recharge from north bank discharges.
- Assess the connection of the confined aquifer to the sea, as this has implication for the groundwater budget and potentially also for the vulnerability of the aquifer to sea water intrusion. Measure groundwater age in the confined aquifer in coastal aquifer sentinel wells.
- Carry out test drilling to sample changes in chemistry, MRT and recharge sources.
- More detailed investigation of the Southern Valley aquifers that are connected to their tributary rivers.

A number of open groundwater questions could be addressed and resolved via GNS's MBIE-funded groundwater research programme 'Te Whakaheke o te Wai':

- A radon survey carried out in the Wairau River along the Wairau Fan, in particular at the boundary of confinement, would show the upwelling groundwater flow back into the river at this zone.
- More samples should be collected from coastal wells with very negative $\delta^{18}O$ to identify the reason for these unusual ratios.

- Surveys should be carried out at low baseflow conditions to identify if there are near-coast groundwater discharges from the confined aquifer to the surface. These should be identified via their low chloride concentrations, low stable isotope ratios and old water ages. If no such active discharges from the confined aquifer exist near the coast, the implication would be that the Wairau Aquifer is not a blind aquifer in its central part near the coast and has an outflow into the sea, potentially through diffuse seepage as discrete springs have not yet been observed. This is a fundamental question relevant to many coastal aquifers, with significant implications for their water budgets. This requires field surveys of DO and EC, and sampling for Cl, stable isotopes and age tracers.
- A tracer experiment should be performed in a large-diameter well in the zone of high groundwater flow velocities near the river recharge area to confirm groundwater flow rates and direction.

7.0 ACKNOWLEDGEMENTS

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APPENDICES

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APPENDIX 1 GROUNDWATER AGES

Table A1.1 MDC groundwater ages. Mean residence times in bold are based on time series and therefore are more robust than others.

Well ID River/Stream ID	Project	NZTM E	NZTM N	Bore Depth (m)	Mean Residence Time (y)
1		1687120	5416990	1	0.5
5		1684287	5406299	?	**9**
5		1684387	5414197	30.2	135
25		1682988	5413097	0	-
32		1680488	5412998	27.5	-
34	Time series	1683981	5412906	29.6	**66**
35		1681488	5412898	26.8	2
41		1682888	5412697	30.5	-
42		1682488	5412697	27.5	-
47		1684087	5412597	6.7	**14**
50		1681688	5412398	0	-
59		1683687	5411898	29	49
62		1682388	5411798	19.4	-
68		1683387	5411698	28.4	35
85		1684487	5411098	30.5	108
96		1644996	5398505	8	-
110		1683587	5410598	28.4	-
122		1642297	5396306	-	220
124		1665005	5428168	11	12
125		1681988	5410298	21.6	-
134		1638798	5395606	47	135
147		1642297	5396406	-	135
154		1685187	5409798	32.3	20
169		1694585	5369518	4	-
188	SOE	1682647	5409369	24.4	**5.5**
196		1682987	5409298	42.7	-
199		1681088	5409198	18.3	-
205		1684987	5409198	2.5	-
208	Stratification	1677289	5409099	22	1.5
208	Stratification	1677289	5409099	39.6	19
208	Stratification	1677289	5409099	45.1	20
208	Stratification	1677289	5409099	0 ??	-

Well ID River/Stream ID	Project	NZTM E	NZTM N	Bore Depth (m)	Mean Residence Time (y)
323		1669690	5407400	7.3	-
327		1677289	5409099	22	-
338	Time series	1685886	5407398	36.6	**9.5**
347		1677788	5407099	10.7	-
371		1681887	5406799	26.2	-
373		1668150	5406700	18	-
376		1683287	5407798	20.1	-
384		1681487	5406499	25	**5**
394		1684287	5406299	34.2	**4**
398	NGMP	1667684	5406335	10	**0.03**
403		1685786	5403299	46.6	17
419		1681987	5405999	30	**1.5**
448	SOE	1679470	5421271	11	11
518		1684286	5405099	34.8	**6**
518		1684286	5405099	26	-
532		1688086	5404899	54.3	-
542		1661163	5430615	13	**7**
543		1685786	5404699	39.7	-
548	SOE	1668113	5404683	27	**1.5**
572		1687386	5404599	49	**47**
595		1683387	5404499	24.4	-
596		1688485	5404399	60.4	94
615		1681787	5404299	25.9	1.5
624		1683587	5404199	27.4	**6**
634		1671490	5404101	19.5	-
642		1673689	5404000	9.2	-
662	SOE	1672759	5403907	22	0.1
663		1682687	5403899	27.5	9.5
677		1686786	5403699	?	-
678		1670390	5403601	21.6	-
679		1678987	5400601	43.3	**14**
681		1668990	5403701	3.4	-
683		1667091	5403601	3.1	-
703		1680887	5403200	0.18	-
708	SOE	1687570	5403253	42.7	**90**
736		1687086	5402699	40	**185**
744		1685186	5402599	36.6	42

Well ID River/Stream ID	Project	NZTM E	NZTM N	Bore Depth (m)	Mean Residence Time (y)
748		1683686	5402600	35.1	-
749		1683586	5402600	27.5	25
765	SOE	1686186	5402299	38.7	**60**
770		1672189	5402301	20.4	-
773		1670889	5396902	33.5	90
775		1684486	5402200	33.6	31
782		1683386	5402100	25.6	25
785		1681487	5402100	23.2	31
816		1685086	5401700	38.1	32
834		1673423	5401556	-	83
839		1686485	5401300	38.1	69
840		1685886	5401200	38.1	52
848		1686785	5400800	38.1	55
857		1687586	5404499	69	**100**
864		1673689	5400101	29	**40**
865		1675288	5400101	47.2	78
874		1675588	5399701	31.4	**900**
875		1674788	5399701	44.2	42
894		1668690	5402501	?	**14**
903	Stratification	1662970	5405735	8	0.02
922		1665191	5400102	10.4	-
950		1678188	5404600	25.3	-
955		1667890	5400202	28	106
972		1667990	5403601	14.6	86
980	Paleo	1678888	5401360	87	39000
981	Time series	1685686	5407198	42.4	28
990		1673289	5402401	18.7	-
1047		1675189	5404700	?	-
1119		1681787	5402800	25.4	-
1147		1686134	5402449	41	**72**
1148		1686160	5402647	41	**53**
1154		1663691	5396503	?	-
1283		1681587	5402100	32.7	-
1366		1667790	5398402	34	130
1396		1684587	5414197	4	-
1428	sw-gw	1676066	5403077	13	6
1477		1679387	5402100	7.2	-

Well ID River/Stream ID	Project	NZTM E	NZTM N	Bore Depth (m)	Mean Residence Time (y)
1616		1683087	5407699	?	-
1634	NGMP	1686789	5415991	6	**2/13**
1652	SOE	1668111	5404801	16	-
1678		1683713	5402567	32	25
1681		1674289	5403001	14	-
1685	Stratification	1671250	5408278	10	0.04
1690	ESR temperature	1664670	5406154	13	0.021
1696	ESR temperature	1667405	5407349	13	0.006
1731		1675788	5403100	12.5	-
1733	NGMP	1686354	5407087	50	**11**
1829		1674189	5404000	8	-
1830		1680787	5402900	0.2	-
1831		1684187	5413297	14.1	-
1833		1682787	5410798	?	80
1863		1667690	5399802	19	104
1895		1669893	5398391	53	130
1945	NGMP	1667503	5399389	60	**>210**
2096		1673948	5399631	33	**133**
2333	SOE	1668105	5404914	18	0.5
2651	SOE	1663908	5405012	12	2
3009	NGMP	1675121	5408640	6	**0.33**
3069	SOE	1665829	5401051	6	2.5
3120	NGMP	1678208	5404337	25	**1.5**
3217	NGMP	1670555	5398702	140	**>250**
3242		1685015	5412374	-	**2**
3278	Paleo	1673935	5402664	189	19500
3287	Paleo	1672536	5402086	255	>250
3291	Paleo	1675355	5401917	151	9100
3333	Paleo	1671113	5402283	318	21300
3375		1672421	5398974	113	**210**
3390		1677412	5401190	19.4	**150**
3439		1684279	5413571	28	210
3447		1685856	5401900	35.7	160
3667		1686069	5412686	40	**210**
3668		1686068	5412684	8	**3**
3821	Stratification	1667691	5406530	22	0.05
4025	Stratification	1663868	5405238	52	1.5

Well ID River/Stream ID	Project	NZTM E	NZTM N	Bore Depth (m)	Mean Residence Time (y)
4100		1685590	5415581	6	13
4118	SOE	1673118	5405223	22	**1**
4174		1688192	5397251	62	**150**
4246		1685016	5414489	6	22
4297		1685576	5412631	8	25
4349		1687202	5416048	10	6
4402	NGMP	1682327	5402305	26	**10**
4403	SOE	1683817	5404764	46	**16**
4404	SOE	1678588	5407267	15	**1**
4442		1684450	5413798	7	**6**
4476		1623500	5388838	13.4	**3**
4577	ESR temperature	1677393	5409349	15	0.11
4650		1674900	5411939	19	**5**
4722	ESR temperature	1667276	5405961	26	0.078
4723	Stratification	1667123	5405954	32	-
4724	Stratification	1666973	5405945	25	0.10
4732		1666680	5410054	17	**17**
7007	Stratification	1669795	5408315	10	0.0003
10346	SoE	1687617	5403463	43	**90**
10485	Stratification	1666584	5406847	14	0.023
10498	Stratification	1672697	5407984	11	0.04
10608	Stratification	1669796	5408320	25	0.001
PD4.0		1686780	5415994	4	2
PD5.0		1686780	5415994	5	7
PD5.9		1686780	5415994	5.9	22
Malthouse		1683713	5402567	32	**20**
Wairau River WRR-33	Stratification	1667595	5407850	NA	4
Doctors Creek	sw-gw	1676647	5402982	NA	7
Doctors Creek	sw-gw	1678636	5403673	NA	6.5
Fairhall Drain	sw-gw	1676628	5403210	NA	5
Fulton Creek	sw-gw	1679268	5404595	NA	1.5
Murphys Creek	sw-gw	1678899	5404191	NA	1.5
Spring Creek	sw-gw	1676689	5408999	NA	0.33
Taylor River		1677787	5396502	-	-
Tuamarina River	sw-gw	1679689	5421296	NA	8

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