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

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GNS Science Report 2019/63
December 2019

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BIBLIOGRAPHIC REFERENCE

Morgenstern U, Davidson P, Townsend DB, White PA, van der Raaij RW, Stewart MK, Moreau M, Daughney C. 2019. From rain through river catchment to aquifer: the flow of water through the Wairau hydrologic system. Lower Hutt (NZ): GNS Science. 83 p. (GNS Science report; 2019/63). doi:10.21420/7125-ST46.

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ISSN 2350-3424 (online)
ISBN 978-1-98-856992-5 (online)
http://dx.doi.org/10.21420/7125-ST46

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ABSTRACT

Groundwater is an important source of water for the Wairau Plain. Concerns about its sustainable yield and contamination from nutrients have prompted several hydrogeological studies over time to better understand the groundwater system. The main aim of this study is the review and consistent interpretation of age-tracer, isotope and chemistry data, collected between 1968 and 2019, to obtain the hydraulic parameters necessary to understand the declining water levels and spring flows and to assess the groundwater storage that feeds the river and springs.

Hydrogeology

The Wairau Fan, comprising Holocene postglacial highly permeable fluvial gravels, forms a highly conductive unconfined aquifer over most of the Wairau Plain. The underlying Pleistocene Wairau Gravels form an aquifer that is significantly less permeable. Near the coast, estuarine sediments form an aquiclude over the Pleistocene gravels with artesian pressures of up to 7 m in this confined system. The main source of water through the highly transmissive Holocene gravel fan is losses of water from the Wairau River channel, essentially, an underground extension of the river. The main groundwater flow from the gravel fan is forced back to the surface near the boundary of the confined aquifer, discharging via Spring Creek and the urban spring belt to feed highly valued streams with crystal-clear water but declining flow.

Methods Used

To understand the flow of the water through the Wairau hydrologic system, we utilised various environmental tracers, such as age tracers, stable isotopes of the water, hydrochemistry, and temperature. To establish the tritium input into the Wairau hydrologic system, we measured tritium in monthly rain samples from Blenheim over two years; they show significantly higher tritium concentrations compared to the nearby Kaitoke reference station due to the mountain ranges shielding the Wairau Plain from direct precipitation of low-tritium oceanic moisture. For the extremely young groundwaters in the unconfined Wairau Fan, < 1 year, we developed a dating method that utilises tracing the seasonal river temperature variability through the aquifer. The lags of the temperature synodal signal were calibrated to true age via the ^{18}O synodal signal.

Groundwater Source

A useful tool for distinguishing potential groundwater recharge sources is provided by oxygen-18 ($\delta^{18}O$) and the hydrochemical composition of the water, in particular, chloride. 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 river, indicating the Wairau River as their recharge source. Where multi-depth wells are available close to the Wairau River north of Renwick, the shallower wells match the river signature but 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 recharge 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, underlying the water flux recharged from the Wairau River. The wells close to the boundary between the Holocene and the Pleistocene deposits and the shallow well in the Holocene deposits of Omaka River contain groundwater with significantly less negative $\delta^{18}O$ ratios, closer to those of coastal rain near Rarangi, indicating local rain as the main recharge source. These groundwaters are also characterised by the highest nitrate concentrations, confirming the recharge pattern obtained from ^{18}O.

As indicated by the $\delta^{18}O$ ratios of the water, Spring Creek discharges water mainly derived from Wairau River, with a small contribution of 4.5% of land surface recharge. Doctors Creek and Fairhall Drain are fed by discharge from the southern hills around Fairhall River. Murphy and Fulton Creeks are fed by a mix between these southern hill discharges and groundwater fed from Wairau River.

Groundwater Age

All groundwaters within the Pleistocene gravel deposits in the southern part of the Wairau Plain are very old, > 100 years, and up to 39,000 years in the Deep Wairau Aquifer south of the Fairhall Fan and Blenheim. In major contrast, throughout the unconfined Wairau Fan we observed only very young groundwater, with mean residence time (MRT) of 0–1 years, even in the deeper wells of > 20 m. In the confined part of the gravel deposits in the centre of the valley, groundwater ages increase, from MRT of two years near the boundary of confinement to 10–40 years near the coast. On the northern margin of the confined aquifer, near the coast, groundwaters are older than 100 years, indicating stagnant conditions, while on the southern margin groundwaters are also relatively old but still contain small amounts of tritium that also indicate an age increase from the west toward the coast, from c. 50 to 100 years. In the south near the coast, shallow groundwaters overlying the confined aquifer have MRTs of 0–25 years.

Restriction in Flow

Flow rates estimated from groundwater age gradients show that, in the upper half of the unconfined Wairau Fan, the Wairau River is well connected to the Wairau Fan. Extremely high flow rates of up to > 30 km/y in this area indicate extremely high hydraulic conductivity in these Holocene deposits near the river. Towards the coast, the flow rates reduce considerably, with rates of c. 13 km/y at around 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 > 20, is related to the flow loss from the aquifer, mainly to the spring belt and through abstraction. Flow rates off-centre near the coast decrease to 0.2 km/y. The northern and southern parts of the confined aquifer near the coast contain old water, indicating near-stagnant flow conditions due to thinning gravel layers that are increasingly clogged with clay. Most of the groundwaters in the Pleistocene deposits south of the Wairau Fan have near-stagnant flow conditions. 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.

Hydraulic conductivities, derived from the flow rates, are c. 11,700 m/day in the unconfined Wairau Fan near the river, and 11,900 m/day in the central part of the unconfined Wairau Fan, indicating similar hydraulic conductivity throughout the unconfined Wairau Fan. Near the coast, in the central part of the confined aquifer, the estimated hydraulic conductivity is 800 m/day.

Despite relatively uniform hydraulic conductivities, the Wairau Fan becomes less transmissive downstream due to decreasing piezometric gradients. This is likely to cause the restriction in the flow system. 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.

Nitrate

In the Wairau Plain groundwater, only a few samples display NO_3-N concentrations above the threshold level of 2.5 mg/L, indicative of high-intensity land use. They are all younger than 10 years, and therefore indicate recent nitrate sources. In the wells containing water with MRT of < 140 years, recharged after the onset of low and high-intensity land use, NO_3-N is elevated in about half of the groundwaters indicative of low-intensity land use, with concentrations high enough to cause environmental issues once discharged to the surface. The very young groundwaters with MRT of < 0.1 years are from wells close to the river, and their low nitrate concentrations likely reflect high dilution by river water. The NO_3-N concentrations of the locally recharged groundwaters representative of the prevailing land use, without dilution by river water, are about 2–3 mg/L.

Transit Time through Catchment and Storage

The Wairau Aquifer is closely linked to the Wairau River. To understand the buffer of the entire system against prolonged drought, the mean transit time of the water through the Wairau River catchment was estimated from tritium time-series data. With a mean transit time (MTT) of four years, the Wairau catchment would be able to maintain baseflow in the river for several years. The active groundwater storage, defined as the water stored in the subsurface that is mobile and flowing toward a stream or river, can be estimated to be approximately 6,200M m^3.

Similarly, MTTs and storage were estimated for the main streams. Spring Creek, in relation to its relatively high flow, has a very low water storage of 29M m^3 in the Wairau Fan. With its short transit time of only 0.33 years, the flow of Spring Creek is very dependent on continuous recharge from the Wairau River, and is likely to mimic the Wairau River flow very closely in the event of extended drought. 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 for Doctors Creek of 51M m^3 is that representative of low baseflow.

KEYWORDS

Wairau Aquifer, Wairau River, Groundwater age, Recharge source, Groundwater storage, Aquifer transmissivity.

1.0 INTRODUCTION

Groundwater is an important source of water for the Wairau Plain in the Marlborough District. Agricultural users are almost totally reliant on groundwater, principally for vineyard irrigation during the usually long dry spells in summer. Groundwater is also the sole source of supply for the urban population in the main towns of Blenheim, Woodbourne and Renwick. The Wairau Plain aquifer system supplies water to spring-fed streams that are navigable in part, and which are popular amenities widely used for recreation.

Wells in the Wairau Fan abstract water from highly conductive gravels that are in close hydraulic connection with the Wairau River. Groundwaters in the shallow aquifers are also the source of unique spring-fed creeks that are re-emergences of shallow groundwater flows originating from river stretches losing water upstream, with some addition of water from local rainfall in the Wairau Plain (Davidson and Wilson 2011; White et al. 2016).

Concerns about the sustainability of the groundwater resources and contamination from nutrients have prompted a number of studies to assess the Wairau Plain groundwater system (e.g. Brown 1981; Taylor et al. 1992; Davidson and Wilson 2011; Raiber et al. 2012; White et al. 2016; Wöhling et al. 2018). This new study focuses on environmental tracers (age, isotopes, temperature, gas and chemistry) to obtain a better understanding of the groundwater flow and hydrochemical processes in the aquifers of the Wairau Plain. These tracers can be used to understand the dynamics of the groundwater from recharge to discharge; its interaction with surface water; and the processes that control the hydrochemical properties (quality) of the groundwater, including sources of contaminants.

Current issues for the Wairau Plain aquifers include:

- Declining trend in groundwater levels and spring flows observed since the early 1970s.
- Full allocation of groundwater with no obvious alternative source to meet future demand for human settlement, crop irrigation or industrial/food processing.
- Refining the sustainable yield of the Wairau Aquifer for introduction of seasonal restriction thresholds on consented groundwater users to maintain spring flows.
- Impact of yet-to-be-consented harvesting of Wairau River high flows on Wairau Aquifer recharge rates.
- Impact of land uses on groundwater quality and downstream aquifer-fed springs.

This collaborative study between Marlborough District Council (MDC) and GNS Science (GNS) aims to improve our understanding of the Wairau Plain aquifers to enable robust policy development for the Wairau Aquifer, including the setting of better allocation limits by 2019 and nutrient limits by 2024. Specifically, this report aims to contribute to the following questions and problems:

1. Groundwater recharge, flow and discharge questions

- Which Wairau River recharge and Wairau Aquifer flow mechanisms potentially account for much of the long-term decline in water level?
- How are surface waters and groundwaters connected, and how do the dynamics between these change between wet and dry periods?

- Are seasonal water level declines more related to variable rates of recharge or to human abstraction?
- Where does the river-recharged groundwater flow within the aquifer?
- Where is river-recharged groundwater significantly mixed with rain-recharged groundwater?
- What are the time scales of the water flow through the aquifer? What are the flow rates? How are shallow and deeper groundwaters connected? Is there a vertical stratification in groundwater age?
- Is there likely to be discharge from the aquifer out to sea?
- Can the flow rates, deduced from the age-tracer data, help to calibrate hydraulic parameters based on the Darcy flow equation?
- Is the source of the water abstracted through the wells across the Wairau Plain changing over time?

2. Groundwater chemistry questions

- What are the drivers of nitrate and phosphorous levels in the groundwater?
- Why do some monitoring wells show a high variability in hydrochemistry parameters, including nitrate? Is the source of the water abstracted through the wells across the Wairau Plain changing over time?
- What is being monitored by the established monitoring wells? Is the water too old to be sensitive to current land-use changes or too diluted by river water?
- What pathways do surface contaminants, such as agricultural nutrients, take?
- Does groundwater geochemistry have potential as an indicator of groundwater age and residence time?

3. Groundwater management questions

- To enable better management of water takes, can we estimate water stored within the aquifer and define what can be used versus groundwater needed to sustain spring flow?
- Is the long-term age (residence time) of groundwater varying due to abstraction? Are declining water levels in the aquifer related to changes in flow within the aquifers or due to changes in recharge rate?

Due to the declining water levels in the Wairau Aquifer and increasing water demand, MDC requires a better understanding of the dynamics of the water flow through the aquifer, the storage that buffers against drought and how properties of the groundwater system vary in the vertical direction. Therefore, this study included pairs of samples from shallow groundwater and surface water to assess the link between surface water and groundwater, and pairs of samples from shallow and deep groundwater to assess the link between shallow and deep groundwater.

In addition to previous modelling approaches of water mass balance and hydrochemistry, and previous evaluation of tritium and ^{18}O, this project aims to obtain detailed water ages and flow rates to provide hydraulic parameters that allow the addressing of current water issues.

2.0 SETTING

2.1 Geology of the Wider Wairau River Catchment

The Wairau River catchment covers a large area of northern Marlborough in the South Island. Its geology includes relatively impermeable basement rocks overlain by much younger, generally permeable or open, gravels (Figure 2.1). The active Wairau Fault bisects the catchment and separates major basement rock units. North of this fault, the basement rocks consist primarily of metamorphosed Permian to Cretaceous igneous and sedimentary rocks. South of the fault, the basement rocks are predominantly Triassic and Cretaceous sandstone and argillite (greywacke), with minor overlying Tertiary sediments (Begg and Johnston 2000).

Remnants of late Pliocene to Early Pleistocene Hillersden Gravel are preserved near the coast. These generally tight gravels (Taylor et al. 1992) overlie basement greywacke and Tertiary rocks near the coast, and dip beneath the valley floor to the north (Begg and Johnston 2000). Pleistocene and Holocene gravels have accumulated on the floor of the Wairau valley and in many of the secondary catchments. Major gravel aggradation episodes generally coincided with glacial (colder) climatic stages and significant river down-cutting is commonly attributed to interglacial (warmer) stages. However, Holocene gravels (Rapaura gravels of Taylor et al. 1992) have formed a low-angle fan on the valley floor (the Wairau Fan), down-valley from about the confluence with the Waihopai River. These young gravels interfinger and merge with fine-grained estuarine and swamp deposits (Dillons Point Formation) that have accumulated near the coast during the mid-late Holocene (Taylor et al. 1992).

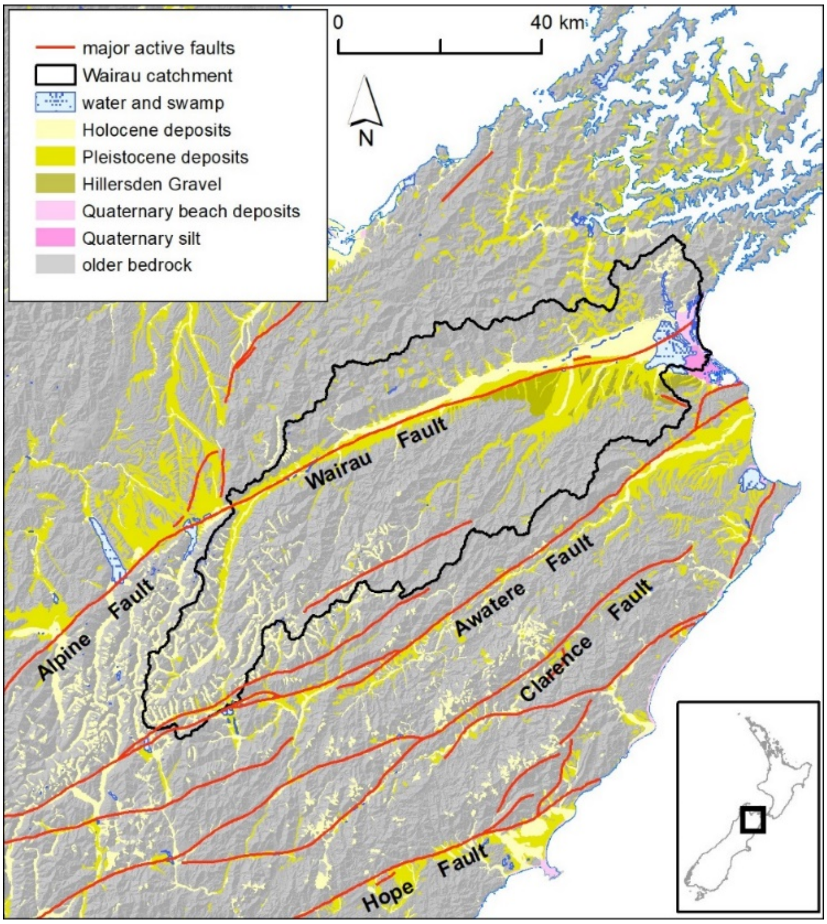

Figure 2.1 Basic geology of the wider area of the Wairau River catchment and major faults (modified from Heron 2018).

The Wairau Fault is the northward continuation of the Alpine Fault, and it is part of the Marlborough Fault System – a series of four major strike-slip structures that make up the Pacific-Australia plate boundary zone in Marlborough. The trace of the Wairau Fault is almost entirely within gravels on the valley floor. It displaces these gravels and young geomorphic features right-laterally by as much as 10 m, and vertically by up to 2 m (Zachariasen et al. 2006). There is no trace of the Wairau Fault within about 800 m of the coast (Grapes and Wellman 1986), indicating that either the most recent fault movement(s) terminated inland, or that the sediments at the surface are younger than the last movement in this area.

The 2016 Kaikōura Earthquake produced varying groundwater responses. It hardly affected wells or groundwater levels tapping the inland Wairau Aquifer, where the fabric of the aquifer consists of mutually interlocking gravels. Changes in groundwater level there were only short-lived, despite that monitoring wells tapping the confined aquifers near the Cloudy Bay coast east of Blenheim displayed significant responses to the seismic shock waves, with rapid changes in water levels damaging monitoring instruments at many stations. This contrasts with the dramatic long-term response at deep wells penetrating the aquifers in the southern valleys of Marlborough, where groundwater levels rose by up to 5 m and have yet to recede in most cases.

2.2 Climate and Hydrology

The Wairau River catchment (Figure 2.2) is characterised both by a wet climate with an annual rainfall of greater than 2000 mm in the upper mountain catchment and by a dry climate with an annual rainfall of around 600 mm in the Wairau Plain. This rainfall gradient from west to east is a result of the location of the catchment. It lies on the lee side of steep mountain ranges on the northern catchment boundary that shield the catchment from the prevailing rain-bearing weather from W–NW and an even higher mountain range on the south-western catchment boundary facing this prevailing circulation (Figure 2.2 left). The greatest precipitation occurs along the ridges facing these weather circulations (Figure 2.2 right).

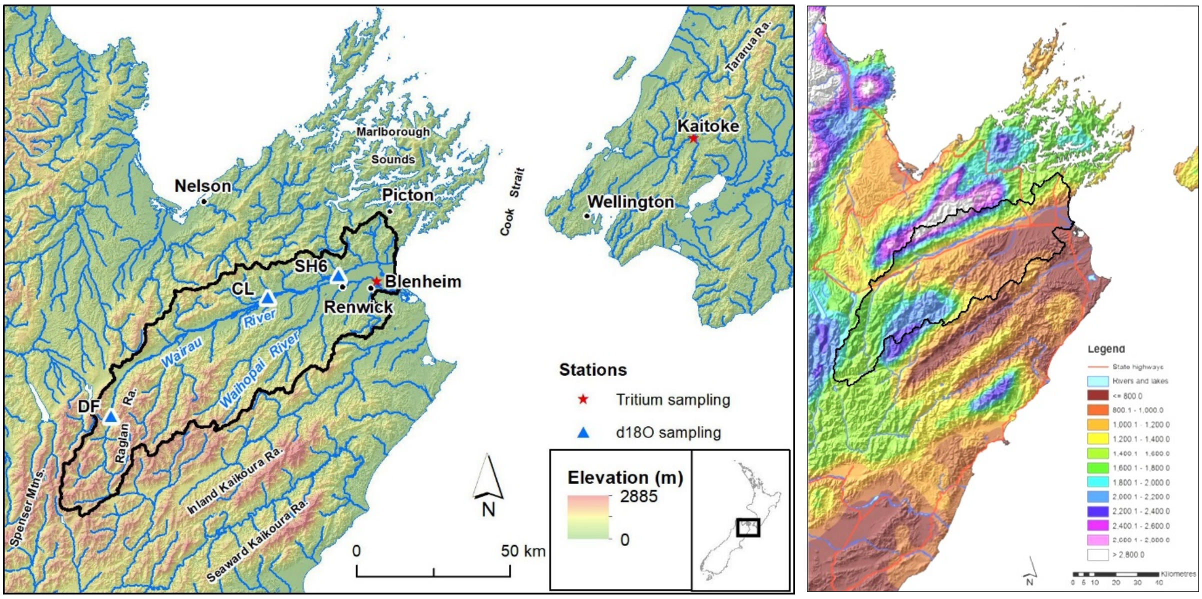

Figure 2.2 Wairau River catchment and median annual rainfall. (Left) Wairau River catchment (3430 km^2) with main mountain ranges; (Right) Median annual rainfall for Marlborough district (Tait 2017). Del ^{18}O sampling stations: DF – Dip Flat, CL – Church Lane, SH 6 – State Highway.

At the Spencer Mountains and Raglan Range, the air is driven to heights well above 2000 m, causing intense precipitation in the Upper Wairau catchment from moisture that is already depleted in short-distance oceanic moisture. The Upper Wairau catchment, including the Waihopai River, therefore discharges water with an isotopic signature reflecting the higher troposphere, with more negative stable isotope ratios and higher tritium concentrations. In contrast, a major contribution to the Wairau Plain rainfall is derived from the less shielded NE weather direction, with less negative stable isotope ratios and lower tritium concentrations. Drainage from the lower altitude ranges at the south-eastern catchment boundary exhibits intermediate isotopic signatures. The contrast in stable isotope composition of the drainage from the various catchment areas was well established by Taylor et al. (1992).

The surface hydrology of the Wairau Plain has been highly modified over the last 100 years since European settlement to allow settlement and agriculture on what was essentially a wetland within 5 km of the coast. Realignment of channels and drainage has transformed the Wairau Plain, with few of the rivers or springs resembling their natural state. Today's main hydrologic features of the Wairau Plain are shown in Figure 2.3. In addition to the main drainage channels shown, the side valley streams have a complex network of channels that are often dry, and there are myriad smaller channels and drains on the plain.

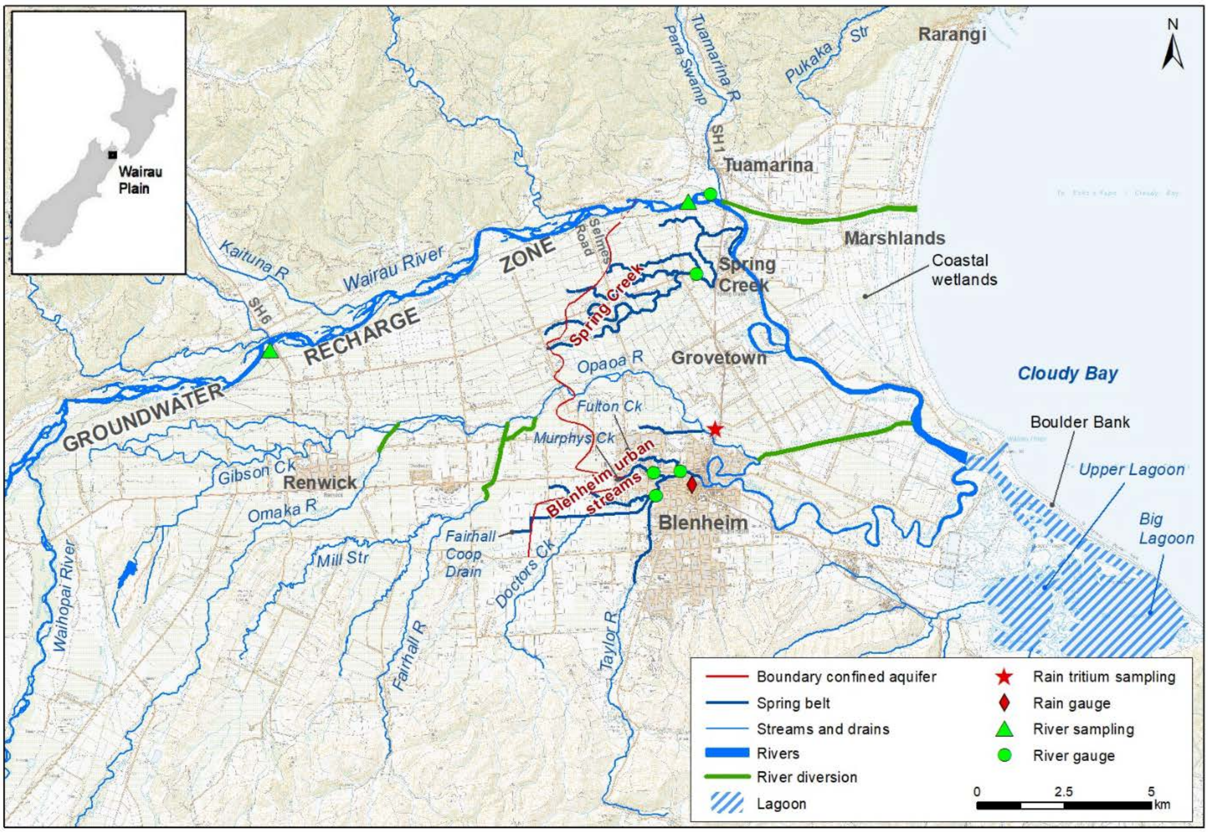

Figure 2.3 Hydrologic features of the coastal Wairau Plain, including the location of the spring-fed stream belt at the boundary of the confined aquifer. The Wairau Plain covers an area of 170 km^2.

The many modifications to the surface hydrology include stop-banks that confine the Wairau River over its entire course from below the Waihopai River confluence, diversion channels that provide additional flood protection, a previous natural Wairau River flood channel in the upper Plain that has been closed, and flow from Waihopai River that is diverted into Gibson Creek to compensate potential loss of flood recharge into the aquifer. The coastal area has a network of drains and overflow channels.

Between the confluence of Waihopai River and Selmes Road, the Wairau River loses about 7 m^3/s of water from the channel into its highly transmissive Holocene gravel fan, which is essentially an underground extension of the river (Davidson and Wilson 2011). Drainage from the southern tributary valleys and Pukaka Valley are likely to contribute groundwater to the Wairau Aquifer through their fans, in contrast to Tuamarina Valley, which terminates into Para Swamp, with the stable isotope ratios indicating no significant contribution from this blocked valley to the Wairau Aquifer (Taylor et al. 1992).

The main groundwater flow from the gravel fan is forced back to the surface near the boundary of the confined aquifer (Figure 2.3), with about 4 m^3/s of crystal-clear water discharging via the Spring Creek (Awarua). Both the stable isotope composition and the water balance indicate that Spring Creek discharges mainly Wairau River water, with only a low percentage contribution from local Wairau Plain precipitation (Taylor et al. 1992). Within the urban area of Blenheim, spring-fed Fulton and Murphys Creeks exhibit sparkling clear water and aquatic life, appreciated by thousands of residents every day, and sustains the baseflow of the Taylor River during summer.

In terms of aquifer recharge source, the hydrology of the Wairau Plain can be divided into a northern and southern half. The northern Wairau Plain aquifers are dominated by exchange with the perennially flowing Wairau River and, to a lesser extent, the Waihopai River. The southern half of the Wairau Plain receives recharge from the southern valleys, which drain much smaller catchments draining lower rainfall areas. The isotopic distribution of the underlying groundwater reflects the surface deposits related to common sources (Brown 1981). During summer, the streams usually dry up before reaching the plain, indicating that they provide recharge to their fans and, subsequently, to the aquifer. Wells sampled in the area yielded stable isotope signatures, indicating contributions both from the tributary valleys (mountain-derived streams) and from local rain recharge. The valley stream contribution vanishes abruptly on the plain, except in the Omaka fan, where groundwater derived from Wairau River dominates (Taylor et al. 1992).

The spring-fed creeks have a relatively stable flow regime due to the moderating nature of their groundwater reservoirs, in comparison to the flashy nature of the Wairau River, which indicates significant contribution from quick flow run-off (Figure 2.4). Of the creeks in the Blenheim urban area, Doctors Creek experiences the highest peak flows, due to hill catchment run-off. Fulton and Murphys Creek flows are closely related to the groundwater level, with only a minor contribution from rainfall or storm water (Davidson and Wilson 2011).

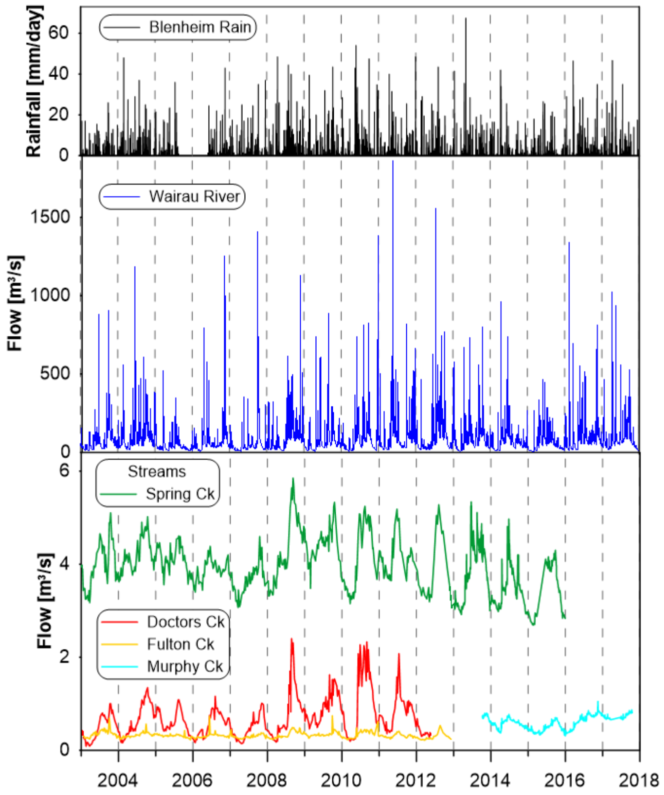

Figure 2.4 Hydrograph of the Wairau River and major discharges from the groundwater-fed spring belt, together with daily rain.

2.3 Hydrogeology

The geological structure of the Wairau Plain was described by Brown (1981) and later refined into a multi-layered three-dimensional (3D) geological model to characterise the aquifer geometry and synthesise hydrogeological and hydrogeochemical data for different aquifers (Raiber et al. 2012). Integration of water chemistry data within the physical framework of the 3D geological model helped create a better understanding and conceptualisation of the groundwater systems in these complex geological settings. Principal Component Analysis and Hierarchical Cluster Analysis were applied to groundwater chemistry data to identify the hydrochemical facies that are characteristic of distinct evolutionary pathways and a common hydrologic history of groundwaters and to demonstrate that natural water–rock interactions, redox potential and human agricultural impact are the key controls of groundwater quality in the Wairau Plain.

White et al. (2018) developed facies models of the sedimentary deposition to identify hydraulic properties of the Wairau Plain Aquifer. These models describe the key features of the development of Late Pleistocene and Holocene geomorphic units associated with the coastal aquifer and show the evolution of these features in an animation covering the last 20,000 years at 1000-year time steps.

This evolution was categorised by three key periods:

1. 20,000 years to 8,000 years before present (BP), when sea level rose to a position inland of the current coast and Holocene gravels were deposited above a Pleistocene gravel fan.

2. 8,000 years BP to 5,000 years BP, when a gravel riser was formed landward of the current coast and an estuary formed behind the Boulder Bank. This period was significant for the formation of the present-day Wairau Plain groundwater system because the drowning of the Pleistocene Wairau River channel and the formation of the estuary probably led to development of artesian conditions. Springs also formed in the area west of the gravel riser.
3. The period 5,000 years BP to the current day, when in-filling of the estuary continued and the Wairau River channel shifted to its present position behind the Boulder Bank and Rarangi gravels were deposited in northern Cloudy Bay.

The following units are important for groundwater flow in the Wairau Plain (Figures 2.5 and 2.6).

- Holocene postglacial highly permeable fluvial gravels (Wairau Fan) with some sand-silt-clay matrix/lenses, which form a highly conductive aquifer overlying the Pleistocene sediments over most of the plain.
- Pleistocene Wairau Gravels comprised of undifferentiated gravel, sand, silt and clay, which are located below all Holocene units and form an aquifer that is significantly less permeable than the Holocene gravels.
- Rarangi gravel, a thin layer of sands and fine gravels, including lenses of finer sand, clay and peat, overlaying the confined Pleistocene gravels but without a hydraulic connection.
- Boulder Bank, a beach deposit that formed along Cloudy Bay by about 5,000 years ago. The formation of Boulder Bank led to the development of the paleo-estuary, with deposition of relatively impermeable estuarine sediments that provide the confinement of today's coastal Wairau Aquifer. The Boulder Bank is formed of relatively permeable marine gravels and sands, providing pathways for shallow groundwater to discharge into the sea.
- Estuarine sediments, which form an aquiclude as they are mainly sands, silts and clays. These generally fill the area between the Boulder Bank and the gravel riser.
- Gravel riser, providing a lateral hydrogeological boundary between Holocene sediments, permeable alluvial gravels in the west and relatively impermeable estuarine sands, silts and clays forming an aquitard in the east, forcing much of the Wairau River recharged water to the surface via spring-fed streams to the west of the riser.
- Buried valley sediments, largely silts and sands, are a local aquiclude in the general vicinity of the spring-fed streams.

The division of the Wairau Plain area into confined, transitional and unconfined aquifer areas is shown in Figure 2.7. In the confined aquifer, water levels are up to 7 m above ground. In the unconfined Wairau Fan, water levels are typically 2–5 m below ground. In the southern unconfined Pleistocene gravels, water levels are typically 10–20 m below ground (Davidson and Wilson 2011).

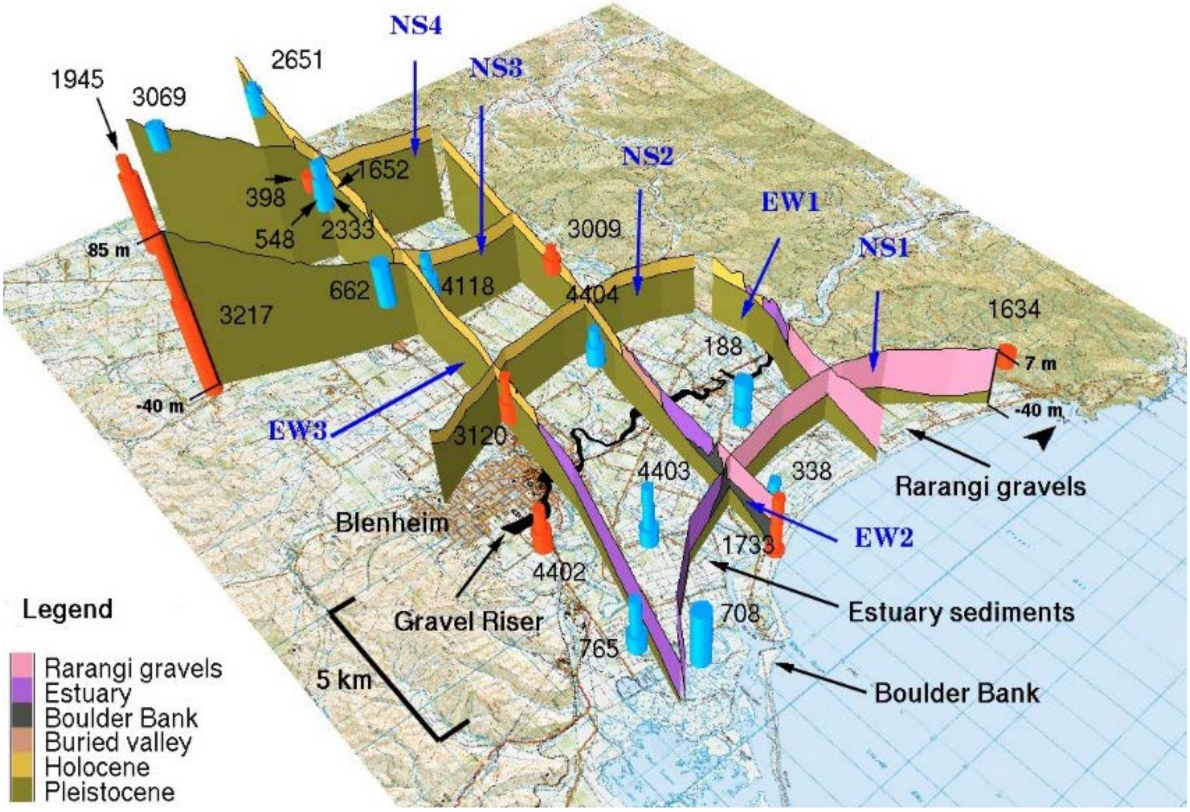

Figure 2.5 Location and 3D view of facies model cross-sections. Four cross-sections are shown in Figure 2.6. The larger diameter cylinders indicate well screens. National Groundwater Monitoring Programme (NGMP) wells are in red, State of the Environment (SoE) wells are in blue. EW1: Holocene sediments thickening towards the coast. Holocene gravels are located in the west. Estuarine sediments are observed between Holocene gravels and Rarangi gravels, and Rarangi gravels are located in the east and extend to the coast; EW2: Holocene gravels approximately 10 m thick in the west. Aquicludes (i.e. buried valley and estuarine sediments) are located between Holocene gravels and Boulder Bank sediments. Rarangi gravels are mapped to the east of Boulder Bank sediments; EW3: Holocene gravels approximately 10 m thick in the west. Estuarine sediments (i.e. an aquiclude), located in the east, thicken towards the coast; NS1: Rarangi gravels are located to the north of the Boulder Bank; Boulder Bank sediments are located in the middle of the section. Estuarine sediments are located in the south. NS2: Holocene gravels at the ground surface across the whole section; NS3 and NS4: Holocene gravels at the ground surface in the north and Pleistocene sediments at the ground surface in the south.

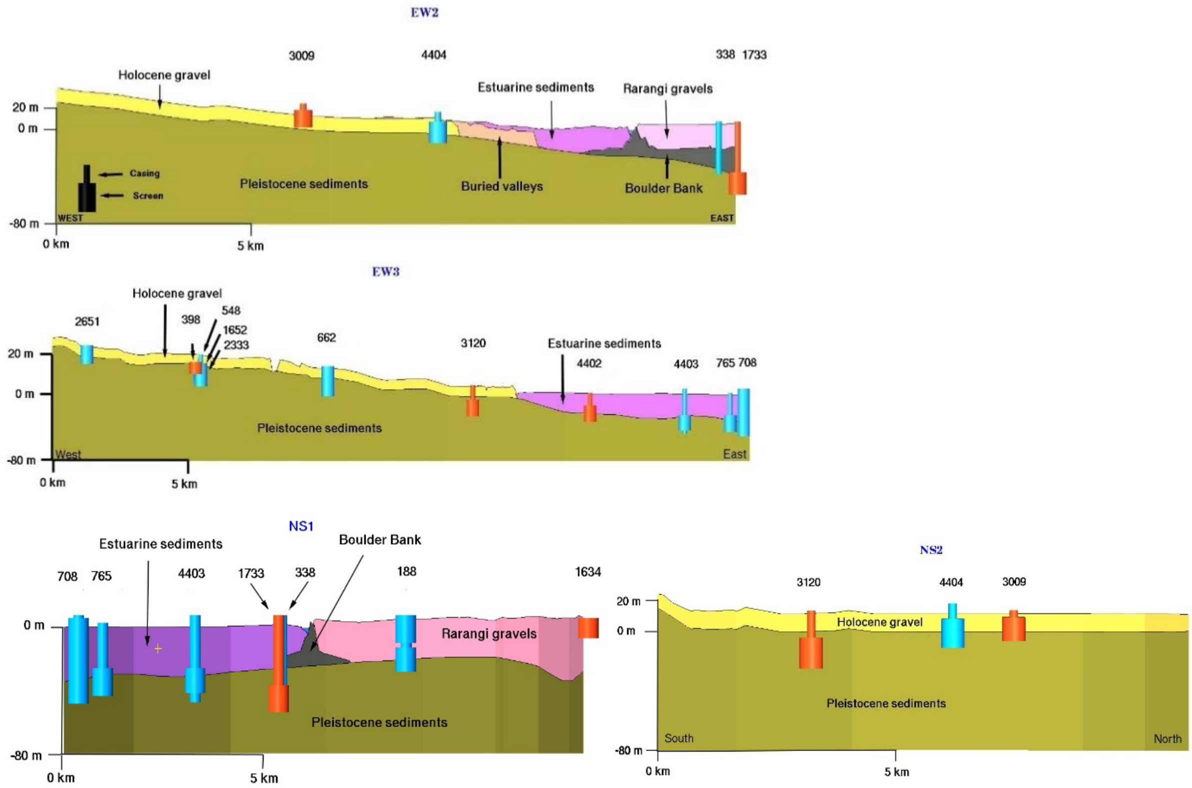

Figure 2.6 Geologic cross-sections of facies for four cross-sections (EW2, EW3, NS1 and NS2) shown in Figure 2.5.

The tight Pleistocene Wairau Gravels, although often water-bearing, constitute the lower boundary of active groundwater circulation, as indicated by significantly older groundwater compared to the Holocene gravels, which contain very young groundwater (Taylor et al. 1992; Stewart 2008). Artesian groundwater is encountered in the Pleistocene Wairau Gravels where these become confined (Figure 2.7). The Rarangi gravels form a local aquifer near the coast.

The hydraulic links between surface water and groundwater in the Wairau Plain were the subject of a number of studies (Close 2014; Close et al. 2017; Wilson 2016; Wöhling et al. 2018). White et al. (2016) developed a three-dimensional model of shallow sediment types and static groundwater pressure from observations in a large number of wells that have been drilled since the 1860s. The locations of spring-fed streams were commonly associated with discharge points at the end of the shallow Holocene Wairau gravel fan. In addition, stream locations were bounded to the east of Blenheim by relatively thick fine sediments and an associated buried gravel riser that dips relatively steeply towards the coast (Figure 2.5; White et al. 2016). Groundwater, recharged mainly from the Wairau River but also from rainfall on the Wairau Plain, enters the unconfined gravel aquifer in the west and then mostly flows to the spring-fed streams (Figure 2.3). The static groundwater pressure model also demonstrated that groundwater flows toward the areas of historic swamps, now drained, were significant features of the historic hydrology of the Wairau Plain, including the area of Blenheim township.

Along the Wairau Plain there is a significant decrease in mean annual rainfall toward the east, with c. 900 mm north of Renwick at the intersection of SH 6 and Rapaura Road and c. 650 mm in Blenheim (Tait 2017; Figure 2.2), with implications for rates of land surface recharge, drainage of agricultural pollutants, and isotopic and chemical composition of the groundwater. For example, during most summers, the Rarangi area does not receive sufficient rainfall to balance the high rates of evapotranspiration, resulting in limited groundwater recharge in this area during summer.

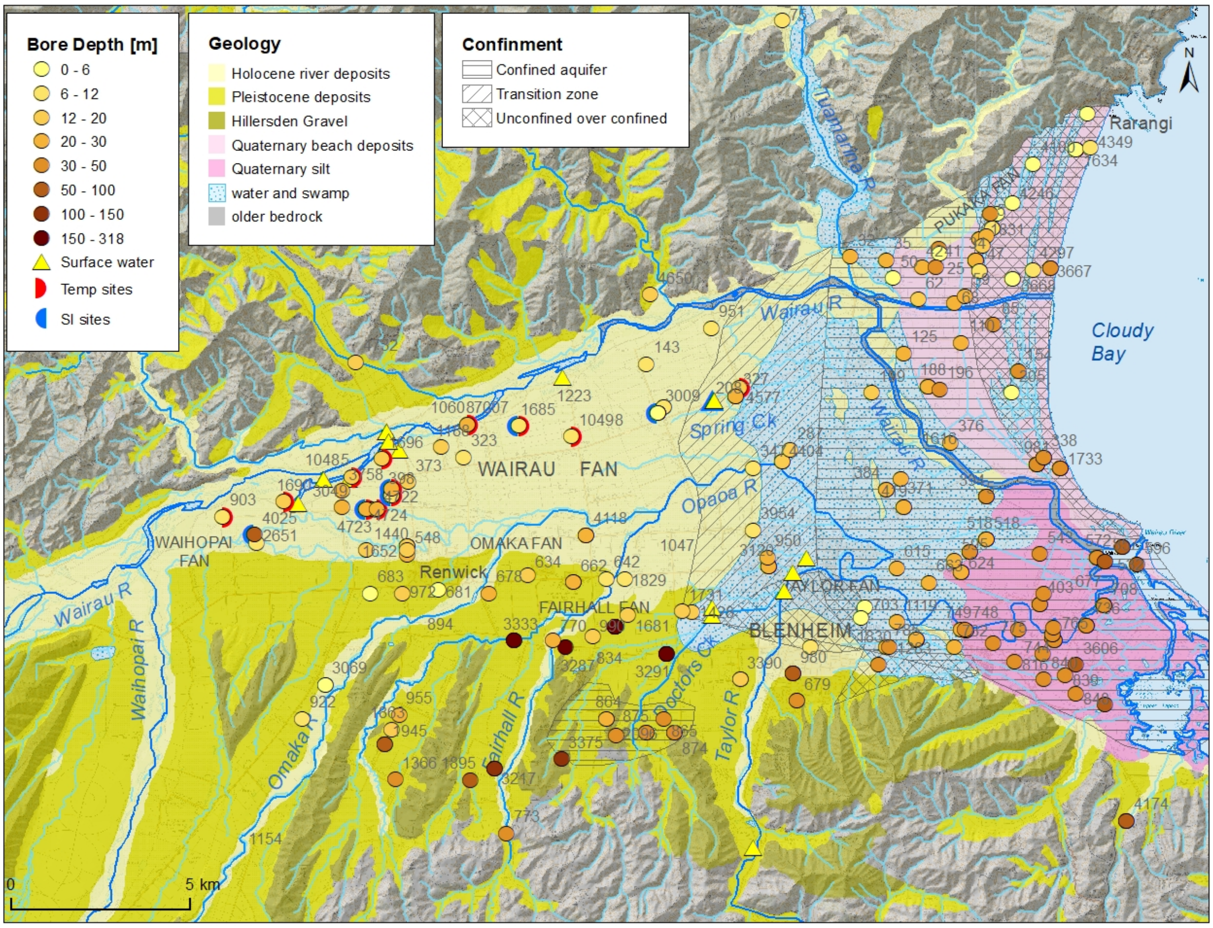

Figure 2.7 Well location and depth in the Wairau Plain aquifer. Confinement status from Taylor et al. (1992). 'SI' and 'Temp' denote sites with long-term stable isotope and temperature measurements (Section 4.1.1.2). Labels refer to well IDs in Appendix 1.

It is estimated that over 5,000 wells have been drilled in the Wairau Plain since the 19th century, mainly for crop irrigation or rural domestic drinking supplies. Most of the wells were drilled in the areas with the largest population, and where the significant aquifers occur. Many wells no longer exist, as they either did not produce enough, have been replaced with deeper wells during droughts or have been filled in following land subdivision for residential settlement or other changes in land use. MDC has kept a record of the drilling information for all wells, irrespective of how successful the wells were. This information on aquifer lithology and yield has been valuable in informing various hydrogeologic models of the Wairau Plain aquifers (Raiber et al. 2012; Wöhling et al. 2017).

Wells tapping the Wairau Aquifer conform to a standard design, a vertical mild steel pipe with a screen at the base to let the groundwater in at the most productive aquifer strata. Wells range in depth from < 10 m to up to 400 m, typically around 20 m. The deepest well drilled to date is the 400-m deep test well constructed in the Omaka-Hawkesbury Valley by MDC in 1995. Well depths have generally increased slightly over time, reflecting a small decreasing trend in groundwater levels and a desire by well owners to have a more reliable water supply.

In the Wairau Aquifer, the most productive strata are the Holocene gravels close to the surface (Figure 2.7). Therefore, only shallow wells exist in this area. Shallow wells also exist in unconfined or riparian aquifers at Rarangi (Figure 2.7). They are typically less than 10 m deep and have small diameters, as their predominantly domestic use requires only low abstraction rates. Shallow wells also exist near waterways, for example, within the spring belt. Wells in the

Southern Valley tapping the Pleistocene sediments are constructed differently due to the stratified and low-yielding nature of the sediments, including limited recharge from local ephemeral rivers. Wells intercepting the deeper layers can be up to 300 m deep, with very long screens to take advantage of limited inputs of groundwater from multiple layers rather than a single discrete water-bearing lens.

In the Pleistocene deposits between Blenheim and Renwick are a number of deep wells, drilled into the Deep Wairau Aquifer following the 1997/98 summer drought. These wells contain extremely old water, up to 40,000 years old (Selzer et al. 2015), indicating limited active recharge of this aquifer.

Groundwater is the source for municipal drinking water supplying the towns of Renwick and Blenheim, with well fields of large wells with large pumps. Agricultural and urban activitiesand septic tanks in densely settled areas pose a contamination risk to the drinking water supplies.

One of MDC's key functions is to monitor the state of the groundwater resources with respect to quality and quantity. In the Wairau Plain, eight wells are part of the National Groundwater Monitoring Programme, and the council has a network of 25 wells that are part of the 'State of the Environment' monitoring of the main economic aquifers. Most of these wells are used for continuous measurement of groundwater level variations and are fitted with automatic loggers that record and send information about the aquifer at that site to the Council at 15-minute intervals. Some of these wells also log temperature and electrical conductivity, especially along the coastal margin to provide early warning of seawater intrusion that could affect the freshwater aquifers. All of these monitoring wells are sampled quarterly for major ions and nutrients, and occasionally for advanced tracers such as age tracers, stable isotopes and radon.

The Wairau Plain Aquifer monitoring network is somewhat biased in terms of depth. As the most productive strata are the Holocene gravels close to the surface (Figure 2.7), only shallow wells exist in this area, making it difficult to obtain samples from deeper strata. On the other hand, wells in the Southern Valley tapping the deeper Pleistocene sediments have long screens due to low water yield, so samples from these represent an average value across the profile of the hole and not at a specific level or aquifer.

In addition to the permanent network that will stay in existence in perpetuity and measure longer-term trends and spatial patterns, MDC also operate temporary logger sites as part of short-term specific investigations. At Pauls Road next to the Wairau River, the council drilled two wells of differing depths to measure differences in groundwater pressure and chemistry/age to better understand the exchange between river water and groundwater and the recharge of the aquifer. The council have also excavated shallow pits in the Wairau River bed near the SH 6 road bridge to investigate whether the gravels are saturated and if there are preferred flow pathways. This showed that the gravels were fully saturated everywhere and confirmed the likelihood of open framework gravels that transmit groundwater at preferential flow paths and high rates.

The Wairau Aquifer, which represents the largest groundwater resource in Marlborough, receives the bulk of its recharge water from Wairau River channel leakage reaching from opposite the Waihopai River confluence to Selmes Road (Figure 2.3). Measuring the difference in channel flow along the so-called recharge reach has been used by MDC to study the recharge mechanism for many decades to identify any changes in the recharge pattern. Unfortunately, the channel flow loss method has insufficient precision in braided gravel river beds due to large errors in flow measurements and underflow that is not captured.

Water levels over time for three representative sites, together with Wairau River flow, are shown in Figure 2.8. Wells 398 and 3821, and well 3009, lie in the unconfined Wairau Fan, with wells 398 and 3821 close to the recharge area near the Wairau River and well 3009 near the discharge area at Spring Creek. Well 1733 lies near the coast and taps into the confined aquifer in the centre of the Wairau Valley (Figure 2.7).

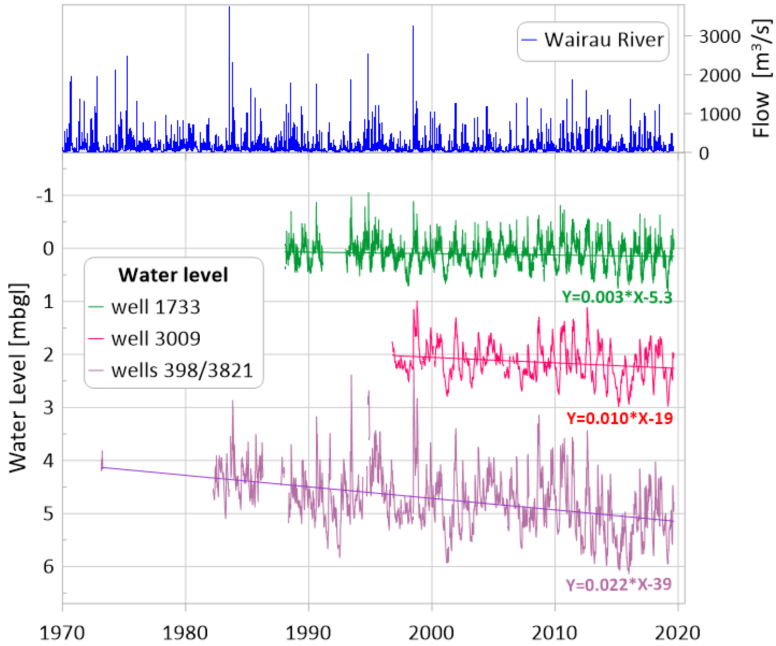

Figure 2.8 Water levels at representative sites, together with Wairau River flow at Tuamarina (for locations, see Figure 2.7). Lines are linear fits. Unconfined Wairau Fan: wells 398 and 3821 lie close to the recharge area, and well 3009 lies near the discharge area at Spring Creek. Confined aquifer: well 1733 lies near the coast.

Declining water levels are characteristic at all the sites during dry periods, which is indicated by decreased river flow around, for example, 2015. This is thought to be due to a number of reasons: decreased aquifer recharge from the river at lower river levels due to decreased pressure head and area of wetted gravel through the losing reaches, and increased abstraction of water from the aquifer during these dry periods. Water levels nearly recover in the following wet period, but in the unconfined aquifer a long-term decrease is obvious. Up until now, water levels in the confined aquifer show only an insignificant long-term trend of decline.

Figure 2.9 shows the close hydraulic connection between Spring Creek and the river-recharged Wairau Fan. Spring Creek flow closely mimics the water levels in the unconfined Wairau Fan. Shown for comparison are the water levels at wells 398 and 3821 near the river recharge area. A similar correlation between Spring Creek flow and water level is observed for well 3009 near the discharge area of Spring Creek (Davidson and Wilson 2011).

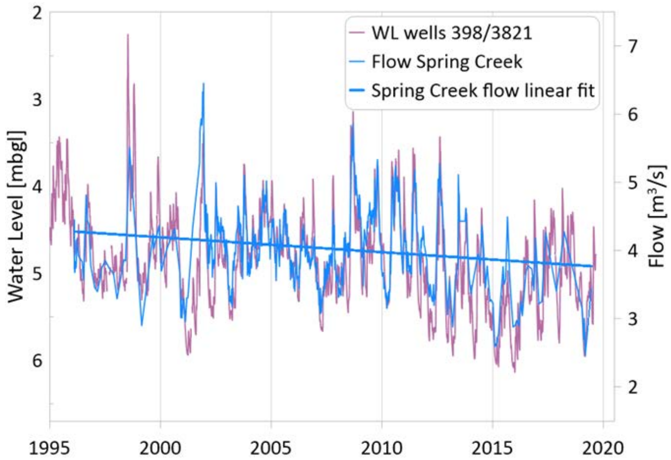

Figure 2.9 Water level in the unconfined Wairau Aquifer near the river recharge area, and Spring Creek flow.

Figures 2.8 and 2.9 demonstrate the main groundwater issue in the Wairau Plain – declining water levels in the unconfined aquifer and, in response to that, declining Spring Creek flow. The decline in water level at wells 398 and 3821 near the recharge area is about 1 m since 1973. The water level record of well 3009 near the discharge at Spring Creek is shorter, but indicates a rate of decline of about half of that. The observed decline in Spring Creek flow is about 0.5 m^3/s through the recent 24 years.

3.0 METHODS

To understand the flow dynamics and recharge sources of the Wairau Plain groundwater, we utilised various environmental tracers such as age tracers, the stable isotopes of the water, hydrochemistry, temperature, and argon and nitrogen.

3.1 Groundwater Dating

The methods for groundwater dating in the Southern Hemisphere are described in Morgenstern and Daughney (2012). Groundwater dating utilises convolution of a known time-dependent tracer input via the rain into the groundwater with a suitable system response function and matching to the tracer concentration measured in the groundwater. A range of groundwater age tracers are available (Beyer et al. 2014); they should be applied in a complementary way, as application of a single tracer can result in ambiguous interpretations. Multi-tracer approaches can improve the robustness of the age interpretation and help us to understand groundwater recharge processes. We routinely use the most robust and cost-effective age tracers in New Zealand, i.e. tritium, SF_6, CFCs and Halon-1301 (Figure 3.1).

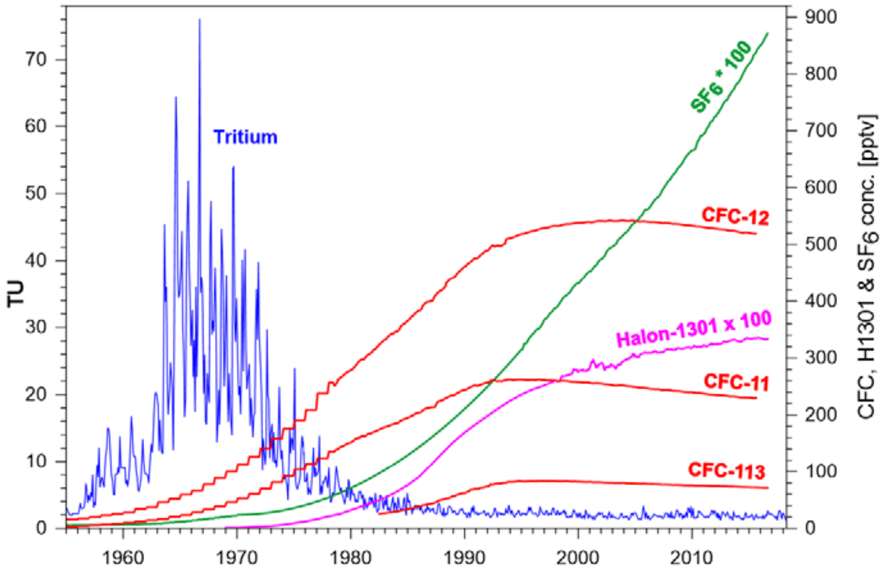

Figure 3.1 Tritium, CFCs, Halon-1301 and SF_6 input for New Zealand rain. Tritium concentrations are in rain at Kaitoke, 40 km north of Wellington (monthly samples), and CFCs, Halon-1301 and SF_6 concentrations are for southern hemispheric air. TU=1 represents a $^3H/^1H$ ratio of 10^{-18}, and 1 pptv is one part per trillion by volume of CFCs, Halon-1301, or SF_6 in air, or 10^{-12}. Pre-1978 CFC data are reconstructed using methods of Plummer and Busenberg (1999) and scaled to the southern hemisphere by a factor of 0.83 (CFC-11) and a factor of 0.9 (CFC-12). Post-1978 CFC data are from Tasmania. Pre-1970 SF_6 data are reconstructed (USGS Reston), 1970–1995 data are from Maiss and Brenninkmeijer (1998), and post-1995 data were measured in Tasmania. Halon-1301 data are from Beyer et al. 2017.

The measured tracer output concentration in the groundwater (C_{out}) is compared to its historical input (C_{in}) using the convolution integral:

$$C_{out}\,(t) = \int_0^\infty C_{in}\,(t-\tau)\,e^{-\lambda\tau}\,g(\tau,\mathrm{f})\,d\tau \qquad \text{Equation 1}$$

where t is time of observation, τ is transit time (age), $e^{-\lambda\tau}$ is decay term with λ being $\ln(2)/T_{1/2}$ (radioactive decay of tritium with a half-life $T_{1/2}$ = 12.32 yrs), and $g(\tau,f)$ is system response function (Maloszewski and Zuber 1982, 1991; Zuber et al. 2005; Cook and Herczeg 1999). The response function describes the distribution of ages within the water sample, for example, arising from mixing of groundwater of different ages within the aquifer or at the well. The two most commonly employed response functions are the dispersion model and the exponential piston flow model (Zuber et al. 2005). The exponential piston flow model is a combination of the piston flow model, which assumes piston flow in a single flow tube with minimal mixing of water from different flow lines at the discharge point (e.g. confined aquifer), and the exponential model, which assumes full mixing of water from different flow paths with exponentially distributed transit times at the groundwater discharge point (e.g. mixing of stratified groundwater at an open well in an unconfined aquifer).

The various response functions are described in Zuber et al. (2005) and Cook and Herczeg (1999). For age interpretation of the Wairau Plain dataset, we used the exponential piston flow model. Stewart et al. (2017) showed that this model covers the age distributions of typical groundwater discharges. The exponential piston flow model response function is given by:

$$g(\tau) = 0 \quad \text{for } \tau < t_t(1- f) \qquad \text{Equation 2}$$

$$g(\tau) = (f\ t_t)^{-1} \exp\left[-(\tau / f t_t) + (1/f) - 1)\right] \quad \text{for } \tau > t_t(1- f) \qquad \text{Equation 3}$$

where t_t is the mean residence time (MRT), f is the ratio of the volume of exponential flow to the total flow volume at the groundwater discharge point, and $t_t(1-f)$ is the time water takes to flow through the piston flow section of the aquifer (Maloszewski and Zuber [1982] use the variable η; η=1/f). The model with f = 0 becomes equivalent to the piston flow model and, with f = 1, becomes equivalent to the exponential model.

The two parameters of the response functions, t_t specifying the mean and f the distribution of transit times, are determined by convoluting the input (tritium concentration in rainfall) to simulate passage through the hydrological system in such a way as to match the output (e.g. tritium concentration in wells or springs).

Starting with the work by Taylor et al. (1992), an informative tracer dataset has been established over decades for the Wairau Plain groundwater, including tritium time series that encompass the passage time of tritium from nuclear weapons testing through the groundwater system, which is particularly sensitive to the mixing processes. Around 50 wells have such time-series tritium data, which is useful for constraining both parameters of the age distribution, the mean residence time and the mixing parameter. ^{18}O proved very efficient for constraining the recharge source of the groundwater (river versus local rain), and tritium time-series data from the rivers helped to constrain the tritium input signal in the absence of rain data. The tritium data of the young groundwaters (< 30 years) in the 1980s was ambiguous in age interpretation at the time due to the still overwhelming presence of bomb-tritium. With the continued tritium monitoring and complementary application of CFCs and SF_6, most of the historic data can now be interpreted to provide groundwater ages.

To give an overview of the history of tracer studies in the Wairau Plain, Figure 3.2 shows tritium, SF_6 and CFC tracer analyses over time. The first comprehensive tritium sampling programmes started in the late 1960s, immediately after the spike in tritium from weapons testing arrived within rain in New Zealand and continued throughout the 1970s. A large tritium and isotope sampling programme was carried out in 1988–89 to clarify and extend interpretation of earlier data. With the onset of the gas age-tracer analyses at GNS, CFCs were also measured in selected groundwater samples since 2002, and SF_6 since 2005. After 2010, tritium samples were also collected again from surface waters (rivers and streams) as by then the decay of the bomb-tritium to insignificant concentrations meant that the data from surface water could provide interpretation of water ages. The age-tracer data was collected through various programmes at MDC and, at GNS, through the National Groundwater Monitoring Programme and the National Tracer Survey. Without the availability of such comprehensive tritium time-series and multi-tracer monitoring programmes, it would be difficult to understand the dynamics of groundwater movement through the aquifers.

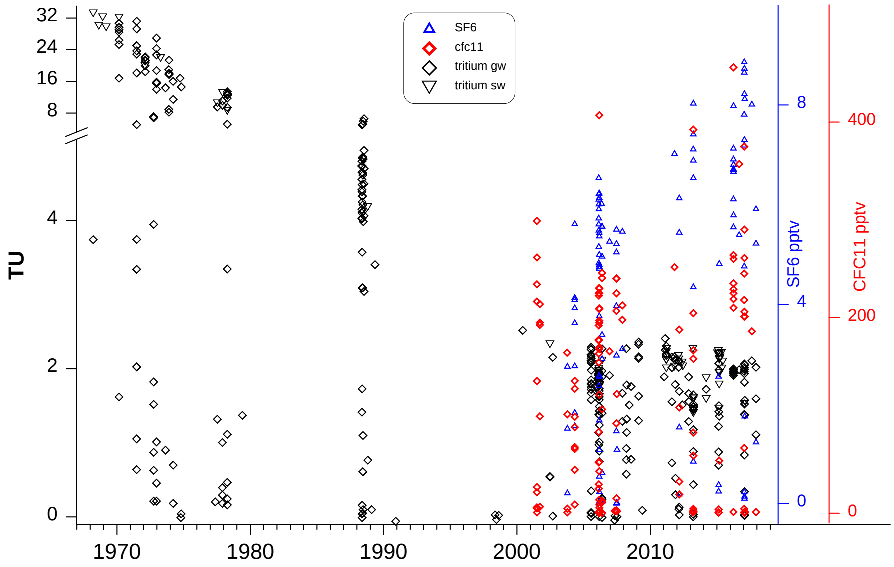

Figure 3.2 Available tritium, SF_6, and CFC tracer data over time from Wairau Plain groundwaters. Tritium samples are from groundwater (gw) and surface water (sw).

We used the Exponential Piston Flow Model (EPM) to account for mixing of groundwater with different flow-path lengths, and therefore different ages. For wells with insufficient time-series data to constrain both parameters of the age distribution, we estimated the mixing parameter according to Morgenstern and Daughney (2012); for wells with a long well screen interval in unconfined conditions, a high fraction of exponential (mixed) flow of 80–95% was applied; and for wells with a narrow screen interval in confined conditions, a lower fraction of exponential flow of 50–60% was used.

3.1.1 Age Tracers

Tritium is produced naturally in the atmosphere by cosmic rays. In addition, large amounts of tritium were released into the atmosphere in the early 1960s during the atmospheric thermonuclear weapons testing, giving rain and surface water high tritium concentrations at that time (Figure 3.1). Surface water becomes separated from the atmospheric tritium source when it infiltrates into the ground; the tritium concentration in the groundwater then decreases over time due to radioactive decay and is therefore is a function of the time the water has been underground (age).

Tritium, with its pulse-shaped input, is a particularly sensitive tracer for identifying the two unique age distribution parameters via the delay and the dispersion of the bomb-pulse in the groundwater compared to the rain input. This approach is particularly useful for age interpretation of wells with little other information on mixing of groundwater from varying depths and of different ages. The superimposed bomb-tritium can very sensitively identify water recharged between 1960 and 1975, enabling identification of complicated age distributions in groundwaters, e.g. from multi-screen wells, if tritium time-series and/or multi-tracer data are available.

Tritium has now become the most robust groundwater dating tool in New Zealand. Tritium is part of the water molecule and has no sources or sinks in the groundwater system through chemical processes. The relatively small amount of bomb-tritium that mixed from its northern hemispheric sources into the southern hemisphere (Taylor 1968) has now decayed and, since about 2010, no longer results in ambiguous age interpretations for New Zealand hydrologic systems. Figure 3.3 shows the tritium output of a typical transfer function for New Zealand in comparison to that of Vienna, which is typical for the mid-latitude continental northern hemisphere. Dashed lines show the tritium output 10 years ago, when still-significant levels of bomb-tritium were present in the groundwater systems. In New Zealand, a monotonous decline in tritium output versus MRT was already observed 10 years ago, allowing determination of unique groundwater ages with a single tritium measurement. In the northern hemisphere, there is still a significant amount of bomb-tritium present in the groundwater systems, requiring complementary age tracers (SF_6, helium-3) or tritium time-series data to find unique ages. However, from Figure 3.3, it can be derived that in the coming years, the bomb-tritium will also have declined sufficiently in the northern hemisphere, similar to the situation in New Zealand in 2010, to allow determination of unique ages from single tritium measurements, including surface water dating where no complementary age tracers are available.

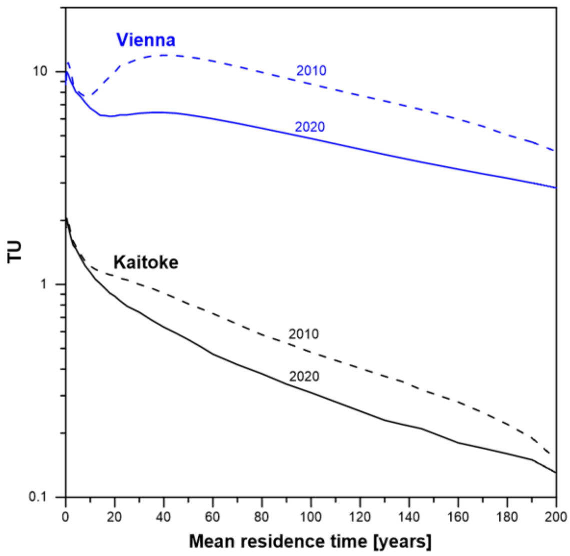

Figure 3.3 Tritium output for a typical transfer function of 80% exponential flow volume within an exponential piston flow model (EPM), calculated using the Kaitoke (New Zealand) and Vienna (Europe) tritium input. Solid lines are current tritium output, dashed lines are previous tritium outputs from 10 years ago for comparison to show the decline of the bomb-tritium.

Tritium now also enables dating of river and stream water over time scales of years and decades. No other readily available tracer is able to date surface water, as other tracers are significantly altered when the groundwater is exposed to air. In other parts of the world, the application of accurate and robust groundwater dating for the understanding of hydrological systems on large scales, with respect to groundwater lag times, storage, recharge, hydrochemical evolution, and land use versus geologic impact on groundwater quality, is still more complicated because bomb-tritium remains present. Therefore, these new opportunities offered by the tritium method in New Zealand are currently leading to needed improvements in the understanding of hydrologic systems (McDonnell 2017).

To provide the tritium input into New Zealand hydrologic systems, tritium concentrations are measured in rainfall at Kaitoke, 40 km north of Wellington (monthly values, Figure 3.1). This data is used for locations around New Zealand by applying a scale factor to adjust for latitude, altitude and coastal influence. The scale factor is deduced from an additional eight New Zealand rain records at least two years in length.

Chlorofluorocarbons (CFCs) are entirely man-made contaminants. They were mainly used for refrigeration and pressurising of aerosol cans, and their concentrations in the atmosphere gradually increased until the mid-1990s (Figure 3.1). CFCs were then phased out of industrial use because of their destructive effects on the ozone layer. Thus, rates of increase of atmospheric CFC concentrations slowed greatly in the 1990s and concentrations are now decreasing, meaning that CFCs are not as effective for dating water recharged after 1990. CFCs are relatively long-lived and slightly soluble in water, and therefore enter the groundwater systems with groundwater recharge. Their concentrations in groundwater record the atmospheric concentrations when the water was recharged, allowing determination of the recharge date of the water.

Another chemical compound, **Halon-1301 ($CBrF_3$)**, holds promise to remain a more efficient age tracer, with still slightly increasing concentrations in the atmosphere (Figure 3.1) and absence of local contamination sources that interfere with the dating (Beyer et al. 2017). Halon-1301 has been used as a refrigerant gas and fire suppressant agent in the mid-1990s but also faces production restriction due to its ozone-depleting effect.

Sulphur hexafluoride (SF_6) is primarily anthropogenic in origin but can also occur in some volcanic and igneous fluids. Significant production of SF_6 began in the 1960s for use in high-voltage electrical switches, leading to increasing atmospheric concentrations (see Figure 3.1). The residence time of SF_6 in the atmosphere is extremely long (800–3200 years). It holds considerable promise as a dating tool for post-1990s groundwater because, unlike CFCs, atmospheric concentrations of SF_6 are expected to continue increasing for some time (Busenberg and Plummer 2000), as evidenced by the recent more-than-linear increase, which makes SF_6 a very sensitive tool for dating young groundwater.

3.1.2 Tracing Seasonal Variability Signals

Several parameters of river and stream water vary throughout the seasons, including temperature and stable isotope ratios. As the Wairau River is a main water source of the Wairau Plain Aquifer, these seasonal variabilities from the recharge source may be traceable through parts of the aquifer, at least near the recharge source where the water is very young (<< 1 year). Further down-gradient, these seasonal variability signals will become undetectable due to damping in the groundwater system. The delayed arrival of the seasonal variability (lag) and the damping of the amplitude at the groundwater wells or springs are related to groundwater age.

Groundwater temperature is a non-conservative tracer because it lags behind the water flux due to the thermal mass of the aquifer material. However, if the seasonal temperature input variability is still traceable in groundwater, its phase shift to the input signal (river temperature) can provide a minimum groundwater age.

Along the groundwater flow through the aquifer, modification of the temperature input signal by the ground surface temperature at the discharge point (well, spring), or anywhere along the water flow path, can interfere with the use of temperature variability as an indicator of groundwater age. However, the seasonal ground surface temperature variation does not penetrate into the ground significantly beyond 4 m depth and shows a phase shift of c. 6 months at a depth of 2–3 m (Florides and Kalogirou 2004). This pattern of seasonal temperature phase shift and damping from the ground surface temperature would not be expected to correlate with water travel-time along the groundwater flow path. Increasing damping of the amplitude of the temperature variability along the water flow path with increasing distance from the recharge source would indicate that the seasonal temperature variability is not caused by thermal flux from the surface.

Close et al. (2017) assessed temperature logs from 17 wells in the recharge zone of the Wairau Aquifer. Sinusoidal temperature responses in the wells ranged from 0.2 to 15.1°C, close to that of the river temperature variability of 15.8°C. The lags of the temperature signals to that of the river ranged from one day to nearly a year, decreasing with distance from the river recharge source. These results show clearly the potential of temperature as a tracer for water transit time through the Wairau aquifer.

The stable isotopes of the water are considered conservative tracers of the water flow because there are no sources or sinks in the groundwater system that could alter their ratios. If groundwater is sufficiently young and the seasonal stable isotope variability from the recharge source is still measurable, the phase shift of the measured seasonal signal and the damping of the amplitude can provide information about the travel time of the water through the aquifer.

Application of both temperature and stable isotope variability enables calibration of the temperature lag to 'true' water transit time. The retardation of the phase shift between the temperature and the stable isotopes is expected to be independent of flow path length and distance to the river source if the ratio of water to rock (porosity) is relatively constant. Measurement of temperature variability using down-hole temperature loggers is easier than measurement of the seasonal stable isotope variability, which requires frequent sampling and analyses. By calibrating the temperature variability to the stable isotope variability, temperature logger data can directly be converted to 'true' groundwater transit times.

3.1.3 Radon

Radon-222 (^{222}Rn) gas is a radioactive decay product of uranium, which is ubiquitous in almost all rocks and soils. Groundwaters, in a closed system in contact with these rocks, accumulate ^{222}Rn released from the minerals, resulting in elevated ^{222}Rn concentrations in the groundwater. Radon concentrations in the groundwater are a result of equilibrium between ^{222}Rn delivery and radioactive decay (half-life 3.8 days) and can vary considerably depending on the uranium content and the radon emanation potential of the aquifer material. In surface waters, ^{222}Rn concentrations are low because of limited contact with its source and because of decay and degassing into the air.

This contrast between high ^{222}Rn concentrations in groundwater and low concentrations in surface water allows the identification of fresh groundwater discharges into surface water, as indicated by elevated ^{222}Rn concentrations in the river water. Conversely, fresh river water recharge into groundwater systems is indicated by low ^{222}Rn concentrations in groundwater, as it takes approximately three weeks (5–6 half-lives) for the ^{222}Rn to equilibrate to the ambient concentration of the groundwater. Close et al. (2014) used the ^{222}Rn technique in the Wairau Plain groundwater to identify young (days to weeks) groundwater and estimated groundwater flow velocities of up to 94 m/day in an area with high hydraulic conductivity.

We have measured ^{222}Rn in Wairau Plain groundwater through various monitoring projects, starting in 2007 with the National Groundwater Monitoring Programme (NGMP) survey, to assess the distribution of ^{222}Rn equilibrium concentration in the area and identify wells with ^{222}Rn concentrations below equilibrium, indicative of the presence of young (up to weeks) groundwater.

3.2 Stable Isotopes of the Water

The stable isotope signature of meteoric water depends on the history of the water masses with regard to temperature-dependent kinetic processes, such as evaporation of the water from the sea and re-precipitation. For example, rivers from colder, higher-altitude catchments usually have a more negative isotope signature than local low-altitude rain near the coast, allowing us to distinguish whether groundwater recharge is derived from the river or from local rainfall.

This Wairau Plain study relies on ^{18}O data, but some river and groundwater samples were measured for ^{2}H. The relationship between ^{18}O and ^{2}H was assessed by Taylor et al. (1992). The data show a regular relationship, with some scatter around the global meteoric water line. To establish precipitation processes within the Wairau River catchment and a local meteoric water line in more detail, more ^{2}H data would be required. However, for the purpose of this study of distinguishing between recharge source from the river versus local rain, ^{18}O alone is sufficient.

Taylor et al. (1992) showed trends for the ^{18}O data: most negative ^{18}O ratios in the Wairau River match ratios in the groundwaters near the river and transition along the flow path toward the coast to less negative ^{18}O ratios, indicating increasing contribution of recharge from local rain. Stewart (2008) established the mixing fraction between river water and local rain water, but concluded that, because the river and groundwater close to the river showed significant temporal variability, mean values are required.

3.3 Hydrochemistry

The hydrochemical composition of groundwater reflects its recharge conditions and evolutionary flow pathways. Various land-use activities or geologic formations can result in specific groundwater chemistry signatures that can be traced back to recharge source or area. Increasing ion concentrations of the water due to leaching from the aquifer material can indicate flow pathways and groundwater processes.

Using Hierarchical Cluster Analysis (HCA), we assessed variations in the hydrochemical composition of the groundwaters within the Wairau Plain and their potential for distinguishing between different recharge sources (e.g. local rain versus river recharge) and identification of flow-evolutionary processes. HCA is a multivariate statistical method that categorises the chemistry data into hydrochemical units based on similarities in selected characteristics.

Approaches for HCA were based on best-practices from previous experience in New Zealand and overseas (e.g. Güler et al. 2002; Daughney and Reeves 2005). HCA was initially conducted using the nearest-neighbour linkage rule. This approach identifies sites where hydrochemistry is most different from other sites. However, no sites were identified as potential outliers in the dataset. Following this, HCA was then conducted using Ward's linkage rule (Ward 1963). Ward's method is based on an analysis of variance and produces smaller distinct clusters than other linkage rules, in which each site in a cluster is more similar to other sites in the same cluster than to any site assigned to a different cluster. The square of the Euclidean distance was used in HCA as the measure of similarity for both linkage rules.

The hydrochemistry data for the Wairau Plain groundwater samples were obtained from two sources: historical data provided by MDC, including State of Environment monitoring data, and historical data provided by GNS through the National Groundwater Monitoring Programme. Some wells had data collected multiple times, while others had data from only one sampling event. For the wells with multiple data, median values have been used in the HCA. These median values were calculated using the Excel spreadsheet calculator of Daughney (2007, 2010), which uses a log-probability regression method to estimate median values for datasets, in which up to 80% of results are below the detection limit. Sites that had been sampled only once were still included in the hydrochemical assessment to maximise the number of sites available. The appropriateness of this was checked by also performing the HCA on the sites with long-term data only. No difference in clustering was observed for wells with long-term data compared to those in which single samples were included.

Log-transformed and normalised concentrations of the ions Ca, Mg, Na, K, HCO_3, Cl, SO_4 and NH4, as well as dissolved silica and electrical conductivity, were used for the HCA. In total, 45 groundwater sites had data for all 10 of these parameters and were included in the HCA. Data for other parameters, such as pH, dissolved Fe, dissolved Mn, and P, were not available for all sites and therefore were not included in the analysis. Nitrate in groundwater is mainly a reflection of the land use in the recharge area and is considered separately for assessment of the recharge area. Excluding nitrate from the HCA better focuses on groundwater evolutionary processes. This made a slight difference in clustering, mainly between clusters 3 and 4, involving more evolved wells that show some signs of reverse anion exchange (Section 4.3.1).

3.4 Recharge Temperature and Excess Air

Recharge temperature (RT) and excess air (EA), derived from argon and nitrogen concentrations, can provide insight into the mechanisms controlling recharge. Ingram et al. (2007) found that EA concentrations are linked to the magnitude of fluctuations in groundwater level and used this relationship to delineate recharge sources and rates. River-recharged groundwaters, in areas where groundwater levels can be expected to show small fluctuations, can have lower EA concentrations than rainfall-recharged groundwater in areas with large groundwater level fluctuations. In the nearby Linkwater catchment in the Marlborough Sounds, Morgenstern et al. (2009) found a clear pattern of low EA in river-recharged groundwater and high EA in local rain-recharged groundwater related to larger water level fluctuations.

RT and dissolved EA have been derived from dissolved argon and nitrogen concentrations using the total dissolution model of Heaton and Vogel (1981). In this model, small bubbles of air entrapped in soil pores are completely dissolved into the groundwater under favourable recharge conditions, thus forming an EA component.

In other areas of New Zealand, this method of assessment of RT has enabled assessment of recharge sources and identification of paleo-groundwaters recharged during previous colder climates (Morgenstern et al. 2017). Such old paleo-groundwaters also occur in the Deep Wairau Aquifer, with lower RTs than today indicated by noble gas concentrations (Seltzer et al. 2015). However, deriving RT from only argon and nitrogen is not sufficient for such old groundwaters from highly anoxic environments where the gas composition, in particular nitrogen, may be modified. In addition, the stable isotope composition cannot corroborate the RT method in the Wairau Plain Aquifer due to anomalously low $\delta^{18}O$ ratios in parts of the aquifer (Section 4.3). Therefore, we have not further pursued this avenue.

3.5 Analytical Techniques

Activities of tritium were determined at GNS, New Zealand, using liquid scintillation in Quantulus™ ultra-low-level counters following vacuum distillation and electrolytic enrichment (Morgenstern and Taylor 2009). Tritium activities are expressed in tritium units (TU), in which 1 TU represents a $^{3}H/^{1}H$ ratio of 1×10^{-18}. Tritium enrichment by a factor of 95 at GNS yields a detection limit of 0.02 TU, and deuterium calibration of each sample ensures a 1% reproducibility of tritium enrichment. Relative precision (1 SD) of routine individual analyses are 1.8–2.3%. Tritium measurement of eight river water samples in 2015 was performed with a lower, just sufficient accuracy using lower tritium enrichment by a factor of 20.

Concentrations of CFCs (CFC-11, CFC-12, CFC-113), argon, nitrogen and methane were analysed using an analytical system like that of Busenberg and Plummer (1992); the analytical system for SF_6 is described in van der Raaij (2003). The CFC and SF_6 concentrations in Figure 3.1 are for southern hemispheric air (where 1 pptv is one part per trillion by volume of CFC, SF_6, or Halon-1301 in air, or 10^{12}).

Detection limits in terms of gas dissolved in water were 5 x 10^{-14} mol kg-1 water for CFCs, 1 x 10^{-16} mol kg-1 water for SF_6 and 3 x 10^{-16} mol for H-1301. Dissolved argon and nitrogen concentrations (analytical accuracy 1% and 3%, respectively) were measured to estimate the temperature at the time of recharge and the excess air concentration, as described by Heaton and Vogel (1981), for calculation of the atmospheric partial pressure (ppt) of CFCs and SF_6 at the time of recharge.

Radon-222 samples from groundwater and river water were collected in 20 mL glass vials with metal-lined lids. Due to the short half-life of radon, the samples were measured within a few days after sampling. We used liquid scintillation spectroscopy with 10 mL of sample water transferred into counting vials and mixed with a mineral-oil-based scintillant and radon absorber, followed by decay counting in a Quantulus™. Detection limits were typically < 0.1 Bq/L. The Radon-222 analytical technique was validated by an inter-laboratory comparison organised by Flinders University, Adelaide, in 2018.

The stable isotope ratios $^{18}O/^{16}O$ and $^{2/1}H$ are expressed as δ values and represent the difference in parts per thousand between isotope ratios in water relative to those in Vienna Standard Mean Ocean Water (V-SMOW): $\delta^{18}O$ (‰) = $[(^{18}O/^{16}O)_{sample}/(^{18}O/^{16}O)_{VSMOW} - 1] \times 1000$. $\delta^{2}H$ is expressed in a similar way. The stable isotope analysis was carried out in the Rafter Stable Isotope Lab at GNS using mass spectrometry.

For the measurement of dissolved oxygen in the field, optical probes were used that produce more robust data than membrane probes.